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Hydrogeology and Trichloroethene Contamination in the Sea-Level Aquifer Beneath the Logistics Center, Fort Lewis, Washington

Scientific Investigations Report 2005–5035

U.S. Department of the Interior
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Gale A. Norton, Secretary

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Charles G. Groat, Director

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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
acre	0.004047	square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	1	meter per meter
foot per year (ft/yr)	0.3048	meter per year
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
pound, avoirdupois (lb)	0.4536	kilogram

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Tritium units (TU) are used to report tritium concentration. One TU equals tritium concentration in picoCuries per liter divided by 3.22.

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

Abbreviations	Meaning
L/min	liter per minute
mL/min	millimeter per minute
pptv	parts per trillion by volume
pg/kg	picogram per kilogram

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Hydrogeology and Trichloroethene Contamination in the Sea-Level Aquifer Beneath the Logistics Center, Fort Lewis, Washington

By R.S. Dinicola

Abstract

The U.S. Army disposed of waste trichloroethene (TCE) and other materials in the East Gate Disposal Yard near the Logistics Center on Fort Lewis, Washington, from the 1940s to the early 1970s. As a result, ground water contaminated with primarily TCE extends more than 3 miles downgradient from the East Gate Disposal Yard. The site is underlain by a complex and heterogeneous sequence of glacial and non-glacial deposits that have been broadly categorized into an upper and a lower aquifer (the latter referred to as the sea-level aquifer). TCE contamination was detected in both aquifers. This report describes an investigation by the U.S. Geological Survey (USGS) of the source, migration, and attenuation of TCE in the sea-level aquifer.

A refined conceptual model for ground-water flow and contaminant migration into and through the sea-level aquifer was developed in large part from interpretation of environmental tracer data. The tracers used included stable isotopes of oxygen (^{18}O), hydrogen (^{2}H), and carbon (^{13}C); the radioactive hydrogen isotope tritium (^{3}H); common ions and redox-related analytes; chlorofluorocarbons; and sulfur hexafluoride. Tracer and TCE concentrations were determined for samples collected by the USGS from 37 wells and two surface-water sites in American Lake during 1999-2000. Ground-water levels were measured by the USGS in more than 40 wells during 2000-01, and were combined with measurements by the U.S. Army and others to create potentiometric-surface maps.

Localized ground-water flow features were identified that are of particular relevance to the migration of TCE in the study area. A ridge of ground water beneath American Lake diverts the flow of TCE-contaminated ground water in the sea-level aquifer to the west around the southern end of the lake. Tracer data provided clear evidence that American Lake is a significant source of recharge to the sea-level aquifer that has created that ridge of ground water. High ground-water altitudes at locations north and northeast of the Logistics Center combined with the ridge beneath American Lake prevent TCE contaminated water beneath the Logistics Center from migrating toward municipal water-supply wells northeast of the site.

The 1999-2000 TCE concentrations measured by the USGS at older wells screened in the sea-level aquifer were similar to those measured since 1995, but the known downgradient extent of the TCE contamination expanded nearly 2 miles after the Army installed and sampled new wells during 2003-04. Concentrations of TCE in the sea-level aquifer were consistently highest in the upper part of the aquifer throughout the plume, although TCE has spread throughout much of the thickness of the aquifer in the downgradient portions of the plume.

Environmental tracer data indicated that the primary pathway for contaminant migration into the sea-level aquifer is through the previously identified confining unit window, an area where the predominately fine-grained confining unit is relatively coarse grained and more permeable. Other less substantial pathways for contaminant migration also were identified near the East Gate Disposal Yard and the I-5 pump-and-treat facilities. Those areas are near active pumping wells and ground-water reintroduction facilities, but there is no evidence that the contaminant migration was caused or enhanced by those activities.

Within the sea-level aquifer, TCE concentrations continue to migrate westward in the flow field strongly influenced by ground-water recharge from American Lake. Historical data are not available to definitively determine if the 5-μg/L leading edge of the current TCE plume is stable or if it is still moving downgradient. However, an evaluation of the available data combined with TCE traveltime estimates indicates that the peak TCE concentrations in the sea-level aquifer may have not yet reached the wells near the currently defined leading edge of the plume. Hypothetically, the 5-μg/L leading edge of the current TCE plume will move farther downgradient in the years ahead.

Attenuation of TCE concentrations in the sea-level aquifer is most rapid near the confining unit window, but slows substantially farther downgradient in the current contaminant plume. Biodegradation of TCE is not an important attenuation mechanism in the sea-level aquifer. As the plume advances downgradient into previously uncontaminated areas, attenuation due to sorption likely will continue, but the longevity of sorption-related attenuation is uncertain. Conditions become more favorable for attenuation due to lateral and vertical dispersion and mixing in areas west of American Lake.

TCE concentrations already have been detected in two Army water-supply wells in the sea-level aquifer that are within the footprint of the existing contaminant plume, and there is a potential for TCE migration toward additional water-supply wells west of American Lake. The risk is low for TCE migration to a Fort Lewis backup supply well west of the lake, but the TCE plume possibly will migrate to a more distant public-water supply in the years ahead. However, the likelihood for detecting TCE at concentrations greater than the 5-μg/L drinking-water standard in that well is low.

Introduction

The U.S. Army disposed of waste trichloroethene (TCE) and other hydrocarbons in the East Gate Disposal Yard (EGDY) near the Logistics Center on Fort Lewis, Washington (fig. 1) from about the 1940s through the early 1970s. A substantial amount of TCE has migrated to ground water resulting in a dissolved-phase TCE plume that extends more than 2 mi to the northwest and west of the East Gate Disposal Yard source area. TCE contamination has been detected in the uppermost 300 ft of unconsolidated glacial and non-glacial deposits that underlie Fort Lewis. Those deposits have been broadly categorized into an upper and a lower aquifer type unit separated by a fine-grained confining unit; (U.S. Army Corps of Engineers, 2002). The upper aquifer type unit is referred to as the "upper aquifer" in this report and also is referred to locally as the Vashon aquifer. The lower aquifer type unit is referred to both locally and in this report as the "sea-level aquifer." Dissolved TCE has been measured in the upper aquifer beneath the East Gate Disposal Yard at concentrations exceeding 250,000 μg/L in a plume that extends about 13,000 ft to the northwest. Beneath the East Gate Disposal Yard, only trace amounts of dissolved TCE have been detected in the sea-level aquifer, but concentrations as high as 170 μg/L have been detected in a plume beginning 5,000 ft northwest of the disposal yard and extending westward more than 12,000 ft.

TCE contamination in the upper aquifer beneath the Logistics Center was first investigated in the mid-1980s, and the site was included on the Environmental Protection Agency's National Priorities List in December 1989. Additional studies led to a 1990 Record of Decision (ROD) for the site that selected ground-water extraction and treatment as the remedy for shallow ground-water contamination (U.S. Environmental Protection Agency, 1990). Active remediation of the upper aquifer at the site began in 1995 with the operation of two ground-water pump-and-treat systems; one near the East Gate Disposal Yard, and a second downgradient near U.S. Interstate 5 (I-5). Post-ROD characterization work (U.S. Army Corps of Engineers, 2002) found a substantial amount of non-aqueous phase liquid (NAPL) TCE beneath the disposal yard, so accelerated source-area remediation strategies were implemented. During 2001, buried drums and incidental soil were excavated from the disposal yard, resulting in the removal of an estimated 50,000 lb of non-aqueous phase TCE (Garry Struthers Associates, Inc., 2001). An in-situ thermal remediation system began operation in December 2003 to remove additional TCE from the vadose zone and upper aquifer. An estimated 140,000 lb of non-aqueous phase TCE remained beneath the disposal yard at the start of the thermal remediation project (U.S. Army Corps of Engineers, 2002).

TCE was detected in one of six wells screened in the sea-level aquifer that were sampled beneath the Logistics Center during the 1980s, so the ROD specified that additional investigations were needed. Additional investigations conducted in the early 1990s identified a TCE plume in the sea-level aquifer with concentrations as high as 160 μg/L (Ebasco Environmental, 1993; 1994). It was hypothesized that TCE was migrating from the upper aquifer to the sea-level aquifer through a more permeable "window" through the intervening confining unit, and that the TCE in the sea-level aquifer would migrate beneath American Lake and North Fort Lewis to eventually discharge into Puget Sound with little chance of impacting any existing water-supply wells. The ROD specified that a ground-water extraction and treatment system would be installed in the sea-level aquifer if contamination was detected, but the system has not been installed to date (2004). Instead, an Explanation of Significant Difference (ESD) was signed in 1998 that called for additional studies on the transport of contaminants into and through the sea-level aquifer, with particular regard to the possible effects that more aggressive source-area remediation may have on sea-level aquifer contamination (U.S. Environmental Protection Agency, 1998). This report describes the results of one such additional study conducted by the USGS on the transport of TCE into and through the sea-level aquifer.
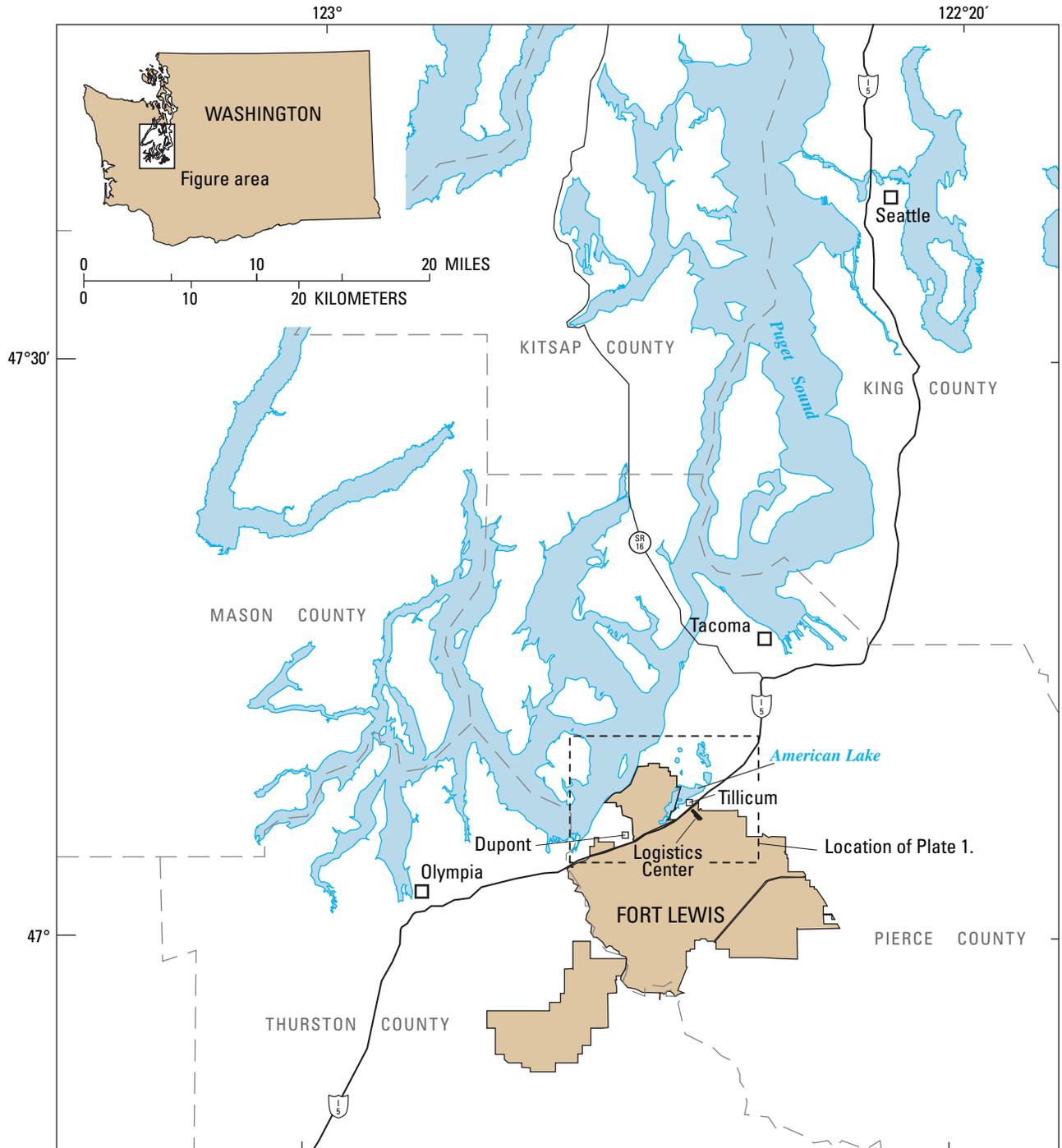
Figure 1.   Location of the study area and Logistics Center, Fort Lewis, Washington.

Purpose and Scope

The purpose of this report is to describe the source, extent, and possible future migration of TCE in the sea-level aquifer beneath the Logistics Center at Fort Lewis, Washington. This report presents an updated and expanded conceptual model for the hydrogeology, the current extent of contamination, and the current and potential migration of contamination into and through the sea-level aquifer. The conceptual model was developed using both new and historic data. The new data include water-level measurements, contaminant concentrations, and environmental tracer concentrations collected by the USGS and the Army during 1999 through 2004.

Description of Study Area

The study area includes the Fort Lewis Logistics Center and other Federal and non-Federal lands to the west and northwest of the Center (fig. 1). Fort Lewis is an 86,176-acre facility about 10 mi south of the city of Tacoma in the Puget Sound lowlands of western Washington. The Logistics Center is near the northeast corner of Fort Lewis. Fort Lewis is bordered on the north by McChord Air Force Base and suburban and urban development; on the east and south by rural areas, forested land, and several small communities; and on the west by Puget Sound, the rural Nisqually Indian Reservation, and the growing city of Dupont. Fort Lewis is bisected by I-5, and the northern part is divided by the town of Tillicum and the 1,150-acre American Lake.

Fort Lewis sits atop a gently rolling upland plain about 200 to 300 ft above sea level and is underlain by more than 1,000 ft of unconsolidated glacial and inter-glacial sediments (Jones, 1999). The physiography of the region is primarily a result of the last Pleistocene glaciation that ended about 13,000 years ago. Much of the ground surface in the study area is coarse-grained glacial-outwash derived soils that retain little water, generate little runoff, and are excessively well drained.

Fort Lewis has a temperate marine climate characterized by warm dry summers and cool wet winters. January is the coolest month with average maximum and minimum temperatures of 36 and 48°F and August is the warmest with average maximum and minimum temperatures of 55 and 77°F. Mean annual precipitation is about 40 in., 76 percent of which falls from October through March. Snowfall is infrequent and rainfall generally is not intense.

Hydrogeologic System

This description of the study area hydrogeologic system was condensed primarily from Borden and Troost (2001) and from various Fort Lewis site reports. The description also reflects unpublished communications with the Fort Lewis Working Group that includes personnel from Fort Lewis, USGS, U.S. Army Corps of Engineers Seattle District, Pacific Northwest National Laboratory, and U.S. Environmental Protection Agency. The hydrogeologic system description in this report focuses on the sea-level aquifer; the upper aquifer near the East Gate Disposal Yard is described in detail in U.S. Army Corps of Engineers (2002).

Generalized Stratigraphy

Borden and Troost (2001) expanded and modified the understanding of Pleistocene stratigraphy south of Seattle in the Puget lowland, and the nomenclature from that report is used in this report. The modified stratigraphic sequence generally is comparable to that described in previous Fort Lewis reports, but new units in the lower part of the upper aquifer have been delineated, and the confining unit between the upper and sea-level aquifers has been correlated to a different formation.

The study area is underlain by a complex and heterogeneous sequence of glacial and non-glacial deposits (fig. 2) that have been broadly categorized into an upper aquifer (also referred to as the Vashon unconfined aquifer) and a lower aquifer (also referred to as the sea-level aquifer). The upper aquifer is continuous throughout the study area, generally is unconfined, and ranges in thickness from about 100 to 200 ft. Three mostly continuous aquifer type units and three discontinuous confining type units have been identified in the upper aquifer, although the lower two aquifer type units are difficult to differentiate in most drillers' logs from Fort Lewis. In this report, the uppermost aquifer type unit in the upper aquifer is referred to as the Qv(1) unit, and the lower two aquifer type units are referred to as the Qv(2) unit.

The upper aquifer is underlain by a regionally extensive, but locally breached confining unit composed of as much as 30 ft or more of primarily fine-grained non-glacial sediments (referred to the Qpon unit in figure 2). This unit and similar massive, organic-rich clayey units throughout central Pierce County commonly have been referred to as the Olympia-aged Kitsap Formation. Use of that term is now discouraged because the ages and correlation of the units throughout the region are uncertain. The Qpon unit is locally breached by younger erosional features.

Vashon recessional outwash, unit Qv	Interbedded brown to gray sandy gravel and sand with minor silt interbeds	Qv(1) unit in this report	Upper aquifer (Vashon unconfined aquifer)
Vashon till and ice contact deposits, unit Qv	Dense, gray, silty sandy gravel and gravelly sandy silt, generally matrix supported	Discontinuous confining unit	
Vashon advance outwash, unit Qv	Interbedded brown to gray sandy gravel and sand with minor silt interbeds	Qv(2) unit in this report	
Glaciolacustrine silt/clay (Lawton Clay), unit Qv	Gray, laminated to massive silt and clayey silt with minor fine sand interbeds	Discontinuous confining unit	
Olympia beds, unit Qob	Mottled, massive, organic-rich, clayey, sandy gravel (mudflows) or lavender silt, peat, sand, and gravelly sand (fluvial and overbank deposits)	Discontinuous confining unit	
Pre-Olympia drift, unit Qpog	Gray-brown, fine to medium-grained sand with minor sandy gravel interbeds, oxidized at top; common silt interbeds at base, rare and discontinuous till	Qv(2) unit in this report	
Second nonglacial deposits, unit Qpon	Mottled, massive, organic-rich, clayey, sandy gravel (mudflows) or lavender silt, peat, sand, and gravelly sand (fluvial and overbank deposits)	Confining unit (locally breached)	
Third glacial drift, unit $Qpog_2$	Interbedded orange to dark gray sandy gravel and sand with minor silt interbeds, intensely iron-oxide stained at top		Lower aquifer (Sea level aquifer)
	Dense, gray, silty sandy gravel and gravelly sandy silt, generally matrix supported (till)	Discontinuous confining unit	
	Interbedded gray-brown to dark gray sandy gravel and sand with minor silt interbeds		
Third nonglaial deposits, unit $Qpon_2$	Lavender silt, peat, sand, and gravelly sand (fluvial and overbank deposits)	Confining unit	

Figure 2.   Generalized stratigraphy and hydrogeologic units for west-central Pierce County, Washington. (Adapted from Borden and Troost, 2001.)

The Qpon confining unit is underlain by the sea-level aquifer composed of 80 to 200 ft of glacial deposits (referred to the $Qpog_2$ unit in figure 2). That aquifer is so-named because the altitude of the top of the unit is near sea level. Three separate subunits in the sea-level aquifer have been described, including a water-bearing recessional outwash, a compact lodgement till, and a water-bearing advance outwash. The sea-level aquifer as a whole generally was easy to discern in drillers' logs and it appears to be continuous throughout the study area. The continuity of the subunits across the study area is questionable, and the correlation of the subunits from one borehole to another is uncertain. The sea-level aquifer is underlain by a regionally extensive confining unit composed of fine-grained non-glacial sediments referred to as the $Qpon_2$ unit.

Hydrogeologic Framework

The upper and sea-level aquifers appear to be continuous across the study area, but the Qpon unit between the aquifers is discontinuous. One previously identified breach in the Qpon unit is a trough that was eroded through the bottom of the Qpon unit and was subsequently filled with fine-grained glaciolacustrine sediments (pl. 1). That trough is oriented north to south and extends from at least the northeast tip of American Lake to somewhere south of the Logistics Center. The Qpon unit also may be absent across a large area north of Fort Lewis and American Lake.

The trough eroded through the Qpon unit is of particular interest because the TCE plume in the upper aquifer extends across (and beyond) the entire width of the trough. Although the trough itself is filled with primarily fine-grained glaciolacustrine deposits, sediments near the western margin of the trough beneath the Logistics Center appear to be coarser and more permeable than those within the center of the trough. Those coarse sediments near the trough's western edge are referred to as the confining unit window in this report (pl. 1). The presence of the confining unit window near the centerline of the existing TCE plume in the upper aquifer originally was determined by interpretation of three drillers' logs (Ebasco Environmental, 1994), but the actual dimensions of the window shown on plate 1 were inferred using TCE and tracer data from the sea-level aquifer. As will be discussed later in this report, the confining unit window is a significant pathway for migration of ground water and contaminants from the upper aquifer into the sea-level aquifer.

Ground-Water Flow

The general direction of ground-water flow in the upper aquifer is from the southeast to the northwest (from the East Gate Disposal Yard toward Silcox Island in American Lake on plate 1). The average horizontal potentiometric gradient in the upper aquifer between the disposal yard and American Lake ranges from about 0.002 to 0.003 ft/ft, and the estimated range of ground-water flow velocities is 0.05 to 15 ft/d (U.S. Army Corps of Engineers, 2002). Outside of the immediate vicinity of the pump-and-treat (and reintroduction) systems, the vertical potentiometric gradient in the upper aquifer primarily is downward. The upper aquifer outcrops on the eastern side of American Lake, and ground water from at least part of the upper aquifer presumably discharges into the lake. The water-table surface in the upper aquifer varies seasonally by about 5 to 6 ft, and varies as much as 15 ft over periods of several years. However, the general flow direction in the study area is relatively constant.

The general direction of ground-water flow in the sea-level aquifer also is from the southeast to northwest between the East Gate Disposal Yard and the confining unit window, but new data presented in this report indicate that downgradient from the window, the flow direction is to the west toward the southwest tip of American Lake (pl. 1). Previous investigations of the sea-level aquifer indicated that ground-water flow in the sea-level aquifer continued northwest beneath American Lake and out to Puget Sound (Ebasco Environmental, 1994). The average horizontal potentiometric gradient in the sea-level aquifer between the disposal yard and the confining unit window ranges from about 0.002 to 0.004 ft/ft. At the location of the confining unit window, the gradient steepens substantially to about 0.05 ft/ft over a distance of about 500 ft, followed by a decrease in gradient back to about 0.002 ft/ft over a distance of about 7,000 ft. Ground water from the sea-level aquifer does not likely discharge to American Lake because the top of the sea-level aquifer appears to be at least 20 ft below the deepest part of American Lake, the Qpon unit appears to be continuous between the lake and the sea-level aquifer, and the water level in American Lake appears to exceed that in the sea-level aquifer. There is a downward vertical potentiometric gradient within the sea-level aquifer near the confining unit window and the I-5 pump-and-treat system, but vertical gradients are inconsistent away from those areas. The potentiometric surface in the sea-level aquifer varies seasonally by about 5 to 20 ft, but the variation over periods of several years is unknown. Much like the upper aquifer, the general flow direction in the sea-level aquifer beneath the study area appears to be relatively constant throughout the year.

Between the upper and the sea-level aquifers, there is a downward potentiometric gradient throughout the study area, but the magnitude of that gradient varies with location. The head difference between the upper and sea-level aquifers beneath the East Gate Disposal Yard is about 2 to 4 ft. The head difference increases substantially near the confining unit window to more than 20 ft, and increases to more than 70 ft farther downgradient near I-5.

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Study Methods

Ground-Water Altitudes

Ground-water altitude data used during this investigation were collected by the USGS, the U.S. Army, the U.S. Air Force, and various well drillers and water purveyors. The primary purpose for collecting and assembling the data was to determine general ground-water flow directions in the sea-level aquifer throughout an area more extensive than that covered by the Army's routine monitoring program for the Logistics Center. Recent data from existing Logistics Center monitoring wells were combined with a mix of recent and historical data from both existing and abandoned monitoring and water-supply wells in the region (table 1 and pl. 1.)

The USGS, U.S. Army, and U.S. Air Force all measured depth to ground water in monitoring wells using a steel or electric tape and calculating water-level altitude by subtracting the measured depth from a surveyed measuring-point altitude at the top of the well casing. Depth to water was likely measured in a similar way by well drillers and water purveyors, although surveyed measuring-point altitudes generally were not available. For wells without surveyed measuring-point altitudes, the USGS calculated water-level altitudes by subtracting the measured depths from the land-surface altitudes that were estimated by the driller or purveyor and checked by the USGS using a 1:24,000-scale topographic map.

The following process was used to assemble appropriate ground-water altitude data for creating potentiometric surface maps for the sea-level aquifer. Drillers' logs and associated information for all wells and test holes in the study area deeper than about 150 ft were assembled and reviewed. Using the drillers' logs and Borden and Troost's (2001) generalized stratigraphy as a guide, any well in which the uppermost screened interval was in the sea-level aquifer was considered for use. Many supply wells had additional screened intervals at greater depths, but the vertical potentiometric gradient appears to be primarily downward throughout most of the study area (Brown and Caldwell, 1985). Thus, a water level measured in a multi-screen well primarily reflects the water level of the aquifer penetrated by the uppermost screen. Potentiometric-surface maps for the separate subunits were not developed because it was not possible to discern specific subunits of the sea-level aquifer in many of the drillers' logs examined. At the few locations where more than one depth interval of the sea-level aquifer was screened, the water-level altitude from the uppermost interval was selected for use.

After selecting the set of suitable wells, potentiometric-surface maps were created for wet and dry conditions. A relatively high and a relatively low set of concurrent water-level data from Logistics Center monitoring wells were selected as "typical." The choices were limited to a few data sets from 2003 because data from five important new multi-level wells at the Logistics Center (LC-79D through LC-83D) were first available then. April 2004 data from five additional new wells (LC-84D through LC-88D) were added to the "high" potentiometric-surface map only because those wells were just completed while this report was being finalized. For the Logistics Center data, February-March 2003 was selected for the high data set, and July 2003 for the low data set. High and low sets of measurements also were selected from historical monitoring-well network data collected at nearby Fort Lewis and McChord Air Force Base Installation Remediation Program (IRP) sites. The high and low data selected for use were collected concurrently within a given IRP site, such as April and September 1995 data for McChord sites, and March and July 1992 data for Fort Lewis Landfill 4 and Landfill 5 sites. However, there was little or no temporal overlap between data sets from the Logistics Center and the other IRP sites in the area, so the data sets from the Logistics Center and the other IRP sites are not concurrent. Finally, high and low data were selected from the somewhat limited historical data from other monitoring wells and from private and public water-supply wells in the region. The data were as old as 1940 and as recent as 2003, and few were collected concurrently. Many of the historical data were from municipal water-supply wells and although many of the wells still exist, the current water levels are affected by current schedules of pumping. Thus, for consistency, only static (non-pumping) water-level data were selected for use, and many of those data were collected when the wells were first installed. Only one water-level measurement was available for some wells (or test holes), in which case that single measurement was used to represent both high and low water-level conditions.

Table 1.   Locations and characteristics of wells and surface-water data-collection sites, Fort Lewis, Washington.

[**Well No.**: Locations of wells are shown on plate 1. **USGS Site IDs** are latitude and longitude in degrees-minutes-seconds, followed by a 2-digit sequence number. **Eastings and Northings** are Washington State Plane Coordinates, NAD27 South zone. Altitudes are given in feet above NGVD29. **Well type:** M, monitoring well; S, supply well; U, unknown. **Well depths** and **Depths to top of screen** are given in feet below land surface. **Abbreviations:** USGS, U.S. Geological Survey; ft, foot; na, not applicable; –, not available]

Well No.	USGS site ID.	Easting	Northing	Well or site type	Land-surface altitude at well (ft)	Well depth (ft)	Depth to top of screen (ft)
			Surface-water site (SW)				
AML-1	470740122341001	1484914	661141	na	na	na	na
AML-2	470713122343701	1483119	658655	na	na	na	na
			Upper aquifer (Qv)				
FL-02	470606122313201	1495617	651334	M	284	45	40
FL-04A	470612122320901	1493048	652011	M	277	138	133
LC-11	470639122313701	1495289	654752	M	275	60	20
LC-149C	470603122305101	1498353	651059	M	269	48	28
LC-149D	470603122305202	1498334	651072	M	269	80	60
SILCOX-2	470742122334703	1486509	661302	S	–	–	10
			Confining unit (Qpon)				
LC-21B	470619122312001	1496420	652728	M	280	116	111
LC-40C	470659122325003	1490282	656906	M	278	152	147
			Sea-level aquifer (Qpog$_2$)				
09F01	470857122333501	1487537	668877	S	235	165	160
13J01	473756122365001	1473898	663055	M	220	350	–
22K01	470717122392201	1463284	659390	U	168	185	169
22K02	470717122392101	1463353	659388	M	198	210	200
22P01	470712122393101	1462648	658901	S	208	252	192
22P02	470712122393201	1462579	658902	S	208	266	220
27C01	470636122394001	1461926	655272	S	217	331	220
36D01	470545122300701	1502066	649563	S	336	116	110
88-11-SS	470709122384101	1466053	658546	M	–	178	170
88-16-SS	470723122383501	1466540	660007	M	–	185	175
88-1-SS	470656122372201	1471543	657079	M	220	195	185
88-5-SS	470708122381001	1468231	658349	M	–	180	170
89-18-SD	470719122385301	1465270	659557	M	–	220	210
89-20-SS	470710122381901	1467585	658616	M	–	183	171
89-21-SD	470717122392701	1462875	659448	M	–	217	207
89-22-SD	470742122390301	1464612	661920	M	–	208	198
90-19-SS	470713122380701	1468458	658931	M	–	198	188
93-LF5-4-SS	470705122380501	1468566	658129	M	–	171	161
ASPE-21	470535122292201	1504569	647866	S	340	130	120
BELLHILL-1	470557122372501	1470415	651899	S	260	298	248
CW-14d	471120122293701	1504381	662970	M	304	275	265
CW-15d	470813122292701	1504574	663982	M	291	265	255
CW-30c	470827122290101	1506425	665308	M	280	280	270
CW-31b	470822122293201	1504247	664889	M	296	197	186
-31c						311	300
CW-32b	470840122293001	1504429	666768	M	277	247	242
CW-33d	470735122291601	1505230	660076	M	300	217	207
CW-34d	470722122291601	1505171	658775	M	309	234	224
DA-02D	470725122295202	1502672	659250	M	300	202	192
DA-12C	470737122310801	1497486	660600	M	273	230	220
-12D						305	295

Table 1.   Locations and characteristics of wells and surface-water data-collection sites, Fort Lewis, Washington.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **USGS Site IDs** are latitude and longitude in degrees-minutes-seconds, followed by a 2-digit sequence number. **Eastings and Northings** are Washington State Plane Coordinates, NAD27 South zone. Altitudes are given in feet above NGVD29. **Well type:** M, monitoring well; S, supply well; U, unknown. **Well depths** and **Depths to top of screen** are given in feet below land surface. **Abbreviations:** USGS, U.S. Geological Survey; ft, foot; na, not applicable; –, not available]

Well No.	USGS site ID.	Easting	Northing	Well or site type	Land-surface altitude at well (ft)	Well depth (ft)	Depth to top of screen (ft)
Sea-level aquifer (Qpog$_2$)—Continued
DA-15C	470814122310601	1497688	664272	M	269	209	199
-15D						287	277
DA-17C	470748122313501	1495595	661732	M	272	182	172
-17D						308	298
DA-20C	470727122321201	1492972	659706	M	272	260	250
-20D						298	288
FLS-1	470732122355201	1477842	660518	S	234	224	122
FLS-13	470622122332101	1487390	653170	S	275	240	190
FLS-16	470707122331101	1488912	657672	S	268	358	298
FLS-19B	470637122354701	1478548	655477	S	–	280	244
FLS-2	470737122354901	1478063	661018	S	234	239	216
FLS-22	470528122315801	1461597	648387	S	–	295	250
FLS-3	470717122361001	1476760	658680	S	235	229	185
FLS-4A	470806122352901	1479523	663919	S	233	1,110	276
FLS-5	470520122352901	1479077	647107	S	282	990	210
FLS-8	470628122312701	1493630	653428	S	287	1,010	235
LC-126	470708122330301	1489442	657843	M	270	180	160
LC-166D	470700122345201	1481896	657256	M	242	178	168
LC-21C	470620122312003	1496427	652742	M	280	144	139
LC-26D	470612122310301	1497565	651916	M	277	149	135
LC-35D	470627122314203	1494905	653531	M	288	205	195
LC-40D	470659122325102	1490263	656928	M	277	178	168
LC-41D	470642122322702	1491859	655153	M	282	203	193
LC-41E	470642122322703	1491859	655153	M	282	290	280
LC-47D	470643122320401	1493403	655176	M	282	219	209
LC-50D	470614122313201	1495547	652150	M	272	160	150
LC-66D	470700122322301	1492176	656901	M	282	186	176
LC-67D	470648122324901	1490344	655738	M	267	158	149
LC-68D	470628122321601	1492565	653737	M	280	250	241
LC-69D	470642122322501	1491984	655128	M	282	204	194
LC-70D	470642122322801	1491765	655182	M	281	216	206
LC-72D	470657122331201	1488748	656736	M	264	176	166
LC-73D	470651122331901	1488281	656096	M	270	175	165
LC-74D	470637122332801	1487614	654744	M	274	220	210
LC-75D	470619122330301	1489607	652896	M	279	178	173
LC-76D	470642122340601	1485391	655293	M	279	208	198
LC-77D	470718122325401	1490384	658835	M	275	206	196
LC-79D-1	470725122323101	1491718	659444	M	273	278	197
-2							211
-3							227
-4							275
LC-80D-1	470711122333801	1487049	658146	M	264	285	235
-2							251
-3							265
-4							282

Table 1. Locations and characteristics of wells and surface-water data-collection sites, Fort Lewis, Washington.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **USGS Site IDs** are latitude and longitude in degrees-minutes-seconds, followed by a 2-digit sequence number. **Eastings and Northings** are Washington State Plane Coordinates, NAD27 South zone. Altitudes are given in feet above NGVD29. **Well type:** M, monitoring well; S, supply well; U, unknown. **Well depths** and **Depths to top of screen** are given in feet below land surface. **Abbreviations:** USGS, U.S. Geological Survey; ft, foot; na, not applicable; –, not available]

Well No.	USGS site ID.	Easting	Northing	Well or site type	Land-surface altitude at well (ft)	Well depth (ft)	Depth to top of screen (ft)
Sea-level aquifer (Qpog$_2$)—Continued							
LC-81D-1	470639122343801	1482816	655014	M	268	283	184
-2							211
-3							243
-4							280
LC-82D-1	470625122340001	1485406	653528	M	274	290	217
-2							235
-3							265
-4							287
LC-83D-1	470643122334201	1486699	655318	M	266	295	196
-2							208
-3							243
-4							292
LC-84D-1	–	–	–	M	269	236	214
-2	–	–	–			292	276
LC-85D-1	–	–	–	M	286	231	209
-2	–	–	–			286	243
LC-86D-1	–	–	–	M	260	218	197
-2	–	–	–			286	225
LC-87D-1	–	–	–	M	275	250	230
-2	–	–	–			278	254
LC-88D-1	–	–	–	M	255	216	196
-2	–	–	–			258	229
LC-89D-1	–	–	–	M	261	222	208
-2	–	–	–			278	232
LC-90D-1	–	–	–	M	262	229	205
-2	–	–	–			273	234
LF4-MW12B	470709122360301	1477005	658234	M	236	193	188
LF4-MW14	470704122360901	1476549	657725	M	235	187	182
LF4-MW2C	470702122353201	1479172	657434	M	226	197	192
LF4-MW4	470653122354901	1477961	656547	M	246	224	219
LF4-MW9B	470700122360501	1476838	657399	M	231	213	208
LW-C	470859122322001	1492725	668944	M	263	196	196
LW-D1	470846122321801	1492829	667624	M	270	638	310
LW-G	470944122292601	1504862	673195	M	280	175	153
LW-S1	470953122325501	1490447	674475	S	240	355	303
LW-T2	470942122292401	1504995	672989	M	280	177	177
LW-TH10	473911122340001	1485847	670339	M	265	308	308
LW-TH13	470942122341001	1485238	673497	M	340	893	223
LZ-04C	470709122311702	1496741	657756	M	277	225	215
-04D						297	284
MAMC-3	470629122330901	1488925	653837	S	266	181	151
MAMC-4	470628122331001	1488892	653730	S	268	292	261
MC-GC4	470708122303601	1499701	660556	S	289	249	209
MC-GC5	470708122303701	1499632	660558	S	290	255	205
19-2-22K01	470707122315701	1494023	657558	S	281	320	310
22B01	470729122320701	1493387	659806	S	280	222	217
RD-01	470648122330801	1489008	655800	M	272	207	197

Table 1. Locations and characteristics of wells and surface-water data-collection sites, Fort Lewis, Washington.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **USGS Site IDs** are latitude and longitude in degrees-minutes-seconds, followed by a 2-digit sequence number. **Eastings and Northings** are Washington State Plane Coordinates, NAD27 South zone. Altitudes are given in feet above NGVD29. **Well type:** M, monitoring well; S, supply well; U, unknown. **Well depths** and **Depths to top of screen** are given in feet below land surface. **Abbreviations:** USGS, U.S. Geological Survey; ft, foot; na, not applicable; –, not available]

Well No.	USGS site ID.	Easting	Northing	Well or site type	Land-surface altitude at well (ft)	Well depth (ft)	Depth to top of screen (ft)
Sea-level aquifer ($Qpog_2$)—Continued							
SILCOX-1	470742122334702	1486509	661302	S	255	234	234
SRC-MW1B	470634122361201	1476257	654764	M	222	181	176
STEILACOOM-1	471003122351101	1481155	675936	S	265	204	157
STEILACOOM-2	470923122351901	1480421	671699	S	260	247	193
T-09	470736122325602	1490000	660683	M	272	212	197
T-09E	470737122325501	1490037	660709	M	272	304	294
Lower confining unit ($Qpon_2$)							
LC-55D	470630122311002	1497114	653766	M	290	230	220
LC-71D	470707122330401	1489355	657746	M	270	232	222
LF4-MW16B	470658122362901	1475180	657238	M	232	266	261

The accuracy of all the considered data was estimated and the data were designated accordingly to highlight greater or lesser uncertainty. Most of the February-March 2003 and July 2003 Logistics Center well data were designated as high quality because they were concurrent and based on surveyed well measuring-point altitudes. Most of the other IRP site data from Fort Lewis and McChord were designated as medium quality because although they were based on surveyed measuring-point altitudes, they were not concurrent with the Logistics Center data. Most of the other data were designated as low quality because measuring-point altitudes were estimated from topographic maps (with an uncertainty of ±20 ft), and they were not concurrent with the Logistics Center data.

Ground-Water Chemistry

For this investigation, the USGS sampled ground water from 27 existing wells primarily during May-June 2000 and December 2000, and from 5 newly installed multi-level monitoring wells from December 2002 to February 2003. The USGS also sampled surface water from two sites in American Lake during June 2000. Additional data that were used in the study were collected and analyzed by the USGS during February 1999 and by the Army from 1995 to 2004. The sampling and analytical procedures used by the Army were similar to those used by the USGS.

Sample Collection

Most standard monitoring wells were purged and sampled with USGS submersible pumps and discharge line; water-supply wells were sampled with the in-well equipment. Selected Logistics Center monitoring wells were equipped with dedicated in-well pumps and discharge lines; that equipment was not used for sampling during this investigation and was carefully removed, kept clean and protected, and replaced to the original depths when sampling was completed.

Standard monitoring wells with 2-inch-diameter casings were purged by first pumping at least three casing volumes of water from near the top of the water column. Pumping was at a slow enough rate to never draw down the water surface to below the top of the well screen. The field parameters—dissolved oxygen (DO), pH, and specific conductance—were monitored in a flowthrough chamber while purging. After at least three casing volumes of water were removed and sequential measurements of DO, pH, and specific conductance were within 0.3 mg/L, 0.1 units, and 5 percent, respectively, the pump was lowered to mid-screen depth, the pumping rate was decreased to about 1 L/min, and the field parameters were monitored until sequential measurements met the same criteria. Wells with 4-inch-diameter casings or larger were purged using the same general strategy, but two pumps were used. The sampling pump (with copper tubing discharge line) was lowered to

mid-screen depth, and the purge pump was lowered to near the top of the water column. After purging three casing volumes, the purge rate was decreased to about 1 L/min, and the sampling pump was turned on at a similar rate. The purge pump was left on while sampling in order to increase water flow across the sampling pump and avoid overheating. All equipment that came into contact with ground water was decontaminated before reuse. Decontamination consisted of a surface washing and interior washing and flushing with Liquinox® detergent (or equivalent), followed by at least three serial rinses with deionized water.

The five multi-level monitoring wells installed during 2002-03 were constructed of continuous multi-channel tubing (CMT) that required a different sampling procedure. The purging and sampling at the CMT wells was done by the Army, with USGS personnel present to fill sample containers. The sampling procedure involved using a small diameter inertial pump configured with two in-line check valves; one at the bottom of the pump tubing and one at the top. The upper check valve was a specialized "high-flow" valve that allowed water to pass through more efficiently. Tubing was of 1/4-inch-diameter FEP Teflon®, the bottom of which was placed about 15 to 25 ft below static water level. For the initial December-January 2003 sampling event, three well chamber volumes were purged from each chamber prior to sampling, and the Army collected and analyzed samples for TCE concentration after purging one-, two-, and three-chamber volumes. The Army's TCE results suggested that samples collected after two chamber volumes were nearly identical to those collected after three chamber volumes, so subsequent sampling of the CMT wells by the Army followed a purge of two chamber volumes. The USGS collected samples only during December-January 2003 after three chamber volumes were purged. The Army monitored the stability of the field parameters DO, pH, temperature, specific conductance, turbidity, and oxygen-reduction potential (ORP) in a flowthrough chamber while purging the CMT wells. However, the purge rate generally was about 30 to 50 mL/min at the most, and the DO measurements from the flow through cell were suspect at that low rate; nearly all DO readings at all wells were 0.2 mg/L. Gas bubbles were regularly being brought up in the pump line and discharged into the flow cell.

Two samples of surface water were collected by the USGS from near the bottom of American Lake at two different locations using a peristaltic pump. The lake depth was first sounded and then a length of weighted, polyethylene tubing was lowered to within 1 ft of the lake bottom to pump a sample to a boat on the lake surface. The lake samples were processed and analyzed for stable isotopes of water (^{18}O and ^{2}H) and carbon (^{13}C), sulfur hexafluoride, and dissolved gasses following methods described below.

Duplicate samples and field blanks (deionized or VOC-free water run through the pump and sampling equipment in the field) were collected by the USGS at the same time as the related ground-water samples during the May through December 2000 field effort. Duplicate samples for volatile organic compounds (VOCs), total organic carbon (TOC), and common ion analyses were collected at a frequency of about 10 percent, and field blank samples for those same analytes were collected twice. Field determinations of alkalinity, ferrous iron, and sulfide also were duplicated at a frequency of about 10 percent. Environmental tracer samples were collected as duplicates or triplicates according to the standard procedures outlined by the appropriate analytical laboratory. Duplicate and blank results for USGS data are presented in Appendix A.

Investigation derived waste during sampling consisted of personal protective equipment (primarily nitrile® gloves) and well purge water. Personal protective equipment was disposed of as commercial waste. Well purge water was disposed of following procedures agreed to by the USGS, Army, and U.S. Environmental Protection Agency. Purge water from known uncontaminated wells was collected and disposed of in the sanitary sewer system at Fort Lewis. Purge water from known or suspected VOC-contaminated wells was collected and run through the East Gate Disposal Yard treatment center at Fort Lewis.

Field Analyses

Ground-water temperature, specific conductance, DO, pH, and oxygen reduction potential (ORP) were measured in the field immediately before collection of samples according to methods described in the USGS National Field Manual for the Collection of Water-Quality Data (U.S Geological Survey, variously dated). Specific conductance and temperature were measured using a temperature-compensated probe and meter that were checked daily with standard reference solutions. pH was measured using an electrode and a temperature-compensated meter calibrated daily with two pH standards. DO and ORP were measured using electrodes and temperature-compensated meter, and the DO meter was calibrated daily with water-saturated air. DO concentrations of less than 1 mg/L were confirmed using 0–1 mg/L CHEMets Rhodazine-D™ colorimetric ampoules. CHEMets ampoules also were used to measure DO of sample water discharging directly from the sample tubing at the CMT wells.

For most wells, alkalinity was measured in the field by titration of a sample filtered through a 0.45-micrometer membrane filter (Rounds and Wilde, 2001), and concentration of the bicarbonate ion (HCO_3^-) was calculated from the titration results. For the five new multi-level wells, the concentration of the bicarbonate ion (HCO_3^-) was calculated

from laboratory titration results of an unfiltered sample. Concentration of iron (II) was measured in the field using a Hach Model 2010 spectrophotometer immediately after collection and filtration of sample (Hach Company, 1998). Concentration of sulfide species also was measured in the field using a Hach Model 2010 spectrophotometer immediately after collection of unfiltered sample (Hach Company, 1998).

Laboratory Analyses

Samples for common-ion analyses were filtered into polyethylene bottles. Cation samples were acidified with nitric acid to a pH less than 2 and chilled to less than 4 °C. Common-ion samples were sent to the USGS National Water Quality Laboratory (NWQL) for analysis by inductively coupled plasma spectroscopy and ion chromatography.

Unfiltered TOC samples were collected in amber glass bottles, chilled to less than 4 °C, and shipped to the USGS laboratory in Ocala, Fla., for analysis using EPA Method 415.1. Unfiltered VOC samples were collected in 40-mL glass vials, acidified to a pH of less than 2 with hydrochloric acid, sealed, and chilled to less than 4 °C for shipment to the NWQL for analysis using EPA Method 8260A.

Unfiltered stable isotope samples for water were collected in 60-mL glass bottles fitted with Teflon/silicon septum. Samples were sent to the U.S. Geological Survey Stable Isotope Laboratory of the Isotope Fractionation Project for determination of $\delta^{18}O$ using a CO_2 equilibration technique (Epstein and Mayeda, 1953), and δ^2H using a hydrogen equilibration technique (Coplen and others, 1991). Filtered carbon isotope (^{13}C) samples were collected in 1,000-mL glass bottles fitted with Teflon/silicon septum. Samples were sent to the University of Waterloo for mass spectrometric analysis. Unfiltered tritium samples were collected in 1,000-mL polyethylene bottles fitted with a polyseal cap. Samples were sent to the NWQL for analysis by liquid scintillation.

Chlorofluorocarbon (CFC) samples were collected in welded glass ampoules. Sulfur hexafluoride (SF_6) samples were collected in 0.5-gal glass bottles with polyseal caps. Dissolved-gas samples for estimating recharge temperature estimates and obtaining alternative measurements of dissolved oxygen were collected in 150-mL glass bottles with rubber stoppers. All those samples were sent to the USGS Chlorofluorocarbon Laboratory in Reston, Va , for analysis. Detailed sampling and analytical procedures are available on-line at http://water.usgs.gov/lab/cfc/sampling/, http://water.usgs.gov/lab/sf6/sampling/, http://water.usgs.gov/lab/dissolved-gas/sampling/, http://water.usgs.gov/lab/cfc/background/, http://water.usgs.gov/lab/sf6/background/, and http://water.usgs.gov/lab/dissolved-gas/lab/DG_method.html.

Hydrogeology and Contamination of the Sea-Level Aquifer

A refined conceptual model for ground-water flow and contaminant migration into and through the sea-level aquifer is presented in this section of the report. Ground-water altitude data from the sea-level aquifer beneath the entire study area are presented first, followed by observed concentrations of TCE, *cis*-DCE, and vinyl chloride. Environmental tracer data are then evaluated to explain the observed ground-water flow field and distribution of contaminants in the sea-level aquifer. The reasons for the somewhat unexpected flow directions in the sea-level aquifer are described, as are the pathways for contaminant migration into the sea-level aquifer, the stability of the current contaminant plume, contaminant attenuation in the sea-level aquifer, and the downgradient risks from TCE migration.

Ground-Water Altitudes and Flow Directions

Potentiometric surface maps for the sea-level aquifer (figs. 3 and 4) were drawn using ground-water altitude data from various wells (table 2). The maps represent static conditions during relatively high and low water-level periods in the sea-level aquifer for a typical year, and comparison of the two maps illustrates that the overall flow pattern changes little over the course of a year. The Army has produced additional seasonal potentiometric-surface maps for the sea-level aquifer beneath the Logistics Center as part of their long-term monitoring program (URS Corporation, 2004 and previous monitoring reports). Those maps cover a much smaller area than figures 3 and 4, but they confirm that the overall flow pattern in the sea-level aquifer changes little seasonally or annually.

The potentiometric surface and ground-water flow directions in the sea-level aquifer are far from uniform. The potentiometric surfaces mapped during this investigation are similar to previously published regional-scale maps (Brown and Caldwell, 1985; AGI Technologies, 1996; Robinson and Noble, Inc., 1997) with regard to the predominant east-to-west ground-water flow direction and the overall potentiometric gradient across the study area. However, the maps produced for this report are more detailed near the Logistics Center.

Three localized ground-water features were identified that are of particular relevance to the migration of TCE contamination from the Logistics Center. The most relevant feature is a "ridge" of ground water beneath American Lake.
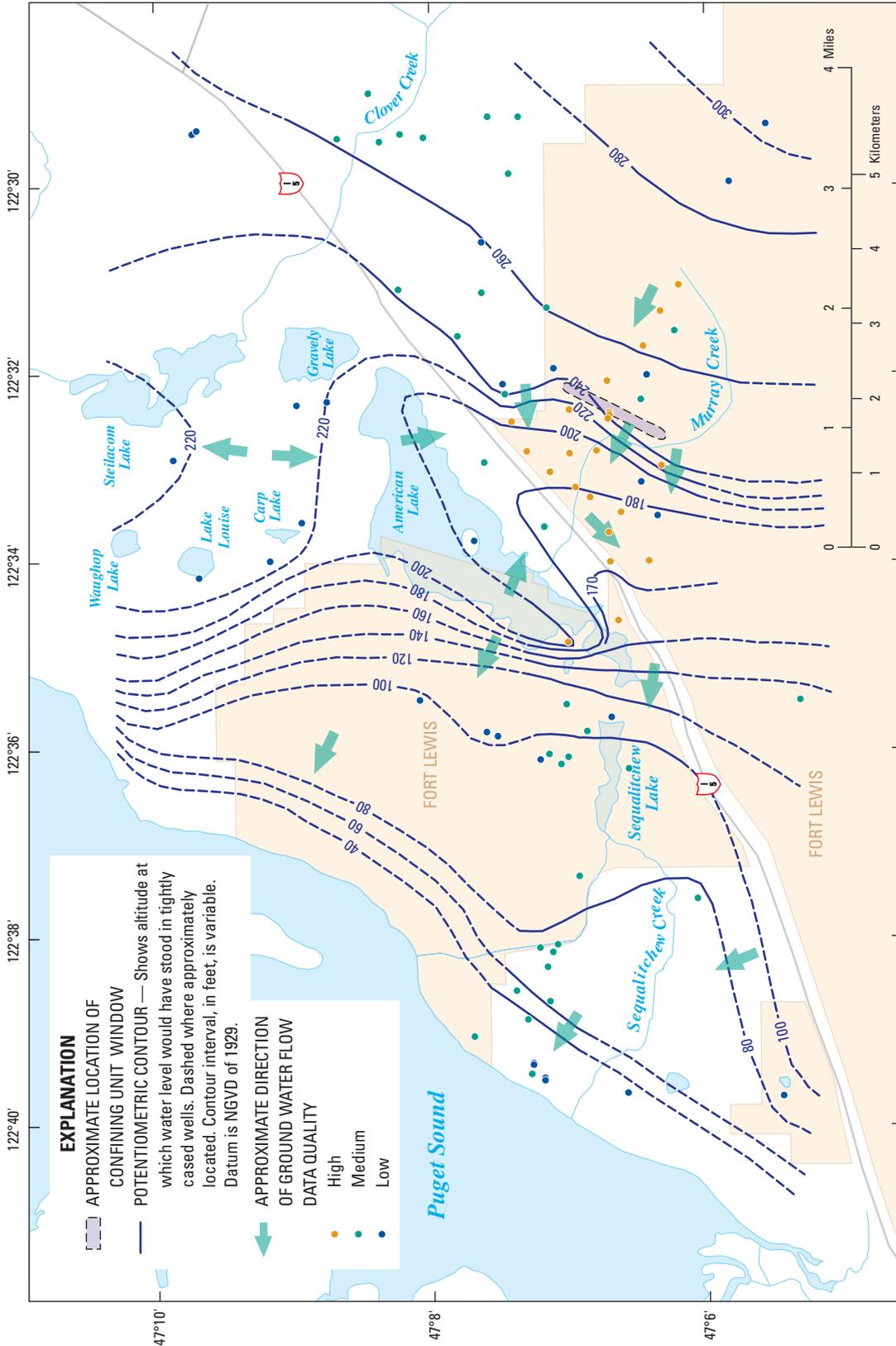
Figure 3.   Relatively high ground-water altitudes in the sea-level aquifer beneath Fort Lewis, Washington.

Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 10, Datum NAD27

EXPLANATION

APPROXIMATE LOCATION OF CONFINING UNIT WINDOW

POTENTIOMETRIC CONTOUR — Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval, in feet, is variable. Datum is NGVD of 1929.

APPROXIMATE DIRECTION OF GROUND WATER FLOW

DATA QUALITY

High

Medium

Low

EXPLANATION

- - - - APPROXIMATE LOCATION OF
         CONFINING UNIT WINDOW

—— POTENTIOMETRIC CONTOUR — Shows altitude at
    which water level would have stood in tightly
    cased wells. Dashed where approximately
    located. Contour interval, in feet, is variable.
    Datum is NGVD of 1929.

↓ APPROXIMATE DIRECTION
   OF GROUND-WATER FLOW

DATA QUALITY

- High
- Medium
- Low

Figure 4. Relatively low ground-water altitudes in the sea-level aquifer beneath Fort Lewis, Washington.

Table 2.   Ground-water altitude data for the sea-level aquifer, Fort Lewis, Washington.

[**Well No.**: Locations of wells are shown on plate 1. **Depths to top of screen** are given in feet below land surface. **Altitude of ground water:** Altitudes are given in feet above NGVD29. **Data quality:** High denotes concurrent data with surveyed measuring-point altitudes; medium denotes non-concurrent data with surveyed measuring-point altitudes; low denotes non-concurrent data with estimated measuring-point altitudes. **Abbreviations:** ft, foot; –, not available]

Well No.	Depth to top of screen (ft)	Low-period measurement			High-period measurement		
		Sample date	Altitude of ground water (ft)	Data quality	Sample date	Altitude of ground water (ft)	Data quality
09F01	160	Aug. 1954	223	Low	Feb. 1960	226	Low
13J01	–	Oct. 1940	118	Low	–	–	–
22K01	169	July 1943	3	Low	–	–	–
22K02	200	July 1943	2	Low	–	–	–
22P01	192	Dec. 1941	0	Low	–	–	–
22P02	220	Dec. 1941	0	Low	–	–	–
27C01	220	Aug. 1944	11	Low	–	–	–
36D01	110	Aug. 1957	290	Low	Mar. 1960	290	Low
88-11-SS	170	Oct. 1989	65.93	Medium	Apr. 1989	68.73	Medium
88-16-SS	175	Oct. 1989	49.86	Medium	Apr. 1989	51.34	Medium
88-1-SS	185	Oct. 1989	80.63	Medium	Apr. 1989	84.03	Medium
88-5-SS	170	Oct. 1989	75.60	Medium	Apr. 1989	78.87	Medium
89-18-SD	210	Oct. 1989	4.68	Medium	Apr. 1989	9.38	Medium
89-20-SS	171	May 1990	76.72	Medium	Jan. 1990	77.03	Medium
89-21-SD	207	Oct. 1989	2.55	Medium	Apr. 1989	3.46	Medium
89-22-SD	198	Oct. 1989	1.85	Medium	Apr. 1989	3.48	Medium
90-19-SS	188	May 1990	79.07	Medium	Jan. 1990	79.09	Medium
93-LF5-4-SS	161	Mar. 1993	78.80	Medium	–	–	–
ASPE21	120	Dec. 2002	311	Low	–	–	–
BELLHILL-1	248	Aug. 1998	74.00	Medium	Nov. 2001	76.90	Medium
CW-14d	265	Sept. 1995	261.61	Medium	Apr. 1995	267.31	Medium
CW-15d	255	Sept. 1995	252.66	Medium	Apr. 1995	258.84	Medium
CW-30c	270	Sept. 1995	250.36	Medium	Apr. 1995	258.24	Medium
CW-31b	186	Sept. 1995	260.19	Medium	Apr. 1995	263.04	Medium
-31c	300	Sept. 1995	251.37	Medium	Apr. 1995	255.93	Medium
CW-32b	242	Sept. 1995	258.02	Medium	Apr. 1995	262.27	Medium
CW-33d	207	Sept. 1995	264.31	Medium	Sept. 1995	264.31	Medium
CW-34d	224	Sept. 1995	267.21	Medium	Apr. 1995	274.13	Medium
DA-02D	192	Sept. 1995	259.68	Medium	Apr. 1995	265.36	Medium
DA-12C	220	Sept. 1995	251.45	Medium	Apr. 1995	257.36	Medium
-12D	295	Sept. 1995	239.14	Medium	Apr. 1995	246.75	Medium
DA-15C	199	Sept. 1995	236.30	Medium	Apr. 1995	243.57	Medium
-15D	277	Sept. 1995	220.75	Medium	Apr. 1995	230.42	Medium
DA-17C	172	Sept. 1995	233.18	Medium	Apr. 1995	240.98	Medium
-17D	298	Sept. 1995	226.03	Medium	Apr. 1995	235.19	Medium
DA-20C	250	Nov. 1989	236.17	Medium	Mar. 1990	241.67	Medium
-20D	288	Nov. 1989	218.20	Medium	Mar. 1990	233.57	Medium
FLS-1	122	Mar. 1960	84	Low	Nov. 1940	109	Low
FLS-13	190	Mar. 1964	175	Low	–	–	–
FLS-16	298	Sept. 1969	168	Low	–	–	–
FLS-19B	244	Dec. 1986	110	Low	Jan. 1988	118	Low
FLS-2	216	Mar. 1960	95	Low	Dec. 1940	111	Low
FLS-22	250	Jan. 1994	94	Low	Dec. 1993	99	Low
FLS-3	185	Jan. 1941	96	Low	Mar. 1960	97	Low
FLS-4A	276	Jan. 1943	95	Low	Jan. 1945	95	Low
FLS-5	210	Jan. 1941	125	Low	Mar. 1942	137	Low
FLS-8	235	Oct. 1943	254	Low	Oct. 1943	254	Low
LC-126	160	July 2003	176.77	High	Mar. 2003	181.84	High
LC-166D	168	July 2003	210.78	High	Mar. 2003	210.59	High

Table 2.   Ground-water altitude data for the sea-level aquifer, Fort Lewis, Washington.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **Depths to top of screen** are given in feet below land surface. **Altitude of ground water:** Altitudes are given in feet above NGVD29. **Data quality:** High denotes concurrent data with surveyed measuring-point altitudes; medium denotes non-concurrent data with surveyed measuring-point altitudes; low denotes non-concurrent data with estimated measuring-point altitudes. **Abbreviations:** ft, foot; –, not available]

Well No.	Depth to top of screen (ft)	Low-period measurement			High-period measurement		
		Sample date	Altitude of ground water (ft)	Data quality	Sample date	Altitude of ground water (ft)	Data quality
LC-21C	139	July 2003	266.28	High	Mar. 2003	268.75	High
LC-26D	135	July 2003	268.30	High	Mar. 2003	268.75	High
LC-35D	195	July 2003	260.89	High	Mar. 2003	262.12	High
LC-40D	168	July 2003	177.78	High	Mar. 2003	182.99	High
LC-41D	193	July 2003	245.24	High	Mar. 2003	249.11	High
LC-41E	280	Nov. 2001	231.96	Medium	Jan. 2001	233.49	Medium
LC-47D	209	July 2003	252.20	High	Mar. 2003	255.31	High
LC-50D	150	July 2003	264.47	High	June 2002	265.62	Medium
LC-66D	176	July 2003	202.61	High	Mar. 2003	207.28	High
LC-67D	149	July 2003	187.95	High	Mar. 2003	193.20	High
LC-68D	241	Dec.1993	250.52	Medium	–	–	–
LC-69D	194	July 2003	251.47	High	Mar. 2003	254.95	High
LC-70D	206	July 2003	230.28	High	Mar. 2003	235.61	High
LC-71D	222	July 2003	175.23	High	Mar. 2003	180.99	High
LC-72D	166	July 2003	174.88	High	Mar. 2003	180.18	High
LC-73D	165	July 2003	173.97	High	Mar. 2003	179.24	High
LC-74D	210	July 2003	170.50	High	Mar. 2003	176.02	High
LC-75D	173	July 2003	234.44	High	Mar. 2003	239.14	High
LC-76D	198	July 2003	166.48	High	Mar. 2003	171.46	High
LC-77D	196	July 2003	181.81	High	Mar. 2003	186.61	High
LC-79D-1	197	July 2003	198.98	High	Mar. 2003	203.82	High
-2	211	July 2003	199.75	High	Mar. 2003	204.70	High
-3	227	July 2003	199.61	High	Mar. 2003	205.75	High
-4	275	July 2003	199.59	High	Mar. 2003	205.75	High
LC-80D-1	235	July 2003	173.44	High	Feb. 2003	175.97	Medium
-2	251	July 2003	173.41	High	Feb. 2003	175.94	Medium
-3	265	July 2003	173.40	High	Feb. 2003	175.92	Medium
-4	282	July 2003	173.36	High	Feb. 2003	175.86	Medium
LC-81D-1	184	July 2003	161.14	High	Mar. 2003	165.87	High
-2	211	July 2003	161.14	High	Mar. 2003	165.90	High
-3	243	July 2003	161.57	High	Mar. 2003	166.32	High
-4	280	July 2003	162.49	High	Mar. 2003	167.33	High
LC-82D-1	217	July 2003	167.79	High	Mar. 2003	173.07	High
-2	235	July 2003	166.91	High	Mar. 2003	172.04	High
-3	265	July 2003	167.04	High	Mar. 2003	172.25	High
-4	287	July 2003	167.05	High	Mar. 2003	172.25	High
LC-83D-1	196	July 2003	169.78	High	Mar. 2003	175.13	High
-2	208	July 2003	169.49	High	Mar. 2003	174.71	High
-3	243	July 2003	169.52	High	Mar. 2003	174.76	High
-4	292	July 2003	169.83	High	Mar. 2003	175.08	High
LC-84D-1	214	May 2004	164	Low	–	–	–
-2	276	May 2004	164	Low	–	–	–
LC-85D-1	209	May 2004	174	Low	–	–	–
-2	243	May 2004	173	Low	–	–	–
LC-86D-1	197	May 2004	158	Low	–	–	–
-2	225	May 2004	150	Low	–	–	–
LC-87D-1	230	May 2004	168	Low	–	–	–
-2	254	May 2004	168	Low	–	–	–
LC-88D-1	196	May 2004	106	Low	–	–	–
-2	229	May 2004	103	Low	–	–	–

Table 2.   Ground-water altitude data for the sea-level aquifer, Fort Lewis, Washington.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **Depths to top of screen** are given in feet below land surface. **Altitude of ground water:** Altitudes are given in feet above NGVD29. **Data quality:** High denotes concurrent data with surveyed measuring-point altitudes; medium denotes non-concurrent data with surveyed measuring-point altitudes; low denotes non-concurrent data with estimated measuring-point altitudes. **Abbreviations:** ft, foot; –, not available]

Well No.	Depth to top of screen (ft)	Low-period measurement			High-period measurement		
		Sample date	Altitude of ground water (ft)	Data quality	Sample date	Altitude of ground water (ft)	Data quality
LC-89D-1	208	May 2004	128	Low	–	–	–
-2	232	May 2004	125	Low	–	–	–
LC-90D-1	205	May 2004	155	Low	–	–	–
-2	234	May 2004	155	Low	–	–	–
LF4-MW12B	188	July 1992	94.21	Medium	Mar. 1992	96.17	Medium
LF4-MW14	182	Nov. 1992	91.35	Medium	Dec. 1992	91.98	Medium
LF4-MW2C	192	July 1992	112.39	Medium	Mar. 1992	114.64	Medium
LF4-MW4	219	July 1992	100.01	Medium	Mar. 1992	102.24	Medium
LF4-MW9B	208	July 1992	90.33	Medium	Mar. 1992	92.40	Medium
LW-C	196	Feb. 1945	225	Low	Feb. 1945	225	Low
LW-D1	310	Dec. 1947	220	Low	Dec. 1947	220	Low
LW-G	153	July 1950	257	Low	July 1950	257	Low
LW-S1	303	Jan. 1987	191	Low	Mar. 1995	216	Low
LW-T2	177	Nov. 1949	255	Low	Nov. 1949	255	Low
LW-TH10	308	Jan. 1958	238	Low	Jan. 1958	238	Low
LW-TH13	223	Jan. 1961	232	Low	Jan. 1961	232	Low
LZ-04C	215	Mar. 1990	260.41	Medium	–	–	–
LZ-04D	284	June 1990	256.91	Medium	–	–	–
MAMC-3	151	Jan. 1997	194.80	Medium	–	–	–
MAMC-4	261	Mar. 1997	226.60	Medium	–	–	–
MC-GC4	209	Jan. 1995	256	Low	–	–	–
MC-GC5	205	Feb. 1995	255	Low	–	–	–
19-2-22K01	310	July 1976	249	Low	–	–	–
22B01	217	Jan. 1976	270	Low	–	–	–
RD-01	197	Mar. 1982	257	Low	–	–	–
SILCOX-1	234	Feb. 1903	190	Low	Feb. 1901	192	Low
SRC-MW1B	176	July 1992	92.67	Medium	Mar. 1992	94.64	Medium
STEILACOOM-1	157	Jan. 1966	178	Low	–	–	–
STEILACOOM-2	193	Oct. 1953	113	Low	–	–	–
T-09	197	July 1986	186.40	Medium	–	–	–
T-09E	294	Nov. 1901	180.36	Medium	Jan. 1901	182.73	Medium

That ridge diverts TCE-contaminated ground water flowing in the sea-level aquifer from the northwest to the west-southwest and around the southern end of American Lake. Although the mapped ridge is primarily a result of water-level data from only two wells (LC-166D on the north shore near the west end of American lake and Silcox-1 on Silcox Island), the drillers' logs for those wells clearly indicate that the screens are in the sea-level aquifer, and the water levels have been measured repeatedly with consistent results. Both the presence

of the ridge and the relatively steep potentiometric gradient located immediately to the west of American Lake suggest that there is a substantial amount of recharge to the sea-level aquifer from American Lake even though the lake bottom does not penetrate the aquifer. As will be described later, environmental tracer data strongly support the hypothesis of substantial recharge to the sea-level aquifer from American Lake.

Another relevant ground-water feature is the substantial steepening of the potentiometric surface at the presumed location of the confining unit window beneath the Logistics Center. This steep horizontal gradient in the sea-level aquifer has been confirmed by many rounds of water-level measurements in many wells, and the vertical hydraulic gradient is downward between the upper and sea-level aquifers at the location of the confining unit window. The conditions allow for inflow of contaminated upper-aquifer ground water into the sea-level aquifer at and downgradient from the presumed confining unit window.

A final feature indirectly relevant to TCE migration is that ground-water altitudes are relatively high north and northwest of the Logistics Center where multiple municipal water-supply wells are pumping from the sea-level aquifer. Those higher altitudes to the north combined with the ridge beneath American Lake prevent TCE contaminated water beneath the Logistics Center from migrating toward the municipal wells. The potentiometric-surface maps better represent static rather than pumping conditions for the region; there has been little to no discernible drawdown in the sea-level aquifer due to pumping outside of the immediate vicinity of major supply wells (Robinson and Noble, Inc., 1996).

Extent of TCE, *cis*-DCE, and Vinyl Chloride

Concentrations of TCE, cis-DCE, and vinyl chloride in the sea-level aquifer (table 3 and pl. 1) have not changed significantly since regular monitoring began in 1995 (fig. 5). Most sea-level aquifer data presented in table 3 and plate 1 were collected by the USGS; the Army collected data from the newest sea-level aquifer wells (LC-79D through LC-90D) and from the Madigan Hospital well MAMC-3, as well as the historical data shown in figure 5. Most data presented were collected during May-June 2000, although data from 1998 through 2004 were included to make the dataset complete. The lines of equal TCE concentrations were drawn using the highest measured concentration at locations where multi-level CMT wells (LC-79D through LC-83D) or pairs of wells were screened at different depths. Based on the most recent sampling by the Army, the downgradient extent of the TCE plume illustrated on plate 1 is representative of spring 2004 conditions, but the maximum 160-µg/L TCE concentration illustrated at the confining unit window was somewhat lower during spring 2004 at 110 µg/L. Concentrations of TCE in the uppermost unit of the upper aquifer [Qv(1)] also are shown on plate 1 based on data from URS Corporation (2004).

The sea-level aquifer TCE plume essentially begins at the western margin of the trough eroded through the Qpon unit, which is the presumed location of the confining unit window. Low concentrations of TCE have been sporadic

upgradient (southeast) of the window in previous sampling rounds by the Army. The highest TCE concentrations in the sea-level aquifer are directly at the confining unit window, which indicates that flow through the window is the primary pathway for TCE migration into the sea-level aquifer. However, TCE concentrations in the sea-level aquifer in much of northwest part of the plume are nearly the same as the TCE concentrations in the upper aquifer, which indicates that TCE could be migrating into the sea-level aquifer over an area much more extensive than just the one known confining unit window.

Concentrations of TCE in the sea-level aquifer were consistently highest in the upper part of that aquifer, and little TCE was detected at depths greater than 250 ft. Data from multi-level wells more than 1 mi downgradient from the confining unit window indicate that TCE is present throughout much of the thickness of the sea-level aquifer, but TCE concentrations are highest in the upper part of the aquifer. A trace of TCE was detected in a 304-ft deep well (T-09E) north of the sea-level aquifer TCE plume, but that TCE is thought to be a result of imperfect well construction rather than ambient contamination deep in the sea-level aquifer (as will be discussed later in the "Pathways for TCE Migration into the Sea-Level Aquifer Downgradient from the Confining Unit Window" section of this report.)

The multi-level CMT wells LC-79D through LC-83D were installed during 2003, and the additional paired wells LC-84D through LC-90D were installed during 2004 while this report was being finalized. The initial data from those newest wells confirmed the previously characterized lateral extent of TCE contamination in the sea-level aquifer, and demonstrated that TCE exceeding the 5-µg/L cleanup level extends farther downgradient than previously thought.

The separate 50-µg/L line of equal concentration on plate 1 around well LC-126 depicts the hypothesis that there is a separate pathway for TCE migration into the sea-level aquifer in that vicinity. The uncertainty in that hypothesis is discussed later in the "Pathways for TCE Migration into the Sea-Level Aquifer Downgradient from the Confining Unit Window" section of this report.

Concentrations of *cis*-DCE generally were about one-tenth of the TCE concentrations, and were less than the site remediation goal of 70 µg/L in all wells screened in the sea-level aquifer (table 3). Vinyl chloride was not detected in any of the sea-level aquifer wells. Consistent ratios of the TCE parent compound to the *cis*-DCE and vinyl chloride degradation products throughout the sea-level aquifer indicate that biodegradation of TCE through reductive dechlorination is minimal. Redox data presented later in this report also indicate that conditions are unfavorable for substantial biodegradation of TCE in the sea-level aquifer.

Table 3.   Concentrations of selected volatile organic compounds in ground water from wells screened in the sea-level aquifer, Fort Lewis, Washington, 1998-2004.

[**Well No.**: Locations of wells are shown on plate 1. **Depths to top of screen** are given in feet below land surface. **Volatile organic compounds:** Concentrations exceeding the detection limit are in **bold**. **Abbreviations:** ft, foot; <, less than; –, not analyzed]

Well No.	Date sampled	Depth to top of screen (ft)	Volatile organic compounds, in micrograms per liter		
			Tri-chloro ethene	*cis*-1,2-dichloro-ethene	Vinyl chlo-ride
Sea-level aquifer upgradient from confining unit window					
LC-21C	05-15-00	139	<0.1	<0.1	<0.2
LC-26D	05-18-00	135	<.1	<.1	<.2
LC-35D	06-13-00	195	<.1	<.1	<.2
LC-47D	05-22-00	209	<.1	<.1	<.2
LC-50D	05-22-00	150	**.2**	<.1	<.2
LC-55D[1]	05-16-00	220	<.1	<.1	<.2
Contaminated sea-level aquifer downgradient from confining unit window					
FLS-13	12-12-00	190	**0.6**	<0.1	<0.2
LC-126	05-31-00	160	**67**	**13.3**	<.2
LC-40D	05-19-00	168	**19**	**3.9**	<.2
LC-41D	09-14-98	193	**170**	**4.1**	<8
LC-66D	06-09-00	176	**55**	**5.0**	<.2
LC-67D	12-12-00	149	**53**	**19.2**	<.2
LC-69D	05-23-00	194	**160**	**3.2**	<.2
LC-70D	05-25-00	206	**.4**	<.1	<.2
LC-72D	05-25-00	166	**24**	**2.1**	<.2
LC-73D	05-26-00	165	**37**	**2.3**	<.2
LC-74D	06-01-00	210	**61**	**3.2**	<.2
LC-75D	05-24-00	173	**.8**	**.1**	<.2
LC-77D	05-23-00	196	**10**	**1.1**	<.2
LC-81D-1	01-15-03	184	**3.9**	**.6**	<.2
-2	01-15-03	211	**4.8**	**.6**	<.2
-3	01-17-03	243	**2.9**	**.5**	<.2
LC-82D-1	02-11-03	217	**6.4**	**.5**	<.2
-3	02-12-03	265	**.4**	<.2	<.2
-4	01-28-03	287	**2.3**	**.4**	<.2
LC-83D-1	01-21-03	196	**44**	**1.6**	<.2
-2	01-22-03	208	**15**	1.4	<.2
-3	01-23-03	243	**11**	1.4	<.2
-4	01-24-03	292	**.8**	<.2	<.2
LC-84D-1	04-12-04	214	**3.1**	–	–
-2	04-12-04	276	**1**	–	–
Contaminated sea-level aquifer downgradient from confining unit window—Continued					
LC-86D-1	04-16-04	197	**6.8**	–	–
-2	04-08-04	225	**5.7**	–	–
LC-88D-1	05-07-04	196	**1.7**	–	–
-2	04-25-04	229	**1.3**	–	–
LC-90D-1	05-13-04	205	**2.1**	–	–
-2	05-21-04	234	<1	–	–
MAMC-3	01-02-03	151	**2.6**	<0.2	<0.2
T-09E	06-01-00	294	**1.1**	<.1	<.2
Uncontaminated sea-level aquifer downgradient from confining unit window					
88-1-SS	06-05-00	185	<0.1	<0.1	<0.2
LC-166D	06-05-00	168	<.1	<.1	<.2
LC-41E	02-17-99	280	<1	<1	<2
LC-71D[1]	05-31-00	222	<.1	<.1	<.2
LC-76D	05-17-00	198	<.1	**.1**	<.2
LC-79D-1	01-30-03	197	<.2	<.2	<.2
-2	01-31-03	211	<.2	<.2	<.2
-3	02-10-03	227	<.2	<.2	<.2
-4	02-10-03	275	<.2	<.2	<.2
LC-80D-1	01-09-03	235	<.2	<.2	<.2
-2	01-10-03	251	<.2	<.2	<.2
-3	01-10-03	265	<.2	<.2	<.2
LC-81D-4	01-20-03	280	<.2	<.2	<.2
LC-85D-1	05-13-04	209	<1	–	–
-2	04-08-04	243	<1	–	–
LC-87D-1	04-26-04	230	<1	–	–
-2	04-26-04	254	<1	–	–
LC-89D-1	05-07-04	208	<1	–	–
-2	05-04-04	232	<1	–	–
LF4-MW2C	06-07-00	192	**.3**	**.3**	<.2
LF4-MW4	06-09-00	219	<.1	<.1	<.2
MAMC-4	12-14-00	261	<.1	<.1	<.2
SILCOX-1	12-15-00	234	<.1	<.1	<.2
SRC-MW1B	06-08-00	176	<.1	<.1	<.2

[1] Well is screened in the lower confining unit (Qpon$_2$) immediately beneath the sea-level aquifer.
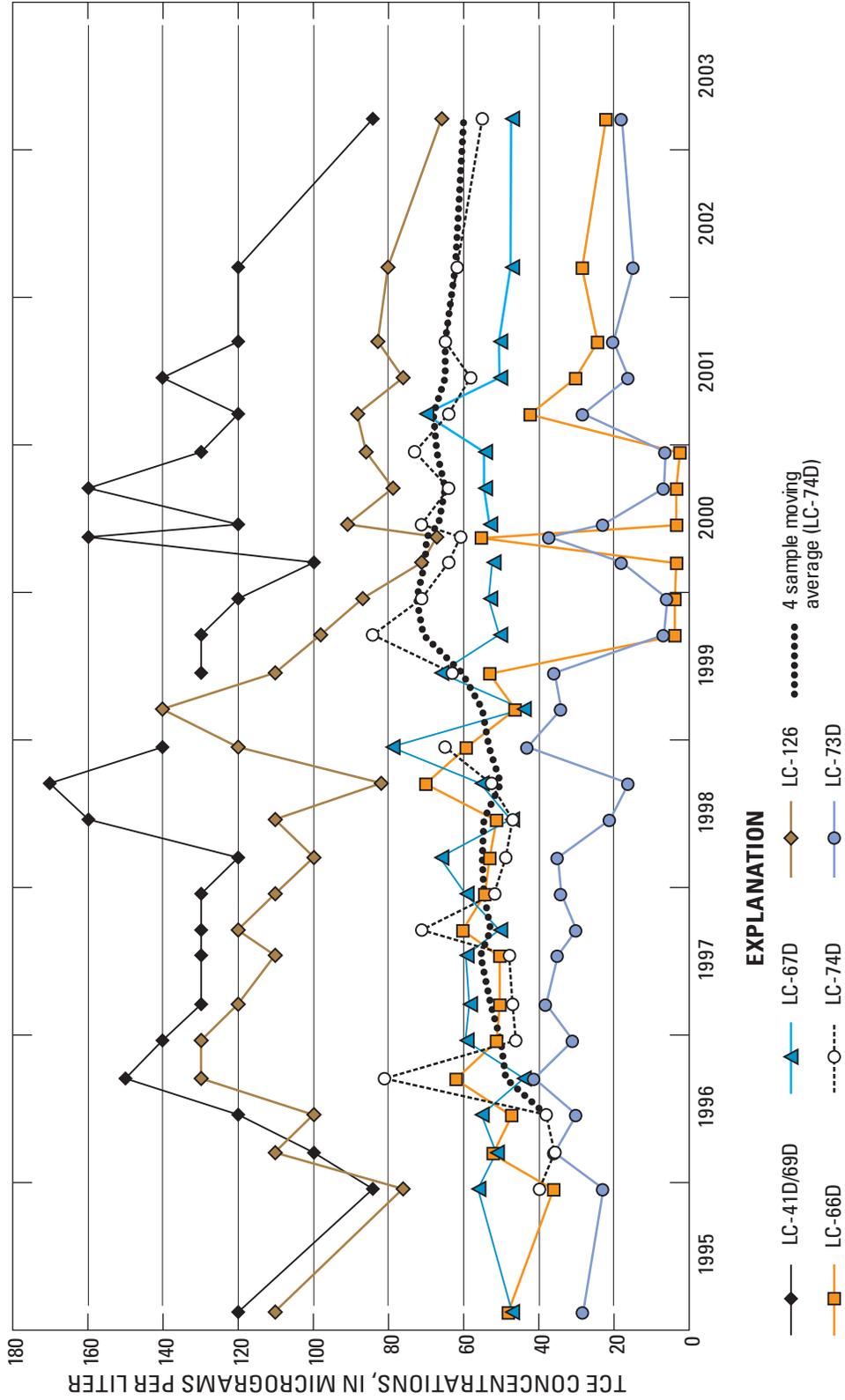
Figure 5. Historical trends in TCE concentrations in selected wells screened in the sea-level aquifer, Fort Lewis, Washington.

Environmental Tracers

Environmental tracers in ground water were used during this investigation to explore the hydrogeology of the study area and contaminant migration in the sea-level aquifer. The theories underlying tracer behavior in ground water combined with the observed distribution of tracers were used to develop and test the following hypotheses:

- Ground water in the upper and sea-level aquifers upgradient of the East Gate Disposal Yard can be differentiated using environmental tracers, so end member mixing models can be used to identify where the two types of ground water mix in downgradient locations.

- Locations and dimensions of permeable windows through the confining unit can be identified by abrupt and substantial changes in tracer concentrations in the sea-level aquifer.

- Tracer data, in combination with water-level and hydrogeologic data, can be used to identify flow paths in the lower aquifer downgradient of the previously known extent of contamination. Tracer data also can provide quantitative insight into the attenuation of contaminant concentrations due to mixing in the sea-level aquifer.

- Water from American Lake has a tracer signature distinct from the upper and sea-level aquifers that can be used to determine if the lake recharges the shallow aquifer and (or) subsequently results in increased recharge to the sea-level aquifer.

The foundation of these hypotheses are the unique chemical signatures identified for so-called end-member waters in American Lake, the upper aquifer, and the sea-level aquifer prior to substantially mixing with lake or upper-aquifer waters. Those chemical signatures result from such factors as evaporation, and the time and location of ground-water recharge. Insight into TCE contamination and migration in the sea-level aquifer was obtained by interpreting ground-water samples from throughout the study area with regard to those unique signatures.

In the following four sections of this report, background information concerning the behavior and use of the various environmental tracers are summarized, followed by a presentation of the tracer data for the study area. A discussion of chemical signatures for each of the three defined end members follows the presentation of all of the tracer data. The background information is summarized primarily from Solomon and Cook (2000), and for brevity the references presented in their book are not repeated in this report. The

isotope data ^{18}O, ^{2}H, and ^{3}H are presented first because they were the most useful tracers for gaining insight into the hydrogeology and contaminant distribution in the sea-level aquifer. Other tracer and chemistry data are then presented and discussed with regard to the hypotheses developed using the isotope data.

Isotopes of Oxygen (^{18}O) and Hydrogen (^{2}H and ^{3}H)

The stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) in water are particularly useful as tracers because they are physically part of a water molecule. The ^{18}O and ^{2}H compositions of water are reported as deviation values (δ) from a standard (Vienna Standard Mean Ocean Water or VSMOW) in units of parts per thousand (permil or ‰). A positive δ value means that a sample contains relatively more of the heavier isotope (^{18}O or ^{2}H) than the standard, and a negative δ value means that a sample contains less of the heavier isotope than the standard.

The different isotopes of oxygen and hydrogen have slightly different chemical and physical properties because of their mass differences. The mass differences are large enough for many physical, chemical, and biological processes or reactions to "fractionate" or change the relative proportions of the isotopes. As a consequence of fractionation processes, waters often develop unique isotopic compositions that may be indicative of their source or of the processes that formed them. ^{18}O and ^{2}H are predominantly fractionated through equilibrium isotope-exchange reactions where the heavier isotope becomes enriched (preferentially accumulates). The ^{18}O and ^{2}H composition of precipitation has been monitored worldwide since 1961, and the relation between δ^{18}O and δ^2H is referred to as a meteoric water line. Isotope fractionation resulting from evaporation is a process that enriches δ^{18}O and δ^2H values in surface water in such a way that the δ^2H/δ^{18}O slope is substantially less than that represented by most global meteoric water lines.

Tritium (^{3}H) is a radioactive hydrogen isotope that was used as a tracer in this investigation primarily to identify relatively old ground water (recharged prior to 1952) that has not been mixed with more modern water. Very small quantities of tritium are produced naturally in the atmosphere, but much larger quantities were introduced into the atmosphere and incorporated into the hydrologic cycle by atmospheric thermonuclear bomb testing between 1952 and 1980. Tritium is physically part of a water molecule and is geochemically conservative like the stable isotopes ^{18}O and ^{2}H. The tritium concentration usually is expressed in tritium units (TU), where one TU represents one molecule of ^{3}H^{1}HO in 10^{18} molecules of ^{1}H$_2$O.

Prior to the 1950's, the natural (pre-bomb) concentration of tritium in Pacific Northwest precipitation was determined to be 3 to 6 TU (Thatcher, 1962). Commencing in 1952, atmospheric thermonuclear testing caused large increases in the tritium concentration of precipitation thereby creating a marker that could be used to identify precipitation from specific periods. The tritium concentration in precipitation in the Pacific Northwest reached a maximum of more than 3,000 TU during 1963, and had decreased back to about 3 to 5 TU by 2000. Precise age-dating with tritium is more ambiguous than it was in the past because the historically elevated tritium concentrations in ground water have decayed substantially over time. However, single observations of tritium in ground water can be used to distinguish between "pre-modern" and "modern" ground water. The only ground water that could have a tritium concentration less than about 0.5 TU would be pre-modern ground water recharged prior to 1952, because radioactive decay would have decreased the 3 to 6 TU pre-atmospheric testing concentration to less than 0.5 TU over the approximately 50-year duration between recharge from precipitation and sampling. Conversely, a tritium concentration greater than about 0.5 TU indicates modern ground water recharged since 1952.

The stable-isotope composition and tritium concentrations for ground-water and surface-water sites in the study area are presented in table 4 and illustrated in figures 6 and 7 (tracer data were not collected from the newest well pairs LC-84D through LC-90D) screened in the sea-level aquifer. Recent TCE concentrations in the sea-level aquifer also are included in table 4 to facilitate discussion. Only selected samples are labeled individually in figure 6; a smaller scale detail of the lower left portion of the figure with all other samples labeled is shown in figure 7.

The complete set of isotope data were divided into four subsets based on where the samples came from and whether or not they had detectable concentrations of TCE. Those subsets are represented by different symbols in figure 6. The first subset includes data from American Lake and the well SILCOX-2. The sample from that 10-foot-deep well was isotopically similar to lake water because it is only 20 ft from the shoreline of Silcox Island in American Lake. The second subset includes data from upper-aquifer wells. The third subset includes data from all sea-level aquifer wells with detectable concentrations of TCE. The fourth subset includes data from all sea-level aquifer and deeper wells that have no detectable concentrations of TCE. In addition, wells with tritium concentrations less than 0.5 TU are identified in figure 6. The analytical precision (two standard deviations) for the stable isotope data was ±2 permil for δ^2H and ±0.2 permil for δ^{18}O, and the precision for the tritium analyses ranged from ±0.18 to ±0.81 TU.

The isotope data are reasonably grouped according to the hypothesized end-members: American Lake water, upper-aquifer water, and sea-level aquifer water that has not been mixed with upper-aquifer or lake water. The mixing in varying degrees of those end-members explains the isotope signatures of the TCE-contaminated sea-level aquifer wells. A more thorough discussion of the end-member signatures follows the presentation of the other tracer data.

Chlorofluorocarbons and Sulfur Hexafluoride

Chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) are stable, synthetic (or rare) organic compounds that have been released as gasses into the atmosphere and incorporated into the hydrologic cycle since the early 1930s. Three CFCs in particular [CFC-12 (dichlorodifluoromethane), CFC-11 (trichlorofluoromethane), and CFC-113 (trichlorotrifluoroethane)] can be used for age-dating ground water that has been recharged within about the past 50 years. Production and release of SF_6 came later, so it is useful for age-dating ground water that has been recharged within about the past 25 years. Age-dating with CFCs and SF_6 is possible primarily because the historical atmospheric concentrations (mixing ratios) of the compounds are known or have been reconstructed, and because the compounds' concentrations in both air and young ground water are high enough to measure.

Release of CFCs to the atmosphere increased rapidly through the 1970s and 1980s, but slowed considerably during the 1990s due to phased out production. Release of SF_6 to the atmosphere also increased rapidly above the natural background concentration through the 1970s and 1980s, and has continued to increase through 2000. In North America, air mixing ratios of CFC-11 and CFC-113 peaked in about 1993 and 1994, the ratio of CFC-12 appears to have peaked in 2001, and the ratio of SF_6 has continued to increase. Near urban areas, the air-mixing ratios generally may be enriched relative to North American air as was found with CFC-12 in nearby Kitsap County, Washington (Cox, 2003). Ground-water age-dating with CFCs and SF_6 is based on Henry's law, which states that the equilibrium concentration of CFCs or SF_6 dissolved in water is proportional to the partial pressure of the gasses in air. An air-mixing ratio that corresponds to a measured CFC or SF_6 concentration in ground water is calculated with Henry's law using an estimated shallow ground-water temperature during recharge, a total atmospheric pressure (estimated from the elevation at which recharge occurred), and the known solubilities of a CFC or SF_6. The calculated air-mixing ratio is then compared to the historical air mixing ratios to determine the date of recharge, and the ground-water age is simply the date of sampling minus the date of recharge.
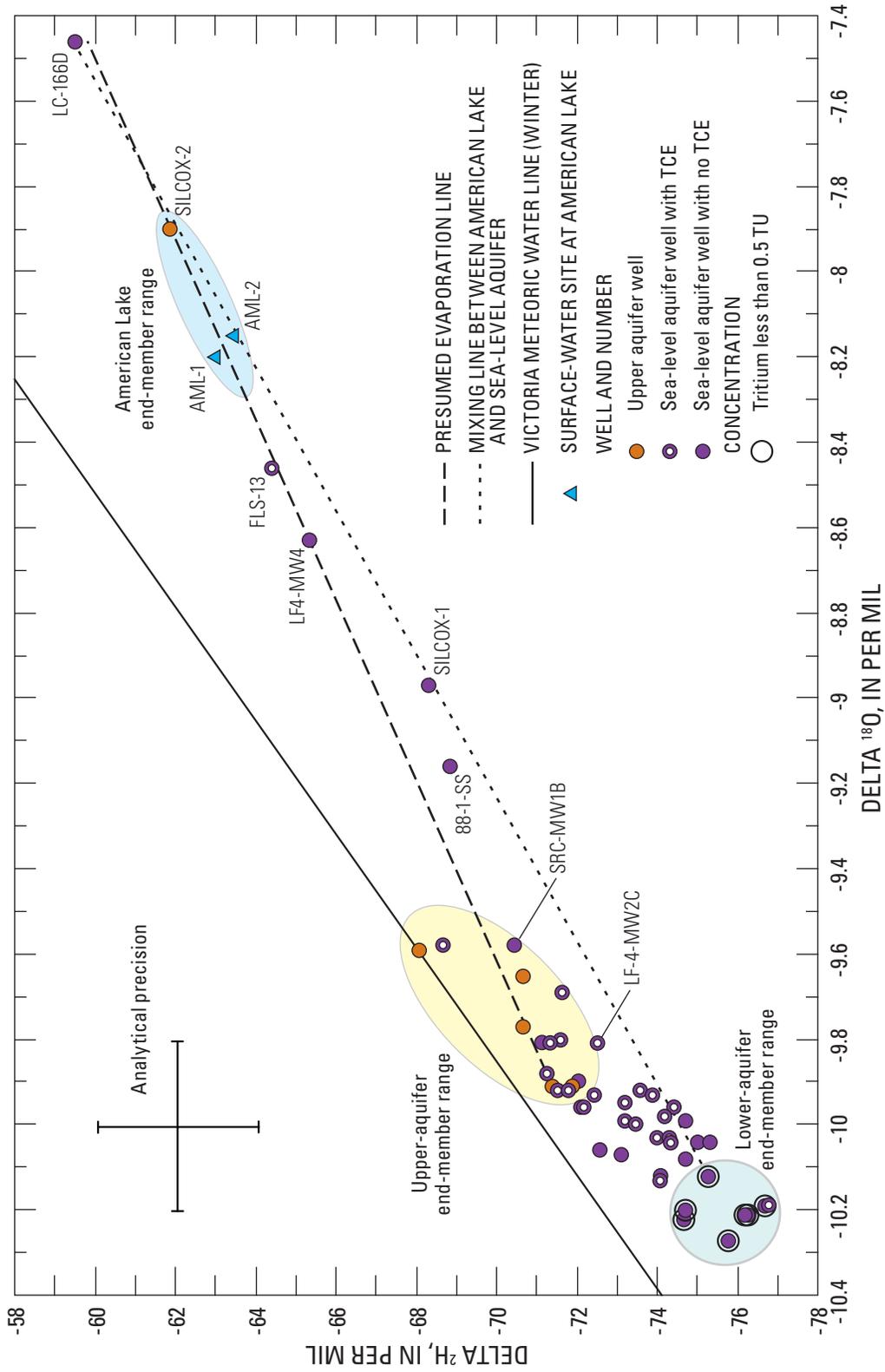
Figure 6. Stable isotope composition in water samples from wells and surface-water sites, Fort Lewis, Washington.
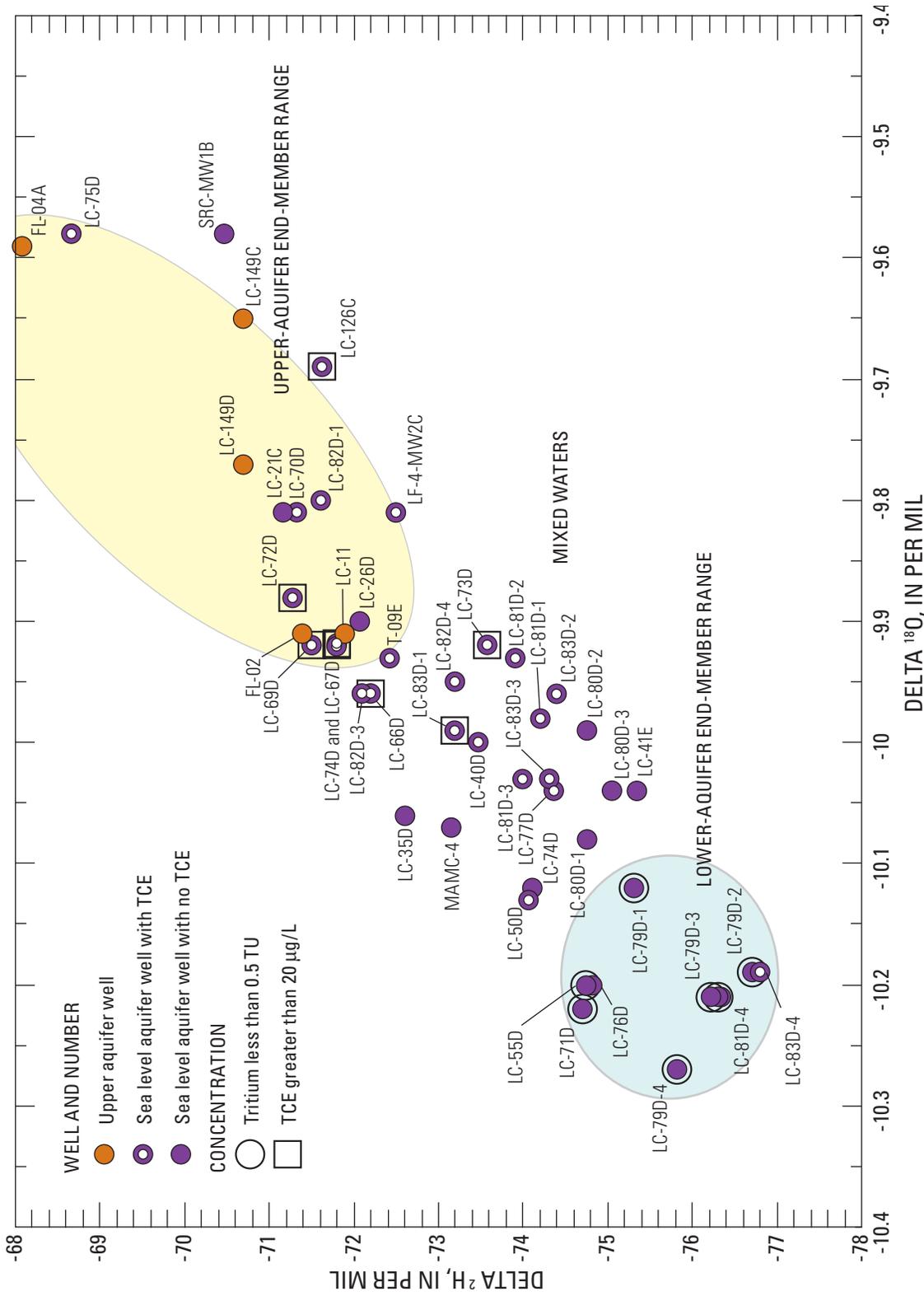
Figure 7. Stable isotope composition in a subset of water samples from wells, Fort Lewis, Washington.

Table 4.   Stable isotope composition and concentrations of trichloroethene and tritium in water samples from wells and surface-water sites, Fort Lewis, Washington, 1999 to 2003.

[**Well No.**: Locations of wells are shown on plate 1. **Hydrogeologic unit:** SW, American Lake; Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; Qpog$_2$, sea-level aquifer; and Qpon$_2$, lower confining unit. **Depths to top of screen** are given in feet below land surface. **Trichloroethene** concentrations exceeding the detection limit are in **bold**. **Abbreviations:** ft, foot; mg/L, microgram per liter; δ^2H, ^{3}H, isotopes of hydrogen; δ^{18}O, isotope of oxygen; δ^{13}C, isotope of carbon; permil, parts per thousand; <, less than; –, not analyzed]

Well No.	Date sampled	Hydro-geologic unit	Depth to top of screen (ft)	Trichloro-ethene (μg/L)	δ^2H (permil)	δ^{18}O (permil)	δ^{13}C (permil)	^{3}H (tritium units)
				American Lake				
AML-1	06-14-00	SW	63[1]	–	-63.0	-8.20	-15.40	4.1
AML-2	06-14-00	SW	58[1]	–	-63.5	-8.15	-15.10	4.1
				Upper aquifer				
FL-02	12-21-00	Qv(1)	40	**94**	-71.4	-9.91	-17.6	4.2
FL-04A	05-17-00	Qv(2)	133	**1.5**	-68.1	-9.59	-20.07	4.4
LC-11	12-21-00	Qv(1)	20	<.1	-71.9	-9.91	-19.42	3.5
LC-149C	02-16-99	Qv(1)	28	<1	-70.7	-9.65	-20.05	4.5
LC-149D	02-16-99	Qv(1)	60	<1	-70.7	-9.77	-19.70	3.7
LC-21B	02-18-99	Qpon	111	<1	-75.1	-10.08	-17.54	.6
LC-40C	05-18-00	Qpon	147	<1	-73.5	-9.94	-20.70	7.8
SILCOX-2	12-15-00	Qv(1)	10	<.1	-61.9	-7.90	–	4.5
				Sea-level aquifer upgradient from confining unit window				
LC-21C	05-15-00	Qpog$_2$	139	<0.1	-71.1	-9.81	-19.50	4.4
LC-26D	05-18-00	Qpog$_2$	135	<.1	-72.0	-9.90	-20.00	4.4
LC-35D	06-13-00	Qpog$_2$	195	<.1	-72.6	-10.06	-19.70	4.7
LC-47D	05-22-00	Qpog$_2$	209	<.1	-74.1	-10.12	-18.30	3.8
LC-50D	05-22-00	Qpog$_2$	150	**.2**	-74.1	-10.13	-18.40	1.5
LC-55D[2]	05-16-00	Qpon$_2$	220	<.1	-74.7	-10.20	-18.70	.2
				Contaminated sea-level aquifer downgradient from confining unit window				
FLS-13	12-12-00	Qpog$_2$	190	**0.6**	-64.4	-8.46	–	–
LC-126	05-31-00	Qpog$_2$	160	**67**	-71.7	-9.69	-20.90	8.8
LC-40D	05-19-00	Qpog$_2$	168	**19**	-73.5	-10.00	-19.90	5.6
LC-66D	06-09-00	Qpog$_2$	176	**55**	-72.2	-9.96	-19.20	3.1
LC-67D	12-12-00	Qpog$_2$	149	**53**	-71.8	-9.92	-20.1	8.7
LC-69D	05-23-00	Qpog$_2$	194	**160**	-71.5	-9.92	-21.20	4.4
LC-70D	05-25-00	Qpog$_2$	206	**.4**	-71.3	-9.81	-19.60	9.4
LC-72D	05-25-00	Qpog$_2$	166	**24**	-71.3	-9.88	-19.80	5.0
LC-73D	05-26-00	Qpog$_2$	165	**37**	-73.6	-9.92	-19.70	6.0
LC-74D	06-01-00	Qpog$_2$	210	**61**	-71.8	-9.92	-19.50	5.6
LC-75D	05-24-00	Qpog$_2$	173	**.8**	-68.7	-9.58	-19.50	5.2
LC-77D	05-23-00	Qpog$_2$	196	**10**	-74.4	-10.04	-18.80	2.8
LC-81D-1	01-15-03	Qpog$_2$	184	**3.9**	-74.2	-9.98	-19.55	4.7
-2	01-15-03	Qpog$_2$	211	**4.8**	-73.9	-9.93	-19.58	4.8
-3	01-17-03	Qpog$_2$	243	**2.9**	-74.0	-10.03	-18.95	4.1
LC-82D-1	02-11-03	Qpog$_2$	217	**6.4**	-71.6	-9.80	-19.58	4.9
-3	02-12-03	Qpog$_2$	265	**.4**	-72.1	-9.96	-19.48	5.8
-4	01-28-03	Qpog$_2$	287	**2.3**	-73.2	-9.95	-19.67	3.4
LC-83D-1	01-21-03	Qpog$_2$	196	**44**	-73.2	-9.99	-19.82	4.1
-2	01-22-03	Qpog$_2$	208	**15**	-74.4	-9.96	–	4.3
-3	01-23-03	Qpog$_2$	243	**11**	-74.3	-10.03	-19.24	4.5
-4	01-24-03	Qpog$_2$	292	**.8**	-76.8	-10.19	-17.85	1.1
LF4-MW2C	06-07-00	Qpog$_2$	192	**.3**	-72.5	-9.81	-18.40	4.4
MAMC-3	–	Qpog$_2$	151	**2.6**	–	–	–	–
T-09E	06-01-00	Qpog$_2$	294	**1.1**	-72.4	-9.93	-18.80	4.4

Table 4.   Stable isotope composition and concentrations of trichloroethene and tritium in water samples from wells and surface-water sites, Fort Lewis, Washington, 1999 to 2003.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **Hydrogeologic unit:** SW, American Lake; Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; $Qpog_2$, sea-level aquifer; and $Qpon_2$, lower confining unit. **Depths to top of screen** are given in feet below land surface. **Trichloroethene** concentrations exceeding the detection limit are in **bold**. **Abbreviations:** ft, foot; mg/L, microgram per liter; δ^2H, ^3H, isotopes of hydrogen; $\delta^{18}O$, isotope of oxygen; $\delta^{13}C$, isotope of carbon; permil, parts per thousand; <, less than; –, not analyzed]

Well No.	Date sampled	Hydro-geologic unit	Depth to top of screen (ft)	Trichloro-ethene (µg/L)	δ^2H (permil)	$\delta^{18}O$ (permil)	$\delta^{13}C$ (permil)	^3H (tritium units)
Uncontaminated sea-level aquifer downgradient from confining unit window								
88-1-SS	06-05-00	$Qpog_2$	185	<0.1	-68.8	-9.16	-17.30	3.3
LC-166D	06-05-00	$Qpog_2$	168	<.1	-59.5	-7.46	-14.20	6.9
LC-41E	02-17-99	$Qpog_2$	280	<1	-75.3	-10.04	-18.51	1.6
LC-71D[2]	05-31-00	$Qpon_2$	222	<.1	-74.7	-10.22	-17.90	.1
LC-76D	05-17-00	$Qpog_2$	198	<.1	-74.8	-10.20	-20.20	1.2
LC-79D-1	01-30-03	$Qpog_2$	197	<.2	-75.3	-10.12	-18.70	.3
-2	01-31-03	$Qpog_2$	211	<.2	-76.7	-10.19	-18.12	.1
-3	02-10-03	$Qpog_2$	227	<.2	-76.2	-10.21	-17.22	.1
-4	02-10-03	$Qpog_2$	275	<.2	-75.8	-10.27	-17.06	-.2
LC-80D-1	01-09-03	$Qpog_2$	235	<.2	-74.7	-10.08	-19.51	4.9
-2	01-10-03	$Qpog_2$	251	<.2	-74.7	-9.99	-26.98	4.9
-3	01-10-03	$Qpog_2$	265	<.2	-75.0	-10.04	-9.40	4.9
LC-81D-4	01-20-03	$Qpog_2$	280	<.2	-76.3	-10.21	-17.77	.3
LF4-MW4	06-09-00	$Qpog_2$	219	<.1	-65.3	-8.63	-17.20	5.0
MAMC-4	12-14-00	$Qpog_2$	261	<.1	-73.1	-10.07	-19	3.9
SILCOX-1	12-15-00	$Qpog_2$	234	<.1	-68.3	-8.97	–	7.6
SRC-MW1B	06-08-00	$Qpog_2$	176	<.1	-70.4	-9.58	-18.80	5.3

[1]Depth below lake surface where sample was collected.

[2]Well is screened in the lower confining unit ($Qpon_2$) immediately beneath the sea-level aquifer.

Ground-water ages based on CFC or SF_6 concentrations are referred to as apparent ages. An apparent age would equal the actual transit time of ground water from the location of recharge to the location of sampling only if CFC or SF_6 were transported without fractionation, dispersion, and mixing. However, tracer concentrations in ground water are always affected to a certain degree by at least dispersion, so there is always some difference between apparent ages and actual ages. CFC and SF_6 concentrations in ground water also may be affected by degradation, sorption, or processes occurring during recharge. CFC and SF_6 dating generally is most likely to be successful in rural settings, with shallow water tables, where ground water is aerobic, and not impacted by local sources of the tracers. Likely problems to be encountered with CFCs or SF_6 age-dating at the Fort Lewis study area include contamination from urban air and local sources, microbial degradation in anaerobic parts of the sea-level aquifer, and mixing of waters with different ages.

The ground-water CFC concentration data collected for this investigation (Appendix B) added little insight into sea-level aquifer flow and transport phenomena primarily due to CFC contamination from local urban air sources. Local contamination of CFC samples was unequivocally indicated by CFC concentrations in about 40 percent of the samples that exceeded the maximum possible ground-water concentration that could be calculated using the North American air-mixing ratios. And although the CFC concentrations in 60 percent of the samples were less than the maximum possible using the air-mixing ratios, the CFC concentrations in those samples also probably were contaminated. Additionally, CFC concentrations probably were affected by microbial degradation in anaerobic parts of the sea-level aquifer. There generally was a positive correlation between TCE and CFC concentrations in the samples, but the uncertainty in the CFC content of precipitation over the study area did not allow ground-water age-dating.

The ground-water sulfur hexafluoride data and estimated apparent ages (table 5) did not appear to be affected by local contamination. The average apparent age was about 3 years for American Lake samples, about 7 years for upper-aquifer samples, 15 years for sea-level aquifer samples contaminated with TCE, and 19 years for sea-level aquifer samples not contaminated with TCE (near the limit of age-dating with sulfur hexafluoride.) Those data add additional support for the hypothesized end-members in the study area.

Table 5.   Concentrations of sulfur hexafluoride and apparent-age dates in water samples from wells and surface-water sites, Fort Lewis, Washington, 1999 to 2000.

[**Well No.**: Locations of wells are shown on plate 1. **Hydrogeologic unit:** SW, American Lake; Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; $Qpog_2$, sea-level aquifer; and $Qpon_2$, lower confining unit. **Depths to top of screen** are given in feet below land surface. **Abbreviations:** ft, foot; pptv, parts per trillion by volume; >, greater than]

Well No.	Date sampled	Hydro-geologic unit	Depth to top of screen (ft)	Sulfur hexafluoride (SF_6) (pptv)	Apparent SF_6 age (years)
American Lake					
AML-1	06-14-00	SW	63[1]	4.06	3
AML-2	06-14-00	SW	58[1]	4.01	3
Upper aquifer					
FL-02	12-21-00	Qv(1)	40	2.92	7
FL-04A	05-17-00	Qv(2)	133	1.83	13
LC-11	12-21-00	Qv(1)	20	3.42	5
LC-149C	02-16-99	Qv(1)	28	3.21	5
LC-149D	02-16-99	Qv(1)	60	3.66	3
LC-21B	02-18-99	Qpon	111	.27	>25
LC-40C	05-18-00	Qpon	147	2.90	7
SILCOX-2	12-15-00	Qv(1)	10	3.64	4
Sea-level aquifer upgradient from confining unit window					
LC-21C	05-15-00	$Qpog_2$	139	2.33	10
LC-26D	05-18-00	$Qpog_2$	135	1.66	14
LC-35D	06-13-00	$Qpog_2$	195	.53	24
LC-47D	05-12-00	$Qpog_2$	209	.42	25
LC-50D	05-22-00	$Qpog_2$	150	.74	21
LC-55D[2]	05-16-00	$Qpon_2$	220	.19	>25

Well No.	Date sampled	Hydro-geologic unit	Depth to top of screen (ft)	Sulfur hexafluoride (SF_6) (pptv)	Apparent SF_6 age (years)
Contaminated sea-level aquifer downgradient from confining unit window					
FLS-13	12-12-00	$Qpog_2$	190	2.58	9
LC-126	05-31-00	$Qpog_2$	160	1.86	13
LC-40D	05-19-00	$Qpog_2$	168	1.69	14
LC-66D	06-09-00	$Qpog_2$	176	1.07	18
LC-67D	12-12-00	$Qpog_2$	149	1.16	17
LC-69D	05-23-00	$Qpog_2$	194	2.89	7
LC-70D	05-25-00	$Qpog_2$	206	1.07	18
LC-72D	05-25-00	$Qpog_2$	166	2.14	11
LC-73D	05-26-00	$Qpog_2$	165	.97	19
LC-74D	06-01-00	$Qpog_2$	210	1.64	14
LC-75D	05-24-00	$Qpog_2$	173	1.98	12
LF4-MW2C	06-07-00	$Qpog_2$	192	.42	25
T-09E	06-01-00	$Qpog_2$	294	2.00	12
Uncontaminated sea-level aquifer downgradient from confining unit window					
88-1-SS	06-05-00	$Qpog_2$	185	0.24	>25
LC-166D	06-05-00	$Qpog_2$	168	2.29	10
LC-41E	02-17-99	$Qpog_2$	280	1.08	17
LC-71D[2]	05-31-00	$Qpon_2$	222	.43	25
LC-76D	05-17-00	$Qpog_2$	198	1.49	15
LF4-MW4	06-09-00	$Qpog_2$	219	1.36	16
MAMC-4	12-14-00	$Qpog_2$	261	1.07	18
SILCOX-1	12-15-00	$Qpog_2$	234	1.09	18
SRC-MW1B	06-08-00	$Qpog_2$	176	.57	23

[1]Depth below lake surface where sample was collected.

[2]Well is screened in the lower confining unit ($Qpon_2$) immediately beneath the sea-level aquifer.

Common Ions

Common ion concentrations (Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, SO_4^-, Cl^-) in local ground-water systems such as the Fort Lewis study area primarily are established in recharge water that has passed through the unsaturated zone. Although, some additional changes in ground-water chemistry may result from saturated zone chemical and biological processes. In anaerobic ground water with relatively abundant organic carbon available, one could expect SO_4^- concentrations to decrease and HCO_3^- concentrations to increase due to microbial activity. Those changes were not apparent in ground water in the study area because the ambient organic carbon available to sustain ground-water microbial processes is minimal (data from this investigation). Other possible changes to common-ion concentrations could come from dissolution of aquifer sediment minerals as ground water migrates along flow paths. Those changes were not apparent in ground water in the study area because the minerals comprising the unconsolidated aquifer sediments are relatively non-reactive and of low-carbonate content (Walters and Kimmel, 1968; Vermeul and others, 2000).

Common-ion chemistry of upper and sea-level aquifer waters in the study area (table 6) was very consistent. Thus, the data added no new information for characterizing hypothesized end-members in the study area. In most samples, calcium and magnesium together made up more than 70 percent of the cations in solution, and bicarbonate made up more than 80 percent of the anions. Those calcium-magnesium/bicarbonate waters are typical for the unconsolidated aquifers of the Puget Sound region. Samples from some intervals in the newly installed multi-level CMT wells contained relatively high concentrations of sodium (greater than 10 mg/L). However, that was most likely due to sample contamination by bentonite grout used during well construction.

Redox-Related Geochemistry and Stable Carbon Isotopes

Redox-related geochemical data (DO, TOC, Mn, Fe(II), sulfide, and methane) primarily were used to identify ground water with past or present enhanced microbial activity. If microbial activity was relatively high, DO concentrations would decrease with coincident increases in either Mn, Fe(II), sulfide, or methane concentrations. However, the relatively low concentrations of TOC measured in the study area are not conducive to abrupt changes in concentrations of redox-sensitive analytes, and aerobic ground water with low TOC appears to remain aerobic over long distances.

The stable isotope of carbon (^{13}C) in dissolved inorganic carbon (DIC) also was used as an indicator of microbial activity in ground water. Carbon isotope concentrations are reported as deviation (δ) values from a standard (Vienna Peedee belemnite or VPDB) in units of parts per thousand (permil or ‰).

Atmospheric CO_2 with a $\delta^{13}C$ value of about -7 ‰ is a source of dissolved inorganic carbon in ground water, but a more important source is soil CO_2 produced by root respiration. In northern latitudes, the $\delta^{13}C$ value of soil CO_2 and DIC in ground-water recharge is about -18 to -22 ‰. Dissolution of carbonate-bearing minerals could enrich $\delta^{13}C$ values (make them less negative or positive), but the aquifer sediments in the study area lack carbonate-bearing minerals. Thus, the likely cause for enriched $\delta^{13}C$ values of DIC in study area waters is microbial processes that produce carbon dioxide. Microbial processes are examples of kinetic isotope reactions where fractionations occur in systems out of isotopic equilibrium because forward and backward reaction rates are not identical. During kinetic reactions, the lighter isotopes react more readily and become concentrated in the products, and the residual reactants become enriched in the heavy isotopes. Thus, $\delta^{13}C$ values in DIC can become enriched due to methanogenesis or similar carbon-dioxide producing processes. Identification of waters with enriched $\delta^{13}C$ is relevant because methanogenic conditions in ground water also are favorable for biodegradation of TCE.

The redox-related signatures of waters (table 7) are illustrated by grouping the data according to (1) American Lake; (2) upper-aquifer samples; (3) sea-level aquifer samples upgradient from the confining unit window; (4) contaminated sea-level aquifer samples downgradient from the confining unit window; and (5) uncontaminated sea-level aquifer samples downgradient from the confining unit window.

Dissolved-oxygen concentrations (table 7) were consistent with the end-members identified using the isotope data. American Lake water is at least seasonally anaerobic (when the lake is stratified), the upper aquifer is aerobic, contaminated ground water in the sea-level aquifer is generally aerobic, and uncontaminated ground water in the sea-level aquifer generally is anaerobic. Throughout the contaminated part of the sea-level aquifer, conditions generally are not favorable for biodegradation of TCE. That is because of the generally aerobic conditions found, and because of consistently low concentrations of organic carbon. The $\delta^{13}C$ values that ranged between -18 and -22 ‰ in contaminated parts of the sea-level aquifer were consistent with concentrations in soil gas in the region (Cox, 2003), which indicate that subsequent microbial processes in ground water are limited.

Table 6. Selected water-quality measurements and concentrations of common ions in water samples from wells, Fort Lewis, Washington, 1998-2003.

[**Well No.**: Locations of wells are shown on plate 1. **Hydrogeologic unit:** Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; Qpog$_2$, sea-level aquifer; and Qpon$_2$, lower confining unit. **Depths to top of screen** are given in feet below land surface. **Abbreviations:** ft, foot; μS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligram per liter; –, not analyzed]

Well No.	Date sampled	Hydro-geo-logic unit	Depth to top of screen (ft)	pH (units)	Specific conduc-tance (μS/cm)	Cal-cium (mg/L)	Magne-sium (mg/L)	Sodium (mg/L)	Potas-sium (mg/L)	Bicar-bonate (mg/L)	Chlo-ride (mg/L)	Sul-fate (mg/L)
					Upper aquifer							
FL-02	12-21-00	Qv(1)	40	6.7	–	10.7	3.52	4.84	0.91	51	2.61	4.9
FL-04A	05-17-00	Qv(2)	133	7.2	132	11.8	5.27	5.68	1.15	64	2.77	6.3
LC-11	12-21-00	Qv(1)	20	6.3	–	12.3	3.32	4.37	.8	54	1.3	3.9
LC-149C	02-16-99	Qv(1)	28	6.8	118	11.5	4.39	4.51	.87	59	2.33	4.5
LC-149D	02-16-99	Qv(1)	60	6.6	118	11.3	4.13	4.48	.93	56	2.24	5.5
LC-40C	05-18-00	Qpon	147	7.4	147	11	6.77	6.36	3.24	72	3.08	6.2
SILCOX-2	12-15-00	Qv(1)	10	7	157	14.7	6.19	5.68	1.9	61	4.09	6.6
					Sea-level aquifer upgradient from confining unit window							
LC-21C	05-15-00	Qpog$_2$	139	7.1	120	10.3	5.00	5.69	1.58	59	2.39	3.9
LC-26D	05-18-00	Qpog$_2$	135	7.3	134	11	5.82	6.44	2.21	71	2.34	3.2
LC-35D	06-13-00	Qpog$_2$	195	7.5	128	9.92	5.58	7.12	1.95	63	2.19	3.6
LC-47D	05-22-00	Qpog$_2$	209	8.1	145	15.7	2.98	7.96	2.12	76	2.17	4.7
LC-50D	05-22-00	Qpog$_2$	150	7.7	119	7.34	4.28	9.8	1.77	67	1.83	1.7
LC-55D[1]	05-16-00	Qpon$_2$	220	7.8	113	8.26	4.51	7.23	2.28	69	2.1	1.5
					Contaminated sea-level aquifer downgradient from confining unit window							
FLS-13	12-12-00	Qpog$_2$	190	7.9	132	12.3	3.96	7.29	1.08	60	5.2	0.1
LC-126	05-31-00	Qpog$_2$	160	7.7	175	16.9	7.81	6.4	1.94	85	3.17	7.3
LC-40D	05-19-00	Qpog$_2$	168	7.7	132	10.6	5.36	6.44	2.58	58	2.78	4.4
LC-41D	09-14-98	Qpog$_2$	193	6.8	149	12.3	6.33	5.85	1.53	67	2.59	6.7
LC-66D	06-09-00	Qpog$_2$	176	7.4	144	12.7	5.18	6.31	2.6	74	2.26	4.3
LC-67D	12-12-00	Qpog$_2$	149	7.8	170	15.2	7.35	7.3	2.87	83	2.64	8.2
LC-69D	05-23-00	Qpog$_2$	194	7	152	12.3	6.79	5.47	2.35	68	3.3	7
LC-70D	05-25-00	Qpog$_2$	206	7.9	152	11.4	7.34	6.83	2.68	78	2.94	7.5
LC-72D	05-25-00	Qpog$_2$	166	6.9	129	10.5	5.36	5.48	1.78	62	2.67	4.9
LC-73D	05-26-00	Qpog$_2$	165	7.2	145	11.5	6.43	6.44	2.65	68	3.12	6.3
LC-74D	06-01-00	Qpog$_2$	210	7.3	147	12.1	6.36	6.17	2.4	73	3.19	5.8
LC-75D	05-24-00	Qpog$_2$	173	8.9	147	13.7	5.87	5.63	1.61	73	3	7.7
LC-77D	05-23-00	Qpog$_2$	196	9.6	176	10	5.58	15.2	2.44	89	1.89	.2
LC-81D-1	01-15-03	Qpog$_2$	184	7.1	179	3.61	1.9	34.5	–	93	2.13	13.8
-2	01-15-03	Qpog$_2$	211	6.8	133	9.95	5.35	8.97	–	73	2.14	4.8
-3	01-17-03	Qpog$_2$	243	7.2	132	9.58	5.56	8.03	–	72	2.06	4.5
LC-82D-1	02-11-03	Qpog$_2$	217	7.3	148	10.4	5.97	8.41	–	77	2.36	8.2
-3	02-12-03	Qpog$_2$	265	7.1	152	5.95	3.52	18.1	–	77	2.46	7.3
-4	01-28-03	Qpog$_2$	287	7	149	9.79	5.99	10.3	–	82	2.15	8.3
LC-83D-1	01-21-03	Qpog$_2$	196	6.9	128	9.57	5.64	6.7	–	68	2	4.8
-2	01-22-03	Qpog$_2$	208	7.4	180	10.5	5.67	17.2	–	85	3.06	16.9
-3	01-23-03	Qpog$_2$	243	7.4	137	7.7	3.88	13.8	–	77	1.91	4.8
-4	01-24-03	Qpog$_2$	292	8	125	10.1	4.36	7.69	–	77	1.25	.8
LF4-MW2C	06-07-00	Qpog$_2$	192	7.5	130	10.4	5.8	6.1	1.7	66	2.85	3.6
MAMC-3	01-02-03	Qpog$_2$	151	7.67	98	–	–	–	–	–	–	–
T-09E	06-01-00	Qpog$_2$	294	7.2	175	14	7.68	7.95	2.78	83	4.3	6.2

Table 6.   Selected water-quality measurements and concentrations of common ions in water samples from wells, Fort Lewis, Washington, 1998-2003.—Continued

[**Well No.**: Locations of wells are shown on plate 1. **Hydrogeologic unit:** Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; Qpog$_2$, sea-level aquifer; and Qpon$_2$, lower confining unit. **Depths to top of screen** are given in feet below land surface. **Abbreviations:** ft, foot; µS/cm, microsiemens per centimeter at 25º Celsius; mg/L, milligram per liter; −, not analyzed]

Well No.	Date sampled	Hydro-geo-logic unit	Depth to top of screen (ft)	pH (units)	Specific conduc-tance (µS/cm)	Cal-cium (mg/L)	Magne-sium (mg/L)	Sodium (mg/L)	Potas-sium (mg/L)	Bicar-bonate (mg/L)	Chlo-ride (mg/L)	Sul-fate (mg/L)
					Uncontaminated sea-level aquifer downgradient from confining unit window							
88-1-SS	06-05-00	Qpog$_2$	185	7.4	164	12.9	8.33	6.81	1.97	92	3.52	3.2
LC-166D	06-05-00	Qpog$_2$	168	7.5	147	13.1	6.44	5.94	1.43	76	3.87	4.8
LC-41E	02-17-99	Qpog$_2$	280	7.9	134	11.1	4.35	6.8	2.92	72	2.2	3.8
LC-71D[1]	05-31-00	Qpon$_2$	222	7.8	110	7.47	4.58	7.03	2.77	63	1.8	2
LC-76D	05-17-00	Qpog$_2$	198	8.9	113	10.9	3.42	6.65	1.91	59	2.03	2
LC-79D-1	01-30-03	Qpog$_2$	197	−	105	6.5	4.3	6.31	−	59	1.12	2
-2	01-31-03	Qpog$_2$	211	7.1	117	6.76	3.58	10	−	67	1.13	1.5
-3	02-10-03	Qpog$_2$	227	7.8	175	4.36	1.96	27.7	−	107	1.82	4
-4	02-10-03	Qpog$_2$	275	7.3	163	6.75	3.18	20.8	−	101	1.67	2.6
LC-80D-1	01-09-03	Qpog$_2$	235	6.6	133	10.4	6.3	6.92	−	74	2.94	5.1
-2	01-10-03	Qpog$_2$	251	7	137	11	6.68	6.95	−	74	2.37	4.7
-3	01-10-03	Qpog$_2$	265	6.8	139	11	6.76	7.2	−	76	2.34	4.5
LC-81D-4	01-20-03	Qpog$_2$	280	8.2	153	1.57	.835	31.4	−	90	1.92	6.8
LF4-MW4	06-09-00	Qpog$_2$	219	7.2	138	12	5.56	6.19	1.35	68	3.35	5.5
MAMC-4	12-14-00	Qpog$_2$	261	7.5	142	11.3	6.28	5.76	2.17	72	2.51	.1
SILCOX-1	12-15-00	Qpog$_2$	234	7.9	−	−	−	−	−	−	−	−
SRC-MW1B	06-08-00	Qpog$_2$	176	7.2	134	9.17	6.21	6.98	1.74	66	3.13	4.9

[1]Well is screened in the lower confining unit (Qpon$_2$) immediately beneath the sea-level aquifer.

Table 7.   Geochemical data related to redox conditions and carbon-13 isotope data from water samples from wells and surface-water sites, Fort Lewis, Washington, 1997-2003.

[**Well No. :** Locations of wells are shown on plate 1. **Hydrogeologic unit:** SW, American Lake; Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; Qpog$_2$, sea-level aquifer; and Qpon$_2$, lower confining unit. **Trichloroethene** concentrations exceeding the detection limited are in **bold**. **Abbreviations:** mg/L, milligram per liter; µg/L, microgram per liter; δ^{13}C, isotope of Carbon; permil, parts per thousand; <, less than; n/a, not applicable; –, not analyzed]

Well No.	Date sampled	Hydro-geologic unit	Dis-solved oxygen (mg/L)	Tri-chloro-ethene (µg/L)	Filtered man-ganese (mg/L)	Unfil-tered iron (II) (mg/L)	Filtered iron (mg/L)	Unfil-tered sulfide (mg/L)	Dis-solved methane (mg/L)	Total organic carbon (mg/L)	δ^{13}C of dissolved inorganic carbon (permil)
					American Lake						
AML-1	06-14-00	SW	–	–	–	–	–	–	–	–	-15.4
AML-2	06-14-00	SW	0.1	–	–	–	–	–	0.65	–	-15.1
					Upper aquifer						
FL-02	12-21-00	Qv(1)	8.1	**94**	–	–	–	–	<0.001	–	-17.6
FL-04A	05-17-00	Qv(2)	9.6	**1.5**	<0.002	<0.01	<0.01	<0.01	<.001	<0.1	-20.7
LC-11	12-21-00	Qv(1)	8.1	<.1	–	–	–	–	<.001	–	-19.4
LC-149C	02-16-99	Qv(1)	9.7	<1	<.002	–	<.01	–	–	–	-20.1
LC-149D	02-16-99	Qv(1)	9	<1	<.002	–	<.01	–	–	.2	-19.7
LC-21B	02-18-99	Qpon	<.1	<1	–	–	–	–	–	–	-17.5
LC-40C	05-18-00	Qpon	3.1	<1	.001	<.01	.007	<.01	<.001	<.1	-20.1
SILCOX-2	12-15-00	Qv(1)	<.1	<.1	.055	.63	.15	–	<.001	–	–
				Sea-level aquifer upgradient from confining unit window							
LC-21C	05-15-00	Qpog$_2$	8.7	<0.1	<0.002	<0.01	<0.01	<0.01	<0.001	–	-19.5
LC-26D	05-18-00	Qpog$_2$	4.7	<.1	<.002	<.01	<.01	<.01	<.001	<0.1	-20.0
LC-35D	06-13-00	Qpog$_2$	.8	<.1	.004	–	<.01	–	<.001	.1	-19.7
LC-47D	05-22-00	Qpog$_2$	<.1	<.1	.049	<.01	.007	<.01	–	.3	-18.3
LC-50D	05-22-00	Qpog$_2$	.3	**.2**	.008	<.01	<.01	<.01	<.001	.2	-18.4
LC-55D[1]	05-16-00	Qpon$_2$	<.1	<.1	.11	<.01	.051	<.01	<.001	.4	-18.7
			Contaminated sea-level aquifer downgradient from confining unit window								
FLS-13	12-12-00	Qpog$_2$	10	**0.6**	<0.002	–	0.006	–	–	–	–
LC-126	05-31-00	Qpog$_2$	5.3	**67**	<.002	<0.01	.007	<0.01	<0.001	<0.1	-20.9
LC-40D	05-19-00	Qpog$_2$	3.5	**19**	<.002	<.01	<.01	<.01	<.001	<.1	-19.9
LC-41D	09-14-98	Qpog$_2$	6.3	**170**	<.002	.02	<.01	–	<.001	–	–
LC-66D	06-09-00	Qpog$_2$	1.5	**55**	.004	–	<.01	–	<.001	.4	-19.2
LC-67D	12-12-00	Qpog$_2$	5.7	**53**	<.002	–	<.01	–	<.001	.5	-20.1
LC-69D	05-23-00	Qpog$_2$	6	**160**	<.002	<.01	.009	<.01	<.001	.1	-21.2
LC-70D	05-25-00	Qpog$_2$	<.1	**.4**	.14	<.01	<.01	<.01	<.001	.4	-19.6
LC-72D	05-25-00	Qpog$_2$	2.9	**24**	<.002	.01	.008	<.01	<.001	.7	-19.8
LC-73D	05-26-00	Qpog$_2$	2.4	**37**	.002	<.01	<.01	<.01	<.001	.6	-19.7
LC-74D	06-01-00	Qpog$_2$	3.7	**61**	<.002	<.01	<.01	<.01	<.001	.3	-19.5
LC-75D	05-24-00	Qpog$_2$	8.4	**.8**	<.002	<.01	<.01	<.01	<.001	.5	-19.5
LC-77D	05-23-00	Qpog$_2$	9.6	**10**	.007	<.01	<.01	<.01	<.001	.2	-18.8
LC-81D-1	01-15-03	Qpog$_2$	1	**3.9**	.079	–	.011	–	.002	1.1	-19.6
-2	01-15-03	Qpog$_2$	1	**4.8**	.002	–	<.01	–	.004	.8	-19.6
-3	01-17-03	Qpog$_2$	1	**2.9**	.038	–	<.01	–	.004	.7	-19.0
LC-82D-1	02-11-03	Qpog$_2$	3	**6.4**	.004	–	.027	–	.008	.8	-19.6
-3	02-12-03	Qpog$_2$	3	**.4**	.015	–	<.01	–	.011	.7	-19.5
-4	01-28-03	Qpog$_2$	2	**2.3**	.002	–	<.01	–	.005	.6	-19.7

Table 7.   Geochemical data related to redox conditions and carbon-13 isotope data from water samples from wells and surface-water sites, Fort Lewis, Washington, 1997-2003.—Continued

[**Well No. :** Locations of wells are shown on plate 1. **Hydrogeologic unit:** SW, American Lake; Qv(1) and Qv(2), upper and lower subunits of the upper aquifer; Qpon, confining unit; Qpog$_2$, sea-level aquifer; and Qpon$_2$, lower confining unit. **Trichloroethene** concentrations exceeding the detection limited are in **bold**. **Abbreviations:** mg/L, milligram per liter; µg/L, microgram per liter; $\delta^{13}C$, isotope of Carbon; permil, parts per thousand; <, less than; n/a, not applicable; –, not analyzed]

Well No.	Date sampled	Hydro-geologic unit	Dis-solved oxygen (mg/L)	Tri-chloro-ethene (µg/L)	Filtered man-ganese (mg/L)	Unfil-tered iron (II) (mg/L)	Filtered iron (mg/L)	Unfil-tered sulfide (mg/L)	Dis-solved methane (mg/L)	Total organic carbon (mg/L)	$\delta^{13}C$ of dissolved inorganic carbon (permil)
Contaminated sea-level aquifer downgradient from confining unit window—Continued											
LC-83D-1	01-21-03	Qpog$_2$	4	**44**	0.007	–	<0.01	–	<0.001	0.9	-19.8
-2	01-22-03	Qpog$_2$	4	**15**	.023	<0.01	<.01	–	<.001	1.7	–
-3	01-23-03	Qpog$_2$	.8	**11**	.13	–	.006	–	.005	.2	-19.2
-4	01-24-03	Qpog$_2$	.8	**.8**	.1	<.01	.022	–	.003	3.7	-17.9
LF4-MW2C	06-07-00	Qpog$_2$	2	**.3**	<.002	–	<.01	<0.01	<.001	<.1	-18.4
MAMC-3	01-02-03	Qpog$_2$	.8	**2.6**	–	–	–	–	–	–	–
T-09E	06-01-00	Qpog$_2$	4	**1.1**	.006	<.01	.006	<.01	<.001	.5	-18.9
Uncontaminated sea-level aquifer downgradient from confining unit window											
88-1-SS	06-05-00	Qpog$_2$	<0.1	<0.1	0.004	<0.01	<0.01	<0.01	<0.001	<0.1	-17.3
LC-166D	06-05-00	Qpog$_2$	<.1	<.1	.11	<.01	<.01	<.01	<.001	<.1	-14.2
LC-41E	02-17-99	Qpog$_2$	<.1	<.1	.054	–	.083	–	–	<.1	-18.5
LC-71D[1]	05-31-00	Qpon$_2$	<.1	<.1	.11	<.01	.013	<.01	<.001	.3	-17.9
LC-76D	05-17-00	Qpog$_2$	.6	<.1	.004	<.01	<.01	<.01	<.001	<.1	-20.2
LC-79D-1	01-30-03	Qpog$_2$	1	<.2	.14	<.01	.049	–	.006	1	-18.7
-2	01-31-03	Qpog$_2$	.6	<.2	.19	.1	.029	–	.006	3.2	-18.1
-3	02-10-03	Qpog$_2$	.9	<.2	.012	–	<.01	–	.006	1.1	-17.2
-4	02-10-03	Qpog$_2$	1	<.2	.076	–	<.01	–	.01	1.2	-17.1
LC-80D-1	01-09-03	Qpog$_2$	.5	<.2	.003	–	<.01	–	.002	1.1	-19.5
-2	01-10-03	Qpog$_2$	2	<.2	.009	–	.015	–	.002	–	-27.0
-3	01-10-03	Qpog$_2$	1	<.2	.017	–	.009	–	.002	1.5	-9.4
LC-81D-4	01-20-03	Qpog$_2$	1	<.2	.031	.4	.043	–	.014	1	-17.8
LF4-MW4	06-09-00	Qpog$_2$	1.6	<.1	.002	–	.013	–	<.001	<.1	-17.2
MAMC-4	12-14-00	Qpog$_2$	.9	<.1	.002	–	.009	–	–	–	-19.0
SILCOX-1	12-15-00	Qpog$_2$	.3	<.1	–	.11	–	–	.022	<.1	–
SRC-MW1B	06-08-00	Qpog$_2$	.6	<.1	<.002	<.01	<.01	<.01	<.001	.4	-18.8

[1]Well is screened in the lower confining unit (Qpon$_2$) immediately beneath the sea-level aquifer.

In American Lake, the lack of dissolved oxygen (0.1 mg/L), the relatively abundant methane (0.65 mg/L), and enriched (more positive) $\delta13C$ values (average of -15.3 permil) suggest that deep lake waters were methanogenic (anaerobic and strongly reducing) during the time of sampling. More complete historical data from 1971 (Bortleson and others, 1974) suggest that the lake is stratified and anaerobic at depth during the summer and autumn, and is well mixed and aerobic throughout during winter and spring. Ground water from well SILCOX-2 is representative of shallow American Lake water that recharges to ground water because that 10-foot-deep drive-point well is on the shoreline of Silcox Island in American Lake. The redox-related chemical signature at that well included no dissolved oxygen, but no methane. Thus, ground-water recharge from American Lake water may be traceable in the ground water by the lack of oxygen, the abundance of methane, and relatively enriched $\delta13C$ values, but the seasonal nature of the signature does not make it definitive.

The upper-aquifer redox-related data indicate that the shallow ground water generally is aerobic with relatively little organic carbon available to consume oxygen (table 7). The Army has collected much additional upper-aquifer data from contaminated wells and has found shallow ground water to be aerobic outside of localized zones beneath the East Gate Disposal Yard source area (U.S. Army Corps of Engineers, 2002). In an upper aquifer well located at the presumed confining unit window (adjacent to well LC-41E), the Army measured dissolved oxygen concentrations between 5 to 8 mg/L since 1995. It is widely accepted that aerobic conditions are unfavorable for biodegradation of TCE, so TCE also can be considered a relatively conservative tracer for contaminated upper-aquifer water. Although the δ^{13}C value for the most contaminated upper-aquifer well sampled by the USGS (FL-02) was relatively enriched at -17.6 permil, that result is likely indicative of past microbial activity upgradient in the East Gate Disposal Yard rather than on-going TCE biodegradation near the clearly aerobic well. The δ^{13}C value for samples from most upper-aquifer wells ranged from -18 to -22 permil, which is typical for ground-water recharge in northern latitudes (Cox, 2003).

Redox conditions in samples from sea-level aquifer wells upgradient from the confining unit window are likely anaerobic when not affected by the pump-and-treat activities near the East Gate Disposal Yard. The three anaerobic upgradient wells are outside the immediate area of the disposal yard. The aerobic well LC-26D is adjacent to the disposal yard recharge field where treated water was introduced back into the ground prior to 2004, and the aerobic well LC-21C is adjacent to the primary disposal yard extraction field. As will be discussed later in this report, there is some isotopic evidence that water in those aerobic wells is mixed with some water from the upper aquifer despite the presence of the Qpon unit beneath the disposal yard. The δ^{13}C values of samples from sea-level aquifer wells upgradient from the confining unit window range from -18 to -22 permil, typical for ground-water recharge in northern latitudes.

In contrast to those upgradient waters, the ground-water redox condition in TCE-contaminated wells downgradient from the confining unit window generally is aerobic. In addition, high dissolved-oxygen concentrations generally coincide with high TCE concentrations, and anaerobic conditions coincided with little or no TCE. The δ^{13}C values of samples from TCE-contaminated sea-level aquifer wells downgradient from the confining unit window also ranged from about -18 to -22 permil.

Redox conditions in uncontaminated sea-level aquifer wells downgradient from the confining unit window generally were anaerobic, although the TOC concentrations were low. The δ^{13}C values for these wells were lower and more variable than in the other groups; the values averaged -18 permil and ranged from about -9 to -27 permil. Despite the anaerobic conditions and the more positive δ^{13}C values that are indicative of microbial activity, the low organic carbon concentrations and high sulfate concentrations indicate that the potential for complete biodegradation of TCE is low.

Chemical Signatures of End-Member Waters from American Lake, the Upper Aquifer, and the Sea-Level Aquifer

The environmental tracer data considered as a whole shows distinct chemical signatures for the three end-member waters in the study area (table 8). The end-members are American Lake, upper-aquifer ground water, and sea-level aquifer ground water that has not substantially mixed with the other waters (based on their tritium concentrations of less than 0.5 TU). The environmental tracers chosen to define the end-members include ^{2}H, ^{18}O, tritium, ^{13}C, SF_6, dissolved oxygen, and TCE. With the exception of TCE, the values shown as characteristic for the end-members are the averages of the representative samples listed. TCE concentrations in the upper aquifer vary widely across the study area. The characteristic TCE concentration of 160 µg/L for the upper aquifer in table 8 was the approximate long-term average concentration in a shallow and a deep upper-aquifer well (LC-41A and LC-41B) located at the confining unit window. The letters in the columns following each average value indicate which values were significantly different from others at the 99-percent confidence level. Values followed by the same letter are not significantly different, and values followed by different letters are significantly different. The significance of the differences was calculated using a two-tailed Student's t-test for samples with unequal variance.

The distinct chemical signature of the American Lake end-member primarily is a result of evaporation from the lake and seasonal stratification in the lake. δ^{18}O and δ^2H values for American Lake were significantly more positive than local ground water (fig. 6), and the disproportionate enrichment in ^{2}H indicated that evaporation is the likely cause of the enrichment (Clark and Fritz, 1997). The isotope signature in the SILCOX-2 shallow well sample was more positive than the lake samples themselves, likely because the lake

Table 8. Characteristic end-member chemical values defined for the study area, Fort Lewis, Washington.

[**Well No.:** Locations of wells are shown on plate 1. **End-member:** Values followed by the same letter are not significantly different, and values followed by different letters are significantly different. Different letters in the columns following each average value (except trichloroethene) indicate the value is significantly different from others at the 99-percent confidence level calculated using a two-tailed Student's *t*-test for samples with unequal variance. **Abbreviations:** δ^2H, ^3H, isotopes of hydrogen; $\delta^{18}O$, isotope of oxygen; $\delta^{13}C$, isotope of carbon; permil, parts per thousand; SF_6, Sulfur hexafluoride; mg/L, milligram per liter; µg/L, microgram per liter; <, less than; >, greater than; –, no data]

Well No.		δ^2H (permil)	$\delta^{18}O$ (permil)	$\delta^{13}C$ (permil)	^3H (tritium units)	Apparent SF_6 age (years)	Dissolved oxygen (mg/L)	Trichloro-ethene (µg/L)
		American Lake end-member						
AML-1, AML-2, SILCOX-2	Average	-62.8 a	-8.08 a	-15.3 a	4.2 a	3 a	0.1 a	<0.1
	Range	-61.9 to -63.5	-7.90 to -8.20	-15.1 to -15.4	4.1 to 4.5	3 to 4	0 to 0.1	<.1
		Upper aquifer end-member						
FL-02, FL-04A, LC-11, LC-149C, LC-149D	Average	-70.6 b	-9.77 b	-19.46 b	4.1 a	7 a	8.9 b	[1]160
	Range	-68.1 to -71.9	-9.55 to -9.91	-17.6 to -20.1	3.5 to 4.4	3 to 13	8.1 to 9.7	–
		Sea-level aquifer end-member						
LC-79D-1, LC-79D-2, LC-79D-3, LC-79D-4, LC-81D-4, LC-55D, LC-71D[2]	Average	-75.7 c	-10.20 c	-17.9 b	0.1 b	>25 b	0.6 a	<0.1
	Range	-74.7 to -76.7	-10.12 to -10.27	-17.1 to -18.7	0 to 0.3	25 to >25	0 to 1	<.1

[1]Concentration is estimated for upper aquifer water directly above window through the confining unit.

[2]Well is screened in the lower confining unit ($Qpon_2$) immediately beneath the sea-level aquifer.

samples were collected from near the stratified lake bottom that was subject to less evaporation at the time of sampling. American Lake water also was relatively "young" with an SF_6-based apparent-age date of 3.3 years and a modern-water tritium concentration, but it was not significantly younger than upper-aquifer water (table 8). American Lake water is anaerobic and has a significantly low $\delta^{13}C$ value.

$\delta^{18}O$ and δ^2H values for the upper aquifer were significantly more negative than American Lake water because ground water is subject to less evaporation than lake water. Upper-aquifer water also was relatively young like the lake water, but it had significantly higher dissolved-oxygen concentrations, and significantly more positive $\delta^{13}C$ values.

$\delta^{18}O$ and δ^2H values for the sea-level aquifer end-member samples were significantly more negative than either American Lake or upper-aquifer water. The reason for this is not certain, although the sea-level aquifer water may have been recharged during colder temperatures. Tritium concentrations in the sea-level aquifer end-member indicated the water was recharged prior to 1951; the SF_6-based apparent age of greater than 25 years is consistent with the tritium results. Sea-level aquifer end-member water was anaerobic, and $\delta^{13}C$ values were significantly more negative compared to American Lake, but significantly more positive compared to the upper aquifer.

Recharge to the Sea-Level Aquifer from American Lake

The environmental-tracer data provide evidence in addition to the water-level data that American Lake is a substantial source of recharge to the sea-level aquifer. That recharge has created the ridge of ground water beneath the lake that effects migration of the TCE plume in the sea-level aquifer (figs. 3 and 4). The tracer data were interpreted using the end-member characteristics previously described and a linear algebraic mixing model. The δ^2H and $\delta^{18}O$ data were the most suitable tracers to use in a mixing model between any two end members because they are chemically conservative, and because their concentrations in the end-members can be assumed to be relatively constant over the span of decades.

The clearest evidence for the lake recharge is that δ^2H and $\delta^{18}O$ values for a number of sea-level aquifer samples fit on a mixing line between the American Lake and sea-level aquifer end members (fig. 6). Samples from five sea-level aquifer wells clearly plot near the mixing line, including those from the two wells (LC-166D and SILCOX-1) with the high water levels that best define the ground-water ridge beneath the lake, those from the two wells (LF4-MW4 and 88-1-SS) to the west (downgradient) from American Lake, and that from a backup Fort Lewis water-supply well (FLS-13). The FLS-13 well is not in an area affected by recharge from American Lake. Ground water from FLS-13 had relatively elevated concentrations of DO (10 mg/L) and chloride (5.2 mg/L), and δ^2H and $\delta^{18}O$ values that also fit near the apparent evaporation line beginning at the upper-aquifer end-member (fig. 6). Those data indicate that the water in FLS-13 may contain evaporated upper-aquifer water from a local source, and that the sample may have been affected by aeration and evaporation during sample collection (the sample was collected while the down-hole turbine pump was operating).

The sea-level aquifer recharge from American Lake is essentially unmixed at the top of the aquifer beneath the lake (LC-166D), and is mixed with ambient sea-level aquifer water as it moves both vertically and horizontally away from the lake. The isotope signature of the LC-166D sample indicated that at least the top 20 ft of the sea-level aquifer beneath the southern tip of American Lake was essentially filled with recharge from American Lake. Well LC-166D was screened at the top of the sea-level aquifer, was anaerobic, and had the most positive δ^2H and $\delta^{18}O$ values. The stable-isotope signature of the SILCOX-1 sample indicated that the American Lake recharge signature was still easily discernible at a depth of 80 ft below the

top of the sea-level aquifer, the depth at which the well is screened. The SILCOX-1 sample was an approximate mix of 60 percent American Lake end-member water and 40 percent sea-level aquifer end-member water. About 0.6 mi west (downgradient) of American Lake, the stable-isotope signature from well LF4-MW4 indicated a mix of 75 percent American Lake end-member water and 25 percent sea-level aquifer end-member water. The δ^2H and $\delta^{18}O$ values for well LF4-MW4 also fit near that evaporation line and the sample had 1.6 mg/L of DO, so it is not certain if the well was affected by recharge from American Lake or recharge from a local source of evaporated upper-aquifer water. About 1.5 mi west of the lake, the signature from well 88-1-SS indicated a mix of 50 percent lake and sea-level aquifer waters.

The stable-isotope signature in a sample from one other well west of American Lake (SRC-MW1B) appears to be affected by American Lake recharge, although the isotope signature was in the range where it also could include ground water from the upper aquifer. Because the SRC-MW1B sample was anaerobic, uncontaminated, and had an apparent SF_6 age-date of more than 20 years, the sample likely includes a substantial proportion of end-member water from the sea-level aquifer in addition to some end-member water from American Lake. Assuming a linear mixing model between just the end-members from the lake and sea-level aquifer, the sample was an approximate mix of 30 percent American Lake and 70 percent sea-level aquifer end-member water.

The stable-isotope signature in a sample from well LF4-MW2C west of American Lake was ambiguous and could include water from all three end-members. The well contained TCE, but the contaminants likely entered the well from a local source of contaminated, upper-aquifer water rather than from the Logistics Center plume. Concentrations of BTEX fuel compounds (benzene, toluene, and xylenes) were detected in historical samples from the well as early as 1992 (Applied Geotechnology Inc., 1993). Ground-water-flow directions did not indicate that contaminants from the Logistics Center would flow toward the well (figs. 3, 4, and pl. 1), and concentrations of BTEX have not been detected in the TCE plume in the sea-level aquifer.

Migration of TCE into and Through the Sea-Level Aquifer

According to the conceptual model, the greatest flux of TCE migration into the sea-level aquifer is from contaminated upper-aquifer water flowing through the known confining unit window near well LC-41D. Additional high permeability connections between the upper and sea-level

aquifers also may be present (U.S. Army Corps of Engineers, 2002). Data collected for this investigation confirm that the primary pathway for TCE migration into the sea-level aquifer is through the confining unit window. Two other less important pathways were tentatively identified, although the data supporting those pathways are inconclusive. The other possible pathways are near the East Gate Disposal Yard and the I-5 pump-and-treat facilities. Ground-water pumping and (or) reintroduction activities are active in both of those areas, but those activities do not appear to be the cause of the TCE migration into the sea-level aquifer.

An expanded plot of the δ^2H and $\delta^{18}O$ data (fig. 7) illustrates the pattern of isotope signatures that are not substantially affected by recharge from American Lake. Most uncontaminated sea-level aquifer samples had relatively low δ^2H and $\delta^{18}O$ values and plot in the lower left. Most upper-aquifer samples had relatively high δ^2H and $\delta^{18}O$ values and plot in the upper right. Most contaminated sea-level aquifer samples had intermediate δ^2H and $\delta^{18}O$ values and plot between those end-members. Additional insight into TCE migration was gained by comparing tracer data from individual sea-level aquifer wells to "typical" tracer signatures for the upper-aquifer and sea-level aquifer end-members defined in table 8. Those typical signatures were defined by adding or subtracting two standard deviations from the average end-member values. Most sample to end-member comparisons were made for δ^2H and $\delta^{18}O$ values, although comparisons were sometimes made for tritium, SF_6, DO, and $\delta^{13}C$. A source of uncertainty in these comparisons is that differences in many of the compared δ^2H and $\delta^{18}O$ values were less than the estimated analytical precision for δ^2H and $\delta^{18}O$ (2 and 0.2 permil, respectively). The findings are discussed in the following three subsections of this report for (1) wells upgradient from the confining unit window, (2) wells at the confining unit window, and (3) wells downgradient from the confining unit window.

TCE Contamination Upgradient from the Confining Unit Window

Even though the upper aquifer is severely contaminated, data from five sea-level aquifer wells upgradient of the confining unit window (LC-21C, LC-26D, LC-35D, LC47D, and LC-50D) indicate that only a small amount of upper-aquifer water migrates downward into the sea-level aquifer near the East Gate Disposal Yard. The flux of upper-aquifer water (with some TCE) into the sea-level aquifer

appears to be localized because TCE was detected in only one of the wells during this study. TCE has been previously detected in well LC-21C, however, at concentrations as high as 5 μg/L.

The migration through the Qpon unit may be facilitated by hydraulic stresses imposed by the disposal yard pump-and-treat remediation system that extracts about 500 gal/min of upper-aquifer ground water from four wells near well LC-21C, and (prior to 2004) reinjected and infiltrated treated water into the upper aquifer near well LC-26D (pl. 1). The potentiometric difference between the upper aquifer and the sea-level aquifer near the disposal yard generally is less than 5 ft, but the gradient generally is upward near the extraction well (LC-21C) and downward near the pre-2004 recharge/infiltration facilities (LC-26D). The detection of TCE in the sea-level aquifer beneath the disposal yard in wells LC-50D and LC-21C 5 years prior to the onset of pump-and-treat activities indicates that the migration is not entirely due to pump-and-treat activities. The Qpon unit is only 10-ft thick at well LC-21C, is less than 5-ft thick at well LC-50D, and was reported as missing during recent well drilling at a location about 1,000 ft south of well LC-50D, so migration of some upper aquifer water through the unit is not unexpected.

Data indicate that the fine-grained glaciolacustrine deposits prevent downward migration of TCE where the Qpon unit is missing in the erosional trough. TCE has not been detected at well LC-35D, which is about 1,700 ft directly downgradient from the East Gate Disposal Yard and is in the erosional trough area where the Qpon unit is missing. The LC-35D well screen is vertically separated from the upper aquifer and the secondary disposal yard extraction wells by about 110 ft of fine-grained glaciolacustrine sediments. The stable-isotope composition at well LC-35D (table 4) indicates that ground water is about a 50-percent mixture of upper and sea-level aquifer end-members. TCE also has not been detected at well LC-47D, about 2,200 ft farther downgradient. Well LC-47D also is in the erosional trough area where the Qpon unit is missing, and its screen also is vertically separated from the upper aquifer by about 110 ft of fine-grained glaciolacustrine sediments. The results from those two downgradient wells indicate that (1) the flux of upper-aquifer water into the sea-level aquifer beneath the disposal yard is minimal because the upper-aquifer tracer signature attenuates within about 2,500 ft, and (2) the glaciolacustrine sediments that fill most of the erosional trough effectively isolate the upper and the sea-level aquifers.

TCE Contamination at the Confining Unit Window

The data indicate that a substantial amount of TCE-contaminated upper-aquifer water migrates to the sea-level aquifer through the confining unit window. As previously described, the window is in an area of coarse-grained deposits near the western margin of the trough eroded through the Qpon unit (pl. 1). Samples were collected from three closely spaced sea-level aquifer wells of different depths that are immediately downgradient from where the centerline of the upper-aquifer TCE plume crosses the confining unit window. TCE contamination was detected only in the upper 20 to 30 ft of the sea-level aquifer near the confining unit window.

Well LC-69D is the shallowest and is screened from about 20 to 30 ft below where the estimated elevation base of the Qpon unit would be if it were present. There is no indication of Qpon unit sediments in the LC-69D well log. Well LC-70D is screened 12 ft deeper, well LC-41E is screened another 74 ft deeper, and there is good evidence of the Qpon unit in those well logs.

TCE measured in well LC-69D of 160 μg/L is nearly equal that measured in upper-aquifer wells at the same location. The stable-isotope composition of water from the well is nearly the same as upper-aquifer end-member water. In contrast, the deepest well (LC-41E) is uncontaminated and its water has a stable-isotope composition similar to that of the sea-level aquifer end-member. Concentrations of tritium and SF_6 in the LC-41E sample was slightly elevated, which indicates mixing with a small amount of younger upper-aquifer water, but the amount of mixing was similar to that seen in upgradient well LC-47D and likely occurred upgradient beneath the East Gate Disposal Yard. Tracer composition of water from the intermediate depth well (LC-70D) at the confining unit window indicates a mix of upper and sea-level aquifer end-member waters that is difficult to interpret. Stable-isotope concentrations indicate that the sample was primarily upper-aquifer end-member water; tritium and SF_6 concentrations indicate a mix of upper and sea-level aquifer end-members; and low dissolved-oxygen and TCE concentrations indicate that the sample is primarily sea-level aquifer end-member water. A possible explanation for those apparently inconsistent data is that some upper-aquifer water that migrates to the sea-level aquifer at the confining unit window may not be as aerobic or highly contaminated with TCE as is presumed for the upper-aquifer end-member.

Samples also were collected from two additional sea-level aquifer wells that are immediately downgradient from the confining unit window but north and south of the centerline of the TCE plume in the upper aquifer. Well LC-75D is near the south end of the confining unit window and there is some evidence in the drillers' log that Qpon sediments may be about 6-ft thick at the site. Well LC-66D is near the north end of the confining unit window, and there is good evidence that Qpon sediments are about 30-ft thick at the site.

The LC-75D sample was isotopically and chemically similar to samples from the upper aquifer (table 4), a clear indication of water migration from the upper aquifer. The stable-isotope signature in LC-75D closely matches the signature from an upper-aquifer well directly upgradient on the same flow path along the southern margin of the Logistics Center (FL-04A, table 4). A reasonable interpretation of those two similar signatures is that upper-aquifer water represented by well FL-04A migrates into the sea-level aquifer near the confining unit window just upgradient from well LC-75D. The TCE concentration at well FL-04A ranges from about 1 to 5 μg/L, and it is about 1 μg/L at well LC-75D.

Well LC-66D is about 700 ft downgradient from (rather than directly at) the confining unit window location, but it is included in this section because it is the nearest downgradient well at the northern end of the window. TCE concentration in well LC-66D was 55 μg/L, and the TCE concentration in the upper aquifer near both the well and the confining unit window ranged from about 90 to 110 μg/L. TCE concentration at well LC-66D appears to have attenuated through mixing and possible sorption over the 700 ft between the confining unit window and the well. The stable-isotope composition for the LC-66D sample was similar to upper-aquifer end-member water, and is a clear indication of nearby migration from the upper aquifer to the sea-level aquifer.

TCE Contamination Downgradient from the Confining Unit Window

Data from some wells downgradient from the confining unit window indicate that some contaminated water from the upper aquifer may migrate into the sea-level aquifer near the I-5 pump-and-treat facilities. The drillers' logs indicate that the Qpon confining unit is present beneath the I-5 system, but chemistry and isotope data indicate that upper-aquifer water is migrating through the unit. Outside of that area, there was no discernible flux of upper-aquifer water into the sea-level aquifer between the known confining unit window and the southwest tip of American Lake. Once in the sea-level aquifer, the TCE migrates downgradient in the flow field influenced by ground-water recharge from American Lake. By 2004, the TCE from the East Gate Disposal Yard had migrated more than 3.5 mi downgradient to beyond the western tip of American Lake (pl. 1). There is no definitive evidence for determining whether or not the TCE will continue to migrate downgradient beyond the currently (2004) known extent, although some data indicate that the plume will continue to expand.

Pathways for TCE Migration into the Sea-Level Aquifer Downgradient from the Confining Unit Window

There are many contaminated sea-level aquifer wells downgradient from the confining unit window with stable-isotope composition similar to water from the upper aquifer (table 4 and fig. 7). Data from these wells were examined to determine if they indicate TCE migration into the sea-level aquifer at locations downgradient from the confining unit window. The TCE contamination in one of these wells (T-09E) likely migrated downward through the well borehole rather than through a leaky confining unit, as was described previously in the "Extent of TCE, *cis*-DCE, and Vinyl Chloride" section of this report.

Data from wells screened in the sea-level aquifer near the I-5 pump-and-treat facilities indicate that there may be migration of contaminated water from the upper aquifer into the sea-level aquifer in that area, although the evidence is not definitive. Well LC-126 is about 1,000 ft downgradient (northwest) from a row of 15 extraction wells, and about 500 ft upgradient from the infiltration galleries for treated water (pl. 1). When compared to data from the two contaminated wells (LC-66D and LC-40D) that lie between the confining unit window and well LC-126, the sample from LC-126 had more positive $\delta^{18}O$ and δ^2H values, had a younger apparent age, and had high TCE and dissolved-oxygen concentrations (fig. 7 and tables 4, 5, and 7). Those data are consistent with the hypothesis that there is a local source for contaminated upper-aquifer water migration into the sea-level aquifer near well LC-126. The TCE concentrations in upper-aquifer monitoring wells in the vicinity were less than the 67 μg/L in LC-126 (pl. 1), although the TCE concentrations in at least three of the I-5 system extraction wells exceeded 67 μg/L (extraction well data were not used on pl 1.). Unlike well T-09E, the entire annulus between the land surface and the well screen in well LC-126 was backfilled with bentonite grout so the borehole seals are not likely to leak. The flux of contaminated water migrating into the sea-level aquifer near the I-5 pump-and-treat system likely is far less than the flux migrating through the known confining unit window. Water levels in the upper aquifer near well LC-126 were more than 60 ft greater than those in the sea-level aquifer, which indicates that the Qpon layer greatly limits downward flow. Hydraulic stresses imposed by the I-5 pump-and-treat facilities/infiltration system possibly have an affect on downward TCE migration, although the substantial ambient head difference between the two aquifers would minimize the significance of the effect.

Data from well LC-77D also is consistent with the downward migration of contaminated water from the upper aquifer into the sea-level aquifer near the I-5 pump-and-treat system (table 4). The $\delta^{18}O$ and δ^2H values for well LC-77D indicate about a 1:1 mixture of upper and sea-level aquifer end-member waters (fig. 7). Well LC-77D appears to be north of any flow path originating at the confining unit window (pl. 1, figs. 3 and 4), thus, TCE contamination is not likely originating at the confining unit window. Near well LC-77D, TCE concentrations were about 20 μg/L in the lower part of the upper aquifer, and 10 μg/L in the sea-level aquifer at well LC-77D. Dissolved-oxygen data from LC-77D (table 7) also were consistent with localized downward migration of upper-aquifer water. The relatively high DO concentration of 9.6 mg/L at well LC-77D is consistent with water that has been sent through an air-stripping treatment tower and reinfiltrated.

In summary, the primary pathway for TCE migration into the sea-level aquifer is through the previously identified confining unit window. A secondary pathway through the presumably intact Qpon unit was tentatively identified near the I-5 pump-and-treat system. Outside of those two locations, there was no discernible flux of upper-aquifer water into the sea-level aquifer between the known confining unit window and the southwest tip of American Lake.

TCE Migration and Plume Stability Downgradient from the Confining Unit Window

By 2004, TCE contamination from the Logistics Center had migrated more than 3.5 mi downgradient to beyond the western tip of American Lake (pl. 1). Prior to the installation of wells LC-79D through LC-90D, the lack of TCE in well LC-76D was interpreted to mean that the plume had migrated only about 2.5 mi downgradient. However, relatively negative $\delta^{18}O$ and δ^2H values and relatively low tritium (1.2 TU) and DO (0.6 mg/L) concentrations from well LC-76D indicate that the well has little modern, upper-aquifer type water in it, and that it is clearly not on a flow path originating at the confining unit window. A likely explanation for those data is that well LC 76D lies to the north of the TCE plume in the sea-level aquifer, and that the higher potentiometric-surface beneath American Lake confines the plume to the south of the well. TCE was detected an additional 0.5 mi downgradient from well LC-76D after installation and sampling of multi-level well LC-81D during 2003. Although the 2003 TCE concentration in well LC-81D did not exceed the 5 μg/L cleanup level, the potentiometric-surface maps (figs. 3-4) indicated that the centerline of the sea-level aquifer plume may actually lie south of well LC-81D. Thus, five additional sea-level aquifer well pairs (LC-84D, LC-86D, LC-88D, LC-89D, and LC-90D) were installed during 2004 to fully characterize the extent of the plume.

There are too few historical data to directly determine if the 5-µg/L leading edge of the current TCE plume is stable or is still moving downgradient. A trend analysis of 1995-2003 TCE concentrations in sea-level aquifer wells (URS Corporation, 2003b) showed no significant trends at most wells, although a trend of increasing concentration was identified in the farthest downgradient well analyzed (LC-74D). A visual examination of some of those data (fig. 5) with a line depicting the 4-sample moving average concentration at well LC-74D confirm that TCE concentrations at most wells have been relatively stable since 1995, but that a peak in concentrations passed by well LC-74D during 2000. There are only post-2002 data available from wells downgradient from LC-74D.

The historical TCE data from well LC-74D and estimated contaminant traveltimes indicate that the identified concentration peak that passed by well LC-74D during 2000 has not yet migrated to the current leading edge of the plume near well LC-86D. TCE concentrations at well LC-74D increased about 75 percent (from 40 to about 70 µg/L) between 1995 and early 2000. A similar concentration peak appears to have passed through the confining unit window (LC-41D/69D in fig. 5) about 1.5 years prior to the peak at well LC-74D. The hydraulic gradient downgradient near well LC-74D is relatively low at about 0.003 ft/ft. Assuming a horizontal hydraulic conductivity of 185 ft/d, a porosity of 0.22, and a TCE retardation factor of 2 (Truex and others, 2004), the TCE concentration peak should have migrated downgradient at a rate of about 460 ft/yr. Thus, between 2000 and 2004, the peak would have migrated downgradient about 1,800 ft, which is less than one-third of the distance to well LC-86D. This indicates that the peak TCE concentrations in the sea-level aquifer may not have reached the wells near the currently defined leading edge of the plume, and thus, the 5-µg/L leading edge of the current TCE plume hypothetically will move farther downgradient in the future. That hypothesis is consistent with numerical modeling results of the flow system completed by the Army (Truex and others, 2004). Simulation results for 2002 conditions indicated that the plume is still expanding at the southern end of American Lake (which coincides with the model boundary) due to the relatively constant flux of TCE through the confining unit window. The simulation results also indicated that the rate of plume expansion (and the downgradient plume boundary) will increase as it approaches the southern end of American Lake. That simulated increased rate of plume expansion is supported by the increased horizontal hydraulic gradient mapped during this investigation for the sea-level aquifer west of American Lake (figs. 3 and 4). A number of years of additional monitoring will be required to definitively determine whether or not the current TCE plume in the sea-level aquifer is still expanding downgradient.

Natural Attenuation of TCE Concentrations

TCE concentrations in the current sea-level aquifer TCE plume (pl. 1) clearly decrease (attenuate) in the downgradient direction. The observed attenuation is in part attributable to the fact that the plume is not likely at steady-state conditions, and is in part attributable to natural attenuation processes such as dispersion, sorption, biodegradation, or mixing and dilution with uncontaminated water. Environmental-tracer data are used in this section of the report to discern the role that natural attenuation processes play in TCE attenuation.

Redox conditions and organic-carbon concentrations in the sea-level aquifer are not favorable for biodegradation of TCE (table 7), as confirmed by relatively constant and low *cis*-DCE concentrations and the absence of vinyl chloride (table 3). Half-lives associated with abiotic transformation of TCE in ground water were estimated to be on the order of tens of thousands of years (Jeffers and others, 1989), although a few researchers have suggested that under some circumstances the process could be more rapid (for example, Richmond and Braddock, 1998); abiotic TCE degradation in this evaluation is assumed to be negligible. Given that, natural attenuation in the sea-level aquifer primarily is the result of dispersion, mixing and dilution, and possibly sorption of TCE to previously uncontaminated aquifer materials.

The potential for natural attenuation due to dispersion and mixing can be explored for part of the sea-level aquifer plume using isotope and TCE data from the multi-level wells LC-83D and LC-81D. The same data also provide additional indirect evidence that the current sea-level aquifer plume is not at steady-state. Well LC-81D is about 4,000 ft downgradient from well LC-83D. Isotope signatures with depth at both wells were nearly identical (table 4 and fig. 7). The isotope signatures from the upper three ports of both wells indicate approximately 50-percent mixtures of upper and sea-level aquifer end-member waters, and isotope signatures from the lower ports at both wells indicate sea-level aquifer end-member water only. Tritium concentrations in the upper three ports of both wells (all greater than 4 TU) indicate modern water, and the tritium concentration at the lower port at only the upgradient well (LC-83D-4) indicates significantly older water (1.1 TU). TCE concentrations decrease with depth from 44 to 0.8 µg/L over about 100 ft of thickness at well LC-83D, and they decrease with depth from about 5 to less than 0.2 µg/L over about 100 ft of thickness at well LC-81D. One interpretation of the nearly identical isotope signatures at wells LC 81D and LC-83D is that both wells receive significant recharge of upper-aquifer water through the confining unit window, but that well LC-81D is north of the most contaminated flow path. Given that the mix of upper-aquifer and sea-level aquifer water was nearly the same

in both wells, and given the small and inconsistent vertical hydraulic gradients at the wells (table 2), the potential for natural attenuation through dispersion and mixing between the wells probably is minimal.

Isoptope data for evaluating the potential for natural attenuation due to dispersion and mixing were not available from the newest well pairs at the distal end of the TCE plume, but data were available from a well about 1,300 ft north of the presumed contaminant flow path (well SRC MW1B). The stable-isotope signature for the water sample from well SRC-MW1B appeared to be affected by American Lake recharge, although the isotope signature is in the range where it could also include upper-aquifer ground water. Because the SRC-MW1B sample was anaerobic, uncontaminated, and had an apparent SF_6 age-date of more than 20 years, the sample most likely includes a substantial proportion of sea-level aquifer end-member water in addition to some American Lake end-member water. Assuming linear mixing between just the lake and sea-level aquifer end-members, the SRC-MW1B sample was an approximate end-member water mix of 30 percent American lake and 70 percent sea-level aquifer water. Thus, TCE contaminated water in the sea-level aquifer plume also may become similarly diluted with lake water as it flows west of American Lake. The amount of such dilution is uncertain, however, because it is uncertain whether the lake water is mixing with the plume as far south as the presumed centerline of the plume near well LC-88D.

Insight into natural attenuation (and plume stability) in the existing sea-level aquifer plume also can be gained by exploring the TCE attenuation as a first-order decay process. TCE concentrations attenuate along the approximate plume centerline between the confining unit window (well LC-69D), mid-plume (wells LC-74D, LC-83D, and LC-86D), and near the current leading edge of the plume (well LC-88D). Over that assumed flow path distance of 14,700 ft, the peak TCE concentrations decrease from 160 μg/L at LC-69D, to 61 μg/L at LC-74D, to 44 μg/L at LC-83D, to 6.8 μg/L at LC-86D, and to 1.7 μg/L at LC-88D. First-order decay coefficients (also referred to as field-attenuation coefficients) between successive wells along the flow path were calculated using estimates of TCE traveltime between the wells. Approximate traveltimes for TCE between well pairs were estimated using the potentiometric differences between well pairs of interest and assumed horizontal hydraulic conductivity of 185 ft/d, porosity of 0.22, and TCE retardation coefficient of 2 (from Truex and others, 2004). The traveltime estimates and maximum TCE concentrations between each pair of successive wells were then fitted to first-order equations to estimate the field-attenuation coefficients. Larger field-attenuation coefficients represent faster attenuation rates. The fact that the wells evaluated may not be on the plume centerline is a significant source of uncertainty in the

calculated field-attenuation coefficients. Calculations were done separately using data from wells LC-74D and LC-83D as representative centerline wells to minimize the uncertainty in the mid-plume area, but data from single wells only were used farther downgradient. Despite the uncertainty, the attenuation rates highlight some relevant hypotheses.

The resulting TCE attenuation rates along the flow path of interest (table 9) indicate that attenuation is relatively rapid (0.6 per year) at the beginning of the flow path between wells LC 69D and LC-74D or LC-83D-1. The historical data indicate near steady-state conditions in that part of the plume (fig. 5), so the attenuation rates represent actual attenuation processes. The attenuation can be attributed in large part to vertical dispersion and mixing in the aquifer where contaminated upper-aquifer water from the confining unit window mixes with uncontaminated sea-level aquifer water. Only the upper 30 ft of aquifer is contaminated at well LC-69-D, while nearly the entire aquifer thickness is likely contaminated at well LC-83D.

The calculated TCE attenuation rates are much slower (0.1 per year) in the middle portion of the plume between either well LC-74D or LC-83D-1, and well LC-86D-1. Whether the plume is at steady-state conditions in the vicinity is less certain, so the actual attenuation rates may even be slower than those calculated. The slower attenuation in mid-plume is most likely due to the lack of vertical dispersion and mixing. In contrast to the steep downward vertical hydraulic gradient near the confining unit window (nearly 2 ft/ft between wells LC-69D and LC-70D), there is essentially no vertical hydraulic gradient at mid-plume wells LC-83D or LC-81D. Linear mixing calculations using $\delta^{18}O$ values from wells LC-74D, LC-83D, and LC-81D indicate that the proportion of upper-aquifer type water in the sea-level aquifer decreases from about 70 percent at well LC-74D to about 50 percent at well LC-83D, and remains steady at about 50 percent at well LC-81D. Those data also indicate that there is negligible recharge through the confining unit between wells LC-83D and LC-81D to attenuate concentrations through dilution or to enhance vertical hydraulic gradients. In addition to limited dispersion and mixing in the vertical, the converging ground-water flow lines (figs. 3 and 4) act to minimize lateral dispersion and mixing in ground water between wells LC 83D and LC-86D.

The calculated TCE attenuation rate increases substantially to 0.7 per year between the well pair LC-86D-1 and LC-88D-1 in the distal portion of the plume, but that apparent increase is at least partly a result of non-steady-state conditions. Isotope data were not available for wells LC-86D or LC-88D to evaluate mixing directly. Preliminary water-level data indicate that the vertical hydraulic gradient changes from essentially zero at wells LC-83D and LC-81D, to 0.3 ft/ft downward at well LC-86D, to 0.05 ft/ft downward

Table 9. Field attenuation-rate estimates between selected sea-level aquifer wells, Fort Lewis, Washington.

[**Well No.:** Locations of wells are shown on plate 1. **Abbreviations:** ft, foot; ft/ft, foot per foot; ft/d, foot per day; TCE, trichloroethene; ft/yr, foot per year; yr, year; μg/L, microgram per liter]

Well No.	Distance between wells (ft)	Water-level difference between wells (ft)	Hydraulic gradient (ft/ft)	Hydraulic conduc-tivity (ft/d)	Poro-sity	TCE Retar-dation coeffi-cient	TCE migration rate (ft/yr)	Travel-time between wells (yr)	TCE concen-trations (μg/L)	Field-attenuation coefficient (per year)
					Beginning of plume					
LC-69D to LC-74D	4,300	80	0.019	185	0.22	2	2,855	1.5	158 to 61	0.6
LC-69D to LC-83D-1	5,100	80.8	.016	185	.22	2	2,431	2.1	158 to 44	.6
					Mid-plume					
LC-74D to LC-86D-1	6,500	18	0.003	185	0.22	2	425	15	61 to 6.8	0.1
LC-83D-1 to LC-86D-1	5,700	17	.003	185	.22	2	458	12	44 to 6.8	.1
					Distal portion of plume					
LC-86D-1 to LC-88D-1	3,900	52	0.013	185	0.22	2	2,046	1.9	6.8 to 1.7	0.7
					Downgradient scenarios					
LC-83D-1 to BELLHILL-1 (pumping)	16,800	145	0.009	185	0.22	2	1,325	13	44 to 5	0.2
LC-83D-1 to BELLHILL-1 (static)	16,800	95	.006	185	.22	2	868	19	44 to 5	.1

at well LC-88D. That increasing vertical gradient would be expected to increase vertical dispersion and mixing in the distal portion of the plume. In addition, the ground-water flow lines no longer converge west of American Lake, so the potential for increased lateral dispersion and mixing likely will lead to increased natural attenuation west of well LC-86D. It is uncertain if those changes to more favorable conditions for attenuation downgradient from well LC-86D are substantial enough to result in TCE attenuation rates that are as rapid as those calculated for the beginning part of the plume where conditions are highly favorable for attenuation through vertical dispersion and mixing.

The contribution of TCE sorption to overall attenuation can be indirectly evaluated by comparing mixing model results based on isotope composition to those based on TCE concentrations for wells screened in the beginning

portion of the plume where steady-state conditions are approached (table 10). The samples compared were assumed to be mixtures of average upper-aquifer and sea-level aquifer end-member waters (table 8). Because the isotope compositions are unaffected by sorption, they directly reflect the proportions of upper aquifer and sea-level aquifer water in the wells. In contrast, TCE concentrations may be reduced by sorption. Thus, if the proportions of upper-aquifer- to sea-level-aquifer water calculated using isotopic and TCE data are similar, sorption could be assumed to be minimal. However, if the proportion of upper-aquifer- to sea-level-aquifer water calculated using TCE concentration data were less than that calculated using isotope concentrations, substantial sorption is indicated.

Table 10. Calculated percentages of upper-aquifer end-member water in selected mixed samples, Fort Lewis, Washington.

[**Well No.:** Locations of wells are shown on plate 1. **Abbreviations:** δ^2H, isotope of hydrogen; δ^{18}O, isotope of oxygen; –, not analyzed]

Well No.	Calculated percentage of upper-aquifer end-member water in mixture based on δ^2H and δ^{18}O values, and on trichloroethene concentrations		Percentage difference between calculated percentage of upper-aquifer end-member water in mixture
	Average for δ^2H and δ^{18}O	Trichloroethene	
LC-69D	76	100	31
LC-74D	74	38	-48
LC-83D-1	51	28	-45
LC-83D-2	43	9	-78
LC-83D-3	35	7	-80
LC-83D-4	0	1	–

TCE sorption was consistently indicated for two mid-plume wells in the sea-level aquifer (wells LC-74D and LC-83D). The percentages of upper-aquifer end-member water in wells LC 74D and LC-83D-1 calculated using TCE concentrations (38 and 28 percent) were about one half the percentages of upper-aquifer end-member water calculated using isotope concentrations (74 and 51 percent). Those results indicate that about one-half of the TCE that entered the sea-level aquifer near well LC-69D was not observed in the downgradient wells even after dispersion and mixing with sea-level aquifer water is accounted for. For the two deeper ports at the multi-level well LC-83D, the results indicate that about 80 percent of the TCE that entered the sea-level aquifer near well LC-69D was not observed at depth in the downgradient wells even after dispersion and mixing with sea-level aquifer water is accounted for. Thus, about one-half of the decrease in TCE concentrations between wells LC-69D and LC-74D or LC-83D can be attributed to sorption in the upper part of the sea-level aquifer, and more than three-fourths of the TCE attenuation can be attributed to sorption deeper in the aquifer.

In summary, the attenuation of TCE concentrations in the sea-level aquifer through dispersion, mixing, and sorption is most rapid at the beginning of the flow path, presumably due to large vertical hydraulic gradients and associated vertical dispersion in the aquifer. The attenuation rate slows substantially mid-plume due to less vertical dispersion and mixing, and by converging ground-water flow in the horizontal direction. In the distal portion of the plume, increasing vertical hydraulic gradients are expected to increase vertical dispersion and mixing, and less convergent ground-water flow is expected to allow increased horizontal dispersion and mixing, but there are no stable-isotope data to confirm those expectations. Approximately one-half of the decrease in TCE concentrations in the mid-plume vicinity can be attributed to sorption in the upper part of the sea-level aquifer, and more than three-fourths of the TCE attenuation deeper in the aquifer can be attributed to sorption.

Potential Far-Field Attenuation and Migration of TCE to Water-Supply Wells

The results concerning the existing TCE plume in the sea-level aquifer are considered with information concerning the hydrogeologic setting to discuss the potential for downgradient migration and attenuation of the plume. The potential for TCE migration to existing water-supply wells is of particular concern. TCE has already been detected in two Army water-supply wells in the sea-level aquifer that are located within the footprint of the existing contaminant plume (FLS 13 and MAMC-3 in pl. 1). TCE has not been detected in two other Army water-supply wells that are screened at greater depths in the sea-level aquifer (FLS-16 and MAMC-4), but the Army is aware of the potential risk for contamination of those wells (URS Corporation, 2002). The potential for TCE migration to existing water-supply wells west of American Lake is evaluated in this section of the report to gain an understanding of any additional near-future risk that the contaminant plume may pose.

Potential Downgradient Attenuation of TCE Concentrations

The potential downgradient attenuation of TCE concentrations in the sea-level aquifer west of American Lake cannot be quantified with the available data, but the results and discussion presented for the existing sea-level aquifer plume provide some insight into what could be expected. The current TCE plume appears to be at steady-state as far downgradient as well LC-83D where a maximum TCE concentration of 44 µg/L was detected. The plume is less likely to be at steady-state downgradient from well LC-83D, and the TCE concentrations there are expected to increase in the future. Attenuation due to dispersion and mixing between wells LC-83D and LC 81D was negligible, although some attenuation due to sorption between the two wells could be expected.

Attenuation of TCE concentrations also can be expected as the plume advances downgradient beyond LC-81D, but the attenuation rate and the longevity of sorption-related attenuation is uncertain. In addition to the previously described changes to a more uniform flow pattern and increased vertical hydraulic gradients in the distal portion of the sea-level aquifer TCE plume, the substantial flux of sea-level aquifer recharge from American Lake has some potential to mix with the sea-level aquifer TCE plume west of the lake. The tracer signature for American Lake recharge was clearly identified in multiple wells screened beneath and immediately downgradient from the lake, although all of those wells are north of the primary contaminated flow path in the sea-level aquifer. Overall, there is good potential for the rate of attenuation to increase once the plume advances to the west of American Lake.

Potential TCE Migration to Water-Supply Wells West of American Lake

Two existing water-supply wells west of American Lake are potentially downgradient from the current sea-level aquifer TCE plume. The nearest well is FLS-19B, immediately east of Sequalitchew Lake. The well is currently a backup water-supply well owned by Fort Lewis that is planned for decommissioning. The well appears to be north of the sea-level aquifer plume flow path (similar to monitoring well SRC-MW1B), and likely draws water that is a mix of American Lake and sea-level aquifer waters. Thus, the potential for TCE to migrate in detectable concentrations to well FLS-19B is low primarily due to its location north of the contaminant plume.

The next nearest water-supply well screened in the sea-level aquifer that potentially lies downgradient of the TCE plume is BELLHILL-1, about 7,400 ft west-southwest of the contaminated well LC-88D. The BELLHILL-1 production well is a public-supply well owned by the Weyerhaeuser Real Estate Company, and has the capacity to produce about 1,000 gal/min with an estimated 100-day drawdown of 50 ft (Hart Crowser, 1990). The potential for TCE to migrate to BELLHILL-1 at concentrations exceeding 5 µg/L can be explored using some hydraulic and field attenuation estimates. The evaluation begins at well LC-83D where the assumed steady-state TCE concentration of 44 µg/L was observed. Assuming the same hydraulic and retardation parameters as used previously, and assuming pumping conditions with a 50-ft drawdown at BELLHILL-1, the estimated TCE traveltime between LC-83D-1 and BELLHILL-1 is 13 years (table 9). Assuming static (non-pumping) conditions at BELLHILL-1, the estimated traveltime is 19 years. Given those traveltime estimates, the field attenuation rates needed between the two wells to decrease the TCE concentration from 44 to 5 µg/L were calculated to be 0.2 per year for pumping conditions and 0.1 per year for static conditions. Those attenuation rates are substantially less than the rate estimated for the beginning of the sea-level aquifer plume (0.6 per year), but are greater than the rate estimated for the mid-plume (<0.1 per year). Overall, this evaluation does not clearly support or refute the hypothesis that sea-level aquifer ground water with TCE concentrations greater than 5 µg/L will extend downgradient to the BELLHILL-1 water-supply well.

Even if the TCE plume eventually extends downgradient to the BELLHILL-1 supply well, the potential is low for actually detecting TCE at concentrations greater than the 5 µg/L clean-up level in the well. TCE concentrations in the existing sea-level aquifer plume decrease substantially with lateral distance away from the centerline of the most contaminated flow path. The limited water-level data available between the Logistics Center and BELLHILL-1 do not allow precise definition of the flow path, but it would be an unlikely coincidence if BELLHILL-1 was directly on the centerline. The potentiometric surfaces mapped in figures 3 and 4 indicate that the well is south of the most probable plume centerline. The BELLHILL-1 well also has a 46-ft-long well-screen that pulls in water from a much thicker part of the aquifer than is represented by the 5 to 20-ft intervals screened in the monitoring wells near the Logistics Center. Unless the aquifer was uniformly contaminated with more than 5 µg/L over much of its thickness, the TCE concentrations in the pumped water would be less than the maximum concentration that may exist in discrete intervals in the aquifer.

Implications for Remediation Plans

In 2004, the Army was actively working on removing TCE from the upper aquifer. As of June 2002, an estimated 140,000 lbs of TCE in NAPL remained beneath the East Gate Disposal yard, and about 13,000 lb remained in the dissolved-phase plumes. As of July 2004, the first phase of thermal remediation at the disposal yard had removed 6,500 lb of TCE and *cis*-DCE in vapor, water, and NAPL, and thermal remediation is planned for two additional areas. The two pump-and-treat systems have been removing about 1,000 lbs/yr from the dissolved phase over the past 7 years, although much of that has been continually replenished by dissolution of NAPL. In the long term, those activities will greatly reduce the flux of TCE into the sea-level aquifer.

The 2004 TCE plume in the sea-level aquifer does not likely represent steady-state or pseudo-steady-state conditions. TCE concentrations in wells within the downgradient portion of the plume likely will increase over the coming years, and the currently defined leading edge of the plume likely will extend farther downgradient. The magnitude of that continued plume expansion is difficult to quantify due to the scarcity of data from locations west of American Lake. Because of the TCE that has already migrated into the sea-level aquifer, the plume expansion is expected to continue for some time despite remediation activities in the upper aquifer. Even if the flux of TCE into the sea-level aquifer were to immediately cease, about 20 years would be required for the existing contamination at the known confining unit window to migrate to the farthest downgradient monitoring well LC-88D. In recognition of this, the Army initiated in early 2004 a focused feasibility study of more immediate approaches to remediate sea-level aquifer TCE contamination. The results presented in this report will help the Army determine methods for appropriate and effective remediation in the sea-level aquifer.

Summary

The U.S. Army disposed of waste trichloroethene (TCE) and other materials in the East Gate Disposal Yard near the Logistics Center on Fort Lewis, Washington, during the 1940s through the early 1970s. As a result, ground water contaminated with primarily TCE extends more than 3 miles downgradient from the East Gate Disposal Yard. The site is underlain by a complex and heterogeneous sequence of glacial and non-glacial deposits that have been broadly categorized into an upper and a lower aquifer (the latter referred to as the sea-level aquifer). TCE contamination is found in both aquifers. This report describes an investigation by the U.S. Geological Survey (USGS) of the source, migration, and attenuation of TCE in the sea-level aquifer.

A refined conceptual model for ground-water flow and contaminant migration into and through the sea-level aquifer was developed in large part from interpretation of environmental tracer data. The tracers used included common ions and selected general ground-water chemistry analytes; TCE; stable isotopes of oxygen (^{18}O), hydrogen (^{2}H), and carbon (^{13}C); the radioactive hydrogen isotope tritium; chlorofluorocarbons; and sulfur hexafluoride. Tracer concentrations were determined for samples collected by the USGS from 37 wells and 2 locations in American Lake during 1999-2000. Ground-water levels were measured by the USGS in more than 40 wells during 2000-01, and were combined with measurements by the Army and others to create potentiometric surface maps.

Localized ground-water flow features were identified that are of particular relevance to the migration of TCE contamination. A ridge of ground water beneath American Lake causes ground water in the sea-level aquifer that flows from beneath the East Gate Disposal Yard to veer to the west-southwest and flow around the southern end of American Lake. A substantial steepening of the potentiometric surface at the presumed location of a relatively high permeability window through the confining unit separating the upper and sea-level aquifers results in downward gradients that facilitate inflow of contaminated upper-aquifer ground water into the sea-level aquifer. High ground-water altitudes at locations north and northeast of the Logistics Center combined with the ridge beneath American Lake prevent TCE-contaminated water beneath the Logistics Center from migrating toward municipal water-supply wells northeast of the site.

The 1999-2000 concentrations of TCE, *cis*-DCE, and vinyl chloride detected at older wells in the sea-level aquifer are similar to those detected since regular monitoring began in 1995, but the known extent of the TCE contamination expanded nearly 2 miles downgradient after the Army installed and sampled new wells during 2003-04. The sea-level aquifer TCE plume essentially begins at the known confining unit window and concentrations exceeding 5 µg/L extend at least 10,000 ft to the west. Concentrations of TCE in the sea-level aquifer were consistently high in the upper part of the aquifer throughout the plume, although TCE has spread throughout much of the thickness of the aquifer in the downgradient one-third of the plume. Concentrations of *cis*-DCE generally were about one-tenth of the TCE concentrations, and vinyl chloride was not detected in any of the wells screened in the sea-level aquifer.

The environmental tracer data showed distinct chemical signatures for three hypothesized end-member waters in the study area—American Lake, upper-aquifer ground water, and sea-level aquifer ground water that has not been substantially mixed with American Lake or modern upper-aquifer waters. The chemical signatures of samples from nearly all wells screened in the sea-level aquifer can be explained by the mixing of those end-members in varying degrees. The stable-isotope and tritium data were the primary basis for characterizing hypothesized end-members. The CFC concentration data were not useful primarily due to contamination from local urban air or ground-water sources. The sulfur-hexafluoride data and the associated apparent ages were consistent with the hypothesized end-members, although the data were difficult to interpret in a mixture of end-member waters. The relative distribution of common ions between the hypothesized end-members varied little, so the data were not particularly useful as tracers. Redox-related data were consistent with the hypothesized end-members and indicated that the generally aerobic conditions in the sea-level aquifer generally are not favorable for biodegradation of TCE.

The tracer data provide clear evidence that American Lake is a significant source of recharge to the sea-level aquifer. That recharge has created the ridge of ground water beneath the lake that significantly controls migration of the TCE plume in the sea-level aquifer.

Environmental tracer data indicated that the primary pathway for contaminant migration into the sea-level aquifer is through the known confining unit window. Less substantial pathways were identified near the East Gate Disposal Yard and the I-5 pump-and-treat facilities. Both of those areas are near active pumping wells and ground-water reintroduction wells or trenches, but there is no evidence that the contaminant migration was caused or enhanced by pumping and reintroduction.

Within the sea-level aquifer, TCE continues to migrate westward in the flow field strongly influenced by ground-water recharge from American Lake. There are too few historical data to definitively determine if the 5 µg/L leading edge of the current TCE plume is stable or is still moving downgradient. However, an evaluation of the limited historical data combined with TCE traveltime estimates suggest that the peak TCE concentrations in the sea-level aquifer may not have reached the wells near the currently defined leading edge of the plume, and the 5 µg/L leading edge of the current TCE plume hypothetically will move farther downgradient in the future. That hypothesis is consistent with numerical modeling results of the flow system completed by the Army.

Tracer data indicated that attenuation of TCE in the sea-level aquifer is most rapid near the confining unit window, but slows substantially in the downgradient part of the current contaminant plume. Biodegradation of TCE is not an important attenuation mechanism in the sea-level aquifer. As the plume advances downgradient into previously uncontaminated areas, attenuation due to sorption likely will continue, but the longevity of sorption-related attenuation is uncertain. Conditions become more favorable for attenuation due to lateral and vertical dispersion and mixing in areas west of American Lake.

TCE has already been detected in three Army water-supply wells in the sea-level aquifer (FLS-13, FLS-16, and MAMC-3) that are located within the footprint of the existing contaminant plume. There also is a potential for TCE migration to existing sea-level aquifer water-supply wells west of American Lake and downgradient from the currently defined plume. The risk is low for TCE migration to the Fort Lewis backup supply well FLS-19B, because it is north of the contaminant plume. The TCE plume possibly will migrate to the BELLHILL-1 well in the years ahead. However, TCE likely will not be detected at concentrations greater than the 5 µg/L drinking-water standard at BELLHILL-1 because of likely TCE attenuation west of American Lake, the unlikely coincidence that BELLHILL-1 is located directly on the plume centerline, and the dilution of TCE concentrations in the pumped water.

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Appendix A. Duplicate and Field-Blank Sample Results for USGS Data

Duplicate samples provided information on the variability of concentrations determined from the sample processing and analytical methods, and on the consistency of quantifying target analytes. Duplicate samples for various constituents were collected at one-to-four wells and were analyzed for major cations and anions, TOC, VOCs, and the isotopes tritium, carbon-13 (^{13}C), deuterium (^2H) and oxygen-18 (^{18}O) (table A1). All samples for sulfur hexafluoride (SF_6) were collected in duplicate or triplicate (table A2).

Overall, the duplicate analyses indicated good precision. TOC concentrations showed poor precision although the measured concentrations were near the method detection limit of 0.2 mg/L. Most duplicate SF_6 results also showed very good precision, and the standard deviation of difference for all SF_6 duplicate samples was 0.22 pptv.

Two field blanks of deionized water or specially prepared blank water were processed in the same manner as ground-water samples and sent to the laboratory for analysis. Although no criteria were set for constituent concentrations in blanks, the significance of any constituent present in a blank was based on how close the constituent concentration was to the detection limit, and the number of times the constituent was detected in blank samples. When compared to these criteria, all constituent concentrations in blanks were insignificant except for TOC and iron (table A3). TOC was detected in one of the two blanks, and the reported concentration of 0.7 mg/L was large relative to the range of concentrations in ground-water samples of 0.1 to 3.7 mg/L, with a median concentration of 0.6 mg/L. Iron was detected at a concentration of 26 µg/L in one of the two blanks.

Table A1.   Concentrations of selected constituents in duplicate ground-water samples from wells, Fort Lewis, Washington, 2000.

[**Constituent:** Concentrations in milligram per liter unless otherwise noted. **Abbreviations:** δ^2H, ^3H, isotopes of Hydrogen; $\delta^{18}O$, isotope of Oxygen; $\delta^{13}C$, isotope of Carbon; –, no data; <, less than; µg/L, microgram per liter; permil, parts per thousand]

Constituent	Well LC-035D		Well LC-66D		Well LC-75D		Well FL-02	
	Reported	Duplicate	Reported	Duplicate	Reported	Duplicate	Reported	Duplicate
Calcium	–	–	12.7	12.8	13.6	13.6	–	–
Chloride	–	–	2.26	2.28	3	2.99	–	–
cis-1,2 dichloroethene (µg/L)	–	–	5	4.5	.1	.1	25.0	24.3
$\delta^{13}C$ (permil)	-19.7	-19.4	-19.2	-19.4	-19.5	-17.5	–	–
δ^2H (permil)	–	–	–	–	–	–	-71.4	-72.8
$\delta^{18}O$ (permil)	–	–	–	–	–	–	-9.91	-9.9
Fluoride	–	–	<.1	<.1	<.1	<.1	–	–
^3H (tritium units)	14.6	14.5	10	8.9	16.5	16.7	13.5	12.8
Iron (µg/L)	–	–	<10	<10	<10	<10	–	–
Magnesium	–	–	5.21	5.21	5.87	5.86	–	–
Manganese (µg/L)	–	–	4.1	4.1	<2.2	<2.2	–	–
Potassium	–	–	2.6	2.28	1.61	1.65	–	–
Silica	–	–	37.8	38.1	27.9	28.1	–	–
Sodium	–	–	6.31	6.37	5.63	5.67	–	–
Sulfate	–	–	4.3	4.3	7.7	7.6	–	–
Total organic carbon	–	–	.4	.1	.5	.6	–	–
Trichloroethene (µg/L)	–	–	55.2	53.4	.8	.8	93.7	95.8
Vinyl chloride (µg/L)	–	–	<.2	<.2	<.2	<.2	<.2	<.2

Table A2.   Concentrations of sulfur hexafluoride in samples from wells and surface-water sites, Fort Lewis, Washington, 2001.

[Samples collected by the U.S. Geological Survey. Concentrations from two to six replicate analyses per well are shown. **Well No.:** Locations of wells are shown on plate 1. **Abbreviations:** pptv, parts per trillion by volume]

Well No.	Sulfur hexa-fluoride (pptv)	Well No.	Sulfur hexa-fluoride (pptv)
88-1-SS	0.27	LC-69D	2.77
	.16		3.24
	.24		3.03
AML-1	3.89	LC70D	1.70
	4.09		.54
	4.07	LC-72D	2.07
AML-2	3.95		2.01
	3.87		2.54
	4.07	LC-73D	.97
FL04A	2.94		1.08
	2.36		.90
LC-21B	.27	LC-74D	1.62
	.26		1.64
LC-21C	2.71		1.78
	2.92	LC-75D	2.49
LC-26D	1.92		2.64
	1.98		2.72
	1.64		2.66
	1.49		2.66
	1.85		2.04
LC-35D	.43	LC-76D	2.28
	.39		2.00
	.53	LC77D	5.25
	.46		5.83
	.60	LC-149C	3.19
	.61		3.23
	.55	LC-149D	3.65
LC40C	2.85		3.68
	.96	LC166D	2.05
	1.28		4.39
LC40-D	1.36		2.11
	1.76	LF4-MW2C	.50
	1.55		.29
LC-41E	1.09		.45
	1.08	LF4-MW4	1.27
LC47D	.71		1.41
	.27		1.31
	.28	SRC-MW1B	.58
LC55D	.20		.57
	.18	T-09E	1.88
LC-66D	1.00		1.89
	.99		

Table A3.   Summary of constituent concentrations reported for blank samples, Fort Lewis, Washington, 2000.

[**Constituents:** Concentrations in milligram per liter unless otherwise noted. **Abbreviations:** µg/L, microgram per liter; nd, not detected]

Constituents	Number of field blanks	Number of detections	Maximum concentration in blank
All volatile organic compounds (µg/L)	2	0	nd
Calcium	2	1	0.03
Chloride	2	0	nd
Fluoride	2	0	nd
Iron (µg/L)	2	1	26
Magnesium	2	1	.009
Manganese (µg/L)	2	0	nd
Potassium	2	0	nd
Silica	2	0	nd
Sodium	2	0	nd
Sulfate	2	0	nd
Total organic carbon	2	1	.7

Appendix B. Chlorofluorocarbon Data

Table B1.   Concentrations of chlorofluorocarbons in samples from wells and surface-water sites, Fort Lewis, Washington, 2001.

[The concentrations from two to six replicate analyses per well are shown. **Well No.:** Locations of wells are shown on plate 1. **Abbreviations:** pg/kg, picogram per kilogram; CFC, chlorofluorocarbon]

Well No.	Concentrations (pg/kg)			Well No.	Concentrations (pg/kg)		
	CFC-11	CFC-12	CFC-113		CFC-11	CFC-12	CFC-113
88-1-SS	167	2,190	0.0	LC-70D	3.20	–	0.0
	137	2,230	.0		3.14	10.13	.0
	142	2,250	.0		2.37	–	.0
AML-1	352	435	125	LC-71D[1]	.72	–	.0
	1,010	431	148		1.13	2.56	.0
	156	458	93.9	LC-72D	3,450	695	92.8
AML-2	287	463	96.6		3,170	723	108
	246	499	108		3,060	713	107
	56.8	485	108	LC-73D	471	780	33.0
FL-02	808	453	133		559	841	22.1
	910	295	134		561	774	23.6
	878	431	96	LC-74D	4,200	1,110	59.4
	933	418	82		4,280	1,090	60.9
FL-04A	252	221	899		3,560	1,070	72.2
	284	243	1,000		837	379	921
	284	238	1,000		884	367	952
LC-11	751	324	85.7		887	423	1,000
	753	319	80.2	LC-75D	816	405	941
	738	322	81.2		826	400	971
LC-21C	594	307	63.7		1,020	403	994
	599	337	57.8	LC-76D	73.1	51.9	.0
	594	310	61.5		81.2	47.1	3.26
LC-26D	272	230	18.9		81.4	62.7	.0
	304	243	19.6	LC-77D	696	226	68.1
	294	279	17.2		688	253	64.3
LC-35D	31.7	71.2	2.52		754	266	76.4
	30.9	85.7	2.46	LC-126	6,080	564	92.6
	30.4	86.3	2.39		7,060	525	91.6
LC-40C	13.4	175	.0		7,020	559	95.8
	2.49	186	.0	LC-166D	7.38	28.9	.0
	2.55	191	.0		4.17	34.8	.0
	2.60	187	.0		4.10	29.2	.0
LC-40D	1,000	362	.0	LF4-MW2C	7.28	351	16.8
	1,100	387	.0		188	49.8	13.0
	1,050	335	.0	LF4-MW4	502	847	59.9
	908	328	.0		452	886	62.0
LC-47D	17.1	24.9	2.59		185	357	9.32
	16.8	28.9	.0	SILCOX-1	44.8	54.6	8.3
	19.6	26.4	2.02		32.2	53.0	2.4
LC-50D	10.1	20.6	2.25		59.8	44.8	.0
	12.6	23.7	2.40	SILCOX-2	–	79.6	.0
	23.4	54.3	5.37		.75	99.7	.0
LC-66D	1,420	143	28.3		1.35	105	125
	1,340	151	37.2	SRC-MW1B	121	349	5.24
	1,320	140	33.5		121	346	5.17
LC-67D	1,330	2,460	54.4		262	344	5.82
	1,450	2,580	58.2	T-09E	1,540	684	1,720
	1,480	2,650	55.3		1,550	707	1,770
LC-69D	281	2,470	101		1,560	729	1,800
	5,400	2,700	105				
	5,250	2,660	200				

[1]Well is screened in the lower confining unit (Qpon$_2$) immediately beneath the sea-level aquifer.

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