

EXTENT AND SOURCE OF ORGANIC SOLVENTS IN GROUND WATER
IN THE ARGONNE ROAD AREA NEAR SPOKANE, WASHINGTON

By N. P. Dion and S. S. Sumioka

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CONVERSION FACTORS

For the convenience of readers who may prefer to use metric units rather than the inch-pound units used in this report, values may be converted by using the following factors:

<u>Multiply inch-pound units</u>	<u>By</u>	<u>To obtain metric units</u>
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.590	square kilometer (km ²)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per day (gal/day)	3.785	liter per day (L/day)

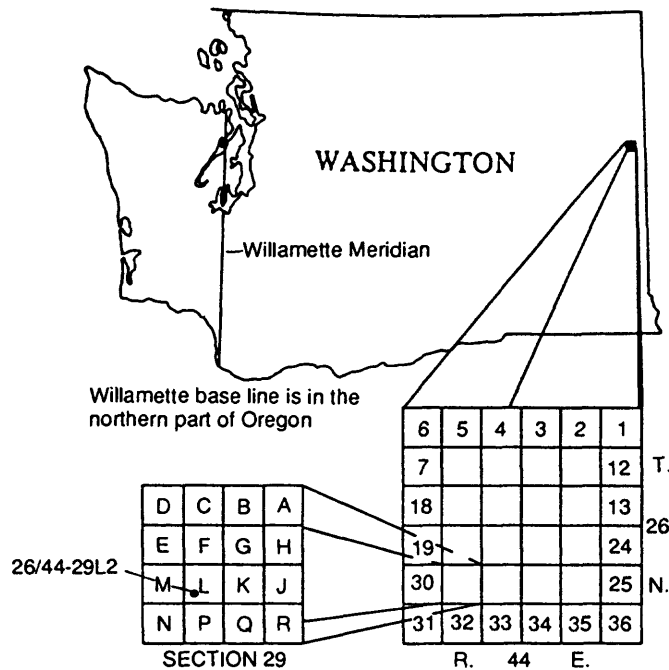
Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

degree Fahrenheit (°F) to degree Celsius (°C): °C = 5/9 (°F - 32)

WELL-NUMBERING SYSTEM

In this report, wells are designated by symbols that indicate their location according to the rectangular-grid system for subdivision of public land. For example, in the symbol 26/44-29L2, the part before the hyphen indicates, successively, the township and range (T.26 N., R.44 E.) north and east of the base line and Willamette Meridian. Because all townships mentioned in this report are north of the base line and east of the Willamette Meridian, the letters "N" and "E" are omitted in the text. The first number after the hyphen indicates the section (29) in which the well is located; the letter denotes the 40-acre tract of the section as shown in the sketch below. The last number is the serial number of the well in the 40-acre tract. Thus, well 26/44-29L2 is in the NE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 29, T.26 N., R.44 E., and is the second well in that 40-acre tract to have been recorded.

In this report, well numbers are commonly abbreviated to the last part of the local well number (for example, 29L2) where the township and range of all wells being discussed are the same. In illustrations where the section number is plainly shown, well numbers are further abbreviated for the sake of clarity by dropping the section number (for example, L2).



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ABSTRACT

An alluvium-filled trough cut into granite east of Spokane, Washington, contains an unconfined ground-water body that is hydraulically connected to the "sole source" Spokane aquifer to the south. Water in the unconfined aquifer moves southward at an estimated 1.4 to 4.0 feet per day.

In the spring of 1981, water in the alluvial aquifer was found to contain dissolved organic solvents tetrachloroethene, trichloroethene, 1,1,1-trichloroethane, and 1,2-trans-dichloroethene. The suspected source of the solvents is a nearby septic-tank sludge-disposal area. Solvent concentrations in at least two domestic wells in the study area have decreased with time since first detected.

Data show that the organic solvents have reached the Spokane aquifer; however, the solvents were not detected in two wells in that aquifer immediately downgradient of the alluvial aquifer. Therefore, the solvents either have not yet reached the susceptible wells, or they have been diluted to below minimum analytical detection levels. The Spokane aquifer wells likely to be affected are few in number, but serve about 2,600 people. In addition to the solvents dissolved in ground water, some of the same compounds may occur as an immiscible organic liquid phase near the base of the aquifer(s) and consequently may follow different flow paths from that of the dissolved phase.

Although this study did not confirm that the sludge-disposal area is the source of the organic solvents, the data indicate that wastes or leachates generated at that disposal site would flow to the alluvial aquifer and eventually to the Spokane aquifer.

INTRODUCTION

The State of Washington Department of Ecology (WDOE) has identified more than 400 sites in Washington where the ongoing or previous handling of wastes might damage the environment. One of these sites is near Spokane in a ravine just east of and parallel to Argonne Road (fig. 1), where chlorinated hydrocarbons have been detected in privately owned wells used for domestic supply.

In the spring of 1981, a complaint from a well owner who resides at the upper end of the narrow, wooded ravine led County and State authorities to begin an investigation of possible organic solvents in ground water. Chemical analyses of water samples from the well in question (well 26/44-32C1; see figs. 2), indicated that the ground water contained tetrachloroethene and, to a lesser extent, trichloroethene. These chlorinated hydrocarbons are used extensively as industrial solvents, degreasing agents, dry-cleaning solvents, and septic-tank cleaners. Subsequent analyses of samples from other wells both upgradient and downgradient from well 32C1 revealed that wells 26/44-32C2 and 32D1, downgradient of 32C1, contained the same compounds and that all three wells also contained small concentrations of 1,1,1-trichloroethane and 1,2-trans-dichloroethene.

The suspected source of the solvents was an unlined, 40-acre-disposal area for septic-tank sludge, about 0.3 mile northwest of the well in which the solvents were first detected (see fig. 2). Disposal activities at the site consisted largely of the discharge of septic-tank sludge directly onto the sloping soil surface. Although no records were kept, on an average day several truckloads of waste were dumped at the site. The site had first been licensed for disposal in the early 1970's by the Spokane County Health District. Once the presence of organic solvents in the ground water was confirmed, the county did not renew the disposal permit and all disposal ceased in April 1984.

Because of the confirmed presence of solvents, WDOE notified the owners of the three wells not to use their well water for domestic purposes, but to import water until arrangements could be made by the WDOE and the Pioneer Irrigation Company to extend the Pasadena Park area (fig. 1) municipal water service northward along Argonne Road. The well owners were encouraged, however, to continue using the water for stock and irrigation in an effort to accelerate the flushing and natural restoration of the affected aquifer.

Sampling of the affected wells and analysis of the water for organic and inorganic constituents began in spring 1981 and continued semiannually through April 1984 and intermittently thereafter. Although many other wells and a spring in the Argonne Road area eventually were sampled, none was reported to contain the solvents. Traces of the solvents were found, however, in samples of soil from the disposal site.

The concern over the presence of organic solvents in the local ground water extends further than the three wells known to be affected. The geologic materials along the axis of the ravine contain ground water that could be in hydraulic connection with the Spokane aquifer in the Spokane Valley to the south (figs. 1 and 2). This aquifer has been accorded "sole source" status in

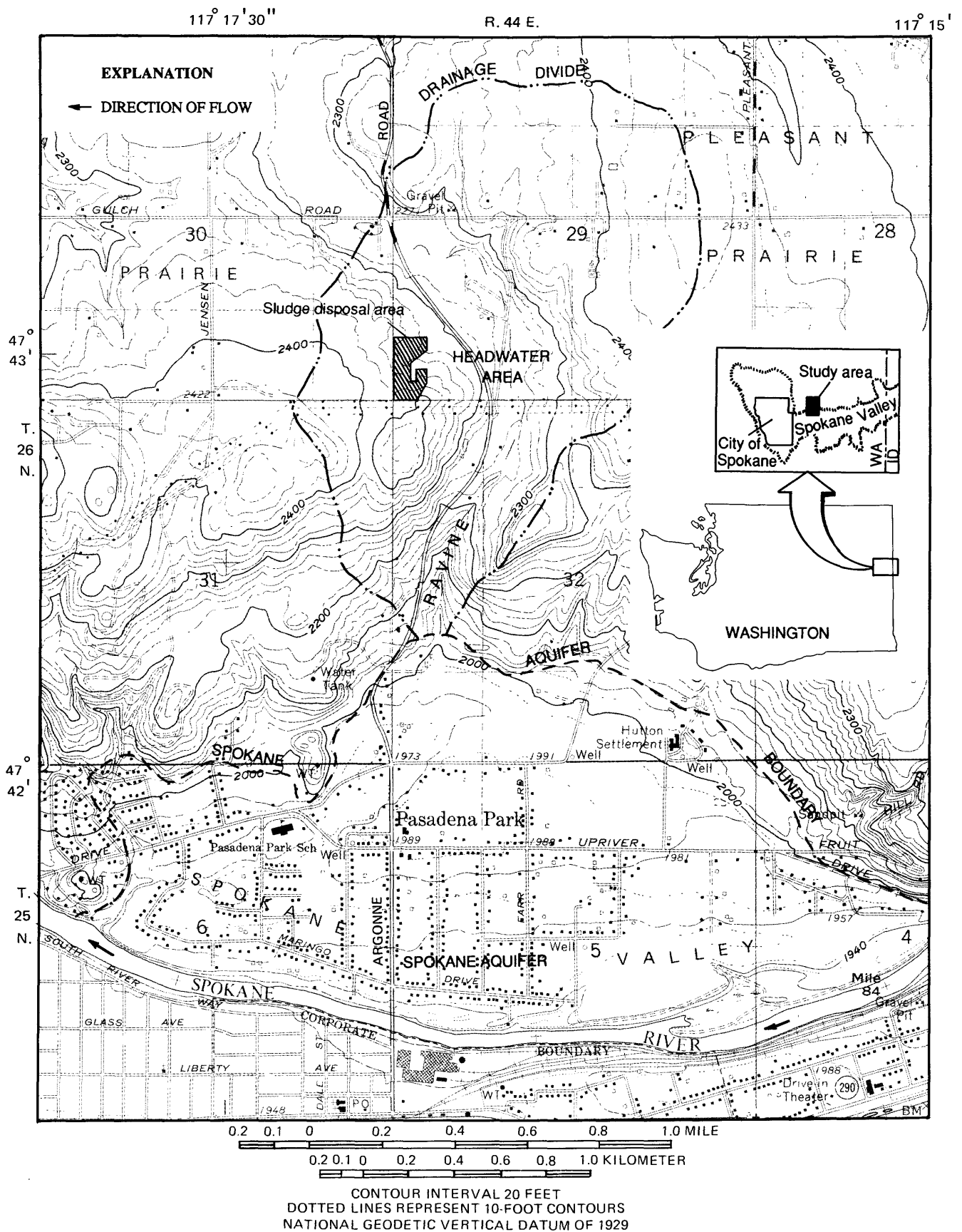


Figure 1.--Location of study area.

the Spokane Valley under Section 1424(e) of the Safe Drinking Water Act of 1974 (Public Law 93-523). Several high-capacity public-supply wells are located in the Spokane aquifer near the mouth of the ravine, and the concern is that the same chlorinated hydrocarbons found in the three affected domestic wells could find their way into wells in the Spokane aquifer.

In 1985, the U.S. Geological Survey, in cooperation with WDOE, completed a reconnaissance investigation of the problem. The findings of that study (Dion, 1987) were as follows:

- (1) An unconfined ground-water body exists at the base of the alluvium that fills the wooded ravine along Argonne Road and at the fractured and weathered top of the underlying granite.
- (2) The ground water in the alluvial aquifer locally contains organic solvents that are commonly used as commercial degreasers and septic-tank cleaners.
- (3) The ground water and solvents in question are probably moving southward, toward the Spokane aquifer, at an estimated velocity of 0.40 to 4.0 ft/d.
- (4) The movement of the solvents in the subsurface would not be affected significantly by sorption, volatilization, chemical activity, or biodegradation.
- (5) On the basis of the estimated velocity range of the ground water, it would take 2.5 to 25 years for the plume of solvents to reach the Spokane aquifer from the time they were first detected in a domestic well at the head of the ravine (spring 1981).

Because of the preliminary nature and limited scope of the reconnaissance study, numerous questions remained unanswered and many preliminary conclusions needed to be confirmed and refined. Accordingly, in 1986 a second study was undertaken cooperatively between WDOE and the U.S. Geological Survey to address those needs.

Purpose and Scope

This report presents the results of the second (1986) study, designed to: (1) refine the knowledge of the alluvial aquifer along Argonne Road gained in the reconnaissance study; (2) determine the degree of hydraulic connection between the alluvial aquifer and the Spokane aquifer; (3) determine the lateral and vertical extent of the plume of organic solvents in the ground water in the Argonne Road area; (4) attempt to determine the source of the solvents; and (5) identify wells in the Spokane aquifer likely to be affected by solvent-laden water in the alluvial aquifer, if a hydraulic connection exists.

The geohydrology of the alluvial aquifer, including the geologic and hydrologic boundaries, ground-water head gradients, flow directions, and flow velocities were determined, in part, using published reports, field observations, surface geophysical techniques, augering and drilling of test wells, ground-water-level measurements, and estimates of porosity obtained from the literature for the materials that compose the local aquifer. These data and published descriptions of rock units known to exist in the Spokane aquifer were used in determining the degree of hydraulic connection between the Argonne Road alluvial aquifer and the Spokane aquifer.

Analyses of water samples from existing wells in the Argonne Road area, and from wells installed as part of this study, were used to describe the lateral extent of the organic solvents in the alluvial aquifer, and the likely source of those solvents.

The wells in the Spokane aquifer likely to be affected by organic contamination from the Argonne Road aquifer were selected from the U.S. Geological Survey's Ground-Water Site Inventory (GWSI) data base using knowledge of local ground-water conditions. An estimate of the number of people likely to be affected by the presence of organic solvents in the Argonne Road aquifer was made by summing the population served by each of the wells likely to be affected.

Description of the Study Area

The Argonne Road study area (figs. 1 and 2) is located about 6 miles east of the city of Spokane, Wash., and about 12 miles west of the Washington-Idaho State line. The area lies partly in foothills and partly in a major river valley.

The northern part of the study area lies in the northern Rocky Mountain physiographic province described by Fenneman (1931), and consists of rolling hills that reach altitudes of almost 2,500 feet above sea level. For the most part, the southern slopes of the hills are covered with ponderosa pine. Local residents refer to the gently rolling areas where trees are absent as "prairies."

The southern part of the study area is in the Columbia Plateau physiographic province described by Fenneman (1931), and consists of part of the relatively flat Spokane Valley, with an altitude of 1,900 to 2,000 feet. For practical purposes, the Spokane River forms the southern boundary of the study area.

Argonne Road is oriented generally north-south and lies along the western slope of a steep, narrow, wooded ravine cut into the hills by an unnamed, intermittent stream. Local residents say that the stream flows only when winter "chinook" winds melt the snow cover that overlies frozen ground, and that the water sinks into the ground shortly after debouching from the ravine and before reaching the Spokane River. The area drained by the stream is about 7 square miles (see fig. 1).

Immediately north of the ravine is an area of low relief referred to in this report as the "headwater" area. Residential development of the headwater area is sparse; the chief land use there is dry farming for wheat. The septic-tank sludge-disposal area, suspected as the source of the organic solvents, lies just west of the headwater area.

Residential development is sparse in the hills and prairies, but concentrated in Spokane Valley. Historically, the prairies have been used for the cultivation of grass seed for lawns. In the more recent past, however, much of this agricultural land has been taken out of production to make room for single-family dwellings.

The Spokane area has the characteristics of both marine and continental climates (Phillips, 1965). Summers are typically warm and dry, winters are cold and damp. The mean annual air temperature at the Spokane airport is 47.1 °F; July is the warmest month (69.7 °F) and January the coldest (25.1 °F). Prevailing winds are from the southwest in summer and northeast in winter. A few warm "chinook" winds are common each winter.

The mean annual precipitation at Spokane is 16.7 inches; July has the smallest mean monthly precipitation (0.50 inch) and December the largest (2.49 inches). Most of the precipitation between early December and late February falls as snow and remains on the ground (Phillips, 1965).

Previous Investigations

The bedrock and the unconsolidated materials within the areas included in the Spokane and Greenacres 15-minute quadrangle maps are described by Griggs (1966) and Weis (1968), respectively. A seismic refraction study (Newcomb and others, 1953) of the Spokane Valley provided information on the thickness of the Spokane aquifer and the nature of the material underlying the aquifer. Cline (1969) studied the ground-water resources of north-central Spokane County. VanDenburgh and Santos (1965) and Ebbert (1984) presented and discussed ground-water-quality data for areas that include the Argonne Road study site. Several recent studies (Drost and Seitz, 1978; Bolke and Vaccaro, 1981; and Vaccaro and Bolke, 1983) described the hydrologic characteristics of the Spokane aquifer. A reconnaissance study by Dion (1987) was discussed previously, and was based on readily available historical geological data only.

Acknowledgments

The authors express their appreciation to land owners Mrs. Lloyd Bonenko, Mr. Wes Crosby, Mr. Lloyd Gill, Mr. Glenn Kettleson, Dr. Howard Miller, and to the officials of the Pasadena Park and the Pleasant Prairie water companies for their cooperation and assistance during this study.

STUDY METHODS

A surface-geophysical technique, seismic refraction, was used to obtain estimates of the depth to bedrock and the configuration of the bedrock surface. The locations of the geophysical transects are shown in figure 2. The information was used to determine the locations and depths of the test wells to be installed. Descriptions of seismic refraction methods may be found in many publications on geology and geophysics, as well as in publications dealing with ground water (Water Well Journal, 1971; Mooney, 1973; Zohdy and others, 1974; Collett, 1978; Freeze and Cherry, 1979; Sendlein and Yazicigil, 1981; and Driscoll, 1986).

The equipment utilized in the geophysical survey consisted of a 12-channel signal-enhancing seismograph and 12 standard land geophones with cable. The energy source was an 8-pound sledge hammer and inertia trigger switch connected to the seismograph. Geophone spacing ranged from 10 to 20 feet (13- and 260-foot spreads, respectively) and the seismic profiles consisted of several spreads joined lengthwise.

The geophysical survey provided data that allowed the construction of preliminary geologic sections based on estimates of the depth to bedrock (thickness of overlying unconsolidated materials). These preliminary sections then were used to determine where to locate the test wells that would test the accuracy of the geophysical survey and permit a refinement of the existing geologic description of the study area.

Ten test wells (piezometers) were installed (see fig. 2) to determine the extent, depth, and lithologic character of unconsolidated materials overlying granitic bedrock in the study area, and to confirm the depth-to-bedrock estimates obtained from the seismic refraction survey. Much of the headwater area is dry-farmed for wheat, and permission could not be obtained to install test wells on that land. Six of the wells were installed to depths of up to 80 feet using a hollow-stem auger. The other four wells, which range in depth from 38 to 223 feet, were installed using a mud-rotary drill. Lithologic samples of the earth materials encountered while augering or drilling were collected at 3- to 5-foot intervals. After drilling, care was taken to remove as much of the drilling fluid from the borehole and surrounding geologic material as possible before setting the screen. All wells were cased with polyvinyl chloride (PVC) pipe; 2-inch diameter pipe in the augered holes and 2- and 4-inch diameter pipe in the drilled holes. The bottom of each well was finished with 3 to 10 feet of No. 10 slotted PVC pipe of corresponding diameter and the annular space packed with round, graded sand. The wells were then backfilled with native materials and the top 5 feet of annular space sealed with concrete. The 2-inch wells were developed by hand bailing until all water removed from the well was clear. The 4-inch wells were developed using compressed air.

Ground-water levels in some of the test wells and a few privately owned domestic wells were measured periodically to the nearest 0.01 foot using a steel tape. Water levels in other wells were measured to the nearest 0.1 foot using an electrical sounder because of excessive moisture on the inside casing walls. Water levels in public-supply wells that lacked access holes for tapes were measured by airline to an accuracy of about 2 feet.

The hydraulic conductivity of the aquifer materials was determined in each test well using a slug-test technique described by Bouwer and Rice (1976). Porosity values for the clay, silt, and sands composing the aquifer were estimated from information in the literature (Freeze and Cherry, 1979; Todd, 1980). The lithologic and hydrologic data then were used to determine ground-water gradients, flow directions, and flow velocities.

Seismic refraction, exploratory drilling, and water-level measurements near the mouth of the ravine were used to define the physical and hydraulic connection between the alluvial aquifer along Argonne Road and the Spokane aquifer. The lithology of geologic materials encountered in test wells near the mouth of the ravine was compared with that known to exist in the Spokane aquifer. Similarly, ground-water levels in the study-area wells were compared with ground-water levels in wells known to be completed in the Spokane aquifer.

Water samples from test wells, domestic wells, and public-supply wells in the Argonne Road area were collected and analyzed for the presence of the four organic compounds found originally in the three domestic wells. The chemical analyses also included nitrate-nitrogen and chloride determinations because concentrations of these constituents are typically present in septic-tank effluent and sludge. Sample collection was in keeping with procedures set forth in U.S. Geological Survey technical publications (Skougstad and others, 1979; Wershaw and others, 1983). Prior to sampling, the wells were bailed to remove water that had been standing in the casing (Bryden and others, 1986). Samples generally were collected with a glass, bottom-filling bailer; a sample from the bottom of one relatively deep well (32M3) was obtained with a stainless steel, piston-operated point sampler. Field measurements included temperature, specific conductance, alkalinity, and pH. Chemical analyses were performed by a laboratory in Manchester, Wash., operated jointly by the U.S. Environmental Protection Agency and WDOE because previous analyses of samples from the study area were performed there. This eliminated one possible source of variation between historical and current data.

With a knowledge of ground-water flow conditions in the alluvial aquifer and in the Spokane aquifer, it was possible to determine the part of Spokane Valley (or Spokane aquifer), downgradient of the study area, that was likely to be affected by solvent-laden ground water from the study area. The number and locations of wells within that susceptible area then were determined by a review of the ground-water data base for that area and by field reconnaissance. The primary criteria for well selection were location and depth. On the basis of this knowledge, and data from selected public and private water districts, estimates were made of the number of people likely to be affected by organic solvents in ground water of the Spokane aquifer.

GEOHYDROLOGY

Geologic and hydrologic descriptions of the Spokane area, including the Argonne Road area, are provided by Griggs (1966) and Cline (1969). These descriptions were modified, on the basis of results of the geophysical survey and exploratory drilling completed as part of this study, to provide a more detailed description of the geohydrology of the Argonne Road area. Selected geologic sections that resulted from the geophysical survey are shown in figure 3. The modified geology of the study area is presented in figures 4-6.

Geologic Setting

Granitic rocks form the basement of the study area and are partly covered by lava, loess, glacial deposits, and alluvium. The granitic rocks are of Cretaceous age (table 1) and are referred to in this report as "bedrock"; they have been deeply eroded and possibly faulted, and therefore have a surface of considerable relief.

The foothills in the central part of the study area are underlain by bedrock, which is exposed on both sides of the alluvium-filled ravine (fig. 4). In addition, drillers' logs of wells (Dion, 1987) suggest that the bedrock occurs at depth throughout the study area beneath younger geologic units. The granitic rocks typically weather to a coarse sand.

Basalt of the Columbia River Basalt Group is exposed in the northern and eastern parts of the study area. In addition, drillers' logs indicate that the dense, dark-colored rock, which is of Miocene age, occurs beneath the younger sediments in the same general area and that the basalt is as thick as 77 feet. The basalt exposed at the land surface commonly forms a hard, resistant cap over the soft, easily eroded sediments of the Latah Formation.

The exposures of the semiconsolidated, fine-grained sediments of the Latah Formation in the study area are few and relatively small. The formation, of Miocene age, overlies the bedrock below an altitude of about 2,400 feet (Cline, 1969) and is both interbedded with and overlain by basalt of the same (Miocene) age.

Much of the northern part of the study area is mantled with the loess of the Palouse Formation of Pleistocene age. In most places, the material overlies the basalt and the Latah Formation; less commonly it also overlies the bedrock.

The Pleistocene glaciolacustrine deposits of the study area consist of clay, silt, sand, and some interbeds of gravel; they were laid down in a large lake formed by the damming of the Spokane River by a glacier west of the study area. The deposits are exposed in the east-central part of the study area.

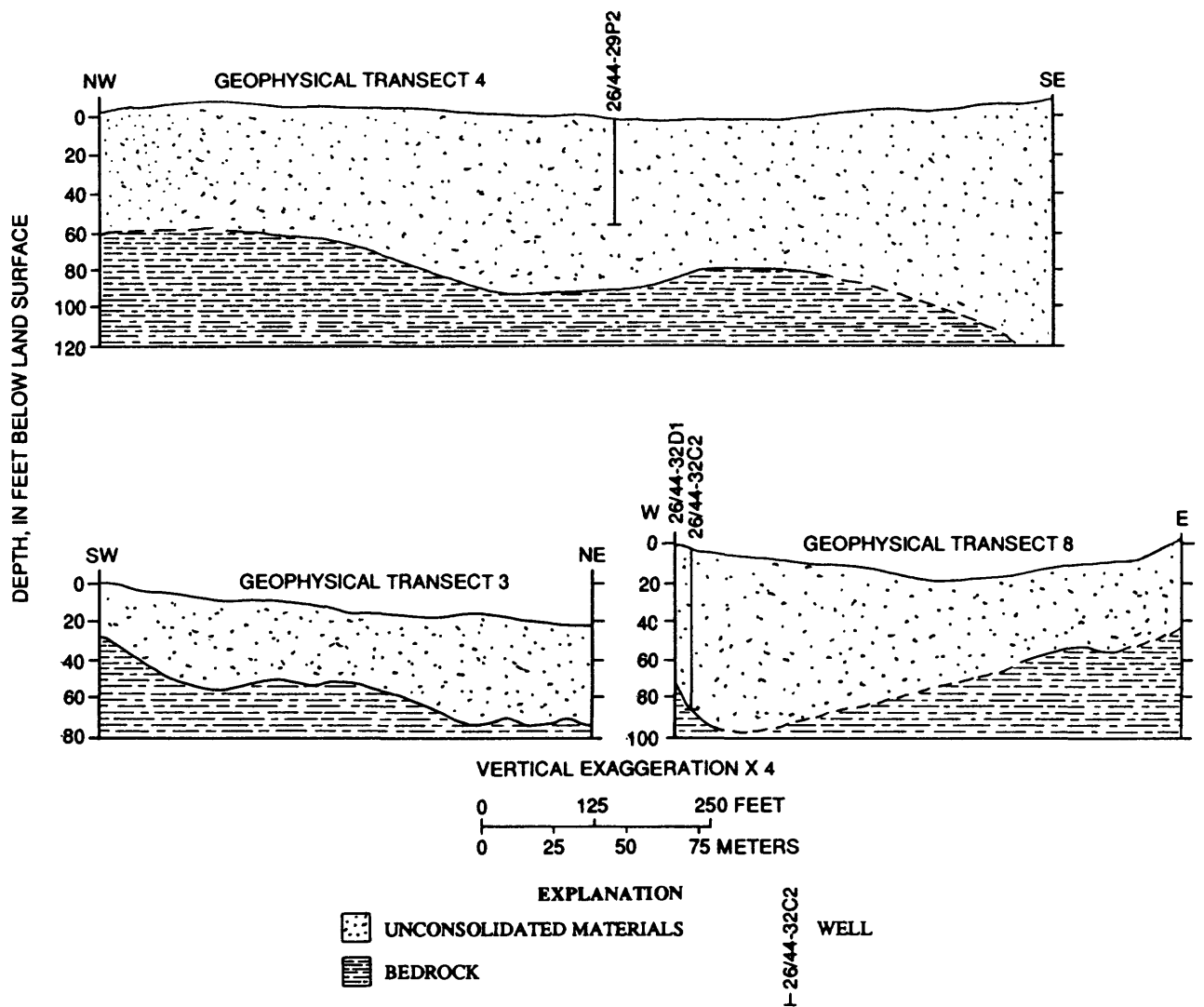


Figure 3.--Preliminary geologic sections based on geophysical transects. See figure 2 for location of transects.

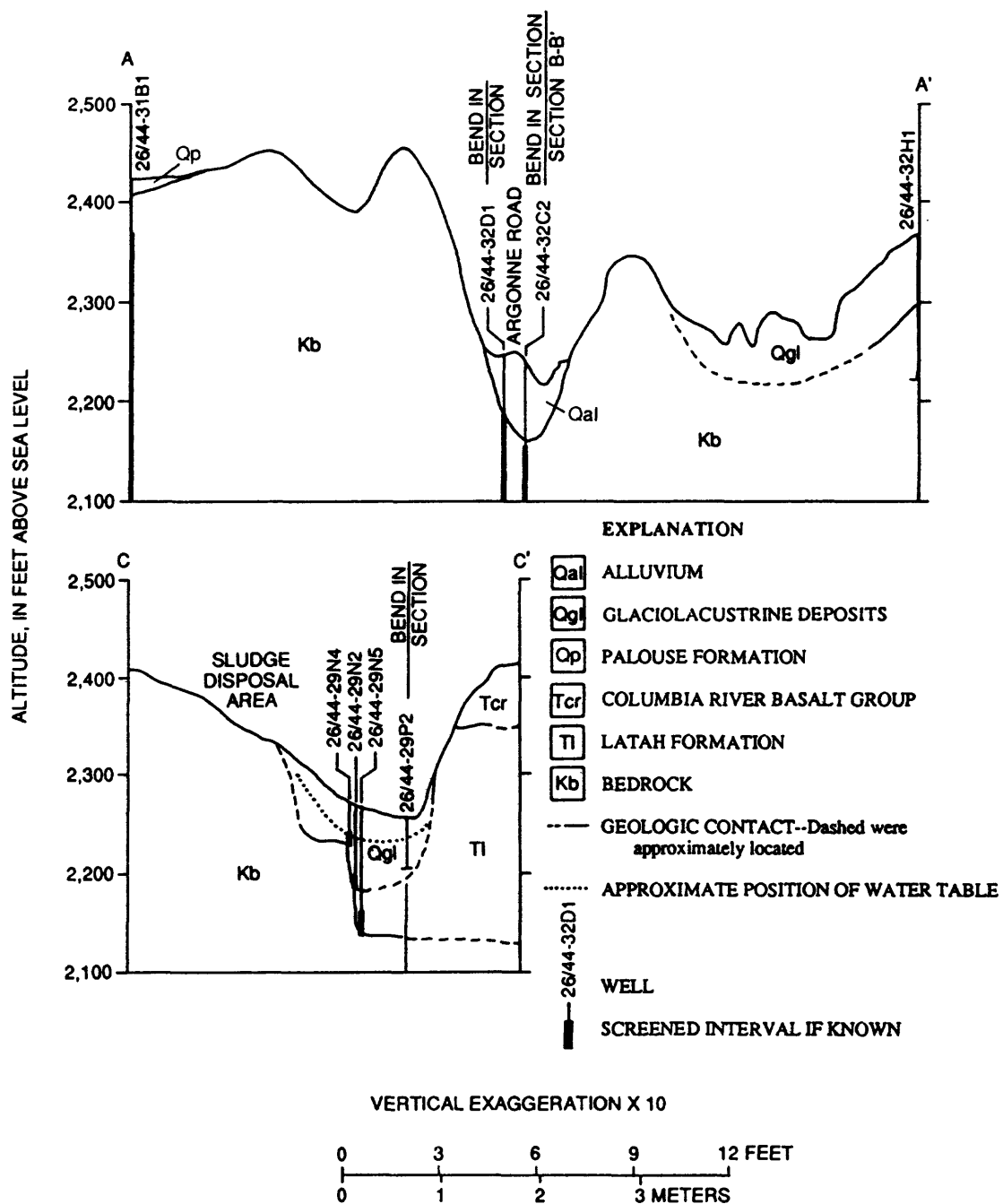


Figure 5.--Geohydrologic sections A-A' and C-C'. See figure 4 for location of sections.

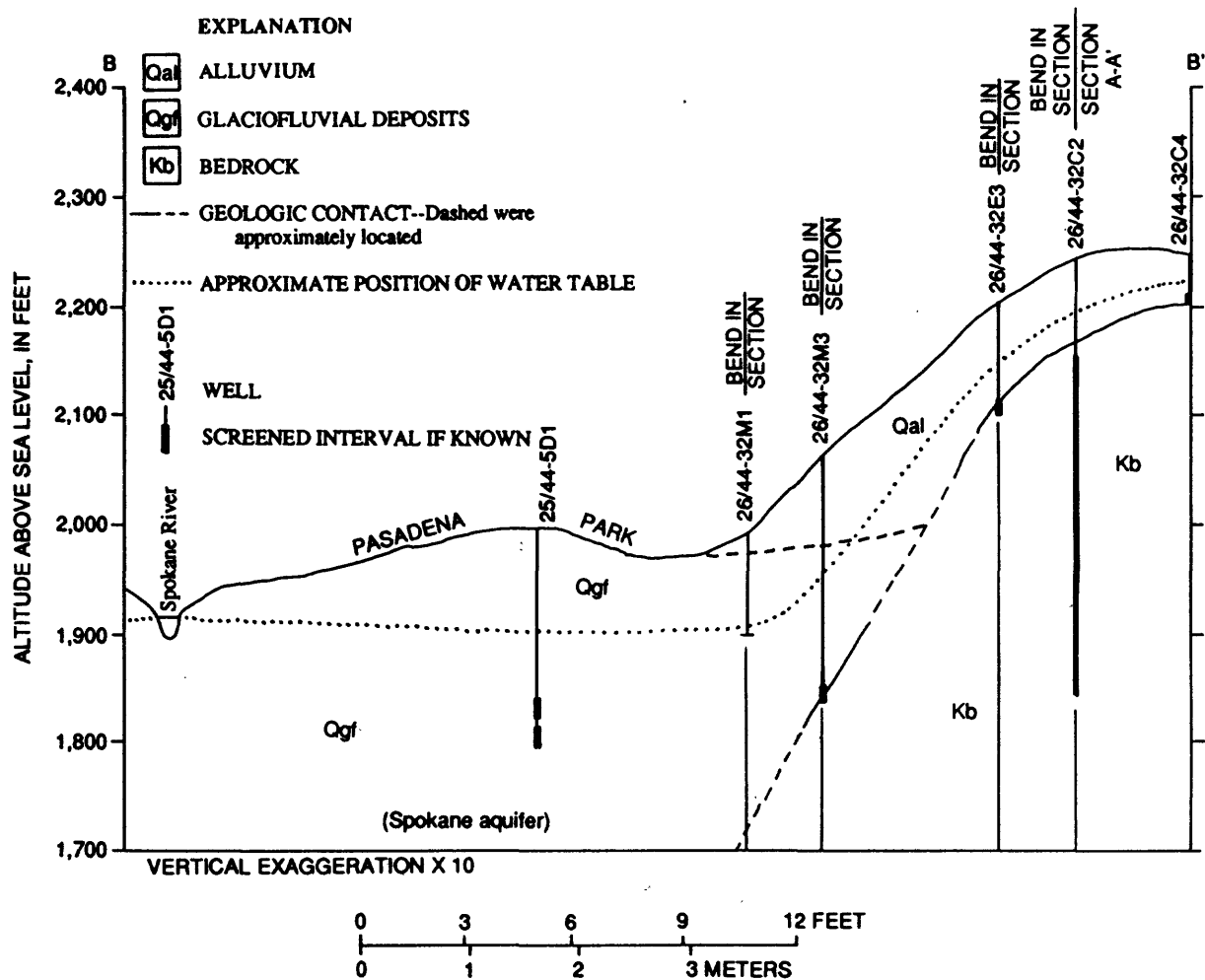


Figure 6.--Geohydrologic section B-B'. See figure 4 for location of section.

Table 1.--Lithologic and hydrologic characteristics of rock units in the study area
(modified from Cline, 1969)

Period	Epoch	Rock unit	Lithologic characteristics	Hydrologic characteristics
QUATERNARY	HOLOCENE	Alluvium	Silt, sand, gravel, and lesser amounts of colluvium	Moderately productive aquifer. Well yields range from 5 to 100 gal/min (gallons per minute)
		Glacio-fluvial deposits	Poorly sorted, coarse-grained sand, gravel, and, in some places, boulders	Highly productive aquifer. Yields from the Spokane aquifer are commonly several thousand gallons per minute
	PLEISTOCENE	Glacio-lacustrine deposits	Well sorted, fine-grained clay and silt, with lesser amounts of sand and gravel	Yields are highly variable; from 5 to 600 gal/min. Highest yields are from sand or gravel lenses
		Palouse Formation	Wind-blown loess, consisting of clay, silt, and fine sand	Yields are small and erratic. Where saturated, yields up to 20 gal/min from sand lenses
TERTIARY	MIOCENE	Columbia River Basalt Group	Lava flows of dense, dark basalt	Yields up to 35 gal/min from joints, fractures, and rubbly zones at tops and bottoms of flows
		Latah Formation	Generally fine-grained claystone and siltstone, with thin lenses of sand or gravel that intertongue with basalt flows	Yields up to 35 gal/min from lenses of coarse sand or gravel
CRETACEOUS	LATE CRETACEOUS	Bedrock	Granitic rocks, chiefly granodiorite and quartz monzonite. Older metamorphic rocks locally	Mostly impermeable, but yields up to 35 gal/min from fractures and weathered surfaces

During Pleistocene time, a major channel (the Spokane Valley, fig. 1) was cut into the bedrock at the south end of the study area by the catastrophic outburst of a large glacier-dammed lake to the east (Bretz, 1959). The channel subsequently was filled with coarse glaciofluvial deposits consisting of poorly sorted sand, gravel, and, in places, boulders. Although the sediments are as much as 700 feet thick in the deeper parts of the Spokane Valley, the deposits in the study area occur near the mouth of the ravine and are much thinner.

As shown in section C-C' (fig. 5), the bedrock surface in the headwater slopes northeast, and the ridge that makes up the eastern drainage divide in that area is capped by basalt. Data from wells 29N2, 29N4, and 29N5 indicate that the bedrock surface in that area has much relief, possibly as a result of faulting. The geologic unit at the land surface in the headwater area beneath an altitude of about 2,325 feet has been shown as Quaternary glaciolacustrine deposits in figure 4, although locally the unit contains much sand and gravel and lithologically resembles glacial till. This surficial unit may be underlain by the Palouse or Latah Formations in the headwater area.

The alluvium-filled ravine is flanked by ridges composed of bedrock (section A-A', fig. 5). The axis of the trough in which the alluvium has been deposited lies slightly west of the present-day position of the intermittent stream channel. Near the mouth of the ravine, some of the unconsolidated glaciofluvial deposits that make up the Spokane aquifer appear to extend northward into the ravine and to underlie the alluvium (section B-B', fig. 6).

Occurrence of Ground Water

The geologic units in the study area differ markedly in hydrologic characteristics and water-yielding capabilities (table 1). Physical and hydrologic data for selected wells in the study area are presented in table 2. Lithologic data for many of these selected wells are presented in table 3.

The coarse-grained glaciofluvial deposits of the Spokane Valley are the most permeable and productive rock units in the study area; it is these rocks that make up the highly productive Spokane aquifer. Yields to wells of several hundred to several thousand gallons per minute from this aquifer are common. Most of the ground water in the aquifer enters from the east, flows along the axis of the valley, and leaves the aquifer many miles to the west, largely as flow into the Spokane and Little Spokane Rivers. The quantity of water flowing through the Spokane aquifer has been estimated by Bolke and Vaccaro (1981) to be in excess of 243,000 gal/min (more than 8,000 acre-ft/d). The hydraulic conductivity at well 26/44-32M3, installed as part of this study and thought to be finished in the edge of the Spokane aquifer, is 55 ft/d. This value was calculated using a slug-test method described by Bouwer and Rice (1976).

Table 2.--Physical and hydrologic data for selected wells and piezometers in the study area

[H, domestic; O, observation; P, public supply; U, unused; L, driller's log available; Q, water-quality data available; D, destroyed.]

Well no.	Land-surface altitude (feet above mean sea level)	Well depth (feet)	Casing diameter (inches)	Water use	Water level ¹ (feet below land surface)	Date measured	Remarks
25/44-5D1	1,996	202	16	P	² 95	2-10-87	L,Q
-5K1	1,958	234	16	P	² 49	2-10-87	L
-6A2	1,982	155	16	P	80.6	2-10-87	L
26/44-29L2	2,300	10	48	H	--	--	Q
-29M2	2,263	79	2	O	20.8	3- 2-87	L,Q
-29M3	2,267	60	6	H	22.7	3- 2-87	Q
-29N2	2,281	79	2	O	33.9	3- 2-87	L,Q
-29N3	2,302	60	2	O	20.4	3- 2-87	L,Q
-29N4	2,281	40	2	O	32.7	3- 2-87	L,Q
-29N5	2,281	116	2	O	35.1	3- 2-87	L,Q
-29P1	2,264	55	8	H	18.5	3- 2-87	Q
-29P2	2,260	55	6	U	16.2	3- 2-87	
-29P3	2,262	30	2	O	19.7	3- 2-87	L,Q
-31B1	2,425	505	6	H	--	--	L
-32C1	2,245	72	6	H	45.9	11-17-86	Q
-32C2	2,240	400	6	H	82.4	11-17-86	L,Q
-32C3	2,240	20	2	O	13.0	3- 2-87	L,Q
-32C4	2,253	47	2	O	27.4	3- 2-87	L,Q
-32D1	2,245	312	6	H	78.7	6-24-47	L,Q
-32E1	2,160	168	6	H	--	--	Q
-32E2	2,240	372	6	H	318.0	2-10-87	Q
-32E3	2,200	90	4	O	--	--	L
-32H1	2,365	140	6	U	--	--	L,D
-32M1	1,988	92	6	U	82.7	3- 2-87	
-32M3	2,060	223	4	O	106.0	3- 3-87	L,Q
-32N2	1,970	170	6	H	--	--	L,Q
-32P1	1,990	141	12	U	87.0	2-10-87	
-32Q1	1,988	148	8	P	82.5	2-10-87	L,Q

¹ Measured by steel or electric tape except as noted.

² Measured by airline.

Table 3.--Lithologic logs of selected wells and piezometers

Local well number	Altitude (feet)	Material	Thickness (feet)	Depth (feet)
25/44-5D1	1,996	Topsoil	1	1
		Gravel	42	43
		Sand	37	80
		Sand and clay	40	120
		Sand	30	150
		Sand and clay	30	180
		Sand	22	202
25/44-5K1	1,958	Gravel and boulders	39	39
		Gravel	40	79
		Clay	6	85
		Sand	102	187
		Sand and gravel	47	234
25/44-6A2	1,982	Topsoil	1	1
		Gravel and sand	124	125
		Sand and gravel	31	156
		Sand and silt	4	160
26/44-29M2	2,263	Sandy soil	3	3
		Fine sand	10	13
		Sandy clay	31	44
		Clayey sand	12	56
		Clay with rock chips	23	79
		Clayey silt	6	6
26/44-29N2	2,281	Gravel	5	11
		Sandy gravel	27	38
		Sand and gravel	2	40
		Sandy clay	39	79
		Silty soil	5	5
		Silt	3	8
26/44-29N3	2,302	Clay silt	9	17
		Clayey sand	1	18
		Sandy clay	5	23
		Clayey sand	1	24
		Sand and gravel	4	28
		Clayey sand	6	34
		Sand and gravel	6	40
		Clay	20	60
		Topsoil	1	1
		Sand and gravel	34	35
		Weathered granite	5	40
26/44-29N5	2,281	Gravel	36	36
		Clayey gravel	21	57
		Gravelly clay	17	74
		Silt, sand, and clay	9	83
		White rock fragments	8	91
		Clay	4	95
		Sand and rock fragments	23	118
		Clay	8	126
		Rock fragments	6	132

Table 3.--Lithologic logs of selected wells and pizometers--Continued

Local well number	Altitude (feet)	Material	Thickness (feet)	Depth (feet)
26/44-29P3	2,262	Topsoil	7	7
		Sand	23	30
		Rock	1	31
26/44-31B1	2,425	Topsoil	2	2
		Sand	18	20
		Sand and boulders	28	48
		Decomposed granite	457	505
26/44-32C2	2,240	No record	85	85
		Granite	276	361
26/44-32C3	2,240	Silt	4	4
		Gravel	11	15
		Sand	5	20
		Rock	1	21
26/44-32C4	2,253	Silty topsoil	5	5
		Sand	42	47
		Rock	--	47
26/44-32D1	2,245	Sandy topsoil	6	6
		Sand	44	50
		Granite	262	312
26/44-32E3	2,200	Sand and gravel	24	24
		Gravel and sand	26	50
		Clay and gravel	29	79
		Weathered granite	6	85
		Granite	5	90
26/44-32H1	2,365	Sand	65	65
		Decomposed granite	75	140
26/44-32M3	2,060	Sand and gravel	45	45
		Clayey sand	29	74
		Clayey gravel	6	80
		Gravelly clay	14	94
		Gravel and rock fragments	22	116
		Rock fragments	9	125
		Gravel and silt	15	140
		Silt and gravel	20	160
		Coarse gravel	58	218
		Granite	5	223
26/44-32N2	1,970	Topsoil	--	--
		Sand and gravel	--	--
		Sand	8	170
26/44-32Q1	1,988	Sand, gravel, boulders	52	52
		Sand	96	148

The granitic bedrock is mostly impermeable. The unit has local secondary permeability, however, and ground water moves through the uppermost part of the bedrock, which is fractured, faulted, and decomposed by weathering. Although the bedrock does supply up to 35 gal/min of water to wells locally, the unit as a whole is neither a dependable nor a productive source of ground water.

The aquifer of chief concern to this study is the alluvial silt and sand, and weathered granite that composes the unconfined aquifer within the wooded ravine. It is this aquifer that was found to contain organic solvents in 1981. Only two wells (26/44-29P3 and 32C4) finished in the alluvium could be slug-tested for hydraulic conductivity. The two values (2.11 and 2.52 ft/d) are significantly lower than that at well 29/44-32M3, finished in the coarser deposits of the Spokane aquifer, but they are within the range (1.5 to 15 ft/d) estimated for the alluvium by Dion (1987). Hydraulic conductivity values as measured by slug tests, however, may not be representative of the aquifer in general. At best, slug tests typically measure hydraulic properties in a small volume of the aquifer adjacent to the well screen or sand pack.

The three domestic-supply wells that contain organic solvents are near the upper end of the ravine and draw water from the unconfined alluvium and (or) the top of the fractured granitic bedrock. All that is known about well 32C1 (fig. 2) is that it is 72 feet deep and draws water from either the alluvium or the granite. Well 32D1 is 312 feet deep, has been cased into the granite since first drilled in 1947, and taps three fractures within the granite.

Well 32C2 was originally drilled and cased to 70 feet; the aquifer tapped at that time is unknown. In 1961, the well was deepened to 361 feet and the casing was set in the top of the granite and perforated opposite a water-bearing horizon in the alluvium. Shortly after the discovery of solvents in this well and wells 32C1 and 32D1, well 32C2 was deepened to 400 feet and the openings to the alluvial aquifer were sealed.

Exploratory drilling has indicated that the headwater area is underlain by generally fine-grained sediments that contain lenses of coarse sand and gravel. Five wells installed in these sediments were slug-tested to determine hydraulic conductivity. The resulting values ranged from 0.03 to 0.57 ft/d, and are typical of values given by Todd (1980, p. 72) for similar geologic materials.

The ground-water gradient in the study area (figs. 6 and 7) is relatively steep (0.089 ft/ft) in the alluvium of the ravine, but much gentler in the headwater area and in the Spokane aquifer. The general ground-water flow directions are southward in the headwater area and ravine, and westward in the Spokane aquifer.

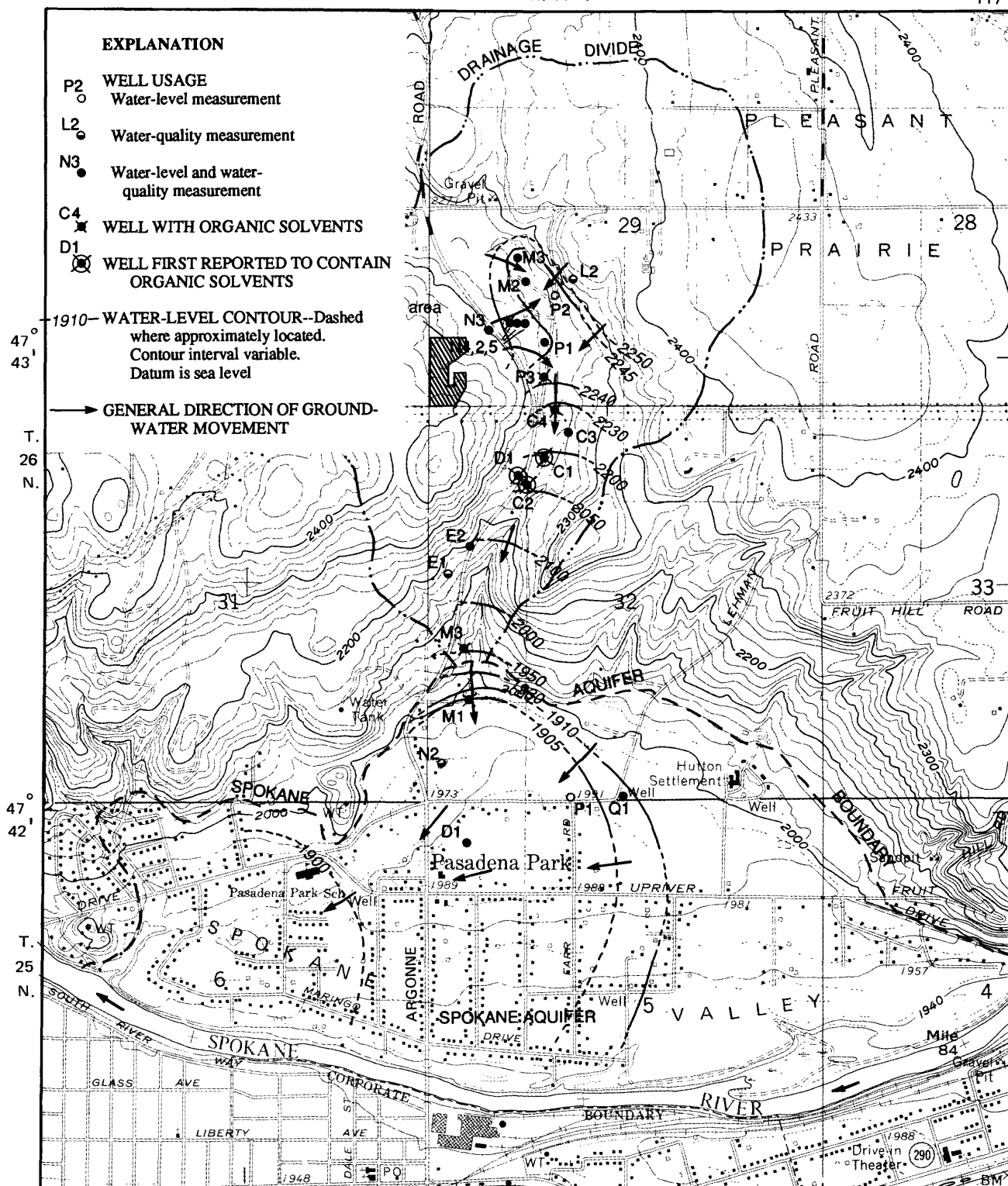


Figure 7.--Water-level contours and wells with organic solvents in the study area, March 1987.

In summary, lithologic and water-level data collected as part of this study indicate that the alluvial aquifer in the wooded ravine is connected physically and hydraulically to the Spokane aquifer. The materials encountered in drilling test well 26/44-32M3 (fig. 2 and table 3) indicate that at this location coarse sand and gravel, characteristic of the Spokane aquifer, extend into the ravine and are overlain by alluvium that is characteristic of the aquifer in the ravine. Similarly, water levels in this and nearby wells indicate that ground water in the alluvial aquifer is tributary to the much larger ground-water body of the Spokane aquifer (see fig. 7).

PRESENCE OF ORGANIC SOLVENTS IN GROUND WATER

Background water-quality conditions in the region are summarized by Dion (1987). Ground water in the study area is typical of the region: calcium bicarbonate type, moderately to very hard, and slightly alkaline. Locally, nitrate concentrations are higher than the recommended level of 10 mg/L (milligrams per liter) established by the Washington State Department of Social and Health Services (1978). The cause of these elevated nitrate concentrations is not known, but may be related to the use of septic tanks or to various agricultural practices.

The principal organic compounds found in the three domestic wells in 1981 are the following solvents. The abbreviations shown below will be used throughout the remainder of this report.

<u>Scientific name (Weast, 1975)</u>	<u>Common name</u>	<u>Abbreviation</u>
tetrachloroethene	Perchloroethylene ("perc")	PCE
trichloroethene	Trichloroethylene	TCE
1,1,1-trichloroethane	Methyl chloroform	TCA
1,2- <u>trans</u> -dichloroethene	Acetylene dichloride	EDC

Nature of Organic Solvents

The organic solvents originally found in three domestic wells in 1981 are technically classified as halogenated aliphatic hydrocarbons. Aliphatic hydrocarbons are compounds in which the carbon atoms are joined in such a way as to form open chains, as opposed to the closed chains or rings of the aromatic compounds. The halogenated aliphatic hydrocarbons contain atoms of the halogen group, usually chlorine (Cl), in their molecular structure. Pettyjohn and Hounslow (1983) presented a concise and basic discussion of organic compounds and how they relate to ground-water contamination.

The four compounds of interest--PCE, TCE, TCA, and EDC--commonly are considered industrial solvents and are used extensively to clean grease and oil from industrial machines, to remove stains from clothes in dry cleaning, to clean pipes and drains connected to septic tanks (Viraraghvan and Hashem, 1986), in household cleaning products, and as refrigerants, fumigants, and anesthetics. Because all four compounds are similar in chemical composition and behavior, they will be discussed as a group and referred to as solvents.

The solvents are only slightly soluble in water (table 4) and are more dense (specific gravity 1.26 to 1.62) than water. Organic liquids more dense than water commonly are referred to as "sinkers." When present in amounts larger than can be dissolved, they commonly sink to the bottom of an aquifer or to a layer of lower permeability (Pettyjohn and Hounslow, 1983) as an immiscible non-aqueous phase liquid (NAPL). It is possible that a NAPL exists in the alluvial aquifer of the study area and serves as another source of solvents away from the original source, but determining this was not within the scope of this study. In general, the fate and movement of NAPL's are poorly understood. It is known, however, that a dissolved phase exists, as

evidenced by the solvent concentrations observed in several affected wells. Consequently, the discussion in this report is confined to the processes that influence the fate of organic solutes in ground water. These processes include advection, dispersion, sorption, volatilization, and chemical and biological transformation.

Table 4.--Physical and chemical characteristics of organic solvents and water (taken in large part from Callahan and others, 1979; U.S. Environmental Protection Agency, 1985; and Hunt and others, 1988)

	Water	Halogenated aliphatic hydrocarbon			
		Tetrachlo- roethene (PCE)	Trichlo- roethene (TCE)	1,1,1- trichlo- roethane (TCA)	1,2- trans - dichlo- roethene (EDC)
Chemical formula	H_2O	$\text{Cl}_2\text{C}=\text{CCl}_2$	$\text{ClHC}=\text{CCl}_2$	$\text{H}_3\text{C}-\text{CCl}_3$	$\text{ClHC}=\text{CHCl}$
Molecular weight	18	166	131	133	97
Specific gravity	1.00	1.62	1.46	1.32	1.26
Melting point ($^{\circ}\text{C}$)	0	-23	-73	-30	-50
Boiling point ($^{\circ}\text{C}$)	100	121	87	74	48
Vapor pressure at 20 $^{\circ}\text{C}$ (torr)	18	14	58	96	200
Solubility in water (milligrams per liter)	--	140	1,100	720	6,300
Log of octanol/water partition coefficient	--	2.88	2.29	2.17	1.48
Odor threshold in water (micrograms per liter)	--	300	500	--	--

Advection is the process by which solutes are transported by the motion of flowing ground water. In the absence of other influences, these solutes would be expected to travel at the same rate (velocity) as the ground water in which they are dissolved (Keely and others, 1986).

Field and laboratory evidence indicate that dissolved solvents mix both longitudinally and transversely as they move with the ground water. This process, called dispersion, together with advection, results in the formation of a solvent plume downgradient of a source. There is a progressive dilution of the solvents in the plume and an attenuation of concentration peaks downgradient of the source. Existing data are insufficient to quantify the effects of dispersion in the study area. As in most field situations, however, dispersion in the direction of flow is likely to be greater than dispersion transverse to the flow (Mackay and others, 1985).

Because the organic solvents are hydrophobic (Roberts and others, 1982), their sorption to solid aquifer materials would generally be expected; this sorption would tend to retard their movement through the aquifer. However, Pettyjohn and Hounslow (1983) stated that low-molecular-weight hydrocarbons, such as TCE, are sorbed only by soils that contain appreciable amounts of organic matter. It is unknown whether the alluvium or bedrock in the Argonne Road area contain amounts of organic matter sufficient for partitioning-related retardation.

The distribution, or partitioning, of a compound between solid organic matter and water in an aquifer can be approximated by the octanol/water partition coefficient of that compound (Newsom, 1985). The octanol/water partition coefficient is defined as the ratio of the solubility of the compound in octanol, an alcohol, to its solubility in water. Although the partition coefficients shown in table 4 for the solvents of concern are considered low compared with many other organic compounds, the movement of the solvents through an aquifer would be slowed substantially if organic matter were present in the aquifer. Wilson and others (1981) found that halogenated aliphatic hydrocarbons moved readily through fine sand such as that found in the alluvial aquifer near Argonne Road. The same investigators postulated that this may account for the frequent occurrence of these compounds in ground water.

The volatilization of most industrial solvents at land surface can be rapid; the solvents in question near Argonne Road have low molecular weight, high vapor pressure, and low boiling point (table 4). Even when dissolved in water, they evaporate appreciably more rapidly than the water. This may explain the almost ubiquitous presence of these compounds in the atmosphere in minute quantities (McConnell and others, 1975). Callahan and others (1979) reported that, once transported to the troposphere, the compounds are rapidly photooxidized in the presence of sunlight.

Volatilization, however, proceeds at a much slower rate in the subsurface. According to Pettyjohn and Hounslow (1983), the rate of volatilization is greatly reduced when the compounds lie deeper than a foot below land surface. Indeed, Wilson and others (1981) found that, compared with volatilization from water, soil inhibited the process by an order of magnitude.

Organic solvents can be transformed or degraded into other compounds by numerous chemical and biological mechanisms. As pointed out by MacKay and others (1985), chemical reactions that generally affect organic solvents in water, such as hydrolysis and oxidation, may not be significant in a ground-water environment, and most chemical reactions occurring in the ground-water zone are likely to be slow compared with transformations mediated by microorganisms. Much uncertainty exists about whether halogenated aliphatic hydrocarbons in particular are transformed or degraded biologically. The consensus of opinions seems to be that microbial degradation does not occur aerobically, and that if it occurs anaerobically, it does so at a slow rate (Bouwer and others, 1981; Newsom, 1985). Parsons and others (1984) have observed that PCE and TCE, under carefully controlled laboratory conditions, are biotransformed to EDC and other compounds. The presence of EDC in study wells, therefore, could be construed as evidence of the biotransformation of PCE and (or) TCE, instead of the direct introduction as EDC (Canter and others, 1987, p. 165).

Extent of Organic Solvent Plume

The lateral extent of the plume of solvents in the aquifer was determined by sampling selected wells in November 1986 and March 1987 and analyzing the waters for the presence of volatile organic compounds, including the four present in the three domestic wells (26/44-32C1, 32C2, and 32D1) originally found to contain solvents in 1981. The selection of wells was based on the generalized ground-water flow directions depicted in figure 8. The water samples also were analyzed for concentrations of major cations and anions, including chloride and nitrate. These constituents generally are chemically conservative and commonly serve as indicators of pollution from the disposal or improper handling of sewage and other types of organic wastes (Baedecker and Apgar, 1984). The locations of sampled wells are shown in figure 7; the results of chemical analyses of samples collected in November 1986 and March 1987 are presented in tables 5 and 6, respectively. The drinking-water guidance levels for PCE and TCE, as suggested by the World Health Organization (1984), are 10 and 30 $\mu\text{g/L}$ (micrograms per liter), respectively.

Organic solvents were detected in several wells both upgradient and downgradient of the three wells originally found to contain the solvents (fig. 7). The most upgradient well in the study area found to contain solvents in November 1986 was 26/44-29N4, located east of the sludge-disposal area, the suspected source of the solvents. Well 29N4 is 40 feet deep and extends to bedrock. However, well 29N3, located even closer to the disposal area, showed no sign of the solvents. Well 29N3 is 60 feet deep and is finished about 5 feet above bedrock. When well 29N4 was resampled in March 1987, no solvents were found, despite the fact that the well water contained almost 600 $\mu\text{g/L}$ of PCE four months previously (table 5). An attempt to resolve this apparent anomaly by subsequent sampling in April 1988 was unsuccessful. At that time, the water level in well 29N4 was below the bottom of the well and could not be sampled. In addition, the sample taken from well 29P3 in April 1988 contained 467 $\mu\text{g/L}$ of PCE and 244 $\mu\text{g/L}$ of EDC; when originally sampled in November 1986, no organic solvents had been detected in well 29P3. The reason for these apparent anomalies in concentrations is not known. A possible explanation is a substantial change in ground-water flow conditions between the various sampling periods, resulting in vastly different solvent concentrations. The resolution of these problems would require a considerable amount of resampling, an effort that would delay the publication of the other findings of this study and is therefore considered unjustified.

The most downgradient well in the study area known to contain a solvent was 32M1, an unused well 92 feet deep and finished near the water table in the Spokane aquifer. The concentration of the one solvent (PCE) found in the well in March 1987 was only 1.4 $\mu\text{g/L}$, suggesting one of the following explanations: the compound was diluted within the Spokane aquifer; the solvent plume had just arrived at well 32M1; most of the plume had sunk beneath the intake of the well; or the small concentration of solvent detected actually originated from the Spokane valley and not the alluvial aquifer.

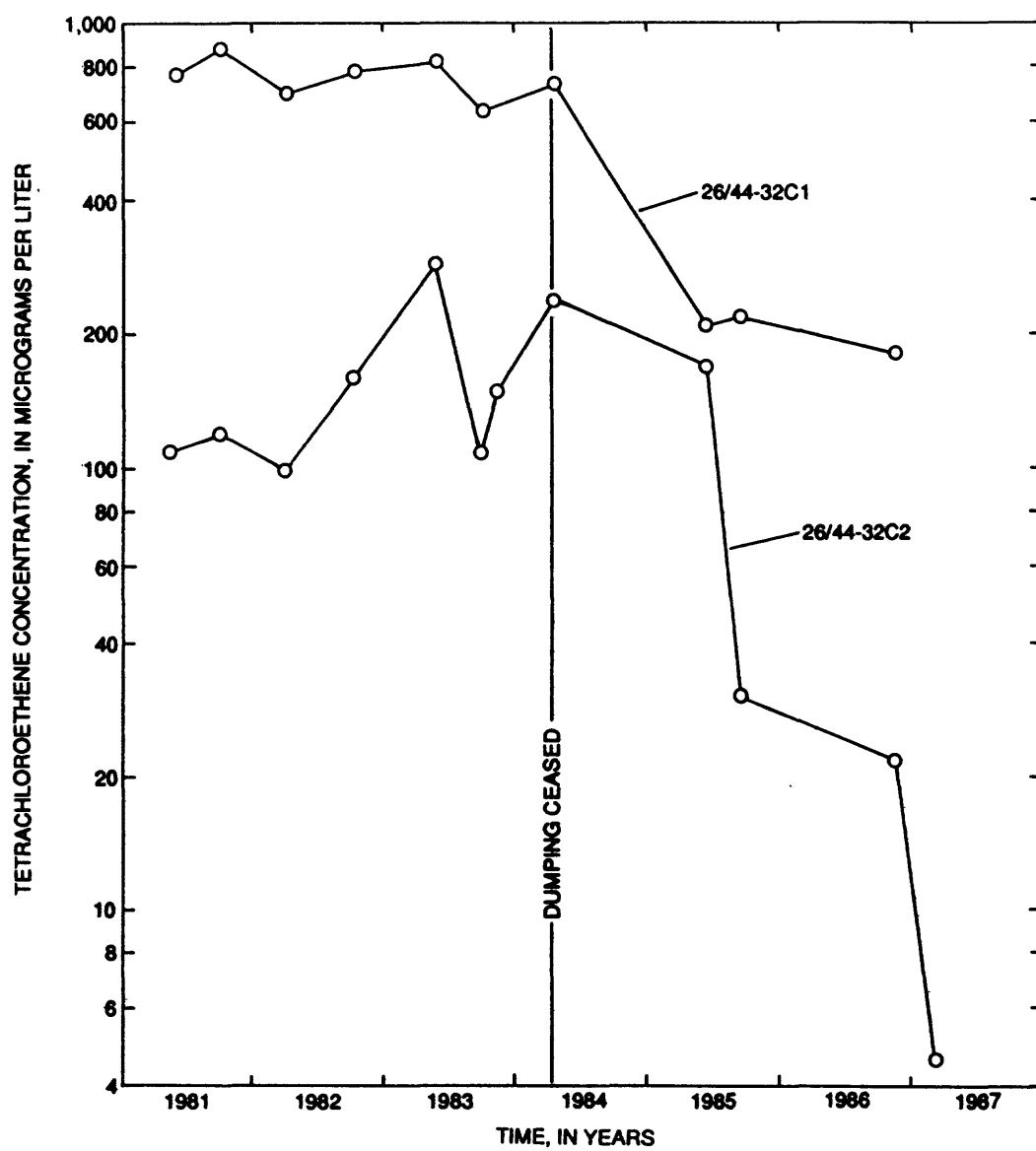


Figure 8.--Tetrachloroethene (PCE) concentrations in selected wells.

Table 5.---Ground-water quality in selected wells and piezometers, November 18-19, 1986

[All quantities are dissolved and expressed in milligrams per liter unless otherwise stated; μ g/L, micrograms per liter. PCE, tetrachloroethene; TCE, trichloroethene; TCA, 1,1,1-trichloroethane; EDC, 1,2-trans-dichloroethene; ND, not detected]

Well 26/44-																
	29L2	29M2	29M3	29N2	29N3	29N4	29N5	29P1	29P3	32C1	32C2	32C3	32C4	32D1	32M3	
Specific conductance (microsiemens per centimeter)	358	224	213	148	174	193	269	534	812	575	350	380	605	380	600	
pH (units)	6.8	7.7	7.0	6.9	7.4	6.9	7.0	6.8	6.8	7.3	7.6	8.0	7.2	7.3	7.2	
Temperature (°C)	10.3	--	8.3	--	--	--	--	10.2	--	9.7	10.2	--	--	11.8	--	
Hardness (as CaCO ₃)	160	100	90	50	59	74	100	250	170	280	140	240	320	160	280	
Alkalinity (as CaCO ₃)	92	110	56	52	72	64	130	130	320	220	110	190	250	822	220	
Sulfate	22	.3	18	8.5	4.3	17	19	25	19	19	19	12	25	28	26	
Chloride	12	1.7	3.8	1.8	.8	2.0	4.2	22	3.1	18	7.3	4.0	23	11	17	
Nitrite plus nitrate (as N)	12	.02	6.6	.00	.03	.20	.69	22	6.4	8.2	7.6	.07	8.0	13	7.5	
Total phosphorus	.09	.02	.10	.01	.01	.22	.01	.06	.02	.01	.05	.12	.01	.03	.02	
Organic carbon	3	2	2	2	2	2	3	2	6	5	1	9	7	2	8	
PCE (µg/L)	ND	ND	ND	ND	ND	592	ND	ND	ND	180	ND	ND	167	ND	122	
TCE (µg/L)	ND	ND	ND	ND	ND	78	ND	ND	ND	10	22	ND	15	1.5	8.8	
TCA (µg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
EDC (µg/L)	ND	ND	ND	ND	ND	420	ND	ND	ND	64	3.2	ND	88	ND	32	

Table 6.--Ground-water quality in selected wells and piezometers, March 3-4, 1987

[All quantities are dissolved and expressed in milligrams per liter unless otherwise stated; $\mu\text{g/L}$, micrograms per liter. PCE, tetrachloroethene; TCE, trichloroethene; TCA, 1,1,1-trichloroethane; EDC, 1,2-trans-dichloroethene; ND, not detected]

	Well 26/44-															
	5D1	29M3	29M4	29P1	32C2	32C4	32E1	32E2	32H1	32H3 ¹	32M3 ²	32N2	32N1	534	510	570
Specific conductance (microsiemens per centimeter)	245	252	187	540	295	738	240	252	900	590	570	510	534			
pH (units)	7.9	7.0	7.3	7.0	7.3	7.2	8.1	7.7	7.2	7.7	7.2	8.0	7.8			
Temperature ($^{\circ}\text{C}$)	11.4	7.7	--	9.6	9.7	--	--	6.2	--	--	--	9.8	12.3			
Hardness (as CaCO_3)	140	110	99	250	110	360	140	110	440	310	290	250	270			
Calcium	26	23	24	63	32	95	26	28	106	78	78	62	46			
Magnesium	12	7.8	4.4	13	3.5	17	13	5.3	23	15	15	16	29			
Sodium	4.4	10	14	16	22	14	4.3	14	10	12	12	8.9	13			
Potassium	2.1	2.7	1.3	3.5	.9	3.2	2.1	.9	13	3.2	3.1	2.6	4.6			
Alkalinity (as CaCO_3)	111	70	75	136	110	264	112	106	337	231	229	181	161			
Sulfate	13	19	17	26	18	31	14	19	100	24	22	22	26			
Chloride	3.0	5.7	1.7	20	5.9	28	2.8	3.2	28	19	19	17	50			
Nitrite plus nitrate (as N)	2.2	9.8	1.9	9.5	.08	24	6.3	5.0	2.3	2.1	.43	12	9.5			
Organic carbon	7.0	4.2	3.7	8.9	3.8	7.6	1.2	3.4	12	4.2	6.7	2.6	3.5			
PCE ($\mu\text{g/L}$)	ND	ND	ND	ND	4.6	279	ND	ND	1.4	136	72	ND	ND			
TCE ($\mu\text{g/L}$)	ND	ND	ND	ND	ND	18	ND	ND	ND	11	ND	ND	ND			
TCA ($\mu\text{g/L}$)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND			
EDC ($\mu\text{g/L}$)	ND	ND	ND	ND	ND	139	ND	ND	ND	35	19	ND	ND			

¹Top of water column.

²Bottom of water column.

The most downgradient well to contain significant concentrations of multiple organic compounds was well 32M3, a 223-foot well that is most likely finished in the edge of the Spokane aquifer (see fig. 6). This well is open (screened) to the aquifer only in the lowermost 10 feet. Because of the relatively great depth of the well and height of the water column within it, in March 1987 the well was sampled both near the top of the water column, using a glass bottom-filling bailer, and near the bottom of the well, using a stainless steel point sampler that works on the suction principle. Concentrations of organic solvents near the top of the water column were approximately twice the concentrations at the bottom, opposite the well screen (table 6). The reason for this observation is unknown, but could be due to the use of different sampling devices (Pearsall and Eckhardt, 1987).

The extent of the ground-water body, and consequently of the plume, within the ravine is constrained by the geometry of the alluvial aquifer. However, data are insufficient to define the vertical and lateral variability of solvents within the ravine. The compound of highest concentration in this study, as in a previous study (Dion, 1987), was the solvent PCE. Unlike the previous study, no TCA was detected in this investigation.

A plot of selected chemical data (fig. 8) suggests both temporal and spatial trends. Concentrations of PCE in wells 32C1 and 32C2, two of the wells originally found to contain solvents, generally have decreased since dumping ceased in April 1984. This temporal decrease in concentrations, however, could be due to numerous factors other than the cessation of dumping alone.

Concentrations in well 32C1 have been consistently greater than in downgradient well 32C2. At first glance, this fact suggests a spatial trend in which concentrations closer to a source are higher than concentrations farther from the source (Keely and others, 1986). Such is not necessarily the case. Variations in solvent concentrations within a plume can be greater in the lateral and vertical directions than in the longitudinal. Because the shape of the PCE plume within the ravine is ill-defined, no definite conclusions can be made regarding differences in concentrations between wells of differing longitudinal (gradient) positions.

One of the objectives of this investigation was to determine the vertical extent of the solvent plume in the study area. This objective was not met, due largely to the relative thinness of the ground-water body in most of the locations where test wells were installed, and to the large number of wells (piezometers) that would have been required at locations where the ground-water body was relatively thick.

Source of Organic Solvents and Velocity of Ground Water

Ground water in the vicinity of the sludge-disposal area, the suspected source of solvents, flows generally eastward (fig. 7) through fine-grained sediments intercalated with sands and gravels. The water then flows southward through the somewhat coarser sediments of the alluvial aquifer in the ravine until it reaches the much coarser sediments of the Spokane aquifer. Solvents that originate as leachate in the disposal area, therefore, eventually would reach the Spokane aquifer. However, this does not prove conclusively that the sludge-disposal area is the source of the solvents observed, or that they would flow in exactly the same direction as indicated by the generalized ground-water contours (fig. 7). As pointed out by Keely and others (1986), if ground-water pathways are controlled by cleavage planes (faults) and fractures, the directions and rates of flow are not necessarily perpendicular to equipotential lines. It is probable that the preponderance of ground-water flow in the headwater area is through relatively thin layers of coarse sand and gravel that are separated by thicker and finer grained silts and clays. What does appear certain is that any wastes or leachates generated at the disposal area would eventually be carried in the general directions indicated in figure 7.

Other, less likely, possibilities also exist. For instance, some ground water probably flows westward and southwestward from the eastern edge of the headwater area, even though the bedrock surface in that area slopes eastward. Consequently, any solvents originating in that area also eventually would reach the Spokane aquifer. The investigation of such a hypothetical situation was not within the scope of this study, and the chance of such a situation existing, given existing land-use practices, is considered remote.

According to Baedecker and Apgar (1984), leachate from a conventional landfill contains elevated concentrations of several constituents, in particular alkalinity, chloride, nitrate, and organic carbon. Even though the suspected source of solvents, the septic-tank sludge-disposal area, is not considered a conventional landfill, leachate from that disposal area most likely would be high in alkalinity and concentrations of chloride, nitrate, and organic carbon. This fact might facilitate delineation of the plume of organic solvents and might also be used to determine the source of the leachate from a chemical standpoint. However, an examination of the chemical data generated as part of this study (tables 5 and 6) revealed no discernible pattern in the distribution of the constituents in question. In addition, no correlation was found between the concentrations of the selected constituents discussed above and those of the organic compounds (PCE, TCE, and EDC). There was also poor correlation between the concentrations of the organic compounds and those of dissolved organic carbon (see tables 5 and 6).

This study has confirmed that organic solvents dissolved in ground water have reached the Spokane aquifer; it also has shown that additional amounts of the same compounds occur in the alluvial aquifer and are moving toward the Spokane aquifer. The speed at which these compounds are moving, therefore, is of concern. In a previous study (Dion, 1987), the average linear ground-water velocity through the alluvial aquifer was calculated to range from 0.4 to 4.0 ft/d. That calculation was based on estimated values of hydraulic conductivity (1.5-15 ft/d), porosity (0.35), and water-table gradient (0.093 ft/ft).

The data collected in the current study allowed a refinement of only the gradient (to 0.089 ft/ft), and that small change had virtually no effect on the estimated ground-water velocity range. Observations from the current study can be used, however, to refine the velocity range that can be expected in the alluvial aquifer. This can be done by determining when the solvents first reached certain wells, a known distance apart, and calculating the velocity required for the solvents to travel that distance.

The assumption is made that the solvents first reached well 32C1, near the head of the ravine, in June 1981. At that time the owner and user of the well reported the possible contamination of his domestic water supply, based on odors observed. The presence of solvents was confirmed shortly thereafter by County and State health officials. Well 32M3, near the mouth of the ravine and 2,750 feet downgradient of well 32C1, already contained the solvents when first sampled in November 1986. In order for the compounds to have traveled that distance in the time observed, they would have had to travel at least 1.4 ft/d. Because it is not known when the solvents first reached well 32M3, the true velocity is most likely greater than the calculated value of 1.4 ft/d. The refined ground-water velocity range for the alluvial aquifer, therefore, is 1.4 to 4.0 ft/d.

Fate of Organic Solvents

The information presented above suggests that the dissolved phase of the organic solvents found in ground water near Argonne Road will not be significantly affected by volatilization or chemical activity; less is known about the likely effects of sorption and biotransformation. The process of dispersion, however, most likely would dilute the solvents with distance traveled and lead to the formation of a plume. Taken in aggregate, the properties of the aquifer materials and of the solvents may be varied enough to lead to slight differences in the attenuation, separation, and movement of the compounds in question. As a result, each compound could exist in an individual plume of unique dimensions.

The fate of solvents in ground water reaching the Spokane aquifer would be dictated most likely by regional flow conditions within the aquifer, the geometry of the aquifer, the physical and chemical characteristics of both the aquifer and solvents, and numerous other factors. Dissolved solvents would become greatly diluted upon entering the Spokane aquifer because of the relatively large volume of water contained within it. The diluted solvents then would follow the ground-water flow pattern of the receiving aquifer. Water-level data indicate that ground water in the part of the Spokane aquifer within the study area flows generally westward (fig. 7). Bolke and Vaccaro (1981) indicated that the ground-water flow velocities in the Spokane aquifer in that area are 10 to 50 ft/d, much faster than in the alluvial aquifer along Argonne Road. Assuming that the solvents became dispersed throughout the Spokane aquifer, wells finished in the aquifer would be susceptible to drawing ground water that contained solvents in concentrations considerably lower than those observed in the alluvial aquifer.

As part of this investigation, two wells in the Pasadena Park area, downgradient of the alluvial (ravine) aquifer, were sampled and the waters analyzed for the presence of organic solvents; none was found. There are several possible explanations for this lack of detection; the principal ones are:

- (1) the solvents may not yet have reached the sampled wells;
- (2) the solvents may have been diluted to concentrations below detection levels; and
- (3) the solvents may have taken a flow path that does not intersect the sampled wells.

It is estimated that about 2,600 people are dependent on domestic and public-supply wells in the Pasadena Park area; no ground-water sampling was done outside the Pasadena Park area. Those wells considered most likely to be affected by organic solvents from the Argonne Road area include domestic wells 26/44-32M1 and 32N2, and public-supply wells 25/44-5D1 and 6A2 (see fig. 2). Even though only two public-supply wells of the Pasadena Park water company are considered susceptible to solvent-laden ground waters from the alluvial aquifer, the entire population served by that utility was considered vulnerable because all the wells within the system pump into a common reservoir.

As mentioned previously, the organic solvents in question are only slightly soluble and considerably more dense than water (see table 4). It is likely, therefore, that in addition to the solvents dissolved in ground water, some of the same compounds may occur as an immiscible organic liquid phase near the base of the aquifer(s) and may follow different flow paths than that of the dissolved phase (Keely and others, 1986). In the Argonne Road alluvial aquifer, the relatively dense liquid phase would tend to flow along the alluvium-bedrock contact. Likewise, in the Spokane aquifer the liquid phase would tend to sink to the base of the coarse glaciofluvial deposits and migrate toward the deepest part of the trough in which these sediments were deposited. According to Newcomb and others (1953), the axis of the trough is toward the middle of the Spokane Valley, south of the study area (see figs. 1 and 2). In such a situation, only wells that extend to the bottom of the Spokane aquifer would be likely to yield water containing the organic solvents in question. Such wells are rare, both in the study area and elsewhere in the Spokane Valley. The wells sampled in the Pasadena Park area are relatively shallow, extend only a few feet below the water table, and are probably typical of Spokane aquifer wells in general.

ADDITIONAL STUDY NEEDS

This investigation has added to the knowledge gained in an earlier reconnaissance study (Dion, 1987), but an even better understanding of ground-water conditions in the Argonne Road area is needed. Additional seismic profiling and confirmatory test drilling would be useful in defining more accurately the configuration of the top of the bedrock. Such would be especially useful in the headwater area, upgradient of the wooded ravine.

Additional sampling of selected new and existing wells is needed to: (1) determine long-term temporal trends in the concentrations of the organic solvents; (2) reconcile discrepancies in some of the analytical results of this investigation, in particular the presence or absence of organic solvents in wells 26/44-29N4 and 29P3; (3) determine if the solvents are moving through the alluvial aquifer at a uniform velocity or in surges; and (4) monitor key wells in the Spokane valley for the presence of organic solvents from the Argonne Road area.

To pinpoint the source of organic solvents, multilevel test wells would need to be installed in the headwater area, especially upgradient of the most upgradient well known to contain the solvents. If ground-water flow in the headwater area is controlled by bedrock relief or stratigraphic heterogeneity of the overlying sediments, a large number of test wells would be needed to define the resulting plume of solvents and thereby pinpoint their definite source. Data obtained from sampling the new and existing wells probably would shed light on the relations between the organic compounds in question and those more common constituents, such as chloride and nitrate, known to be contained in leachate from landfills. This chemical knowledge, combined with the lithologic and hydrologic information gained by installing the new wells, would provide yet another tool to aid in the detection of the source of the organic solvents.

SUMMARY AND CONCLUSIONS

In the spring of 1981, three domestic wells near the head of a wooded ravine along Argonne Road near Spokane were found to contain the organic solvents tetrachloroethene, trichloroethene, 1,1,1-trichloroethane, and (or) 1,2-trans-dichloroethene. The suspected source of the solvents was a 40-acre septic-tank sludge-disposal area about 0.3 mile northwest of the wells. The solvents were also found in samples from several other wells in the area, but solvent concentrations in at least two wells have decreased since sludge disposal ceased in April 1984. A major concern was that the solvent-laden aquifer in which the domestic wells were completed could be in hydraulic connection with the highly productive Spokane aquifer to the south, which supplies numerous domestic and public-supply wells and which has been accorded "sole source" status.

The ravine along Argonne Road consists of an alluvium-filled trough cut into granitic bedrock. An unconfined aquifer is present at the base of the alluvium and at the fractured and weathered top of the granite. Water in this alluvial aquifer moves southward at an estimated velocity of from 1.4 to 4.0 ft/d and discharges to the Spokane aquifer.

It is unlikely that the dissolved phase of the solvents in the ground water would be significantly affected by volatilization or chemical activity. However, the solvents could be diluted (mixed) with native ground water or their migration retarded by partitioning onto organic matter. The occurrence and effects of biotransformation are largely unknown.

Even though the organic solvents have reached the Spokane aquifer, they were not detected in two wells in that aquifer. The Spokane aquifer wells likely to be affected in the future by solvent-laden ground water from the alluvial aquifer are few in number but may serve as many as 2,600 people. In addition to the solvents dissolved in ground water, some of the same compounds may occur as a nonaqueous phase liquid (NAPL) near the base of the aquifer(s), following different flow paths than that of the dissolved phase and serving as a source of solvents to the dissolved phase.

The results of the study do not confirm the sludge-disposal area as the source of the organic solvents. However, the study data indicate that wastes or leachates generated at the disposal site would flow to the alluvial aquifer and eventually to the Spokane aquifer. This indirect evidence as to the source of solvents is not corroborated by water-quality data. No discernible pattern was observed in the concentrations of those constituents, such as alkalinity, chloride, nitrate, and organic carbon, that would be expected to be found in large concentrations downgradient of a sludge-disposal site.

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