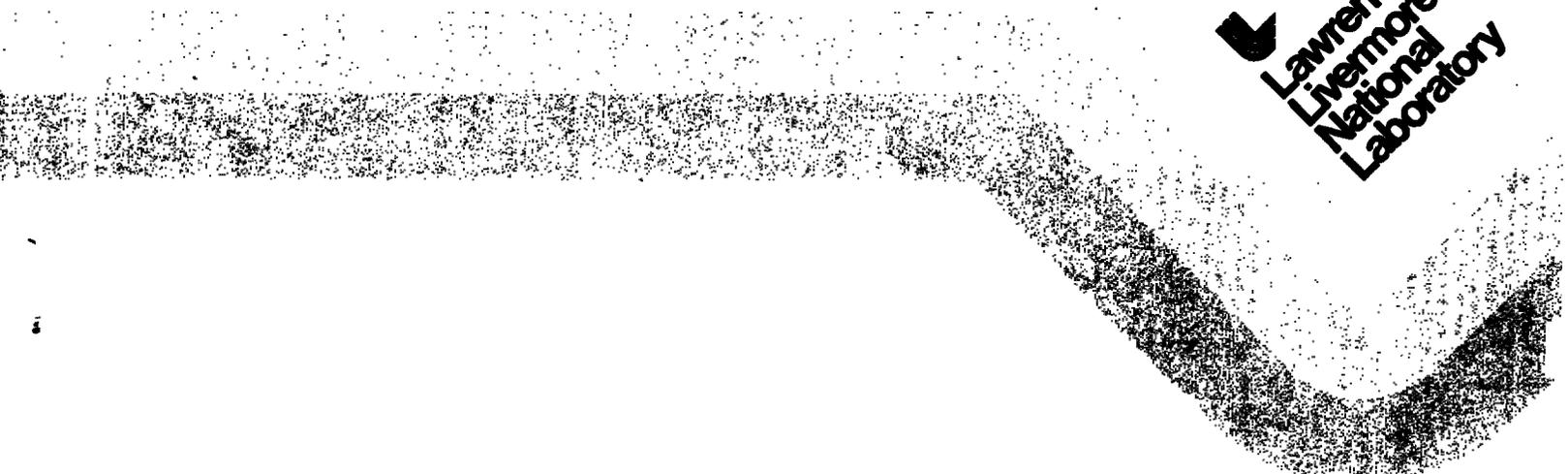


# **Ground-Water Quality and Movement at Lawrence Livermore National Laboratory**

**Randolph Stone  
Michael R. Ruggieri**

**December 1, 1983**



**Lawrence  
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**Manuscript date: December 1, 1983**

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# Ground-Water Quality and Movement at Lawrence Livermore National Laboratory

## Abstract

This report is an extension of earlier work in evaluation of the potential for contamination of the saturated ground-water system at Lawrence Livermore National Laboratory (LLNL). The objectives were to complete the sampling and analysis of water from observation wells at LLNL and to estimate the shallow areal ground-water flow speed for various portions of the LLNL site. Sampling and analysis of water from 13 observation wells at LLNL was completed. A series of field and laboratory hydraulic aquifer tests provided estimates of the hydraulic conductivity and effective porosity of the alluvial aquifer beneath LLNL. These estimates were the basis for calculating ground-water flow speeds beneath LLNL. All water samples tested contained tritium well below the limit for drinking water. The water from a well in the northeastern part of the site had about two times the nitrate concentration allowed in drinking water. Two wells contained trichloroethylene (TCE) in concentrations above the suggested drinking water limit. Two wells produced water with tetrachloroethylene (PCE) concentrations above the suggested drinking water limit. Water from four wells contained detectable concentrations of chloroform. Ground-water flow speeds in shallow alluvium at LLNL were estimated to be between 1 and 42 m/yr. PCE-contaminated ground water may move offsite in 10 months to 3 years from a contaminated well in the southwest part of the site, if it has not already done so. Elsewhere, chlorinated hydrocarbons in ground water will likely take 11 to 550 years to move offsite.

## Introduction

Operations at the Lawrence Livermore National Laboratory (LLNL) in the southeastern portion of the Livermore Valley in California involve the generation, handling, processing, storage, and transportation of materials which constitute potential sources of ground-water contamination. These materials include radioisotopes (transuranic wastes, tritium, mixed fission products), petroleum fuels, electroplating solutions, waste machine-coolant oil, and various solvents. Because ground water drawn from the alluvium of the Valley constitutes an important potable water supply source, it is important to understand the possible effects of LLNL operations on the local ground-water quality.

A recent report (Stone et al., 1983) addressed many of these questions and evaluated the potential for contamination of the saturated ground-

water system at and near LLNL. The present report is an extension of the earlier work of Stone et al., and addresses more of the questions about effects of LLNL on ground-water quality. Sampling and analysis of water from 13 observation wells at LLNL was completed. A series of hydraulic aquifer tests was performed using the observation wells. The results of the tests were analyzed to provide estimates of the hydraulic conductivity of the alluvial aquifer beneath LLNL. Laboratory measurements led to estimates of the effective porosity of the aquifer materials. These estimates, in turn, allowed the calculation of ground-water flow speeds beneath LLNL and estimation of contaminant travel times to site boundaries.

The general understanding of the occurrence and movement of ground water at and near LLNL that has emerged through the investigations will

provide a basis for addressing public concerns about the influence of the Laboratory on groundwater quality. This understanding is needed for a

rational approach to the investigation of specific contaminant sources and their effect on groundwater quality now and in the future.

## Analysis of Water from Wells

Water from 13 of the 15 shallow groundwater observation wells on and very near the LLNL site was sampled and analyzed for a variety of dissolved substances. The well locations are given in Fig. 1. Descriptions of the wells are found in Stone et al. (1983) and Carpenter et al. (1982). One of the offsite wells, TB21, was not sampled because it is not downgradient from LLNL. One of the wells at LLNL, MW14, was not sampled because its method of construction prevented removal of water from it. Analyses of water from the 13 wells included determinations of a variety of organic compounds, major inorganic cations and anions, total organic carbon, total dissolved solids, trace metals, and tritium content (Table 1).

This sampling completes that begun earlier in the investigation (Stone et al., 1983).

### Sampling Procedures

Water was bailed from wells MW19 and MW12 until the water level was near the well bottoms. The water levels were allowed to recover somewhat and then samples were bailed from these two wells. The hydraulic conductivity of alluvium penetrated by both wells is small. The same is true of the alluvium penetrated by well MW17. About 0.08 m<sup>3</sup> (22 gallons) of water was pumped out of well MW17 on two consecutive

**Table 1. Summary of analysis of water samples from wells on the LLNL site.**

Well No.	Screened internal depth (ft)	Date sampled	Sampling method	Analyses performed						
				<sup>3</sup> H	Total organic carbon	Total dissolved solids	General inorganic	Trace metal	PCB	Organics
MW1	95-100 104-114	4-20-83 6-09-83	Bennett pump	-	-	-	-	-	-	x
MW2	86-101	4-23-83 6-09-83	Bennett pump	-	-	-	-	-	-	x
MW4	75-90	5-04-83 6-09-83	Submersible pump	-	-	x	x	-	-	x
MW5	56-71 81-86	4-29-83	Teflon bailer	-	-	-	-	-	-	x
MW7	76-81 88-98	4-12-83	Teflon bailer	x	x	x	x	x	-	x
MW8	72-77 92-102	5-05-83	Submersible pump	x	x	x	x	x	-	-
MW10	85-95 100-105	4-08-83	Teflon bailer	x	-	x	x	-	x	-
MW11	136-141 177-187	4-14-83	Bennett pump	x	x	x	x	x	x	x
MW12	99-114	3-14-83	SS bailer <sup>a</sup>	-	-	x	x	-	x	-
TB11	97-107	4-22-83 6-07-83	Bennett pump	x	x	x	x	x	-	x
MW17	94-109	3-25-83	Bennett pump	x	x	x	x	x	x	x
MW18	80-90 100-105 112-117 127-132 142-153	3-29-83 3-31-83	Bennett pump	x	x	x	x	x	x	x
MW19	147-157	3-10-83	SS bailer	-	-	x	x	-	-	x

<sup>a</sup> SS = stainless steel.

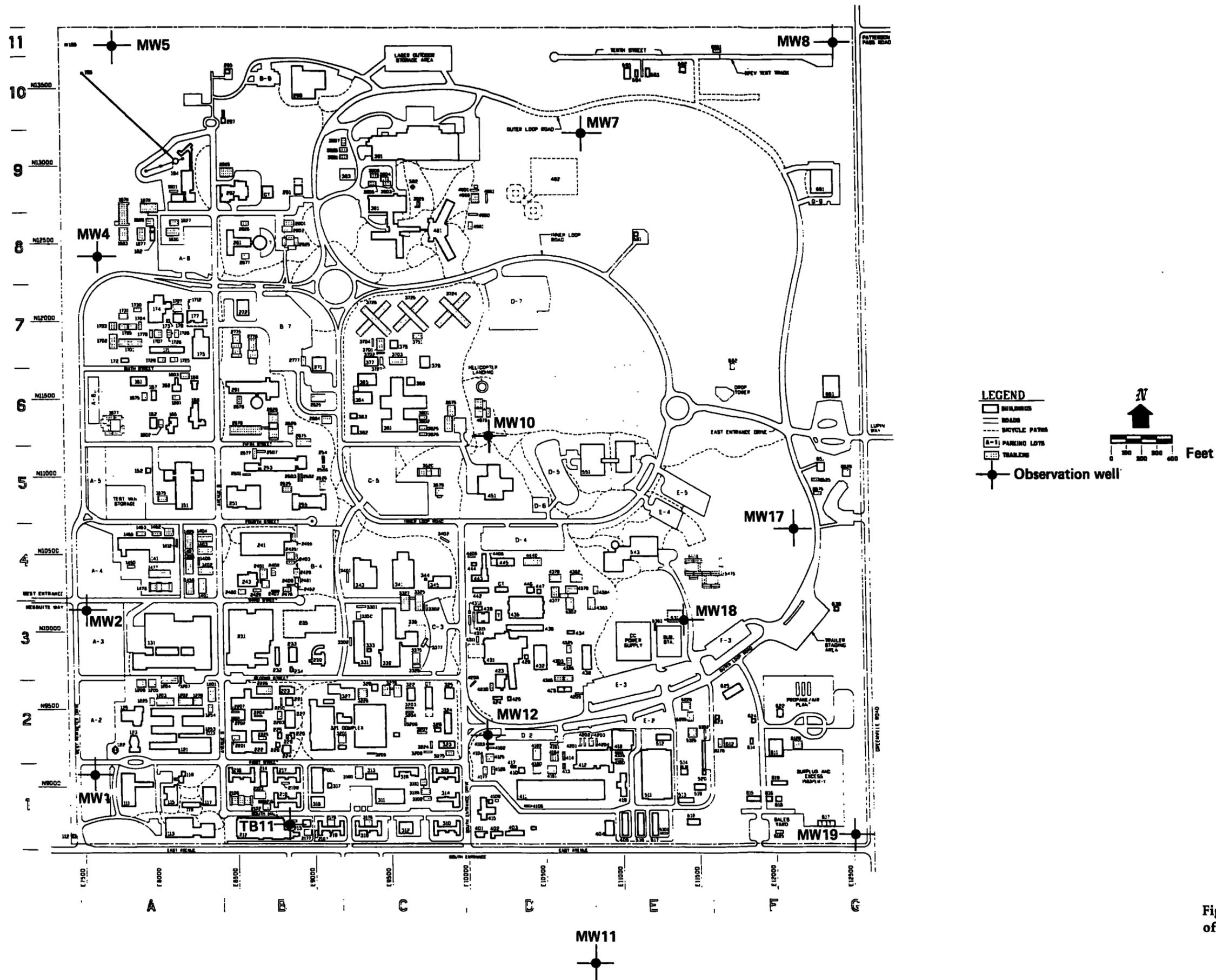


Figure 1. LLNL site map showing locations of observation wells.

days with a multistage centrifugal submersible pump. On the third day a like amount of water was pumped with a positive-displacement, gas-operated Bennett pump prior to drawing water samples. About two casing volumes of water was bailed and pumped (using the Bennett pump) from well TB11 before a sample was drawn. At least four casing volumes of water was pumped from each of the remaining wells with the submersible pump before water samples were drawn.

The primary sample preservation technique employed was to chill the water samples. As the samples were taken, they were placed in an insulated ice chest. The samples that were analyzed for  $^3\text{H}$  content were delivered to the LLNL Nuclear Chemistry Laboratory within one day of being taken. All other samples were delivered to the Brown and Caldwell, Inc., laboratory within a day or two of being taken. No samples were acidified in the field, though the samples for general inorganic, trace metal, and tritium analyses were filtered using a  $0.45\text{-}\mu\text{m}$  pressure filter. This procedure was deemed appropriate since the field storage time for the samples was brief.

Brown and Caldwell, Inc., provided appropriate sample containers of various types for the analyses they performed. The containers were prepared in accordance with standard procedures that included rinsing with nitric acid and deion-

ized water where appropriate. The amber glass containers for the tritium samples were washed, rinsed with distilled water, dried in a low temperature oven, and cooled in argon.

## Water Sample Analyses

Water samples from ten of the wells were submitted for general inorganic analysis. The results are given in Table 2. The water from wells MW4, MW10, MW11, MW12, TB11, MW17, MW18, and MW19 is of sodium-calcium bicarbonate type. Water from wells MW7 and MW8 is of sodium-calcium chloride type. The moderate total-dissolved-solids content of water from all of the wells, except well MW8, places it in the category of fresh water. Water from well MW8 is nearly brackish. The water quality in wells MW7 and MW8 may be influenced by subsurface flow from late Cretaceous and early Tertiary marine sediments in the hills to the east and north (CDWR, 1974).

The water from well MW7 had about two times the nitrate concentration allowed in drinking water by Title 22 of the California Administrative Code. Well MW7 is near livestock pens on the LLNL site, which may be the nitrate source. Water from well MW8 had more chloride and

Table 2. General inorganic analysis of water from wells at LLNL. Concentrations in mg/liter.

Constituent	Well No.									
	MW4	MW7	MW8	MW10	MW11	MW12	TB11	MW17	MW18	MW19
Sodium	130	240	430	50	36	87	58	130	37	70
Potassium	1.7	2.2	2.6	1.7	1.7	5.0	2.7	0.92	1.7	5.0
Calcium	50	107	124	42	38	101	69	77	49	46
Magnesium	15	25	62	7.8	18	39	23	54	15	42
Nitrate (as $\text{NO}_3$ )	20	<u>71<sup>a</sup></u>	13	12	11	0.13	3.8	<0.04	16	0.58
Chloride	68	<u>328</u>	<u>610</u>	35	45	30	19	232	60	73
Sulfate	33	156	<u>315</u>	30	20	1.7	15	109	23	18
Bicarbonate	338	278	300	195	207	731	465	327	188	407
Carbonate	25	—	7.2	—	—	—	—	—	—	—
Iron	<0.01	<0.01	<0.01	<0.01	<0.01	<u>3.3</u>	0.02	<0.01	<0.01	<0.01
Manganese	<0.01	<0.01	<0.01	<0.01	<0.01	<u>3.0</u>	<u>0.69</u>	<u>0.11</u>	<0.01	<u>0.13</u>
Copper	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	0.01	<0.02	<0.01
Total dissolved solids	524	954	<u>1770</u>	258	332	550	400	688	534	402
Specific conductance ( $\mu\text{mho}$ )	989	1820	3130	500	496	1080	746	1220	N.T. <sup>b</sup>	806
pH	7.7	7.6	7.3	7.8	8.0	7.3	7.6	7.7	7.8	8.0

<sup>a</sup> Underline means greater than drinking water standards.

<sup>b</sup> N.T. = not tested.

greater total-dissolved-solids concentrations than are recommended for drinking water. These concentrations are the result of natural ground-water quality evolution. Water from well MW12 had greater iron concentration than is recommended for drinking water, and water from wells MW12, TB11, MW17, and MW19 had greater manganese concentration than is recommended for drinking water. These concentrations are likely the result of natural ground-water quality evolution. Although not ideal, the general inorganic quality of waters from the wells listed in Table 2 suits them for drinking, with the exception of water from well MW7, which contained too much nitrate.

The results of the analyses for trace metals and total organic carbon (TOC) in water samples from six wells are given in Table 3. The selenium concentration in water from well TB11 was at the limit for drinking water. All other dissolved trace metals listed in Table 3 occurred in small, benign concentrations or below detection limits. An indicator of organic contamination of water is its total organic carbon content. TOC concentrations for tap water are commonly between 1 and 2 mg/liter (Harrar, 1982). Wells MW7, TB11, and MW17 do not produce much water and have not been pumped as much as the other wells listed in Table 3. The TOC in water from these wells may be a relict of the biodegradable natural polymer used as a drilling-fluid additive during well drilling. The other wells listed in Table 3 have been pumped extensively, and water from them had lower TOC.

Water from wells MW10, MW11, MW12, MW17, and MW18 was analyzed for polychlorinated biphenyl (PCB) content. No PCB was detected in water from any of these wells.

Water samples from ten of the wells were analyzed, using gas chromatography/mass spectrometry, for their purgeable-organic-pollutant content. The results of these analyses are given in Table 4. Water from several of the wells was sampled twice. Table 4 contains the results of both analyses of water from these wells. It appears that real concentrations of chloroform, trichloroethylene, tetrachloroethylene, 1,1-dichloroethylene, and tetrahydrofuran exist in water sampled from some of the wells. The tetrahydrofuran found in water from wells MW1, MW2, TB11, MW17, and MW19 probably was leached from the cement used to glue the PVC well casing together and hence is likely of limited extent in the ground water. The other pollutants identified likely have somewhat greater extent in the ground-water system, and some are present at concentrations great enough to be of concern.

No legal drinking water standards (concentration limits) for the various organic compounds listed in Table 4 have been set by California State Law or Federal agencies. The U.S. Environmental Protection Agency (EPA) has drafted "water health effects advisories" for several organic compounds. These advisories, called Suggested No Adverse Response Levels (SNARLs), recommend "the level of contaminant in drinking water at which adverse health effects would not be anticipated." According to the EPA, contaminants found above the recommended levels involve "unusual amounts of the chemicals in drinking water which may warrant state regulatory action." While SNARLs are not legally enforceable standards, they could eventually be adopted as national drinking water standards or maximum contaminant levels (MCLs).

**Table 3. Trace metals and total organic carbon (TOC) in water from wells at LLNL. Concentrations in mg/liter.**

Constituent	MW7	MW8	MW11	TB11	MW17	MW18
TOC	29	<5	11	42	14	13
Arsenic	0.002	0.004	0.005	0.002	<0.001	0.005
Barium	<0.1	<0.4	0.1	<0.2	<0.1	<0.1
Cadmium	<0.0001	<0.0001	0.0007	<0.0001	<0.0001	0.0015
Chromium	0.0044	0.0057	0.019	0.0004	<0.0001	0.0014
Lead	<0.001	<0.001	<0.002	<0.001	<0.001	<0.01
Mercury	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Selenium	<0.001	0.004	<0.01	0.012 <sup>a</sup>	<0.001	<0.001
Silver	0.0002	<0.0001	<0.0001	<0.0001	0.0006	<0.0001

<sup>a</sup> Selenium limit for drinking water.

**Table 4. Purgeable organic pollutants in water from wells at LLNL. Concentrations in µg/liter.**

Constituent	Well No.										SNARL <sup>b</sup>
	MW1	MW2	MW4	MW5 <sup>a</sup>	MW7 <sup>a</sup>	MW11 <sup>a</sup>	TB11	MW17	MW18	MW19	
Chloroform	3,2	10,11	3,2	ND <sup>c</sup>	ND	ND	36,28	ND	ND,ND	ND	NA <sup>d</sup>
1,1,1-trichloroethane	3,ND	1,ND	ND,ND	ND	ND	ND	ND,ND	ND	ND,ND	ND	1000
Trichloroethylene	1,ND	ND,ND	ND,ND	ND	ND	ND	120,66 <sup>e</sup>	ND	65,36 <sup>e</sup>	ND	4.5
Tetrachloroethylene	9,7 <sup>f</sup>	ND,ND	ND,ND	ND	ND	ND	13,10 <sup>f</sup>	ND	ND,ND	ND	3.5
1,1-dichloroethylene	3,ND	3,3	3,2	ND	ND	ND	ND,ND	ND	ND,ND	ND	70
Tetrahydrofuran	70,30	ND,10	ND,ND	ND	ND	ND	20,5	10	ND,ND	36	NA
Carbon tetrachloride	ND,ND	ND,2	ND,ND	ND	ND	ND	ND,ND	ND	ND,ND	ND	20

<sup>a</sup> No purgeable organic pollutants detected.

<sup>b</sup> SNARL = EPA's Suggested No-Adverse-Response Level.

<sup>c</sup> ND = none detected.

<sup>d</sup> NA = not available.

<sup>e</sup> Above SNARL for trichloroethylene.

<sup>f</sup> Above SNARL for tetrachloroethylene.

**Table 5. Tritium in water from wells at LLNL.**

Well No.	Tritium concentration (TU ± 1 std dev) <sup>a</sup>
MW7	34 ± 8
MW8	46 ± 7
MW10	856 ± 19
MW11	< LOS <sup>b</sup>
TB11	136 ± 9
MW17	< LOS
MW18	< LOS

<sup>a</sup> TU = tritium unit =  $3.23 \times 10^{-3}$  pCi/ml.

<sup>b</sup> LOS = limit of sensitivity.

The SNARLs that are available for compounds listed in Table 4 appear in the last column. One can see that water from wells TB11 and MW18 contains trichloroethylene in concentrations above the suggested limit for drinking water. Likewise, wells MW1 and TB11 produced water with tetrachloroethylene concentrations above the drinking water limit. We have no guidance on allowable concentration of chloroform in drinking water for comparison, but water from four wells obviously contains detectable concentrations of the compound. The occurrence of trichloroethane in MW1 and MW2 is discounted because analysis of the second sample from these wells failed to detect any of the compound.

The tritium concentration in water from seven wells was determined by LLNL Nuclear Chemistry using sample-to-gas conversion followed by gas proportional counting. The results of the tritium analyses are given in Table 5. All of the samples contained tritium well below the 6200-TU drinking water limit set by the State of California.

The tritium concentration in water from wells MW7 and MW8 is not much different from that of the water used in drilling the wells, 40 to 60 TU. Well MW7 produces little water, and the tritium concentration in water drawn from it may be a relict of the drilling operation. The  $^3\text{H}$  content of water from well MW7 does not suggest substan-

tial nearby infiltration to the water table from the surface. This is in agreement with earlier interpretations of the hydrologic regime at and near well MW7 (Stone et al., 1983). Infiltration from the surface to the saturated zone is thought to occur routinely at well MW8 (Stone et al., 1983). The very modest  $^3\text{H}$  concentration of water from the well, however, does not indicate infiltration of rainfall having typical elevated  $^3\text{H}$  concentrations (200 to 1000 TU), such as normally falls on LLNL. Offsite rainfall, having lower  $^3\text{H}$  concentration, contributes much of the flow to Arroyo Las Positas, which runs past well MW8. Because 1982-83 was a very wet year, the  $^3\text{H}$  concentration of water infiltrating to the saturated zone at MW8 may have been significantly diluted by rainfall, contributing to the modest  $^3\text{H}$  concentration of water from MW8 given in Table 5.

The tritium concentration of water from wells TB11 and MW10 is great enough to indicate that the water was derived, at least in part, from very recent tritium-containing rainfall on the site. Other considerations (Stone et al., 1983) indicate that infiltration to the saturated zone occurs very near both wells. The  $^3\text{H}$  concentration in water from wells MW11, MW17, and MW18 was less than the detection sensitivity. This indicates that no infiltration to the saturated zone is occurring near the wells, which is in agreement with other observations (Stone et al., 1983).

## Evaluation of Aquifer Hydraulic Characteristics

### Estimates of Hydraulic Conductivity

A series of measurements was performed, using many of the observation wells at LLNL, to derive estimates of the saturated hydraulic conductivity of the lenticular sand and gravel layers in the alluvium that make up the shallow, heterogeneous, leaky aquifer system. The limited time available for the measurements and the fairly large spacing between wells dictated that the measurements be made in individual wells, separately. The measurements involved (1) pumping water from the wells that would produce at least  $10.9 \text{ m}^3/\text{day}$  to  $16.3 \text{ m}^3/\text{day}$  (2 to 3 gpm) while measuring the declining water levels in them, and (2) rapidly removing a "slug" of water from less productive wells and measuring the recovery of

the water level in them to its original position. The water level measurements were used to obtain estimates of hydraulic conductivity by comparing them with analytical radial ground-water flow models.

The analytical solution to the problem of radial ground-water flow to a well with constant discharge was provided by Theis (1935). Cooper and Jacob (1946) devised a method to analyze pumping test data—based on the Theis model—which we used to interpret our pumping test measurements. With this method, drawdown in a well is plotted as a function of time on semilogarithmic paper, and transmissivity,  $T$ , is calculated from

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (1)$$

where

$Q$  = the constant discharge rate from the pumped well,  $L^3/t$ ,

$\Delta s$  = the linear water level drawdown per logarithmic cycle of time,  $L$ .

The hydraulic conductivity,  $K$ , of sand and gravel layers is estimated from

$$K = \frac{T}{b} \quad (2)$$

where  $b$  is the effective thickness of sand and gravel layers penetrated by the well.

Constant-discharge pumping tests were carried out for six different wells at LLNL. In each test, a submersible pump was used to withdraw water at a constant rate from the well while the declining water level in the well was measured. The resulting drawdown record for the six pumping tests is displayed in Figs. 2 through 7.

Well-bore storage effects early in testing are apparent only in Figs. 4 and 7. Straight lines were fitted by linear regression to the portion of the data for each test between the end of well-bore storage effects (if any) and the beginning of any boundary effects. The straight-line fits are displayed in Figs. 2 through 6. The straight line de-

scribing the drawdown history in well MW18 (Fig. 7) was fitted approximately to the data set following well-bore storage effects. Well MW18 behaved erratically because it could not be completely developed.

The drawdown response in well MW1 (Fig. 2) suggests that the stressed aquifer is leaky. A positive hydraulic boundary condition is indicated by the decrease in rate of drawdown after about 20 minutes. The drawdown response after about 200 minutes in well MW4 (Fig. 3) indicates a negative hydraulic boundary condition that may be the result of radial heterogeneities in the aquifer—the “patchy aquifer” effect of Barker and Herbert (1982). This increase in rate of drawdown may result when the head transient reaches the limit of a lenticular aquifer of small extent. The drawdown response after 10 minutes in well MW8 (Fig. 5) suggests that the lower one or two sand and gravel layers feeding water to the well are leaky, and it seems that the upper sand exhibited some delayed gravity drainage to the well after the pumping level dropped below it. The drawdown response after about 100 minutes in well MW11 (Fig. 6) indicates the effects of a “patchy aquifer.”

The records of water-level recovery in four wells that were slug-tested are displayed in Figs. 8

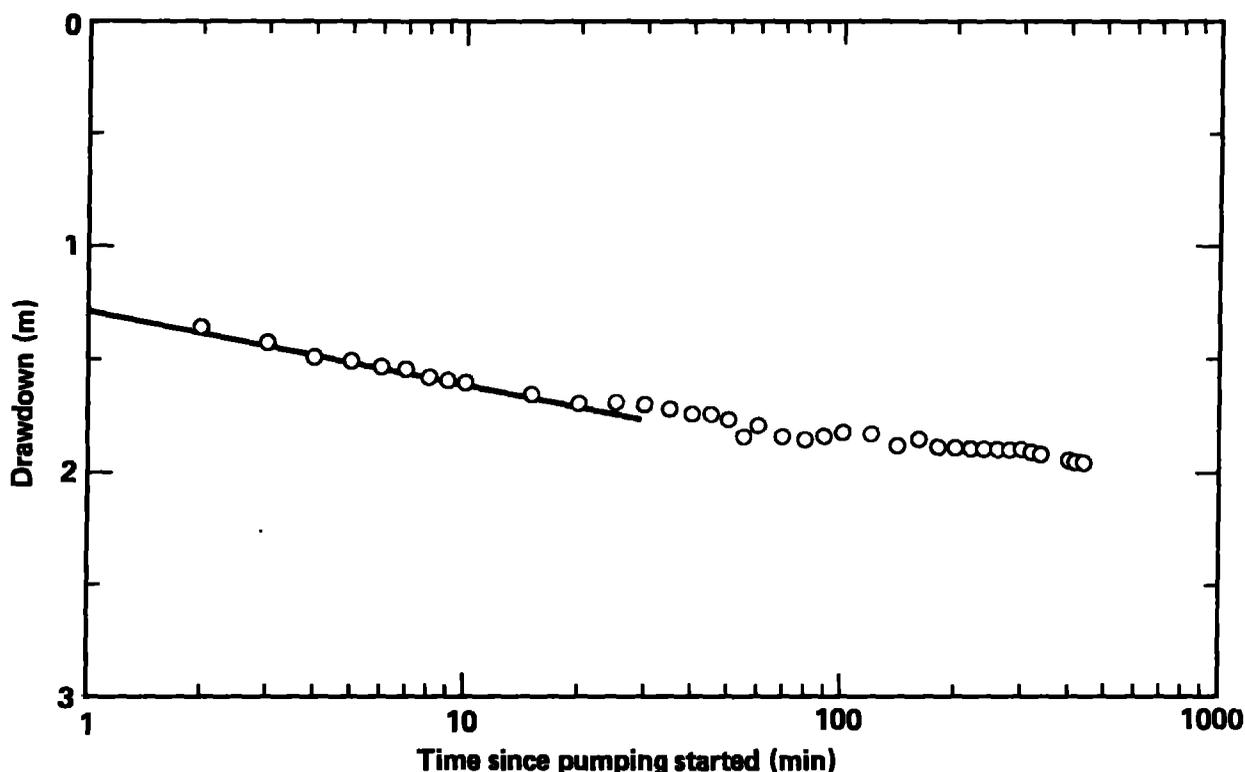


Figure 2. Drawdown response in well MW1 to pumping it at  $31.1 \text{ m}^3/\text{day}$ .

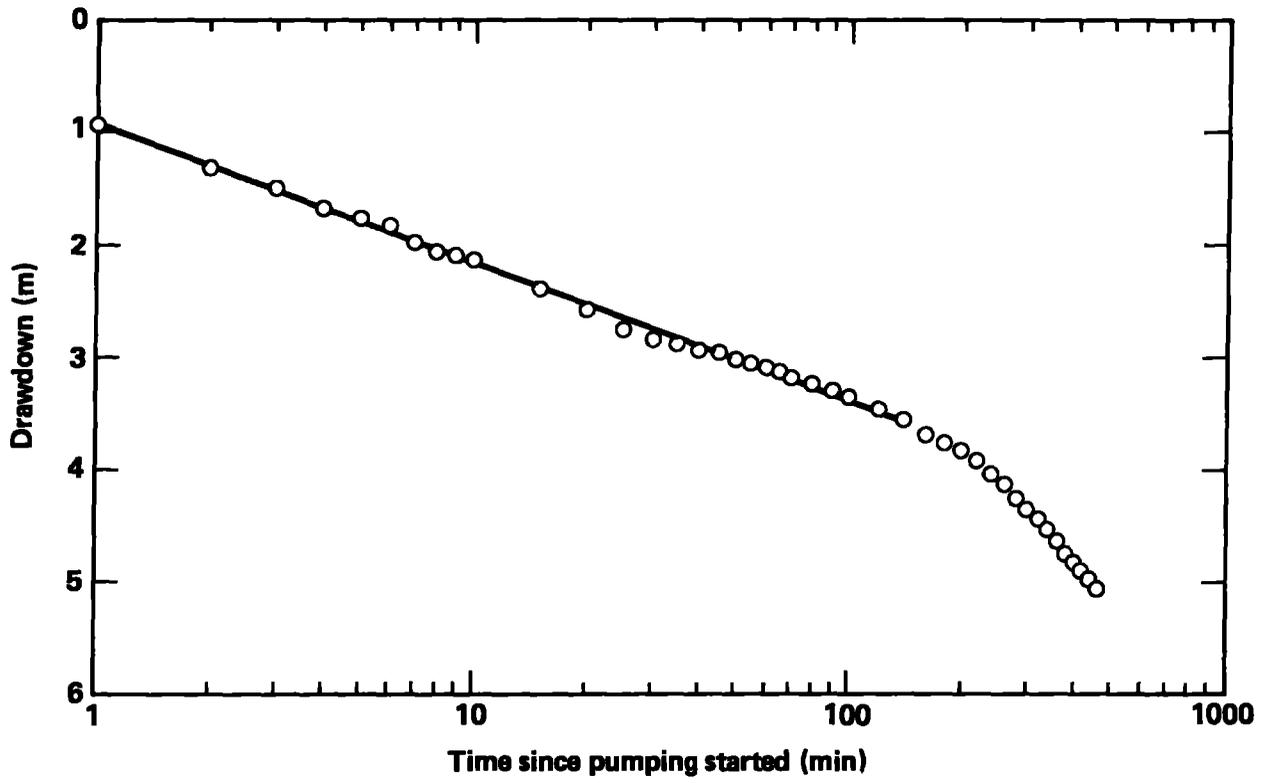


Figure 3. Drawdown response in well MW4 to pumping it at 18.0 m<sup>3</sup>/day.

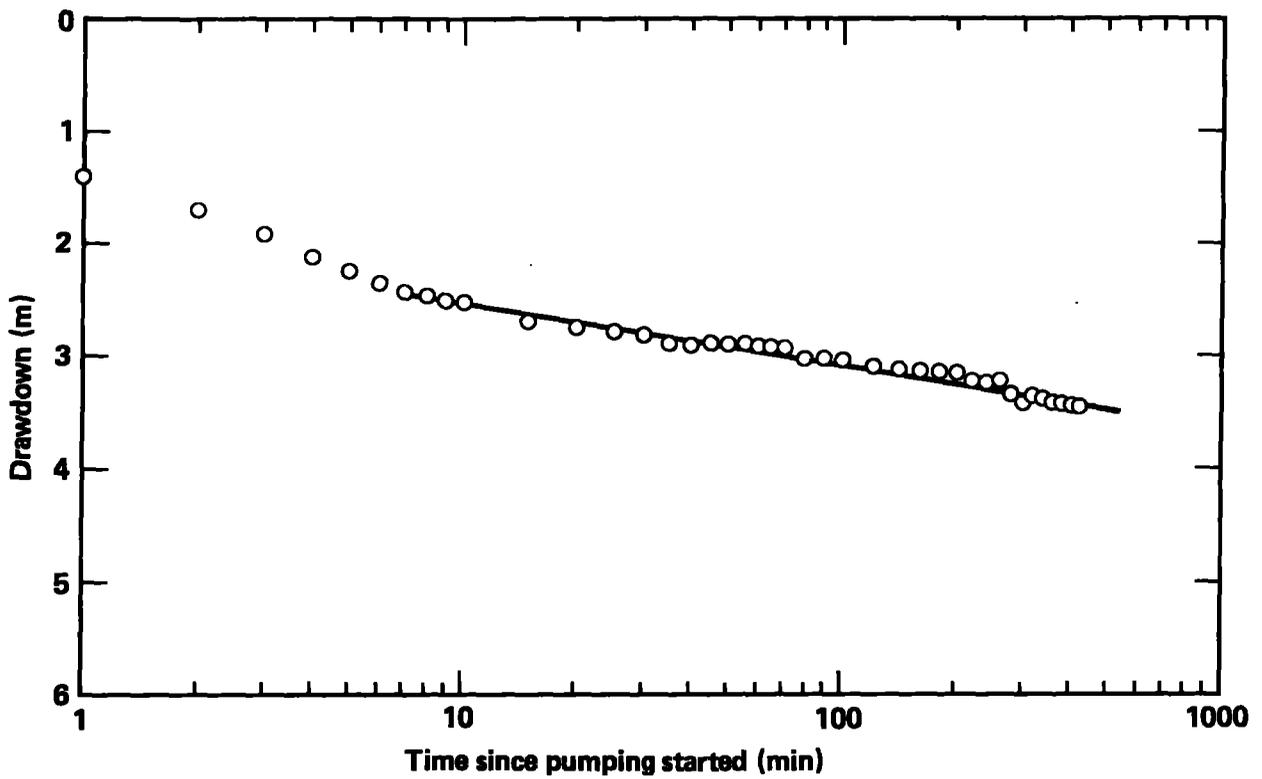


Figure 4. Drawdown response in well MW5 to pumping it at 23.4 m<sup>3</sup>/day.

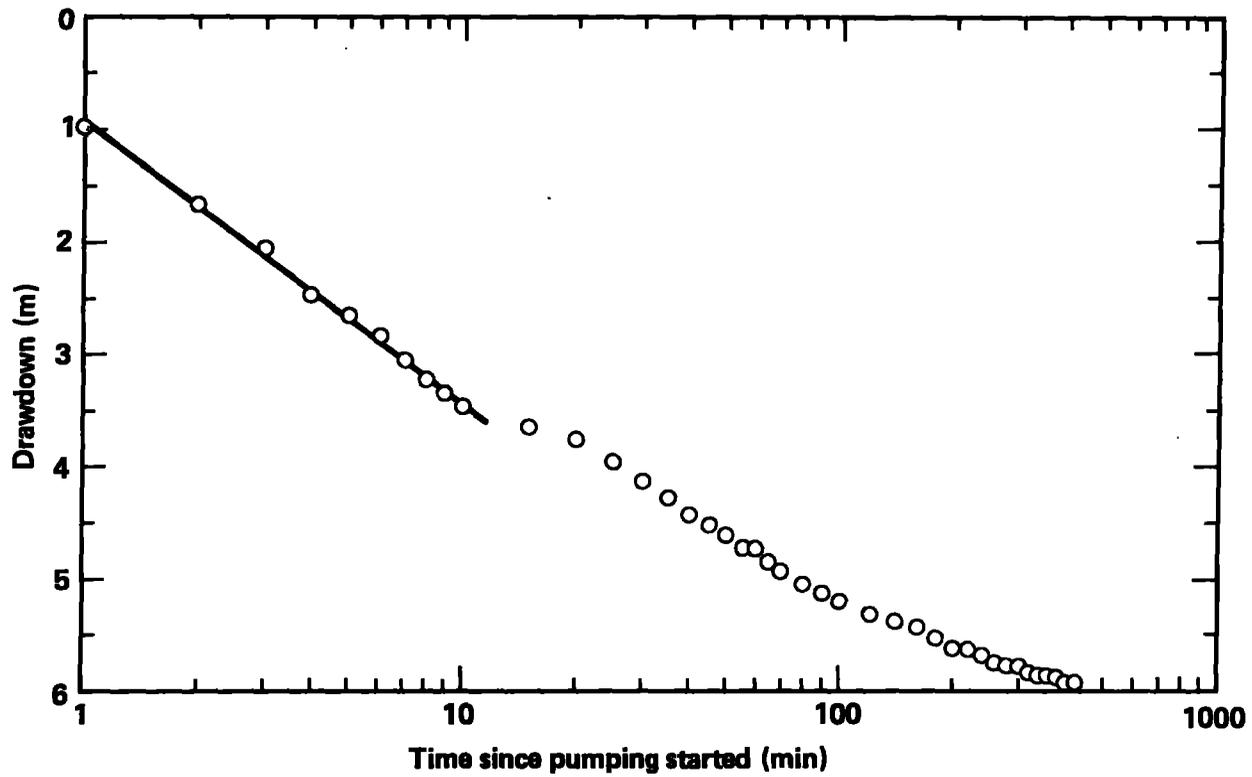


Figure 5. Drawdown response in well MW8 to pumping it at  $15.8 \text{ m}^3/\text{day}$ .

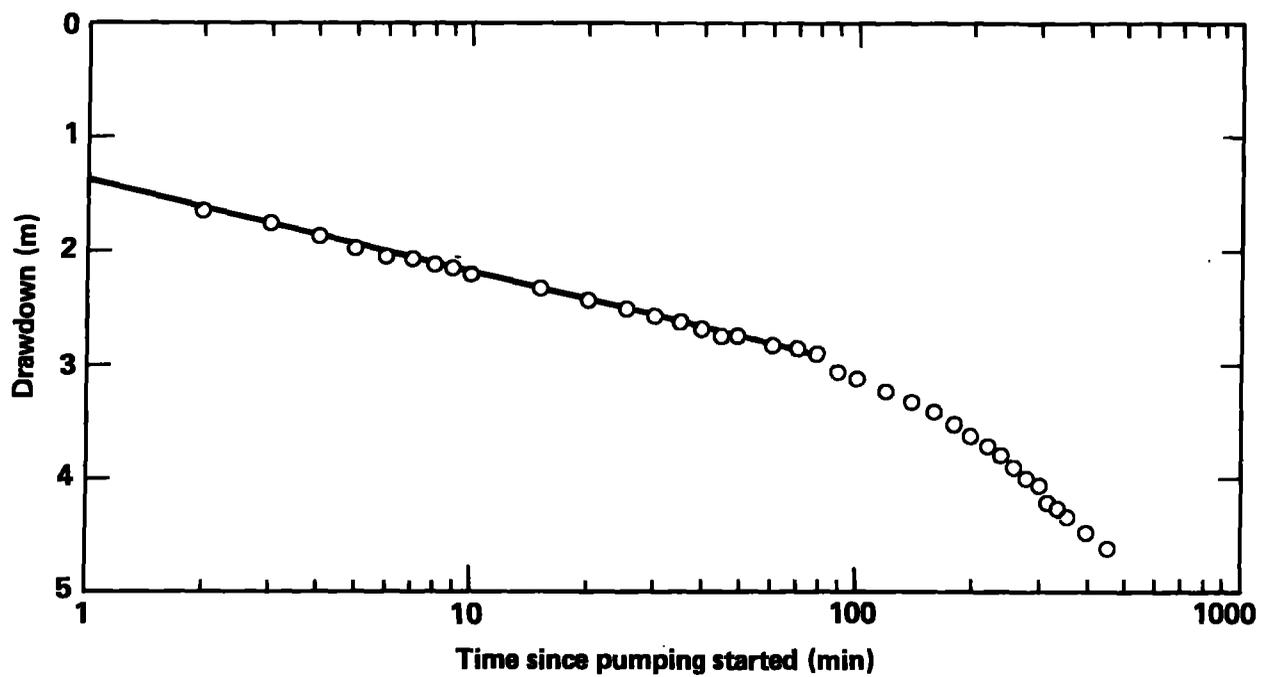


Figure 6. Drawdown response in well MW11 to pumping it at  $22.3 \text{ m}^3/\text{day}$ .

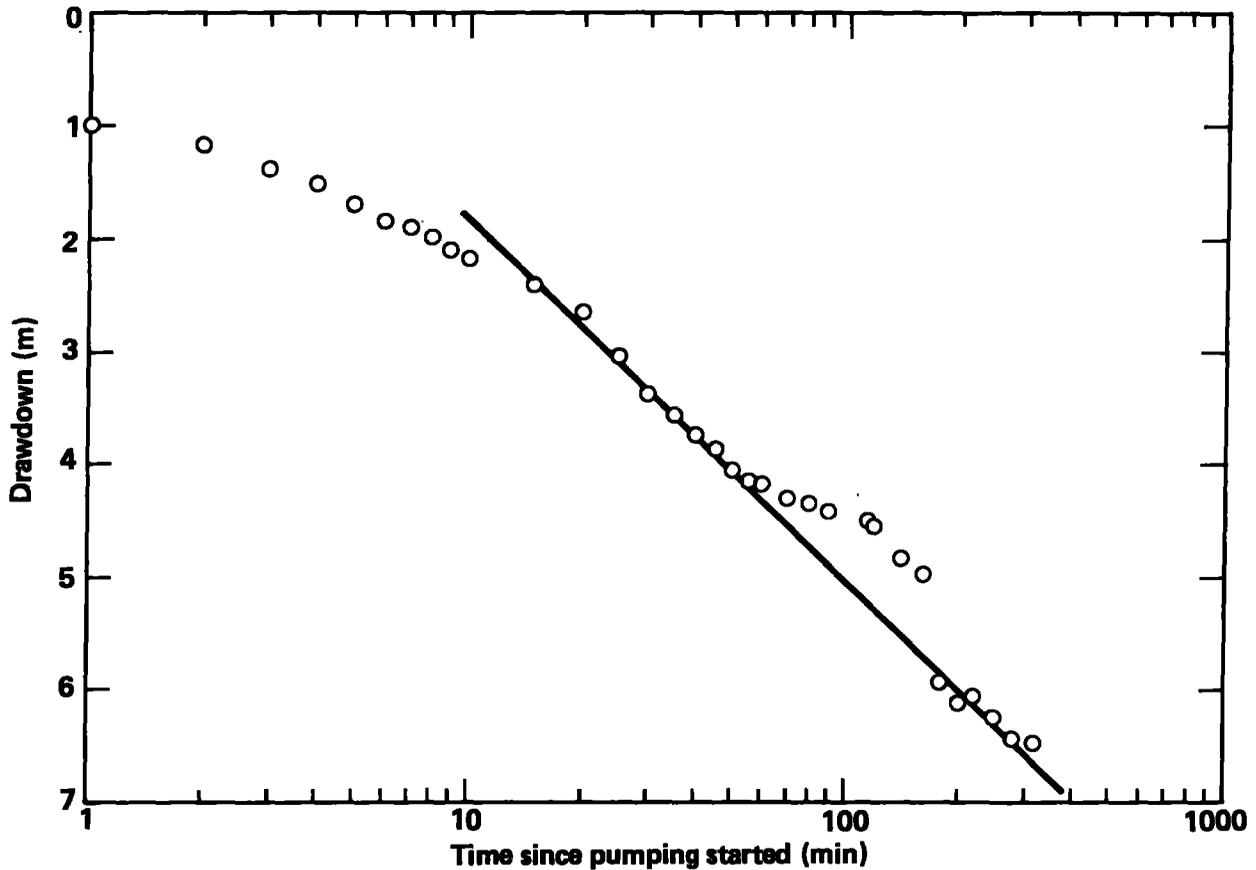


Figure 7. Drawdown response in well MW18 to pumping it at 14.0 m<sup>3</sup>/day.

through 11. A known volume of water was rapidly removed from each well with the submersible pump, and the recovery of water level was measured. The wells have a casing radius,  $r_w$ , of about 0.06 m. The slug tests were analyzed according to the method of Cooper et al. (1967). The recovery data were matched to a recovery-type curve, and the value of time on the data graph where  $Tt/r_w^2 = 1$  on the type curve was noted. Transmissivity was then estimated from

$$T = \frac{1.0r_w^2}{t} \quad (3)$$

where  $t$  is the value of time on the data graph where  $Tt/r_w^2 = 1$  on the type curve. Hydraulic conductivity of the sand and gravel layers was calculated in the same manner as in the pumping test analyses.

The hydraulic conductivity estimates for sand and gravel aquifers based on pump and slug tests are listed in Table 6. The greatest conductivity found, that in well MW1, is only moderate for an aquifer. The rest of the values describe sparingly permeable aquifer materials. The range of conductivity estimates covers something over an order of magnitude, which is not surprising considering the wide variability in the nature and characteristics of the sand and gravel layers. The hydraulic conductivity values of Table 6 are plotted at the observation well locations in Fig. 12. Conductivity values seem smallest in the central and southeastern portions of the site. The greatest conductivity value, that from the test of well MW1, may be related to the proximity of the well to Arroyo Seco and the more permeable sediments associated with the arroyo.

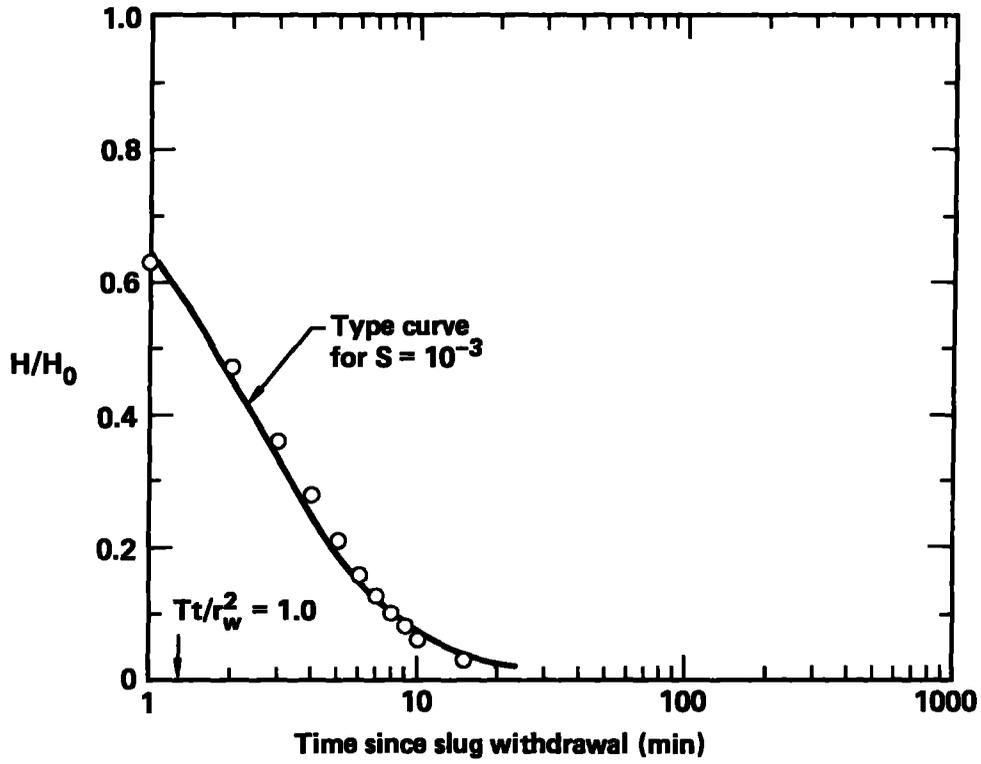


Figure 8. Water-level recovery following slug withdrawal from well MW2.

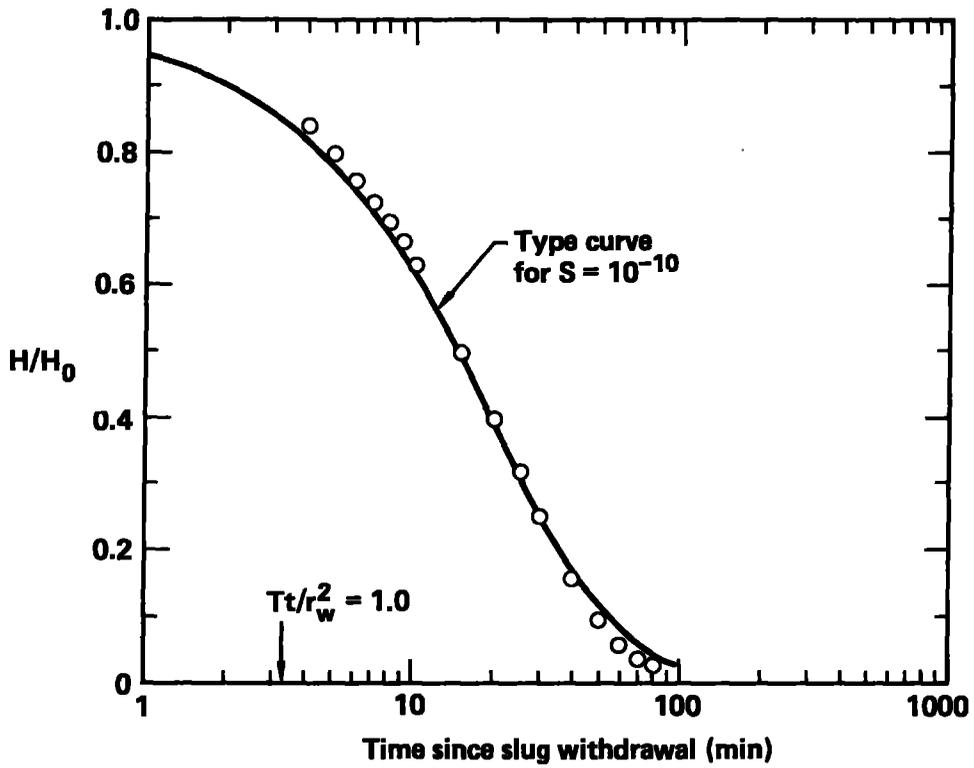


Figure 9. Water-level recovery following slug withdrawal from well MW7.

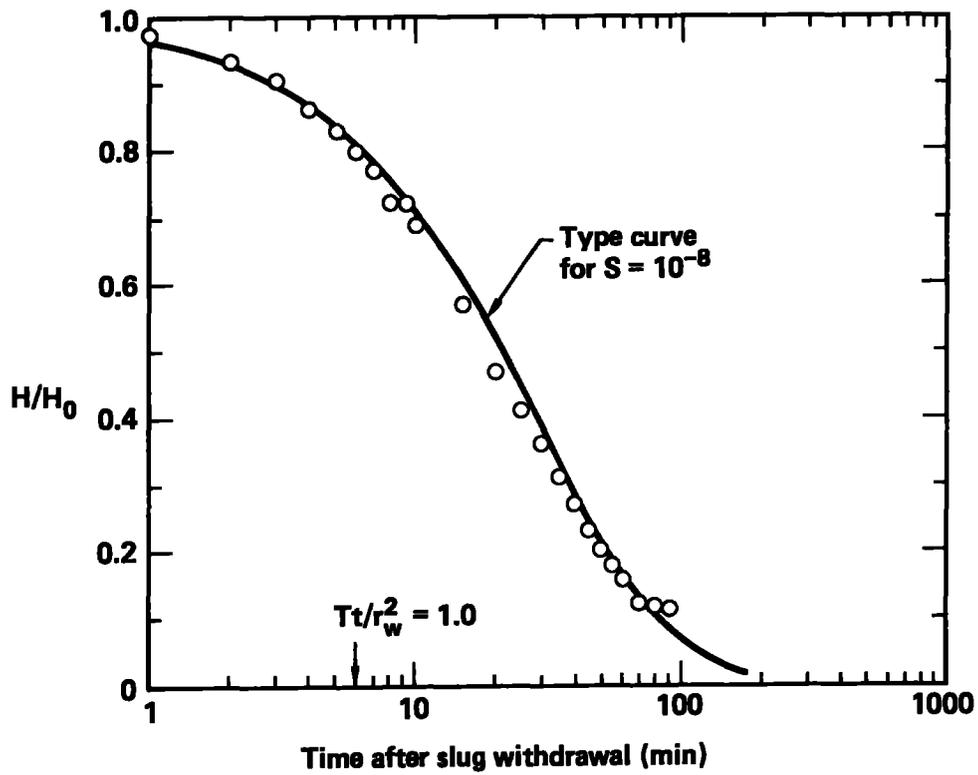


Figure 10. Water-level recovery following slug withdrawal from well MW10.

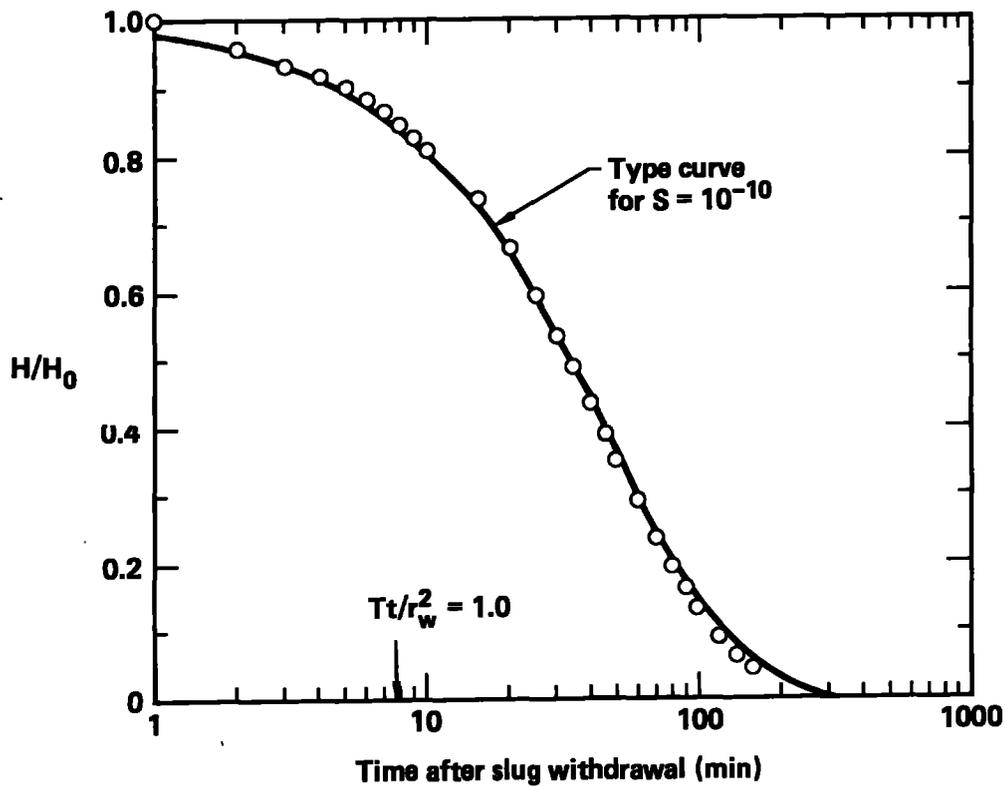


Figure 11. Water-level recovery following slug withdrawal from well MW17.

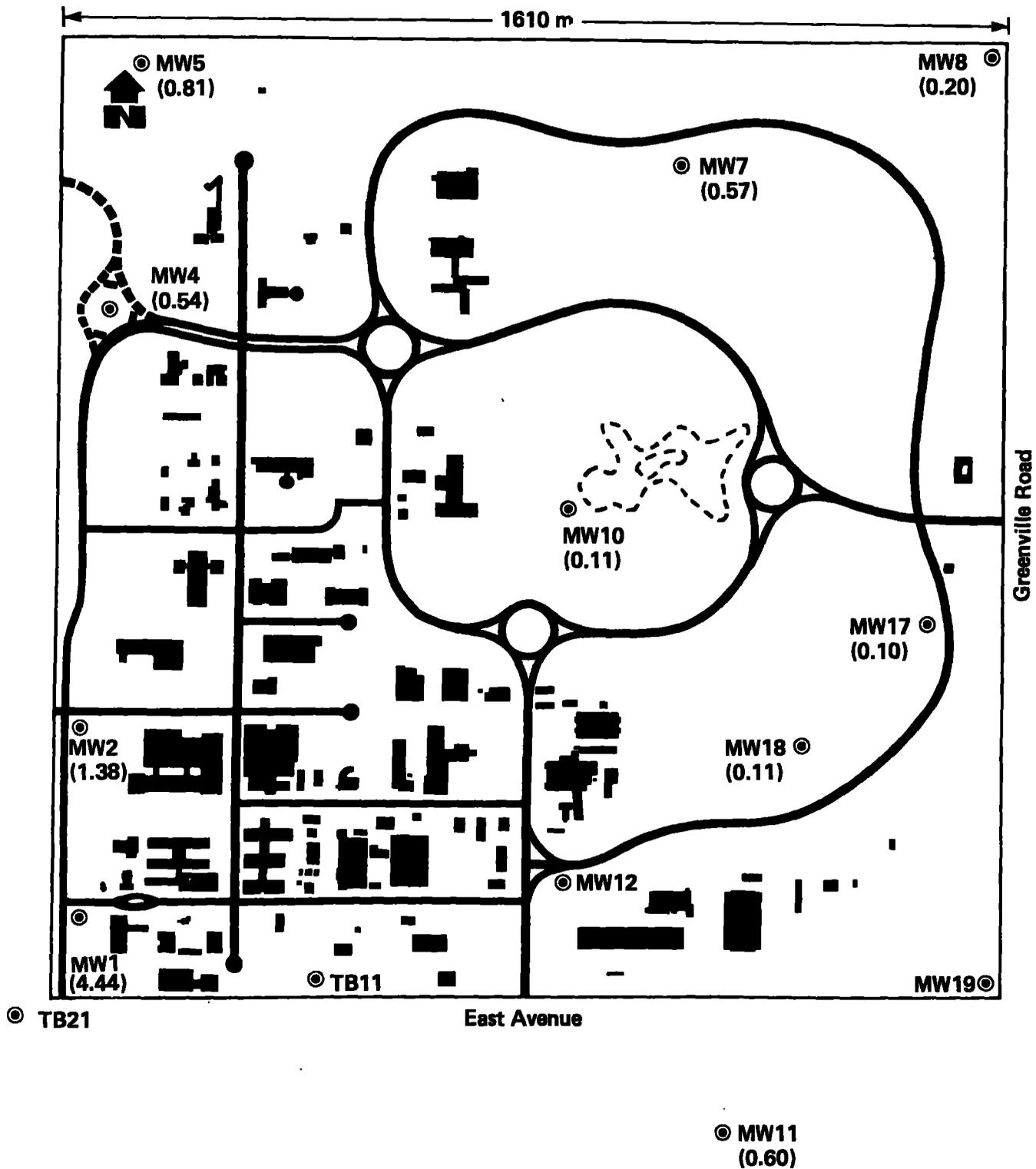


Figure 12. Estimates of hydraulic conductivity in shallow sand and gravel layers at LLNL. Estimates (in m/day) appear in parentheses by wells tested.

**Table 6. Estimates of hydraulic conductivity of sand and gravel aquifer material at LLNL.**

Well No.	Test type	Hydraulic conductivity (m/day)
MW1	Constant-Q pump test	4.44
MW4	Constant-Q pump test	0.54
MW5	Constant-Q pump test	0.81
MW8	Constant-Q pump test	0.20
MW11	Constant-Q pump test	0.60
MW16	Constant-Q pump test	0.11
MW2	Slug test	1.38
MW7	Slug test	0.57
MW10	Slug test	0.11
MW17	Slug test	0.10

### Estimates of Effective Porosity

The effective porosity of a porous material is the percentage of total volume occupied by interconnected void spaces. It is the fraction of the material through which water will freely flow. Four samples of alluvial aquifer material were tested to estimate their effective porosity. The material was of sand texture and had been recovered in Pitcher tubes during the drilling of wells MW8 and MW10. No gravel samples were obtained with Pitcher tubes during well and test-hole drilling because the gravel generally falls out of the Pitcher tube as the tube is brought back to the surface.

Sand samples 3 or 4 cm long were obtained by cutting off portions of the Pitcher tubes con-

taining the original samples. The short lengths of Pitcher tube around the samples acted as convenient sleeves to contain them during processing and testing. The samples were then saturated with water and weighed. Next the samples were placed in a volumetric pressure plate extractor. Moisture was driven out of the samples by applying approximately one-third atmosphere of air pressure to the extractor. The pressure was maintained until no more water was driven from the samples. The total water volume driven from the samples was noted and the samples were weighed again. The difference in sample weight and calculation of sample volume allows one to estimate their effective porosity. The results of these porosity estimates are given in Table 7. The range of effective porosity estimates, from approximately 10 to 30%, is about that to be expected for poorly sorted alluvial sand.

**Table 7. Effective porosity of alluvial aquifer material from beneath LLNL.**

Sample well	Depth interval (m)	Approximate effective porosity (%)	Sample texture
MW 8	(16.0-16.8)	19	Argillaceous fine to medium sand
MW 8	(24.4-25.1)	11	Argillaceous fine to medium sand
MW10	(21.6-22.4)	23	Medium to coarse sand
MW10	(24.7-25.4)	33	Silty fine to coarse sand with some gravel

### Estimates of Ground-Water Flow Speed

The speed of ground-water flow,  $b$ , can be estimated using Darcy's law:

$$v = \frac{K}{\theta} \frac{dh}{dl} \quad (4)$$

where

- $\theta$  = effective porosity,
- $\frac{dh}{dl}$  = hydraulic gradient,
- $K$  = hydraulic conductivity.

The hydraulic gradients driving shallow horizontal ground-water flow at LLNL as of late 1981 can be obtained from the water-table contour map given by Stone et al. (1983). Table 8 lists gradients

**Table 8. Horizontal hydraulic gradients at the LLNL site.**

Portion of site	Direction	Hydraulic gradient
Southeast	ESE to SSE	0.0077
Southwest	WNW	0.0026
Northeast	WSW	0.0083
Northwest	WNW	0.0019

obtained from that map for the four quadrants of the site. These gradients, together with the range of effective porosities found for sand aquifer material (10–30%), and the hydraulic conductivities in the quadrants, were used to estimate a range of ground-water flow speeds within the quadrants. These estimates appear in Table 9. The greatest estimated shallow ground-water flow speeds are for the southwestern portion of LLNL, because of the relatively large hydraulic conductivity estimate for alluvium in well MW1.

**Table 9. Estimated shallow horizontal ground-water flow speeds at the LLNL site.**

Portion of site	Direction	Ground-water flow speed (m/yr)
Southeast	ESE to SSE	1-3
Southwest	WNW	14-42
Northeast	WSW	6-17
Northwest	WNW	2-6

## Contaminant Travel Times to Site Boundaries

The extent of ground-water contamination by trichloroethylene near wells MW18 and TB11 and the extent of ground-water contamination by tetrachloroethylene near wells MW1 and TB11 is not well known. Because no large waste-disposal operation is known to have been carried out at LLNL, it is assumed that the regions of contaminated ground water are of limited extent. This assumption is supported by the fact that the substantial organic contamination of ground water was detected in water from only three of the wells sampled. The maximum trichloroethylene and tetrachloroethylene concentrations in ground water beneath LLNL in the vicinity of wells MW1, MW18, and TB11 are not known, and the shapes and dimensions of the regions of contaminated ground water have not been defined.

If it is assumed that the center of the region contaminated with trichloroethylene (TCE) near well MW18 is located at the well, and that no retardation of the TCE in flow will occur, it will take from about 180 to 550 years for the TCE-contaminated ground water to move about 550 m to the southeast corner of the LLNL site.

If it is assumed that the center of the region contaminated with TCE and tetrachloroethylene

(PCE) near well TB11 is located at the well, and that no retardation of the TCE and PCE in flow will occur, it will take from about 11 to 33 years for the TCE- and PCE-contaminated ground water to move about 460 m to the western boundary of the LLNL site.

If it is assumed that the center of the region contaminated with PCE near well MW1 is located at the well, and that no retardation of the PCE in flow will occur, it will take from about 10 months to 3 years for the PCE-contaminated ground water to move about 36 m to the western boundary of the LLNL site. Actually, it is fairly likely that ground water with low-level PCE contamination has already moved offsite to the west of well MW1.

The probable sources for the TCE contamination near well MW18 and for the TCE and PCE contamination near wells TB11 and MW1 have not been identified or characterized. No present source or sources for the organic contaminants in the two areas is obvious other than possible leakage or spillage from 55-gallon drums in outdoor storage and dispensing racks. It is possible that some or all of the contamination at wells TB11 and MW1 originated offsite.

## Summary and Conclusions

The moderate total-dissolved-solids content of water from all of the wells, except well MW8, places it in the category of fresh water. Water from well MW8 is nearly brackish. All samples tested contained tritium well below the limit for drinking water.

The water from well MW7 had about two times the nitrate concentration allowed in drink-

ing water by Title 22 of the California Administrative Code. Well MW7 is near livestock pens on the LLNL site, which may be the nitrate source. Water from well MW8 had more chloride and greater concentrations of total dissolved solids than are recommended for drinking water. These concentrations are the result of natural ground-water quality evolution. Water from well MW12

had greater iron concentration than is recommended for drinking water, and water from wells MW12, TB11, MW17, and MW19 had greater manganese concentration than is recommended for drinking water. These concentrations are likely the result of natural ground-water quality evolution. The general inorganic quality of waters from the wells sampled suits them for drinking, with the exception of water from well MW7, which contained too much nitrate.

The selenium concentration in water from well TB11 was at the limit for drinking water. All other dissolved trace metals occurred in small benign concentrations or below detection limits.

Water from wells TB11 and MW18 contained trichloroethylene in concentrations above the suggested limit for drinking water. Wells MW1 and TB11 produced water with tetrachloroethylene concentrations above the drinking water limit. We have no guidance on allowable concentration of chloroform in drinking water for comparison, but water from four wells obviously contained detectable concentrations of the compound.

The drawdown responses during pump tests of the wells included the effects expected of leaky, heterogeneous alluvial aquifer systems. Estimates of the hydraulic conductivity of shallow sand and gravel units tested range from 0.10 m/day to 4.44 m/day. The greatest conductivity is only moderate for an aquifer. The majority of the conductivity estimates describe sparingly permeable aquifer materials. Conductivity values are smallest in the central and southeastern portions of the site. The greatest hydraulic conductivity of sand and gravel layers was found in the southwestern portion of the site, near Arroyo Seco.

Estimates of effective porosity of the alluvial aquifer material range from 10 to 30% and are considered typical for poorly sorted alluvial sand. Ground-water flow speeds were estimated to be 1 to 3 m/yr in the southeast part of the site, 14 to 42 m/yr in the southwest part of the site, 6 to 17 m/yr in the northeast part of the site, and 2 to 6 m/yr in the northwest part of the site.

The extent of ground-water contamination by trichloroethylene near wells MW18 and TB11 and

the extent of ground-water contamination by tetrachloroethylene near wells MW1 and TB11 is not well known. It is assumed that the regions of contaminated ground water are of limited extent. The maximum trichloroethylene and tetrachloroethylene concentrations in ground water beneath LLNL in the vicinity of wells MW1, MW18, and TB11 are not known, and the shapes and dimensions of the regions of contaminated ground water have not been defined. The probable sources for the TCE contamination near well MW18 and for the TCE and PCE contamination near wells TB11 and MW1 have not been identified or characterized. No present source for the organic contaminants in the two areas is obvious other than possible leakage or spillage from 55-gallon drums in outdoor storage and dispensing racks. It is possible that some or all of the contamination at wells TB11 and MW1 originated offsite.

If it is assumed that no retardation of the TCE in flow will occur, it will take from about 180 to 550 years for the TCE-contaminated ground water to move about 550 m from well MW18 to the southeast corner of the LLNL site.

If it is assumed that no retardation of the TCE and PCE in flow will occur, it will take from about 11 to 33 years for the TCE- and PCE-contaminated ground water to move about 460 m from well TB11 to the western boundary of the LLNL site.

If it is assumed that no retardation of the PCE in flow will occur, it will take from about 10 months to 3 years for the PCE-contaminated ground water to move about 36 m from well MW1 to the western boundary of the LLNL site.

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