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Xenon Tracer Test at Woodland Aquifer Storage and Recovery Well

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1 INTRODUCTION

The objective of this study is to conduct a tracer test to evaluate the use of Aquifer Storage and Recovery (ASR) as a supplemental supply for the Davis Woodland Water Supply Project (DWWSP). The test was conducted using the City of Woodland's Well 28, which is designed for ASR. During a seven day test injection, xenon was introduced as a tracer. The arrival of introduced xenon at two monitoring wells during the injection phase of the test was investigated to derive the effective porosity, isotropy and dispersivity of the aquifer. During the retrieval of the injected water over a period of 10 days after the injection, the ASR well was sampled to investigate the mixing of injected water with ambient groundwater.

2 METHODS

Xenon Injection

Xenon gas with natural isotopic composition was pre-dissolved in water in the laboratory. Deionized water was first degassed using the Lawrence Livermore National Laboratory (LLNL) Gas Extraction System (GES). Removing atmospheric gases allows xenon gas to dissolve without increasing the total dissolved gas pressure above 1 atmosphere, which would result in ebullition of the xenon gas. The xenon gas was introduced using 100 feet (ft) of thin-walled silicon tubing (diffusion tubing). Preliminary tests showed that saturation (a dissolved xenon concentration in equilibrium with 1 atmosphere of xenon) was reached overnight. The xenon-enriched water was transferred to 100L Mylar (party) balloons inside 20-liter (L) buckets. The gas impermeable Mylar balloon prevents the escape of xenon to the atmosphere while the xenon-enriched water is pumped out. Because the Mylar balloon is fragile, the bucket holds the weight of the water.

This xenon-enriched water was injected into the ASR well with a pulsed injection system using the sampling port at the well head. Xenon-enriched water saturated at atmospheric pressure contains 0.102 liters at standard temperature and pressure (L-STP) xenon per liter water at 24 degrees Centigrade (°C). The xenon concentration in the injected water was monitored daily and concentrations were found to be 0.084 L-STP/L water (± 5 percent), 83 percent of the saturated xenon concentration. During the seven-day injection period, the injection rate was monitored by weighing the bucket with xenon-enriched water daily. A total of 56 liters of xenon-enriched water were injected at an average rate of 5.6 (± 8 percent) milliliters per minute. Based on these metrics, it was estimated that a total of 4.75 L of xenon gas was introduced. The dilution of xenon-enriched water by the total injection flow rate of 892 gallons

per minute (gpm) was expected to result in a xenon concentration of 12 times the natural background in injected ASR water.

Groundwater Age Sample

Before the start of the test, a groundwater sample was analyzed for groundwater age tracers: tritium, the helium isotope ratio of dissolved helium and the concentrations of dissolved noble gases (helium, neon, argon, krypton, and xenon). Noble gas concentrations are used to examine recharge conditions, including recharge temperatures and excess air concentrations. Additional background information describing the interpretation of tritium and noble gas concentrations is provided in Appendix A.

Sample Collection and Analysis

Samples were collected by West Yost Associates (West Yost) staff at variable time intervals during the injection and recovery period. Samples were collected in 40-mL amber glass vials and analyzed in duplicate. Samples were analyzed by the Environmental Radiochemistry Noble Gas Mass Spectrometry Laboratory at LLNL using the noble gas membrane inlet mass spectrometer (NG-MIMS). The analysis of noble gas samples by the NG-MIMS is described in detail in (Visser et al., 2013). All analysis results are listed in Appendix B. The concentration of xenon is expressed in cubic centimeters (cm^3) xenon at standard temperature and pressure per gram of water ($\text{cm}^3\text{STP/g}$) and relative to the injected xenon concentrations (C/C_0).

3 RESULTS

Groundwater Age of ASR Well before Injection Test

One sample collected from the ASR well prior to the tracer test was analyzed for both tritium and noble gases. Analytical results and derived parameters are presented in Table 1. The sample contained a tritium concentration of 3.0 ± 0.2 picocuries per liter (pCi/L), indicating the presence of modern water that has recharged since 1950. From the dissolved noble gas composition, a recharge temperature of 15 ± 1 °C was derived. The sample contained a typical amount of excess air of 40 percent, expressed as relative excess to the equilibrium neon concentration at the recharge temperature (ΔNe).

Radiogenic helium, indicative of a groundwater component with a residence time of more than 1,000 years, was not detected. The calculated tritium-helium ($^3\text{H}/^3\text{He}$) mean apparent groundwater age was 27 ± 4 years. The uncertainty expresses the propagation of analytical uncertainty in the mean apparent groundwater age, not the range of possible ages in the sampled groundwater. The initial concentration of tritium at the time of recharge was 14 ± 1 pCi/L. This value is close to the historical reconstructed concentrations of tritium in precipitation for 1987, indicating that the age range of sampled groundwater is rather narrow. Based on the presence of tritium, the absence of radiogenic helium, the $^3\text{H}/^3\text{He}$ age and value of initial tritium, the sampled groundwater is “modern” and recharged after 1950.

Table 1: Analytical results and derived parameters from the pre-injection sample

Analyte	Concentration	Derived parameter	Value
Tritium (pCi/L)	3.0 ± 0.2	Recharge temperature	15±1 °C
³ He/ ⁴ He (10 ⁻⁶ cm ³ STP/g)	1.48 ± 0.01	Excess air (ΔNe)	40%
⁴ Helium (10 ⁻⁸ cm ³ STP/g)	7.39 ± 0.15	Radiogenic helium	-
Neon (10 ⁻⁷ cm ³ STP/g)	3.01 ± 0.06	³ H/ ³ He age	27±4 years
Argon (10 ⁻⁴ cm ³ STP/g)	4.00 ± 0.08	Initial ³ H	14±1 pCi/L
Krypton (10 ⁻⁸ cm ³ STP/g)	8.19 ± 0.25		
Xenon (10 ⁻⁸ cm ³ STP/g)	1.19 ± 0.04		

Arrival of Xenon in Monitoring Wells

Xenon was detected in two monitoring wells at the end of the seven-day injection period (Figure 1, Table 2). The arrival of the tracer was reported as the first significant detection above natural background and as the (interpolated) time when the sampled concentration reached half of the initial injected concentration. The first arrival time represents the transport velocity including the effect of dispersion. The second arrival time represents the mean groundwater flow velocity from the injection well to the monitoring well.

Table 2: Detection and arrival times of xenon at monitoring wells 3 and 4.

Monitoring Well Screen	Distance (ft)	Screened Interval (ft-bgl)	First Arrival ^a	C/C ₀ = ½	Mean Velocity (ft/day)
MW-3A	85	82-92	Not detected		
MW-3B	85	228-248	Not detected		
MW-3C	85	426-476	2/25 0:00 (15h)	2/25 20:00 (35h)	48
MW-3D	85	524-534	Not detected		
MW-4A	186	79-88	Not detected		
MW-4B	186	224-244	Not detected		
MW-4C	186	429-459	2/25 9:45 AM (25h)	2/28 15:40 (103h)	49

a: Xenon injection was initiated at 9:00 AM on 24 February 2014.

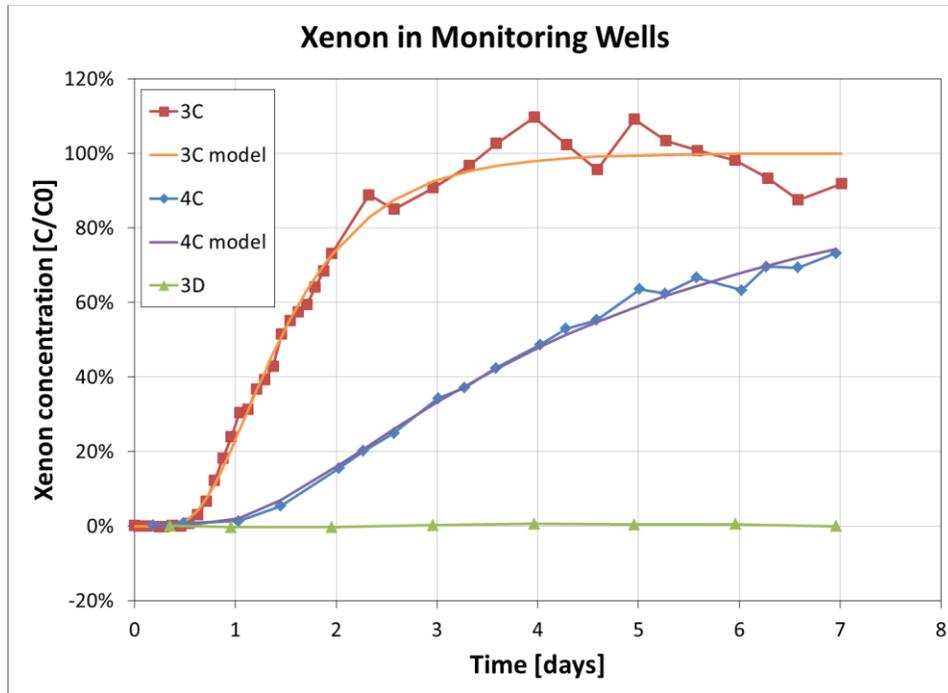


Figure 1: Concentrations of xenon in monitoring wells 3C, 3D and 4C, relative to the fitted concentration of xenon in the injected water.

Figure 1 also shows the fitted breakthrough curves developed using a one-dimensional (1D) analytical advection-dispersion model (Eq. 1).

$$\frac{C}{C_0} = \frac{1}{2} \left[\operatorname{erfc} \left(\frac{x - vt}{2\sqrt{\alpha_L vt}} \right) + \exp \left(\frac{x}{\alpha_L} \right) \times \operatorname{erfc} \left(\frac{x + vt}{2\sqrt{\alpha_L vt}} \right) \right] \quad [\text{Eq. 1}]$$

The 1D model, which predicts the concentration of xenon in groundwater as a function of distance from the injection well (x) and time since beginning of injection (t), uses the complementary error function (erfc) to fit the following parameters: the injected xenon concentration of injection water (C_0), the mean flow velocity to the monitoring well (v), and the dispersivity of the aquifer (α_L). Table 3 lists the fitted parameter values.

Wells 3C and 4C are on opposite sides of the ASR injection well, and their breakthrough curves were fit separately. The xenon concentration at well 3C leveled off after three days of injection. In contrast, the xenon concentration at well 4C was still rising at the end of the seven-day injection period. For well 3C, all three of the fitting parameters (injected xenon concentration, flow velocity and dispersivity) were fit to the 1D model of the breakthrough curve. For well 4C, however, only the mean flow velocity and dispersivity were fit to the breakthrough curve. For this well the injected xenon concentration value was assumed to be the same as for well 3C.

Table 3: Fitted parameters of the analytical 1D advection-dispersion model.

Monitoring Well Screen	Distance (ft)	Injected Concentration C_0 (relative to background)	Flow Velocity v (ft/day)	Dispersivity α_L (ft)
MW-3C	85	9.7	53	12
MW-4C	186	9.7	33	66

The fitted concentration of xenon in injected water (C_0 , expressed in Table 3 relative to the concentration of xenon in ambient groundwater $1.19 \times 10^{-8} \text{ cm}^3\text{STP/g}$) was 9.7 times background. The two estimates of the xenon concentration in the injected ASR water, calculated from either (1) the dilution of the xenon-enriched tracer water in the ASR injected water and (2) fitted to the breakthrough curve at the monitoring well, agree reasonably well. Based on the observed xenon concentrations in the monitoring wells, it appears that only 4.0 L-STP of xenon was introduced during the seven-day injection period, instead of the estimated 4.75 L-STP.

The similarity in mean flow velocity for 3C and 4C is surprising. The expanding plume of injected water, which slows down the flow velocity at greater distances from the injection well, was expected to cause a delayed arrival at the far-off monitoring well 4C. The cause for the difference in estimated dispersivity is unknown. Both aspects indicate a significant anisotropy of the aquifer or a strong regional groundwater flow velocity.

Injected Water Retrieval

Well 28 was pumped from March 3rd 15:20 until March 17th 8:00 to recover the injected water. The pumping rate was initially 1,205 gpm, but was increased on March 13th 13:00 to 1,615 gpm. Samples were collected three times per day from the sample port through which the xenon-enriched water was introduced during the injection phase. Sample results showed that the injection port was a source of xenon contamination. In response to the contamination, the recovery period was extended by four days during which samples were collected three times per day from the discharge point of the well structure rather than from the injection port. In this period, the concentrations slowly decreased from 6.4 percent to 1.3 percent of the injected concentration (C_0) (Figure 2).

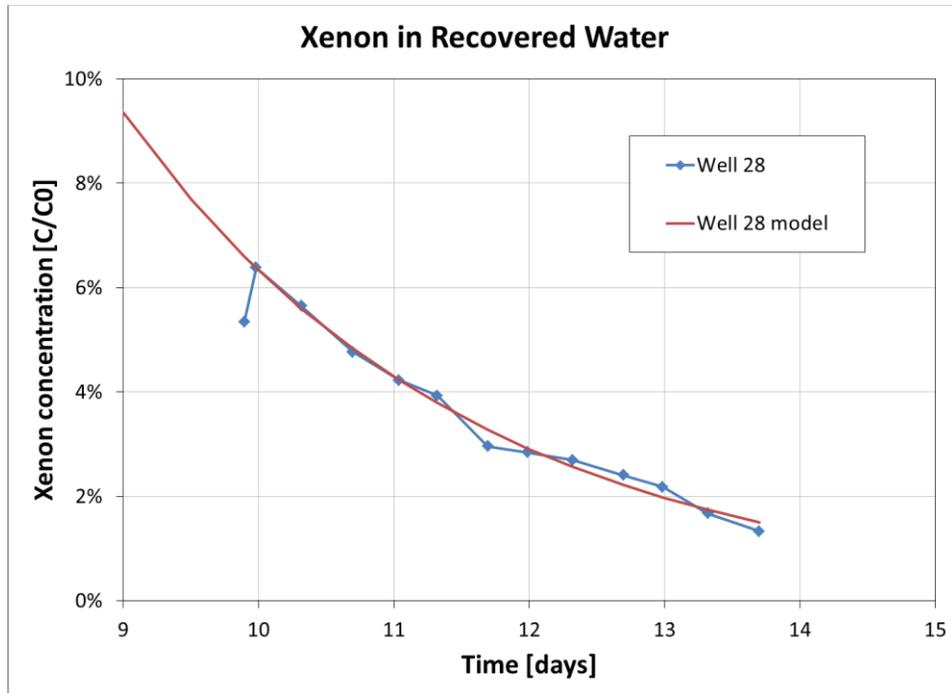


Figure 2: Concentrations of xenon in the recovered water from Well 28, from 10-14 days after the start of the retrieval.

This time series collected 10-14 days after the start of the retrieval were used to calibrate an analytical 1D advection-dispersion model to reconstruct the concentrations during the first 10 days of the retrieval period (Figure 3). The area underneath the xenon concentration in the recovered well water, multiplied by the extraction rate, represents the recovered amount of xenon.

During the seven day injection period, 4.0 L-STP of xenon was introduced, together with 9 million gallons of water. During the 14 day recovery period, 26 million gallons of water were produced from the aquifer, representing 288 percent of the injected water volume. Based on the reconstructed concentration curve and extraction rates, 3.8 L-STP of xenon was recovered. The estimated xenon recovery is in good agreement with the injected amount of xenon. Although there is no data to support the exact concentration curve during the first 10 days of the recovery period, the agreement between the injected and recovered amount of xenon lends credibility to the reconstructed curve.

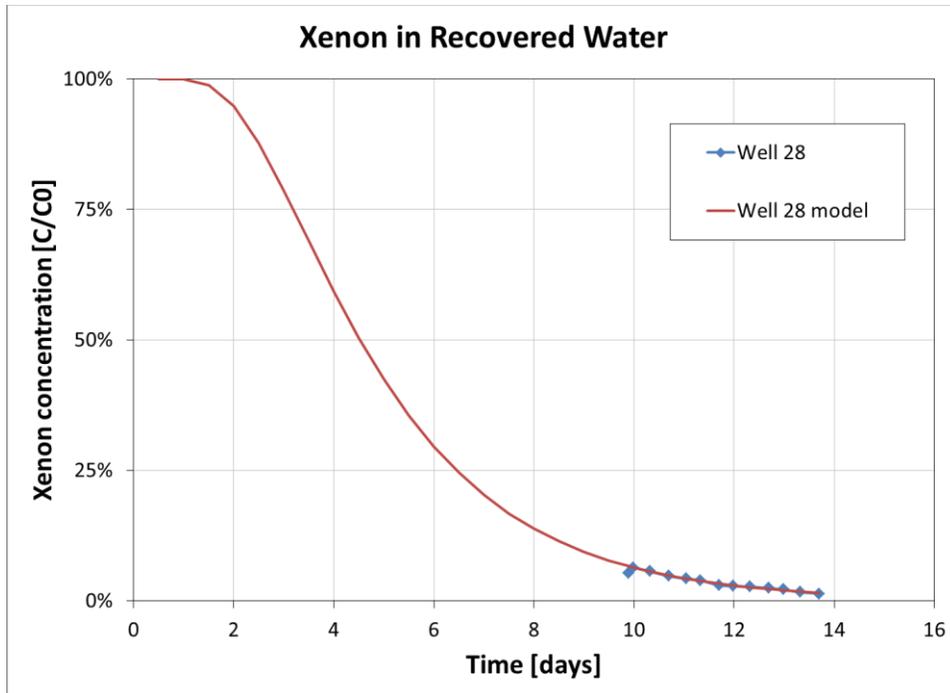


Figure 3: Reconstructed xenon concentrations using an analytical 1D advection-dispersion model.

Figure 4 shows the progress of water and xenon recovery. The entire volume of water was recovered after 5 days of extraction. At that time, 75 percent of the xenon had also been recovered. The remaining xenon was almost entirely recovered over the following 9 days.

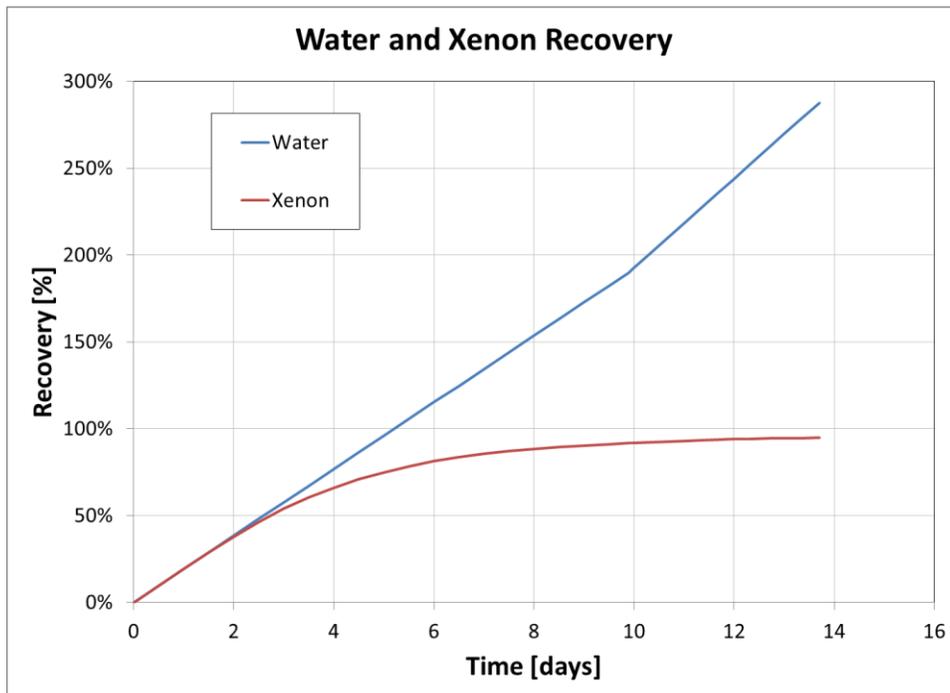


Figure 4: Recovery of water and xenon, expressed as percentage of injected volumes.

Xenon Concentrations in Monitoring Wells after Recovery Period

Xenon was detected in monitoring well 3C at the end of the recovery phase. The concentration was 17 percent above background, representing 1.7 percent of the injected concentration.

Xenon was not detected in any of the other wells after the recovery phase.

4 SUMMARY AND CONCLUSIONS

The results of groundwater age and xenon analyses of the ASR injection test can be summarized as follows:

- Native groundwater extracted by the ASR well has a $^3\text{H}/^3\text{He}$ age of 27 ± 4 years. (The uncertainty expresses the propagation of analytical uncertainty in the mean apparent groundwater age, not the range of possible ages in the sampled groundwater.)
- Injected water reached monitoring well 3C on February 25th 0:00 AM, 15 hours after the start of the injection.
- The mean linear groundwater velocity between the injection well and well 3C was 16 m/day (53 ft/day). The associated longitudinal dispersivity is 3.6 m (12 ft).
- Injected water reached monitoring well 4C on February 25th 9:45 AM, 25 hours after the start of the injection.
- The mean linear groundwater velocity between the injection well and well 4C was 10 m/day (33 ft/day). The associated longitudinal dispersivity is 22 m (66 ft).
- Injected water was not detected in monitoring wells 3A, 3B, 3D, 4A and 4B.
- The similarity in mean flow velocity for 3C and 4C is surprising because the expanding plume of injected water should result in a lower mean linear flow velocity at a greater distances from the injection well. This indicates a significant anisotropy of the aquifer or a strong regional groundwater flow velocity.
- During the first 10 days of the recovery phase, samples were contaminated by the injection/sampling port.
- The port used to introduce xenon into the injected water should not be used to take samples during recovery.
- Samples collected from the 10th until the 14th day after injection showed decreasing xenon concentrations from 6.4 percent to 1.3 percent of the initial concentration.
- The estimated xenon recovery is in good agreement (95 percent) with the injected amount of xenon (4.0 L) estimated from on the observed concentrations in the monitoring well.

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Appendix A: Interpretation of tritium and dissolved noble gas concentrations

Groundwater Age-Dating Technique

Tritium (^3H) is a very low abundance (around 1 part in 10^{17} of total hydrogen), radioactive isotope of hydrogen with a half-life of 12.34 years. Natural tritium is produced in the earth's atmosphere by cosmic radiation. Atmospheric nuclear weapons testing in the 1950's and early 1960's released tritium to the atmosphere at levels several orders of magnitude above the background concentration (figure 1). This atmospheric tritium enters groundwater (as HTO, with one hydrogen atom as tritium) during recharge. Tritium concentration in groundwater is reported in units of picoCuries per liter, and has a regulatory limit (Maximum Contaminant Level or MCL) of 20,000 pCi/L. Its concentration in groundwater decreases by radioactive decay, dilution with non-tritiated groundwater, and dispersion. While the presence of tritium is an excellent indicator of water that recharged less than about 50 years ago, age dating groundwater using tritium alone results in large uncertainties due to spatial and temporal variation in the initial tritium at recharge. Measurement of both tritium and its daughter product helium-3 (^3He) allows calculation of the initial tritium present at the time of recharge (figure 2), and ages can be determined from the following relationship:

$$\text{Groundwater Age (years)} = -17.8 \times \ln(1 + {}^3\text{He}_{\text{trit}}/{}^3\text{H})$$

The age measures the time since the water sample was last in contact with the atmosphere. The ${}^3\text{He}_{\text{trit}}$ indicated in the equation is the component of ${}^3\text{He}$ that is due to the decay of tritium. Methodologies have been developed for correcting for other sources of ${}^3\text{He}$, such as the earth's atmosphere and potential small contributions from thorium and uranium decay (Aesbach-Hertig et al., 1999; Ekwurzel et al., 1994).

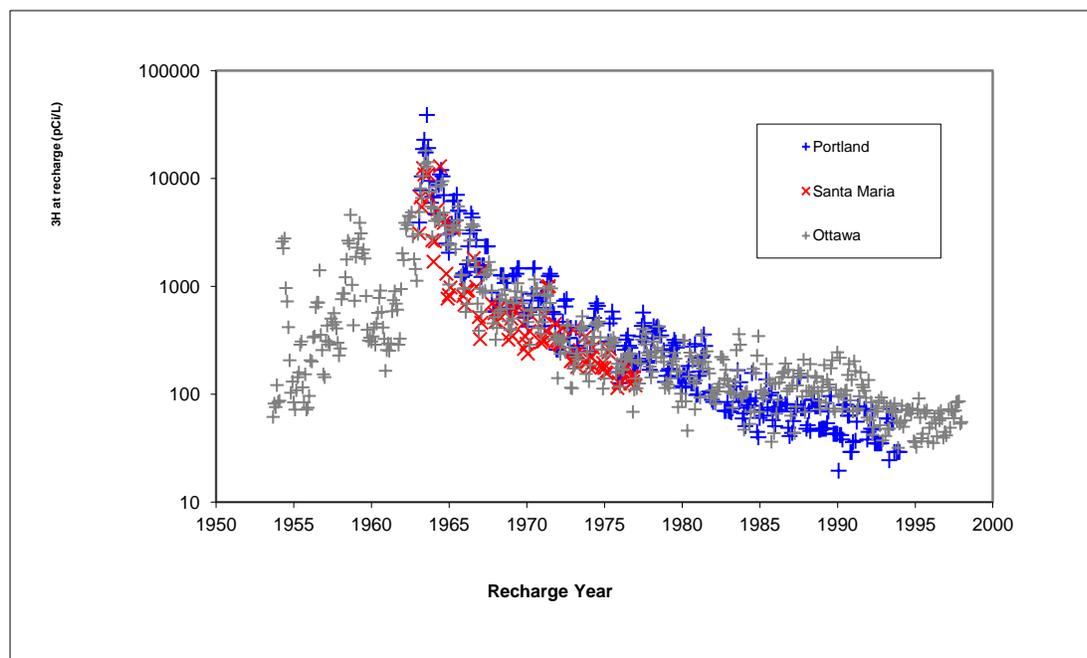


Figure 1. The tritium concentration measured in precipitation at three North American locations. Nuclear weapons testing introduced a large amount of tritium into the atmosphere in the 1960's, peaking in 1963.

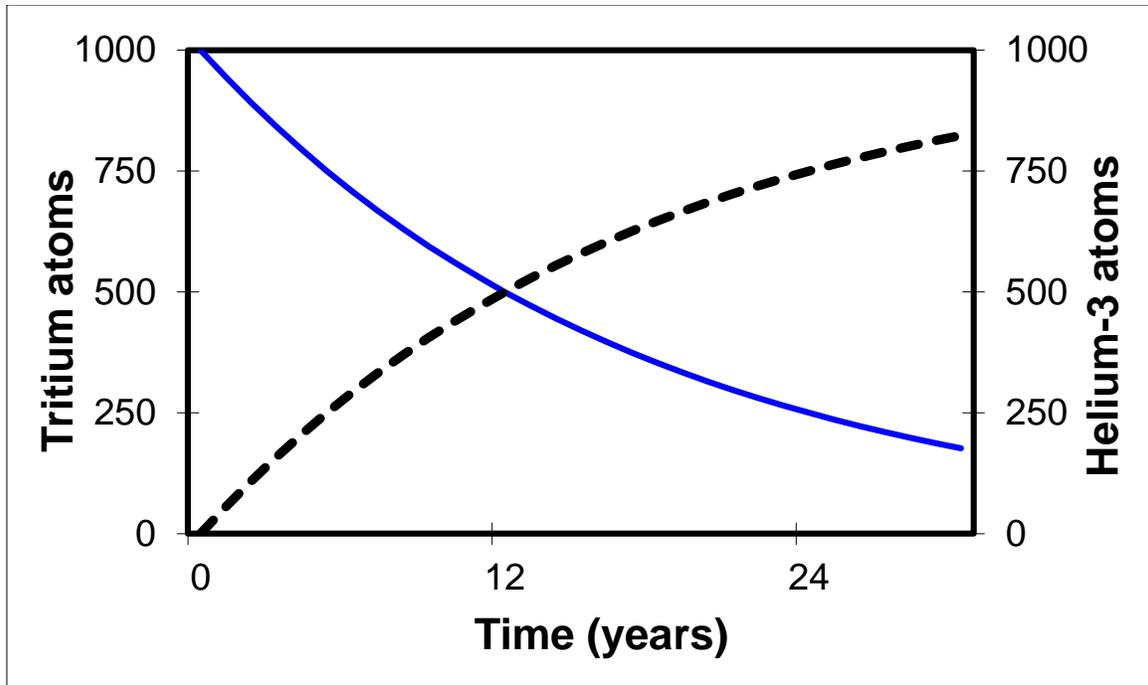


Figure 2. Solid line shows the decay of tritium, with a half-life of 12.34 years, while the dashed line shows the growth of the daughter product, ^3He . The sum of tritium and ^3He is the same at any time, and equal to the initial tritium value. This is the basis for the groundwater age-dating technique used in this study.

Well water samples are always a mixture of water molecules with an age distribution that may span a wide range. The reported groundwater age is the mean age of the mixed sample, and furthermore, is the age only of the portion of the water that contains measurable tritium. Groundwater age dating has been applied in several studies of basin-wide flow and transport (Poreda et al., 1988, Schlosser et al., 1988, Solomon et al., 1992, Ekwurzel et al., 1994, Szabo et al., 1996). The basic premise for using groundwater age to establish vulnerability is that young groundwater has been transported to a well capture zone relatively rapidly from the earth's surface. Most contaminants have been introduced in shallow zones, by human activity in the past 100 years, so younger groundwater is more likely to have intercepted contamination. On the other hand, old groundwater is likely to be isolated from the contaminating activities that are ubiquitous in modern urban environments.

Characteristics of Groundwater Derived From Dissolved Noble Gases

Excess air

During transport through the vadose zone, infiltrating water may entrain or trap air bubbles that subsequently dissolve in groundwater. Air bubbles may also become trapped in groundwater during fluctuations in the water table. This dissolved gas component is termed 'excess air' (Aesbach-Hertig et al., 2000, Holocher et al., 2002). The concentration of excess air provides valuable information about the recharge process, and is an important consideration during reduction of dissolved noble gas data to the calculated age (figure 3). For example, each measured ^3He concentration must be apportioned between the equilibrium solubility, excess air, and tritiogenic components. Excess air concentrations are derived from the measurement of excess Neon concentration because Neon can

be assumed to derive solely from the atmosphere. Excess air is reported in units of cm^3 at standard temperature and pressure (STP) per gram of water.

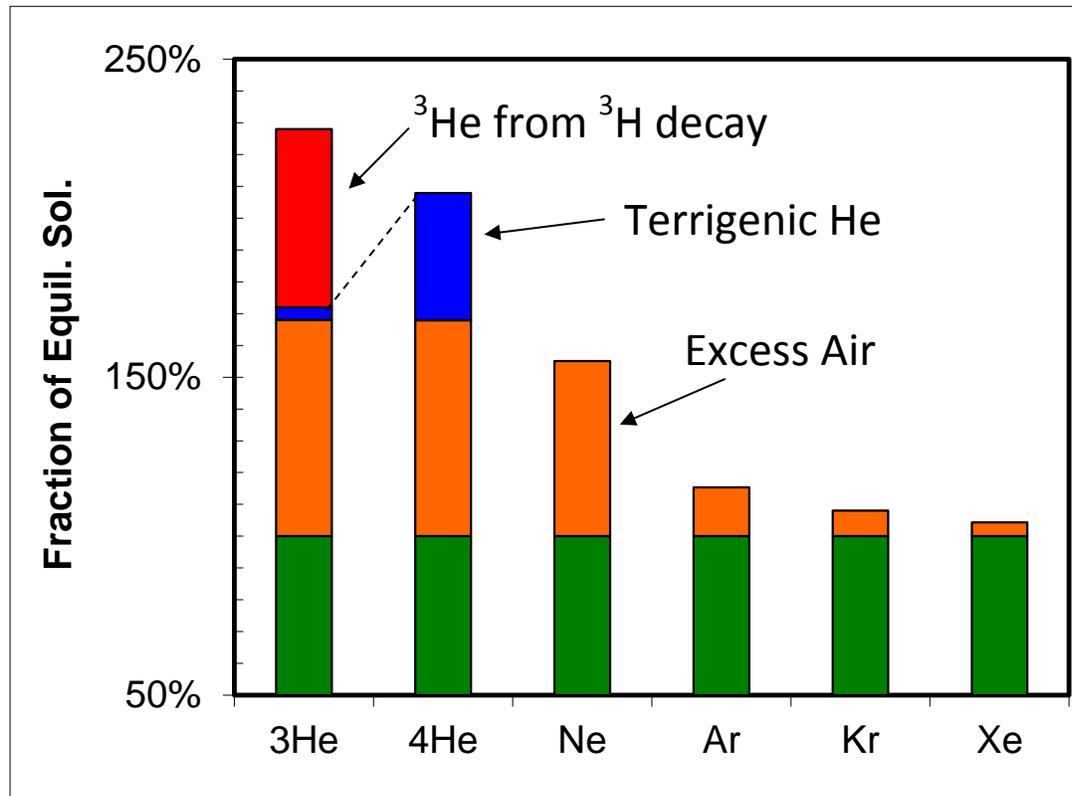


Figure 3. Graphical representation of the various dissolved noble gas components in a typical groundwater sample, relative to equilibrium solubility concentrations.

Radiogenic ^4He

The tritium-helium age dating method provides a mean age for the portion of groundwater that contains tritium (the post-modern or post-1955 portion). In many wells, a large component of pre-modern water is present, as determined by the fraction pre-modern (described above). A qualitative estimate of groundwater age for this old groundwater component comes from the in-growth of helium due to radioactive decay of uranium and thorium in crust. During the decay of naturally occurring uranium (^{238}U decaying to ^{206}Pb), alpha particles (which, after picking up electrons, become ^4He atoms) are emitted. Thus, ^4He accumulates significantly in groundwater on time scales of hundreds to thousands of years. The ^4He from U and Th decay in the earth's crust is termed 'radiogenic ^4He ', and is expected to increase along a groundwater flow path. Precise age dating using ^4He is not possible because the accumulation rate depends on poorly known factors such as host rock U and Th concentrations and rock porosity (Solomon et al., 1996; Castro et al., 2000), but groundwater with a subsurface residence time greater than a few hundred years usually contains detectable radiogenic ^4He (Moran et al., 2002, Hudson et al., 2002). This technique has been applied in deep groundwater basins in France and in Sweden and has been compared with ^{14}C dating of groundwater (Marty et al., 2003, Castro et al., 2000). Radiogenic ^4He has units of cm^3 (STP) per gram of water, and these concentrations are converted to an apparent "age" using an assumed, constant flux of ^4He from the earth's crust of $2 \times 10^{-7} \text{ cm}^3 \text{ STP cm}^{-2} \text{ yr}^{-1}$.

Noble Gas Recharge Temperature

The solubilities of the noble gases in water vary as a function of temperature and pressure and are well known from theoretical and empirical studies (figure 4; Andrews, 1992). A robust estimate of the temperature at which recharge took place is determined by measuring the concentrations of all of the dissolved noble gases, and comparing the results to the solubility curves. The temperature determination is weighted by the dissolved xenon concentration since it is most strongly dependent upon temperature. Under natural conditions, the temperature of recharge is strongly dependent upon the altitude of recharge, and noble gas recharge temperatures have been used successfully to determine recharge elevation in mountainous regions (Manning and Solomon, 2003). Another application of this technique has been in studies of paleoclimate, in which groundwater recharged under significantly colder conditions is identified (Andrews and Lee, 1979, Aesbach-Hertig et al., 2002, Clark et al., 1997). In the intensively managed groundwater basins of the coastal plain in southern California, high noble gas recharge temperatures demarcate the region affected by artificial recharge. Variation in recharge temperature occurs because natural recharge in southern California takes place in cold, high elevation areas that surround the groundwater basin, while recharging water in low elevation artificial recharge facilities equilibrates at higher temperatures (Hudson et al., 2002).

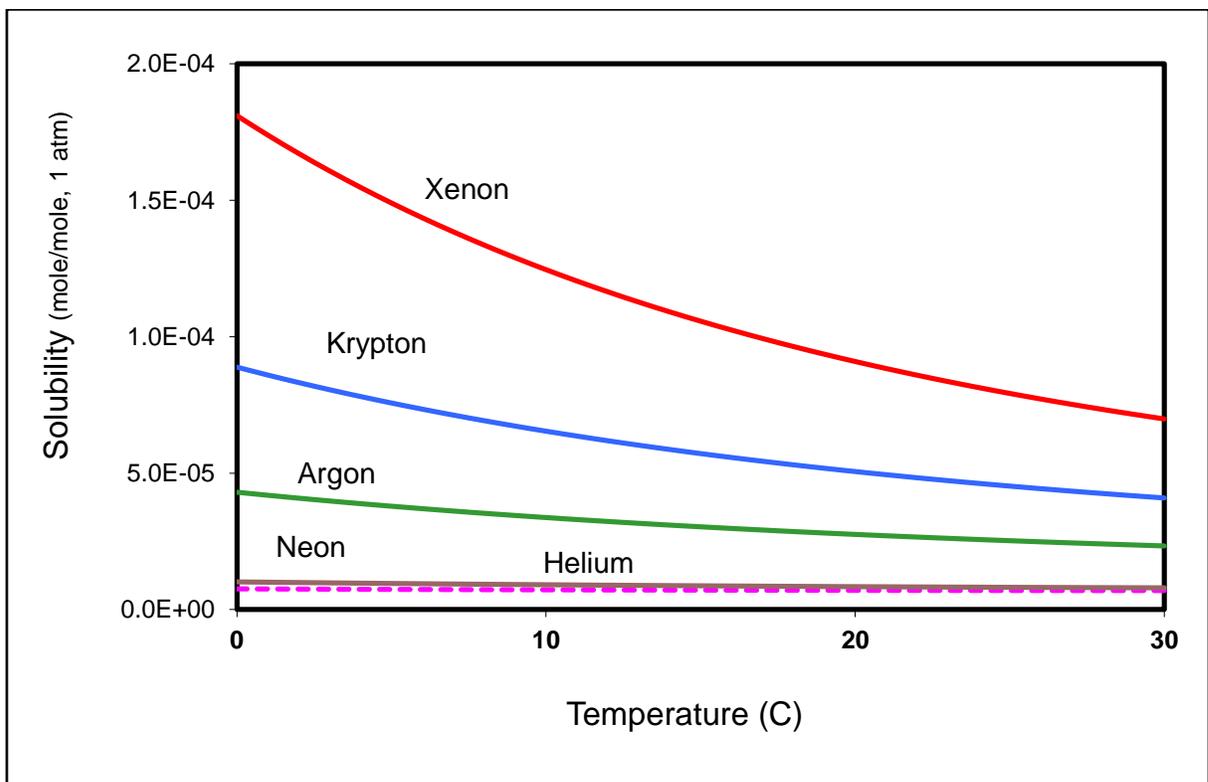


Figure 4. The solubility curves for the noble gases according to water temperature, showing the strongest temperature dependence for Xe. Noble gas recharge temperatures are calculated from these well-established curves.

Analytical methods

The Noble Gas Mass Spectrometer facility at LLNL has been operational for over twenty years. The collection and analysis of samples is described in two Standard Operating Procedures (SOPs) (Visser et al., 2013a; Visser et al., 2013b). A groundwater sample for analysis of dissolved noble gases is collected by pumping water through a soft copper tubing (0.95 cm diameter, 35 cm length) that is subsequently sealed under back-pressure with steel pinch clamps to create a gas-tight cold weld. The cold-welded copper tube typically contains 9.75 grams of water, determined accurately by weighing tube and clamps before and after analysis. The helium isotope ratio and abundances of all noble gases (He, Ne, Ar, Kr, and Xe) are measured in groundwater samples in the laboratory by mass spectrometry techniques using a VG5400 noble gas mass spectrometer. The gas samples are prepared for mass spectrometric analysis using a combination of chemical gettering and cryogenic separations. Tritium concentrations were determined on 500 g sub-samples by the ^3He in-growth method (approximately 25 day accumulation time). Analytical uncertainties are approximately 1% for $^3\text{He}/^4\text{He}$, 2% for He, Ne, and Ar, and 3% for Kr and Xe. Errors for derived parameters such as groundwater age and recharge temperature are propagated using analytical errors for the individual measured quantities.

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Xenon Tracer Test at Woodland Aquifer Storage and Recovery Well

Appendix B:

LLNLID	Well	Date/Time	Sample point	Xenon concentration ($\times 10^{-8}$ cm ³ STP/g)	Xenon concentration (percent of injected concentration)
110588	3C	February 24 09:00		1.21	0.2%
110589	3C	February 24 10:00		1.19	0.0%
110590	3C	February 24 12:00		1.19	0.0%
110591	4C	February 24 13:30		1.22	0.3%
110592	3C	February 24 14:50		1.17	-0.2%
110593	3C	February 24 16:00		1.17	-0.2%
110594	3D	February 24 17:30		1.20	0.1%
110595	3C	February 24 18:00		1.21	0.2%
110596	3C	February 24 20:05		1.19	0.0%
110597	4C	February 24 20:40		1.28	0.8%
110598	3C	February 24 22:00		1.28	0.8%
110599	3C	February 25 00:00		1.54	3.0%
110600	3C	February 25 02:00		1.97	6.7%
110601	3C	February 25 04:00		2.60	12.2%
110602	3C	February 25 06:00		3.29	18.1%
110603	3C	February 25 08:00		3.95	23.9%
110604	3D	February 25 08:00		1.15	-0.3%
110605	4C	February 25 09:45		1.34	1.3%
110606	3C	February 25 10:00		4.71	30.5%
110607	3C	February 25 12:00		4.81	31.4%
110608	3C	February 25 14:00		5.45	36.8%
110609	3C	February 25 16:00		5.73	39.3%
110610	3C	February 25 18:00		6.15	42.9%
110611	4C	February 25 19:45		1.81	5.4%
110612	3C	February 25 20:00		7.15	51.6%
110613	3C	February 24 22:00		7.57	55.2%
110614	3C	February 26 00:00		7.84	57.5%
110615	3C	February 26 02:00		8.06	59.4%
110616	3C	February 26 04:00		8.60	64.1%
110617	3C	February 26 06:00		9.10	68.4%
110618	3C	February 26 08:00		9.65	73.2%
110619	3D	February 26 08:00		1.16	-0.3%
110620	4C	February 26 09:45		2.99	15.5%
110621	4C	February 26 15:30		3.52	20.1%
110622	3C	February 26 16:45		11.46	88.9%
110623	3C	February 26 22:45		11.01	85.0%

LLNLID	Well	Date/Time	Sample point	Xenon concentration ($\times 10^{-8}$ cm ³ STP/g)	Xenon concentration (percent of injected concentration)
110624	4C	February 26 22:45		4.07	24.9%
110625	3C	February 27 08:05		11.69	90.8%
110626	3D	February 27 08:05		1.22	0.3%
110627	4C	February 27 09:20		5.16	34.3%
110628	4C	February 27 15:30		5.48	37.1%
110629	3C	February 27 16:40		12.37	96.7%
110630	4C	February 27 23:00		6.09	42.4%
110631	3C	February 27 23:05		13.06	102.7%
110632	3C	February 28 08:10		13.87	109.7%
110633	3D	February 28 08:10		1.26	0.6%
110634	4C	February 28 09:40		6.81	48.7%
110635	4C	February 28 15:40		7.31	52.9%
110636	3C	February 28 15:50		13.03	102.4%
110637	4C	February 28 23:00		7.58	55.2%
110638	3C	February 28 23:10		12.24	95.6%
110639	3C	March 01 08:00		13.80	109.1%
110640	3D	March 01 08:00		1.24	0.4%
110641	4C	March 01 09:15		8.54	63.6%
110642	4C	March 01 15:15		8.40	62.4%
110643	3C	March 01 15:30		13.14	103.4%
110644	4C	March 01 22:50		8.89	66.6%
110645	3C	March 01 23:00		12.84	100.8%
110646	3C	March 02 08:00		12.54	98.2%
110647	3D	March 02 08:05		1.25	0.6%
110648	4C	March 02 09:35		8.51	63.3%
110649	4C	March 02 15:30		9.24	69.6%
110650	3C	March 02 15:45		11.98	93.3%
110651	4C	March 02 22:55		9.21	69.4%
110652	3C	March 02 23:00		11.31	87.5%
110653	4C	March 03 08:00		9.65	73.2%
110654	3D	March 03 08:05		1.19	0.0%
110655	4B	March 03 09:00		1.29	0.9%
110656	3C	March 03 09:15		11.81	91.9%
110657	4A	March 03 09:20		1.17	-0.2%
110658	3B	March 03 10:00		1.09	-0.9%
110659	3A	March 03 10:00		1.19	0.0%
110660	Well28	March 03 15:20	sample port	96.64	825.7%
110661	Well28	March 03 23:20	sample port	25.59	211.1%

Xenon Tracer Test at Woodland Aquifer Storage and Recovery Well

LLNLID	Well	Date/Time	Sample point	Xenon concentration ($\times 10^{-8}$ cm ³ STP/g)	Xenon concentration (percent of injected concentration)
110662	Well28	March 04 08:06	sample port	29.54	245.3%
110663	Well28	March 04 15:15	sample port	22.33	182.9%
110664	Well28	March 04 23:15	sample port	22.12	181.0%
110665	Well28	March 05 07:55	sample port	26.81	221.6%
110666	Well28	March 05 15:20	sample port	41.13	345.5%
110667	Well28	March 05 23:10	sample port	18.95	153.6%
110668	Well28	March 06 08:35	sample port	28.73	238.3%
110669	Well28	March 06 15:00	sample port	26.44	218.4%
110670	Well28	March 06 23:15	sample port	18.91	153.3%
110671	Well28	March 07 08:21	sample port	25.77	212.6%
110672	Well28	March 07 15:10	sample port	22.95	188.2%
110673	Well28	March 07 23:00	sample port	10.92	84.1%
110674	Well28	March 08 08:00	sample port	10.39	79.6%
110675	Well28	March 08 15:10	sample port	9.02	67.8%
110676	Well28	March 08 23:05	sample port	8.85	66.3%
110677	Well28	March 09 08:03	sample port	7.41	53.8%
110678	Well28	March 09 15:00	sample port	6.13	42.7%
110679	Well28	March 09 22:55	sample port	7.04	50.7%
110680	Well28	March 10 08:16	sample port	9.90	75.4%
110681	Well28	March 10 15:00	sample port	10.41	79.8%
110682	Well28	March 10 23:00	sample port	11.50	89.2%
110683	Well28	March 11 07:45	sample port	9.71	73.7%
110684	Well28	March 11 14:50	sample port	9.17	69.1%
110685	Well28	March 11 23:00	sample port	7.56	55.1%
110686	Well28	March 12 08:45	sample port	10.13	77.3%
110687	Well28	March 12 15:00	sample port	6.68	47.5%
110688	Well28	March 12 22:55	sample port	9.78	74.3%
110689	Well28	March 13 08:00	sample port	7.56	55.1%
110690i	Well28	March 13 12:47	sample port	20.90	170.5%
110690o	Well28	March 13 12:47	discharge point	1.81	5.3%
110691	Well28	March 13 14:50	sample port	8.57	63.8%
110692	Well28	March 13 14:55	discharge point	1.93	6.4%
110693	Well28	March 13 22:55	discharge point	1.84	5.6%
110694	Well28	March 14 08:00	sample port	11.72	91.1%
110695	Well28	March 14 08:00	discharge point	1.74	4.8%
110696	Well28	March 14 16:15	sample port	5.16	34.3%
110697	Well28	March 14 16:15	discharge point	1.68	4.2%
110698	Well28	March 14 23:00	sample port	4.01	24.4%

LLNLID	Well	Date/Time	Sample point	Xenon concentration ($\times 10^{-8}$ cm ³ STP/g)	Xenon concentration (percent of injected concentration)
110699	Well28	March 14 23:00	discharge point	1.64	3.9%
110700	Well28	March 15 08:00	sample port	2.92	15.0%
110701	Well28	March 15 08:00	discharge point	1.53	3.0%
110702	Well28	March 15 15:00	sample port	10.06	76.8%
110703	Well28	March 15 15:00	discharge point	1.52	2.8%
110704	Well28	March 15 23:00	sample port	3.69	21.6%
110705	Well28	March 15 23:00	discharge point	1.50	2.7%
110706	Well28	March 16 08:00	sample port	4.36	27.4%
110707	Well28	March 16 08:00	discharge point	1.47	2.4%
110708	Well28	March 16 15:00	sample port	7.28	52.7%
110709	Well28	March 16 15:00	discharge point	1.44	2.2%
110710	Well28	March 16 23:00	sample port	9.54	72.2%
110711	Well28	March 16 23:00	discharge point	1.38	1.7%
110712	Well28	March 17 08:05	sample port	9.35	70.6%
110713	Well28	March 17 08:05	discharge point	1.34	1.3%
110714	3D	March 19 09:45		1.19	0.0%
110715	4B	March 19 10:20		1.28	0.8%
110716	4A	March 19 11:10		1.22	0.3%
110717	3C	March 19 11:30		1.39	1.7%
110718	3B	March 19 13:00		1.15	-0.3%
110719	4C	March 19 13:30		1.29	0.9%
110720	3A	March 19 14:00		1.18	-0.1%