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Tritium/Helium-3 Apparent Ages of Shallow Ground Water, Portland Basin, Oregon, 1997–98

Scientific Investigations Report 2009–5057

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Conversion Factors

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
	Volume	
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	0.2642	gallon (gal)
	Mass	
gram	0.03527	ounce, avoirdupois (oz)

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

$$°F=(1.8x°C)+32.$$

Datums

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

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

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By Stephen R. Hinkle

Abstract

Water samples for tritium/helium-3 age dating were collected from 12 shallow monitoring wells in the Portland basin, Oregon, in 1997, and again in 1998. Robust tritium/helium-3 apparent (piston-flow) ages were obtained for water samples from 10 of the 12 wells; apparent ages ranged from 1.1 to 21.2 years. Method precision was demonstrated by close agreement between data collected in 1997 and 1998. Tritium/helium-3 apparent ages generally increase with increasing depth below the water table, and agree well with age/depth relations based on assumptions of effects of recharge rate on vertical ground-water movement.

Introduction

The age of ground water is defined as the time of travel of a parcel of water from the water table to a downgradient measurement point such as a well. Knowledge of ground-water age is essential to constraining rates of ground-water movement and of contaminants transported with ground water. To better characterize apparent (piston-flow) ground-water age in selected recharge areas in the Portland basin, the City of Portland Bureau of Environmental Services (BES) and the U.S. Geological Survey (USGS) collected water samples for tritium/helium-3 analysis from 12 shallow monitoring wells (fig. 1). Apparent ground-water age was determined by the tritium/helium-3 method. Samples were collected during October 1997, and again during April 1998. Ten of these twelve wells were originally installed as part of the National Water-Quality Assessment (NAWQA) Program in 1995 (Hinkle, 1997). Two wells were subsequently installed by BES, following NAWQA protocols (Lapham and others, 1995).

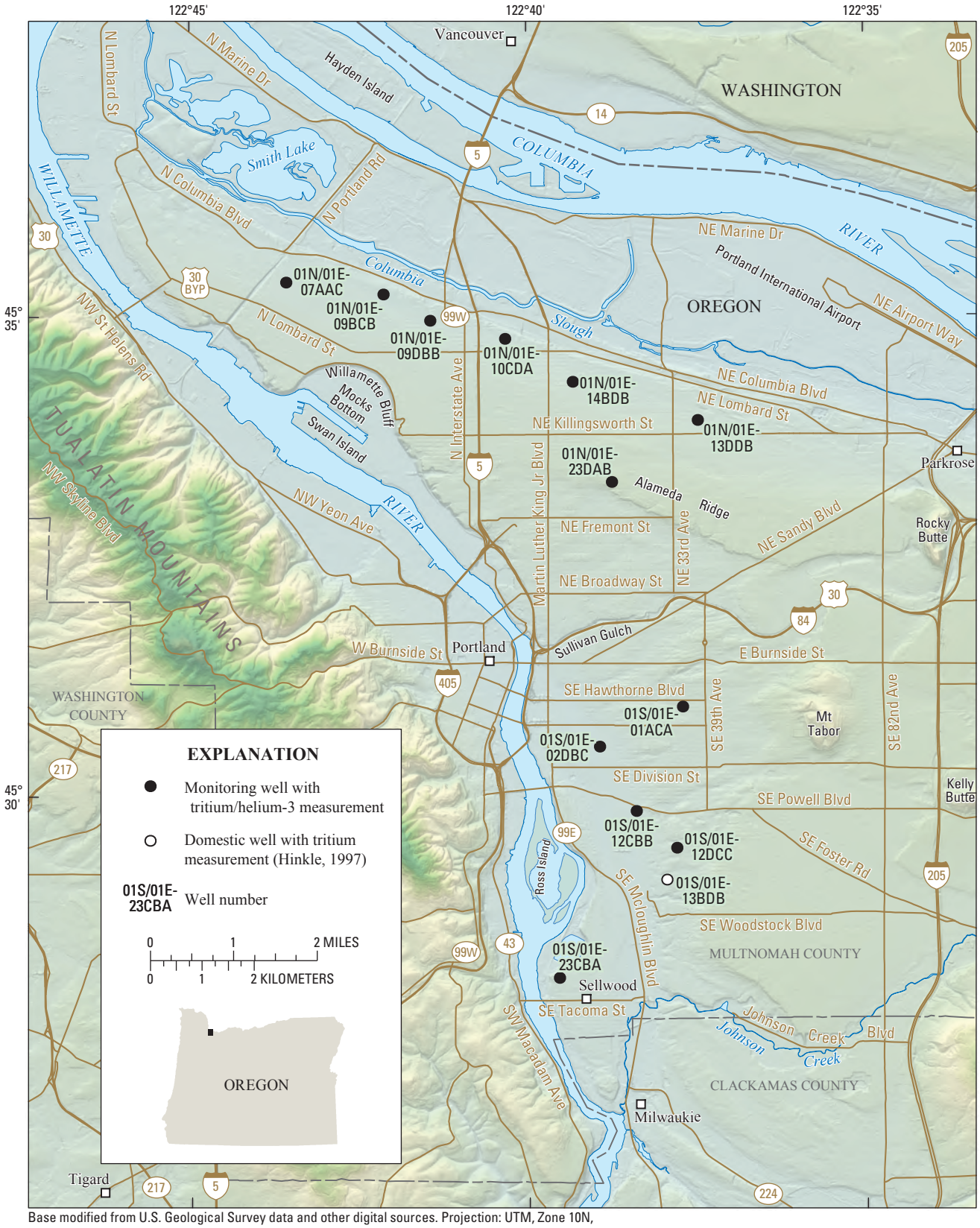
This report documents tritium/helium-3 data collected in 1997–98. Unprocessed data and interpreted apparent ground-water ages are briefly presented. Additional information about the NAWQA monitoring wells and the quality of water sampled from those wells is provided in Hinkle (1997). The environmental setting of these wells is described in Uhrich and Wentz (1999), and the ground-water flow system is described in McFarland and Morgan (1996).

Methods

The tritium/helium-3 method of dating ground water is well established (for example, Schlosser and others, 1989; Solomon and Cook, 2000). Thus, only a brief description of the method is given here.

Tritium (^{3}H) is a radioactive isotope of hydrogen. Prior to 1953, tritium concentrations in western Oregon precipitation were about 3–5 tritium units (TU) (Thatcher, 1962); this range represented natural background (“pre-bomb”) concentrations prior to widespread atmospheric testing of thermonuclear weapons. Thermonuclear testing injected large quantities of tritium into the atmosphere, and tritium concentrations in precipitation increased markedly in the 1950s. Tritium concentrations peaked in the northern hemisphere in 1963, and have been steadily decreasing since that time. The half-life of tritium is 12.43 years. The decay product of tritium is helium-3 (^{3}He).

Helium has two stable isotopes, helium-3 and helium-4 (^{4}He). Most helium in the natural environment is helium-4; helium-3 concentrations are orders of magnitude smaller than helium-4 concentrations. Helium concentrations in ground water originate from several sources; these sources must be accounted for in order to estimate tritium/helium-3 apparent ages.



Base modified from U.S. Geological Survey data and other digital sources. Projection: UTM, Zone 10N, North American Datum 1983, Scale factor= 0.9996, False easting = 500,000, False northing = 0.

Figure 1. Locations of 12 monitoring wells sampled for tritium/helium-3 dating, Portland basin, Oregon.

Water in contact with the atmosphere contains gases, including helium, as a result of equilibrium (Henry's law) partitioning between atmosphere and water. In ground water, final solubility equilibration between water and air occurs as water reaches the water table. This source of gases to water is referred to as "air-water solubility." Air-water solubility is a function of recharge temperature and recharge altitude. When recharge temperature and recharge altitude are well characterized, air-water solubility is well constrained.

Another source of gases to ground water is known as "excess air" (Heaton and Vogel, 1981; Busenberg and Plummer, 2000; Stute and Schlosser, 2000). Excess air is thought to result from a fluctuating water table entraining air bubbles or from recharge water trapping air bubbles near the water table. These air bubbles dissolve into ground water as ground water migrates below the water table and hydrostatic pressure increases. Excess air is nearly ubiquitous in ground water (Busenberg and Plummer, 2000). Gases, including helium and neon, in excess air commonly are assumed to be added to ground water in the proportions in which they exist in the atmosphere (that is, unfractionated) (Heaton and Vogel, 1981; Schlosser and others, 1989; Klump and others, 2008). Unlike helium, neon does not have significant subsurface sources, so neon concentrations in ground water are used, along with estimates of recharge temperature and altitude, to determine the air-water solubility and excess air components of helium in ground water.

Helium also is added to ground water from subsurface radiogenic sources. Radiogenic helium primarily is derived from uranium- and thorium-series decay reactions in the Earth's crust. The helium-3/helium-4 ratio of radiogenic helium is about 2×10^{-8} (Mamyrin and Tolstikhin, 1984).

Mantle helium also may be present in ground water, but probably is rare in young ground water (Solomon and Cook, 2000). The helium-3/helium-4 ratio of mantle helium is on the order of 3×10^{-5} (Mamyrin and Tolstikhin, 1984).

Finally, helium-3 is added to ground water by decay of tritium to helium-3. For determination of apparent ground-water age by the tritium/helium-3 method, tritiogenic helium-3 is considered to be the helium-3 not accounted for by air-water solubility, excess air, and radiogenic sources. Helium-3 and helium-4 from air-water solubility are determined from recharge temperature and altitude, and the known helium-3 and helium-4 content of air. Helium-3 and helium-4 from excess air are proportional to the neon from excess air. Neon contributed from excess air is the neon in excess of air-water solubility. Any helium-4 not accounted for by air-water solubility and excess air is assumed to represent helium from radiogenic sources, and the helium-3/helium-4 ratio of radiogenic helium is used to determine the helium-3 contributed from radiogenic sources. Any remaining helium-3 is assumed to represent tritiogenic helium-3. Once the tritiogenic helium-3 is known, the reconstructed (that is, original, or beginning-of-the-flowpath) tritium concentration can be calculated; it is the sum of the measured tritium and the tritiogenic helium-3. Determination of the ground-water apparent age is then simply a matter of calculating the time required for the original tritium concentration to decay to the measured tritium concentration. When recharge temperature and altitude are known, these various sources of helium may be well defined, and reliable estimates of ground-water apparent ages may be obtained. The reliability of the tritium/helium-3 method has been demonstrated in studies comparing tritium/helium-3 apparent ages with estimates of traveltimes obtained by other means such as chlorofluorocarbon dating (for example, Solomon and others, 1993; Ekwurzel and others, 1994; Szabo and others, 1996).

Based on argon and nitrogen concentrations in ground water, Hinkle and Snyder (1997) calculated a mean recharge temperature of 8°C for Portland basin ground water. This recharge temperature was used in calculating tritium/helium-3 apparent ages. Recharge altitudes were assumed to be the altitude of the water table at the time of sampling. Tritium/helium-3 apparent ages in this report would vary by about 0.6 year for a difference of 2°C in the recharge temperature, and by about 0.1 year for a 100-m change in recharge altitude.

Water samples were collected in-line, in 8-mm inside-diameter, 0.9-m length copper tubes and sealed at each end with cold-weld clamps. Samples were analyzed at Lamont-Doherty Earth Observatory of Columbia University. Helium-4 concentrations and helium-3/helium-4 ratios were measured in a dedicated helium isotope mass spectrometer. Neon was measured in a quadrupole mass spectrometer. Tritium was determined using the helium-3 ingrowth method. Details of methods used to collect and analyze samples are given in Koterba and others (1995) and Plummer and Mullin (1997a, 1997b), and references therein.

Tritium, Helium, and Neon Data, and Apparent Ages

Tritium, helium, and neon data, and tritium/helium-3 apparent ages are presented in table 1. Apparent ages are reasonable for 10 of the 12 sites; apparent ages range from 1.1 to 21.2 years. Data for the other two wells indicate site-specific problems, and can not be reliably dated (see sections, "Helium-4 and Neon Data" and "Tritium Data"). Apparent ages derived from data collected in 1997 and 1998 agree well; absolute differences range from 0.2 to 5.8 years, with a median absolute difference of 1.2 years. Reasonable method precision also is demonstrated in replicate data (table 1).

Table 1. Tritium, helium, and neon data, and tritium/helium-3 apparent ages for water from monitoring wells, Portland basin, Oregon, 1997–98.

[**Local park or property name**: Name of City of Portland park or property where well is located. **Sample date** presented in month/day/year. **Helium-4** and **Neon** in cubic centimeters per 10^8 grams water at standard temperature and pressure. **Helium-3** reported in percent (%) using standard delta notation. –, not analyzed in replicate]

Site No.	Site name	Local park or property name	Sample date	Tritum (tritium units)	Helium-4	Delta-Helium-3 (percent)	Neon	Apparent age (years)
			Environmental Data					
453523122433001	01N/01E-07AAC	North Gate	10/20/1997	4.03	5.95	-4.07	25.92	([1])
			04/09/1998	3.85	5.90	-3.72	24.46	([2])
453515122420301	01N/01E-09BCB	Trenton	10/10/1997	8.59	5.74	4.90	22.86	7.1
			04/06/1998	8.65	5.76	8.24	22.72	9.0
453458122412201	01N/01E-09DBB	Kenton	10/09/1997	8.31	5.48	0.05	22.36	3.8
			04/07/1998	8.79	6.88	2.18	25.08	9.6
453447122401501	01N/01E-10CDA	Faragut	10/08/1997	8.88	5.44	-0.62	21.01	6.3
			04/08/1998	8.06	5.45	-1.59	20.97	6.5
453356122372401	01N/01E-13DDB	Fernhill	10/22/1997	7.04	5.18	-3.90	21.24	2.4
			04/20/1998	6.71	5.05	-2.89	20.78	3.3
453419122391501	01N/01E-14BDB	Woodlawn	10/23/1997	7.79	6.25	-14.33	22.81	1.1
			04/22/1998	6.48	5.64	-10.64	21.42	2.6
453317122384101	01N/01E-23DAB	Vernon Tanks	10/24/1997	8.74	7.16	-21.31	22.05	5.6
			04/23/1998	7.98	7.13	-22.61	21.62	6.1
453037122373701	01S/01E-01ACA	Sunnyside	10/06/1997	13.64	5.90	72.87	22.16	20.2
			04/15/1998	12.69	5.84	74.84	22.16	21.2
453032122385201	01S/01E-02DBC	Ladd	10/07/1997	2.17	6.43	2.19	23.31	([3])
			04/16/1998	2.24	6.46	1.71	23.36	([4])
452950122382001	01S/01E-12CBB	Powell	10/21/1997	14.33	7.24	9.24	22.15	13.2
			04/21/1998	12.31	7.61	11.18	21.89	16.8
452927122374501	01S/01E-12DCC	Kenilworth	10/17/1997	7.37	5.90	8.36	23.24	10.2
			04/01/1998	6.26	5.93	4.32	23.54	8.8
452807122392901	01S/01E-23CBA	Sellwood	10/16/1997	6.85	5.83	8.09	24.40	7.0
			04/02/1998	6.14	5.94	6.31	24.90	6.2
			Replicate Data (in addition to environmental analyses above)					
453523122433001	01N/01E-07AAC	North Gate	04/09/1998	3.83	5.88	-3.26	24.37	([5])
			04/09/1998	–	5.98	-5.04	24.58	([6])
453356122372401	01N/01E-13DDB	Fernhill	04/20/1998	–	5.10	-3.66	20.70	3.6
453037122373701	01S/01E-01ACA	Sunnyside	10/06/1997	13.53	5.85	71.05	21.97	20.0
453032122385201	01S/01E-02DBC	Ladd	10/07/1997	2.12	6.48	2.01	23.33	([7])
			04/16/1998	–	6.51	1.32	23.36	([8])
			04/16/1998	2.26	6.41	3.11	23.42	([9])
			04/16/1998	–	6.46	2.55	23.46	([10])
452950122382001	01S/01E-12CBB	Powell	04/21/1998	11.71	7.60	9.11	21.81	16.9

[1]Degassing during sampling; apparent age of -16.3 years reflects degassing.

[2]Degassing during sampling; apparent age of -1.2 years reflects degassing.

[3]Apparent age 24.8 years, but affected by mixing.

[4]Apparent age 24.2 years, but affected by mixing.

[5]Degassing during sampling; apparent age of -0.4 years reflects degassing.

[6]Degassing during sampling; apparent age of -2.4 years reflects degassing.

[7]Apparent age 25.4 years, but affected by mixing.

[8]Apparent age 24.5 years, but affected by mixing.

[9]Apparent age 24.2 years, but affected by mixing.

[10]Apparent age 24.3 years, but affected by mixing.

Helium-4 and Neon Data

Helium-4 and neon concentrations are plotted in figure 2. For the most part, the various sources of helium-4 and neon are clearly seen in figure 2. A component from air-water solubility at 8°C is represented by the 8°C point on the air-water solubility curve. Additional helium and neon are derived from excess air. The component of excess air varies in each sample and is represented by movement along the excess air curve away from the air-water solubility curve. The radiogenic component of helium-4 also varies in each sample; it is represented by the departure away from (and to the right of) the excess air curve, and parallel to the abscissa (*x*-axis).

Data for well 01N/01E-07AAC (henceforth, 7AAC) is a low-yield well. Well 7AAC was sampled at a flow rate of 1.8 L/min (the well is unable to sustain a faster flow rate), resulting in a 4-minute time-of-travel through the 56 m of collection lines. Gas bubbles were observed in the collection lines, apparently a result of degassing during the long travel time in the collection lines. Degassing also might have occurred in the well if the water level in the well casing had been drawn down below the top of the screen, resulting in cascading water in the well; this is a possibility, given the fact that the well was repeatedly pumped dry during well development. Data from samples that have degassed are not suitable for tritium/helium-3 dating. Such data commonly plot above the excess air curve and tend to yield unreasonable or negative apparent ages. The 1997 sample lies above the excess air curve (fig. 2), and both the 1997 and 1998 samples have negative apparent ages (table 1). Meaningful apparent ages can not be assigned from the data for well 7AAC; therefore, the data are not interpreted further.

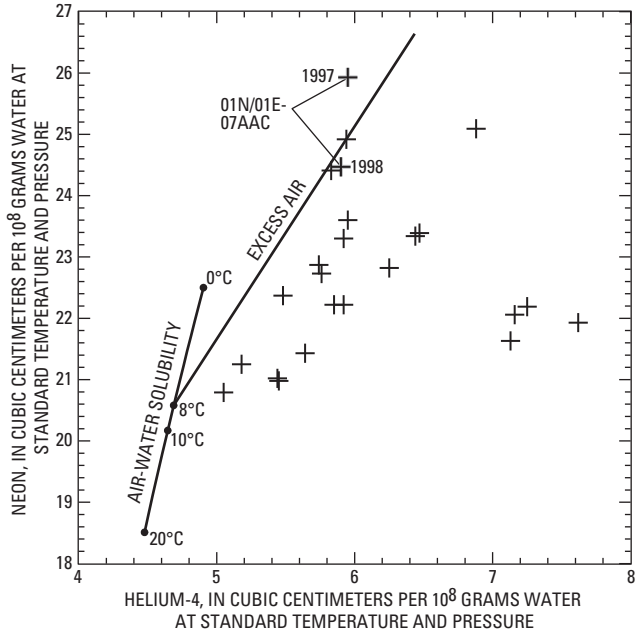


Figure 2. Comparison of helium-4 and neon concentrations for water from monitoring wells in the Portland basin, Oregon, with air-water solubility curve (Weiss, 1971) and excess air curve. Air-water solubility curve and excess air curve calculated for mean sea level; gas concentrations for water samples were adjusted (United States Committee on Extension to the Standard Atmosphere, 1976) to equivalent mean sea level concentrations.

Tritium Data

Concentrations of tritiogenic helium-3 can be combined with measured tritium concentrations to calculate reconstructed (beginning-of-the-flowpath) tritium concentrations. Reconstructed tritium concentrations are compared to apparent recharge date (sampling date minus apparent age) in figure 3. Annual precipitation-weighted tritium concentrations of Portland precipitation for 1963–93 (International Atomic Energy Agency/World Meteorological Organization, 1998) also are shown in figure 3.

Most of the reconstructed tritium concentrations plot close to, but to the right of, the precipitation data (fig. 3). This offset commonly is observed and has been attributed to the time-of-travel through the unsaturated zone (Solomon and others, 1995; Cook and Solomon, 1997; Solomon and Cook, 2000). An apparent age is an estimate of the time of travel to a measurement point from the water table, not from land surface. Water just arriving at the top of the water table will have entered the unsaturated zone at some time in the past.

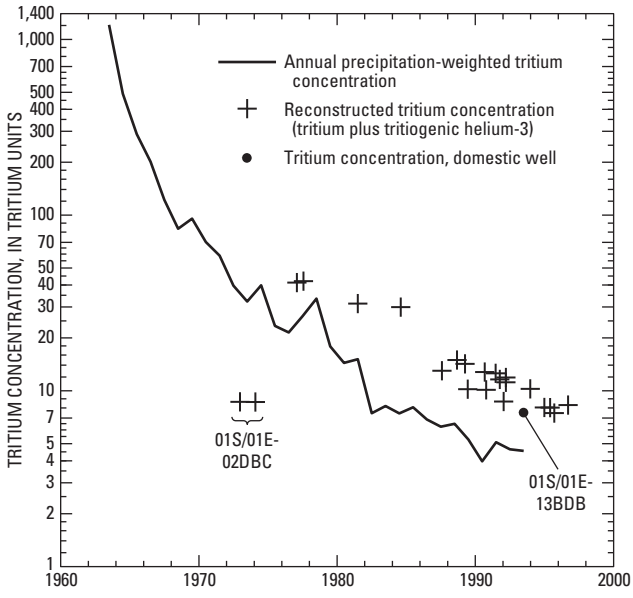


Figure 3. Comparison of reconstructed tritium concentrations for water from monitoring wells in the Portland basin, Oregon, with annual precipitation-weighted tritium concentrations in Portland precipitation, 1963–93.

The time of travel through the unsaturated zone can be on the order of years, and a response in water-table altitude during the rainy season does not indicate that the water being added to the water table from the bottom of the unsaturated zone is the same water that is entering the top of the unsaturated zone.

Another process that can cause apparent offset from the tritium input function for an aquifer is dispersion of tritium in the unsaturated zone. The tritium input function shown in figure 3 represents tritium in Portland precipitation; however, tritium crossing the water table will be affected by dispersion in the unsaturated zone (on the order of 24 m near the sampled wells). Dispersion of tritium results in moderation of the 1963 peak and an increase in later-time tritium concentrations relative to piston flow (for example, Solomon and Cook, 2000). Thus, at least some of the apparent offset from the tritium input function probably reflects actual dispersion in the unsaturated zone, which is not represented in figure 3.

Offset to the right of the precipitation data also is demonstrated (fig. 3) by data from well 01S/01E-13BDB (henceforth, 13BDB), a domestic well in the Portland basin sampled in 1993 for tritium (but not helium) as part of NAWQA activities (Hinkle, 1997). Well 13BDB is given consideration because it was screened near the top of the water table (from 0.0 to 0.8 m below the water table) when sampled. Thus, water from well 13BDB should have an age of essentially 0 years, and the reconstructed tritium concentration for this water sample should be essentially equal to the measured tritium concentration. Data for well 13BDB are offset from the precipitation data by about the same amount as the other reconstructed tritium data (except for well 01S/01E-02DBC), suggesting that these offsets are real, and not artifacts of the tritium/helium-3 method.

Data for one well, 01S/01E-02DBC (henceforth, 2DBC), plot below the tritium input function. Analytical precision is not the source of the problem with well 2DBC, as the data demonstrate reasonable precision for the six samples analyzed for this site (table 1). Offset below a tritium input function can be caused by mixing along flowpaths or in wells (Aeschbach-Hertig and others, 1998). Thus, data for well 2DBC probably represent mixing of water of different ages. For example, a mixture of 85 percent water recharged in 1947 (initial tritium concentration of 4 TU) with 15 percent water recharged in 1980 (initial tritium concentration of 35 TU) would yield the tritium and tritiogenic helium-3 concentrations observed in the 1997 and 1998 samples. This example is given only to demonstrate the effect of mixing on tritium/helium-3 apparent ages, and is not meant to imply that this mixing example represents the mixing proportions that actually occurred.

A mixing hypothesis for well 2DBC is supported by the observation that of the 12 wells sampled for this project, well 2DBC had the greatest penetration of the water table, likely increasing the opportunities for mixing in the aquifer. Water from well 2DBC probably is a mixture of water older and younger than the apparent recharge age. The apparent recharge age is considered unreliable. Water from this well is considered undatable by the tritium/helium-3 method, and the data are not further interpreted.

Age/Depth Relations

The relation between apparent age and depth (specifically, depth of the center of the well screen below the water table, or water table penetration) is presented in figure 4. The overall pattern is one of increasing apparent age with increasing depth.

Lines representing age/depth relations based on assumptions of effects of recharge rate on vertical ground-water movement also are shown in figure 4. The recharge-based age/depth relations are derived using the approach of Cook and Böhlke (2000). Briefly, for water close (relative to the thickness of the aquifer) to the water table in a recharge area of an unconfined aquifer, the time of travel can be approximated by:

$$t = \frac{z\theta}{R}, \quad (1)$$

where

t is time of travel (year),
z is depth below water table (meters),
θ is porosity (unitless), and
R is recharge rate (meters per year).

Recharge-based estimates of age/depth relations were made using recharge rate estimates from a Portland basin recharge model (Snyder and others, 1994) and porosity estimates assembled for particle-tracking analysis in the

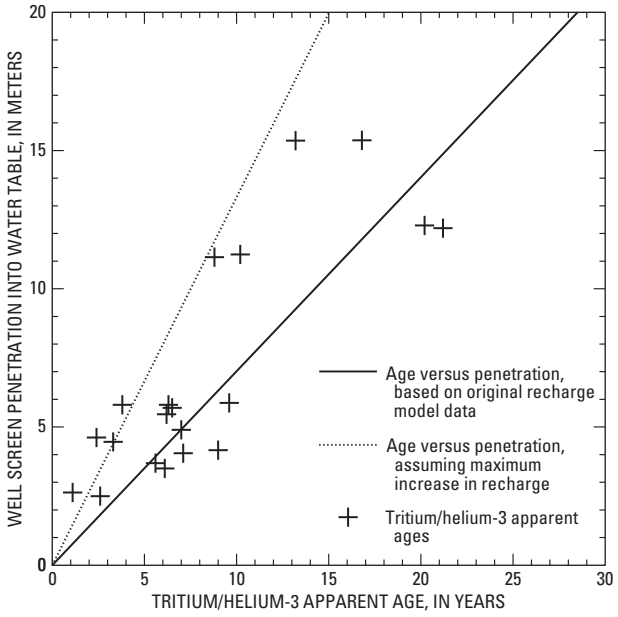


Figure 4. Comparison of tritium/helium-3 apparent age versus well penetration below water table for water from monitoring wells in the Portland basin, Oregon, with recharge-based age/depth relations.

Portland basin (Hinkle and Snyder, 1997; Snyder and others, 1998). Mean recharge rate and porosity estimates for the 10 model grid cells containing these wells were used in these calculations.

The Portland basin recharge model was a simulation of 1987–88 recharge conditions. Recharge in many core urban areas of the Portland basin likely has increased in the time since the late 1980s, in response to a program to divert more stormwater into the ground-water system using so-called drywells. To provide a measure of the possible effect of increased drywell recharge, an alternative recharge-based estimate of age/depth relations was made using recharge estimates revised to account for increased drywell density. This estimate was calculated using the methods of Snyder and others (1994) with the additional assumption that all impervious areas drain to drywells. Thus, this estimate represents the maximum recharge that would be simulated in the recharge model as a result of increased drywell density, and represents an upper bound to the estimate of recharge. Maximum-recharge-based age/depth relations also are shown in figure 4.

Age/depth relations based on original recharge estimates provide a reasonable fit to the tritium/helium-3 data (fig. 4), especially given the assumptions and uncertainties inherent in recharge-based age/depth relations. Ground-water samples with tritium/helium-3 apparent ages of less than 5 years demonstrate a somewhat closer fit to maximum-recharge-based age/depth relations. Although younger water would be most affected by recent changes in recharge rates, the apparent agreement between young (less than 5 year) tritium/helium-3 apparent ages and age/depth relations based on maximum-recharge estimates could be coincidental. Overall, the data shown in figure 4 support the original recharge estimates, but also suggest that effects of increased recharge from recently installed drywells might be starting to appear.

Summary

Age-dating data collected from 12 shallow monitoring wells in the Portland basin yield apparent ground-water ages that generally range from near 0 to about 20 years for wells screened in the uppermost 15 m of the aquifer. The age gradient in the shallow aquifer is consistent with the range of reasonable recharge rates for the aquifer. Estimates of apparent age allow reconstruction of initial tritium concentrations for ground-water samples; the pattern of these reconstructed tritium concentrations matches historical tritium input records, providing support for the interpreted apparent ages. Knowledge of the apparent ages of ground water produced by these monitoring wells could be used to help calibrate flow models or elucidate trends in ground-water quality.

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