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Estimates of Tracer-Based Piston-Flow Ages of Groundwater From Selected Sites: National Water-Quality Assessment Program, 1992–2005

Scientific Investigations Report 2010–5229

U.S. Department of the Interior
U.S. Geological Survey

Cover Upper: Photograph of filled and sealed copper tubes for analysis of tritium/helium-3. (Photograph taken by Stephen R. Hinkle, U.S. Geological Survey, 1999.)
Cover Lower: Photograph of U.S. Geological Survey Hydrologist analyzing a groundwater sample for dissolved chlorofluorocarbon content in the U.S. Geological Survey Reston Chlorofluorocarbon Laboratory, Reston, Virginia, using purge-and-trap gas chromatography with electron-capture detector. (Photograph taken by L. Niel Plummer, U.S. Geological Survey, Reston, Virginia, 2003.)

Estimates of Tracer-Based Piston-Flow Ages of Groundwater from Selected Sites: National Water-Quality Assessment Program, 1992–2005

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Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). The NAWQA Program is designed to answer: What is the quality of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991 to 2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html).

National and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are selectively reassessed. These assessments extend the findings in the Study Units by determining water-quality status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and ground water. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between sources of contaminants, the transport of those contaminants through the hydrologic system, and the potential effects of contaminants on humans and aquatic ecosystems. Included are studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, trace elements, and aquatic ecology are continuing.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Matthew C. Larsen
Associate Director for Water

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)

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

$$°F=(1.8×°C)+32$$

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

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

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Chlorofluorocarbon (CFC) concentrations are given in units of picograms per kilogram (pg/kg) and picomoles per kilogram (pmol/kg). One picogram is 10^{-12} grams. One picomole is 10^{-12} moles. One mole contains 6.022×10^{23} atoms or molecules of a substance. Sulfur hexafluoride (SF_6) concentrations are given in units of femtograms per kilogram (fg/kg) and femtomoles per kilogram (fmol/kg). One femtogram is 10^{-15} grams. One femtomole is 10^{-15} moles. CFC and SF_6 concentrations in gases are expressed as a mixing ratio, that is, volume of gas per volume of dry air, in parts per trillion [parts per trillion by volume (pptv)]. The mixing ratio is calculated as the atmospheric concentration that would yield the measured aqueous concentration assuming equilibrium partitioning between atmosphere and water under the specified conditions (recharge temperature, recharge altitude, and excess-air concentration).

Tritium concentrations are given in units of Tritium Units (TU). Based upon a tritium half-life of 12.32 years (Lucas and Unterweger, 2000), 1 TU is equal to 3.22 picocuries per liter.

Helium-3 (^{3}He) data are reported as δ values computed from the formula

$$\delta^3\mathrm{He} = \left[\left(\frac{R_x}{R_{STD}}\right) - 1\right]100$$

where R_x is the ratio of ^{3}He to ^{4}He in the sample, R_{STD} is the ^{3}He to ^{4}He ratio of the reference standard air (1.384×10^{-6}), and δ^3He is expressed in parts per hundred.

Excess-air concentrations (see Glossary), helium (He) concentrations, and neon (Ne) concentrations are reported in units of cubic centimeters (at standard temperature and pressure) per kilogram of water (cc(STP)/kg). One cc(STP) of He or Ne is equal to 2.6868×10^{19} atoms.

Datum

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

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

Abbreviations and Acronyms

Abbreviation or Acronym	Definition
Ar	argon
^{14}C	carbon-14
CFC	chlorofluorocarbon
CH_4	methane
CO_2	carbon dioxide
DWH	NAWQA Data Warehouse
Fe	iron
FSS	Flow System Study
FY	fiscal year
He	helium
^{3}H	tritium
^{3}He	helium-3
^{4}He	helium-4
LUS	Land-Use Study
MAAT	mean annual air temperature
MAS	Major-Aquifer Study
Mn	manganese
N_2	nitrogen (in the form dinitrogen)
NAWQA	National Water-Quality Assessment Program
Ne	neon
O_2	oxygen (in the form dioxygen)
REF	Reference well
SF_6	sulfur hexafluoride
SIO	Scripps Institution of Oceanography
STP	standard temperature and pressure
SUS	Study-Unit Survey
TU	tritium unit
UA	unfractionated air
USGS	U.S. Geological Survey

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Abstract

This report documents selected age data interpreted from measured concentrations of environmental tracers in groundwater from 1,399 National Water-Quality Assessment (NAWQA) Program groundwater sites across the United States. The tracers of interest were chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and tritium/helium-3 ($^3H/^3He$).

Tracer data compiled for this analysis primarily were from wells representing two types of NAWQA groundwater studies—Land-Use Studies (shallow wells, usually monitoring wells, in recharge areas under dominant land-use settings) and Major-Aquifer Studies (wells, usually domestic supply wells, in principal aquifers and representing the shallow, used resource). Reference wells (wells representing groundwater minimally impacted by anthropogenic activities) associated with Land-Use Studies also were included. Tracer samples were collected between 1992 and 2005, although two networks sampled from 2006 to 2007 were included because of network-specific needs. Tracer data from other NAWQA Program components (Flow System Studies, which are assessments of processes and trends along groundwater flow paths, and various topical studies) were not compiled herein.

Tracer data from NAWQA Land-Use Studies and Major-Aquifer Studies that previously had been interpreted and published are compiled herein (as piston-flow ages), but have not been reinterpreted. Tracer data that previously had not been interpreted and published are evaluated using documented methods and compiled with aqueous concentrations, equivalent atmospheric concentrations (for CFCs and SF_6), estimates of tracer-based piston-flow ages, and selected ancillary data, such as redox indicators, well construction, and major dissolved gases (N_2, O_2, Ar, CH_4, and CO_2).

Tracer-based piston-flow ages documented in this report are simplistic representations of the tracer data. Tracer-based piston-flow ages are a convenient means of conceptualizing groundwater age. However, the piston-flow model is based on the potentially limiting assumptions that tracer transport is advective and that no mixing occurs. Additional uncertainties can arise from tracer degradation, sorption, contamination, or fractionation; terrigenic (natural) sources of tracers; spatially variable atmospheric tracer concentrations; and incomplete understanding of mechanisms of recharge or of the conditions under which atmospheric tracers were partitioned to recharge. The effects of some of these uncertainties are considered herein. For example, degradation, contamination, or fractionation often can be identified or inferred. However, detailed analysis of the effects of such uncertainties on the tracer-based piston-flow ages is constrained by sparse data and an absence of complementary lines of evidence, such as detailed solute transport simulations. Thus, the tracer-based piston-flow ages compiled in this report represent only an initial interpretation of the tracer data.

Introduction

Water "age" in aquifers is a critically important hydrologic variable. The age of a molecule or particle of water from a groundwater system is defined as the time required for that water particle to travel from the point of recharge to a measurement point in the aquifer. Knowledge of groundwater age can be used to infer groundwater flow paths and recognize areas of groundwater recharge. An understanding of groundwater age can be used to reconstruct contaminant loading histories or explain trends in groundwater quality, and can contribute to the understanding of groundwater susceptibility to contamination. Estimates of groundwater age also can be used to constrain groundwater flow and transport models, rates of recharge, rates of groundwater movement, and biogeochemical reaction rates.

Although groundwater age, or time-of-travel, is an important hydrologic variable, it is not possible to sample or date individual water particles. The solution to this problem is to "date" the time-of-travel of environmental tracers that are assumed to travel conservatively with the water. Environmental tracers are widespread elements, compounds, or isotopes that can be used to estimate time-of-travel along groundwater flow paths. In this study, reference to "environmental tracers," or use of "tracers," to estimate groundwater times-of-travel on timescales of years to decades pertains specifically to the use of chlorofluorocarbons (CFCs) (Busenberg and Plummer, 1992; Plummer and Busenberg, 2000; International Atomic Energy Agency, 2006), sulfur hexafluoride (SF_6) (Busenberg and Plummer, 2000; International Atomic Energy Agency, 2006), and the combination of tritium and helium-3 ($^3H/^3He$) (Schlosser and others, 1989; Solomon and Cook, 2000).

CFCs are anthropogenic compounds that have been produced commercially since the 1930s, volatilize into the atmosphere, and subsequently partition into water that is in contact with the atmosphere. Concentrations of CFCs have varied over time, facilitating their use in age dating. In this report, three CFCs were used for age-dating purposes: CFC-11 ($CFCl_3$), CFC-12 (CF_2Cl_2), and CFC-113 ($C_2F_3Cl_3$). SF_6 is a compound that has natural and anthropogenic sources. Like CFCs, SF_6 volatilizes into the atmosphere, and subsequently partitions into water that is in contact with the atmosphere. SF_6 concentrations have been increasing over time, facilitating the use of SF_6 in age-dating applications where natural sources of SF_6 are absent or negligible. $^3H/^3He$ refers to the combined use of ^3H (tritium) and its decay product, ^3He (helium-3). Radioactive decay of ^3H to ^3He allows elapsed time to be calculated.

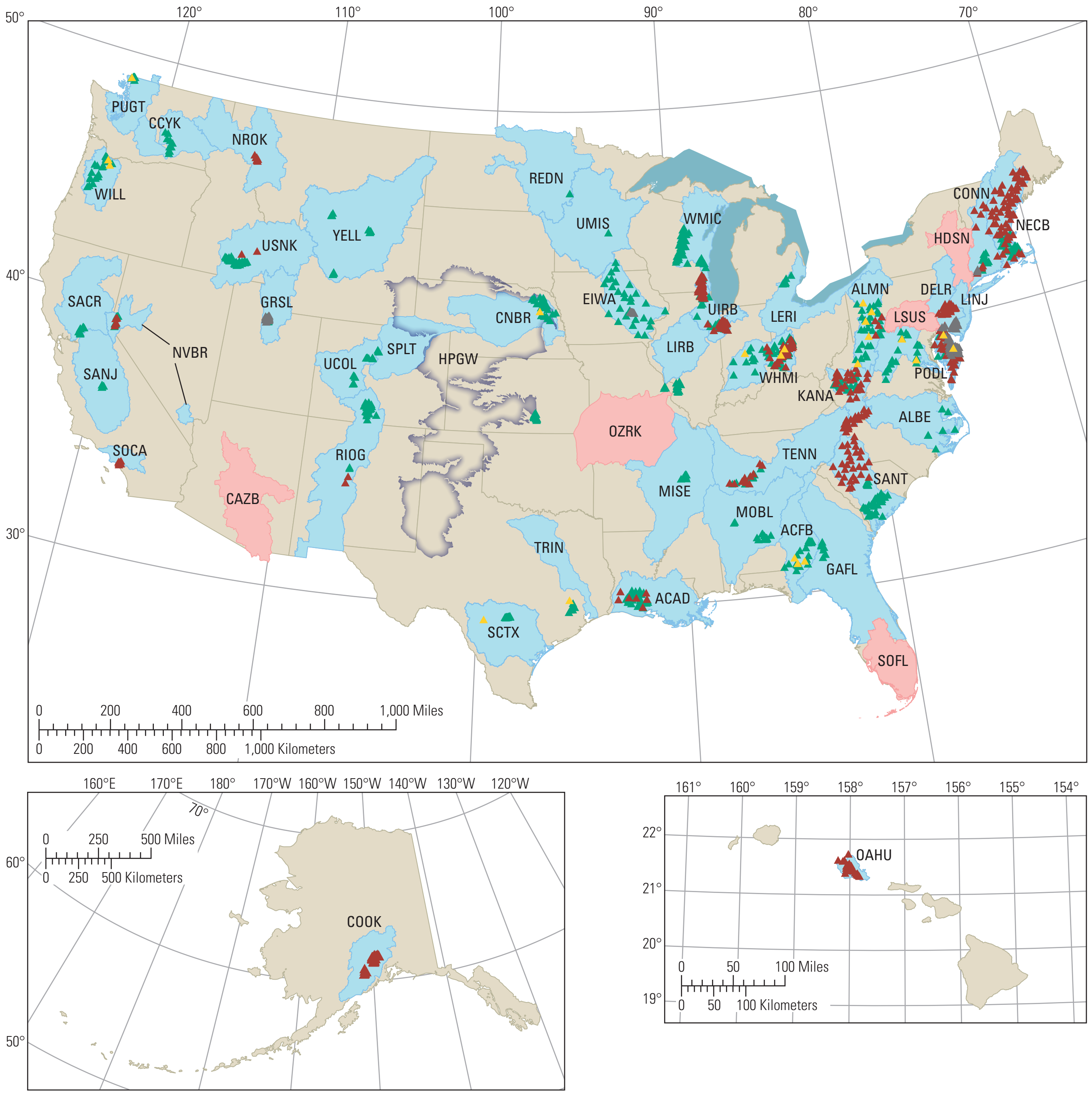
Age interpretation in groundwater systems based on tracers, such as CFCs and SF_6, is complex because it is not known if the tracers travel perfectly with the water. Further, water particles and solutes (including tracers) do not all travel with the same velocity or along identical flow paths. Thus, a water sample collected at a well is composed of a mixture of water particles and solutes associated with a range (distribution) of ages. This mixture is known as the age distribution of the sample. To a first approximation, samples collected from narrow-screened wells more closely approximate a narrow age distribution than those collected from large open intervals of the aquifer. One of the simplest ways to interpret water time-of-travel from tracer data in groundwater is to assume that all solutes arriving at a sampling location, such as a well, follow the same path similar to flow through a pipe, which is commonly referred to as piston flow. For the purposes of this compilation, all ages will be interpreted using the assumption of "piston-flow" conditions. The reported "tracer-based piston-flow ages" are a means of reporting the measured data and do not represent the distribution of groundwater ages. Tracer-based piston-flow ages should be regarded as a beginning rather than an end in estimation of groundwater age in the results presented herein.

The National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS) is tasked with (1) describing the status of and trends in water quality of large, representative portions of the Nation's water resources, and (2) providing an understanding of natural and anthropogenic factors affecting the quality of these resources (Gilliom and others, 1995). Understanding derived from analysis of tracers is an essential component of efforts to achieve these goals.

The NAWQA Program is composed of geographically and hydrologically distinct Study Units. Descriptions of Study Units and bibliographies of Study-Unit publications are available at: http://water.usgs.gov/nawqa/studies/study_units_listing.html.

NAWQA Study Units are shown in figure 1 and are listed in table A1 (appendix A). The 48 Study Units shown in figure 1 include 47 Study Units defined primarily by river basin boundaries, plus a pilot regional groundwater study, the High Plains Regional Groundwater Study. (Note that the number of and the naming convention for Study Units shown in figure 1 reflect the fact that four pairs of Study Units from the first decadal cycle of NAWQA subsequently were merged into four larger Study Units.)

Groundwater assessments within Study Units include networks (groups related by commonality of targeted resource) of 20–30 randomly distributed wells. Major-Aquifer Studies (MASs) (synonymous with "Study-Unit Surveys") are composed of networks of randomly distributed wells (usually domestic supply wells) in principal aquifers. Data from MAS networks contribute to the characterization of water-quality conditions in parts of principal aquifers commonly used for supply and to the characterization of how these water-quality conditions vary across the United States. Land-Use Studies (LUSs) are composed of networks of shallow wells (usually monitoring wells) in recharge areas under dominant land-use settings, such as residential/commercial land use and various classes of agricultural land use. LUS wells are sampled to provide spatial and temporal characterization of groundwater associated with various land uses, and thus contribute to the understanding of relations between groundwater quality and land use and other human as well as natural factors. One goal of LUS network design is to provide access to groundwater younger than 10 years old (Gilliom and others, 1995). Samples from MAS wells generally represent groundwater that is deeper and older than groundwater from LUS wells.



Basemaps modified from U.S. Geological Survey digital data, various scales. Projection (conterminous US and Hawaii): Albers (NAWQA), CM = -96, SP1 = 29.5, SP2 = 45.5, LO = 23, datum is North American Datum of 1983. Projection (Alaska): Albers CM = -154, SP1 = 55, SP2 = 65, LO = 50, datum is North American Datum of 1983.

EXPLANATION

RIOG **NAWQA Study Unit—Full name in table 1.**

- Study unit with age-dating results in this report
- Study unit without age-dating results in this report
- High Plains Study Unit

Well location and network type

- ▲ Land-use study
- ▲ Major-aquifer study
- ▲ Other well
- ▲ Reference well

Figure 1. Locations of National Water-Quality Assessment Program Study Units.

Thus, MAS and LUS networks represent complementary well networks and data, and MAS and LUS networks are the core monitoring component for groundwater in the NAWQA Program. Other standard networks in the NAWQA Program include Reference (REF) wells (wells representing groundwater minimally affected by anthropogenic activities), Flow System Studies (FSSs) (assessments of processes and trends along groundwater flow paths), and wells associated with various process-based topical studies. REF wells provide baseline characterization of natural or near-natural groundwater conditions, and as such, REF well data augment other basic monitoring data. In contrast to MAS, LUS, and REF components, FSSs (Gilliom and others, 1995) and topical studies (http://water.usgs.gov/nawqa/studies/topical_studies.html) are focused, mechanistic studies that provide links between understanding derived from detailed, local-scale investigations and monitoring assessments composed of larger-spatial-scale MAS, LUS, and REF wells.

Purpose and Scope

This report summarizes tracer data that were collected from NAWQA LUS, MAS, and REF wells during the first full decadal cycle of the NAWQA Program (Federal fiscal years 1992–2001) and the first 4 years of the second decadal cycle of the NAWQA Program (that is Federal fiscal years 2002–05). [The Federal fiscal year (FY) begins October 1 and ends September 30 of the year with which it is numbered.] Samples from "OTHER" (miscellaneous) wells also are summarized for sites that were considered potentially useful to the NAWQA Program but are not components of NAWQA FSSs or topical studies. Finally, tracer data collected from LUS and REF wells in two Study Units during FY 2006–07 also are included: wells in the Puget Sound Basin (PUGT) Study Unit (tracer data from FY 2006–07 were considered more reliable than earlier tracer data) and wells in the White, Great, and Little Miami River Basins (WHMI) Study Unit (tracer data from FY 2007 were included to fill a perceived data gap). A total of 1,399 sites are included in this report: 859 LUS, 384 MAS, 21 REF, and 135 OTHER wells.

Tracer data collected from wells that were part of NAWQA FSS and topical studies were not compiled for this report because those data are being or have been assembled and interpreted separately. Tracer data from LUS, MAS, and REF wells collected after FY 2005 were not included in this report (except as noted above), but most of these post-FY 2005 tracer data are being compiled separately. Only samples from wells were assembled for this report; samples from springs were not included because of an almost exclusive programmatic focus on wells for groundwater sampling (Gilliom and others, 1995).

The tracer data of interest were the commonly collected age-dating tracers of recent recharge (tracer-based piston-flow ages on the order of decades): CFCs (CFC-11, CFC-12, and CFC-113), SF_6, and $^3H/^3He$. Other age-dating tracers (for example, ^{14}C) were collected infrequently and they were not compiled herein. In addition to tracer data, major dissolved gas (N_2, O_2, Ar, CH_4, and CO_2) data were assembled because they can be used to constrain the interpretation of tracer data.

The tracer data compiled in this report represent all known CFC, SF_6, and $^3H/^3He$ data associated with the targeted (LUS, MAS, REF, and OTHER) wells and collected during the targeted timeframe (FY 1992–FY 2005) from NAWQA Study Units. The 48 Study Units shown in figure 1 and listed in table A1 (appendix A) comprise the geographic extent of the search effort. Tracer data were available from 43 of the 48 Study Units.

Tracer data that previously had been interpreted and published were compiled but not reinterpreted; this honored the local understanding that went into these interpretations. For tracer data that required interpretation, the processes used are documented in this report. The previously interpreted tracer data and the newly interpreted tracer data are presented herein as estimates of tracer-based piston-flow ages.

Tracer-based piston-flow ages based on measured concentrations of tracers in groundwater assume advective flow without mixing or dispersion. Only tracer-based piston-flow ages are presented because they are a consistent means of reporting the analytical data. In some physical settings (for example, shallow, short-screened wells in recharge areas), the tracer-based piston-flow age may reasonably represent the time-of-travel of water from points of recharge to the well. Generally, selection of the appropriate mixing model to apply to age interpretation, and evaluation of the age distribution in a water sample, depends on detailed knowledge of the hydrogeologic environment and availability of multiple tracers. Such an effort in age interpretation is beyond the scope of this report. Therefore, as a means of reporting the analytical data, and of providing an estimate of the age of each sample, this report presents only the derived tracer-based piston-flow ages for datable samples (for example, those not affected by microbial degradation, substantial mixing, or environmental contamination).

In the following section, the tracer data sets that were assembled for this report are described. This is followed by an explanation of the methods used to interpret tracer data. Limitations of the use of tracers for the purposes of estimating groundwater age are discussed; some notable cautions that pertain to these data sets are presented. Next, tracer-based piston-flow ages are provided. Finally, some insights on recharge temperatures that resulted from this large and geographically diverse data set are discussed briefly.

Approach Used in This Compilation

Tracer data collected between FYs 1992 and 2005 from 1,417 Land-Use Study (LUS), Major-Aquifer Study (MAS), Reference (REF), and OTHER sites were identified in table A1 (appendix A). Of these 1,417 sites, 47 were not compiled in this report. A description of these 47 sites and explanations for their exclusion from this compilation are provided in table B1 (appendix B). Most of these 47 sites were excluded because superior, alternative tracer data were available or because interpretation and publication of tracer data in a separate publication was planned (table B1). Tracer data collected between FYs 2006 and 2007 from 29 LUS and REF sites were added to this compilation. A description of these 29 sites and a list of reasons for inclusion in this compilation are provided in table C1 (appendix C). This report thus summarizes tracer data that were collected from 1,399 sites [1,417 sites (appendix A) – 47 sites (appendix B) + 29 sites (appendix C)], with a total of 43 (of 48) Study Units represented. Table D1 (appendix D) summarizes the number of sites in this compilation along with the types of well networks associated with these sites. Table E1 (appendix E) summarizes the well characteristics of these 1,399 wells.

Previously Interpreted Environmental-Tracer Data

Tracer data from 618 of the 1,399 sites had been evaluated in various publications as part of earlier studies. Tracer-based piston-flow ages assigned in these earlier publications for most of the 618 sites are listed in table F1 (appendix F). References for the publications that contain the piston-flow ages also are given in table F1.

Newly Interpreted Environmental-Tracer Data

Environmental-tracer data that previously had not been interpreted were compiled for 781 of the 1,399 sites. Analytical methods are described elsewhere (Busenberg and Plummer, 1992; Plummer and Mullin, 1997; Busenberg and Plummer, 2000). For internal consistency, CFC concentrations, which originally were measured over a range of analysis dates using various calibration standards, were rescaled to the Scripps Institution of Oceanography (SIO) 2005 scale of atmospheric CFC mixing ratios (Walker and others, 2009). Rescaled CFC concentrations changed by as much as 2.3 percent. All SF_6 data were scaled to the National Oceanic and Atmospheric Administration 2000 scale of atmospheric SF_6 mixing ratios (National Oceanic and Atmospheric Administration, 2008).

Methods of Interpretation

Well-established approaches for determination of tracer-based piston-flow ages are discussed in detail in references listed earlier in this report. These approaches were applied in this effort and are described briefly in this section.

Assigning a CFC- or SF_6-Based Piston-Flow Age

Recharge Altitude, Recharge Temperature, and Excess Air

The application of CFCs and SF_6 to groundwater dating is based, in large part, on relating measured aqueous concentrations of CFCs or SF_6 to atmospheric concentrations inferred to be present at points of recharge at the time of recharge. Relating aqueous concentrations to atmospheric concentrations is based on Henry's Law. Henry's Law states that for water at equilibrium with air, the concentration of a gas dissolved in water is proportional (through the Henry's Law constant, K_H) to the partial pressure of that gas in the air. Values of K_H defining solubility relations for each of the CFCs and for SF_6 are given in International Atomic Energy Agency (2006). Application of Henry's Law requires estimates of recharge altitude, recharge temperature, and excess air. Excess air is the component of atmospheric air (atmospheric gases), beyond the amount that can be attributed to air-water solubility, that is incorporated into shallow groundwater during or following recharge (Heaton and Vogel, 1981).

Dating with CFCs and SF_6 is relatively insensitive to recharge altitude, and for most of the groundwater sites in this report, the water-table altitude served as a reasonable estimate of the recharge altitude. For sites where recharge might occur at altitudes substantially greater than the water-table altitude (more than several hundred feet above the water-table altitude), a sensitivity analysis was done to help constrain results (appendix G).

Recharge temperature generally has a large effect on the interpretation of tracer-based piston-flow ages derived from concentrations of CFCs and SF_6 in groundwater. The major dissolved gases can be used to infer recharge temperature, or, if major dissolved-gas data are not available, climatological data can be used.

Where climatological data were used to estimate recharge temperature, the approach in this report was to use the mean annual ground temperature at the water table [mean annual air temperature (MAAT) + 1°C (Stute and Schlosser, 2000)]. Nearby climate-station data were adjusted to the estimated recharge altitude at a site using the average environmental lapse rate of 0.00198°C/ft (Driscoll, 1986, p. 49). For sites where recharge might occur at altitudes substantially greater than the water-table altitude and, thus, at lower recharge temperatures, a sensitivity analysis was done (appendix G).

In the absence of major dissolved-gas data, an excess-air concentration of 2 cc(STP)/kg was used for groundwater recharge through sandy sediments (Busenberg and Plummer, 1992; Dunkle and others, 1993; Sun and others, 2010); excess-air concentrations in fractured rock and karst aquifers, which can have amounts of excess air larger than those assumed for sandy aquifers, were handled on a case-by-case basis (appendix G).

Where major dissolved-gas data were available, N_2 and Ar data were used in the unfractionated-air (UA) model to infer recharge temperature (Heaton and Vogel, 1981). The UA model rests upon assumptions that gases dissolved in groundwater originate from air-water solubility (Henry's Law partitioning) and the introduction of additional gas during recharge from processes facilitating air-bubble entrainment (for example, resulting from a fluctuating water table). With the UA model, the additional gas is assumed to be unfractionated; that is, the entire volume of the bubble of entrapped excess air is assumed to have the composition of air and to be dissolved completely. Although some fractionation does occur in many aquifers, the effects on calculated recharge temperatures generally are of minor importance in groundwater with low concentrations of excess air (Cey and others, 2008; Klump and others, 2008).

In applying the UA model, there are two known variables—concentrations of Ar and N_2—and four unknown variables—recharge altitude, recharge temperature, excess air, and excess N_2 (generally, N_2 from denitrification of nitrate in suboxic water). The recharge altitude usually can be assumed to be similar to the water-table altitude, as discussed above, but there still remain three unknown variables with only two known variables. Guidelines for interpretation of recharge temperature and excess air are given in Plummer and others (2003) and discussed below.

In this report, samples from a given network that were oxic and thus likely to have had little or no excess N_2 from denitrification were used for the first step of this analysis. Oxic samples were considered those with concentrations of O_2 ≥ 1 mg/L (Lindsey and others, 2003), Mn ≤ 50 µg/L (Paschke, 2007), Fe ≤ 100 µg/L (Paschke, 2007), and $CH_4 \leq 1$ µg/L. In this initial analysis, major dissolved-gas data from these oxic sites were used to estimate recharge temperatures and excess air, under the assumption that N_2 from denitrification was negligible and that the UA model applies. The application of four redox-indicator species (O_2, Mn, Fe, and CH_4) in this analysis resulted in a system in which mixing of oxic water ($O_2 \geq 1$ mg/L) and suboxic water (identified where water contained Mn >50 µg/L, Fe >100 µg/L, and(or) $CH_4 > 1$ µg/L) along flow paths or in well bores could be recognized.

Having estimated recharge temperatures and excess-air concentrations for the oxic sites in a network, as explained in the preceding paragraph, there remains the task of estimating recharge temperatures and excess-air concentrations at the remaining sites in the network. This was accomplished by using the results from the oxic sites to constrain the analysis of the remaining samples in a given network. Two approaches could be used, with usually similar results. The median excess air from the oxic sites could be used as a constraint for the suboxic sites. With excess air constrained, the major dissolved-gas data would be used to estimate recharge temperature and the amount of excess N_2 from denitrification at the suboxic sites. Alternatively, the median recharge temperature from the oxic sites could be used as a constraint for the suboxic sites. With recharge temperature constrained, the major dissolved-gas data would be used to estimate excess air and the amount of excess N_2 from denitrification at the suboxic sites. In this report, the first of these two approaches was used: excess air was held constant and recharge temperature was allowed to vary.

For some oxic sites, these calculations yielded negative excess air. This can result from degassing in the aquifer or during sample collection. In these cases, the major dissolved-gas data for the site were not used, and the recharge temperature was selected, as appropriate, from: (1) the median recharge temperature for the oxic sites or (2) MAAT + 1°C. Usually, the excess-air concentration for the oxic sites was used for the site in question.

Unrecognized denitrification can lead to assignment of overly warm recharge temperatures and large amounts of excess air, resulting in tracer-based piston-flow ages that are too young (overly warm recharge temperature) or too old (large amounts of excess air). For a site that was considered oxic, if the recharge temperature estimated by these methods was unusually warm and if the inferred excess air was unusually large compared to other sites in the network, the site was given additional attention. Such unusual samples were evaluated for possible denitrification by comparing inferred recharge temperatures and excess-air concentrations for conditions of (a) no denitrification and (b) denitrification. These types of unusual samples may have been treated as containing a mixture of oxic and suboxic water, thus allowing for denitrification, or such unusual samples may have been treated as outliers, in which case the major dissolved-gas data for that site may have been discarded and the recharge temperature and excess-air concentration determined as described above. Each occurrence was evaluated on a case-by-case basis, using relevant ancillary data, and documented in appendix G.

Where some samples in a network were not analyzed for major dissolved gases, recharge temperatures were assigned, as appropriate, from the median recharge temperature for the oxic sites in the network, or by other methods described above. For excess air, the median excess-air concentration for the oxic sites typically was used.

Finally, there were some sites for which neon (Ne) data in addition to major dissolved-gas data were available. In these cases, Ne data were used to refine estimates for suboxic sites using an approach similar to that used by Plummer and others (2003). Specifically, for the purpose of estimating excess air, the recharge temperature initially was assumed equal to the MAAT + 1°C, and the estimate of recharge temperature and the Ne concentration for a given site were used to estimate excess air (this approach takes advantage of the fact that Ne solubility is relatively insensitive to temperature). Once the excess air was estimated, this estimate along with the major dissolve gas data (that is, N_2 and Ar) were used to estimate recharge temperature and excess N_2 from denitrification.

Determination of a CFC-Based Piston-Flow Age

Atmospheric CFC mixing ratios that would have been present locally at the time of recharge were calculated from measured aqueous CFC concentrations; estimates of recharge altitude, recharge temperature, and excess air; and application of Henry's Law. These calculated values of atmospheric CFC concentrations were compared to reconstructed records of atmospheric CFC mixing ratios to calculate CFC-based piston-flow ages (Busenberg and Plummer, 1992; International Atomic Energy Agency, 2006). This resulted in the determination of piston-flow ages based on CFC-11, CFC-12, and CFC-113. These CFC-based piston-flow ages then were evaluated on a site-by-site basis: redox chemistry was considered (to minimize impacts of microbial degradation of CFCs) and the relative differences in piston-flow ages based on CFC-11, CFC-12, and CFC-113 were assessed (to identify samples exhibiting evidence of substantial mixing). Datable sites were those that were not likely to have been subject to substantial degradation or mixing. The most appropriate CFC-based piston-flow age for each datable site was then selected to represent the site. CFC-12-based piston-flow ages generally are the most reliable (least affected by sorption and degradation) of the three CFCs (International Atomic Energy Agency, 2006). However, assignment of the most representative CFC-based piston-flow age for a given site requires consideration of site-specific factors as well as network-specific factors, including the degree of consistency among the three CFCs, extent of environmental CFC contamination, and spatial patterns of tracer-based piston-flow ages inferred from the three CFCs. No CFC-based piston-flow ages were assigned to samples having reconstructed CFC mixing ratios that exceeded the atmospheric CFC mixing ratio at the time of sampling. Finally, evaluation of these interpretations was done using hydrologic data (to evaluate age/depth relations), ^3H data (where available) to compare reconstructed ^3H concentrations (measured ^3H concentrations that are back-decayed, on the basis of CFC-based piston-flow ages, to original ^3H concentrations inferred to have been present at the time of recharge; see, for example, Dunkle and others [1993]) to historical ^3H records, and other available information (appendix G). These additional assessments are intended to provide some (limited) context and evaluation of the interpretations.

Determination of SF_6-Based Piston-Flow Age

Atmospheric SF_6 mixing ratios that would have been present locally at the time of recharge were calculated from measured aqueous SF_6 concentrations; estimates of recharge altitude, recharge temperature, and excess air; and application of Henry's Law. Following Busenberg and Plummer (2000), these atmospheric SF_6 mixing ratios were compared to reconstructed records of atmospheric SF_6 mixing ratios to calculate SF_6-based piston-flow ages. SF_6 does not seem to degrade (Busenberg and Plummer, 2000), so screening SF_6 interpretations on the basis of redox conditions was not necessary. No SF_6-based piston-flow ages were assigned to samples having reconstructed SF_6 mixing ratios that exceeded the atmospheric SF_6 mixing ratio at the time of sampling. Finally, evaluation of these interpretations was done by analyzing age/depth relations, reconstructed ^3H relations, and other available information (appendix G).

Assigning $^3H/^3He$-Based Piston-Flow Age

Dating with $^3H/^3He$ is based on measuring ^3H and its decay product ^3He. Recharge temperatures and recharge altitudes, needed for calculating ^3He from air-water solubility, were estimated by methods used for estimating recharge temperatures and recharge altitudes for CFC and SF_6 dating. Measured $^3He/^4He$ ratios and helium (He) concentrations were used to resolve various ^3He sources: ^3He from air-water solubility (constrained by recharge temperature and recharge altitude), from excess air (constrained by Ne concentrations), from terrigenic sources (assuming a terrigenic $^3He/^4He$ ratio of 2×10^{-8} cc/g at STP; Mamyrin and Tolstikhin, 1984; Schlosser and others, 1989), and from ^3H decay (assuming a ^3H half-life of 12.32 years; Lucas and Unterweger, 2000). Samples generally were not dated if : (1) they contained low concentrations of ^3H (less than about 1 TU) in combination with elevated terrigenic helium (20 percent or more of the total helium), (2) they contained high concentrations of ^4He (Δ^4He greater than about 200 percent, where Δ^4He is the amount of ^4He in the water sample that is in excess to that attributed to solubility equilibrium with air, expressed as a percentage of the ^4He in water at solubility equilibrium), and (3) they had gases that had been fractionated (for example, samples in which Δ^4He was less than ΔNe, where ΔNe is the amount of Ne in the water sample that is in excess to that attributed to solubility equilibrium with air, expressed as a percentage of the Ne in water at solubility equilibrium). The interpretations were evaluated using age-depth relations, reconstructed ^3H relations, and other available information (appendix G).

Ancillary Chemistry, Water Level, Well Construction, and Tritium Concentration Data

Ancillary chemistry, water level, well construction, and ^3H concentration data for individual sites were obtained from the NAWQA Data Warehouse (DWH): http://infotrek.er.usgs.gov/traverse/f?p=NAWQA:HOME:0:

Estimates of spatial and temporal variations in ^3H in precipitation were used for reconstructed ^3H analysis. Reconstructed ^3H analysis is based on back-decaying measured ^3H concentrations in groundwater, using tracer-based piston-flow ages to estimate the time-dependent amount of ^3H decay, and comparing these undecayed or original ^3H concentrations to historical ^3H inputs (for example, Dunkle and others, 1993; Ekwurzel and others, 1994). This analysis can provide a valuable check on tracer-based piston-flow ages in aquifers where recharge is dominated by precipitation.

Estimates of ^3H in precipitation were based on International Atomic Energy Agency data from 10 long-term stations in the conterminous United States. Missing temporal records were replaced with values based on correlation using long-term data sets from Ottawa, Canada (August 1953–December 1987), and Vienna, Austria (January 1988–December 2001); and ^3H concentrations were interpolated in space. Concentrations prior to August 1953 were estimated using graphical prebomb distributions (Thatcher, 1962).

Limitations to and Cautions About the Application of Environmental Tracers for Dating

Limitations to the use of tracers for groundwater-dating purposes have been documented (for example: Busenberg and Plummer, 2000; Solomon and Cook, 2000; International Atomic Energy Agency, 2006). Most of the uncertainties are environmental in nature; analytical uncertainty generally is only a minor source of uncertainty.

Limitations include the following for CFCs: mixing (dispersion, diffusion, mixing at sampling points), degradation, sorption, anthropogenic CFC contamination in the aquifer, CFC contamination during sampling, local atmospheric anomalies in CFC concentrations, lack of equilibrium between atmospheric gases and unsaturated-zone gases, effects associated with recharge from sources other than diffuse recharge (for example, recharge of river water that was not at equilibrium with the atmosphere), flattening and overturning of the CFC input curves in the 1990s and early 2000s, and uncertainties in estimation of recharge altitude, recharge temperature, and excess air. Many of these effects are evaluated quantitatively in Busenberg and Plummer (1992) and International Atomic Energy Agency (2006).

Limitations for SF_6 include: mixing, natural subsurface production, degassing in the aquifer or during sampling (potentially problematic because of the low solubility of SF_6), anthropogenic SF_6 contamination in the aquifer, SF_6 contamination during sampling, spatially variable atmospheric SF_6 concentrations, lack of equilibrium between atmospheric gases and unsaturated-zone gases, effects associated with recharge from sources other than diffuse recharge, and uncertainties in estimation of recharge altitude, recharge temperature, and excess air. Many of these effects are evaluated quantitatively in Busenberg and Plummer (2000) and International Atomic Energy Agency (2006).

Limitations for $^3H/^3He$ include: mixing, fractionation of He isotopes and He mass-balance problems associated with He degassing, uncertainties in corrections for ^3He derived from terrigenic sources, uncertainties in age interpretation for samples with low (<1 TU) tritium content, and uncertainties in estimation of recharge altitude, recharge temperature, and excess air. Quantitative evaluation of several of these effects is discussed in Schlosser and others (1989) and Solomon and Cook (2000).

A major limitation common to all three of these dating methods is that tracer-based piston-flow ages are based on the simplifying assumption that tracer transport is by advective flow without hydrodynamic dispersion and mixing in wells (Bethke and Johnson, 2002; Weissmann and others, 2002). Thus, piston-flow concepts represent an end-member condition that may be approached in some simple flow systems, but a condition that is never actually attained. Mixing can be problematic particularly in supply wells—the typical well type in most MAS networks. Supply wells (including domestic supply wells) often are characterized by long screened intervals, which promote mixing in well bores during sampling. High pumping rates in supply wells can promote mixing owing to the hydraulic stresses that pumping can place on aquifers (Busenberg and Plummer, 1992). Supply wells typically are installed at greater depths than are monitoring wells and this can lead to increased mixing in the former due to increased mixing along the typically longer flow paths. A limitation also related to mixing but specific to tracers such as CFCs, SF_6, and $^3H/^3He$ is that these tracers provide information primarily on recharge from recent decades, and generally have provided little information about the distribution of times-of-travel of the older components (if present) in groundwater mixtures. (A groundwater sample may be composed of a multitude of different water parcels, each with a distinct time-of-travel.)

Mixing generally should be less extensive in samples from LUS wells (the dominant network in this compilation) than in samples from MAS wells. The use of short-screened monitoring wells in most LUS networks (85 percent of the LUS wells in this report were monitoring wells) and the typical placement of these wells close to the water table in recharge areas may result in less mixing in well bores and less hydrodynamic dispersion along flow paths (International Atomic Energy Agency, 2006). Low pumping rates may give an additional advantage to monitoring wells because these rates normally cause only minimal disturbance to natural groundwater flow conditions, therefore minimizing mixing in the aquifer. However, all groundwater samples are mixtures of multiple components.

Finally, most of the datasets in this report consist of sites selected by a stratified random design. That is, wells were randomly located in areas that were representative of a particular hydrogeologic setting (MASs) or land-use setting (LUSs). Data from sites that are selected in this manner, rather than from sites located along a targeted groundwater flow path, can sometimes be difficult to interpret because the understanding that can be derived from analysis of position within a flow system may be lacking. Many of the MAS network wells could fall into this category. However, LUS wells typically are positioned close to the water table, which provides flow-system context.

Because the piston-flow model rests on many simplifying assumptions, it has been argued that tracers would be used more appropriately to calibrate transport models than to generate tracer-based piston-flow ages (for example, Bethke and Johnson, 2008). Although such uses may prove to be superior, it is worth noting that tracers do represent point measurements that have the potential to provide understanding that may be lacking in transport models that inherently must simplify the representation of groundwater systems. This understanding might not be generated from a transport model in which geologic heterogeneity is simplified relative to the scale of measurement points (wells). Despite simplifying assumptions and numerous limitations, tracer-based piston-flow ages derived from the commonly used tracers of young groundwater (CFCs, SF_6, and $^3H/^3He$) can be robust under favorable environmental and sampling conditions. For example, CFC-based piston-flow ages from diverse agricultural areas have been shown to be consistent with pesticide application histories (Burow and others, 2007; Tesoriero and others, 2007), distribution patterns of CFC-based piston-flow ages in central Oklahoma have been linked to periods of increased precipitation and recharge (Busenberg and Plummer, 1992), and tracer-based piston-flow ages based on CFCs, SF_6, and $^3H/^3He$ have been shown to agree well with those derived from other tracers (for example, Ekwurzel and others, 1994; Busenberg and Plummer, 2008).

The tracer-based piston-flow ages in this report were derived using a consistent approach and are reported with the limitations described above. If the limitations associated with these tracer-based piston-flow ages are ignored, incorrect conclusions may be drawn. However, these tracer data and interpretations contain useful information that can be used in the context of other lines of evidence to gain an improved understanding of flow and chemistry in groundwater systems.

Tracer-Based Piston-Flow Ages and Related Information

This section documents previously published tracer-age analyses for 618 sites, and newly interpreted tracer data for 781 sites evaluated as part of this project. Additionally, some insights about recharge temperatures, derived from analysis of major dissolved-gas data, are discussed briefly.

Interpretations of tracer data are given as tracer-based piston-flow ages and as tracer-based piston-flow recharge dates. As an example, a groundwater sample collected during calendar year 2000 and attributed with a tracer-based piston-flow age of 10 years would have a tracer-based piston-flow recharge date of (calendar year) 1990. Tracer-based piston-flow ages and tracer-based piston-flow recharge dates often are censored with a “>” (greater than), “<” (less than), “≥” (greater than or equal to), or “≤” (less than or equal to). For example, if CFC degradation appeared to be present in a sample, the tracer-based piston-flow age and tracer-based piston-flow recharge date could have an old bias. The tracer-based piston-flow recharge date could be accompanied by a “>” to indicate a greater (more recent) date, and the tracer-based piston-flow age by a “<” to indicate a smaller (younger) age. Sites with age-dating results that have been censored with >, <, ≥, or ≤ do not have discrete tracer-based piston-flow ages or discrete tracer-based piston-flow recharge dates, and these sites are not included in statistical characterizations of tracer-based piston-flow ages.

Previously Interpreted and Published Environmental-Tracer Data

Tracer data from 618 sites in 22 Study Units have been interpreted and reported (as tracer-based piston-flow ages) in 30 publications. Tracer concentrations also have been reported in many of these publications. The level of interpretation of tracer data in these publications is variable. For example, an urban LUS [LUSRC1, table A1 (appendix A)] in the Great Salt Lake Basins (GRSL) Study Unit was sampled for $^3H/^3He$ in 1999. The $^3H/^3He$-based piston-flow ages were used to reconstruct initial ^3H concentrations that were expected to be present in recharge water at the time of recharge. These reconstructed initial ^3H concentrations matched historical ^3H inputs (discussed and referenced in appendix F), demonstrating consistency between age interpretations and an independent data set. However, many of the CFC-based piston-flow ages from the Kanawha-New River Basin (KANA) Study Unit, although thoroughly documented in a report that focused on age dating (appendix F), may have an old bias as a consequence of the extensive occurrence of highly reducing conditions. (In table F1, potentially affected sites from the KANA Study Unit have comments in the remark fields about this potential problem.)

The original interpretations for these 618 sites have been compiled, without re-interpretation, in table F1. Table F1 lists sampling date, tracer, tracer-based piston-flow age, tracer-based piston-flow recharge date, and citable reference for each site, organized by network and Study Unit. Appendix F also contains a short summary for each group of age results listed in table F1, including information describing the extent to which age interpretation was addressed. These summaries are provided, in part, to facilitate the process of matching these results, or appropriate subsets of these results, to the intended uses.

Newly Interpreted Environmental-Tracer Data

Tracer data from 781 sites in 26 Study Units that previously had not been interpreted and published were interpreted here as tracer-based piston-flow ages. The data are organized by Study Unit and network. Some networks were combined for the purposes of analysis and reporting. Networks were combined where multiple networks were composed of similar land use, or where REF wells and LUS wells were co-located. Data from the Apalachicola-Chattahoochee-Flint Basin (ACFB) and Georgia-Florida Coastal Plain Drainages (GAFL) Study Units also were combined because these two (adjacent) Study Units shared a continuous, cross-Study-Unit LUS.

The measured tracer-concentration data, interpreted tracer-based piston-flow ages, and ancillary data for each network are reported in appendix G. The derived tracer-based piston-flow ages are examined for consistency with available tritium data and local age gradients in appendix G. A summary of the tracer-based piston-flow ages from appendix G is given in table 1 (at back of report).

Where tracer data from more than one tracer type (CFCs, SF_6, $^3H/^3He$) were available for a given site, interpretations from both tracers are provided in appendix G. Multiple tracers were compiled for 20 sites: 2 sites in the Connecticut, Housatonic, and Thames River Basins (CONN); 5 in the South-Central Texas (SCTX); and 13 in the Upper Illinois River Basin (UIRB) Study Units. Some of these cases of multiple tracers occurred on different sampling dates, and some occurred on the same sampling dates. At each of 3 sites (1 in the CONN and 2 in the SCTX Study Units), tracer data from 2 sampling dates were available, and these separate results are included in table 1. At each of 17 sites (1 in the CONN, 3 in the SCTX, and 13 in the UIRB Study Units), the multiple tracers were collected on the same date, but only the most reliable tracer-based piston-flow age is reported in table 1. The multiple tracers were $^3H/^3He$ in combination with either CFCs or SF_6. Generally, $^3H/^3He$ was considered the more reliable tracer because the parent compound (^3H) and the decay product (^3He) are measured, and because this tracer pair is not subject to microbial degradation.

Relation Between Tracer-Based Piston-Flow Ages and Network Type

To what degree have LUS sites achieved the network design goal (Gilliom and others, 1995) of accessing groundwater younger than 10 years of age? Because all groundwater samples are mixtures and represent an age distribution, both the LUS network design goal and this question oversimplify the problem. Ignoring the fact that the groundwater samples are mixtures, 530 of the 859 LUS sites (62 percent) have an uncensored tracer-based piston-flow age (table 1; table F1). For these 530 sites (which probably are not representative of all NAWQA LUS sites), the median tracer-based piston-flow age is 11 years, and 39 percent of the sites had tracer-based piston-flow ages of less than 10 years. (Another 6 percent of the datable LUS sites had a tracer-based piston-flow age equal to 10 years.) Therefore, without consideration of the age distributions in the groundwater samples, the tracer-based piston-flow ages could be construed as indicating that the goal of accessing groundwater younger than 10 years of age was achieved at nearly one-half of these sites. However, each sample actually represents an age distribution, and many of these samples probably contain fractions of groundwater with times-of-travel less than 10 years and fractions with times-of-travel greater than 10 years. So a more meaningful, albeit more challenging, LUS network design goal could have been framed in terms of age distributions.

As might be expected based on the design of LUS and MAS networks, typical tracer-based piston-flow ages of age-dated groundwater samples from MAS networks are somewhat greater than those from LUS networks (fig. 2). The median tracer-based piston-flow age of datable MAS sites was 17 years, compared to 11 years for datable LUS sites (fig. 2). These patterns of generally greater time-of-travel for MAS sites than for LUS sites likely reflect generally greater well depths in MAS wells than in LUS wells. This also may reflect the fact that these LUS and MAS sites were from different populations of wells, from different aquifers with different boundary conditions (for example, recharge rates), geologic composition, geometry, and size. Few data in this compilation are available for direct comparisons between nested LUS and MAS networks (LUS and MAS networks co-located in the same Study Units and principal aquifers), but data from nested LUS and MAS networks in the White, Great, and Little Miami River Basins (WHMI) Study Unit (newly interpreted data, table 1) and the Potomac River Basin and Delmarva Peninsula (PODL) Study Unit (previously interpreted data, table F1) demonstrate results similar to those for the more generalized analysis discussed above. (These two sets of nested networks were the only nested networks from this report that consisted of more than 10 uncensored, datable sites in the LUS and the MAS categories). Median tracer-based piston-flow ages

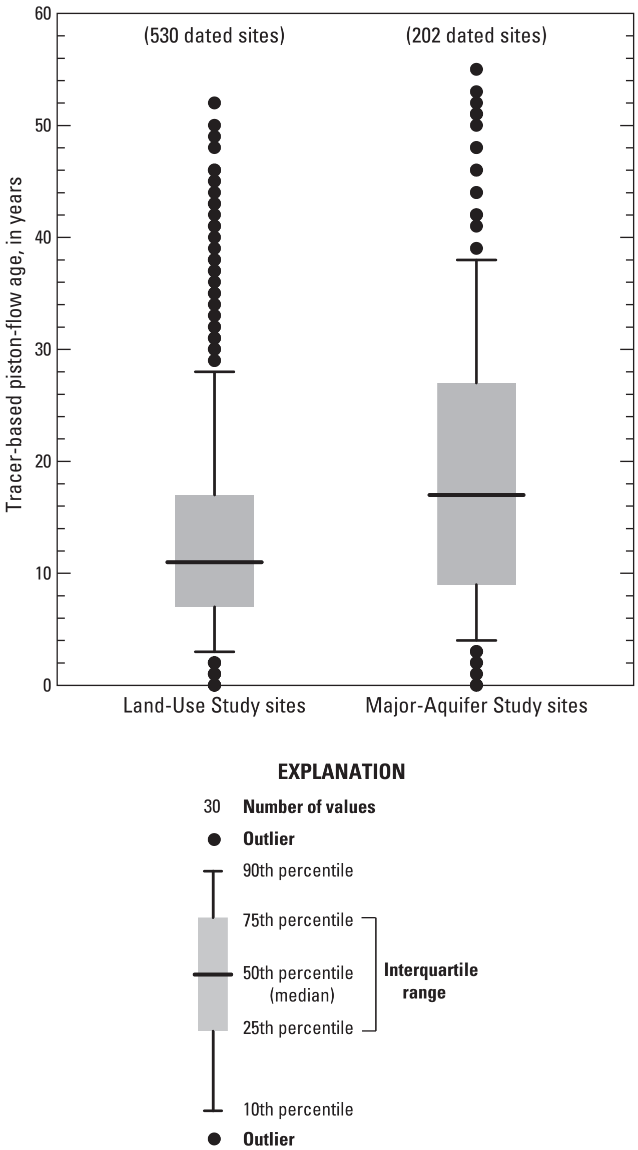


Figure 2. Distribution of tracer-based piston-flow ages in groundwater samples from selected Land-Use Study and Major-Aquifer Study sites. Tracer-based piston-flow ages interpreted in this report (table 1) and previously interpreted (table F1, appendix F) are combined in this figure. Results that were censored with a "<," "≤," ">," "≥," or specifically were commented on in table F1 as likely affected by degradation [selected networks in the Allegheny-Monongahela River Basin (ALMN) Study Unit and Kanawha-New River Basin (KANA) Study Unit] are not shown. Tracer-based piston-flow ages of samples from age-dated wells likely do not represent the tracer-based piston-flow ages of samples from wells that were not dated.

were 2 years (33 WHMI LUS wells) and 9 years (25 WHMI MAS wells), and 8 years (29 PODL LUS wells) and 10 years (29 PODL MAS wells). Differences in tracer-based piston-flow ages between nested LUS and MAS wells (2 years and 7 years for two direct comparisons) were of similar magnitude to the differences observed for the more generalized comparison between the various LUS and MAS networks (6 years).

Major-Dissolved-Gas-Based and Climate-Based Recharge Temperatures

The compilation of tracers in this report is accompanied by a compilation of major dissolved-gas data that were used for, among other things, estimation of recharge temperatures. In the absence of major or noble dissolved-gas data, recharge temperature commonly is assumed to be close to either the MAAT (Andrews, 1992) or the MAAT+1°C (Stute and Schlosser, 2000). (Where major dissolved-gas data were not available in this report, recharge temperatures were assumed to be equal to the MAAT+1°C.) The dataset of major dissolved gases presented herein for aquifers across the United States provides an opportunity to compare a large and diverse group of N_2/Ar-inferred recharge temperatures to those based on climate data. Considering sites in aquifers composed of sediments (most of the sites analyzed in this report), differences between N_2/Ar-inferred recharge temperatures and recharge temperatures based on MAAT+1°C were, on average, about 0.1°C (n=277) (fig. 3). The mean difference was +0.1°C (N_2/Ar-based estimates slightly greater than the climate-based estimates), and the median difference was -0.1°C (N_2/Ar-based estimates slightly less than the climate-based estimates). However, the standard deviation of these differences was 3.1°C. Thus, although this comparison could provide support for the use of climate data for estimation of *average* recharge temperatures, recharge temperatures vary greatly around this central tendency and characterization of site-specific recharge temperatures benefits from site-specific data. Factors contributing to differences between climate data and N_2/Ar-inferred recharge temperatures are not well understood, but include environmental processes, such as type of recharge (for example, focused compared with diffuse recharge), variable intensity or seasonality of recharge, geothermal warming in thick unsaturated zones, and warming or cooling from land surface where unsaturated zones are thin, and also include uncertainties associated with resolving excess-air components (Kipfer and others, 2002; Plummer and others, 2004).

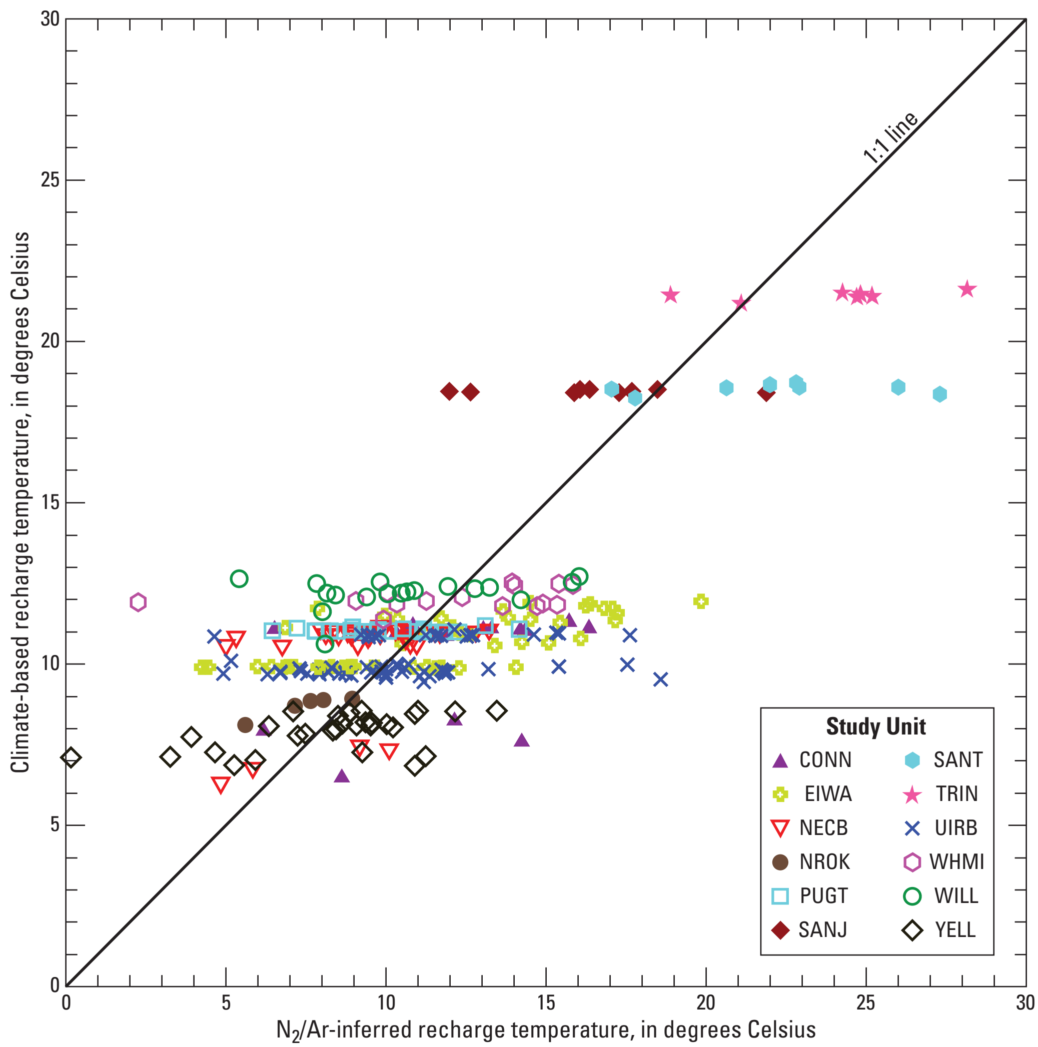


Figure 3. Comparison of nitrogen/argon (N_2/Ar)-inferred recharge temperatures and climate-based recharge temperatures (mean annual air temperature + 1°C) for groundwater sites that were in aquifers composed of sediments and were interpreted in this report. Study-Unit abbreviations are defined in table A1 (appendix A). N_2/Ar-inferred recharge temperatures and climate-based recharge temperatures are listed for individual sites in appendix G.

Summary and Conclusions

Chlorofluorocarbon (CFC), sulfur hexafluoride (SF_6), and tritium/helium-3 ($^3H/^3He$) tracer data collected from 1,399 NAWQA Program groundwater sites across the United States were compiled in this report. The data were from Land-Use Study (LUS), Major-Aquifer Study (MAS), and Reference (REF) networks, and from several OTHER networks composed of miscellaneous wells not represented in other NAWQA groundwater-age archives. The period of data collection focused primarily on Federal fiscal years 1992–2005, although two networks of samples from 2006 to 2007 were included (tracer data collected during 2006–07 from one group of wells was superior to tracer data collected in the 1990s from the same network, and tracer data collected during 2007 from another group of wells was included to fill a data gap). Tracer data from other NAWQA Program components (Flow System Studies and various topical studies) were not compiled herein. Tracer data collected after 2005 were not compiled in this report, except as noted.

Tracer data that previously had been interpreted and published were compiled (618 sites), and tracer data that previously had not been interpreted and published were evaluated (781 sites) using established methods. For the newly interpreted tracer data, the following are compiled: aqueous concentrations, equivalent atmospheric concentrations (for CFCs and SF_6), and estimates of tracer-based piston-flow ages; selected ancillary data (for example, well construction and redox-chemistry data) and brief summaries of each tracer dataset also are included. For the previously interpreted and published tracer data, published tracer-based piston-flow ages are listed, along with documentation of the original references and brief discussions of each dataset.

Tracer-based piston-flow ages have limitations, yet they are derived from point measurements that provide understanding that may be difficult to obtain from other methods. Tracer-based piston-flow ages commonly can be used to represent relative groundwater ages, and (less commonly) can closely represent actual groundwater ages. Tracer-based piston-flow ages can be used in establishing directions of hydrologic progression or geochemical evolution. Tracer-based piston-flow ages also can be used to establish timescales of hydrologic progression or kinetics of geochemical reactions. The degree to which simple tracer-based piston-flow ages can be used for purposes such as these depends on the degree of confidence associated with the interpretations. Multiple tracers or multiple lines of evidence can increase the understanding of tracers and any interpretations based upon those tracers. For the datasets in this report, multiple tracers were in most cases limited to multiple CFCs (which are limited in that the different CFCs have differing degrees of reactivity), or to ^3H (only sporadically collected) in addition to CFCs, SF_6, or $^3H/^3He$. The summaries of the individual tracer datasets provide information about these datasets and interpretations that can help the users of these tracer-based piston-flow ages identify strengths and weaknesses and thus identify appropriate uses for the different datasets.

LUS sites, generally composed of monitoring wells installed near the water table in recharge zones, often seem to yield groundwater that, at least in part, has been recharged in recent years. MAS sites, generally composed of domestic wells and other types of supply wells situated in the shallow regions of principal aquifers also yield young tracer-based piston-flow ages, but these ages tend to be slightly greater (older) than those of LUS sites. The median tracer-based piston-flow age of the dated LUS sites in this compilation was 11 years and for the dated MAS sites was 17 years. Of course, the median tracer-based piston-flow ages of the dated LUS and MAS sites are not likely to represent the median tracer-based piston-flow ages of the undated LUS and MAS sites precisely. Additional tracer analysis at these undated sites is needed.

In the process of analyzing tracer data, major dissolved-gas data also were analyzed where available. Because recharge temperature often is inferred using climate data (recharge temperature often being approximated by MAAT+1°C), the major dissolved-gas data provide an opportunity to compare N_2/Ar-inferred recharge temperatures to climate-based recharge temperatures for a diverse group of aquifers across the United States. For aquifers composed of sediments (the most common aquifer type in this report), differences between N_2/Ar-inferred recharge temperatures and recharge temperatures based on MAAT+1°C were, on average, within about 0.1°C. However, although the average differences were small, the standard deviation of these differences was 3.1°C, indicating that climate data may be useful for characterizing average recharge temperatures, but it also can indicate that recharge temperatures vary greatly from site to site.

Characterizing groundwater age is a complex undertaking. As evidenced in this compilation, collection of tracer data does not necessarily lead to determination of groundwater age. Collecting tracer data is only part of the investigation, but careful selection of tracers as well as ancillary geochemical data, and preparation of a well-thought-out study design can improve the outcome. Some of the more salient lessons from the effort documented in this report are discussed below.

Where characterizing the distribution of groundwater ages in a sample is a goal, multiple tracers along with appropriate use of analytical or numerical models are needed. Even where only a tracer-based piston-flow age is to be reported, multiple tracers can provide support for tracer-based piston-flow age interpretations, or identify cases where the piston-flow model might be inappropriate. If the goal is simply to determine a tracer-based piston-flow age, the availability of multiple tracers can help increase the chances that at least one tracer will yield an interpretable tracer-based piston-flow age.

In the planning phase of a project, design of a network with a flow-system approach provides hydrologic context during tracer interpretation, and a design focusing on short-screened wells will reduce well-bore mixing. Selection of long-screened wells will mandate the use of multiple tracers and perhaps depth-dependent tracer sampling. The choice of tracers and approaches for age dating can be optimized to local environmental conditions. For example: (1) sites in urban areas (which often may contain elevated concentrations of CFCs) might be best served by tracers other than CFCs, (2) sites in silicic igneous rocks (a source of natural SF_6) might be best served by tracers other than SF_6, and (3) sites with thick unsaturated zones (where CFC and SF_6 transport may be impeded) may require that these tracers either not be used or be used in conjunction with unsaturated-zone sampling for CFCs and SF_6 to provide understanding of unsaturated zone transport. Prior to full project sampling, sampling a subset of wells for a wide range of tracers to assess tracer reliability for a given study area may provide information not available by other means. Sampling efforts can benefit where on-site information is used. For example, if degassing is observed during sampling, collection of He samples is likely to result in fractionated samples, whereas if suboxic conditions are observed, collection of CFCs may result in degraded tracers. Major dissolved gases have not been collected consistently with tracers. Major dissolved gases provide critical constraints on recharge temperature, excess air, and redox state. Similarly, ^{3}H has been collected sporadically. Because ^{3}H is a conservative tracer with a known historical record, it can provide valuable insights when used in conjunction with age-dating tracers. Other supporting data are collected infrequently. For example, noble gases can support the improved determination of recharge temperature, gas fractionation at the water table, and recharge altitude. These are but a few of the considerations, many of which have been discussed in published literature, which can contribute to improved age-dating results.

References Cited

Andrews, J.N., 1992, Mechanisms for noble gas dissolution by groundwaters, *in* International Atomic Energy Agency, ed., Isotopes of noble gases as tracers in environmental studies: International Atomic Energy Agency (IAEA), Vienna, Austria, p. 87–110.

Bethke, C.M., and Johnson, T.M., 2002, Ground water age: Groundwater, v. 40, p. 337–339.

Bethke, C.M., and Johnson, T.M., 2008, Groundwater age and groundwater age dating: Annual Review of Earth and Planetary Sciences, v. 36, p. 121–152.

Burow, K.R., Dubrovsky, N.M., and Shelton, J.L., 2007, Temporal trends in concentrations of DBCP and nitrate in groundwater in the eastern San Joaquin Valley, California, USA: Hydrogeology Journal, v. 15, no. 5, p. 991–1007.

Busenberg, Eurybiades, and Plummer, L.N., 1992, Use of chlorofluorocarbons (CCl_3F and CCl_2F_2) as hydrologic tracers and age-dating tools—The alluvium and terrace system of central Oklahoma: Water Resources Research, v. 28, no. 9, p. 2257–2283.

Busenberg, Eurybiades, and Plummer, L.N., 2000, Dating young groundwater with sulfur hexafluoride: Natural and anthropogenic sources of sulfur hexafluoride: Water Resources Research, v. 36, no. 10, p. 3011–3030.

Busenberg, Eurybiades, and Plummer, L.N., 2008, Dating groundwater with trifluoromethyl sulfurpentafluoride (SF_5CF_3), sulfur hexafluoride (SF_6), CF_3Cl (CFC-13), and CF_2Cl_2 (CFC-12): Water Resources Research, v. 44, doi:10.1029/2007WR006150, 18 p.

Cey, B.D., Hudson, G.B., Moran, J.E., and Scanlon, B.R., 2008, Impact of artificial recharge on dissolved noble gases in groundwater in California: Environmental Science and Technology, v. 42, no. 4, p. 1017–1023.

Driscoll, F.G., 1986, Groundwater and wells [2nd ed.]: St. Paul, MN, Johnson Division, 1089 p.

Dunkle, S.A., Plummer, L.N., Busenberg, Eurybiades, Phillips, P.J., Denver, J.M., Hamilton, P.A., Michel, R.L., and Coplen, T.B., 1993, Chlorofluorocarbons (CCl_3F and CCl_2F_2) as dating tools and hydrologic tracers in shallow groundwater of the Delmarva Peninsula, Atlantic Coastal Plain, United States: Water Resources Research, v. 29, no. 12, p. 3837–3860.

Ekwurzel, Brenda, Schlosser, Peter, Smethie, W.M., Jr., Plummer, L.N, Busenberg, Eurybiades, Michel, R.L., Weppernig, Ralf, and Stute, Martin, 1994, Dating of shallow groundwater—Comparison of the transient tracers $^{3}H/^{3}He$, chlorofluorocarbons, and ^{85}Kr: Water Resources Research, v. 30, no. 6, p. 1693–1708.

Gilliom, R.J., Alley, W.M., and Gurtz, M.E., 1995, Design of the National Water-Quality Assessment Program—Occurrence and distribution of water-quality conditions: U.S. Geological Survey Circular 1112, 33 p. (Also available at http://pubs.usgs.gov/circ/circ1112/.)

Heaton, T.H.E., and Vogel, J.C., 1981, Excess air in groundwater: Journal of Hydrology, v. 50, p. 201–216.

International Atomic Energy Agency, 2006, Use of chlorofluorocarbons in hydrology—A guidebook: Vienna, Austria, International Atomic Energy Agency (IAEA), 277 p.

Kipfer, Rolf, Aeschbach-Hertig, Werner, Peeters, Frank, and Stute, Marvin, 2002, Noble gases in lakes and ground waters, *in* Porcelli, D., Ballentine, C.J., and Wieler, R., eds., Reviews in mineralogy and geochemistry—Noble gases in geochemistry and cosmochemistry: Washington, D.C., Mineralogical Society of America, v. 47, p. 615–700.

Klump, Stephan, Cirpka, O.A., Surbeck, Heinz, and Kipfer, Rolf, 2008, Experimental and numerical studies on excess-air formation in quasi-saturated porous media: Water Resources Research, v. 44, doi:10.1029/2007WR006280.

Lindsey, B.D., Phillips, S.W., Donnelly, C.A., Speiran, G.K., Plummer, L.N., Böhlke, J.K., Focazio, M.J., Burton, W.C., Busenberg, Eurybiades, 2003, Residence times and nitrate transport in ground water discharging to streams in the Chesapeake Bay watershed: U.S. Geological Survey Water-Resources Investigations Report 2003-4035, 201 p. (Also available at http://pa.water.usgs.gov/reports/wrir03-4035.pdf.)

Lucas, L.L., and Unterweger, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: Journal of Research of the National Institute of Standards and Technology, v. 105, no. 4, p. 541–549, accessed October 21, 2010, at http://nvl.nist.gov/pub/nistpubs/jres/105/4/j54luc2.pdf.

Mamyrin, B.A., and Tolstikhin, L.N., 1984, Helium isotopes in nature—Developments in geochemistry 3: Amsterdam, Elsevier, 273 p.

National Oceanic and Atmospheric Administration, 2008, NOAA calibration scales for various trace gases: National Oceanic and Atmospheric Administration, accessed February 19, 2010, at http://www.esrl.noaa.gov/gmd/ccl/scales.html.

Paschke, S.S., ed. 2007, Hydrogeologic settings and ground-water flow simulations for regional studies of the transport of anthropogenic and natural contaminants to public-supply wells—Studies begun in 2001: U.S. Geological Survey Professional Paper 1737-A, 288 p. (Also available at http://pubs.usgs.gov/pp/2007/1737a/.)

Plummer, L.N., and Busenberg, Eurybiades, 2000, Chlorofluorocarbons, *in* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Mass., Kluwer Academic Press, chap. 15, p. 441–478.

Plummer, L.N., and Mullin, A.H., 1997, Collection, processing, and analysis of ground-water samples for tritium/helium-3 dating: U.S. Geological Survey National Water Quality Laboratory Technical Memorandum 97.04S, accessed December 15, 2009, at http://nwql.usgs.gov/Public/tech_memos/nwql.1997-04S.pdf.

Plummer, L.N., Böhlke, J.K., and Busenberg, Eurybiades, 2003, Approaches for ground-water dating, *in* Lindsey, B.D., Phillips, S.W., Donnelly, C.A., Speiran, G.K., Plummer, L.N., Böhlke, J.K., Focazio, M.J., Burton, W.C., and Busenberg, Eurybiades, Residence times and nitrate transport in ground water discharging to streams in the Chesapeake Bay Watershed: U.S. Geological Survey Water-Resources Investigations Report 2003-4035, p. 12–24. (Also available at http://pa.water.usgs.gov/reports/wrir03-4035.pdf.)

Plummer, L.N., Sanford, W.E., Bexfield, L.M., Anderholm, S.K., and Busenberg, Eurybiades, 2004, Using geochemical data and aquifer simulation to characterize recharge and groundwater flow in the Middle Rio Grande Basin, New Mexico, *in* Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., Groundwater recharge in a desert environment—The Southwestern United States: Washington, D.C., American Geophysical Union, Water Science and Applications Series, v. 9, p. 185–216.

Schlosser, Peter, Stute, Martin, Sonntag, Christian, and Münnich, K.O., 1989, Tritiogenic ^{3}He in shallow groundwater: Earth and Planetary Science Letters, v. 94, p. 245–256.

Solomon, D.K., and Cook, P.G., 2000, ^{3}H and ^{3}He, *in* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 397–424.

Stute, M., and Schlosser, P., 2000, Atmospheric noble gases, *in* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 349–377.

Sun, Tie, Hall, C.M., and Castro, M.C., 2010, Statistical properties of groundwater noble gas paleoclimate models—Are they robust and unbiased estimators?: Geochemistry, Geophysics, Geosystems, v. 11, doi:10.1029/2009GC002717, 18 p.

Tesoriero, A.J., Saad, D.A., Burow, K.R., Frick, E.A., Puckett, L.J., and Barbash, J.E., 2007, Linking ground-water age and chemistry data along flowpaths—Implications for trends and transformations of nitrate and pesticides: Journal of Contaminant Hydrology, v. 94, p. 139–155.

Thatcher, L.L., 1962, The distribution of tritium fallout in precipitation over North America: Bulletin of the International Association of Scientific Hydrology, v. 7, p. 48–58.

Walker, S.J., Weiss, R.F., and Salameh, P.K., 2009, Reconstructed histories of the annual mean atmospheric mole fractions for the halocarbons CFC-11, CFC-12, CFC-113 and carbon tetrachloride: University of California San Diego, accessed February 18, 2010, at http://bluemoon.ucsd.edu/pub/cfchist/.

Weissmann, G.S., Zhang, Y., LaBolle, E.M., and Fogg, G.E., 2002, Dispersion of groundwater age in an alluvial aquifer system: Water Resources Research, v. 38, no. 10, doi:10.1029/2001WR000907.

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.

[**Abbreviations:** CFCs, chlorofluorocarbons; SF_6, sulfur hexafluoride; $^3H/^3He$, tritium/helium-3; USGS, U.S. Geological Survey. **Symbols:** >, greater than (when used with a date means greater than or more recent than that date); <, less than (where used with a date means less than or older than that date); >, where used with a tracer-based piston-flow age means greater than or older than that age; <, where used with a tracer-based piston-flow age means less than or younger than that age; –, not determined]

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Apalachicola-Chattahoochee-Flint Basin (ACFB)				
LUSAG1	305641084542001	CP 19	04-22-02	1991	11	CFCs
LUSAG1	310552084435601	CP 18	09-15-99	1981	18	CFCs
LUSAG1	310752085271301	CP 13	03-20-02	1974	28	CFCs
LUSAG1	310913084195301	CP 30	04-10-02	>1985	<17	CFCs
LUSAG1	311505085140101	CP 14	03-07-02	1987	15	CFCs
LUSAG1	312119084215601	CP 21	04-08-02	1984	18	CFCs
LUSAG1	312908084151901	CP 29	04-09-02	1991	11	CFCs
LUSAG1	313415084475201	CP 16	04-23-02	1965	37	CFCs
LUSAG1	314357084380001	CP 15	09-16-99	1998	1	CFCs
LUSAG1	314858084194901	CP 23	09-16-99	1970	29	CFCs
LUSAG1	320011084121501	CP 26	09-17-99	1994	5	CFCs
LUSCR1	315947084024001	LC 7A	09-29-99	1979	20	CFCs
LUSCR1	320001084032801	LC 8A	09-28-99	1993	6	CFCs
LUSCR1	320051084061401	LC 6	03-08-02	1961	41	CFCs
LUSCR1	320150083594801	LC 9C	09-07-99	1953	46	CFCs
LUSCR1	320206084084701	LC 1C	09-08-99	>1986	<13	CFCs
LUSCR1	320301084013401	LC 10E	09-28-99	1969	30	CFCs
LUSCR1	320414084052801	LC 5B	09-29-99	1989	10	CFCs
LUSCR1	320541084091501	LC 3A	09-08-99	1969	30	CFCs
LUSCR2	310727084485401	AC 38A	09-13-99	1976	23	CFCs
LUSCR2	311015084511901	AC 36B	09-13-99	1954	45	CFCs
LUSCR2	311141084513401	AC 35B	09-14-99	1984	15	CFCs
LUSCR2	311434084511701	AC 34A	09-14-99	1975	24	CFCs
LUSFO1/ reference[1]	311327084484101	RF 41	09-14-99	1973	26	CFCs
LUSFO1/ reference[1]	311714084275101	RF 44	09-15-99	1983	16	CFCs
LUSFO1/ reference[1]	312737084553301	RF 42	09-30-99	>1991	<8	CFCs
		Albemarle-Pamlico Drainage Basin (ALBE)				
LUSAG1	345516077190001	LU-20	05-21-02	>1983	<19	CFCs
LUSAG1	353111077334402	GR-085 L6	04-22-03	>1987	<16	CFCs
LUSAG1	353221076105501	LU-S9C	05-22-02	>1971	<31	CFCs
LUSAG1	353547076473301	LU-10A	05-21-02	>1956	<46	CFCs
LUSAG1	361714076201301	LU-04A	05-23-02	>1969	<33	CFCs
LUSAG1	362646076361607	GA-067	05-23-02	>1990	<12	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
Central Columbia Plateau - Yakima River Basin (CCYK)						
LUSOR1b/AG2b	462141119130501	PN84	07-24-02	1989	13	SF_6
LUSOR1b/AG2b	462727119115801	ON63	07-25-02	1993	9	SF_6
LUSOR1b/AG2b	462826119145301	ON58	07-23-02	1982	20	SF_6
LUSOR1b/AG2b	463745119164601	PN17	07-23-02	1990	12	SF_6
LUSOR1b/AG2b	463843119095201	ON59	07-23-02	1986	16	SF_6
LUSOR1b/AG2b	464819119091001	PN89	07-23-02	1981	21	SF_6
LUSOR1b/AG2b	465328119195901	ON04	07-17-02	1980	22	SF_6
LUSOR1b/AG2b	465531119315501	ON54	07-16-02	<1970	>32	SF_6
LUSOR1b/AG2b	470850119323501	PN57	07-15-02	1986	16	SF_6
LUSOR1b/AG2b	471013119433401	PN49	07-16-02	1988	14	SF_6
Central Nebraska Basins (CNBR)						
LUSCR1	413340096402701	DO-24	05-15-03	>1945	<58	CFCs
LUSCR1	413853096483801	DO-22	06-04-03	>1945	<58	CFCs
LUSCR1	414343096595801	CO-13	06-04-03	>1977	<26	CFCs
LUSCR1	414401096531301	DO-21	06-02-03	1983	20	CFCs
LUSCR1	414527097094101	S-11	06-03-03	1981	22	CFCs
LUSCR1	414931096321101	B-27	06-05-03	1986	17	CFCs
LUSCR1	415220096214801	B-28	04-28-03	1990	13	CFCs
LUSCR1	420024096485901	CU19	05-28-03	>1969	<34	CFCs
LUSCR1	420425097101301	S-10	05-07-03	1989	14	CFCs
LUSCR1	420526096543901	W-14	05-01-03	>1970	<33	CFCs
LUSCR1	420922096514401	W-18	05-05-03	1984	19	CFCs
LUSCR1	421303097011601	W-15	05-07-03	1977	26	CFCs
LUSCR1	421357097243201	P-02	05-27-03	1976	27	CFCs
LUSCR1	421829097112401	W-08	05-08-03	1989	14	CFCs
LUSCR1	422011096595401	DI-16	05-05-03	1981	22	CFCs
LUSCR1	422031097043501	W-07	05-06-03	1987	16	CFCs
LUSCR1	422156097314301	P-03	05-21-03	1991	12	CFCs
LUSCR1	422441097404601	P-04	05-20-03	1988	15	CFCs
LUSCR1	422756097334901	K-05	05-20-03	1983	20	CFCs
LUSCR1	422802097031601	CE-17	05-19-03	>1976	<27	CFCs
LUSCR1	422947097142701	CE-06	05-20-03	>1990	<13	CFCs
REFPA1	415458097142201	S-R2	06-03-03	1986	17	CFCs
Connecticut, Housatonic and Thames River Basins (CONN)						
Other	413046073122601	CT- WY 67	04-17-03	–	–	SF_6
Other	413121073122701	CT-WY 23	12-30-03	1997	6	$^3H/^3He$
Other	413615073102101	CT- WY 68	04-16-03	–	–	SF_6
LUSRC1	413150072551901	CT- CS 244	07-23-03	–	–	SF_6
LUSRC1	413925072544401	CT-BS-277	09-14-05	2000	5	$^3H/^3He$
LUSRC1	414555072333601	CT- M 193	08-08-03	–	–	SF_6

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
Connecticut, Housatonic and Thames River Basins (CONN)—Continued						
LUSRC1	414825072350901	CT-SW-136	09-21-05	>1953	<52	$^3H/^3He$
LUSRC1	414826072290901	CT-M-192	09-20-05	>1953	<52	$^3H/^3He$
LUSRC1	415336072414801	CT-W-218	09-15-05	1972	33	$^3H/^3He$
LUSRC1	415446072364501	CT- EW 141	08-04-03	–	–	SF_6
LUSRC1	415535072475701	CT- GR 345	08-20-03	–	–	SF_6
LUSRC1	420322072391801	MA-AFW 31	08-05-03	–	–	SF_6
LUSRC1	420757072390101	MA-XCW 144	08-12-03	1994	9	SF_6
LUSRC1	421031072311601	MA-CMW-97	10-18-05	2003	2	$^3H/^3He$ [2]
LUSRC1	421031072311601	MA-CMW 97	08-06-03	1996	7	SF_6 [3]
SUS2	412746073142401	CT-SB-120	11-06-02	>1945	<57	CFCs
SUS2	413225073130401	CT-WY-65	06-06-02	>1945	<57	CFCs
SUS2	413710072553001	CT-S-400	07-29-02	>1945	<57	CFCs
SUS2	414144072505101	CT-F-344	05-30-02	>1958	<44	CFCs
SUS2	415547071563501	CT-WK-232	09-18-02	>1945	<57	CFCs
SUS2	431640072415801	VT-AN-01	08-19-02	1974	28	CFCs
SUS2	434402072152701	NH-HHW-269	09-09-02	>1961	<41	CFCs
SUS2	435633072332001	VT-RA-1	08-21-02	>1991	<11	CFCs
SUS2	440417072002501	NH-HKW-113	09-10-02	>1956	<46	CFCs
Delaware River Basin (DELR)						
SUS1	400808075210401	MG 225	07-28-99	1971	28	$^3H/^3He$
SUS1	400821075164001	MG1724	08-17-99	1988	11	$^3H/^3He$
SUS1	400954075354501	CH1567	07-15-99	1972	27	$^3H/^3He$
SUS1	401154075055001	BK2955	08-18-99	1974	25	$^3H/^3He$
SUS1	401245075300901	MG1712	06-09-99	1973	26	$^3H/^3He$
SUS1	401405075275101	MG1714	06-22-99	1976	23	$^3H/^3He$
SUS1	401416075445601	BE1698	06-29-99	1975	24	$^3H/^3He$
SUS1	401620075055001	BK2823	10-05-99	1999	0	$^3H/^3He$
SUS1	401658074505001	210556	06-08-99	1996	3	$^3H/^3He$
SUS1	401734074470301	210284	10-12-99	1991	8	$^3H/^3He$
SUS1	402027075072901	BK2956	09-08-99	1989	10	$^3H/^3He$
SUS1	402119075173701	BK2958	09-30-99	1980	19	$^3H/^3He$
SUS1	402337075290001	MG1715	06-30-99	1976	23	$^3H/^3He$
SUS1	402341074543601	190074	06-03-99	>1953	<46	$^3H/^3He$
SUS1	402555075114701	BK2954	06-15-99	1992	7	$^3H/^3He$
SUS1	403003075000001	190083	08-19-99	1980	19	$^3H/^3He$
SUS1	403140075052901	BK2048	07-01-99	>1953	<46	$^3H/^3He$
SUS1	403237075185301	BK1411	06-16-99	1999	0	$^3H/^3He$

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name		Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Eastern Iowa Basins (EIWA)					
LUSCR1	405405091335001	Moun		08-02-99	>1945	<54	CFCs
LUSCR1	405601091551901	Fair		07-23-99	>1945	<54	CFCs
LUSCR1	411511091155101	Colu		07-20-99	>1945	<54	CFCs
LUSCR1	411843092105101	Sego		07-08-99	1995	4	CFCs
LUSCR1	412755091114101	Musc		07-20-99	>1960	<39	CFCs
LUSCR1	412927092575201	Pell		07-19-99	1989	10	CFCs
LUSCR1	413248092011301	Nort		07-07-99	1990	9	CFCs
LUSCR1	413540091341201	Hill		07-07-99	1993	6	CFCs
LUSCR1	414208092312601	Malc		07-08-99	1996	3	CFCs
LUSCR1	414912093284201	Lori		07-13-99	>1975	<24	CFCs
LUSCR1	414958090230301	Malo		08-04-99	>1990	<9	CFCs
LUSCR1	415527092190301	Bell		07-12-99	>1983	<16	CFCs
LUSCR1	420117092505601	Legr		07-13-99	>1945	<54	CFCs
LUSCR1	421115091250501	Prai		08-03-99	1996	3	CFCs
LUSCR1	421705092142501	Lapo		07-16-99	>1945	<54	CFCs
LUSCR1	422518092144701	Gilb		07-15-99	>1945	<54	CFCs
LUSCR1	422629092345001	Zane		07-26-99	>1945	<54	CFCs
LUSCR1	423557091560501	Haze		07-14-99	>1953	<46	CFCs
LUSCR1	423639092350901	Newh		07-14-99	>1945	<54	CFCs
LUSCR1	424203092551301	Dumo		07-29-99	>1945	<54	CFCs
LUSCR1	425401093135201	Shef		07-29-99	1997	2	CFCs
LUSCR1	425756092162401	Fred		07-15-99	1993	6	CFCs
LUSCR1	430159093403201	Dune		07-28-99	>1971	<28	CFCs
LUSCR1	430525093023501	Maso		07-29-99	>1995	<4	CFCs
LUSCR1	431222093313301	Mill		07-28-99	>1945	<54	CFCs
LUSCR1	431339093155901	Clea		07-29-99	>1945	<54	CFCs
LUSCR1	432946093161901	Fert		07-27-99	1991	8	CFCs
LUSCR1	433815093000001	Aust		07-27-99	1972	27	CFCs
LUSCR1	435221093001901	Bloo		07-27-99	>1945	<54	CFCs
Other	414752092053201	081N11W26ACC	1984USGS OBS WELL IRA 5A	08-19-98	>1980	<18	CFCs
Other	414752092053202	081N11W26ACC	1985USGS OBS WELL IRA 5B	08-19-98	>1989	<9	CFCs
Other	414752092053203	081N11W26ACC	1985USGS OBS WELL IRA 5C	08-19-98	>1985	<13	CFCs
Other	414816092053401	081N11W23DCC	1984USGS OBS WELL IRA 4A	08-03-98	>1953	<45	CFCs
Other	414816092053402	081N11W23DCC	1985USGS OBS WELL IRA 4B	08-03-98	>1985	<13	CFCs
Other	414816092053403	081N11W23DCC	1985USGS OBS WELL IRA 4C	08-03-98	>1990	<8	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Eastern Iowa Basins (EIWA)—Continued				
Other	414818092055401	081N11W14CCA 1985USGS OBS WELL IRA 26A	08-20-98	>1969	<29	CFCs
Other	414818092055402	081N11W14CCA 1985USGS OBS. WELL IRA 26B	08-20-98	>1977	<21	CFCs
Other	414900092073801	081N11W21ABD 96USGS OBS. WELL IRC 1	08-13-98	>1966	<32	CFCs
Other	414907092083001	081N11W20AAA 1984USGS OBS. WELL IRA 3A	08-10-98	>1962	<36	CFCs
Other	414907092083003	081N11W20AAA 1985USGS OBS. WELL IRA 3C	08-10-98	>1964	<34	CFCs
Other	414907092083004	081N11W20AAAA 1985USGS OBS. WELL IRA 3D	08-06-98	>1980	<18	CFCs
Other	414930092093801	081N11W17CBB 1984USGS OBS. WELL IRA 6	08-13-98	>1964	<34	CFCs
Other	415020092094001	081N11W07DAA 1985USGS OBS. WELL IRA 21A	08-04-98	1985	13	CFCs
Other	415020092094002	081N11W07DAA 1985USGS OBS. WELL IRA 21B	08-05-98	>1979	<19	CFCs
Other	415020092094003	081N11W07DAA 1985USGS OBS. WELL IRA 21C	08-05-98	>1979	<19	CFCs
Other	415020092094004	081N11W07DAA 1985USGS OBS. WELL IRA 21D	08-04-98	>1984	<14	CFCs
Other	415020092094005	0811107WDAAD 1986USGS OBS. WELL IRA 21E	08-04-98	>1993	<5	CFCs
Other	415020092094010	081N11W07DAA 1987USGS OBS. WELL IRA 21F	08-05-98	>1977	<21	CFCs
Other	415039092164001	081N12W05CCC 1984USGS OBS. WELL IRA 17	08-17-98	1986	12	CFCs
Other	415045092145601	081N12W09ABC 1984USGS OBS. WELL IRA 19	08-21-98	1988	10	CFCs
Other	415052092120301	081N12W11AAD 96USGS OBS. WELL IRC 2	08-11-98	>1951	<47	CFCs
Other	415105092132501	081N12W03DDB 96USGS OBS. WELL IRC 3	08-11-98	>1952	<46	CFCs
Other	415105092135201	081N12W03CDA 96USGS OBS. WELL IRC 4	08-18-98	>1975	<23	CFCs
Other	415211092164101	082N12W31DAD 1984USGS OBS. WELL IRA 16A	08-17-98	>1981	<17	CFCs
Other	415211092164102	082N12W31DAD 1984USGS OBS. WELL IRA 16B	08-17-98	>1945	<53	CFCs
Other/REFCR1	414818092055403	081N11W14CCA 1985USGS OBS. WELL IRA 26C	08-20-98	>1972	<26	CFCs
		Georgia-Florida Coastal Plain (GAFL)				
LUSCR1	312021083350101	GAFL 11-1	09-20-99	1973	26	CFCs
LUSCR1	312703083263601	GAFL 12-3	09-24-99	1978	21	CFCs
LUSCR1	313822083311901	GAFL 20-1	09-22-99	1985	14	CFCs
LUSCR1	314421083281601	GAFL 18-1	09-21-99	1987	12	CFCs
LUSCR1	314847083360301	GAFL 15-1	09-22-99	1976	23	CFCs
LUSCR1	315059083350901	GAFL 16-1	09-22-99	1994	5	CFCs
LUSCR1	315747083312901	GAFL 17-2	09-23-99	1980	19	CFCs
		Lake Erie-Lake Saint Clair Basins (LERI)				
LUSRC1	422751083405200	URB093-1/422751083 urb-093-13	11-19-96	>1953	<43	$^3H/^3He$
LUSRC1	422806083493700	URB093/422806083 urb-093-10	11-19-96	1978	18	$^3H/^3He$
LUSRC1	423020083390100	URB125/423020083 urb-125-8	11-21-96	1992	4	$^3H/^3He$
LUSRC1	424010083360200	URB125-2/424010083 urb-125-26	11-26-96	1992	4	$^3H/^3He$
LUSRC1	424614083175300	URB125-1/424614083 urb-125-16	12-11-96	1964	32	$^3H/^3He$

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Lower Illinois River Basin (LIRB)				
LUSRC1	383214089571501	SIL-25	08-03-05	–	–	SF_6
LUSRC1	383321089594601	SIL-23	08-03-05	–	–	SF_6
LUSRC1	383445089535701	SIL-27	08-01-05	2001	4	SF_6
LUSRC1	383453089545001	SIL-27A	08-04-05	–	–	SF_6
LUSRC1	383847090003501	SIL-22	07-12-05	1974	31	SF_6
LUSRC1	384058090010601	SIL-22A	07-12-05	–	–	SF_6
LUSRC1	384323090405801	SMO-12	08-09-05	1982	23	SF_6
LUSRC1	384411090354601	SMO-14	07-27-05	–	–	SF_6
LUSRC1	384515089591801	SIL-28	08-08-05	1993	12	SF_6
LUSRC1	384546089575801	SIL-21	08-02-05	–	–	SF_6
LUSRC1	384613089572001	SIL-30	08-02-05	–	–	SF_6
LUSRC1	384619090382701	SMO-08	07-26-05	1980	25	SF_6
LUSRC1	384646090375501	SMO-9A	07-26-05	–	–	SF_6
LUSRC1	384656089582001	SIL-20	07-13-05	1980	25	SF_6
LUSRC1	384659090003701	SIL-20A	07-14-05	1984	21	SF_6
LUSRC1	384714089585301	SIL-20B	07-13-05	–	–	SF_6
LUSRC1	384734090384801	SMO-06A	07-28-05	1991	14	SF_6
LUSRC1	384955089473001	MRN-1	09-07-05	–	–	SF_6
LUSRC1	385446090015901	SIL-19A	07-11-05	–	–	SF_6
LUSRC1	385735089513901	WDN-1	09-07-05	–	–	SF_6
		New England Coastal Basins (NECB)				
LUSRC1	414541071143501	Swansea	08-30-99	>1945	<54	CFCs
LUSRC1	414913071052701	Berkley	08-31-99	1992	7	CFCs
LUSRC1	415317070434701	Carver	08-11-99	>1968	<31	CFCs
LUSRC1	415423070442901	Carver	08-11-99	1988	11	CFCs
LUSRC1	415541070443001	Plymouth	08-04-99	>1945	<54	CFCs
LUSRC1	415600071022501	Raynham	07-28-99	>1993	<6	CFCs
LUSRC1	420013071161501	T-77	07-22-99	>1945	<54	CFCs
LUSRC1	420044070430301	Duxbury	09-01-99	1994	5	CFCs
LUSRC1	420134070432301	Duxbury	08-31-99	1991	8	CFCs
LUSRC1	420144070541501	Bridgewater	08-03-99	>1945	<54	CFCs
LUSRC1	420239070472201	Pembroke	07-29-99	1993	6	CFCs
LUSRC1	420241071072601	Easton	08-19-99	>1977	<22	CFCs
LUSRC1	420249071035801	Bridgewater	09-02-99	>1945	<54	CFCs
LUSRC1	420607070515501	Hanover	08-25-99	>1945	<54	CFCs
LUSRC1	420634070444201	Marshfield	08-23-99	1990	9	CFCs
LUSRC1	420644071260701	Franklin	07-21-99	>1945	<54	CFCs
LUSRC1	420910070530901	Hanover	08-24-99	>1945	<54	CFCs
LUSRC1	420937070513001	Norwell	08-24-99	>1945	<54	CFCs
LUSRC1	421655071360301	Westboro	07-20-99	>1945	<54	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
New England Coastal Basins (NECB)—Continued						
LUSRC1	421744071115201	Newton	07-23-99	>1945	<54	CFCs
LUSRC1	422651071242601	Concord	08-05-99	>1945	<54	CFCs
LUSRC1	423138071141501	Billercia	07-13-99	>1945	<54	CFCs
LUSRC1	423325071300301	Littleton	08-17-99	1986	13	CFCs
LUSRC1	423501071133101	Tewksbury	08-18-99	1990	9	CFCs
LUSRC1	423527071120601	Tewksbury	08-18-99	>1984	<15	CFCs
LUSRC1	423916070562401	Topsfield	08-10-99	1992	7	CFCs
LUSRC1	424012070581101	Boxford	07-14-99	1988	11	CFCs
LUSRC1	424228071290201	Nashua	07-27-99	1993	6	CFCs
LUSRC1	424730071313401	Nashua	08-09-99	>1945	<54	CFCs
SUS1/SUS2	413024071334101	C11.1 South Kingston 413024071334101	10-31-00	>1987	<13	CFCs
SUS1/SUS2	414046071051001	C12.5 West Port 414046071051001	10-30-00	>1945	<55	CFCs
SUS1/SUS2	415012070461101	C22.1 Carver 415012070461101	10-12-00	>1966	<34	CFCs
SUS1/SUS2	423609070490901	C21.1 Hamilton 423609070490901	10-11-00	>1959	<41	CFCs
SUS1/SUS2	424528071321101	C1.2 Hollis 424528071321101	06-05-00	>1945	<55	CFCs
SUS1/SUS2	424548071403201	C2.1 Brookline 424548071403201	06-22-00	1980	20	CFCs
SUS1/SUS2	424843071112201	C2.1 Salem 424843071112201	06-06-00	>1945	<55	CFCs
SUS1/SUS2	424905071260101	C3.2 Litchfield 424905071260101	06-19-00	>1945	<55	CFCs
SUS1/SUS2	425532070565501	C4.1 Kensington 425532070565501	06-07-00	>1984	<16	CFCs
SUS1/SUS2	425948072024801	C3.3 Hancock 425948072024801	08-14-00	>1945	<55	CFCs
SUS1/SUS2	430140071193801	C13.3 Auburn 430140071193801	08-09-00	>1986	<14	CFCs
SUS1/SUS2	430616071020801	C5.1 Lee 430616071020801	06-08-00	>1945	<55	CFCs
SUS1/SUS2	431300071342701	C9.3 Concord 431300071342701	09-11-00	>1945	<55	CFCs
SUS1/SUS2	431341070441901	C23.4 Berwick 431341070441901	10-03-00	>1972	<28	CFCs
SUS1/SUS2	431350071421001	C4.1 Contoocook 431350071421001	08-21-00	>1983	<17	CFCs
SUS1/SUS2	432143070304101	12.2 Kennebunk ME 432143070304101	06-21-00	1988	12	CFCs
SUS1/SUS2	432203070283201	Kennebunkport	10-14-99	>1945	<54	CFCs
SUS1/SUS2	432406070371301	C9.3 Kennebunk 432406070371301	06-14-00	>1945	<55	CFCs
SUS1/SUS2	432430070305501	Arundel	10-14-99	>1973	<26	CFCs
SUS1/SUS2	432735071273401	C8.1 Belmont 432735071273401	09-11-00	>1945	<55	CFCs
SUS1/SUS2	433325071420301	C5.2 New Hampton 433325071420301	08-15-00	>1945	<55	CFCs
SUS1/SUS2	433605070415401	C8.2 East Waterboro 433605070415401	06-15-00	>1945	<55	CFCs
SUS1/SUS2	433650071101101	C14.4 Wolfboro 433650071101101	08-28-00	>1945	<55	CFCs
SUS1/SUS2	434335071361101	C7.3 Holderness 434335071361101	08-10-00	>1987	<13	CFCs
SUS1/SUS2	434532070555701	Parsonfield	10-12-99	1990	9	CFCs
SUS1/SUS2	434641070383301	Standish	10-12-99	>1967	<32	CFCs
SUS1/SUS2	434700071212701	C15.2 Sandwich 434700071212701	09-25-00	1978	22	CFCs
SUS1/SUS2	435014070232001	C14.1 Windham 4350140702301	07-12-00	>1945	<55	CFCs
SUS1/SUS2	435342070301601	C24.5 Raymond ME 435342070301601	10-16-00	1988	12	CFCs
SUS1/SUS2	435534071530501	C6.1 Warren 435534071530501	08-16-00	>1988	<12	CFCs
SUS1/SUS2	435720070125201	C25.1 New Gloucester 4357070125201	09-14-00	>1945	<55	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
New England Coastal Basins (NECB)—Continued						
SUS1/SUS2	435726070023901	C17.1 Brunswick 435726070023901	07-19-00	>1985	<15	CFCs
SUS1/SUS2	435858070475901	C20.1 Denmark 435858070475901	10-19-00	>1948	<52	CFCs
SUS1/SUS2	440213070080901	C13.4 Lisbon 440213070080901	07-18-00	>1945	<55	CFCs
SUS1/SUS2	440257070282201	C26.5 West Poland ME 440257070282201	08-30-00	>1982	<18	CFCs
SUS1/SUS2	440852071221401	C16.1b Harts location 440852071221401	08-24-00	1993	7	CFCs
SUS1/SUS2	441312070172501	15.3 Turner ME	10-13-99	>1970	<29	CFCs
SUS1/SUS2	441721069584001	C22.3 Winthrop 441721069584001	07-20-00	>1945	<55	CFCs
SUS1/SUS2	442059070502101	C18.2 Albany TWP 442059070502101	08-23-00	>1987	<13	CFCs
SUS1/SUS2	442245069584901	21.3 Readfield 442245069584901	06-29-00	>1945	<55	CFCs
SUS1/SUS2	442407069501801	27.4 Belgrade ME 442407069501801	10-17-00	>1946	<54	CFCs
SUS1/SUS2	442605070122401	Livermore	10-13-99	>1971	<28	CFCs
SUS1/SUS2	442857069282801	South China	10-19-99	>1981	<18	CFCs
SUS1/SUS2	442913070511801	C17.5 Newry 44291307051801	08-22-00	>1975	<25	CFCs
SUS1/SUS2	443626069414301	Fairfield	10-15-99	>1945	<54	CFCs
SUS1/SUS2	443657069303701	C24.4 Benton 443657069303701	06-28-00	>1984	<16	CFCs
SUS1/SUS2	443852070401901	28.5 Ellis pond ME 443852070401901	10-18-00	>1945	<55	CFCs
SUS1/SUS2	444137069121701	26.1 Troy ME 444137069121701	06-20-00	1994	6	CFCs
SUS1/SUS2	444400069111801	C27.5 Plymouth ME 444400069111801	07-06-00	>1945	<55	CFCs
SUS1/SUS2	444525069391101	C25.4 Skowhegan 444525069391101	08-31-00	>1945	<55	CFCs
SUS1/SUS2	444702069490301	C19.2 Madison 444702069490301	07-17-00	>1945	<55	CFCs
SUS1/SUS2	445149069460001	C18.3 Madison 445149069460001	07-13-00	>1945	<55	CFCs
SUS1/SUS2	445249069120901	Newport	10-20-99	>1945	<54	CFCs
SUS1/SUS2	445601069182001	C29.2 Corinna 4456010691801	10-04-00	>1966	<34	CFCs
SUS1/SUS2	445700069183901	Corinna	10-22-99	>1945	<54	CFCs
SUS1/SUS2	445958069301101	C29.4 Harmony 445958069301101	06-27-00	1967	33	CFCs
SUS1/SUS2	450223069162401	Dexter	10-21-99	>1973	<26	CFCs
SUS3	414604070381402	C23.1 Onset MA	07-25-01	1991	10	CFCs
SUS3	415704071380601	C02.1 Mapleville RI	10-03-01	1988	13	CFCs
SUS3	420434071225001	C10.2 Franklin MA	07-18-01	>1945	<56	CFCs
SUS3	422029071223701	C09.1 Wayland MA	07-16-01	>1945	<56	CFCs
SUS3	422754071093101	C14.3 Woburn MA	07-17-01	>1945	<56	CFCs
SUS3	423247071031301	C20.1 Lynnfield	08-06-01	>1987	<14	CFCs
SUS3	423548071074901	C15.8 N Reading MA	07-17-01	>1945	<56	CFCs
SUS3	432708070465901	C27.2 Sanford ME	07-31-01	>1945	<56	CFCs
SUS3	441137070312501	C29.2 Norway ME	09-26-01	>1945	<56	CFCs
SUS3	443021071092501	C17.6 Berlin NH	08-14-01	>1945	<56	CFCs
SUS3	450232069525101	C30.1 Bingham ME	09-25-01	1987	14	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Northern Rockies Intermontane Basins (NROK)				
SUS2	464951114023701	29 #1	06-19-01	2000	1	SF_6
SUS2	465127114055401	16 #1	06-20-01	1985	16	SF_6
SUS2	465323114054301	18 #1	06-20-01	–	–	SF_6
SUS2	465440114022101	30 #1	06-19-01	1997	4	SF_6
SUS2	465741114110601	6 #1	06-27-01	1999	2	SF_6
SUS2	465838114074501	17 #1	06-27-01	2001	0	SF_6
SUS2	470328114164301	3 #1	06-28-01	1997	4	SF_6
		Nevada Basin and Range (NVBR)				
LUSRC1	390834119450701	seeliger	06-11-02	>1945	<57	CFCs
LUSRC1	390943119474801	kings well	06-26-02	>1945	<57	CFCs
LUSRC1	391110119460601	OFFICE DEEP	05-13-02	1967	35	CFCs
LUSRC1	391110119460602	OFFICE SHALLOW	05-13-02	>1945	<57	CFCs
LUSRC1	391111119481901	VC-8	07-07-03	>1945	<58	CFCs
LUSRC1	392837119485901	LAKERIDGE GOLF	06-03-02	>1945	<57	CFCs
LUSRC1	392918119464901	neil rd park	06-27-02	>1945	<57	CFCs
LUSRC1	392937119452601	WASHOE CO	06-12-02	>1977	<25	CFCs
LUSRC1	392944119440301	rosewood lakes	06-06-02	>1962	<40	CFCs
LUSUR2	391030119480701	Ash Canyon	05-28-02	1978	24	CFCs
SUS2	390943119474802	kings 1	10-15-03	>1971	<32	CFCs
SUS2	391231119442901	Goni 2 deep	10-15-03	1970	33	CFCs
SUS2	392231119501901	STMGID WELL 7	11-30-03	1971	32	CFCs
SUS2	392414119474701	STMGID WELL 5	11-13-03	1957	46	CFCs
SUS2	392506119462201	STMGID WELL 1	10-29-03	1953	50	CFCs
		Potomac River Basin and Delmarva Peninsula (PODL)				
LUSAG1	380231079091101	37N 5	06-12-02	1997	5	SF_6
LUSAG1	382014079052701	38Q 2	07-18-00	–	–	SF_6
LUSAG1	382556078565401	39R 8	06-06-02	1985	17	SF_6
LUSAG1	382859078544401	39R 7	06-10-02	1975	27	SF_6
LUSAG1	383645078452101	40S 2	07-19-00	–	–	SF_6
LUSAG1	384037078281201	43T 3	06-04-02	1991	11	SF_6
LUSAG1	384556078385101	41U 1	07-19-00	1978	22	SF_6
LUSAG1	390700078151801	44W 20	06-11-02	1996	6	SF_6
LUSAG1	393319077560801	GV-18	05-23-02	–	–	SF_6
LUSAG1	393815077353001	WA BJ 51	07-20-00	1995	5	SF_6
LUSAG1	394416077393401	FR 537	07-20-00	1994	6	SF_6
LUSAG1	394828077545701	FR 809	05-22-02	1995	7	SF_6
LUSRC1	382805077255801	51R 7	07-15-03	1994	9	SF_6
LUSRC1	383710077222301	51S 15	07-16-03	1989	14	SF_6
LUSRC1	383934077222601	52T 72	07-28-03	1994	9	SF_6
LUSRC1	385305077162101	52V 24	07-23-03	–	–	SF_6
LUSRC1	390812077051001	MO DF 61	06-30-03	–	–	SF_6

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
Potomac River Basin and Delmarva Peninsula (PODL)—Continued						
LUSRC1	391004077132601	MO CE 26	06-19-03	–	–	SF_6
LUSRC1	391102077101901	MO CE 24	06-18-03 1630	–	–	SF_6
REFFO1	393108077561101	BER-0687	06-04-02	2000	2	SF_6
REFFO2	383514077242601	51S 13	07-15-03 1615	1980	23	SF_6
Puget Sound Basin (PUGT)						
LUSCR1	485303122190901	AG-03	08-11-06	1989	17	SF_6
LUSCR1	485608122320501	WC-15	08-30-06	1998	8	SF_6
LUSCR1	485708122311301	AG-01-B, now AG16	08-25-06	1995	11	SF_6
LUSCR1	485749122250301	AG-15	08-29-06	2000	6	SF_6
LUSCR1	485751122241601	AG-04	08-17-06	1999	7	SF_6
LUSCR1	485755122253901	AG-05	08-16-06	>1986	<20	SF_6
LUSCR1	485817122244701	AG-13	08-30-06	1997	9	SF_6
LUSCR1	485917122241901	AG-06	08-24-06	1995	11	SF_6
LUSCR1	490009122233101	ABB5	08-15-06	1993	13	SF_6
LUSCR1	490009122242002	AG-07	08-01-07	1996	11	SF_6
LUSCR1	490009122265001	AG-09	08-28-06	2003	3	SF_6
LUSCR1	490010122223101	AG-08	08-08-06	1994	12	SF_6
LUSCR1	490011122193201	ABB4	08-08-06	1994	12	SF_6
LUSCR1	490012122240001	FT7-22	08-14-06	>1979	<27	SF_6
LUSCR1	490020122213201	ABB2	08-09-06	1999	7	SF_6
LUSCR1	490023122253002	91-15	08-24-06	1993	13	SF_6
LUSCR1	490031122221501	BC-C-25	08-09-06	1997	9	SF_6
LUSCR1	490031122225301	BC-B-20	08-22-06	1999	7	SF_6
LUSCR1	490042122241001	ABB1	08-23-06	1993	13	SF_6
LUSCR1	490101122221501	BC-A-25	08-22-06	2000	6	SF_6
LUSCR1	490103122240301	AG-12	08-29-06	1996	10	SF_6
LUSCR1	490125122201601	Airport, now 91-10	08-16-06	2003	3	SF_6
REFCR1	485751122304601	AG-REF	08-10-06	1994	12	SF_6
Rio Grande Valley (RIOG)						
LUSCR1	370936106010501	SLV 13-1	07-31-00	1982	18	CFCs
LUSCR1	371914106042901	SLV 12-1	08-09-00	1984	16	CFCs
LUSCR1	372233105351101	SLV 35-1	07-28-00	>1970	<30	CFCs
LUSCR1	372311106032501	SLV 14-1	07-21-00	>1945	<55	CFCs
LUSCR1	372401105563001	SLV 24-4	07-21-00	>1969	<31	CFCs
LUSCR1	372732106050401	SLV 11-3	08-09-00	>1974	<26	CFCs
LUSCR1	372849106090201	SLV 01-3	08-01-00	1981	19	CFCs
LUSCR1	373242106004501	SLV 23-1	07-20-00	>1958	<42	CFCs
LUSCR1	373323106025001	SLV 15-1	07-20-00	1989	11	CFCs
LUSCR1	373527105554201	SLV 25-1	08-04-00	1983	17	CFCs
LUSCR1	373611106014501	SLV 22-2	07-19-00	1987	13	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Rio Grande Valley (RIOG)—Continued				
LUSCR1	373732105525601	SLV 34-1	07-18-00	>1972	<28	CFCs
LUSCR1	373754105575201	SLV 26-1	07-18-00	1985	15	CFCs
LUSCR1	373849106074301	SLV 10-1	08-01-00	1987	13	CFCs
LUSCR1	373916106021701	SLV 21-3	07-19-00	>1945	<55	CFCs
LUSCR1	374033105582801	SLV 27-1	07-19-00	1986	14	CFCs
LUSCR1	374101106035601	SLV 16-1	08-02-00	1986	14	CFCs
LUSCR1	374153106153201	SLV 03-1	08-07-00	1991	9	CFCs
LUSCR1	374217106082501	SLV 09-5	08-02-00	1987	13	CFCs
LUSCR1	374223105511401	SLV 33-1	07-24-00	>1971	<29	CFCs
LUSCR1	374225105533101	SLV 32-1	08-08-00	1983	17	CFCs
LUSCR1	374310106032401	SLV 20-1	08-08-00	1990	10	CFCs
LUSCR1	374359106085501	SLV 08-1	08-10-00	1990	10	CFCs
LUSCR1	374423106042801	SLV 17-1	07-25-00	1984	16	CFCs
LUSCR1	374431106000701	SLV 28-1	07-25-00	>1973	<27	CFCs
LUSCR1	374515106192101	SLV 05-1	07-27-00	1984	16	CFCs
LUSCR1	374614106000701	SLV 29-3	07-25-00	1986	14	CFCs
LUSCR1	374734105533001	SLV 31-1	08-08-00	>1968	<32	CFCs
LUSCR1	374757106085301	SLV 07-1	07-26-00	1985	15	CFCs
LUSCR1	374825106021301	SLV 19-1	07-26-00	1982	18	CFCs
LUSCR1	375037106123401	SLV 06-1	07-27-00	1989	11	CFCs
LUSCR1	375054106013401	SLV 30-1	08-03-00	1988	12	CFCs
LUSCR1	375154106021101	SLV 18-2	08-03-00	>1947	<53	CFCs
		Sacramento River Basin (SACR)				
LUSRC1	382450121253601	982390009/7N5E33J1/LICHTENBERGER	07-16-98	<1953	>45	$^3H/^3He$
LUSRC1	382515121262501	982390008/7N5E33D1/PEDERSEN	07-14-98	1987	11	$^3H/^3He$
LUSRC1	382517121252601	9823900010/7N5E34D1/LAGUNA PARK	07-15-98	<1953	>45	$^3H/^3He$
LUSRC1	382537121260001	982390007/7N5E28Q1/CASE	07-13-98	>1953	<45	$^3H/^3He$
LUSRC1	382629121254801	982390006/7N5E21R1/N. LAGUNA CR.	07-20-98	1996	2	$^3H/^3He$
LUSRC1	382757121261101	982390004/7N5E16C1/HITE	07-21-98	>1953	<45	$^3H/^3He$
LUSRC1	382800121270701	982390005/7N5E17B1/MESA GRANDE	07-22-98	>1953	<45	$^3H/^3He$
LUSRC1	382906121322201	982390001/7N3E4J1 CHARTER POINTE	06-18-98	>1953	<45	$^3H/^3He$
LUSRC1	382911121312301	982390003/7N4E3K1/PARKWAY OAKS	06-22-98	>1953	<45	$^3H/^3He$
LUSRC1	382941121320501	9823900011/8N3E3D1/SOJOURNER	06-17-98	1953	45	$^3H/^3He$
LUSRC1	383000121313601	9823900012/8N4E34K1/SEYMOUR	06-16-98	1987	11	$^3H/^3He$
LUSRC1	383655121301601	9823900015/9N4E23R1/BANNON	08-03-98	>1953	<45	$^3H/^3He$
LUSRC1	383659121292201	9823900016/9N4E24Q1/NORTHGATE	08-05-98	1991	7	$^3H/^3He$
LUSRC1	383727121301801	9823900014/9N4E23A1/JEFFERSON	08-06-98	1965	33	$^3H/^3He$
LUSRC1	383746121291101	9823900013/9N4E13R1/CHUCKWAGON	08-04-98	1960	38	$^3H/^3He$
LUSRC1	384145121184101	9823900018/10N6E27F1/TWIN CREEKS	08-17-98	<1953	>45	$^3H/^3He$
LUSRC1	384234121215601	982390002/10N6E19F/BLUE OAK	08-20-98	<1953	>45	$^3H/^3He$
LUSRC1	384303121211701	9823900017/10N6E18R1/ANTELOPE	08-18-98	<1953	>45	$^3H/^3He$
LUSRC1	384318121230001	9823900019/10N5E13F1/LONE OAK	08-19-98	<1953	>45	$^3H/^3He$

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
San Joaquin-Tulare Basins (SANJ)						
LUSOR1	363418119384201	O'Brian Domestic 16S/21E-01E01	08-13-96	>1945	<51	CFCs
LUSOR1	363418119384202	O'Brian Deep 16S/21E-01E02	08-13-96	>1945	<51	CFCs
LUSOR1	363418119384203	O'Brian 16S/21E-01E03	08-13-96	1992	4	CFCs
LUSOR1	363805119345001	Peters New Domestic 15S/22-E09QXX	08-14-96	1987	9	CFCs
LUSOR1	363808119344901	Peters Deep 15S/22E-09Q02	08-14-96	1984	12	CFCs
LUSOR1	363808119344902	Peters Shallow Monitoring 15S/22-E09Q03	08-14-96	>1945	<51	CFCs
LUSOR1	363922119402002	Feaver E1-2 15S/21E-03L02	08-12-96	>1945	<51	CFCs
LUSOR1	363922119402003	Feaver E1-3 15S/21E-03L03	08-12-96	>1945	<51	CFCs
LUSOR1	363928119401701	O'Fraley 15S/21E-03G01	08-14-96	1985	11	CFCs
Santee River Basin (SANT)						
LUSCR1	323759080283701	COL- 359	11-25-97	>1945	<52	CFCs
LUSCR1	324349081092801	HAM- 223	09-23-97	1966	31	CFCs
LUSCR1	324412080485501	COL- 357	09-16-97	>1987	<10	CFCs
LUSCR1	324507081061901	HAM- 224	09-23-97	>1945	<52	CFCs
LUSCR1	324754080573801	HAM- 220	12-05-97	1982	15	CFCs
LUSCR1	325129080453601	COL- 358	09-22-97	1956	41	CFCs
LUSCR1	325618081054101	HAM- 221	09-29-97	1987	10	CFCs
LUSCR1	325812081090901	HAM- 222	10-01-97	1991	6	CFCs
LUSCR1	330051081092501	AL- 383	11-24-97	1986	11	CFCs
LUSCR1	330417081162201	AL- 385	11-24-97	1985	12	CFCs
LUSCR1	330422081130601	AL- 384	11-24-97	1988	9	CFCs
LUSCR1	330540080490701	COL- 356	12-03-97	1989	8	CFCs
LUSCR1	330656080365201	DOR- 325	09-09-97	1986	11	CFCs
LUSCR1	330715081192501	BW- 920	11-24-97	1985	12	CFCs
LUSCR1	331038080545601	BAM- 78	10-02-97	1988	9	CFCs
LUSCR1	331043081022101	BAM- 79	10-02-97	1990	7	CFCs
LUSCR1	331303080464101	ORG- 400	11-25-97	>1949	<48	CFCs
LUSCR1	331305080231301	DOR- 326	09-11-97	1990	7	CFCs
LUSCR1	331842080215301	ORG- 399	08-28-97	1994	3	CFCs
LUSCR1	331934080283701	ORG- 398	09-22-97	>1987	<10	CFCs
LUSCR1	332056080293501	ORG- 397	09-08-97	>1945	<52	CFCs
LUSCR1	332219080390501	ORG- 396	12-03-97	1988	9	CFCs
LUSCR1	332224080123601	BRK- 633	08-27-97	>1945	<52	CFCs
LUSCR1	332355080410401	ORG- 395	12-08-97	1984	13	CFCs
LUSCR1	332446080242201	ORG- 402	08-26-97	1987	10	CFCs
LUSCR1	332534080155701	ORG- 404	08-27-97	>1992	<5	CFCs
LUSCR1	332641080032201	BRK- 634	08-26-97	1976	21	CFCs
LUSCR1	332706080332001	ORG- 394	09-08-97	1984	13	CFCs
LUSCR1	333358080213001	CLA- 138	09-03-97	1992	5	CFCs
LUSRC1	335729080553901	RIC- 572	08-12-99	>1945	<54	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
Santee River Basin (SANT)—Continued						
LUSRC1	335811080580601	RIC- 563	08-16-99	>1945	<54	CFCs
LUSRC1	335838080553301	RIC- 566	09-18-96	>1945	<51	CFCs
LUSRC1	335851080561601	RIC- 567	09-18-96	>1945	<51	CFCs
LUSRC1	335938080581701	RIC- 558	09-17-96	>1945	<51	CFCs
LUSRC1	340122080590301	RIC- 584	10-04-96	>1945	<51	CFCs
LUSRC1	340124080572501	RIC- 559	08-17-99	>1945	<54	CFCs
LUSRC1	340155080582001	RIC- 583	09-16-96	>1945	<51	CFCs
LUSRC1	340158080574601	RIC- 556	09-25-96	>1945	<51	CFCs
LUSRC1	340158080585401	RIC- 561	10-03-96	>1945	<51	CFCs
LUSRC1	340236080585701	RIC- 578	09-12-96	>1945	<51	CFCs
LUSRC1	340304080574401	RIC- 579	08-11-99	>1979	<20	CFCs
LUSRC1	340544080530701	RIC- 576	08-10-99	>1981	<18	CFCs
LUSRC1	340745080543101	RIC- 575	09-19-96	>1945	<51	CFCs
SUS3	335744081514801	SAL- 75	08-03-98	1966	32	CFCs
SUS3	335931081441001	SAL- 74	08-05-98	>1978	<20	CFCs
SUS3	341412081445101	NEW- 965	08-05-98	1978	20	CFCs
SUS3	341421082113201	GNW- 544	07-30-98	>1959	<39	CFCs
SUS3	341450081291201	NEW- 876	07-27-98	>1945	<53	CFCs
SUS3	341638080492001	FA- 337	07-23-98	1969	29	CFCs
SUS3	342406081344001	NEW- 450	07-21-98	1978	20	CFCs
SUS3	342611082013601	LAU-1332	07-21-98	1960	38	CFCs
SUS3	342624081113501	FA- 391	07-29-98	1968	30	CFCs
SUS3	343510082170101	GRV-2984	07-22-98	>1945	<53	CFCs
SUS3	344254080572401	CTR- 625	07-29-98	1978	20	CFCs
SUS3	344413081314901	UN- 158	08-04-98	1994	4	CFCs
SUS3	344415081555201	SP-1607	07-30-98	1985	13	CFCs
SUS3	344600081131401	CTR- 602	08-11-98	>1945	<53	CFCs
SUS3	345323080423701	UN- 143	07-15-98	>1945	<53	CFCs
SUS3	345501082300501	GRV- 1382	07-22-98	>1945	<53	CFCs
SUS3	345503081475601	SP-1743	07-28-98	>1945	<53	CFCs
SUS3	345838082014601	SP-1810	07-28-98	1981	17	CFCs
SUS3	350257081345001	CRK- 145	08-04-98	1968	30	CFCs
SUS3	350824081045901	YK- 430	07-23-98	1961	37	CFCs
SUS3	351252081363401	CV- 135	07-14-98	>1956	<42	CFCs
SUS3	352106081152601	GS- 288	07-06-98	1984	14	CFCs
SUS3	352222081005001	GS- 287	07-15-98	>1945	<53	CFCs
SUS3	352703081391601	CV- 134	07-14-98	1984	14	CFCs
SUS3	353535081133401	CW- 348	07-06-98	1984	14	CFCs
SUS3	354154081532201	MC- 106	07-08-98	1993	5	CFCs
SUS3	354252081372501	BK- 106	07-07-98	>1979	<19	CFCs
SUS3	354911081161401	AX- 39	07-13-98	>1976	<22	CFCs
SUS3	355856081130501	AX- 40	08-17-98	>1945	<53	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		South-Central Texas (SCXT)				
LUSRC1	293252098380801	AY-68-27-610	12-10-98	1984	14	CFCs
LUSRC1	293340098344701	AY-68-28-516	12-08-98	1994	4	$^{3}H/^{3}He$
LUSRC1	293348098334101	AY-68-28-515	11-06-98	1989	9	CFCs
LUSRC1	293350098355801	AY-68-28-406	11-06-98	1987	11	CFCs
LUSRC1	293359098405401	AY-68-27-517	11-10-98	1988	10	CFCs
LUSRC1	293404098382001	AY-68-27-612	12-10-98	1986	12	CFCs
LUSRC1	293405098394201	AY-68-27-609	11-10-98	1984	14	CFCs
LUSRC1	293408098331301	AY-68-28-519	11-14-98	1988	10	CFCs
LUSRC1	293425098350801	AY-68-28-407	11-13-98	>1945	<53	CFCs
LUSRC1	293429098373801	AY-68-27-611	11-12-98	1986	12	CFCs
LUSRC1	293436098343001	AY-68-28-517	06-28-00	1983	17	$^{3}H/^{3}He$ [4]
LUSRC1	293436098343001	AY-68-28-517	12-08-98	1990	8	CFCs [5]
LUSRC1	293439098324101	AY-68-28-518	12-11-98	>1945	<53	CFCs
LUSRC1	293456098280201	AY-68-29-418	12-09-98	1988	10	$^{3}H/^{3}He$
LUSRC1	293459098321401	AY-68-28-609	11-11-98	1988	10	CFCs
LUSRC1	293504098270901	AY-68-29-213	11-05-98	1989	9	CFCs
LUSRC1	293508098375101	AY-68-27-307	10-23-98	1984	14	CFCs
LUSRC1	293516098325501	AY-68-28-211	11-14-98	>1945	<53	CFCs
LUSRC1	293516098362801	AY-68-28-113	11-12-98	1988	10	CFCs
LUSRC1	293520098254101	AY-68-29-214	11-08-98	>1945	<53	CFCs
LUSRC1	293528098274301	AY-68-29-114	11-03-98	>1945	<53	CFCs
LUSRC1	293530098343401	AY-68-28-210	10-26-98	>1945	<53	CFCs
LUSRC1	293534098282801	AY-68-29-113	11-07-98	1982	16	CFCs
LUSRC1	293535098304101	AY-68-28-314	12-07-98	1988	10	CFCs
LUSRC1	293537098262401	AY-68-29-215	11-05-98	1991	7	CFCs
LUSRC1	293559098284801	AY-68-29-112	12-09-98	1987	11	CFCs
LUSRC1	293611098311901	AY-68-28-315	11-11-98	1994	4	CFCs
LUSRC1	293615098262301	AY-68-29-217	11-09-98	1990	8	CFCs
LUSRC1	293635098302301	AY-68-28-313	11-04-98	>1945	<53	CFCs
LUSRC1	293643098264001	AY-68-29-216	06-29-00	1995	5	$^{3}H/^{3}He$ [6]
LUSRC1	293643098264001	AY-68-29-216	11-09-98	>1945	<53	CFCs [7]
LUSRC1	293746098265401	AY-68-21-806	12-07-98	1993	5	CFCs
REFRE1	292628099401401	YP-69-35-602	09-14-99	1981	18	$^{3}H/^{3}He$
		Tennessee River Basin (TENN)				
SUS1	343752086433001	Jefferson G-4555	06-29-99	>1945	<54	CFCs
SUS1	344150086523401	Norris G-4556	06-29-99	1992	7	CFCs
SUS1	344153087280101	Madden G-4562	07-06-99	>1945	<54	CFCs
SUS1	344355087414401	Crosslin G-4561	07-07-99	>1945	<54	CFCs
SUS1	344535087042201	Haney G-4557	06-30-99	>1945	<54	CFCs
SUS1	345343086554701	Dubois G-4558	06-30-99	>1945	<54	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Tennessee River Basin (TENN)				
SUS1	345558086382801	Hazel Green G-4554	07-01-99	>1945	<54	CFCs
SUS1	350102086284001	Quick G-4565	07-15-99	1958	41	CFCs
SUS1	351928085594501	Rhoads G-4563	07-15-99	1974	25	CFCs
SUS1	352402086063201	Hawkersmith G-4559	07-15-99	>1945	<54	CFCs
		Trinity River Basin (TRIN)				
LUSRC1	294800095415801	MW28A	12-21-03	>1991	<12	CFCs
LUSRC1	295358095374101	MW18	12-18-03	>1974	<29	CFCs
LUSRC1	295421095305801	MW19	12-19-03	>1945	<58	CFCs
LUSRC1	295557095360901	MW11	12-16-03	>1967	<36	CFCs
LUSRC1	300011095251801	MW10	12-17-03	>1989	<14	CFCs
LUSRC1	300333095291701	MW03	12-29-03	1977	26	CFCs
LUSRC1	301008095302901	MW13	12-22-03	>1974	<29	CFCs
REFOT1	301716095400501	REF03	12-30-03	1989	14	CFCs
		Upper Illinois River Basin (UIRB)				
LUSCR1	405145087044701	AgLus 22-2	07-07-99	1986	13	CFCs
LUSCR1	405524087152701	AgLus 24	07-08-99	1983	16	CFCs
LUSCR1	405732087282301	AgLus 12	07-19-99	>1989	<10	CFCs
LUSCR1	410030087263101	AgLus 22-1	07-19-99	>1945	<54	CFCs
LUSCR1	410123087385601	AgLus 09	07-21-99	>1945	<54	CFCs
LUSCR1	410253087280701	AgLus 13	07-22-99	1990	9	CFCs
LUSCR1	410422088000001	AgLus 01	07-13-99	>1945	<54	CFCs
LUSCR1	410505087201201	AgLus 20	07-20-99	1993	6	CFCs
LUSCR1	410510087224201	AgLus 21	06-29-99	1989	10	CFCs
LUSCR1	410511087295201	AgLus 14	05-13-99	>1975	<24	CFCs
LUSCR1	410600087113501	AgLus 25	06-29-99	>1945	<54	CFCs
LUSCR1	410715087072301	AgLus 27	06-14-99	1990	9	CFCs
LUSCR1	410748087060901	AgLus 26	06-14-99	>1987	<12	CFCs
LUSCR1	410812087423401	AgLus 07	08-23-99	>1945	<54	CFCs
LUSCR1	410859087370001	AgLus 06	07-13-99	>1987	<12	CFCs
LUSCR1	410925087333201	AgLus 15-101	05-12-99	>1956	<43	CFCs
LUSCR1	410947087050501	AgLus 28	06-15-99	>1967	<32	CFCs
LUSCR1	411029087172401	AgLus 19	06-01-99	>1964	<35	CFCs
LUSCR1	411119087143601	AgLus 29	06-02-99	>1972	<27	CFCs
LUSCR1	411123088061201	AgLus 03	08-23-99	1990	9	CFCs
LUSCR1	411248087304901	AgLus 16	07-20-99	>1978	<21	CFCs
LUSCR1	411329087121201	AgLus 30	06-15-99	>1976	<23	CFCs
LUSCR1	411511087214501	AgLus 18	06-16-99	>1945	<54	CFCs
LUSCR1	411719087171301	AgLus 17	06-01-99	>1949	<50	CFCs
LUSCR1	413141088402401	AgLus 05	07-12-99	1991	8	CFCs
LUSRC1	415752088244001	URBLUS 01	05-24-00	>1949	<51	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Upper Illinois River Basin (UIRB)—Continued				
LUSRC1	420012088191101	URBLUS 12	05-11-00	>1949	<51	CFCs
LUSRC1	421228088160701	URBLUS 22	04-18-00	1983	17	$^3H/^3He$
LUSRC1	421301088191501	URBLUS 11	06-08-00	1988	12	CFCs
LUSRC1	421402088173501	URBLUS 14	04-20-00	1990	10	$^3H/^3He$
LUSRC1	421545087564301	URBLUS 32	05-10-00	<1953	>47	$^3H/^3He$
LUSRC1	421633088125801	URBLUS 25	04-19-00	1983	17	$^3H/^3He$
LUSRC1	422002088263001	URBLUS 02	05-22-00	>1979	<21	CFCs
LUSRC1	422314088140001	URBLUS 20	05-09-00	1992	8	$^3H/^3He$
LUSRC1	423523088244901	URBLUS 04	05-09-00	1976	24	CFCs
LUSRC1	424052088180101	URBLUS 15	05-04-00	1991	9	CFCs
LUSRC1	424700088133201	URBLUS 27	05-03-00	1995	5	$^3H^3He$
LUSRC1	425402088241601	URBLUS 05	05-03-00	1999	1	$^3H/^3He$
LUSRC1	425913088133801	URBLUS 19	04-13-00	1989	11	$^3H/^3He$
LUSRC1	430003088164601	URBLUS 16	04-12-00	1975	25	$^3H/^3He$
LUSRC1	430155088114701	URBLUS 28	05-08-00	>1945	<55	CFCs
LUSRC1	430239088164001	URBLUS 17	04-12-00	>1968	<32	CFCs
LUSRC1	430353088095901	URBLUS 30	05-02-00	2000	0	$^3H/^3He$
LUSRC1	430728088132801	URBLUS 18	05-01-00	1989	11	$^3H/^3He$
LUSRC1	430846088123201	URBLUS 29	04-11-00	1975	25	CFCs
SUS1	421324088105301	MAS1-24	03-26-01	>1970	<31	CFCs
SUS1	421422088174001	MAS1-22	05-15-01	>1945	<56	CFCs
SUS1	421651088190601	MAS1-12	05-16-01	>1963	<38	CFCs
SUS1	421850088252301	MAS1-01	04-09-01	>1949	<52	CFCs
SUS1	422050088194001	MAS1-11	03-29-01	>1977	<24	CFCs
SUS1	422146088124301	MAS1-25	04-24-01	>1947	<54	CFCs
SUS1	422917088132901	MAS1-26	04-26-01	>1949	<52	CFCs
SUS1	423007088305501	MAS1-02	03-27-01	>1950	<51	CFCs
SUS1	423048088105001	MAS1-27	03-28-01	>1945	<56	CFCs
SUS1	423149088151101	MAS1-21	03-28-01	>1980	<21	CFCs
SUS1	423423088233201	MAS1-10	04-25-01	>1945	<56	CFCs
SUS1	423454088303101	MAS1-03	03-27-01	>1950	<51	CFCs
SUS1	423508088162701	MAS1-13	04-10-01	>1950	<51	CFCs
SUS1	423741088252201	MAS1-04	05-16-01	>1945	<56	CFCs
SUS1	423808088203801	MAS1-09	04-25-01	>1949	<52	CFCs
SUS1	424127088135601	MAS1-20	05-03-01	>1945	<56	CFCs
SUS1	424404088134601	MAS1-19	04-05-01	>1977	<24	CFCs
SUS1	424657088132001	MAS1-28	04-03-01	1986	15	CFCs
SUS1	424756088194201	MAS1-08	04-10-01	>1976	<25	CFCs
SUS1	424955088130901	MAS1-15	05-02-01	>1945	<56	CFCs
SUS1	425352088240101	MAS1-05	04-04-01	>1945	<56	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
Upper Illinois River Basin (UIRB)—Continued						
SUS1	425536088180901	MAS1-16	04-12-01	>1949	<52	CFCs
SUS1	425656088124401	MAS1-18	05-02-01	>1945	<56	CFCs
SUS1	425755088210901	MAS1-06	04-04-01	>1945	<56	CFCs
SUS1	425816088231401	MAS1-07	05-01-01	1990	11	CFCs
SUS1	430407088075901	MAS1-30	04-11-01	>1975	<26	CFCs
SUS1	430923088141601	MAS1-17	04-11-01	>1978	<23	CFCs
SUS2	405145087044702	AGSUS 22-2	08-29-00	>1947	<53	CFCs
SUS2	405345087100601	AGSUS 23	08-21-00	>1968	<32	CFCs
SUS2	405357087495001	AGSUS 11	09-28-00	>1949	<51	CFCs
SUS2	405627087142101	AGSUS 24	09-25-00	>1959	<41	CFCs
SUS2	405823087313101	AGSUS 12	08-24-00	>1973	<27	CFCs
SUS2	410025087280701	AGSUS 13	10-03-00	>1945	<55	CFCs
SUS2	410030087263102	AGSUS 22-1	09-11-00	>1945	<55	CFCs
SUS2	410407087200201	AGSUS 20	10-05-00	>1973	<27	CFCs
SUS2	410533087232601	AGSUS 21	10-04-00	>1949	<51	CFCs
SUS2	410541087313701	AGSUS 14	09-27-00	>1948	<52	CFCs
SUS2	410656087092901	AGSUS 25	10-10-00	>1946	<54	CFCs
SUS2	410700087305802	AGSUS 15	09-21-00	>1945	<55	CFCs
SUS2	410715087072001	AGSUS 27	10-16-00	1977	23	CFCs
SUS2	410841087040801	AGSUS 26	09-14-00	>1964	<36	CFCs
SUS2	410940087101001	AGSUS 30-1A	08-22-00	>1989	<11	CFCs
SUS2	410958087050601	AGSUS 28	09-13-00	>1968	<32	CFCs
SUS2	411029087172402	AGSUS 19	10-18-00	>1973	<27	CFCs
SUS2	411041087281101	AGSUS 16	09-26-00	>1978	<22	CFCs
SUS2	411100088074001	AGSUS 03	08-28-00	>1945	<55	CFCs
SUS2	411116087141401	AGSUS 29	10-17-00	>1945	<55	CFCs
SUS2	411409087104701	AGSUS 30	08-23-00	>1978	<22	CFCs
SUS2	411511087214502	AGSUS 18	08-31-00	>1945	<55	CFCs
SUS2	411719087171302	AGSUS 17	09-12-00	>1946	<54	CFCs
White, Great and Little Miami River Basins (WHMI)						
LUSCR1	391636084452800	H-153 MIAM NAWQA LUS WELL BVAS AG-23	08-03-00	>1953	<47	$^{3}H/^{3}He$
LUSCR1	392018084371800	BU-1108 MIAM NAWQA LUS WELL BVAS AG-30	08-02-00	1991	9	$^{3}H/^{3}He$
LUSCR1	392134084563200	MIAM NAWQA LUS WELL BVAS AG-24 AT CEDAR GROVE IN	08-03-00	>1953	<47	$^{3}H/^{3}He$
LUSCR1	392756084300900	BU-1107 MIAM NAWQA LUS WELL BVAS AG-29	08-02-00	1998	2	$^{3}H/^{3}He$
LUSCR1	393119086154101	TP-23	08-14-07	1995	12	SF_6
LUSCR1	393223085534001	TP-7	08-14-07	–	–	SF_6
LUSCR1	393421084003300	GR-654 MIAM NAWQA LUS WELL BVAS AG-20S	07-26-00	2000	0	$^{3}H/^{3}He$
LUSCR1	393831085043500	MIAM NAWQA LUS WELL BVAS AG-1 NR SPRINGERSVILLE IN	08-09-00	>1953	<47	$^{3}H/^{3}He$
LUSCR1	394032085543101	TP-17	08-20-07	1970	37	SF_6

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
White, Great and Little Miami River Basins (WHMI)—Continued						
LUSCR1	394233083576000	GR-656 MIAM NAWQA LUS WELL BVAS AG-21	07-26-00	2000	0	$^3H/^3He$
LUSCR1	394420084463001	PR-202 MIAM NAWQA LUS WELL BVAS AG-7D	08-16-00	2000	0	$^3H/^3He$
LUSCR1	394650084320300	PR-203 MIAM NAWQA LUS WELL BVAS AG-26	07-17-00	2000	0	$^3H/^3He$
LUSCR1	394745085051300	MIAM NAWQA LUS WELL BVAS AG-3 NR HISER IN	08-25-00	>1953	<47	$^3H/^3He$
LUSCR1	394759085071000	MIAM NAWQA LUS WELL BVAS AG-8S NR PENNVILLE IN	08-10-00	2000	0	$^3H/^3He$
LUSCR1	395135085070000	MIAM NAWQA LUS WELL BVAS AG-4S AT JACKSONBURG IN	08-09-00	2000	0	$^3H/^3He$
LUSCR1	395213085052200	MIAM NAWQA LUS WELL BVAS AG-9 NR HOOVER MILL IN	08-24-00	1978	22	$^3H/^3He$
LUSCR1	395248084491600	MIAM NAWQA LUS WELL BVAS AG-6 AT MIDDLEBORO IN	08-16-00	1965	35	$^3H/^3He$
LUSCR1	395713085202901	TP-8	08-16-07	–	–	SF_6
LUSCR1	395849083494501	CL-283 MIAM NAWQA LUS WELL BVAS AG-13D	07-12-00	1999	1	$^3H/^3He$
LUSCR1	395911084422700	D-175 MIAM NAWQA LUS WELL BVAS AG-10	07-24-00	2000	0	$^3H/^3He$
LUSCR1	400019083412000	CL-284 MIAM NAWQA LUS WELL BVAS AG-14	07-19-00	>1953	<47	$^3H/^3He$
LUSCR1	400145084106000	MI-205 MIAM NAWQA LUS WELL BVAS AG-27	08-01-00	1995	5	$^3H/^3He$
LUSCR1	400320084402400	D-176 MIAM NAWQA LUS WELL BVAS AG-11	08-08-00	>1953	<47	$^3H/^3He$
LUSCR1	400356085562101	TP-18	08-23-07	–	–	SF_6
LUSCR1	400850083404700	CH-106 MIAM NAWQA LUS WELL BVAS AG-15S	07-13-00	2000	0	$^3H/^3He$
LUSCR1	401040084154000	MI-204 MIAM NAWQA LUS WELL BVAS AG-12	07-28-00	1998	2	$^3H/^3He$
LUSCR1	401238084144400	SH-75 MIAM NAWQA LUS WELL BVAS AG-28S	07-27-00	>1953	<47	$^3H/^3He$
LUSCR1	401240083492600	CH-110 MIAM NAWQA LUS WELL BVAS AG-17S	07-19-00	1998	2	$^3H/^3He$
LUSCR1	401307083450600	CH-108 MIAM NAWQA LUS WELL BVAS AG-16S	07-18-00	>1953	<47	$^3H/^3He$
LUSCR1	401359083493100	CH-112 MIAM NAWQA LUS WELL BVAS AG-18S	07-25-00	1999	1	$^3H/^3He$
LUSCR1	401837083492900	LO-75 MIAM NAWQA LUS WELL BVAS AG-19	07-20-00	1992	8	$^3H/^3He$
LUSCR1a	393421084003301	GR-655 MIAM NAWQA LUS WELL BVAS AG-20D	07-26-00	1995	5	$^3H/^3He$
LUSCR1a	394759085071001	MIAM NAWQA LUS WELL BVAS AG-8D NR PENNVILLE IN	08-10-00	<1953	>47	$^3H/^3He$
LUSCR1a	395135085070001	MIAM NAWQA LUS WELL BVAS AG-4D AT JACKSONBURG IN	08-15-00	1966	34	$^3H/^3He$
LUSCR1a	400850083404701	CH-107 MIAM NAWQA LUS WELL BVAS AG-15D	07-13-00	1991	9	$^3H/^3He$
LUSCR1a	401238084144401	SH-76 MIAM NAWQA LUS WELL BVAS AG-28D	07-27-00	1969	31	$^3H/^3He$
LUSCR1a	401240083492601	CH-111 MIAM NAWQA LUS WELL BVAS AG-17D	07-19-00	>1953	<47	$^3H/^3He$
LUSCR1a	401307083450601	CH-109 MIAM NAWQA LUS WELL BVAS AG-16D	07-18-00	>1953	<47	$^3H/^3He$
LUSCR1a	401359083493101	CH-113 MIAM NAWQA LUS WELL BVAS AG-18D	07-25-00	1996	4	$^3H/^3He$
LUSCR3a	390244086593401	NAWQA AG WELL FA5S AT ELLISTON, IN	07-21-99	>1953	<46	$^3H/^3He$
LUSCR3a	390505085513301	NAWQA AG WELL FA12S AT AZALIA, IN	07-22-99	1997	2	$^3H/^3He$
LUSCR3a	393455086562101	NAWQA AG WELL FA14 NEAR MANHATTAN, IN	07-21-99	1999	0	$^3H/^3He$
LUSCR3a	393622085483301	NAWQA AG WELL FA17 NEAR SHELBYVILLE, IN	07-20-99	1999	0	$^3H/^3He$

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		White, Great and Little Miami River Basins (WHMI)—Continued				
LUSCR3a	395709086040101	NAWQA AG WELL FA19 AT TRAILS END, IN	07-20-99	1999	0	$^3H/^3He$
LUSRC1	390744084212501	URB-02	11-29-01	–	–	SF_6
LUSRC1	391226084272501	URB-31	11-28-01	–	–	SF_6
LUSRC1	391434084474601	URB-04	11-15-01	–	–	SF_6
LUSRC1	391518084485201	URB-03	11-15-01	–	–	SF_6
LUSRC1	391849084381901	URB-01	11-27-01	–	–	SF_6
LUSRC1	392008084335501	URB-06	11-14-01	1998	3	SF_6
LUSRC1	392008084343801	URB-07	11-26-01	–	–	SF_6
LUSRC1	392047084325101	URB-15	11-14-01	–	–	SF_6
LUSRC1	392049084340301	URB-08	11-27-01	–	–	SF_6
LUSRC1	392121084332101	URB-29	11-13-01	–	–	SF_6
LUSRC1	392917084205601	URB-11	11-07-01	1998	3	SF_6
LUSRC1	393405084203701	URB-12	11-06-01	–	–	SF_6
LUSRC1	393453084131801	URB-13	11-05-01	–	–	SF_6
LUSRC1	393954084132001	URB-17	11-01-01	–	–	SF_6
LUSRC1	393956083575601	URB-23	10-25-01	1994	7	SF_6
LUSRC1	394025084132501	URB-14	10-31-01	–	–	SF_6
LUSRC1	394103084124901	URB-18	10-31-01	–	–	SF_6
LUSRC1	394234084024301	URB-16	10-22-01	1998	3	SF_6
LUSRC1	394256084040701	URB-19	10-23-01	–	–	SF_6
LUSRC1	394320084044301	URB-20	10-04-01	–	–	SF_6
LUSRC1	395210083565001	URB-22	10-24-01	–	–	SF_6
LUSRC1	395244084011901	URB-26	12-03-01	–	–	SF_6
LUSRC1	395247084015801	URB-25	12-03-01	–	–	SF_6
LUSRC1	395614084020301	URB-24	10-17-01	–	–	SF_6
LUSRC1	400642083441601	URB-21	10-03-01	–	–	SF_6
REFOT1	393812084240001	Ref-02	11-07-01	–	–	SF_6
REFOT1	395159086171501	TP Ref 1	08-23-07	1997	10	SF_6
REFOT1	395218084100801	REF-01	10-18-01	–	–	SF_6
SUS1	390832084133300	CT-75 MIAM NAWQA SUS WELL BVAS-30	07-08-99	>1953	<46	$^3H/^3He$
SUS1	391444084474600	H-151 MIAM NAWQA SUS WELL BVAS-27	07-01-99	1992	7	$^3H/^3He$
SUS1	391544084474200	H-150 MIAM NAWQA SUS WELL BVAS-19	07-01-99	1991	8	$^3H/^3He$
SUS1	391843084383200	BU-1105 MIAM NAWQA SUS WELL BVAS-28	07-07-99	1995	4	$^3H^3He$
SUS1	392544084290300	BU-1106 MIAM NAWQA SUS WELL BVAS-29	07-07-99	>1953	<46	$^3H/^3He$
SUS1	392756084330100	BU-1101 MIAM NAWQA SUS WELL BVAS-18	06-07-99	1987	12	$^3H/^3He$
SUS1	393330084204500	W-53 MIAM NAWQA SUS WELL BVAS-25	06-23-99	1999	0	$^3H/^3He$
SUS1	393455084180600	W-52 MIAM NAWQA SUS WELL BVAS-13	07-08-99	1989	10	$^3H/^3He$
SUS1	393512084594500	BVAS-20 MIAM NAWQA SUS WELL NEAR DUNLAPSVILLE, IN	07-09-99	1999	0	$^3H/^3He$
SUS1	393605084013400	GR-653 MIAM NAWQA SUS WELL BVAS-16	06-22-99	1993	6	$^3H/^3He$

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		White, Great and Little Miami River Basins (WHMI)—Continued				
SUS1	394254084003000	GR-650 MIAM NAWQA SUS WELL BVAS-5	05-27-99	1981	18	$^3H/^3He$
SUS1	394302084032700	GR-651 MIAM NAWQA SUS WELL BVAS-9	05-27-99	1991	8	$^3H/^3He$
SUS1	394654084160800	MT-1251 MIAM NAWQA SUS WELL BVAS-17	05-20-99	1993	6	$^3H/^3He$
SUS1	394918084100100	MT-1255 MIAM NAWQA SUS WELL BVAS-11	06-22-99	1987	12	$^3H/^3He$
SUS1	395125084154800	MT-1250 MIAM NAWQA SUS WELL BVAS-1	05-20-99	1996	3	$^3H/^3He$
SUS1	395127083551300	CL-278 MIAM NAWQA SUS WELL BVAS-14	06-10-99	>1953	<46	$^3H/^3He$
SUS1	395149084592900	BVAS-24 MIAM NAWQA SUS WELL NEAR CENTERVILLE IN	06-03-99	1994	5	$^3H/^3He$
SUS1	395235083445700	CL-281 MIAM NAWQA SUS WELL BVAS-10	06-24-99	1990	9	$^3H/^3He$
SUS1	395248084010900	CL-280 MIAM NAWQA SUS WELL BVAS-7	06-29-99	1975	24	$^3H/^3He$
SUS1	395407083553400	CL-277 MIAM NAWQA SUS WELL BVAS-3	06-10-99	1987	12	$^3H/^3He$
SUS1	395528083414400	CL-275 MIAM NAWQA SUS WELL BVAS-8	05-13-99	1985	14	$^3H/^3He$
SUS1	395635083445900	CL-279 MIAM NAWQA SUS WELL BVAS-2	06-24-99	>1953	<46	$^3H/^3He$
SUS1	395706084035400	MI-203 MIAM NAWQA SUS WELL BVAS-22	06-28-99	1984	15	$^3H/^3He$
SUS1	400049084125300	MI-202 MIAM NAWQA SUS WELL BVAS-21	06-23-99	1980	19	$^3H/^3He$
SUS1	400113085051300	BVAS-23 MIAM NAWQA SUS WELL NR ECONOMY IN	06-03-99	1948	51	$^3H/^3He$
SUS1	400142083423900	CH-100 MIAM NAWQA SUS WELL BVAS-6	05-12-99	1995	4	$^3H/^3He$
SUS1	400409083464500	CH-103 MIAM NAWQA SUS WELL BVAS-15	06-29-99	1971	28	$^3H/^3He$
SUS1	400542083420900	CH-101 MIAM NAWQA SUS WELL BVAS-4	06-30-99	1986	13	$^3H/^3He$
SUS1	401200083443100	CH-104 MIAM NAWQA SUS WELL BVAS-26	06-30-99	1992	7	$^3H/^3He$
SUS1	401237083485800	CH-102 MIAM NAWQA SUS WELL BVAS-12	06-30-99	>1953	<46	$^3H/^3He$
		Willamette Basin (WILL)				
LUSAG3	441155123152801	65	07-09-02	>1977	<25	CFCs
LUSAG3	441556123092001	63	07-09-02	1987	15	CFCs
LUSAG3	442252122592201	61	07-10-02	>1968	<34	CFCs
LUSAG3	443226123121701	54	07-08-02	>1979	<23	CFCs
LUSAG3	443437123133901	49	07-08-02	>1945	<57	CFCs
LUSAG3	443646122552701	51	06-28-02	>1945	<57	CFCs
LUSAG3	444128122520901	47	06-27-02	1965	37	CFCs
LUSAG3	444213122481301	48	07-11-02	>1974	<28	CFCs
LUSAG3	444807123140101	41	08-21-02	>1977	<25	CFCs
LUSAG3	444915122493801	44	06-27-02	>1945	<57	CFCs
LUSAG3	450745123015801	29	07-12-02	>1969	<33	CFCs
LUSAG3	450808122440101	31	06-25-02	>1981	<21	CFCs
LUSAG3	450910123113701	28	07-12-02	>1979	<23	CFCs
LUSAG3	451048122420501	25	06-25-02	>1945	<57	CFCs
LUSAG3	452222122145301	15	08-19-02	1963	39	CFCs
LUSAG3	452335122320801	12	08-19-02	>1945	<57	CFCs
REFFO1	451708122204801	20	06-10-02	>1945	<57	CFCs
REFFO1	452842122305801	8	05-28-02	>1987	<15	CFCs

Table 1. Summary of tracer-based piston-flow ages that were interpreted in this report.—Continued

Network	USGS site identification No.	Local site name	Tracer sample date	Tracer-based piston-flow recharge date	Tracer-based piston-flow age (years)	Environ-mental tracer
		Yellowstone River Basin (YELL)				
LUSOT1	424751108455901	RL-10	07-16-01	>1976	<25	CFCs
LUSOT1	424808108453101	RL-09	07-11-01	>1972	<29	CFCs
LUSOT1	424830108450101	RL-08	07-10-01	>1945	<56	CFCs
LUSOT1	425111108430501	RL-07	07-18-01	>1985	<16	CFCs
LUSOT1	425129108432401	RL-05	07-15-01	>1974	<27	CFCs
LUSOT1	425140108430901	RL-04	07-09-01	1987	14	CFCs
LUSOT1	425158108433801	RL-03	07-17-01	1992	9	CFCs
LUSOT1	425253108434501	RL-02	07-12-01	1988	13	CFCs
LUSOT1	425313108440701	RL-01	07-08-01	>1990	<11	CFCs
LUSOT1	443943106594001	RS-10	06-26-01	1984	17	CFCs
LUSOT1	444012106593201	RS-09	06-25-01	1987	14	CFCs
LUSOT1	444047106590901	RS-08	06-25-01	1990	11	CFCs
LUSOT1	444225106580701	RS-07	06-21-01	1988	13	CFCs
LUSOT1	444240106581401	RS-06	06-20-01	>1967	<34	CFCs
LUSOT1	444249106572301	RS-05	06-24-01	>1969	<32	CFCs
LUSOT1	444317106572601	RS-04	06-19-01	1984	17	CFCs
LUSOT1	444333106571001	RS-03	06-18-01	>1971	<30	CFCs
LUSOT1	444536107052201	RS-02	06-27-01	1992	9	CFCs
LUSOT1	444554107043101	RS-01	06-17-01	1991	10	CFCs
LUSOT1	450845109163701	RR-10	09-19-01	1997	4	CFCs
LUSOT1	450925109180001	RR-09	09-18-01	1991	10	CFCs
LUSOT1	450935109161701	RR-08	09-17-01	>1945	<56	CFCs
LUSOT1	450943109161701	RR-07	08-18-01	1993	8	CFCs
LUSOT1	450949109164601	RR-03	09-19-01	1988	13	CFCs
LUSOT1	450949109172301	RR-06	09-16-01	1991	10	CFCs
LUSOT1	450952109162901	RR-05	09-17-01	1987	14	CFCs
LUSOT1	450958109162801	RR-04	09-18-01	1986	15	CFCs
LUSOT1	451510109134801	RR-01	08-08-01	1987	14	CFCs

[1] Forest LUS, serves as reference site.

[2] There also are SF_6 results, but for a different sample date.

[3] There also are $^3H^3He$ results, but for a different sampling date.

[4] There also are CFC results, but for a different sampling date

[5] There also are $^3H^3He$ results, but for a different sampling date.

[6] There also are CFC results, but for a different sampling date.

[7] There also are $^3H^3He$ results, but for a different sampling date.

Glossary

$^3H/^3He$ $^3H/^3He$ refers to the combined use of ^3H (tritium) and its decay product, ^3He (helium-3). Radioactive decay of ^3H to ^3He allows elapsed time to be calculated by comparing the tritiogenic ^3He (that is, the amount of ^3He that is attributed to decay of ^3H) to the original amount of ^3H, where the original amount of ^3H is equal to the measured ^3H plus the tritiogenic ^3He.

Δ^4He The amount of ^4He (helium-4) in a water sample that is in excess to that attributed to solubility equilibrium with air, expressed as a percent of the ^4He in water at solubility equilibrium. Δ^4He usually is from excess air and from elemental radioactive decay such as decay of uranium and thorium in rocks.

ΔNe The amount of Ne (neon) in a water sample that is in excess to that attributed to solubility equilibrium with air, expressed as a percent of the Ne in water at solubility equilibrium. ΔNe usually is from excess air.

anthropogenic Resulting from or pertaining to human activities.

CFCs CFCs, or chlorofluorocarbons, are anthropogenic compounds that have been produced commercially since the 1930s, volatilize into the atmosphere, and subsequently partition into water that is in contact with the atmosphere. Concentrations of CFCs have varied over time, facilitating their use in age dating. In this report, CFCs refers to the CFCs that commonly were used for age-dating purposes during the time period 1992–2005: CFC-11 ($CFCl_3$), CFC-12 (CF_2Cl_2), and CFC-113 ($C_2F_3Cl_3$).

contaminated Where used in the context of CFC or SF_6 dating, indicates concentrations greater than those that would be found in groundwater that was at equilibrium with peak atmospheric CFC or SF_6 concentrations at the assumed recharge altitude, recharge temperature, and excess-air conditions. Samples that are contaminated relative to dating purposes are not necessarily contaminated relative to human-health benchmarks.

Data Warehouse (DWH) The DWH is a publicly available database of NAWQA data (available at http://infotrek.er.usgs.gov/traverse/f?p=NAWQA:HOME:0:).

Environmental Tracer For the purposes of this report, an environmental tracer (or "tracer") is considered to be a widespread element, compound, or isotope that is used to infer groundwater time-of-travel. The term "environmental" indicates widespread occurrence, as compared with a local-spatial-scale tracer injection used to understand tracer movement at one particular study site. In practice, the tracer (not the water) is dated.

excess air Atmospheric air (gases), beyond the amount that can be attributed to the solubility of air in water that is incorporated into shallow groundwater during or following recharge. Excess air is added to groundwater by air entrainment during infiltration and (or) by water-table fluctuations.

Land-Use Study (LUS) A focused investigation of water-quality conditions associated with an individual land-use setting. LUSs generally are composed of shallow wells (usually monitoring wells) in recharge areas of regionally important land-use settings. Variability from hydrogeologic factors is reduced by restricting an individual LUS to a single aquifer.

Major-Aquifer Study (MAS) A broad assessment of water-quality conditions in groundwater of a Study Unit, generally focusing on the shallow used resource. MASs typically are composed of networks of domestic supply wells in principal aquifers. Major-Aquifer Studies formerly were called Study Unit Surveys.

major dissolved gases N_2, O_2, Ar, CH_4, and CO_2. Four of these gases, N_2, O_2, Ar, and CO_2, are the volumetrically dominant gases in dry atmosphere and they are incorporated into groundwater during recharge. Non-atmospheric CO_2 is incorporated into groundwater (for example, from root respiration and from redox reactions), generally at concentrations considerably greater than those from atmospheric sources. CH_4 can be incorporated into groundwater as a result of redox reactions; although CH_4 is not detected ubiquitously in groundwater, CH_4 concentrations not infrequently become a volumetrically major dissolved gas. These five gases, often analyzed as a suite, can be used to infer recharge temperatures (N_2, Ar), redox state (N_2, O_2, CH_4), and excess N_2 from denitrification.

modern Where used in the context of CFC-based piston-flow ages, slight enrichment above concentrations that would be detected in groundwater that was at equilibrium with peak atmospheric CFC concentrations may be referred to as "modern," to differentiate minor enrichment from greater enrichment. Minor enrichment is enrichment that reasonably could be attributed to uncertainties in the methodology, for example, young groundwater recharged under conditions of a local atmospheric CFC anomaly, or minor bias in estimated recharge temperature or recharge altitude. Greater enrichment frequently indicates the presence of CFCs from non-atmospheric sources. This term is used in this report only in appendix G.

piston flow A simplified and idealized concept of groundwater flow in which groundwater moves in discrete packets by advection and without hydrodynamic dispersion or mixing.

reference (REF) well A well selected or installed with the intent of providing samples that represent groundwater minimally impacted by anthropogenic activities, that is, background or natural groundwater.

SF_6 SF_6, or sulfur hexafluoride, is a compound that has both natural and anthropogenic sources. Like CFCs, SF_6 volatilizes into the atmosphere, and subsequently partitions into water that is in contact with the atmosphere. SF_6 concentrations have been increasing over time, facilitating the use of SF_6 in age-dating applications where natural sources of SF_6 are absent or negligible.

Study Unit A major hydrologic system of the United States in which the NAWQA Program has focused water-quality studies. Study Units are combinations of groundwater and surface-water systems. Most NAWQA Study Units are greater than 4,000 square miles (10,000 square kilometers) in area.

Study-Unit Survey (SUS) *See Major-Aquifer Study (MAS)*.

terrigenic helium Helium produced primarily during uranium- and thorium-series decay in the aquifer matrix and in deeper crustal geologic media.

tracer-based piston-flow age The time-of-travel of groundwater, assuming piston-flow conditions and assuming that the time-of-travel, implied by the tracers, reflects the time-of-travel of the groundwater.

Appendix A. Summary of CFC, SF_6, and $^3H/^3He$ Tracer Samples Collected From Selected NAWQA Networks Between Fiscal Years 1992 and 2005

CFC, SF_6, and $^3H/^3He$ tracer data collected from NAWQA LUS, MAS, REF, and selected OTHER networks between fiscal years 1992 and 2005 are documented in table A1.

Appendix B. Summary of Environmental-Tracer Samples Excluded From This Compilation

Tracer data from 47 (table B1) of the 1,417 sites listed in table A1 were not compiled in this report. Reasons for exclusion of these 47 sites are given in table B1. The primary reasons for exclusion are duplication of other results or impending publication elsewhere.

Appendix C. Summary of Selected Environmental-Tracer Samples Collected Between Fiscal Years 2006 and 2007

Tracer data from 29 sites collected after fiscal year 2005 are included in this compilation. These sites and the reasons for their inclusion are listed in table C1.

Appendix D. Number of Sites with Environmental-Tracer Data Compiled in This Report

Tracer data from 1,399 sites are compiled in this report (appendixes A, B, and C). Table D1 lists the number of these sites and the types of well networks associated with the samples collected.

Appendix E. Selected Physical Characteristics of Wells Compiled in This Report

Selected physical characteristics of the 1,399 wells represented in this compilation are summarized in table E1.

Appendix F. Summary of Previously Interpreted and Published CFC, SF_6, and $^3H/^3He$ Data Collected From Selected NAWQA Networks Between Fiscal Years 1992 and 2005

Table F1 lists 618 sites from 22 NAWQA Study Units where CFC, SF_6, and $^3H/^3He$ data collected between fiscal years 1992 and 2005 have been interpreted and published elsewhere. Tracer-based piston-flow ages are associated with most of these 618 sites and are reported in table F1.

A brief overview of these previously interpreted and published data follows, organized by Study Unit and network. Study-Unit abbreviations in this appendix are defined in table A1 (appendix A). Network names in this appendix are as listed in the NAWQA DWH (available at http://infotrek.er.usgs.gov/traverse/f?p=NAWQA:HOME:0:). Information provided for each Study Unit includes the network(s) and number of wells in each network, year of sample collection, tracer(s) that were analyzed in the samples, discussion of the extent of interpretation and an indication of the thoroughness of the interpretations (where possible), cautionary notes specific to each dataset (where appropriate), and the citations to the published work.

ACAD

Samples from 21 sites in the LUSCR1 network, 9 sites in the LUSRC1 network, and 7 sites in the SUS1 network of the ACAD Study Unit were collected during 2001 (LUSCR1, SUS1) and 2002 (LUSRC1) for CFCs. CFC-based piston-flow ages were interpreted and published by Tollett and Fendick (2004) (LUSCR1), Fendick and Tollett (2004) (LUSRC1), and Tollett and others (2003) (SUS1).

Few details regarding the interpretation of the tracer data were provided by Tollett and Fendick (2004), Fendick and Tollett (2004), or Tollett and others (2003). For example, recharge temperature was not discussed. Major dissolved gases were collected, but it is not known if they were used to constrain recharge temperature. CFC-11, CFC-12, and CFC-113 concentrations were reported along with interpreted CFC-based piston-flow ages in each of these publications.

No other tracers were used to check on the interpreted tracer-based piston-flow ages. The paucity of information on the methods of interpretation and the lack of additional lines of evidence to support the interpretations suggest caution in the use of the interpretations of these tracer-based piston-flow ages.

Site identification numbers for the LUSRC1 network that were published in Appendix 5 of Fendick and Tollett (2004) differed from the site identification numbers that were published in table 1 of the same reference. The site identification numbers in table 1 were determined to be the correct site identification numbers and they were used here.

ALBE

Samples from one site in the LUSAG1 network of the ALBE Study Unit were collected during 1999 for CFCs. A CFC-based piston-flow age was interpreted and published by Tesoriero and others (2005).

Major dissolved-gas data were used to constrain recharge temperatures. Data from this one well (a dual-purpose, LUS and FPS, well) were interpreted with data from other sites along a well transect, increasing confidence in the interpretations.

ALMN

Samples from 30 sites in the LUSMI1 (mining land use study), 5 sites in the REFOT1, and 4 sites in the SUS1 networks of the ALMN Study Unit were collected during 1996 (SUS1), 1997 (LUSMI1) and REFOT1 (1998) for CFCs. Tracer-based piston-flow ages were interpreted and published by McAuley and Kozar (2006).

McAuley and Kozar (2006) provided a wealth of information about their tracer data, including their estimates of recharge temperature, recharge elevation, and excess air for each site and the analytical data for each site. However, the tracer-based piston-flow ages likely were biased old due to the presence of reducing conditions (evidenced by extensive methane occurrence, as tabulated in the report). The aquifer is composed of fractured rock, further complicating interpretation of CFC data. Because of the potential limitations associated with reducing conditions, and those associated with the interpretation of tracer data in a fractured rock aquifer, these tracer-based piston-flow ages should be treated with caution.

Of the 30 LUSMI1 sites that were sampled for CFCs, 4 were sampled for $^3H/^3He$ in addition to CFCs. These $^3H/^3He$ data were not interpreted as part of the McAuley and Kozar (2006) report. These $^3H/^3He$ data might provide useful information. (However, He and Ne data for 1 of the 4 sites were not available due to sample loss during analysis, leaving at most 3 sites with usable $^3H/^3He$ data.) Although the CFCs likely have been affected by degradation, no effort was made as part of this project to analyze the $^3H/^3He$ data because (1) the number of sites with $^3H/^3He$ data was relatively small, and (2) there is a relatively low level of focus on mining issues within the NAWQA Program.

COOK

Samples from 26 sites in the SUS1a and 4 sites in the SUS1b networks of the COOK Study Unit were collected during 1999 for $^3H/^3He$. Most sites also were sampled for CFCs. $^3H/^3He$-based piston-flow ages were interpreted and published by Glass (2001, 2002).

Glass (2001, 2002) provides some discussion of the tracer data and his interpretations. Most sites were sampled for both $^3H/^3He$ and CFCs, and Glass (2001, 2002) compared the results. CFCs may have been degraded; Glass (2001, 2002) chose to retain the $^3H/^3He$ results. It is difficult to evaluate the quality of these tracer data or the interpretations based simply upon the information provided by Glass (2001, 2002).

Two sites were dated as "<1953" based upon low 3H concentrations (0.1 TU). Other than the two "<1953" samples, the oldest tracer-based piston-flow recharge date is 1968. Three samples prior to the 1970s (1968, 1969, 1969) may have greater uncertainty, as they push the limits of the method.

Glass (2002) listed measured ^3H and interpreted tritiogenic ^3H, along with $^3H/^3He$-based piston-flow ages. The local ^3H precipitation record (International Atomic Energy Agency, 2009), along with reconstructed $^3H + {}^3He$ (tritiogenic) for dated samples, are shown in figure F1. (One sample, with a $^3H/^3He$-based piston-flow recharge date of greater than 1998 was plotted at year 1998. Given the sampling date of 1999, the assignment to year 1998 introduces negligible uncertainty.)

The reconstructed $^3H + {}^3He$ (tritiogenic) plot demonstrates a lot of scatter, reflecting dispersion, mixing, and possibly some errors in the tritiogenic ^3He concentrations reported by Glass (2002). However, the overall pattern of decreasing $^3H + {}^3He$ (tritiogenic) concentration with increasing $^3H/^3He$-based piston-flow recharge year indicates that many of the $^3H/^3He$-based piston-flow ages are reasonable representations of relative age.

GRSL

Samples from 30 sites in the LUSRC1 network of the GRSL Study Unit were collected during 1999 for $^3H/^3He$. Tracer-based piston-flow ages were interpreted and published by Thiros (2003). The site identification number in Thiros (2003) for site #33 was incorrectly listed; the correct site identification number for site #33 is 403524111572201.

Thiros (2003) presented tracer-based piston-flow ages for 24 of the 30 sites. The 6 sites that were not dated can be considered post-1953, based upon published ^3H data (^3H concentrations greater than 2.8 TU; Thiros, 2003).

Tracer-based piston-flow ages were plotted against reconstructed initial ^3H concentrations (Thiros, 2003, fig. 21, p. 40). Of the 24 dated sites, 23 (including 2 of the 3 with pre-1970 tracer-based piston-flow recharge dates) plotted close to the local ^3H input function, suggesting that the interpretations generally were reasonable.

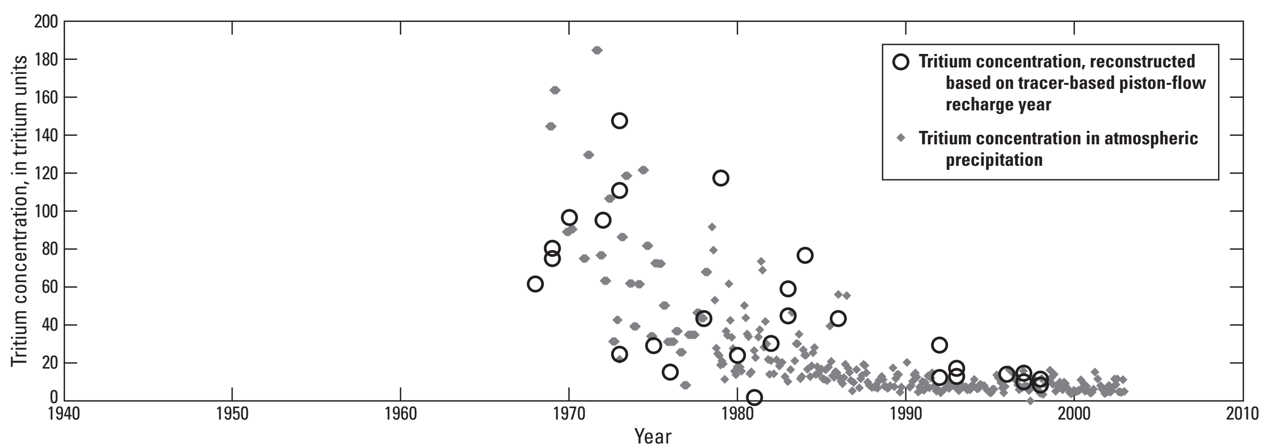


Figure F1. Reconstructed tritium concentrations and tritium in atmospheric precipitation, COOK Study Unit.

GRSL

Samples from 31 sites in an “OTHER” network of the GRSL Study Unit were collected during 2000 and 2001 for $^{3}H/^{3}He$. Tracer-based piston-flow ages were interpreted and published by Manning and others (2005).

In several cases, samples were collected in 2000 (^{3}H and He) and again in 2001 (^{3}H only). In those cases, Manning and others (2005) published interpretations based on both (1) year-2000 data and (2) year-2001 ^{3}H with year-2000 He data. Combining year-2001 ^{3}H data with year-2000 He data could introduce uncertainty associated with temporal variability in water sources. Thus, for the purposes of this compilation, tracer-based piston-flow ages based upon a complete analysis of ^{3}H and He were used rather than tracer-based piston-flow ages based upon combined (year-2000 and year-2001) data.

Tracer-based piston-flow ages were plotted against reconstructed initial ^{3}H concentrations (Manning and others, 2005). This plot indicated that many samples were composed of mixtures. These patterns are consistent with the fact that these wells were supply wells often screened over hundreds of feet (Thiros and Manning, 2004). Tracer-based piston-flow recharge dates prior to the 1970s (15 sites) may be associated with greater uncertainty than the more recent tracer-based piston-flow recharge dates because the older tracer-based piston-flow recharge dates push the limits of the method.

HPGW

Samples from 30 sites in the LUSUR1 network of the HPGW Study Unit were collected during 2000 for CFCs. Tracer-based piston-flow ages were interpreted and published by Pope and others (2002).

Pope and others (2002) provide detailed discussion about their approach to the tracer interpretations. Recharge temperature and recharge elevation were defined. Pope and others (2002) took a conservative approach with degradation, in which samples with field O_2 concentrations ≤ 0.5 mg/L were considered to have potential CFC degradation and were considered undatable.

No other tracers were used to check on the interpreted tracer-based piston-flow ages. The lack of additional lines of evidence to support the interpretations suggests caution in the use of the interpretations of these tracer-based piston-flow ages.

KANA

Samples from 25 sites in the LUSMI1 and 26 sites in the SUS1 networks of the KANA Study Unit were collected during 1997 (SUS1) and 1998 (LUSMI1) for CFCs. Tracer-based piston-flow ages were interpreted and published by McCoy and Kozar (2007). McCoy and Kozar (2007) provide a detailed discussion of their analysis of CFC and major dissolved-gas data in a challenging setting (fractured rock; some highly reducing samples). The highly reducing nature of some of the groundwater samples and the inherent difficulty of using tracers to infer groundwater age in fractured rock aquifers indicate that the interpreted tracer-based piston-flow ages should be used with caution.

CFC-12-based piston-flow ages were used in this compilation. At 3 sites, McCoy and Kozar (2007) reported CFC-12-based piston-flow ages as “nd”, but this designation was not used in a consistent manner. For 2 sites, “nd” indicated non-detect in the original CFC data files; groundwater from these two sites was considered pre-1945. (These 2 sites were 373020081075601 (MER-0170) and 374908080435601 (SUM-0103)). They had 0.0 pg/kg for CFC-12 and for CFC-113, and between 0.0 and 0.3 pg/kg for CFC-11; the 0.3 pg/kg of CFC-11 likely was a small amount of sampling or analytical contamination). One sample (381048081504801 (BOO-0257)) had missing CFC-12 and CFC-113 data, CFC-11 at 2.3 pg/kg, and also high CH_4 concentrations (11.1 and 13.3 mg/L) and low Ar concentrations (0.27 and 0.31 mg/L) indicate highly reducing conditions and degassing (and gas stripping); it is not possible to know if samples from this site had CFC degradation or if they were essentially CFC-free along with a small amount of CFC-11 contamination, and the site was considered undatable.

KANA

Samples from 19 sites in the SUS2 network of the KANA Study Unit were collected during 1997 for CFCs. Tracer-based piston-flow ages were interpreted and published by Kozar and others (2001).

Kozar and others (2001) provided a detailed analysis of the tracer interpretations. Major dissolved gases (available for 12 of the 19 sites) were used to infer recharge temperatures and excess air, and these samples indicated generally oxic conditions (most field O_2 concentrations greater than 1 mg/L and all CH_4 concentrations less than 1 µg/L). However, the inherent difficulty of using tracers in fractured rock aquifers and the absence of additional tracers indicate that the interpreted tracer-based piston-flow ages should be used with caution.

LINJ

Samples from 46 sites in an OTHER network of the LINJ Study Unit were collected between 1992 and 1999 for SF_6 and(or) $^{3}H/^{3}He$. SF_6-based and $^{3}H/^{3}He$-based piston-flow ages were interpreted and published by Kauffman and others (2001). All 46 sites are considered to be FPS sites, but these are not traditional FPS wells in that they do not fall along a transect. They are more of a combination of shallow and deep LUS wells (different parts of flow system), plus some supply wells that represent integrated samples of aquifer water. Of the 46 wells, 16 serve dual purpose in the DWH (7=LUSRC1, 1=LUSFO1, 3=LUSUR1, and 5=LUSCR1), but all behave as LUS or MAS wells to some extent.

Tracer-based piston-flow ages based on $^3H/^3He$ and/or SF_6 were interpreted and published by Kauffman and others (2001) for these 46 sites. Major dissolved-gas data were available for most sites, but it is not known if these were used in the interpretations. There was no discussion of the methods used to assign tracer-based ages (e.g. recharge temperature, recharge elevation), nor even any mention of what kind of groundwater age was assigned (presumably piston-flow, but not stated). However, the tracer-based piston-flow ages were compared against flow-model particle-tracking times-of-travel, and used to calibrate model porosity. The good agreement between tracer-based piston-flow ages and particle-tracking times-of-travel with a (reasonable) porosity of 0.30 indicates that the interpreted tracer-based piston-flow ages are defensible and reasonable.

Four categories of tracer-based piston-flow ages were listed by Kauffman and others (2001):

1. 11 cases in which there were $^3H/^3He$-based piston-flow ages and no SF_6-based piston-flow ages.

2. 6 cases in which there were SF_6-based piston-flow ages and no $^3H/^3He$-based piston-flow ages.

3. 6 cases in which there were both SF_6-based and $^3H/^3He$-based piston-flow ages, and both collected on the same date; the mean of the $^3H/^3He$-based piston-flow age and the SF_6-based piston-flow age were used in this compilation.

4. 23 cases in which there were both SF_6-based and $^3H/^3He$-based piston-flow ages, but collected on different dates. We used the $^3H/^3He$-based piston-flow age for each of these sites.

MISE

Samples from 7 sites in the LUSRC1 and 3 sites in the LUSRC2 networks of the MISE Study Unit were collected during 1998 for CFCs. Tracer-based piston-flow ages were interpreted and published by Gonthier (2002).

Gonthier (2002) interpreted the CFC data by taking into account recharge temperature (assumed to be equal to the mean annual air temperature), estimates of recharge elevation, and apparent CFC-113 contamination and CFC-11 degradation. Gonthier (2002) listed tracer-based piston-flow ages for 6 of the 10 sites.

The remaining 4 sites were not dated. At 2 of the 4 undated sites, the water was considered modern on the basis of the presence of CFCs. At the other 2 undated sites, the water was not assigned to pre-1945 or post-1945 timeframes because CFC-12 concentrations were near the method detection limit and CFC-113 was detected at concentrations in the tens of pg/Kg. It is not clear if the CFC-12 in these two undated samples was present in the ground water, if the CFC-12 had been introduced by sampling contamination, or if the CFC-12 was an artifact of analytical error. Similarly, the source of the CFC-113 in these 2 undated samples was not clear, but Gonthier did note that CFC-113 contamination was common in the 10 samples. Attempting to simply attribute a post-1945 or pre-1945 timeframe to samples from these 2 sites would be subject to great uncertainty.

No multiple tracers were available. The lack of additional lines of evidence to support the interpretations suggests caution in the use of these interpretations.

MOBL

Samples from eight sites in the LUSCR1 network of the MOBL Study Unit were collected during 2001 for CFCs and SF_6. CFC- and SF_6-based piston-flow ages were interpreted and published by Robinson (2003). One erroneous site identification number in Robinson (2003) was corrected using data from Robinson (2003) and data from the DWH.

Tracer-based piston-flow ages were based upon combination of CFCs and SF_6. Robinson (2003) did not mention the mechanism of estimating recharge temperature or recharge elevation. However, samples for major dissolved gases were collected and may have been used to infer recharge temperatures and excess air. The tracer-based piston-flow ages are qualitatively reasonable; Figure 14 (Robinson, 2003) shows a logical geochemical evolution with increasing tracer-based piston-flow age. However, the paucity of information on the methods of interpretation and the lack of additional lines of evidence to support the interpretations suggest caution in the use of these interpretations.

MOBL

Samples from 30 sites in the LUSRC1 network of the MOBL Study Unit were collected during 1999 and 2000 for CFCs and (or) SF_6. CFC- and SF_6-based piston-flow ages were interpreted and published by Robinson (2002). Three erroneous site identification numbers in Robinson (2002) were corrected using data in the original CFCs and SF_6 files and data from the DWH.

Interpreted tracer-based piston-flow ages were based SF_6 and CFC data as well as other information such as field O_2. Major dissolved gases were collected and may have been used to infer recharge temperatures and excess air. Tracer-based piston-flow ages were qualitatively reasonable; for example, direct correlation with pH and inverse correlation with number of pesticide detections (Robinson, 2002) provide confidence in tracer-based piston-flow ages. However, the paucity of information on the methods of interpretation and the lack of additional lines of evidence to support the interpretations suggest caution in the use of these interpretations.

NVBR

Samples from 1 site in the LUSAG1 network and 1 site in the SUS3 network of the NVBR Study Unit were collected during 1996 for CFCs. Tracer-based piston-flow ages were interpreted and published by Thomas and others (1999).

Thomas and others (1999) concluded that ground water at these 2 sites likely contained components of sewage. The likelihood of wastewater-derived CFCs in samples from these 2 sites, and the variable and often contaminant concentrations of CFCs in replicate samples from these sites preclude the establishment of tracer-based piston-flow ages for these sites using these tracer data. However, the presence of CFCs can be used to deduce the presence of modern water in samples from these sites.

OAHU

Samples from 30 sites in the SUS1 network of the OAHU Study Unit were collected during 2000 for CFCs. Tracer-based piston-flow ages were interpreted and published by Hunt (2004).

Hunt (2004) provided an in-depth discussion of the tracer data. Hunt (2004) noted a general pattern of younger tracer-based piston-flow ages in down-gradient regions and older tracer-based piston-flow ages in up-gradient regions. This occurrence pattern was attributed to irrigation practices in down-gradient locations that result in increased recharge rates (recharge rates in areas of furrow irrigation are approximately 20 times recharge rates in areas without irrigation) (Hunt, 2004). Furthermore, Hunt (2004) noted that large numbers of ground-water samples with tracer-based piston-flow recharge dates in the 1970s and early 1980s, and an absence of tracer-based piston-flow recharge dates in the 1990s, could be consistent with conversion from furrow-based to low-irrigation-rate drip-based irrigation practices in the mid-1980s. The careful analysis by Hunt of the OAHU tracer data is partially offset by uncertainties introduced by the use of wells with long screened intervals (median for the 30 wells: 104 feet, according to data presented in Hunt, 2004).

In addition to CFCs, $^3H/^3He$ data were collected. However, the $^3H/^3He$ data were not interpreted by Hunt (2004). Hunt (2004) cited problems with terrigenic He corrections for the absence of $^3H/^3He$ interpretations. Additional difficulties with the OAHU $^3H/^3He$ data include (1) aqueous ^3H concentrations were low, reflecting low ^3H inputs typical of Pacific islands where ^3H inputs tend to be diluted (low ^3H inputs result in little ^3H being available for age-dating); (2) a mantle He component appeared to be present in many samples (mantle He often contains high amounts of poorly constrained and (or) variable ^3He components); and (3) many samples were fractionated or otherwise compromised.

PODL

Samples from 28 sites in an OTHER network of the PODL Study Unit were collected during 2000 for SF_6. This network is similar to a DWGS network. Tracer-based piston-flow ages were interpreted and published by Ferrari (2002).

Major dissolved gases were used to infer recharge temperatures and excess air. Ferrari (2002) presents inferred recharge temperatures, recharge elevations, and excess air concentrations, and provides the SF_6 concentrations. SF_6 concentrations did not exhibit contaminant levels of SF_6. Tracer-based piston-flow recharge dates for the entire set of sites (collected in 2000) ranged from 1976 to 1994, within the optimal time period for the method. However, no other tracers were used to check on the interpreted tracer-based piston-flow ages. Perhaps more significantly, the wells were water supply wells; thus, the tracer-based piston-flow ages from this network may have little relation to actual ground-water age distributions for supply wells that may withdraw water from multiple flow paths.

PODL

Samples from 29 sites in the LUSCR1 network, 29 sites in the SUS1 network, and 2 sites in the REFFO1 network of the PODL Study Unit were collected during 2001, 2002, and 2003 for SF_6. Tracer-based piston-flow ages were interpreted and published by Debrewer and others, 2007.

The approach was only briefly discussed by Debrewer and others (2007). Major dissolved gases were collected and may have been used to infer recharge temperatures and excess air. Debrewer and others (2007) found statistically significant ($p<0.05$) Spearman's correlations between atrazine concentrations and tracer-based piston-flow recharge dates for both the SUS and the LUS networks, whereas Spearman's correlations between atrazine concentrations and well depths were not statistically significant; these findings provide some support for the SF_6 interpretations, insofar as tracer-based piston-flow ages would be expected to provide a better understanding of ground-water residence time than would simple physical measurements such as well depth if the tracer-based piston-flow ages are at least qualitatively correct and internally consistent. SF_6 concentrations did not exhibit contaminant levels of SF_6. Tracer-based piston-flow recharge dates for these sites (collected 2001-2003) ranged from 1974 to 2000, within the optimal time period for the method. However, no other tracers were used to check on the interpreted tracer-based piston-flow ages. The paucity of information on the methods of interpretation and the lack of additional lines of evidence to support the interpretations suggest caution in the use of the interpretations of these tracer-based piston-flow ages.

REDN

Samples from one site in the LUSAG1 network of the REDN Study Unit were collected during 1995 for CFCs. A tracer-based piston-flow age was interpreted and published by Stoner and others (1997) and Cowdery (1997).

Interpretation of the tracers was discussed in detail by Stoner and others (1997). Flow modeling and particle-tracking analysis were done for a transect of wells that included the one LUSAG1 site (a site that serves as both an LUSAG1 site and an FSS site) (Stoner and others, 1997; Cowdery, 1997). The tracer-based piston-flow age (6 years) and the particle-tracking model recharge age (2 years) had a large percentage difference, but the results of these two methods were close relative to the large uncertainties in the two methods, and thus provide support for the interpreted tracer-based piston-flow age for this site.

RIOG

Samples from 2 sites in the LUSUR1 network and 2 sites in the SUS1 network of the RIOG Study Unit were collected during 1996 (LUSUR1) and 1997 (SUS1) for CFCs, SF_6, and(or) $^3H/^3He$. The data and interpretations were published by Plummer and others (2004).

Of the 4 sites, one was datable with $^3H/^3He$. Of the 3 sites that were not datable with $^3H/^3He$, two could be attributed as pre-1940 (no detectable CFC-12) and one could be characterized as post-1940 (on the basis of contaminant levels of CFC-12). SF_6 data were not readily used because of uncertainty surrounding the extent of natural SF_6 in these aquifers.

The Middle Rio Grande project collected multiple tracer and other geochemical samples from 288 groundwater sites. As such, there was little site-specific interpretation for these four samples, but the overall patterns of tracer-based piston-flow ages across the project area lend support for the interpretations.

SOCA

Samples from eight sites in the SUS2 network of the SOCA Study Unit were collected during 2000 for $^3H/^3He$. Tracer-based piston-flow ages were interpreted and published by Hudson and others (2002). The report focused on the interpretation of the tracers, and detailed discussion was presented by Hudson and others (2002). Although tracer-based piston-flow ages were reported, Hudson and others (2002) presented evidence indicating that most of the groundwater samples were mixtures of pre-bomb and bomb water. Thus, the tracer-based piston-flow ages only approximate the relative ages of groundwater from these sites.

TENN

Samples from 9 sites in the LUSAG1 network of the TENN Study Unit were collected during 2000 for CFCs. CFC-based piston-flow ages were interpreted and published by Kingsbury (2003).

Few details regarding the interpretation of the tracer data were provided by Kingsbury (2003). The recharge temperatures and recharge elevations that were used were documented by Kingsbury (2003). Major dissolved gases were collected, but it is not clear whether the major dissolved-gas data were used in the interpretations; however, none of the samples from the 9 sites contained detectable CH_4, indicating redox conditions less reducing than methanogenic. SF_6 samples also were collected from these 9 sites, but extensive SF_6 contamination was observed and was attributed to sample caps. The limited discussion on methods of data interpretation and the lack of additional lines of evidence to support the interpretations suggest caution in the use of the interpretations of these tracer-based piston-flow ages.

UCOL

Samples from 25 sites in the LUSRC1 network of the UCOL Study Unit were collected during 1997 for CFCs. Tracer-based piston-flow ages were interpreted and published by Apodaca and others (2002).

Few details regarding the interpretation of the tracer data were provided by Apodaca and others (2002). However, recharge temperature and recharge elevation were documented. Study Unit expertise may be particularly valuable for this dataset because estimation of recharge elevations in this mountainous terrain probably benefited from local understanding.

Major dissolved gases were not collected. No other tracers were used to check on the interpreted tracer-based piston-flow ages. The paucity of information on the methods of interpretation and the lack of additional lines of evidence to support the interpretations suggest caution in the use of the interpretations of these tracer-based piston-flow ages.

UMIS

Samples from one site in the LUSRC1 network of the UMIS Study Unit were collected during 1997 for CFCs. Tracer-based piston-flow ages were interpreted and published by Andrews and others (2005).

Few details regarding the interpretation of the tracer data were provided by Andrews and others (2005). However, flow modeling and particle-tracking analysis were done for a transect of wells that included the 1 LUSRC1 site (a site that serves as both an LUSRC1 site and an FSS site). There was reasonable agreement between the tracer-based piston-flow recharge date (1990) and the particle-tracking model recharge date (1992) for the LUSRC1 site, providing support for the interpreted CFC data for this site.

USNK

Samples from 2 sites in the SUS1 network, 9 sites in the LUSCR2 network, 17 sites in the LUSCR3 network, and 11 sites in the LUSCR4 network of the USNK Study Unit were collected during 1994 and 1995 for CFCs. Of these 39 sites, 34 also were sampled for $^{3}H/^{3}He$. These data were interpreted and published by Plummer and others (2000).

The tracer data were extensively interpreted by Plummer and others (2000). CFC-113-based piston-flow ages of Plummer and others (2000) were used for the purposes of this compilation. (CFC-113 appeared to be more reliable than CFC-12 or CFC-11 in this network; Plummer and others, 2000.) Tracer-based piston-flow ages were used here to be consistent with the other tracer interpretations compiled for this project. However, Plummer and others (2000) did additional analysis of the data beyond simple piston-flow analysis. CFC, $^{3}H/^{3}He$, and stable isotope data were used to elucidate two-component groundwater mixtures and infer tracer-based piston-flow ages of the younger components. (Although many $^{3}H/^{3}He$ data were uninterpretable, owing to the presence of mantle He and to other problems, many other $^{3}H/^{3}He$ data were interpretable.) Users of USNK tracer results may wish to consult Plummer and others (2000) for these interpretations, especially if the tracer results will be used for Study-Unit-specific interpretations where comparability with results from other Study Units will not be required.

Analysis of $^{3}H/^{3}He$ and CFC data indicated that these CFC-based piston-flow ages have an old bias of up to about 10 years. This old bias appears to result from slow CFC advection through the thick unsaturated zone in this aquifer. However, CFC-based piston-flow ages were used for this compilation because $^{3}H/^{3}He$ results were available for fewer sites and were interpreted by Plummer and others (2000) in terms of mixing models.

One site (425104114283701, or local site 9) was sampled for CFCs 07-18-1994 (tracer-based recharge date 1978) and again 06-11-1995 (tracer-based recharge date 1976). The sample collected 06-11-1995 was retained because it was accompanied by NAWQA chemistry samples, whereas the 07-18-1994 sample was not sampled for NAWQA chemistry samples.

WILL

Samples from 12 sites in the LUSUR1 network of the WILL Study Unit were collected during 1997 and again (same sites) in 1998 for $^{3}H/^{3}He$. Tracer-based piston-flow ages were interpreted and published by Hinkle (2009).

Tracer-based piston-flow ages were provided for 11 of the 12 sites. At the 1 site where $^{3}H/^{3}He$ tracers did not work (due to degassing), published ^{3}H values (4.03 and 3.85 TU) indicate post-1953 water.

Tracer-based piston-flow ages were plotted against reconstructed initial ^{3}H concentrations (Hinkle, 2009). Of the 11 dated sites, 10 plotted close to the local ^{3}H input function, suggesting that the interpretations generally were reasonable. An analysis of the age gradient in relation to local recharge rates also supports the interpretations (Hinkle, 2009).

WMIC

Samples from 8 sites in the LUSAG1a network and 29 sites in the LUSAG2 network of the WMIC Study Unit were collected during 1994 for CFCs. Tracer-based piston-flow ages were interpreted and published by Saad (1997) and Saad (2009).

After publication by Saad (1997), some of the interpretations were modified (Saad, 2009). These changes have been incorporated in this report.

The approach used to interpret the CFC data was discussed in detail by Saad (1997). Part of the analysis included an attempt to account for the effects of CFC transport through unsaturated zones for sites where the assumed unsaturated zone was greater than 30 feet. This was done by using an analytical equation (Cook and Solomon, 1995) with parameters thought to be appropriate for local hydrogeologic conditions. It was some of these unsaturated-zone transport times that were subsequently modified by Saad (2009). Parameterizing models to account for CFC concentration gradients in unsaturated zones is challenging, and there were no unsaturated-zone CFC data for model calibration. However, Saad (1997) found that atrazine-plus-deethylatrazine concentration patterns were well explained by tracer-based piston-flow recharge dates and historical atrazine usage data. The changes in the CFC interpretations (Saad, 2009) do not appear to have substantively changed the relation between atrazine-plus-deethylatrazine concentrations and tracer-based piston-flow recharge dates, and the relation between atrazine-plus-deethylatrazine concentrations and tracer-based piston-flow recharge dates suggests that the interpretations of the CFC data were at least qualitatively reasonable.

Major dissolved gases were not collected. No other tracers were used to check on the interpreted tracer-based piston-flow ages. The lack of multiple lines of evidence to support the interpretations suggests caution in the use of the interpretations of these tracer-based piston-flow ages.

References Cited in Appendix F

Andrews, W.J., Stark, J.R., Fong, A.L., and Fallon, J.D., 2005, Water-quality assessment of part of the Upper Mississippi River basin, Minnesota and Wisconsin—Ground-water quality along a flow system in the Twin Cities metropolitan area, Minnesota, 1997–98: U.S. Geological Survey Scientific Investigations Report 2005-5120, 44 p.

Apodaca, L.E., Bails, J.B., and Smith, C.M., 2002, Water quality in shallow alluvial aquifers, Upper Colorado River Basin, Colorado, 1997: Journal of the American Water Resources Association, v. 38, p. 133–149.

Cook, P.G., and Solomon, D.K., 1995, Transport of atmospheric trace gases to the water table: Implications for groundwater dating with chlorofluorocarbons and krypton 85: Water Resources Research, v. 31, p. 263–270.

Cowdery, T.K., 1997, Shallow ground-water quality beneath cropland in the Red River of the North basin, Minnesota and North Dakota, 1993–95: U.S. Geological Survey Water-Resources Investigations Report 97-4001, 52 p.

Debrewer, L.M., Ator, S.W., and Denver, J.M., 2007, Factors affecting spatial and temporal variability in nutrient and pesticide concentrations in the surficial aquifer on the Delmarva Peninsula: U.S. Geological Survey Scientific Investigations Report 2005-5257, 44 p.

Fendick, R.B., Jr., and Tollett, R.W., 2004, Quality of water from shallow wells in urban residential and light commercial areas in Lafayette Parish, Louisiana, 2001 through 2002: U.S. Geological Survey Water-Resources Investigations Report 03-4118, 58 p.

Ferrari, M.J., 2002, Occurrence and distribution of selected contaminants in public drinking-water supplies in the surficial aquifer in Delaware: U.S. Geological Survey Open-File Report 2001-327, 62 p.

Glass, R.L., 2001, Ground-water quality in the Cook Inlet Basin, Alaska, 1999: U.S. Geological Survey Water-Resources Investigations Report 01-4208, 58 p.

Glass, R.L., 2002, Ground-water age and its water-management implications, Cook Inlet Basin, Alaska: U.S. Geological Survey Fact Sheet 022-02, 4 p.

Gonthier, G.J., 2002, Quality of shallow ground water in recently developed residential and commercial areas, Memphis vicinity, Tennessee, 1997: U.S. Geological Survey Water-Resources Investigations Report 02-4294, 105 p.

Hinkle, S.R., 2009, Tritium/helium-3 apparent ages of shallow ground water, Portland basin, Oregon, 1997–98: U.S. Geological Survey Scientific Investigations Report 2009-5057, 8 p.

Hudson, G.B., Moran, J.E., and Eaton, G.F., 2002, Interpretation of tritium-^{3}helium groundwater ages and associated dissolved noble gas results from public water supply wells in the Los Angeles physiographic basin: Lawrence Livermore National Laboratory report UCRL-AR-151447, variously paged.

Hunt, C.D., Jr., 2004, Ground-water quality and its relation to land use on Oahu, Hawaii, 2000–01: U.S. Geological Survey Water-Resources Investigations Report 03-4305, 76 p.

International Atomic Energy Agency, 2009, GNIP Programme: International Atomic Energy Agency website, accessed June 7, 2009, at http://www-naweb.iaea.org/napc/ih/GNIP/IHS_GNIP.html.

Kauffman, L.J., Baehr, A.L., Ayers, M.A., and Stackelberg, P.E., 2001, Effects of land use and travel time on the distribution of nitrate in the Kirkwood-Cohansey aquifer system in southern New Jersey: U.S. Geological Survey Water-Resources Investigations Report 01-4117, 49 p.

Kingsbury, J.A., 2003, Shallow ground-water quality in agricultural areas of northern Alabama and middle Tennessee, 2000–2001: U.S. Geological Survey Water-Resources Investigations Report 03-4181, 38 p.

Kozar, M.D., Sheets, C.J., and Hughes, C.A., 2001, Ground-water quality and geohydrology of the Blue Ridge physiographic province, New River basin, Virginia and North Carolina: U.S. Geological Survey Water-Resources Investigations Report 00-4270, 36 p.

Manning, A.H., Solomon, D.K., and Thiros, S.A., 2005, 3H/3He age data in assessing the susceptibility of wells to contamination: Ground Water, v. 43, 353–367.

McAuley, S.D., and Kozar, M.D., 2006, Ground-water quality in unmined areas and near reclaimed surface coal mines in the northern and central Appalachian coal regions, Pennsylvania and West Virginia: U.S. Geological Survey Scientific Investigations Report 2006-5059, 57 p.

McCoy, K.J., and Kozar, M.D., 2007, Relation of chlorofluorocarbon ground-water age dates to water quality in aquifers of West Virginia: U.S. Geological Survey Scientific Investigations Report 2006-5221, 36 p.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, Eurybiades, 2004, Geochemical characterization of ground-water flow in the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 03-4131, 395 p.

Plummer, L.N., Rupert, M.G., Busenberg, Eurybiades, and Schlosser, P., 2000, Age of irrigation water in ground water from the Eastern Snake River Plain aquifer, south-central Idaho: Ground Water, v. 38, p. 264–283.

Pope, L.M., Bruce, B.W., Rasmussen, P.P., and Milligan, C.R., 2002, Quality of shallow ground water in areas of recent residential and commercial development, Wichita, Kansas, 2000: Water-Resources Investigations Report 02-4228, 67 p.

Robinson, J.L., 2002, Ground-water quality beneath an urban residential and commercial area, Montgomery, Alabama, 1999–2000: U.S. Geological Survey Water-Resources Investigations Report 02-4052, 37 p.

Robinson, J.L., 2003, Comparison between agricultural and urban ground-water quality in the Mobile River Basin, 1999–2001: U.S. Geological Survey Water-Resources Investigations Report 03-4182, 38 p.

Saad, D.A., 1997, Effects of land use and geohydrology on the quality of shallow ground water in two agricultural areas in the western Lake Michigan drainages, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 96-4292, 69 p.

Saad, D.A., 2009, Errata Sheet for Effects of land use and geohydrology on the quality of shallow ground water in two agricultural areas in the western Lake Michigan drainages, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 96-4292, 69 p., accessed January 16, 2009, at http://pubs.usgs.gov/wri/wri96-4292/errata.html.

Stoner, J.D., Cowdery, T.K., and Puckett, L.J., 1997, Ground-water age dating and other tools used to assess land-use effects on water quality: U.S. Geological Survey Water-Resources Investigations Report 97-4150, 6 p.

Tesoriero, A.J., Spruill, T.B., Mew, H.E., Jr., Farrell, K.M., and Harden, S.L., 2005, Nitrogen transport and transformations in a coastal plain watershed: Influence of geomorphology on flow paths and residence times: Water Resources Research, v. 41, W02008, doi:10.1029/2003WR002953.

Thiros, S.A., 2003, Quality and sources of shallow ground water in areas of recent residential development in Salt Lake Valley, Salt Lake County, Utah: U.S. Geological Survey Water-Resources Investigations Report 2003-4028, 74 p.

Thiros, S.A., and Manning, A.H., 2004, Quality and sources of ground water used for public supply in Salt Lake Valley, Salt Lake County, Utah, 2001: U.S. Geological Survey Water-Resources Investigations Report 2003-4325, 95 p.

Thomas, J.M., Thodal, C.E., and Seiler, R.L., 1999, Identification of nitrate sources contributing to ground water in the Indian Hills area of Douglas County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4042, 22 p.

Tollett, R.W., and Fendick, R.B., Jr., 2004, Quality of water from shallow wells in the rice-growing area in southwestern Louisiana, 1999 through 2001: U.S. Geological Survey Water-Resources Investigations Report 03-4050, 44 p.

Tollett, R.W., Fendick, R.B., Jr., and Simmons, L.B., 2003, Quality of water in domestic wells in the Chicot and Chicot equivalent aquifer systems, southern Louisiana and southwestern Mississippi, 2000–2001: U.S. Geological Survey Water-Resources Investigations Report 03-4122, 85 p.

Appendix G. Documentation and Analysis of Newly Interpreted CFC, SF_6, and $^3H/^3He$ Data

A total of 781 sites with newly interpreted tracer data are summarized in table 1 (in body of report). Tracer data and synopses of the tracer data, and interpretations for these 781 sites are in this appendix. Well construction, water level, and selected ancillary chemical data also are included in this appendix. These data and synopses are organized by Study Unit and network. Data are presented in tables. Data sources were discussed in the body of this report. Synopses include the network(s) and number of wells in each network, year of sample collection, tracer(s) that were analyzed in the samples, general type of aquifer materials, relevant notes about the approach used for estimating recharge temperature and (for CFCs and SF_6) excess air, a list of some of the notable advantages and disadvantages associated with the datasets, the range of water-level depths, presentation of a plot of tracer-based piston-flow age versus depth below water table (age gradient), a reconstructed ^3H plot (where ^3H data were available), and comments specific to a particular dataset (where appropriate).

The range of water-level depths for a network of wells is listed to help characterize the hydrologic system and to provide context for evaluating the possible effects of unsaturated-zone thickness on CFC and SF_6 results. Data on water-level depths can be useful in evaluating CFC and SF_6 results because CFC and SF_6 concentrations at the base of thick unsaturated zones are less likely to be at equilibrium with atmospheric CFC and SF_6 concentrations than are CFC and SF_6 concentrations at the base of thin unsaturated zones, if all other factors such as climate and geology are equal (Busenberg and Plummer, 2000; International Atomic Energy Agency, 2006).

The two types of figures used in this appendix (age-gradient plots and reconstructed ^3H plots) can provide insight into age-dating interpretations and the hydrologic systems associated with the age-dating results, and can help identify outliers in need of additional investigation. An age-gradient plot simply shows tracer-based piston-flow age versus depth of center of open interval below water table for a group of wells. Unconfined, homogeneous aquifers that have simple geometries and receive uniform recharge would be expected to exhibit patterns of increasing tracer-based piston-flow age with increasing depth below the water table in recharge areas. An age gradient showing such a pattern could be construed as providing support for the relative tracer-based piston-flow ages. Where aquifer geometry and porosity are well constrained, recharge rates can be inferred from age gradients if the latter are considered reliable, or age gradients can be evaluated if reliable, independent estimates of recharge rates are available (Cook and Böhlke, 2000); however, these types of quantitative applications were beyond the scope of this report.

A reconstructed ^3H plot shows ^3H concentrations that are back-decayed, on the basis of tracer-based piston-flow ages, to original ^3H concentrations inferred to have been present at the time of recharge, and compared to historical ^3H records. In aquifers that receive recharge primarily from atmospheric precipitation, a comparison of reconstructed ^3H concentrations with historical ^3H records for precipitation can provide a consistency check on the age interpretations. Favorable agreement between reconstructed ^3H concentrations and historical ^3H records demonstrates consistency between interpreted tracer-based piston-flow ages and historical ^3H records. However, such agreement does not provide confirmation of the age interpretations. Lack of agreement between reconstructed ^3H concentrations and historical ^3H records may indicate a violation of the age-dating assumptions; tracer degradation or contamination, mixing in the aquifer or well bore, or other problems may have occurred.

In evaluating reconstructed ^3H data, the time required for ^3H to migrate from land surface to the water table (the latter being the point at which groundwater dating begins) could result in a discrepancy between the ^3H input record and reconstructed ^3H concentrations. This unsaturated-zone time lag will result in post-1960s reconstructed ^3H concentrations being shifted to the right of the ^3H input record. Dispersion of the 1960s ^3H peak in the unsaturated zone will have a similar effect. These two effects (time-of-travel and dispersion of ^3H in the unsaturated zone) generally are not observed in the datasets in this appendix, or are masked if not overwhelmed by other effects such as mixing.

Study-Unit abbreviations in this appendix are defined in table A1 (appendix A). Network names in this appendix are as listed in the NAWQA DWH (available at http://infotrek.er.usgs.gov/traverse/f?p=NAWQA:HOME:0:). Well construction, water level, and ancillary chemistry data are from the NAWQA DWH.

ACFB and GAFL LUSCR1, LUSAG1, LUSCR2, LUSFO1

Samples from 26 sites in the ACFB and 7 sites in the GAFL Study Units were collected during 1999 and 2002 for CFCs (networks and, in parentheses, number of sites):

ACFB:
LUSCR1 (8)
LUSAG1 (11)
LUSCR2 (4)
LUSFO1 (forested land use; equivalent to reference sites) (3)
GAFL:
7 LUSCR1 (7)
See table G1.

The ACFB and GAFL LUSCR1 networks are adjacent to each other and form a continuous, cross-Study-Unit LUS.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that excess air concentrations were 2 cc(STP)/Kg.

Advantages associated with these samples:

- Monitoring wells, so generally low pumping stress and short well screens.
- Generally oxic.

Disadvantages associated with these samples:

- No major dissolved-gas data.
- No tracers other than CFCs.

The 1999 samples show consistent CFC-113 contamination and/or elevated concentrations relative to the other CFCs, which may be indicative of CFC-113 contamination in the sampling equipment.

Depth to water (can affect tracer transport to water table):

Median: 28.10 feet
Mean: 29.55 feet
Minimum: 6.93 feet
Maximum: 67.25 feet

Brief analysis:
The age gradient for these sites is shown in figure G1.

The age gradient for these networks exhibits scatter, as would be expected for samples taken from a wide area. However, there is a clear general increase in tracer-based piston-flow age with increase in depth below water table.

There are 4 sites with tracer-based piston-flow ages of greater than 20 years and depth below water table of less than 5 feet. It is not clear why these 4 shallow sites have relatively old tracer-based piston-flow ages. It is possible that the tracer-based piston-flow ages for these 4 sites could be biased old, or these sites could conceivably be located in discharge areas of a flow system in spite of intentions to install such wells in areas of recharge.

ALBE LUSAG1

Samples from six sites in the ALBE Study Unit were collected during 2002 and 2003 for CFCs (network and, in parentheses, number of sites):

LUSAG1 (6)
See table G2.

The aquifer is composed of sediments.

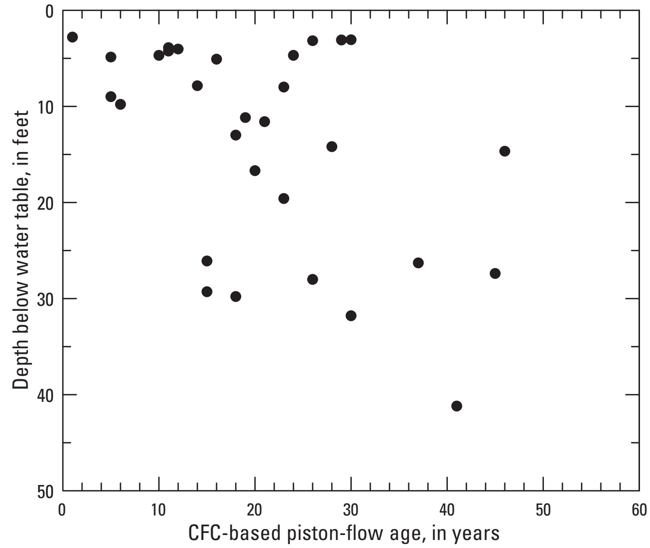


Figure G1. Age gradient for dated sites from the LUSCR1, LUSAG1, LUSCR2, and LUSFO1 networks, ACFB and GAFL Study Units.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that excess air concentrations were 2 cc(STP)/Kg.

Advantages associated with these samples:

- Short saturated open intervals (all ≤10 feet; median = 5.00 feet).
- Median penetration of center of open interval into water table was 14.07 feet (sampling close to the water table, potentially minimizing mixing).
- Monitoring wells, therefore low pumping stress.

Disadvantages associated with these samples:

- No major dissolved-gas data.
- No tracers other than CFCs.
- Generally highly reducing: all field O_2 less than 1 mg/L, median Fe = 3,475 µg/L.

Depth to water (can affect tracer transport to water table):

Median: 3.78 feet
Mean: 3.68 feet
Minimum: 0.64 feet
Maximum: 7.40 feet

Brief analysis:
All of the tracer-based piston-flow ages were censored, and thus there are no data for an age gradient for these wells.

CCYK LUSOR1b and LUSAG2b

Samples from 10 sites in the CCYK Study Unit were collected during 2002 for SF_6 (networks and, in parentheses, number of sites):

LUSOR1b (5)
LUSAG2b (5)
See table G3.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that excess air concentrations were 2 cc(STP)/Kg.

Advantages associated with these samples:

- Short open intervals: median saturated open interval 5.00 feet.
- Median penetration of center of open interval into water table was 12.13 feet (sampling close to the water table, potentially minimizing mixing).
- Monitoring wells, therefore generally low pumping stress.

Disadvantages associated with these samples:

- No major dissolved-gas data.
- No tracers other than SF_6.

Depth to water (can affect tracer transport to water table):

- Median: 16.69 feet
- Mean: 29.18 feet
- Minimum: 5.38 feet
- Maximum: 67.95 feet

Brief analysis:

The age gradient for these sites is shown in figure G2.

The age gradient has a great deal of scatter. Some of this could reflect the fact that two agricultural land use studies have been combined in this analysis, but the land use studies were from similar locations within a single Study Unit. Changing irrigation practices over time, and thus changing recharge rates, could explain some of the variability. Irrigation rates in the portion of the study area where these land use studies were located increased dramatically beginning in the early 1950s in response to irrigation water availability from the Columbia Basin Irrigation Project (Jones and Wagner, 1995); increased irrigation rates probably initially increased recharge rates. Then, beginning in the 1970s, irrigation practices in portions of the study area began changing from dominantly furrow to dominantly sprinkler irrigation methods (Ebbert and Kim, 1998); these changes may have affected recharge rates. The result of these changes in irrigation practices over time would be expected to lead to nonlinear age gradients.

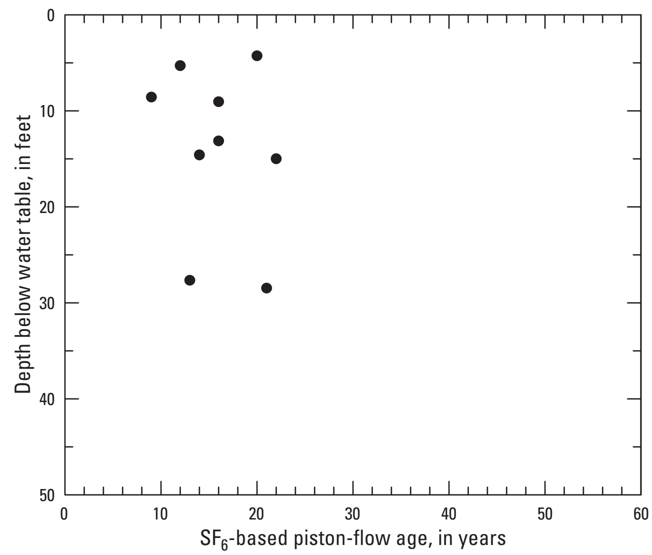


Figure G2. Age gradient for dated sites from the LUSOR1b and LUSAG2b networks in the CCYK Study Unit.

CNBR LUSCR1 and REFPA1

Samples from 22 sites in the CNBR Study Unit were collected during 2003 for CFCs (networks and, in parentheses, number of sites):

LUSCR1 (21)
REFPA1 (1)
See table G4.

The wells were installed in glacial deposit and stream-valley aquifers.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that excess air concentrations were 2 cc(STP)/Kg.

Advantages associated with these samples:

- Short open intervals (saturated open interval ≤ 10 feet; median = 5.00 feet).
- Median penetration of center of OI into water table was 9.14 feet (sampling close to the water table, potentially minimizing mixing).
- Monitoring wells, therefore low pumping stress.
- Most sites contained $O_2 \geq 1$ mg/L (median field O_2 = 4.68 mg/L).

Disadvantages associated with these samples:

- No tracers other than CFCs.
- No major dissolved-gas data.

Depth to water (can affect tracer transport to water table):

- Median: 19.14 feet
- Mean: 23.29 feet
- Minimum: 2.10 feet
- Maximum: 62.30 feet

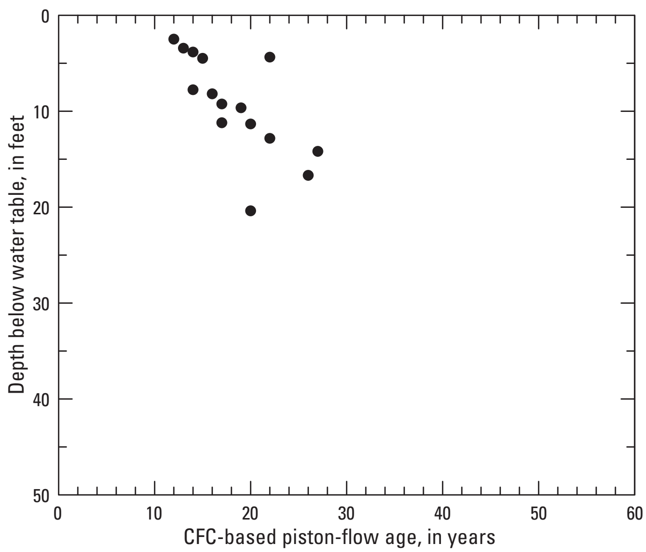


Figure G3. Age gradient for dated sites from the LUSCR1 and REFPA1 networks in the CNBR Study Unit.

Brief analysis:

The age gradient for these sites is shown in figure G3.

The age gradient for these wells shows tracer-based piston-flow age increasing with increasing depth below the water table. Although the overall pattern of increasing tracer-based piston-flow age with increasing depth is reasonable, it is possible that there is an offset towards older tracer-based piston-flow ages in at least some of these samples that could indicate a lag in the transport of CFCs through the unsaturated zone in these networks. Alternatively, it is possible that these samples represent multiple age gradients that reflect a variety of recharge rates, sediment textures, degrees of geologic heterogeneity, and directions of groundwater movement.

CONN SUS2

Samples from nine sites in the CONN Study Unit were collected during 2002 for CFCs (network and, in parentheses, number of sites):

SUS2 (9)

See table G5.

The aquifer is composed of glacial sediments.

Major dissolved-gas data were available for 8 of the 9 sites. For excess air calculations, only 4 of the 8 sites with major dissolved-gas data were oxic. Excess air concentrations for these 4 sites were sufficiently variable as to be considered insufficient for characterizing excess air for the other 5 sites. For the 4 suboxic sites that had major dissolved-gas data, as well as for the 1 site that did not have major dissolved-gas data, a typical excess air concentration of 2 cc(STP)/Kg was assumed.

Recharge temperature calculations for the 1 site (413710072553001, or CT-S-400) that did not have major dissolved-gas data were complicated by the fact that 8 sites that had major dissolved-gas data were spread over 3 states (CT, NH, VT). The mean annual air temperature for sites in these 3 states varies considerably. Thus, using the median recharge temperature from these 8 sites to represent the recharge temperature for site CT-S-400 would be problematic.

The 1 site that did not have major dissolved-gas data was in CT. The median major-dissolved-gas-inferred recharge temperature for the other 4 sites in CT was 11.10 °C. Mean annual air temperature +1°C (adjusted by lapse rate) for CT-S-400 was 11.04 °C. On the basis of these two calculations (11.10 °C and 11.04 °C), a recharge temperature of 11°C (2 significant figures) was used for CT-S-400.

Advantages associated with these samples:

- Major dissolved-gas data were available for 8 of the 9 sites.
- Short open intervals: For the 7 sites for which well construction data were available, the maximum saturated open interval was 8.00 feet.

Disadvantages associated with these samples:

- No tracers other than CFCs.
- Median penetration of center of open interval below water table was 61.85 feet (greater distance below water table possibly allowing for more mixing).
- These were supply wells (more aquifer stress than with monitoring wells).
- Many sites were suboxic (4 sites with field O_2 concentrations $\leq$0.24 mg/L), Mn-reducing (4 sites) and (or) Fe-reducing (3 sites).

Depth to water (can affect tracer transport to water table):

- Median: 20.00 feet
- Mean: 26.78 feet
- Minimum: 6.00 feet
- Maximum: 85.00 feet

Brief analysis:

Only one site was considered datable. As such, no age gradient is shown for this network.

CONN LUSRC1 and OTHER ($^3H/^3He$)

Samples from six sites in the CONN Study Unit were collected during 2003 and 2005 for $^3H/^3He$ (networks and, in parentheses, number of sites):

LUSRC1 (5)

OTHER (1)

See table G6.

The aquifer is composed of glacial sediments.

The standard procedure for $^3H/^3He$ dating that was documented in the body of the report was used for these sites. Four sites were datable (2 sites did not require a correction for terrigenic He; 2 sites did require a correction for terrigenic He), 1 site exhibited evidence of gas fractionation, and at 1 site the sample was lost during analysis.

Recharge elevation assumed equal to the elevation of the water table. For analysis of major dissolved-gas data, all six sites were oxic and all had major dissolved-gas data. However, data for 1 site (414826072290901) yielded unusual results (that is, negative excess air). Recharge elevations would have had to have been 3,000 feet (second sample) to 5,000 feet (first sample) above the water table elevation to get excess air to zero. Thus, these site-specific major dissolved-gas data were not used, and the median major dissolved-gas recharge temperature and excess air values from the other 5 sites were used to represent this 1 site.

Advantages associated with these samples:

Major dissolved gases were available for estimation of recharge temperatures.

Of the four datable wells, three had short open intervals (saturated open intervals ≤ 5.00 feet) and were monitoring wells with low pumping stress. The fourth well was a supply well with a saturated open interval of 15.00 feet.

Disadvantages associated with these samples:

The only substantial limitations specific to these sites are discussed in the next section.

Brief analysis:

The age gradient for these sites is shown in figure G4.

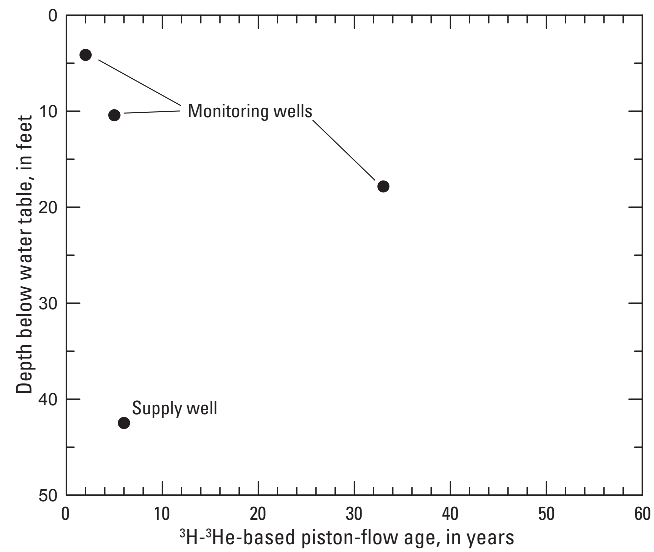


Figure G4. $^3H/^3He$-based age gradient for dated sites from the LUSRC1 and OTHER networks in the CONN Study Unit.

The age gradient for these networks is affected by the inclusion of a supply well with the relatively long well screen. This sample may reflect effects associated with well pumping, where young water may be drawn down to the well screen. If this well is removed from consideration, the age gradient is well defined for the three monitoring wells, all screened in sand and gravel and with short well screens.

The deepest of the four sites shown in the figure, above, also was dated with SF_6 (summarized separately). The SF_6-based piston-flow age was 3 years, compared with the $^3H/^3He$ -based piston-flow age of 6 years. These results could be consistent with a young bias in the SF_6-based piston-flow ages (discussed in the SF_6 summary). The $^3H/^3He$-based piston-flow age for this well probably is more reliable than the SF_6-based piston-flow age.

One of the monitoring wells in the figure above (the shallowest) also was dated with SF_6, but on a different sampling date. The SF_6-based piston-flow age for this well was 7 years, and the $^3H/^3He$-based piston-flow age was 2 years. However, these different tracers were collected on different sampling dates, complicating analysis of multiple tracers. Note that the chemistry was very different on the two sampling dates (e.g. nitrite-plus-nitrate 0.13 mg N/L versus 8.6 mg N/L), suggesting that the water sampled on the different dates was different. If one tracer-based piston-flow age is to be chosen to represent this site, the $^3H/^3He$-based piston-flow age probably is more reliable than the SF_6-based piston-flow age.

The reconstructed ^3H plot is shown in figure G5.

The 3 relatively modern samples plot near the ^3H input function for the wells, consistent with piston-flow conditions. The sample with a tracer-based piston-flow recharge date of 1972 appears to be affected by mixing processes, or possibly the large amount of excess air in the sample.

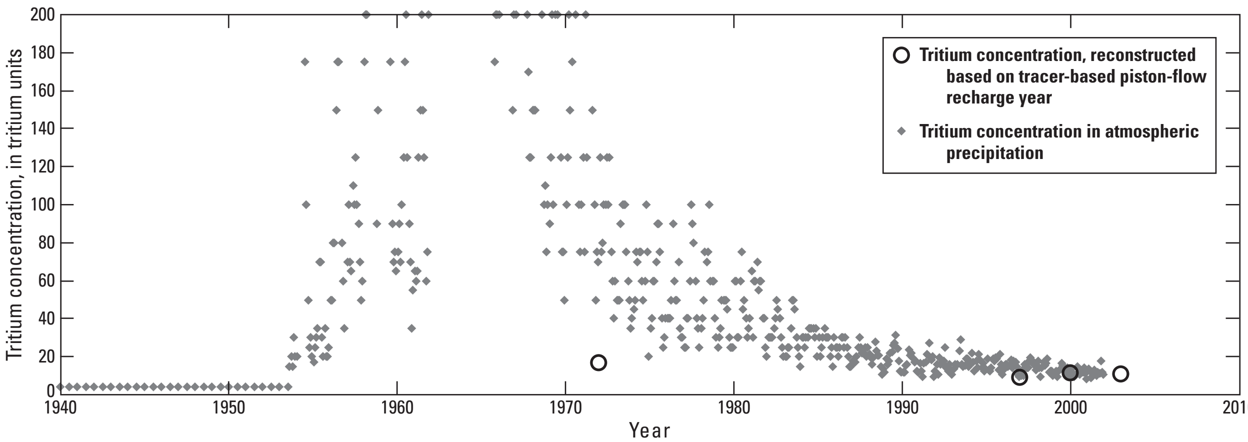


Figure G5. Reconstructed tritium concentrations (reconstruction based on $^3H/^3He$) and tritium in atmospheric precipitation, LUSRC1 and OTHER networks, CONN Study Unit.

CONN LUSRC1 and OTHER (SF_6)

Samples from 10 sites in the CONN Study Unit were collected during 2003 for SF_6 (networks and, in parentheses, number of sites):

LUSRC1 (7)
OTHER (3)
See table G7.

The aquifer is composed of glacial sediments.

Major dissolved-gas data were available for 5 of the 10 sites. Of these 5 sites, 3 were oxic and 2 were suboxic.

For the 3 oxic sites with major dissolved-gas data, the major dissolved-gas data were used to infer recharge temperature and excess air. However, these 3 samples were insufficient to characterize typical excess air concentrations for the other sites. Thus, for the 2 suboxic sites with major dissolved-gas data, a typical excess air concentration of 2 cc(STP)/Kg was used to constrain the calculations for recharge temperature.

For the 5 sites without major dissolved-gas data, the median major-dissolved-gas-inferred recharge temperature from the 5 sites that had major dissolved-gas data was used, and a typical excess air concentration of 2 cc(STP)/Kg was used.

Several of the sites yielded SF_6 atmospheric mixing ratios that were slightly elevated above the atmospheric mixing ratio for the dates of sampling. Although SF_6 contamination from natural or anthropogenic sources is not uncommon, it is possible that bias in estimated recharge temperatures or estimated excess air concentrations contributed to elevated estimates of SF_6 atmospheric mixing ratios. Several alternative approaches were evaluated, but no reasonable and defensible approaches for resolving these interpretations were identified. However, the problem may have sources other than assumptions about recharge temperatures or excess air. SF_6 concentrations in samples from the monitoring wells (n=7) exhibited greater variability among replicates than is typically seen in SF_6 data. Analyzing serial replicates (2 to 4 samples per site), the ratio of the highest SF_6 concentration to the lowest SF_6 concentration was 141, 152, 157, and 168 percent for four of these sets of replicates. Such variability, possibly indicating problems with well purging, sample collection, or sample analysis, complicates data interpretation and may partially explain the elevated atmospheric mixing ratios in some samples.

Advantages associated with these samples:

- Major dissolved-gas data were available for 5 of the 10 sites.
- Short open intervals: of the 9 wells for which well construction data were available, the median saturated open interval was 4.35 feet.
- Of the 9 wells for which well construction data were available, the median penetration of center of open interval into water table was 5.85 feet (sampling close to the water table, potentially minimizing mixing).
- Mostly monitoring wells (7 of the 10), therefore generally low pumping stress.

Disadvantages associated with these samples:

- Possible natural SF_6 present in some of these samples.

Depth to water (can affect tracer transport to water table):

- Median: 9.32 feet
- Mean: 19.18 feet
- Minimum: 4.00 feet
- Maximum: 60.95 feet

Brief analysis:

Many samples contained contaminant levels of SF_6. Only three samples were datable. The age gradient, although represented by only three sites, is shown in figure G6.

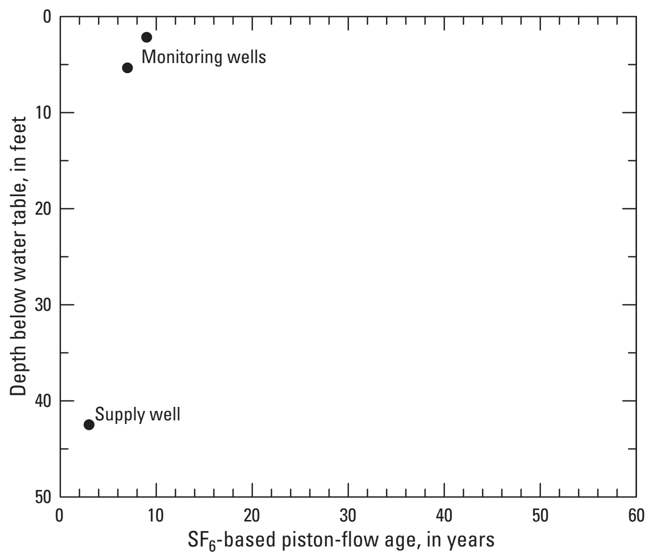


Figure G6. SF_6-based age gradient for dated sites from the LUSRC1 and OTHER networks in the CONN Study Unit.

The three data points yield an age inverse gradient, in which tracer-based piston-flow ages becoming younger with increasing depth. It is possible that for the deeper sample, which is a supply well, pumping stress draws young water to greater depth than would otherwise be found at those depths. Alternatively, the inverse age gradient could indicate the presence of a natural source of SF_6 in the aquifer, such that longer times of travel allow for greater concentrations of SF_6. Certainly, conclusions based on so few data points cannot be drawn, but the age gradient does suggest that these tracer based piston-flow ages be treated with caution.

The deepest of the three sites shown in the figure, above, also was dated with $^3H/^3He$ (summarized separately). The $^3H/^3He$-based piston-flow age was 6 years, compared with the SF_6-based piston-flow age of 3 years. These results could be consistent with a young bias in the SF_6-based piston-flow ages. The $^3H/^3He$-based piston-flow age for this well probably is more reliable than the SF_6-based piston-flow age.

One of the two monitoring wells in the figure above (the deeper of the two) also was dated with $^3H/^3He$, but on a different sampling date. The $^3H/^3He$-based piston-flow age for this well was 2 years, and the SF_6-based piston-flow age was 7 years. The fact that the SF_6-based piston-flow age was greater than the $^3H/^3He$-based piston-flow age is difficult to reconcile with other evidence suggesting a possible young bias in SF_6-based piston-flow ages, but the fact that different tracers were collected on different sampling dates adds uncertainties to any such analysis. Note that the chemistry was very different on the two sampling dates (e.g. nitrite-plus nitrate 0.13 mg N/L versus 8.6 mg N/L), suggesting that the water sampled on the different dates may have been different. If one tracer-based piston-flow age is to be chosen to represent this site, the $^3H/^3He$-based piston-flow age probably is more reliable than the SF_6-based piston-flow age.

The reconstructed ^3H plot (^3H data were available for only one site) is shown in figure G7.

This single reconstructed ^3H sample plots below the ^3H input function. A sample that plots below the ^3H input function can be an indication of a sample mixture. Mixing of different groundwater components would be consistent with particle-tracking simulations for this supply well (Starn and Brown, 2007). However, the combination of the low reconstructed ^3H concentration and the SF_6-based piston-flow recharge date of 2000 are not easily explained by mixing scenarios, especially if one accepts the distribution of simulated times-of-travel (about 0 to about 20 years; Starn and Brown, 2007). A more reasonable explanation for the observed pattern could be bias in the SF_6-based piston-flow age (for example, young bias due to the presence of natural SF_6 sources in the aquifer), and possibly analytical bias in the SF_6 or ^3H determinations.

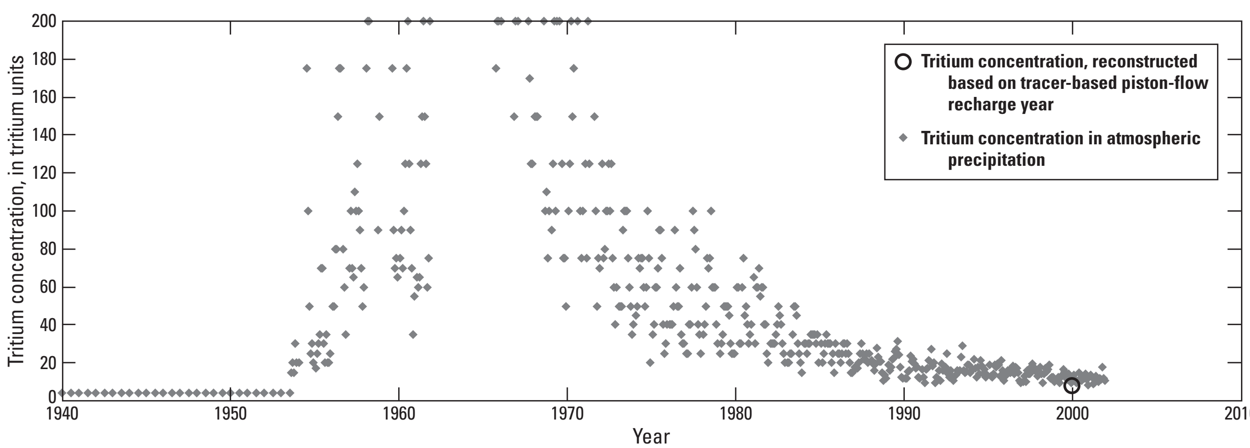


Figure G7. Reconstructed tritium concentrations (reconstruction based on SF_6) and tritium in atmospheric precipitation, LUSRC1 and OTHER networks, CONN Study Unit.

DELR SUS1

Samples from 18 sites in the DELR Study Unit were collected during 1999 for $^{3}H/^{3}He$ (network and, in parentheses, number of sites):

SUS1 (18)
See table G8.

The aquifer is a fractured rock aquifer.

The standard procedure for $^{3}H/^{3}He$ dating that was documented in the body of the report was used for these sites. Of the 18 sites, 16 were datable (8 sites did not require a correction for terrigenic He, and 8 sites did require a correction for terrigenic He). The other 2 sites exhibited evidence of gas fractionation

Advantages associated with these samples:
These samples exhibited few problems with fractionation, with low-^{3}H samples beyond the dating range, or with high He concentrations.

Disadvantages associated with these samples:
These wells have long saturated open intervals.

Brief analysis:
The age gradient for these sites is shown in figure G8.

The age gradient for this network has a great deal of scatter. The deepest site (400808075210401) does have the oldest tracer-based piston-flow age. However, of the 16 datable wells, this site (400808075210401) was the only site that was not a domestic well (it was a commercial well with a 408-foot open interval), and it is possible that the depth of the center of the open interval may be biased deep relative to the location of the water-bearing interval. If this one sample is removed from the age gradient plot, the age gradient for the remaining sites (fig. G9) shows slightly improved structure. However, the youngest samples are in relatively deep locations (see plot below). One of these samples had high ΔHe and ΔNe and a low sample weight indicating that there may have been air contamination and thus problems with the tracer interpretation, however, the other two samples are not affected by this problem. The scatter in the age gradient is consistent with mixing occurring due to the long well screens in the sampled wells.

The reconstructed ^{3}H plot is shown in figure G10.

Overall, these samples plot towards the lower part of, if not below, the ^{3}H input function, possibly indicating the effects of mixing. Alternatively, differences between the assumed $^{3}He/^{4}He$ ratio of terrigenic He and the actual $^{3}He/^{4}He$ ratio of terrigenic He in the study area (as discussed in the body of the report) may have introduced bias in the estimation of tracer-based piston-flow ages.

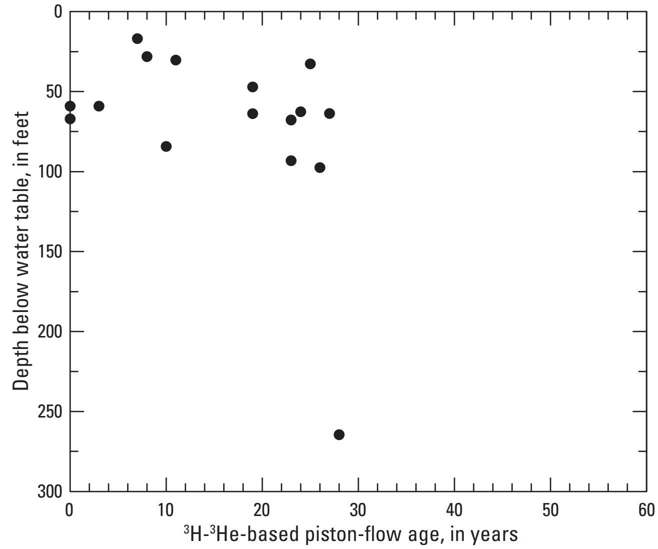


Figure G8. Age gradient for dated sites from the SUS1 network in the DELR Study Unit.

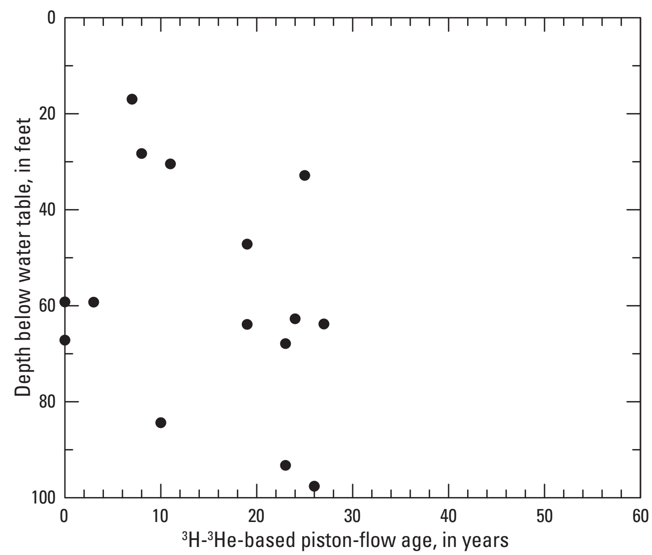


Figure G9. Age gradient for dated sites from the SUS1 network in the DELR Study Unit, with the one deep sample removed.

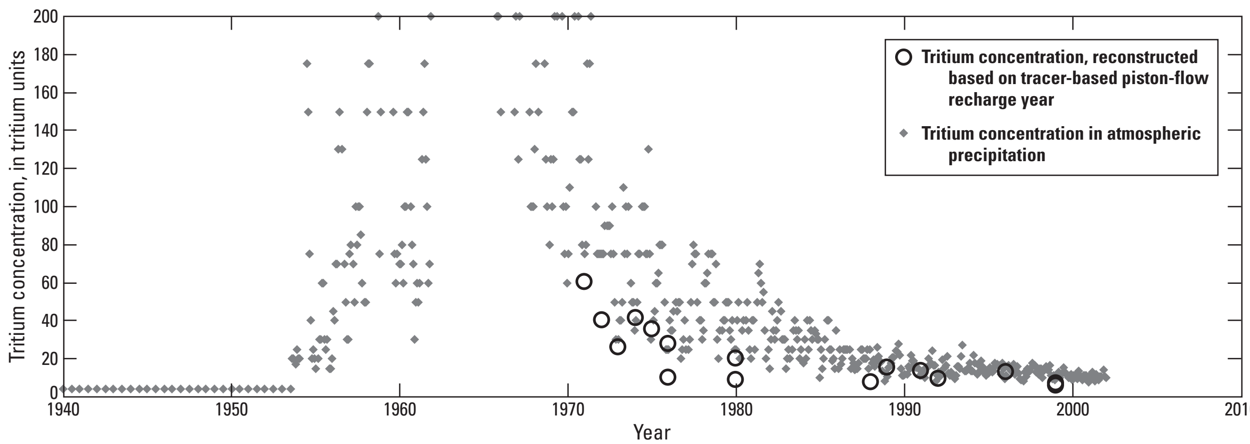


Figure G10. Reconstructed tritium concentrations and tritium in atmospheric precipitation, SUS1 network, DELR Study Unit.

EIWA OTHER

Samples from 27 sites in the EIWA Study Unit were collected during 1998 for CFCs (network and, in parentheses, number of sites):

OTHER (27) (1 site has dual designations as both OTHER and REFCR1)
See table G9.

The aquifer is composed of glacial sediments.

Recharge elevation assumed equal to the elevation of the water table. For analysis of major dissolved-gas data, only 3 sites were considered oxic (but 1 site had obvious analytical problems and was not used to infer recharge temperature or excess air); major dissolved-gas data were used to constrain recharge temperature and excess air for these two usable oxic sites. For the other 21 sites at which major dissolved-gas data were available, excess air was assumed to be 2 cc(STP)/Kg and major dissolved-gas data were used to infer recharge temperatures. For the 3 sites at which no major dissolved-gas data were available, and for the 1 site at which major dissolved-gas data were problematic, excess air was assumed to be 2 cc(STP)/Kg and recharge temperature was assumed to be equal to the mean annual air temperature + 1°C.

Advantages associated with these samples:

Major dissolved-gas data were available for 24 of the 27 sites.

These were monitoring wells, with generally low pumping stress and short well screens.

Disadvantages associated with these samples:

No tracers other than CFCs.

Generally highly reducing conditions. Only 3 sites contained greater than 1 mg O_2/L (field O_2). Of the 24 sites with major dissolved-gas data, 16 contained detectable CH_4.

Depth to water (can affect tracer transport to water table):

Median: 4.35 feet
Mean: 4.68 feet
Minimum: 2.35 feet
Maximum: 16.00 feet

Brief analysis:

Only three sites were considered datable. To be consistent with other network presentations, the age gradient is shown (fig. G11). However, the small number of data points and the lack of substantial vertical spread in those data limit the value of the age gradient figure.

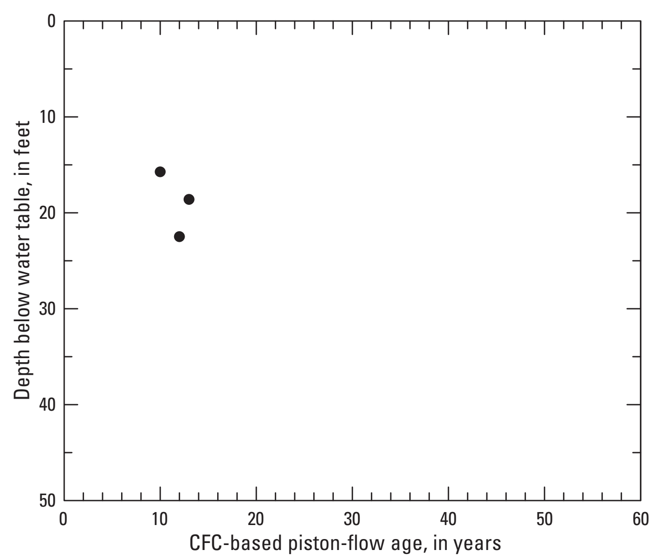


Figure G11. Age gradient for dated sites from the OTHER network in the EIWA Study Unit.

EIWA LUSCR1

Samples from 29 sites in the EIWA Study Unit were collected during 1999 for CFCs (network and, in parentheses, number of sites):

LUSCR1 (29)
See table G10.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. There were three exceptions to this procedure. (1) Site 414208092312601 had anomalous major dissolved-gas data and yielded negative excess air; thus, the median recharge temperature and median excess air estimates from the usable oxic sites were used at this site. (2) One site did not have major dissolved-gas data, so the median recharge temperature and median excess air estimates from the usable oxic sites were used. (3) Site 422629092345001, considered oxic, had a major-dissolved-gas-inferred recharge temperature of 32.8 °C and an inferred excess air of 8.4 cc(STP)/Kg. The apparently elevated inferred recharge temperature and excess air could reflect unrecognized denitrification, but an assumption of denitrification leads to a major-dissolved-gas-inferred recharge temperature of 21.4 °C, still greater than the major-dissolved-gas-inferred recharge temperatures of all the other sites in this network. Additionally, there was only one major dissolved-gas sample for this site, thus the major dissolved-gas data were not reproduced. The site-specific major dissolved-gas data were not used for this site, and the median major-dissolved-gas-inferred recharge temperature and excess air from the usable oxic sites were used for this site.

Advantages associated with these samples:

- Major dissolved-gas data were available for 28 of the 29 sites.
- The saturated open intervals were ≤5 feet.
- These wells were shallow. The median penetration of the center of the open interval into the water table was 9.90 feet (sampling close to the water table, potentially minimizing mixing).
- These were monitoring wells, with low pumping stress.
- Most sites contained $O_2 \geq 1$ mg/L (median field O_2 = 3.46 mg/L).

Disadvantages associated with these samples:

- No tracers other than CFCs.
- CH_4 was detected at 7 of the 28 sites.
- Many sites contained contaminant levels of CFCs.

Depth to water (can affect tracer transport to water table):

- Median: 6.35 feet
- Mean: 6.80 feet
- Minimum: 1.15 feet
- Maximum: 13.60 feet

Brief analysis:
The age gradient for datable sites in this network (fig. G12) shows little structure. The age gradient could reflect hydrologic variability. However, the poorly defined age gradient, in combination with the other limitations of the results from this network (for example, extensive contamination) suggests that these tracer-based piston-flow ages have substantial uncertainty.

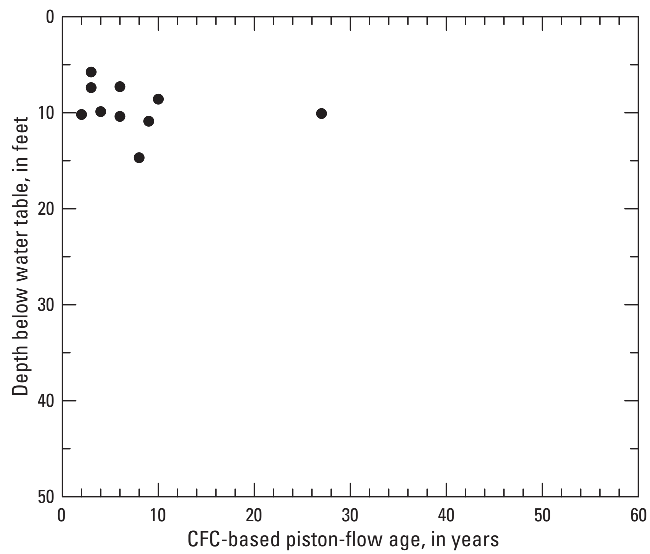


Figure G12. Age gradient for dated sites from the LUSCR1 network in the EIWA Study Unit.

LERI LUSRC1

Samples from five sites in the LERI Study Unit were collected during 1996 for $^3H/^3He$ (network and, in parentheses, number of sites):

LUSRC1 (5)
See table G11.

The aquifer is composed of glacial sediments.

The standard procedure for $^3H/^3He$ dating that was documented in the body of the report was used for these sites. Four sites were datable (1 site did not require a correction for terrigenic He; 3 sites did require a correction for terrigenic He). One site exhibited evidence of gas fractionation and thus was not datable.

Brief analysis:
The age gradient for this network is shown in figure G13. With only 4 data points, few conclusions can be drawn. However, the pattern of generally increasing tracer-based piston-flow age with increasing depth below the water table provides some support for these interpretations.

The reconstructed ^3H plot is shown in figure G14.

Three samples (2 attributed to the 1990s, 1 to the 1970s) have tracer-based piston-flow ages and reconstructed $^3H + {}^3He$ values that are consistent with ^3H inputs to the study area. One sample (1960s) plots lower than the ^3H input function would indicate for piston flow conditions. This sample had high terrigenic He and probably contains a component of pre-bomb water.

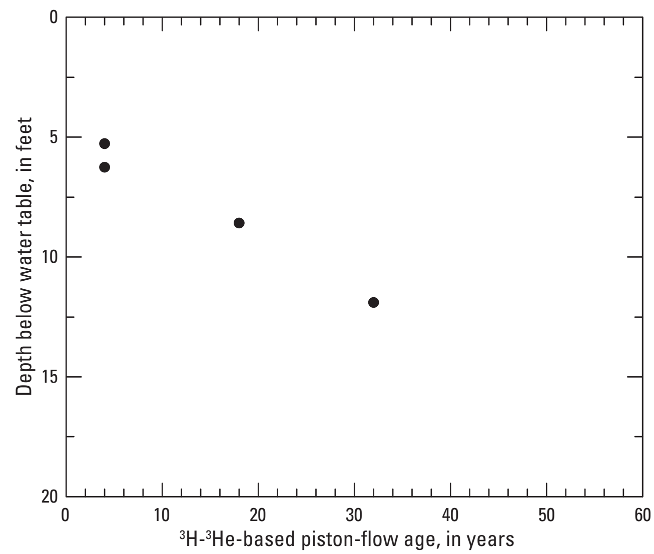


Figure G13. Age gradient for dated sites from the LUSRC1 network in the LERI Study Unit.

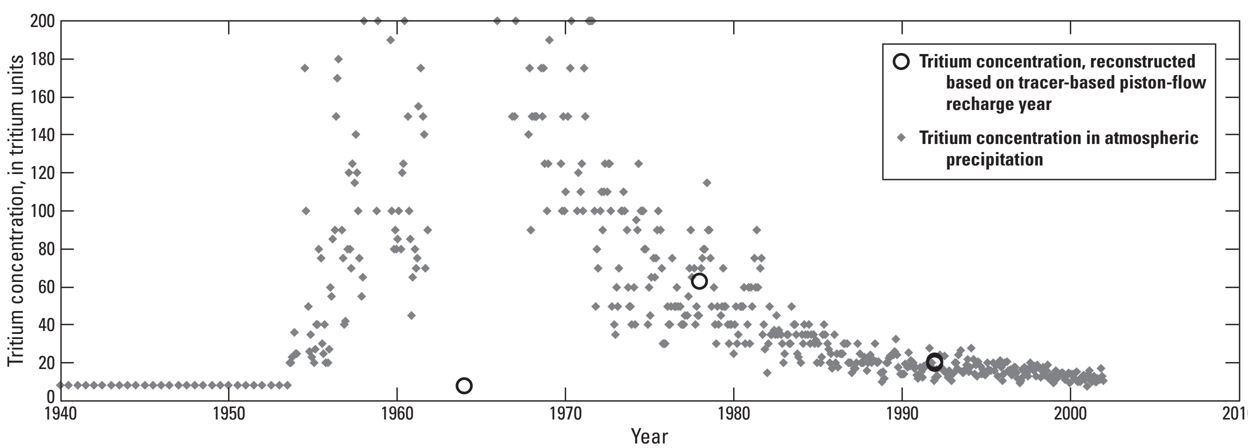


Figure G14. Reconstructed tritium concentrations and tritium in atmospheric precipitation, LUSRC1 network, LERI Study Unit.

LIRB LUSRC1

Samples from 20 sites in the LIRB Study Unit were collected during 2005 for SF_6 (network and, in parentheses, number of sites):

LUSRC1 (20)
See table G12.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that excess air concentrations were 2 cc(STP)/Kg. Although 20 sites were sampled, 7 sites contained contaminant levels of SF_6, and 5 sites were not datable because both of the bottles for each of these sites were cracked. Thus, only 8 sites were datable.

Advantages associated with these samples:

- Short open intervals: median saturated open interval 5.00 feet.
- Median penetration of the center of the open interval into water table was 14.70 feet (sampling close to the water table, thus potentially minimizing mixing).
- These were monitoring wells, associated with generally low pumping stress.

Disadvantages associated with these samples:

- No tracers other than SF_6.
- No major dissolved-gas data.

Depth to water (can affect tracer transport to water table):

- Median: 11.71 feet
- Mean: 12.35 feet
- Minimum: 2.37 feet
- Maximum: 31.13 feet

Brief analysis:
The age gradient for these sites is shown in figure G15.

The age gradient has a great deal of scatter.

The site closest to the water table has a tracer-based piton-flow age of 23 years. This well was screened across the top 2.98 feet of the water table (the figure shows the location of the center of the saturated part of the open interval, and thus shows the point at 1.49 feet). It is possible that the relatively old tracer-based piston-flow age for the sample from this well could be related to the lithology of these sites. This 1 site was screened in silt; the other 7 wells were screened in sand.

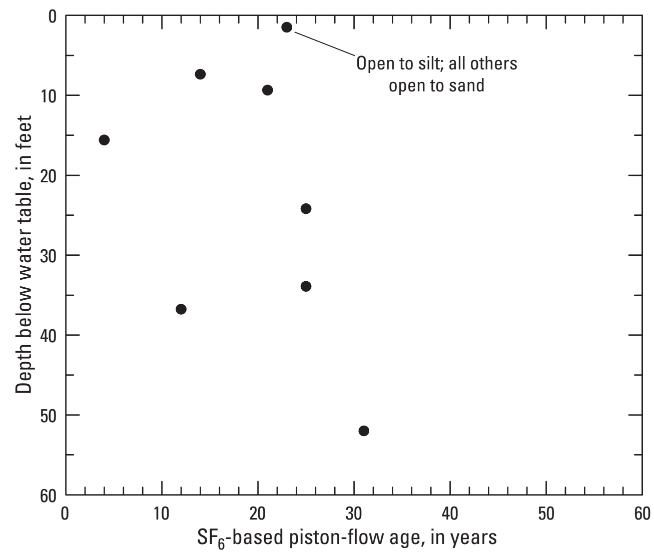


Figure G15. Age gradient for dated sites from the LUSRC1 network in the LIRB Study Unit.

NECB SUS1 and SUS2

Samples from 57 sites in SUS1 and SUS2 networks in the NECB Study Unit were collected during 1999 and 2000 for CFCs.

See table G13.

The aquifer is composed of fractured rock.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites.

One site did not have major dissolved-gas data, so the median recharge temperature and median excess air estimates from the oxic sites were used.

One site (435858070475901) was anomalous. The reducing conditions at this site suggested a need to allow for potential denitrification. However, this resulted in negative recharge temperatures. If denitrification was not allowed, then excess air was greater than typically observed: 7.87 and 7.73 cc(STP)/Kg in the duplicate samples. Given these uncertainties, the median recharge temperature and median excess air estimates from oxic sites were used for this site.

Advantages associated with these samples:

- Major dissolved-gas data were available for 56 of the 57 sites.

Disadvantages associated with these samples:

- These samples were primarily suboxic. The median field O_2 was 0.40 mg/L.
- Long open intervals (median saturated open interval 214 feet).
- No tracers other than CFCs.
- Some of the CFC data were problematic, with "ERR" reported in a concentration field (sometimes accompanied by a note about "peak interference").

CFC concentrations were more variable among samples than is usually seen, perhaps reflecting the nature of fracture flow to long-screened wells or perhaps due to purging problems.

Depth to water (can affect tracer transport to water table):
- Median: 20.80 feet
- Mean: 21.86 feet
- Minimum: 0.00 feet
- Maximum: 81.85 feet

Brief analysis:
The age gradient for these sites is shown in figure G16.

Scatter in these data reflect, in part, the wide geographic diversity of these eight sites (large parts of NH and ME) and the generally greater hydrologic heterogeneity that is found in fractured rocks than is found in sediments. The general pattern of increasing tracer-based piston-flow age with increasing depth below the water table, albeit with scatter, provides some support for the few datable sites.

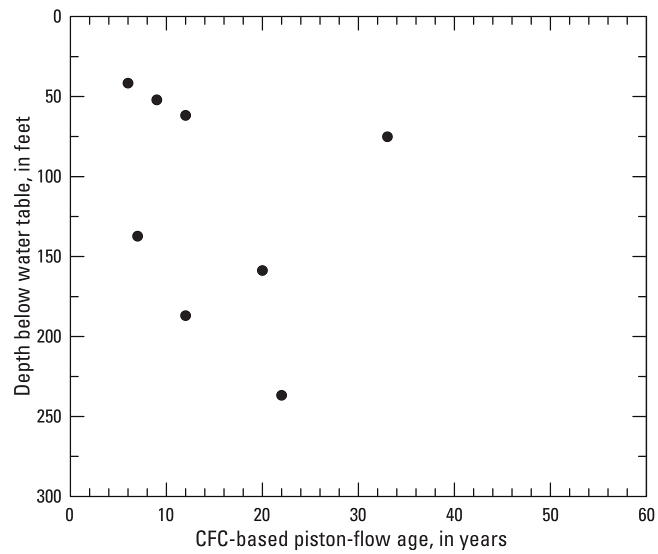


Figure G16. Age gradient for dated sites from the SUS1 and SUS2 networks in the NECB Study Unit.

NECB SUS3

Samples from 11 sites in the SUS3 network in the NECB Study Unit were collected during 2001 for CFCs.

See table G14.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites.

Advantages associated with these samples:
- Major dissolved-gas data were available for all 11 sites.

Disadvantages associated with these samples:
- Supply wells, possibly with large pumping rates and thus an increased potential for groundwater mixing.
- Lots of CFC contamination present.
- Although ^3H data were available for 3 sites, none of these 3 sites were datable.

Depth to water (can affect tracer transport to water table):
- Median: 19.60 feet
- Mean: 21.04 feet
- Minimum: 14.30 feet
- Maximum: 36.50 feet

Brief analysis:
Tracer-based piston-flow age was plotted against depth below water table (fig. G17). Only 3 sites were datable, and 1 of these did not have well construction data. The 2 data points are insufficient to draw conclusions about the age gradient for this network.

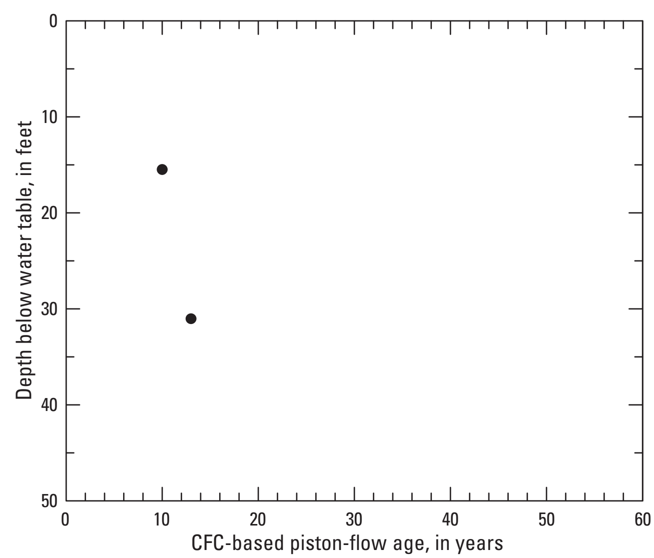


Figure G17. Age gradient for dated sites from the SUS3 network in the NECB Study Unit.

NECB LUSRC1

Samples from 29 sites in the LUSRC1 network in the NECB Study Unit were collected during 1999 for CFCs.

See table G15.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites.

At three sites (420249071035801, 420607070515501, 423527071120601), major dissolved-gas data exhibited evidence of degassing. Argon concentrations were unusually low (<0.6 mg/L), CH_4 concentrations were elevated (up to 9.3 mg/L), and inferred recharge temperatures were high (>20 °C). For these sites, the median recharge temperature and excess air from the oxic sites were used.

Advantages associated with these samples:

Major dissolved-gas data were available for all 29 sites.

These wells were monitoring wells, and as such, subject to generally low pumping stress.

Disadvantages associated with these samples:

Multiple tracers were not collected.

Depth to water (can affect tracer transport to water table):

Median: 12.45 feet
Mean: 14.32 feet
Minimum: 2.00 feet
Maximum: 31.87 feet

Brief analysis:

Tracer-based piston-flow age was plotted against depth below water table in figure G18. The narrow range of depths represented by these samples limits this analysis.

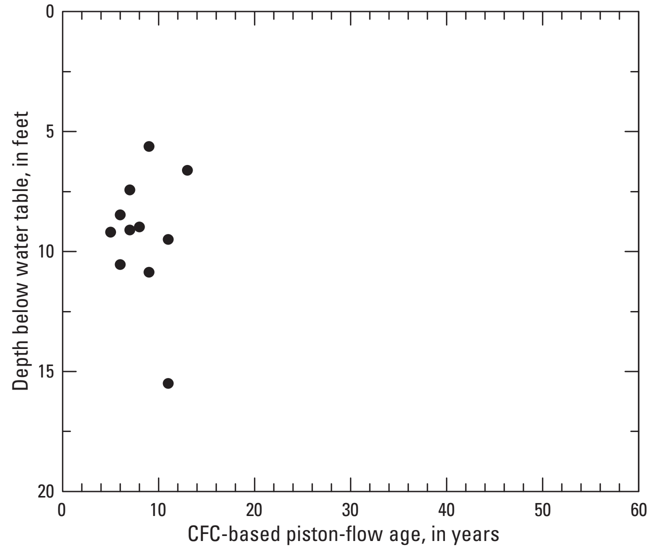


Figure G18. Age gradient for dated sites from the LUSRC1 network in the NECB Study Unit.

NROK SUS2

Samples from seven sites in the NROK Study Unit were collected during 2001 for SF_6 (network and, in parentheses, number of sites):

SUS2 (7)
See table G16.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, and to estimate recharge temperature and excess air based upon major dissolved-gas data. Exceptions were made for two sites: 465741114110601 (#6) and 465838114074501 (#17). The major dissolved-gas data were problematic for these two sites. At site #6, the major-dissolved-gas-inferred recharge temperature (2.0 °C) and major-dissolved-gas-inferred excess air (8.4 cc(STP)/L) were anomalous. At site #17, the major-dissolved-gas-inferred recharge temperature (-1.4 °C) was anomalous. These anomalous results suggest the existence of sampling problems, and the median major-dissolved-gas-inferred recharge temperature and major-dissolved-gas-inferred excess air values from the other sites in the network (all of which were oxic) were used at these 2 sites.

Advantages associated with these samples:

Major dissolved-gas data were available for all 7 sites.

Mostly wells had short open intervals. Of the 7 sites, 5 were open-bottom wells (saturated open interval essentially zero for these 5 sites).

Disadvantages associated with these samples:

The median penetration of the center of the open interval into water table was 50.07 feet; at these depths, the magnitude of hydrodynamic dispersion tends to be greater than for wells screened near the water table.

Depth to water (can affect tracer transport to water table):

Median: 42.50 feet
Mean: 45.03 feet
Minimum: 12.07 feet
Maximum: 72.93 feet

Brief analysis:

The age gradient for these sites is shown in figure G19.

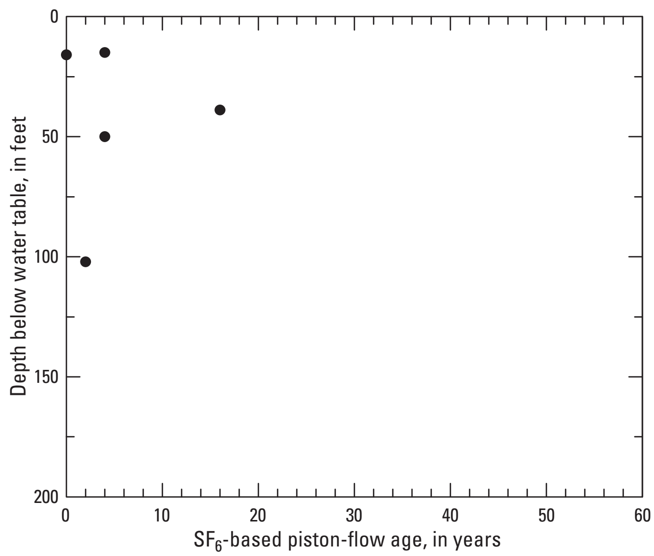


Figure G19. Age gradient for dated sites from the SUS2 network in the NROK Study Unit.

The steep age gradient for these wells might reflect strong vertical gradients. Alternatively, the steep age gradient could be an artifact of the tracers (for example, if some of the SF_6 is from natural sources, the tracer-based piston-flow ages would be biased young, steepening the age gradient).

Six of the 7 sites had ^3H data, and of these 6 sites, 5 were datable. The reconstructed ^3H plot is shown in figure G20.

For the most part, the tracer-based piston-flow ages are consistent with the ^3H input function. One exception is the youngest sample, which plots below the majority of the ^3H values and this could indicate a problem with either the SF_6 or the ^3H data for this site.

NVBR LUSRC1 LUSUR2 and SUS2

Samples from 15 sites in the NVBR Study Unit were collected during 2002 and 2003 for CFCs (networks and, in parentheses, number of sites):

LUSRC1 (9)
LUSUR2 (1)
SUS2 (5)
See table G17.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that excess air concentrations were 2 cc(STP)/Kg.

There is uncertainty in these estimates of recharge temperature and recharge elevation, in part because recharge may largely be from mountain-front and mountain-block recharge. To evaluate the effect of variable recharge temperature and recharge elevation on these tracer-based piston-flow ages, a comparison of results was made using (1) recharge temperatures based on mean annual air temperature + 1°C and recharge elevations based on static water levels, and (2) cooler recharge temperatures and greater recharge elevations based on Study Unit guidance. This comparison showed no substantial differences for these particular data, largely because all of the dated sites had tracer-based piston-flow recharge dates prior to the 1980s, a time when atmospheric CFC concentrations were increasing rapidly and thus a time period where sensitivity to recharge temperature and recharge elevation was small. Thus, the standard approach of using mean annual air temperature + 1°C and static water level elevations was used (consistent with the approach used with most other networks lacking major dissolved-gas data).

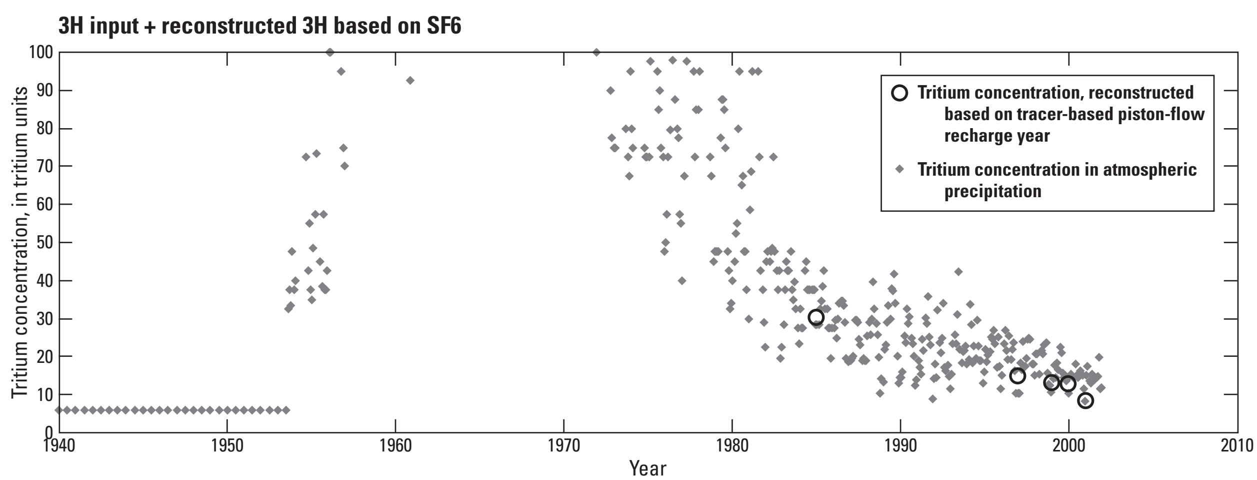


Figure G20. Reconstructed tritium concentrations and tritium in atmospheric precipitation, SUS2 network, NROK Study Unit.

Advantages associated with these samples:
- Primarily monitoring wells, so generally low pumping stress and short well screens.
- Primarily oxic conditions (DWH redox classification for 13 of the 15 sites was "O_2").

Disadvantages associated with these samples:
- No major dissolved-gas data available.

Depth to water (can affect tracer transport to water table):
- Median: 68.77 feet
- Mean: 73.80 feet
- Minimum: 4.30 feet
- Maximum: 298.40 feet

Brief analysis:
The age gradient for these sites is shown in figure G21. One site did not contain a static water level measurement, and thus is not shown. The age gradient appears to be offset towards older tracer-based piston-flow ages. Such offset of the age gradient sometimes can indicate degradation or can indicate the presence of low CFC concentrations in unsaturated zone air near the water table. These sites are O_2-reducing (O_2 present), contraindicating CFC degradation. Sites with thicker unsaturated zones do not have greater offset in the age gradient than do sites with thinner unsaturated zone. It is possible that the age gradient reflects mixing of old (pre-CFC) mixtures with components of modern water.

The reconstructed ^3H plot for the 6 datable sites is shown in figure G22.

For this figure, some of the ^3H samples were collected on different sampling dates than was the case for the CFC samples associated with the ^3H samples, but all ^3H samples were collected in the same calendar year as were the CFC samples. Thus, the overall patterns demonstrated in this figure can still be used to evaluate the CFC interpretations. The reconstructed ^3H plot indicates that these samples probably are mixtures of pre- and post-bomb water. The calculated tracer-based piston-flow ages might have meaning in a relative sense (greater tracer-based piston-flow ages containing relatively less post-bomb water), but the calculated tracer-based piston-flow ages probably have little meaning in an absolute sense (that is, the samples probably do not contain water of piston-flow origin and the tracer-based piston-flow ages probably do not represent the mean age of the samples).

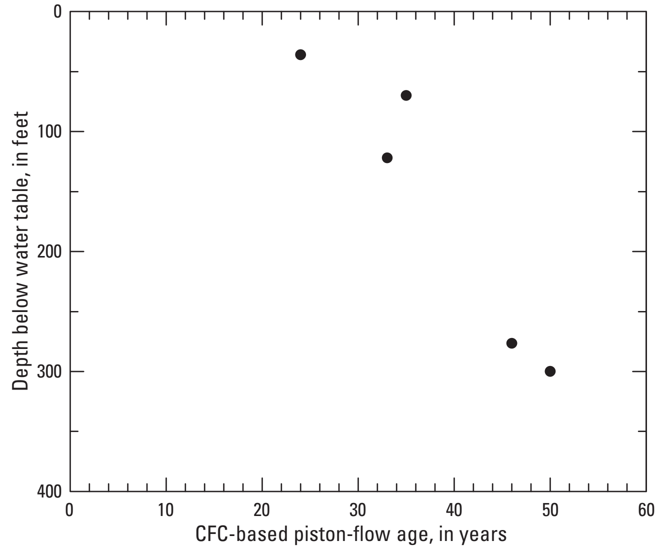


Figure G21. Age gradient for dated sites from the LUSRC1, LUSUR2 and SUS2 networks in the NVBR Study Unit.

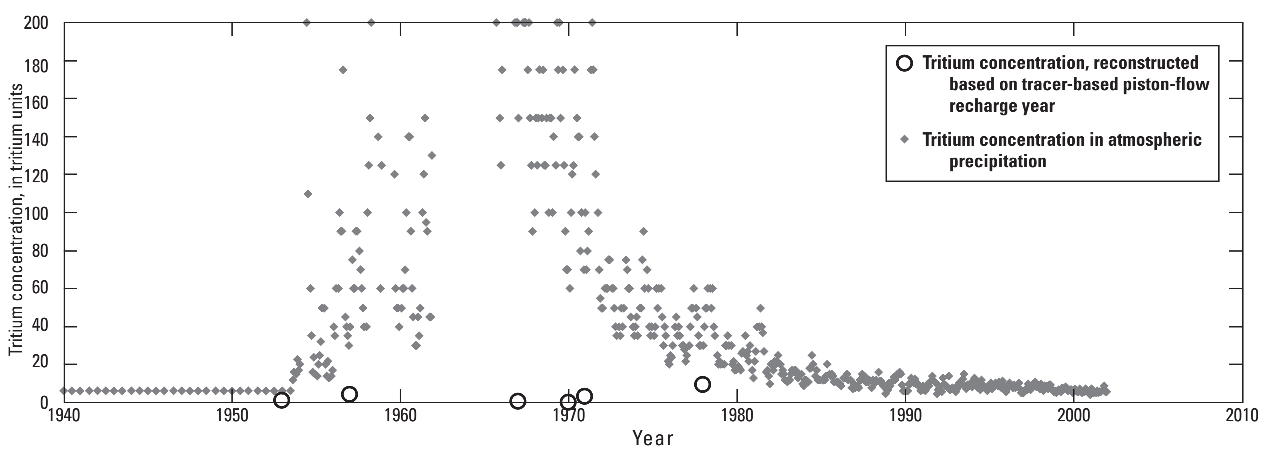


Figure G22. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSRC1, LUSUR2 and SUS2 networks, NVBR Study Unit.

PODL LUSRC1 and REFFO2

Samples from 8 sites in the PODL Study Unit were collected during 2003 for SF_6 (networks and, in parentheses, number of sites):

LUSRC1 (7)
REFFO2 (1)
See table G18.

The aquifer is composed of fractured rock.

Recharge elevation was assumed equal to the elevation of the water table. Recharge temperature and excess air at the one oxic site was based upon major dissolved-gas data. With only one oxic site in these networks, the approach of using the median excess air from the oxic sites to constrain suboxic sites was not feasible. The approach used for recharge temperatures and excess air at the seven suboxic sites was to constrain the major dissolved-gas analysis with an assumption that excess air concentration in this fractured rock aquifer was 3 cc(STP)/Kg. The value of 3 cc(STP)/Kg was similar to the (limited) results from other fractured rock aquifers in this project. In constraining excess air to 3 cc(STP)/Kg, it was assumed that N_2 gas in excess of air-water solubility plus that associated with 3 cc(STP)/Kg of excess air was derived from denitrification. However, for sites that initially contained less than 3 cc(STP)/ Kg of excess air, denitrification was held to zero and excess air was not adjusted.

In this analysis, with excess air constrained to 3 cc(STP)/Kg, there were 4 sites without an excess air adjustment (1 oxic and 3 suboxic sites), and 4 sites that did have an excess air adjustment (all 4 being suboxic). The median inferred recharge temperature for the 4 sites that did not have an excess air adjustment was 13.8 °C, similar to the median inferred recharge temperature of 12.6 °C for the 4 sites that did have an excess air adjustment. This analysis leads to inferred denitrification at 4 sites, at concentrations up to 2.2 mg N_2/Kg. All 4 sites with inferred denitrification also contained detectable CH_4, whereas the other 4 sites (no inferred denitrification) contained no detectable CH_4. The similarity between inferred recharge temperatures among different sites and the association of denitrification with more reduced conditions supports the assumption of 3 cc(STP)/Kg of excess air.

Advantages associated with these samples:

- Major dissolved-gas data were available for all 8 sites.
- These were monitoring wells, thus, associated with low pumping stress.

Disadvantages associated with these samples:

- No tracers other than SF_6.
- Fractured rock aquifers often have increased potential for mixing.
- Although these wells were monitoring wells, they were not as close to the water table as many NAWQA monitoring wells are; the median penetration below water table was 31.22 feet, probably reflecting the challenges of obtaining water from a fractured rock aquifer.

Depth to water (can affect tracer transport to water table):

Median: 15.91 feet
Mean: 14.70 feet
Minimum: 0.05 feet
Maximum: 29.55 feet

Brief analysis:

The age gradient for these sites is shown in figure G23.

Four of the eight sites were undatable due to the presence of SF_6 contamination. The remaining four data points provide very limited information about the age gradient for these networks. There is some structure to the age gradient, in which tracer-based piston-flow age tends to increase with increasing depth.

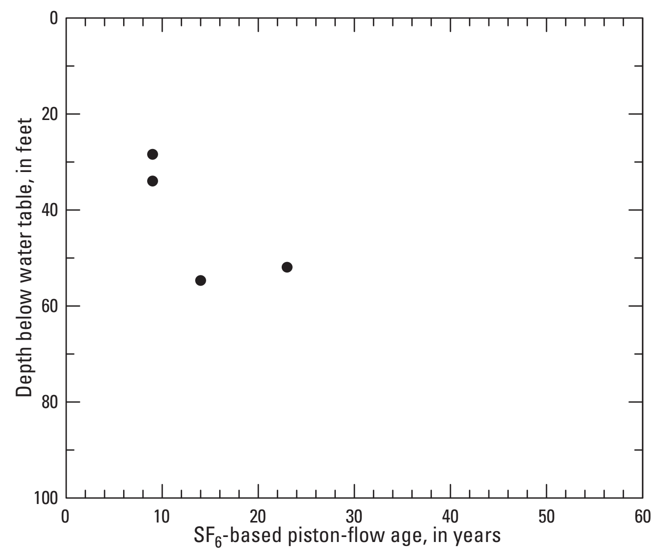


Figure G23. Age gradient for dated sites from the LUSRC1 and REFFO2 networks in the PODL Study Unit.

PODL LUSAG1 and REFFO1

Samples from 13 sites in the PODL Study Unit were collected during 2000 and 2002 for SF_6 (networks and, in parentheses, number of sites):

LUSAG1 (12)
REFFO1 (1)
See table G19.

This is a karst aquifer.

Recharge elevation was assumed equal to the elevation of the water table. Recharge temperature and excess air at the oxic sites based upon major dissolved-gas data. Recharge temperature and excess air at the 1 suboxic site was constrained based upon median excess air at the 12 oxic sites.

At one site (394828077545701), the replicate SF_6-samples yielded SF_6 concentrations of 306 fg/kg and 213 fg/kg (tracer-based piston-flow ages of 0.9 and 7.4 years). The large differences between replicate samples are unusual. It is possible that the sample with the larger SF_6 concentration had a leak or some sample contamination. Certainly, a young tracer-based piston-flow age of 0.9 years seems less likely than a tracer-based piston-flow age of 7.4 years, considering the center of the open interval was 93 feet below the water table, and thus the older tracer-based piston-flow age was chosen.

Advantages associated with these samples:
- Major dissolved-gas data were available for all 13 sites.

Disadvantages associated with these samples:
- Karst aquifer (increased potential for mixing; increased potential for air-water contact within caverns in aquifer).
- Median penetration of center of open interval into water table was 64.10 feet (for the 10 wells that had well construction data); these samples are, for the most part, not located near the water table, increasing the potential for mixing.
- Supply wells with long open intervals (median saturated open interval, for the 10 sites with well construction data: 91.38 feet).
- No tracers other than SF_6.

Depth to water (can affect tracer transport to water table):
- Median: 49.99 feet
- Mean: 63.19 feet
- Minimum: 23.66 feet
- Maximum: 134.40 feet

Brief analysis:
The age gradient for these sites is shown in figure G24.

The age gradient for these wells exhibits scatter that is typical of wells that are dispersed over a large geographic area. However, there is some structure to the relation, indicating a general increase in SF_6-based piston-flow age with depth, and the SF_6-based piston-flow age of 2 years at the shallowest site provides some support for the interpretations.

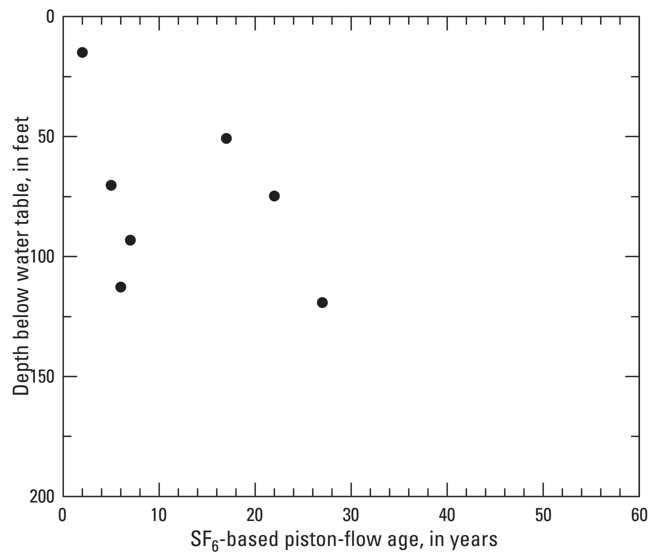


Figure G24. Age gradient for dated sites from the LUSAG1 and REFFO1 networks in the PODL Study Unit.

PUGT LUSCR1 and REFCR1

Samples from 23 sites in the PUGT Study Unit were collected during 2006 and 2007 for SF_6 (networks and, in parentheses, number of sites):

LUSCR1 (22)
REFCR1 (1)
See table G20.

The aquifer is composed of sediments.

Recharge elevation was assumed equal to the elevation of the water table; recharge temperature and excess air at oxic sites were based upon major dissolved-gas data; and recharge temperature and excess air at suboxic sites were constrained based upon the median excess air at the oxic sites. Two exceptions were made: 485755122253901 (AG-05) and 490012122240001 (FT7-22). These 2 sites appear to have had degassing in the aquifer or during sample collection. They had the lowest Ar concentrations (consistent with degassing) and the highest inferred recharge temperatures (elevated inferred recharge temperatures result if ground water degasses). Degassing would be consistent with the chemistry: these 2 sites have the highest CH_4, Fe, and Mn concentrations, and the lowest field O_2 concentrations, of the 23 sites, indicating reducing conditions that could lead to gas super saturation and degassing. Thus, for these 2 sites, the site-specific major dissolved-gas data were not used, and the median major-dissolved-gas-inferred recharge temperature and the inferred excess air from the set of robust oxic sites were used.

Tracer-based piston-flow ages were initially calculated with corrections for excess air, and subsequently calculated without corrections for excess air. These different approaches are discussed below.

Advantages associated with these samples:

Major dissolved-gas data were available for all 23 sites.

These wells had short open intervals: median saturated open interval 5.00 feet.

The median penetration of the center of the open interval into water table was 10.83 feet (sampling close to the water table, potentially minimizing mixing).

Most of the wells (19 of the 23) were monitoring wells, leading to generally low pumping stress.

Disadvantages associated with these samples:

The only tracer other than SF_6 was a single ^3H sample.

Depth to water (can affect tracer transport to water table):

Median: 14.64 feet

Mean: 17.79 feet

Minimum: 6.34 feet

Maximum: 76.12 feet

Brief analysis:

The age gradient for the initial interpretation is shown in figure G25. This interpretation includes the standard correction for excess air.

Two sites, AG-05 and FT7-22, are apparent outliers. These 2 sites likely lost gases to degassing (discussed above). Because SF_6 is only sparingly soluble, SF_6 is easily lost during degassing. Samples from AG-05 and FT7-22 probably have an old bias due to SF_6 loss. Tracer-based piston-flow ages for these 2 samples are considered to be maximum estimates. The other tracer-based piston-flow ages yield an approximately linear age gradient.

The age gradient as a whole (minus AG-05 and FT7-22) is not aligned with the origin, suggesting the possibility that these piston-flow ages could have an old bias. These data could conceivably be affected by fractionation during recharge, a process that favors loss of SF_6 from solution owing to the low solubility of SF_6. An old bias in tracer-based piston-flow ages could be consistent with $^3H/^3He$ data from Wassenaar and others (2006). Wassenaar and others (2006) present $^3H/^3He$ interpretations from some wells in the PUGT study area, including 5 LUSCR1 wells that were also sampled by the USGS for SF_6. The $^3H/^3He$-based piston-flow ages for these 5 sites, along with SF_6-based piston-flow ages for LUSCR1 sites that were sampled for SF_6 (except sites AG-05 and FT7-22, which were omitted because of degassing problems) are shown in figure G26 below. The age gradient of the $^3H/^3He$ data appears to have a generally similar slope to that of the SF_6 data, but appears to intersect the graph near the origin, suggesting that the SF_6 data indeed might have an old bias.

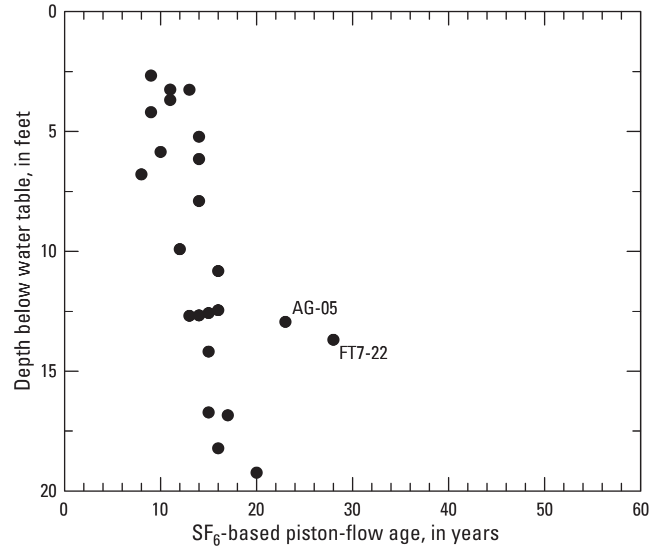


Figure G25. Age gradient for dated sites from the LUSCR1 and REFCR1 networks in the PUGT Study Unit. The tracer-based piston-flow ages were calculated by the standard approach of correcting for the presence of excess air.

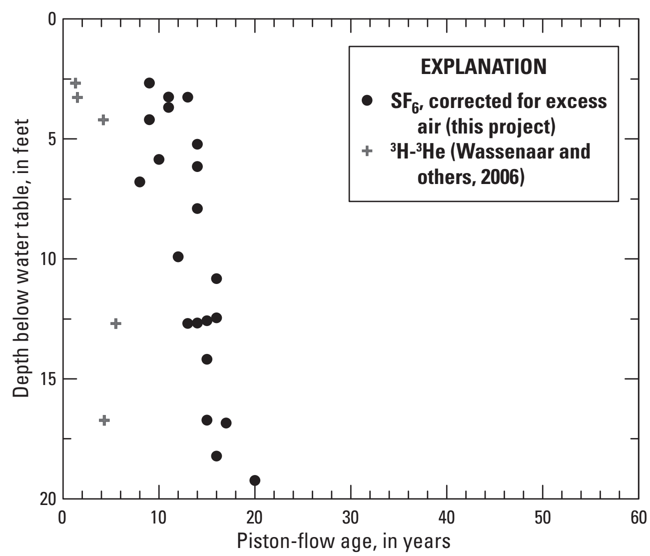


Figure G26. Age gradient for dated sites from the LUSCR1 and REFCR1 networks in the PUGT Study Unit. The tracer-based piston-flow ages were calculated by the standard approach of correcting for the presence of excess air. Two outliers that were shown in figure G25 have been removed. The $^3H/^3He$-based age gradient of Wassenaar and others (2006) is shown for comparison.

Where SF_6 samples have undergone substantial fractionation, tracer-based piston-flow ages without a correction for excess air will be a closer representation of time-of-travel than those with a correction for excess air. The age gradient for these sites, without an excess air correction, is shown in figure G27 (sites AG-05 and FT7-22 omitted).

The age gradient for this analysis (i.e. no correction for excess air) is closer to that of Wassenaar and others (2006), and appears to approximately intersect the origin. These SF_6-based piston-flow ages (uncorrected for excess air) have been retained for these networks.

One site had a ^3H analysis. The ^3H concentration, adjusted for radioactive decay by the SF_6-based piston-flow age of the sample, plots in the expected field on the ^3H input function for the study area (figure G28). However, the existence of just one ^3H analysis and its position on an approximately flat part of the ^3H curve provide little support for the SF_6 analysis. (The SF_6-based piston-flow age shown in the reconstructed ^3H analysis was based on calculations without a correction for excess air, but the calculation with a correction for excess air does not substantially alter the results of the reconstructed ^3H analysis.)

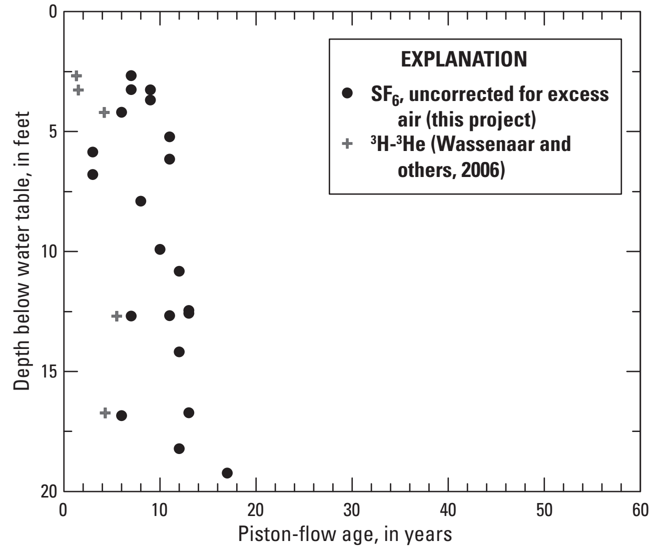


Figure G27. Age gradient for dated sites from the LUSCR1 and REFCR1 networks in the PUGT Study Unit. The tracer-based piston-flow ages were calculated without a correction for the presence of excess air. Two outliers that were shown in figure G25 have been removed. The $^3H/^3He$-based age gradient of Wassenaar and others (2006) is shown for comparison.

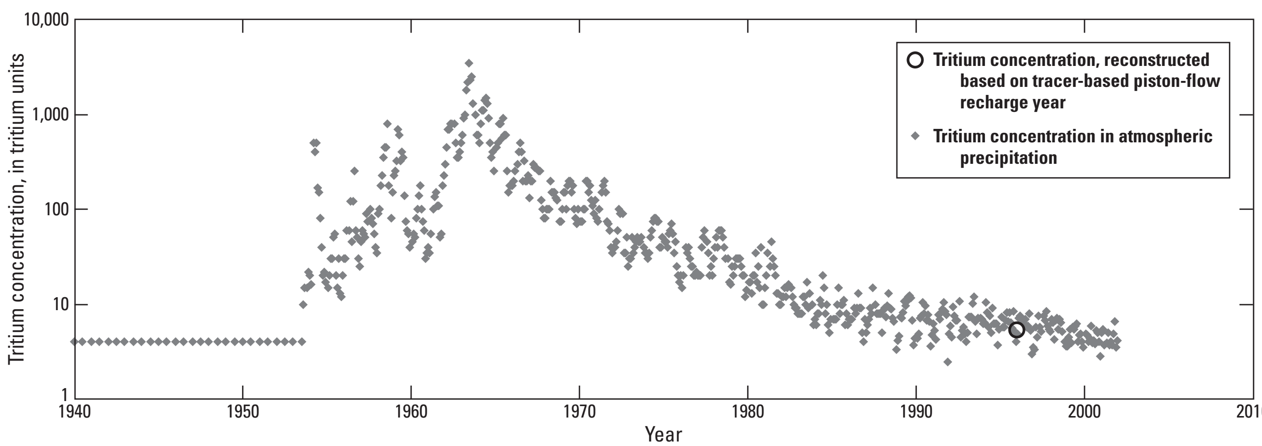


Figure G28. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSCR1 and REFCR1 networks, PUGT Study Unit.

RIOG LUSCR1

Samples from 33 sites in the RIOG Study Unit were collected during 2000 for CFCs (network and, in parentheses, number of sites):

LUSCR1 (33)
See table G21.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1°C, and that excess air concentrations were 2 cc(STP)/Kg.

Advantages associated with these samples:

- Short saturated open intervals (all saturated open intervals were ≤ 10.09 feet).
- Median penetration of the center of the open interval into water table was 4.15 feet (sampling close to the water table, possibly reducing mixing).
- Monitoring wells, therefore low pumping stress.
- Mostly oxic (median field O_2 = 3.40 mg/L).

Disadvantages associated with these samples:

- No tracers other than CFCs.
- No major dissolved-gas data.

Depth to water (can affect tracer transport to water table):

- Median: 10.63 feet
- Mean: 12.33 feet
- Minimum: 3.70 feet
- Maximum: 39.16 feet

Brief analysis:
The age gradient for these sites is shown in figure G29.

The age gradient for this network shows little structure. These wells are located near the water table in areas of irrigated agriculture, and thus there is periodic recharge. However, this aquifer is not a typical aquifer in which there is diffuse recharge and in which discharge occurs primarily at or near surface-water bodies, at wells, or by ground water outflow. Most groundwater discharge in this aquifer is by evapotranspiration (Anderholm, 1996). Thus, relations between tracer-based piston-flow ages and depth below water table would not necessarily be expected to reflect the dynamics of simpler flow systems.

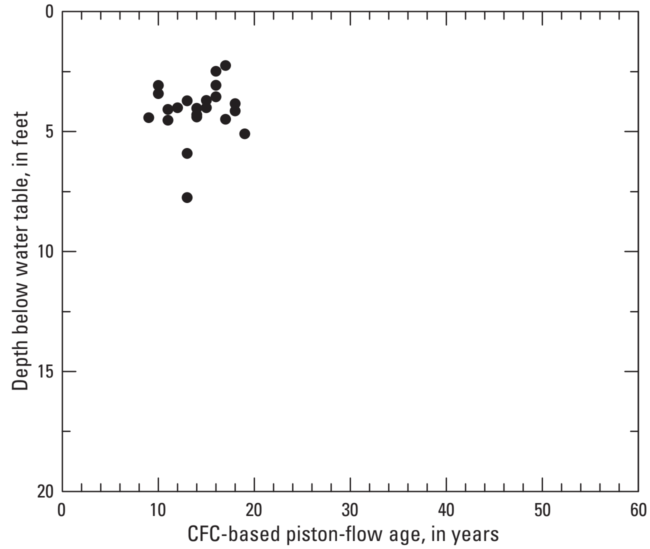


Figure G29. Age gradient for dated sites from the LUSCR1 network in the RIOG Study Unit.

Flow dynamics in this aquifer are particularly complicated. Abundant recharge from irrigation, hydraulic perturbations caused by irrigation pumping, and substantial discharge via evapotranspiration, all contribute to groundwater mixing. As an illustration of the effect that mixing can have on tracer-based piston-flow ages, consider the fact that the CFC concentrations for the datable sites contained 78 percent ± 11 percent (mean and standard deviation) of atmospheric concentrations at the time of sampling. Given these CFC concentrations, the sites represented here could reflect mixtures dominated by relatively young (days to years old) recharge with small amounts of old (decades or centuries old) recharge. Although such scenarios are possible for many groundwater samples, the particular hydrologic regime in this network and the clustering near the water table of data points in the age gradient plot are reasons to suspect that these tracer based piston-flow ages do not reflect the true complexity of flow represented by these samples.

One of the datable sites also had ^3H data. The reconstructed ^3H plot is shown in figure G30 for consistency, but has limited value on account of the single ^3H analysis.

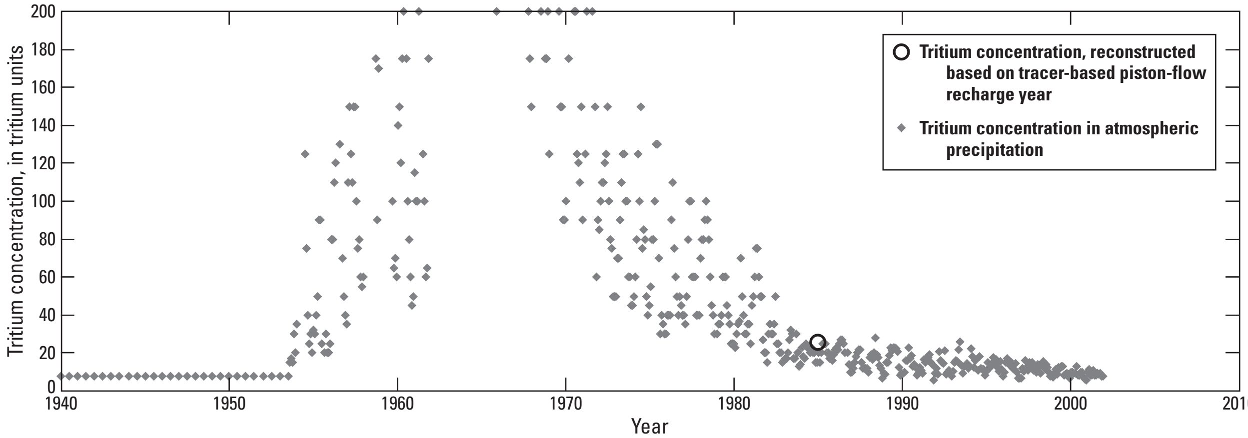


Figure G30. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSCR1 network, RIOG Study Unit.

SACR LUSRC1

Samples from 19 sites in the SACR Study Unit were collected during 1998 for $^3H/^3He$ (network and, in parentheses, number of sites):

LUSRC1 (19)
See table G22.

The aquifer is composed of sediments.

The standard procedure for $^3H/^3He$ dating that was documented in the body of the report was used for these sites. Seven sites were datable (1 site did not require a correction for terrigenic He; 6 sites did require a correction for terrigenic He), 6 site exhibited evidence of gas fractionation, 3 sites were beyond the dating range, and at 3 sites the samples were lost during analysis.

Advantages associated with these samples:

The wells were monitoring wells with low pumping stress and short open intervals.

Disadvantages associated with these samples:

Many samples showed evidence of fractionation. Samples for three of the sites had loose bolts or crimps, which may have contributed to sample fractionation in some samples.

Brief analysis:

The age gradient for these sites is shown in figure G31.

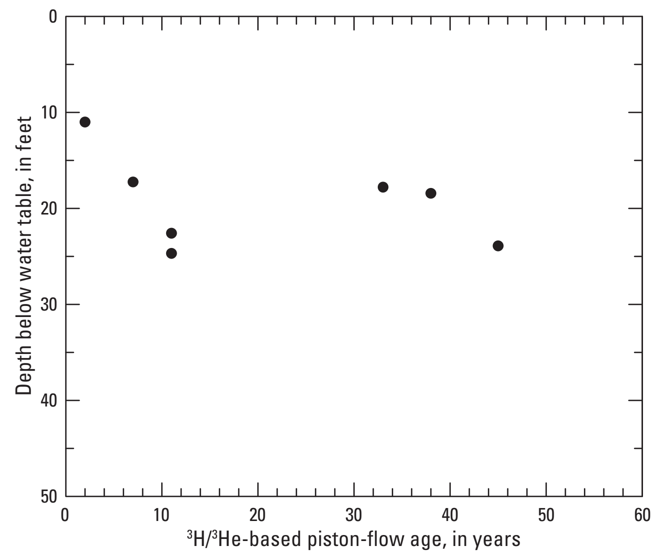


Figure G31. Age gradient for dated sites from the LUSRC1 network in the SACR Study Unit.

Wells with relatively young ages are spread out throughout the network. These sites are located in different geologic deposits and should not necessarily have consistent age-depth gradients. The 3 wells with tracer-based piston-flow ages greater than 30 years, but similar depths to wells with younger ages, are likely affected by mixing. These wells have low concentrations of VOCs and pesticides, as well as mixed redox indicators for 2 of the samples, indicative of mixing of young and old waters.

The reconstructed ^{3}H plot is shown in figure G32.

The 3 samples with tracer-based piston-flow recharge dates older than 1970 have reconstructed ^{3}H concentrations that are consistent with higher concentrations during the 1950s and 1960s. Three of the more modern samples appear to be relatively unmixed and represent piston-flow transport, while the fourth one appears to be affected by mixing processes or diffusive ^{3}He loss. The samples that were beyond the dating range for the $^{3}H/^{3}He$ method all have very low ^{3}H concentrations, are all oxygenated, all have deeper water tables and required mud rotary drilling, and are all located in North Sacramento in the Turlock Lake Formation. These wells had only one VOC detection, had no pesticide detections, and only one had an elevated nitrate concentration. Despite the fact that the $^{3}H/^{3}He$ dating could not be used for these wells, the ^{3}H information alone is useful in determining that the water in these locations is old and is consistent with the minimal occurrence of anthropogenic indicators such as VOCs or pesticides.

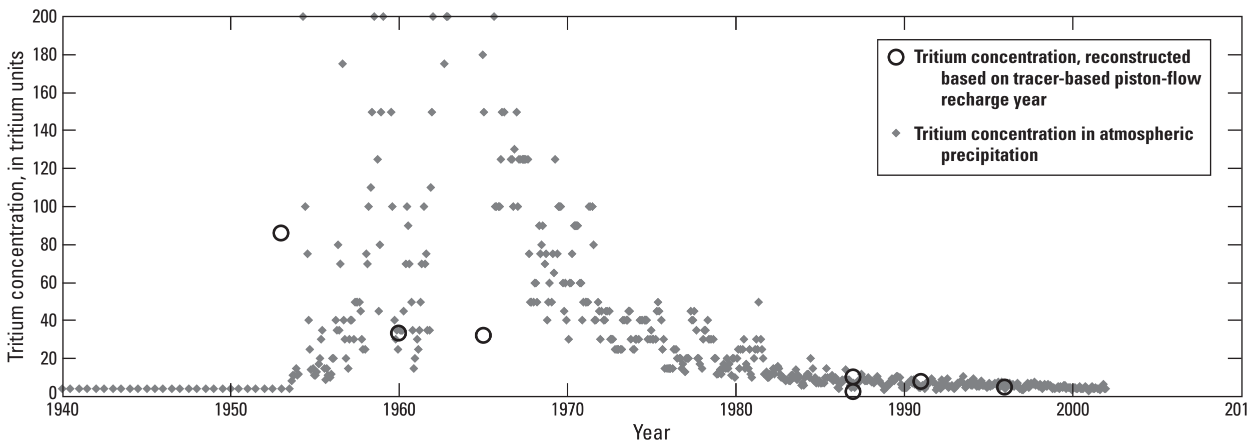


Figure G32. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSRC1 network, SACR Study Unit.

SANJ LUSOR1

Samples from 9 sites in the SANJ Study Unit were collected during 1996 for CFCs (network and, in parentheses, number of sites):

LUSOR1 (9)
See table G23.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites.

Advantages associated with these samples:

- Major dissolved-gas data were available for all 9 sites that had CFC analyses.

Of the 9 wells, 6 were monitoring wells (low pumping stress for these 6 sites).

Mostly oxic redox conditions (median field O_2 = 3.80 mg/L).

Disadvantages associated with these samples:

- No tracers other than CFCs.
- Median saturated open interval was 10 feet and ranged up to 50 feet.

The median penetration of the center of the open interval into the water table was 54.67 feet; at these depths, the magnitude of hydrodynamic dispersion tends to be greater than for wells screened near the water table.

Depth to water (can affect tracer transport to water table):

- Median: 43.65 feet
- Mean: 45.32 feet
- Minimum: 28.26 feet
- Maximum: 57.00 feet

Brief analysis:
The age gradient for these sites is shown in figure G33. The age gradient, although limited to only 4 datable samples, shows a general pattern of increasing tracer-based piston-flow age with increasing depth below the water table.

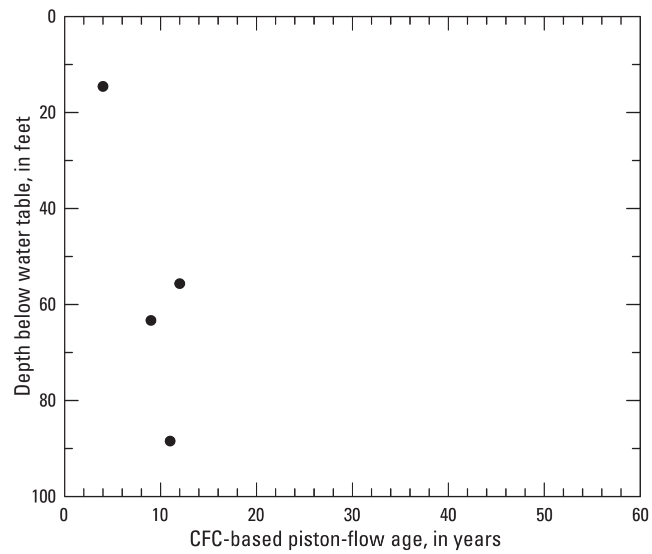


Figure G33. Age gradient for dated sites from the LUSOR1 network in the SANJ Study Unit.

SANT LUSCR1

Samples from 29 sites in the SANT Study Unit were collected during 1997 for CFCs (network and, in parentheses, number of sites):

LUSCR1 (29)
See table G24.

The aquifer is composed of sediments.

Major dissolved-gas data were collected at 10 sites. Two of the three oxic sites had major dissolved-gas data that implied negative excess air; these samples require negative excess N_2 (negative denitrification) or require adding 5,000 to 9,000 feet to the recharge elevation just to bring excess air to 0.00 cc(STP)/Kg. Additional problems with the major dissolved-gas data were the presence of highly variable concentrations among replicate samples. For example, differences in inferred recharge temperatures for replicate samples (assuming no denitrification) = 1.9 °C (median), and differ by as much as 11.5 °C. Because there were these problems with the major dissolved-gas data, and because the major dissolved-gas data were incomplete (available for only 10 of the 29 sites), the major dissolved-gas data were not used. Instead, it was assumed that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1°C, and that excess air concentrations were 2 cc(STP)/Kg.

Well construction data from the DWH for one site required re-interpretation. Taking DWH data at face value, the static water level (SWL) for 332355080410401 (ORG-395) lies below the bottom of the screen. However, DWH data indicate that the bottom of the screened interval for this well lies 6 feet above the bottom of the well. The other 28 LUSCR1 wells that were age-dated are listed in the DWH as having the bottom of the screened interval equal to the bottom of the well. It would appear that the DWH data for ORG-395 are incorrect. Larry G. Harrelson, hydrologist, USGS, South Carolina, written commun., March 9, 2009, confirmed the error, and indicates that depth to top of screen = 6.94 ft, to bottom of screen = 16.94 ft, and well depth = 16.94 ft. These updated well construction data were used in lieu of DWH data.

Advantages associated with these samples:

Short open intervals (median saturated open interval 5.00 feet).

Monitoring wells, therefore low pumping stress.

Median penetration below water table: 4.10 feet, thus sampling near the water table and thus minimizing mixing.

Median field O_2 = 5.70 mg/L.

Disadvantages associated with these samples:

No tracers other than CFCs.

Major dissolved-gas data were not useful.

The SWL data retrieved from the DWH on 12-16-08 and 02-05-09 were used in this analysis. These SWL data do not agree exactly with SWL data on the USGS NWIS-WEB website as of 03-05-09. Study Unit hydrologists are investigating, but this analysis proceeded with the currently available DWH data.

Depth to water (can affect tracer transport to water table):
Median: 10.80 feet
Mean: 11.23 feet
Minimum: 5.20 feet
Maximum: 22.30 feet

Brief analysis:
The age gradient for these sites is shown in figure G34. The center of the screened interval was less than 10 feet below the water table for each of these wells, yielding a small range of depths for evaluating the local age gradient. However, the generally young tracer-based piston-flow ages are consistent with the location of samples near the water table in recharge areas.

SANT SUS3

Samples from 29 sites in the SANT Study Unit were collected during 1998 for CFCs (network and, in parentheses, number of sites):

SUS3 (29)
See table G25.

The aquifer is composed of fractured rock.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. Major dissolved-gas data were not available for 8 sites, so the median recharge temperature and median excess air estimates from the oxic sites were used at these 8 sites.

Advantages associated with these samples:

Major dissolved-gas data were available for 21 of the 29 sites.

Primarily oxic. Median field O_2 = 6.90 mg/L.

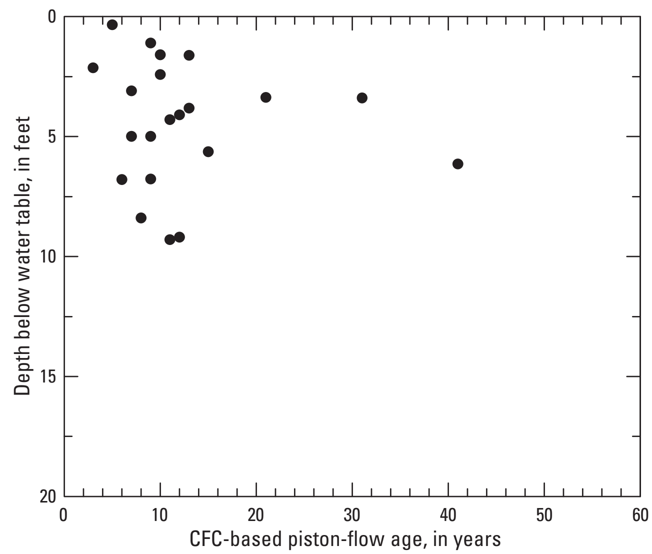


Figure G34. Age gradient for dated sites from the LUSCR1 network in the SANT Study Unit.

Disadvantages associated with these samples:

No tracers other than CFCs.

Long saturated open intervals (median 120 feet) (however, not unusual for fractured rock aquifers).

Depth to water (can affect tracer transport to water table):
Median: 26.00 feet
Mean: 29.23 feet
Minimum: 9.00 feet
Maximum: 134.50 feet

Brief analysis:

The age gradient is shown in figure G35. Scatter in these data reflect, in part, the generally greater hydrologic heterogeneity that is found in fractured rocks than is found in sediments.

Analysis of age gradients can provide useful information about a hydrologic system if the tracer-based piston-flow ages are considered reliable, or alternatively, can provide a tool for screening tracer-based piston-flow ages where hydrologic systems are well characterized. In the case of fractured rock aquifers, hydrodynamics are seldom well characterized and age gradients often exhibit substantial scatter. An alternative tool for screening tracer-based piston-flow ages can be comparing tracer-based piston-flow age to geochemical evolution. One such simple application is to compare tracer-based piston-flow age to pH because there is a tendency of pH to increase with increasing ground-water age in response to (kinetically limited) hydrolysis reactions (for example, Rademacher and others, 2001). Tracer-based piston-flow age was plotted against pH (fig. G36). The pattern of generally increasing pH with increasing residence time as represented by tracer-based piston-flow age provides some support for the age-dating interpretations.

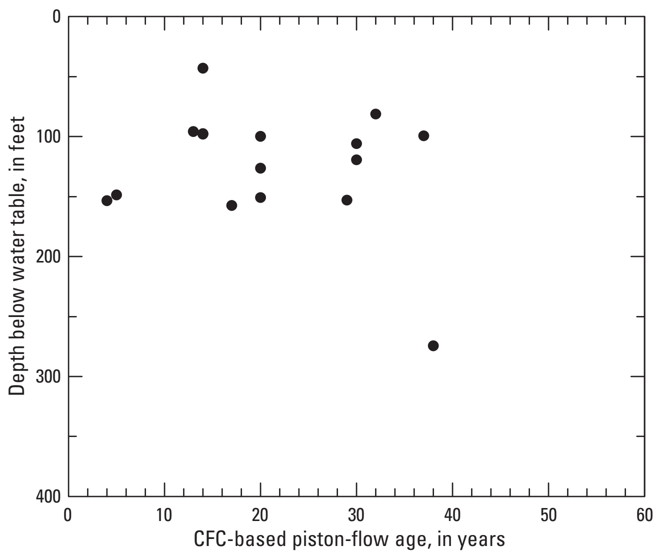


Figure G35. Age gradient for dated sites from the SUS3 network in the SANT Study Unit.

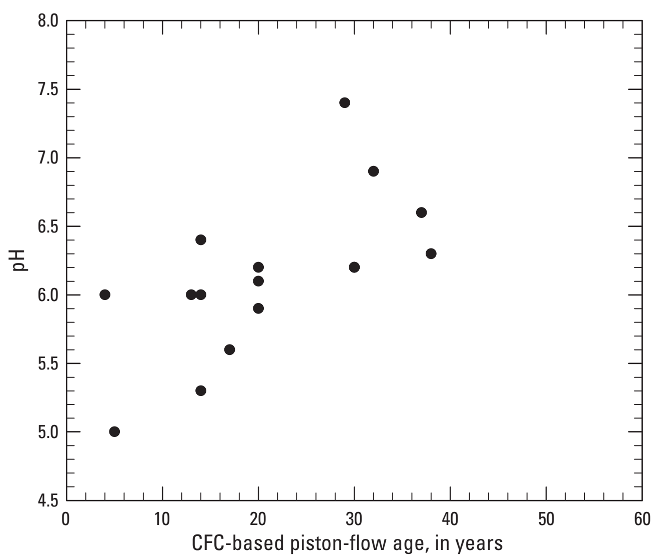


Figure G36. Relation between tracer-based piston-flow age and pH for dated sites from the SUS3 network in the SANT Study Unit.

SANT LUSRC1

Samples from 14 sites in the SANT Study Unit were collected during 1996 and 1999 for CFCs (network and, in parentheses, number of sites):

LUSRC1 (14)
See table G26.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. Major dissolved-gas data were not available for 6 sites, so the median recharge temperature and median excess air estimates from the oxic sites were used at these 6 sites.

Advantages associated with these samples:

Major dissolved-gas data were available for 8 of the 14 sites.

Primarily oxic. Median field O_2 = 4.55 mg/L.

These were monitoring wells, thus subject to low pumping stress.

The wells were screened near the water table (median penetration into the water table: 3.15 feet).

Disadvantages associated with these samples:

No tracers other than CFCs.

Extensive CFC contamination, possibly associated with the urban land use in this urban LUS.

Depth to water (can affect tracer transport to water table):

Median: 11.95 feet
Mean: 16.81 feet
Minimum: 3.20 feet
Maximum: 48.90 feet

Brief analysis:

None of the sites were considered datable.

SCTX LUSRC1 (CFCs)

Samples from 30 sites in the SCTX Study Unit were collected during 1998 for CFCs (network and, in parentheses, number of sites):

LUSRC1 (30)
See table G27.

The aquifer is a karst aquifer (the Edwards aquifer).

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites.

Advantages associated with these samples:

Major dissolved-gas data were available for all 30 sites that had CFC analyses.

The wells were monitoring wells, thus subject to low pumping stress.

These sites were generally oxic (minimum field O_2 = 4.85 mg/L and no detectable CH_4 in any of the 30 samples; however, some samples were mixtures of oxic and reduced components).

Disadvantages associated with these samples:

Long saturated open intervals (median saturated open interval 70.00 feet).

Median penetration of the center of the open interval into water table was 41.17 feet (possibly more mixing at these depths).

Karst aquifers present challenges, including the potential for complex mixtures, and flow that can alternate between saturated and unsaturated conditions (such as flow from saturated conduits to partially flooded caverns and back to saturated conduits).

The mode of introduction of CFCs into Edwards aquifer water includes introduction of CFCs in stream water where streams recharge the aquifer. According to Bush and others (2000): "As the major streams flow across the faulted and fractured carbonate rocks of the Edwards aquifer outcrop (recharge zone), they lose substantial amounts of flow directly into the highly permeable aquifer." Concentrations of CFCs in stream water may be low due to upstream discharge of low-CFC ground water, or may be elevated due to contamination associated with urban or other land uses.

Depth to water (can affect tracer transport to water table):
Median: 179.59 feet
Mean: 176.53 feet
Minimum: 104.51 feet
Maximum: 255.47 feet

Brief analysis:
The age gradient for these sites is shown in figure G37. No structure is evident in this figure, probably reflecting heterogeneity of groundwater flow in this karst aquifer.

At 29 of the sites, ^{3}H data were available. Of these 29 sites, 21 were datable with CFCs. The reconstructed ^{3}H plot is shown in figure G38.

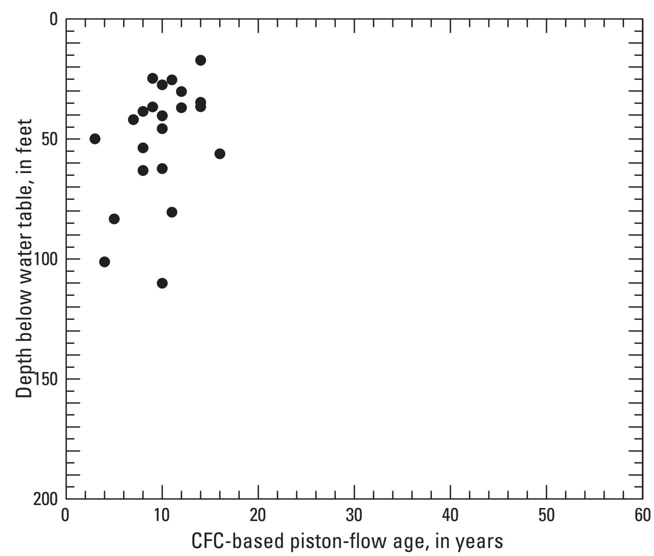


Figure G37. CFC-based age gradient for dated sites from the LUSRC1 network in the SCTX Study Unit.

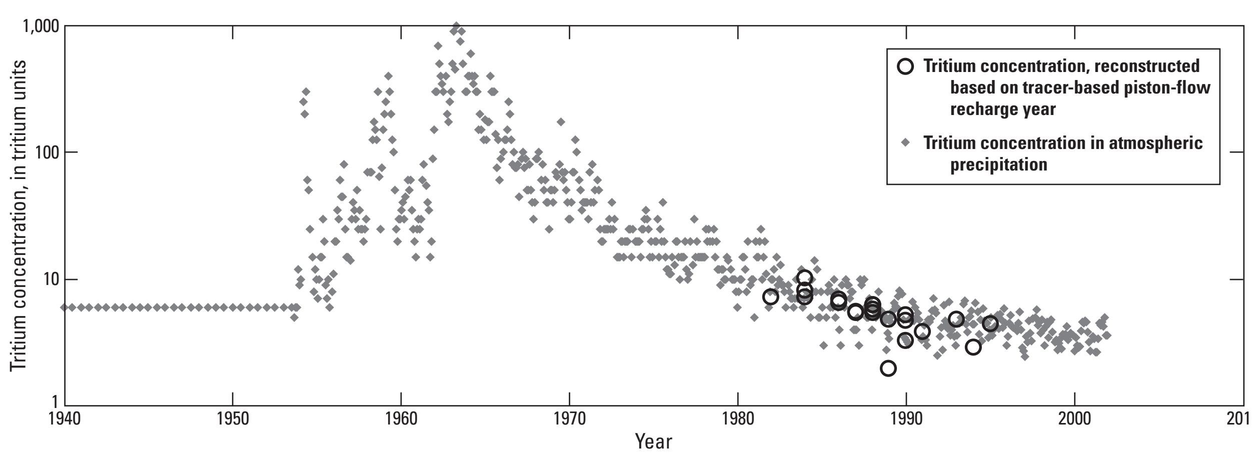


Figure G38. Reconstructed tritium concentrations (reconstruction based on CFCs) and tritium in atmospheric precipitation for the LUSRC1 network, SCTX Study Unit.

The reconstructed ^{3}H analysis could be consistent with the bulk of these samples being relatively unmixed and approximating piston-flow transport.

Five of these sites were sampled for ^{3}H/^{3}He in addition to CFCs. At 3 sites, sampling for ^{3}H/^{3}He and CFCs occurred on the same date. At 2 sites, sampling for ^{3}H/^{3}He and CFCs occurred on different dates. A comparison between the CFC results and the ^{3}H/^{3}He results is presented with the SCTX ^{3}H/^{3}He results (below).

For the three sites where both ^{3}H/^{3}He and CFC samples were collected on the same date, the tracer-based piston-flow ages derived from these two methods agree well, although at one of these sites, the ^{3}H/^{3}He-based piston-flow age was censored (<45 years). In general, a ^{3}H/^{3}He-based piston-flow age is considered more reliable than a CFC-based piston-flow age, and this generalization is thought to apply here with the exception of the one site with a censored ^{3}H/^{3}He-based piston-flow age (site 293404098382001), where the CFC-based piston-flow age is more useful. For the other two sites, if one sample is to be used to characterize the sites, the ^{3}H/^{3}He-based piston-flow age is likely to be more reliable than the CFC-based piston-flow age.

SCTX LUSRC1 and REFRE1 (^{3}H/^{3}He)

Samples from six sites in the SCTX Study Unit were collected during 1998, 1999, and 2000 for ^{3}H/^{3}He (networks and, in parentheses, number of sites):

LUSRC1 (5)
REFRE1 (1)
See table G28.

The aquifer is a karst aquifer (the Edwards aquifer).

The standard procedure for ^{3}H/^{3}He dating that was documented in the body of the report was used for these sites.

Advantages associated with these samples:

The wells were monitoring wells with low pumping stress.

Major dissolved-gas data available for 5 of the 6 sites.

Disadvantages associated with these samples:

Long saturated open intervals (median saturated open interval: 70.00 feet).

Median penetration of the center of the open interval into the water table was 37.76 feet (possibly more mixing at these depths).

Karst aquifers present challenges, including the potential for complex mixtures, and flow that can alternate between saturated and unsaturated conditions (such as flow from saturated conduits to partially flooded caverns and back to saturated conduits).

Brief analysis:

The age gradient for these networks is shown in figure G39. Age gradients in karst aquifers are not expected to be strong, and this age gradient is limited by the small number of data points.

The reconstructed ^{3}H plot is shown in figure G40. The ^{3}H analysis could be consistent with the bulk of these samples being relatively unmixed and approximating piston-flow transport.

Five sites were sampled for both ^{3}H/^{3}He and CFCs. At three sites, sampling for ^{3}H/^{3}He and CFCs occurred on the same date. At two sites, sampling for CFCs occurred in 1998, whereas sampling for ^{3}H/^{3}He occurred during 2000. The CFC data were interpreted separately (above). Three sites with multiple tracers collected on the same date (the year-1998 samples) were not evaluated for possible mixing scenarios because the number of multi-tracer samples was insufficient for such analysis. A comparison between the ^{3}H/^{3}He-based piston-flow ages and the CFC-based piston-flow ages is shown below.

Site identifier	Local identifier	Sample date	^{3}H/^{3}He-based piston-flow recharge year	^{3}H/^{3}He-based piston-flow age	Sample date	CFC-based piston-flow recharge year	CFC-based piston-flow age
293340098344701	AY-68-28-516	12-08-98	1994	4	12-08-98	1995	3
293404098382001	AY-68-27-612	12-10-98	>1953	<45	12-10-98	1986	12
293456098280201	AY-68-29-418	12-09-98	1988	10	12-09-98	1990	8
293436098343001	AY-68-28-517	06-28-00	1983	17	12-08-98	1990	8
293643098264001	AY-68-29-216	06-29-00	1995	5	11-09-98	>1945	<53

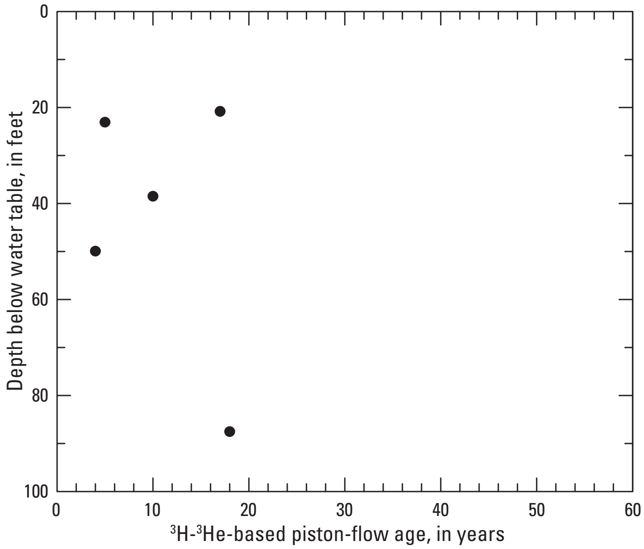


Figure G39. $^3H/^3He$-based age gradient for dated sites from the LUSRC1 and REFRE1 networks in the SCTX Study Unit.

For the 3 sites where both $^3H/^3He$ and CFC samples were collected on the same date, the tracer-based piston-flow ages derived from these two methods agree well, although at one of these sites, the $^3H/^3He$-based piston-flow age was censored (<45 years). In general, a $^3H/^3He$-based piston-flow age is considered more reliable than a CFC-based piston-flow age, and this generalization is thought to apply here with the exception of the one site with a censored $^3H/^3He$-based piston-flow age (site 293404098382001), where the CFC-based piston-flow age is more useful.

For the 2 sites where the $^3H/^3He$ and CFC samples were collected on different dates, the fact that the $^3H/^3He$ and CFC samples were collected on different dates prevents rigorous comparisons, in part because the nature of flow in karstic systems is particularly variable in time. If one sample is to be used to characterize each of these two sites, the $^3H/^3He$-based piston-flow age is likely to be more reliable.

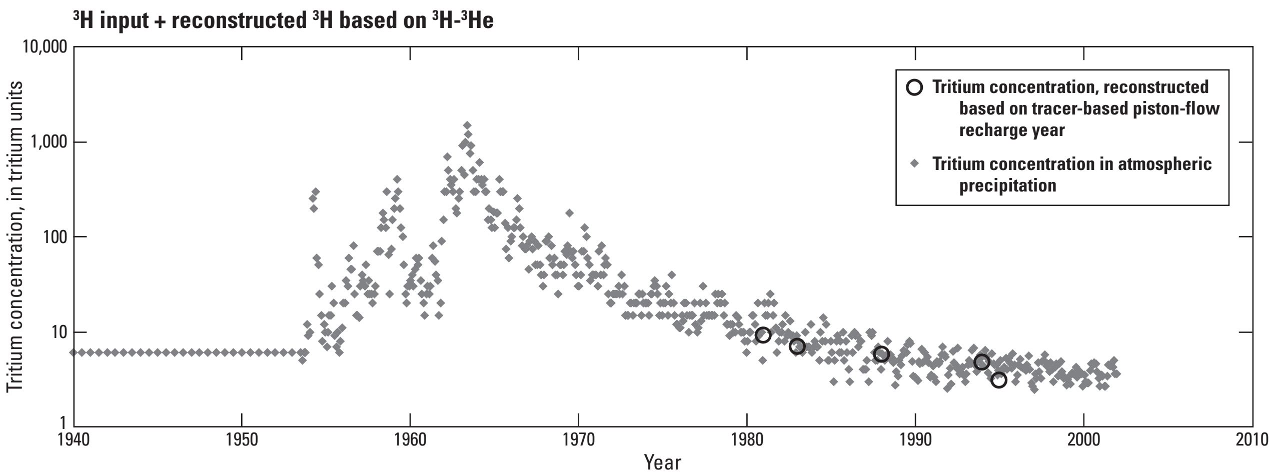


Figure G40. Reconstructed tritium concentrations (reconstruction based on $^3H/^3He$) and tritium in atmospheric precipitation for the LUSRC1 and REFRE1 networks, SCTX Study Unit.

TENN SUS1

Samples from 10 sites in the TENN Study Unit were collected during 1999 for CFCs (network and, in parentheses, number of sites):

SUS1 (10)
See table G29.

The aquifer is a karst aquifer.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at the 9 oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at 1 suboxic site using median excess air at oxic sites.

Advantages associated with these samples:

Major dissolved-gas data were available for all 10 sites.

Redox conditions were generally oxidizing: all field $O_2 \geq 2.7$ mg/L, all Mn < 4 µg/L, and all Fe <30 µg/L. Two sites did have detectable CH4, but at concentrations of 1.7 and <1.0 µg/L, which might be of little significance given the otherwise oxidizing conditions.

Disadvantages associated with these samples:

No tracers other than CFCs.

Karst aquifer (piston flow conditions unlikely)

Supply wells with long saturated open intervals (median = 28.50 feet, for the 8 sites with well construction data).

Depth to water (can affect tracer transport to water table) (9 sites had static water level data):
Median: 37.97 feet
Mean: 32.78 feet
Minimum: 1.00 feet
Maximum: 62.30 feet

Brief analysis:
The age gradient is composed of only 2 data points (3 sites were dated, but well construction data were not available for 1 of the 3 dated sites). Nevertheless, to be consistent with the approach taken with other networks, the age gradient is shown (figure G41).

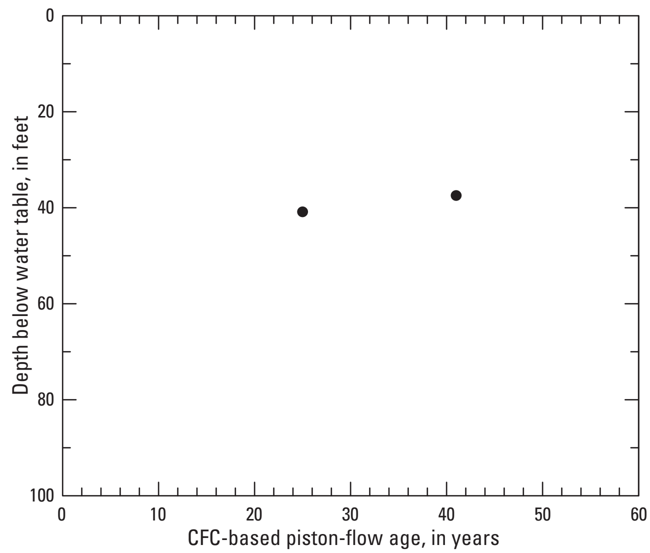


Figure G41. Age gradient for dated sites from the SUS1 network in the TENN Study Unit.

TRIN LUSRC1 and REFOT1

Samples from eight sites in the TRIN Study Unit were collected during 2003 for CFCs (networks and, in parentheses, number of sites):

LUSRC1 (7)
REFOT1 (1)
See table G30.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. At one site, 301008095302901 (MW13), low Ar concentrations (<0.47 mg/L) suggest the possibility of degassing, and the inferred recharge temperature (32.7 °C) appears unusually warm, so the median major-dissolved-gas-inferred recharge temperature and median major-dissolved-gas-inferred excess air from the oxic sites was used for this site.

Advantages associated with these samples:

Major dissolved-gas data available for all 8 sites.

Open intervals were short (saturated open intervals ≤ 10 feet).

The wells were monitoring wells, therefore associated with low pumping stress.

Disadvantages associated with these samples:

Although both CFC and SF_6 samples were collected, the SF_6 samples were at contaminant levels. Thus, only one tracer was available for age-dating purposes.

Half of the samples had field O_2 less than 0.5 mg/L.

Depth to water (can affect tracer transport to water table):
Median: 20.74 feet
Mean: 34.55 feet
Minimum: 7.26 feet
Maximum: 103.14 feet

Brief analysis:
The age gradient is composed of only 2 data points (fig. G42). Nevertheless, to be consistent with the approach taken with other networks, the age gradient is shown.

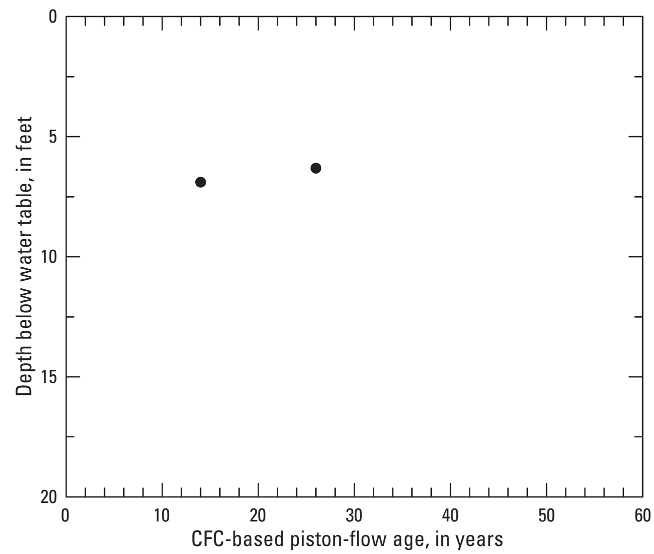


Figure G42. Age gradient for dated sites from the LUSRC1 and REFOT1 networks in the TRIN Study Unit.

UIRB LUSRC1 (3H/3He)

Samples from 13 sites in the UIRB Study Unit were collected during 2000 for $^3H/^3He$ (network and, in parentheses, number of sites):

LUSRC1 (13)
See table G31.

The aquifer is composed of glacial sediments.

The standard procedure for $^3H/^3He$ dating that was documented in the body of the report was used for these sites. A total of 15 sites were sampled, but samples from 2 sites appeared to have been mislabeled or misidentified and were not usable, leaving 13 sites with $^3H/^3He$ data. Of these 13 sites, 10 were datable (2 sites did not require a correction for terrigenic He; 8 sites did require a correction for terrigenic He). The remaining 3 sites were not datable because 2 exhibited evidence of gas fractionation and 1 was beyond the dating range.

Advantages associated with these samples:
Major dissolved-gas data were available for all sites.

Short open intervals (all saturated open intervals were ≤ 5 feet).

The wells were monitoring wells with low pumping stress.

The wells exhibited few problems with fractionation, low ^3H samples beyond dating range, or high He concentrations that would typically escape during measurement.

Disadvantages associated with these samples:
No notable disadvantages.

Brief analysis:
The age gradient for this network is shown in figure G43. The roughly linear age gradient provides support for the interpretations.

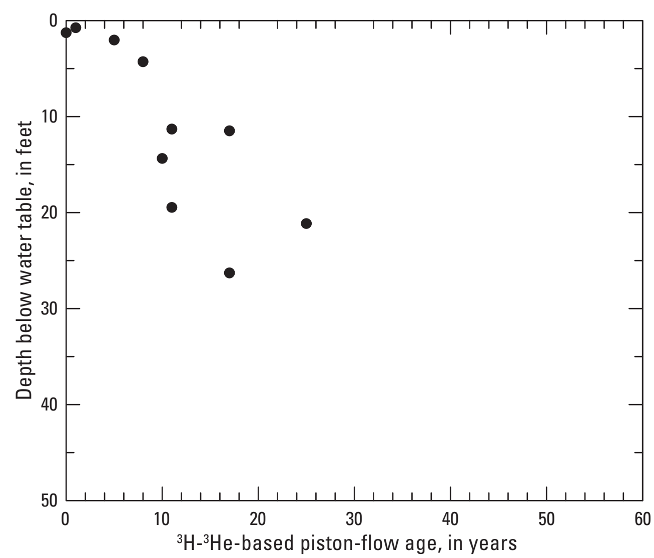


Figure G43. $^3H/^3He$-based age gradient for dated sites from the LUSRC1 network in the UIRB Study Unit.

The reconstructed ^3H plot is shown in figure G44. The ^3H analysis could be consistent with the bulk of these samples being relatively unmixed and approximating piston-flow transport. The one sample with a $^3H/^3He$-based piston-flow recharge date of 1975 is not consistent with piston flow conditions, indicating that the sample may have been affected by dispersion and (or) mixing.

These sites also were sampled for CFCs; those results are discussed separately. In general, the CFC results were less reliable than the $^3H/^3He$ results. However, two of the sites (424052088180101 and 430239088164001) that had inconclusive $^3H/^3He$ results were better represented by the CFC results.

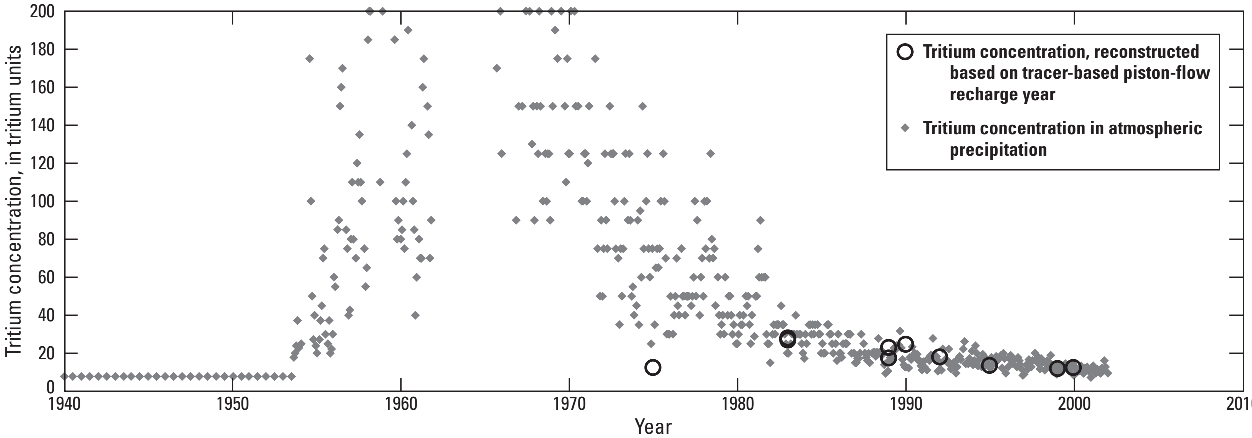


Figure G44. Reconstructed tritium concentrations (reconstruction based on $^3H/^3He$) and tritium in atmospheric precipitation for the LUSRC1 network, UIRB Study Unit.

UIRB LUSRC1 (CFCs)

Samples from 20 sites in the UIRB Study Unit were collected during 2000 for CFCs (network and, in parentheses, number of sites):

LUSRC1 (20)
See table G32.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using Ne data (for those sites with Ne data) or the median excess air from the oxic sites. Results from the oxic sites were used for the one site that did not have major dissolved-gas data.

The one exception to this approach was site 422314088140001 (URBLUS20). At this site, the field O_2 was 1.83 mg/L, Mn was less than 2.2 µg/L, Fe was less than 10 µg/L, and CH_4 was 0.0000 mg/L, thus this site would usually be considered oxic. However, if the site is treated as oxic (no denitrification), the major-dissolved-gas-inferred recharge temperature is 21.5 °C and excess air is 9.8 cc(STP)/Kg. The other oxic sites in this network have median major-dissolved-gas-inferred recharge temperatures of 10.2 °C and median excess air of 2.1 cc(STP)/Kg. The difference (11.3°C) in inferred recharge temperatures between URBLUS20 and the other oxic sites, and the large inferred excess air (9.8 cc(STP)/Kg) at URBLUS20, suggest that URBLUS20 may need different treatment. Although this sample meets the conditions for classification as oxic, the field O_2 is sufficiently low that the sample could have consisted oxic ground water with a large component of suboxic ground water. If denitrification is allowed, the major-dissolved-gas-inferred recharge temperature = 9.4 °C, similar to the 10.2 °C from the oxic sites. The more reasonable value of inferred recharge temperature lead to the decision to treat URBLUS20 as suboxic.

Advantages associated with these samples:

- Major dissolved-gas data were available for 19 of the 20 sites.
- Short open intervals (saturated open interval ≤5 feet).
- Monitoring wells, therefore low pumping stress.
- Median penetration below water table: 11.41 feet, sampling near water table and thus minimizing mixing.

Disadvantages associated with these samples:

- Although most sites were oxic, O_2 was not abundant (median field O_2 = 2.4 mg/L, of 17 sites with field-measured O_2), and 5 sites (out of 20) had Fe concentrations greater than 1 mg/L. CH_4 was commonly detected (8 detections, between 0.0007 and 0.3252 mg/L, with median of the 8 = 0.0130 mg/L).

Depth to water (can affect tracer transport to water table):

Median: 12.64 feet
Mean: 17.13 feet
Minimum: 0.00 feet
Maximum: 47.58 feet

Brief analysis:
The age gradient is composed of only 4 data points (fig. G45). Nevertheless, to be consistent with the approach taken with other networks, the age gradient is shown.

Samples were analyzed for ^3H at 13 sites. Of these 13 sites, 1 was considered datable with CFCs. The reconstructed ^3H plot is shown in figure G46. This one sample could be consistent with the ^3H data.

Thirteen of these sites also were sampled for $^3H/^3He$; those results are discussed separately. In general, the $^3H/^3He$ results were more reliable than the CFC results. However, two of the sites (424052088180101 and 430239088164001) had inconclusive $^3H/^3He$ results and the CFC results were selected to represent these two sites.

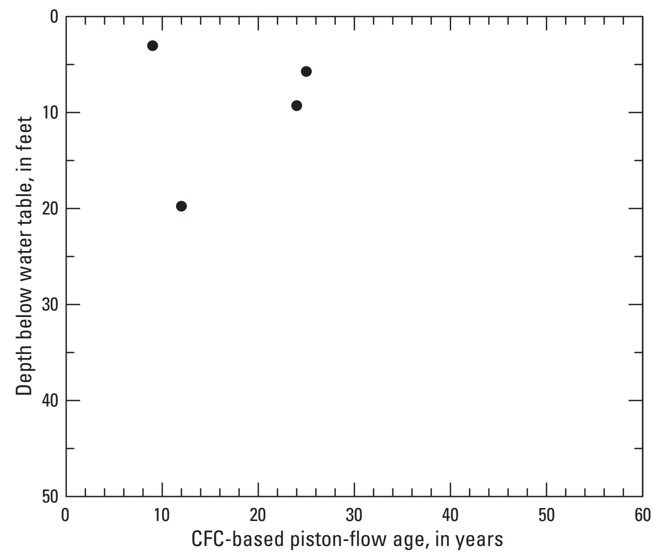


Figure G45. CFC-based age gradient for dated sites from the LUSRC1 network in the UIRB Study Unit.

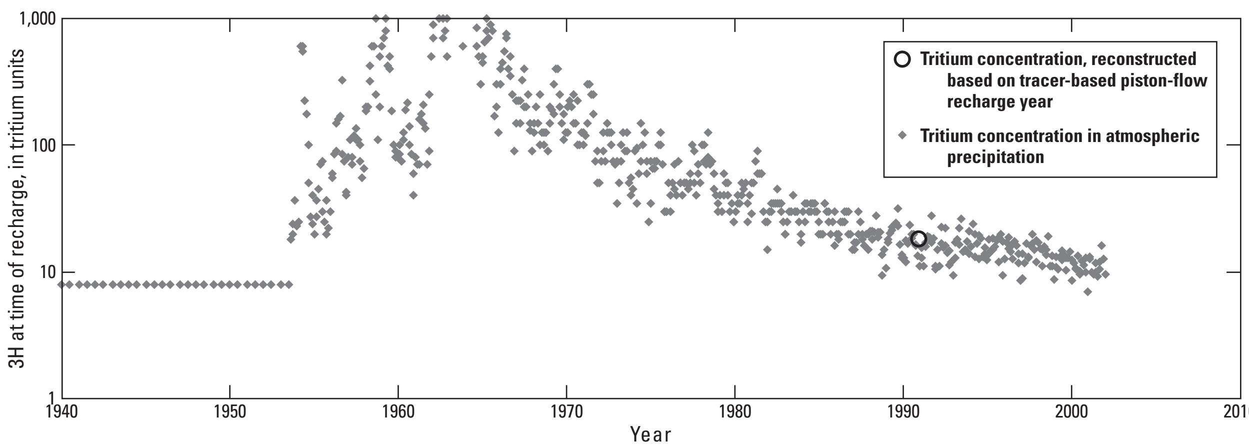


Figure G46. Reconstructed tritium concentrations (reconstruction based on CFCs) and tritium in atmospheric precipitation for the LUSRC1 network, UIRB Study Unit.

UIRB SUS1

Samples from 27 sites in the UIRB Study Unit were collected during 2001 for CFCs (network and, in parentheses, number of sites):

SUS1 (27)
See table G33.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. One site did not have major dissolved-gas data, so the median recharge temperature and median excess air estimates from the oxic sites were used.

Advantages associated with these samples:

Major dissolved-gas data were available for 26 of the 27 sites.

Disadvantages associated with these samples:

No tracers other than CFCs.

Extensive occurrence of strongly reducing conditions. For example, of the 26 sites with major dissolved-gas data, 19 contained ≥1 µg/L of methane.

There appears to be CFC contamination in many samples.

Depth to water (can affect tracer transport to water table):
Median: 29.04 feet
Mean: 22.00 feet
Minimum: 0.00 feet
Maximum: 81.00 feet

Brief analysis:
The age gradient is composed of only 2 data points (fig. G47). Nevertheless, to be consistent with the approach taken with other networks, the age gradient is shown, below.

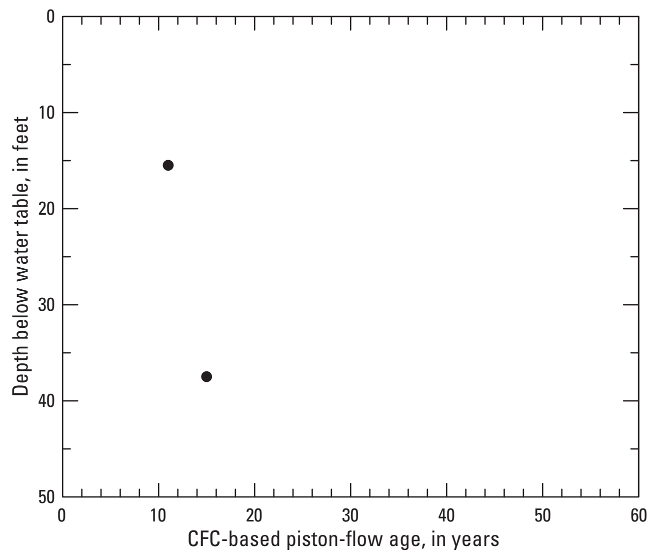


Figure G47. Age gradient for dated sites from the SUS1 network in the UIRB Study Unit.

UIRB SUS2

Samples from 23 sites in the UIRB Study Unit were collected during 2000 for CFCs (network and, in parentheses, number of sites):

SUS2 (23)
See table G34.

The aquifer is composed of glacial sediments.

The major dissolved-gas data were affected at most sites by denitrification, and at one site by degassing. Using standard procedures, the median excess air from the 4 oxic sites was used as a constraint for the suboxic sites. (Four sites is a small number of sites, but the major-dissolved-gas-inferred excess air concentrations exhibited little variation.) With excess air constrained, the major dissolved-gas data were used to calculate recharge temperature for the suboxic sites. However, due to the highly variable recharge temperatures, major-dissolved-gas-inferred recharge temperatures were not relied upon for the CFC age-dating in this network, and the mean annual air temperature + 1 °C was used as a proxy for recharge temperatures.

Advantages associated with these samples:

Thin open intervals; all saturated open intervals, except for one, were ≤5.00 feet.

Disadvantages associated with these samples:

No tracers other than CFCs.

Redox conditions were generally reducing. For example, the median field O_2 concentration was 0.33 mg/L, and CH4 was detected at 20 of the 23 sites.

CFC degradation as well as CFC contamination present.

Depth to water (can affect tracer transport to water table):
Median: 10.00 feet
Mean: 11.52 feet
Minimum: 5.00 feet
Maximum: 40.00 feet

Brief analysis:
Only 1 site from this network was considered datable. As such, no age gradient is shown for this network.

UIRB LUSCR1

Samples from 25 sites in the UIRB Study Unit were collected during 1999 for CFCs (network and, in parentheses, number of sites):

LUSCR1 (25)
See table G35.

The aquifer is composed of glacial sediments.

Major dissolved-gas data were available for 19 of the 25 sites. The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. At one of the sites that had major dissolved-gas data (411329087121201), the major dissolved gases had been partially lost and the major dissolved-gas data were not used; for this site, as well as the 6 sites without major dissolved-gas data, the median recharge temperature and median excess air from oxic sites were used.

Advantages associated with these samples:

Major dissolved-gas data available for 19 of the 25 sites.

Monitoring wells, so generally low pumping stress and short well screens.

Disadvantages associated with these samples:

No tracers other than CFCs.

Many sites yielded reducing groundwater. Median field O_2 = 0.85 mg/L. Median CH_4=0.0007 mg/L (n=18; major dissolved-gas data from 1 of the 19 sites had been degassed and was not included in this calculation).

Depth to water (can affect tracer transport to water table):

Median: 5.83 feet

Mean: 7.15 feet
Minimum: 2.43 feet
Maximum: 14.35 feet

Brief analysis:
The age gradient for these sites is shown in figure G48. The small number of datable samples and the narrow range of depths represented by these wells restrict analysis of the age gradient. However, the overall pattern of relatively young groundwater from sampling points near the water table in recharge areas is consistent with the network design.

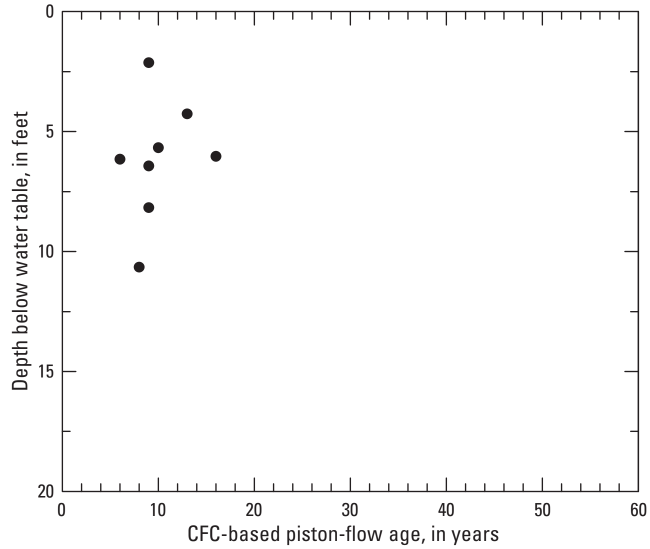


Figure G48. Age gradient for dated sites from the LUSCR1 network in the UIRB Study Unit.

WHMI LUSCR1 LUSCR1a LUSCR3a and SUS1

Samples from 69 sites in the WHMI Study Unit were collected during 1999 and 2000 for $^3H/^3He$ (networks and, in parentheses, number of sites):

LUSCR1 (26)
LUSCR1a (8)
LUSCR3a (5)
SUS1 (30)
See table G36.

The aquifer is composed of glacial sediments.

The standard procedure for $^3H/^3He$ dating that was documented in the body of the report was used for these sites. Of the 69 sites, 52 were considered datable (23 sites did not require a correction for terrigenic He; 29 sites did require a correction for terrigenic He). Of the remaining 17 sites, 10 exhibited evidence of gas fractionation, 3 were beyond the dating range, and at 4 sites the samples were lost during analysis.

Advantages associated with these samples:

The 39 LUS sites are monitoring wells with short open intervals (saturated open intervals all ≤5.00 feet). The 30 SUS sites are supply wells with relatively short saturated open intervals (median 3.00 feet and maximum 11.00 feet).

There were few problems with fractionation, low ^3H concentrations, or high He concentrations.

Disadvantages associated with these samples:

The only substantial limitations specific to these sites are discussed below.

Brief analysis:

The age gradient for these sites is shown in figure G49.

The age gradient for these networks, although weak, does indicate increasing $^3H/^3He$-based piston-flow age with increasing depth below the water table. There is a general pattern, too, in which the LUS wells tend to be shallower and younger, and the MAS wells tend to be deeper and older, consistent with the NAWQA design for LUS and MAS networks. Although tracers are subject to uncertainties, the scatter in the age gradient plot may be dominated by the actual geologic heterogeneity inherent in glacial sediments.

The deepest MAS well, with a $^3H/^3He$-based piston-flow age of 0 years, was the only well in these networks that was not a domestic well; it was a county park well (Donna Runkle, written commun., June 8, 2009). There is a “large reservoir tank” before the sampling point (Donna Runkle, written commun., June 8, 2009); this might have affected the samples. Additionally, the well construction data in the DWH may be incorrect (Mary Ann Thomas, written commun., June 10, 2009). This sample is suspect.

The reconstructed ^3H plot is shown in figure G50. Most samples with $^3H/^3He$-based piston-flow recharge dates in the period from about the mid-1970s to the present are consistent with the ^3H input function for this area. The sample with the $^3H/^3He$-based piston-flow date in the 1940s and a reconstructed $^3H + ^3He$ value of about 10 TU is consistent with pre-bomb ^3H inputs in precipitation for this location (but the flat pre-bomb input function does not provide discrimination of age, just identification as being composed primarily of pre-bomb water). The four samples with $^3H/^3He$-based piston-flow dates in the 1960s and early 1970s plot below the ^3H input function, indicating that mixing and dispersion are operating on at least these samples.

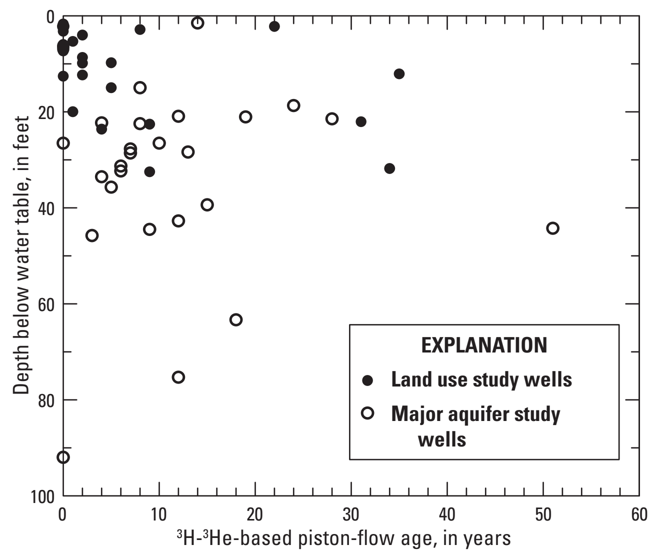


Figure G49. Age gradient for dated sites from the LUSCR1, LUSCR1a, LUSCR3a and SUS1 networks in the WHMI Study Unit.

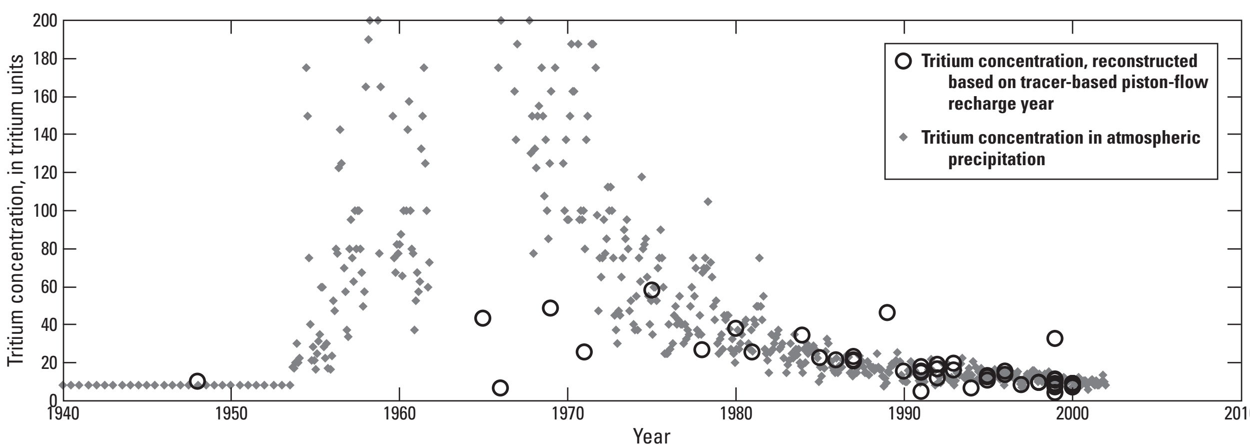


Figure G50. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSCR1, LUSCR1a, LUSCR3a and SUS1 networks, WHMI Study Unit.

WHMI LUSRC1 and REFOT1

Samples from 27 sites in the WHMI Study Unit were collected during 2001 for SF_6 (networks and, in parentheses, number of sites):

LUSRC1 (25)
REFOT1 (2)
See table G37.

The aquifer is composed of glacial sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table. For sites with major dissolved-gas data, the procedure was to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at the 1 suboxic site using median excess air from the 9 oxic sites. For sites without major dissolved-gas data, the median recharge temperature and median excess air estimates from the oxic sites were used.

SF_6 data were collected at 392008084335501 and 392008084343801 on two occasions, in July of 2001 and again in November of 2001. The November SF_6 data were compiled here because they were similar to the July SF_6 data yet had the advantage of being accompanied by a full suite of chemistry and water-level data.

Advantages associated with these samples:

- Major dissolved-gas data available for 10 of the 27 sites.
- Saturated open intervals were short: all were ≤5.00 feet.
- These were monitoring wells, therefore low pumping stress.
- These wells were installed close to the water table; median depth of center of open interval below water table: 10.99 feet.

Disadvantages associated with these samples:

- Extensive SF_6 contamination.

Depth to water (can affect tracer transport to water table):

- Median: 20.07 feet
- Mean: 22.46 feet
- Minimum: 2.87 feet
- Maximum: 42.99 feet

Brief analysis:

Of the 27 sites, 23 were contaminated and only 4 were datable. Given the extensive SF_6 contamination, it is possible that the 4 samples that were in the range of the SF_6 dating method also contained some SF_6 that was not from background atmospheric sources (that is, was from natural sources in sediments or was from atmospheric sources at above-background concentrations), and the tracer-based piston-flow ages may represent minimum ages.

The age gradient for these sites is shown in figure G51. There are few data in this figure for analysis. The essentially vertical age gradient could be consistent with these samples having been affected by natural SF_6 from aquifer sediments.

The reconstructed ^3H plot is shown in figure G52 for the 4 datable samples.

Three of the 4 samples plot within the ^3H input function. However, this analysis does not exclude the distinct possibility that these 4 samples might have been affected by SF_6 contamination. Earlier recharge would yield greater ^3H concentrations that also could plot within the ^3H input function.

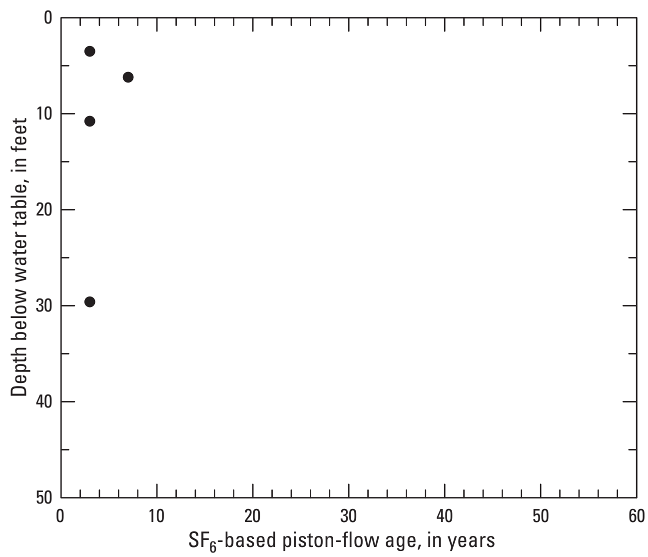


Figure G51 Age gradient for dated sites from the LUSRC1 and REFOT1 networks in the WHMI Study Unit.

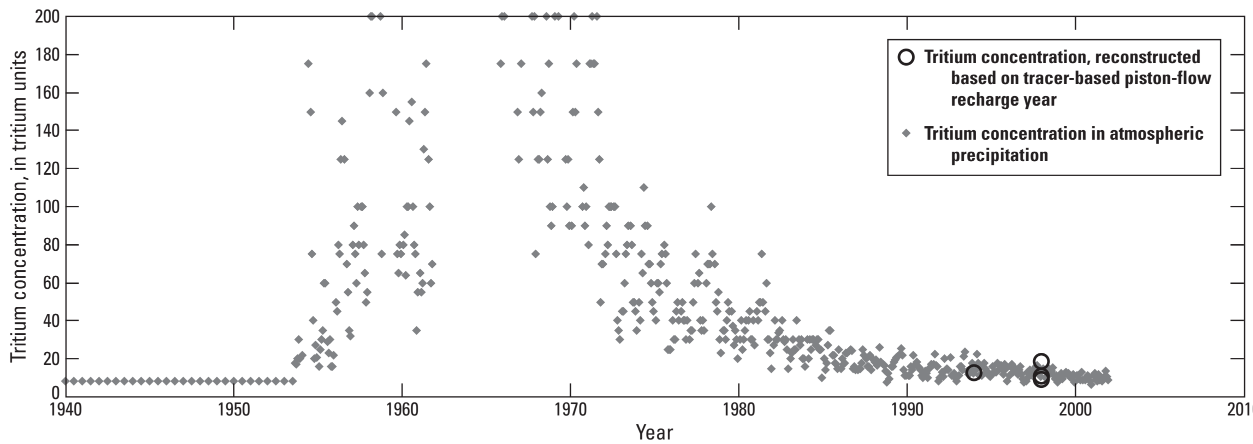


Figure G52. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSRC1 and REFOT1 networks, WHMI Study Unit.

WHMI LUSCR1 and REFOT1

Samples from 6 sites in the WHMI Study Unit were collected during 2007 for SF_6 (networks and, in parentheses, number of sites):

LUSCR1 (5)
REFOT1 (1)
See table G38.

The aquifer is composed of glacial sediments.

Only 1 of the 6 sites was oxic, and that one site had negative excess air (that is, the major dissolved-gas samples exhibited evidence of degassing), so the standard approach of using major dissolved-gas data from oxic sites to estimate typical excess air for the networks could not be used. For the one site with negative excess air, the procedure was to assume that recharge elevation was equal to the elevation of the water table, that recharge temperature was equal to the mean annual air temperature + 1 °C, and that the excess air concentration was 2 cc(STP)/Kg. For the other 5 sites, the procedure was to assume that recharge elevation was equal to the elevation of the water table, and to use 2 cc(STP)/Kg along with major dissolved-gas data to infer recharge temperatures.

Advantages associated with these samples:

Major dissolved-gas data were available for all 6 sites.

Short open intervals: median saturated open interval 5.00 feet.

Median penetration of center of the open interval into the water table was 13.72 feet (sampling close to the water table, potentially minimizing mixing).

These were monitoring wells, thus generally subject to low pumping stress.

Disadvantages associated with these samples:

No tracers other than SF_6.

Depth to water (can affect tracer transport to water table):

Median: 10.04 feet
Mean: 12.59 feet
Minimum: 8.09 feet
Maximum: 26.38 feet

Brief analysis:

The age gradient for these sites is shown in figure G53. The age gradient is composed of only 3 points, but they do suggest the presence of an approximately linear age gradient in the shallow portion of this aquifer.

WILL LUSAG3 and REFFO1

Samples from 18 sites in the WILL Study Unit were collected during 2002 for CFCs (networks and, in parentheses, number of sites):

LUSAG3 (16)
REFFO1 (2)
See table G39.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites.

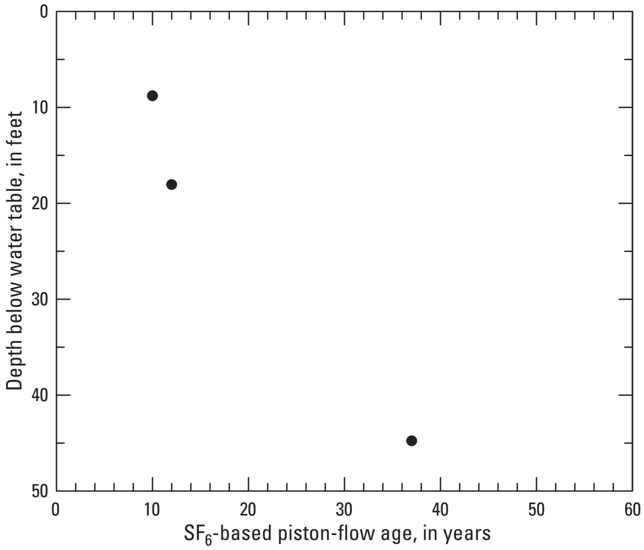


Figure G53. Age gradient for dated sites from the LUSCR1 and REFOT1 networks in the WHMI Study Unit.

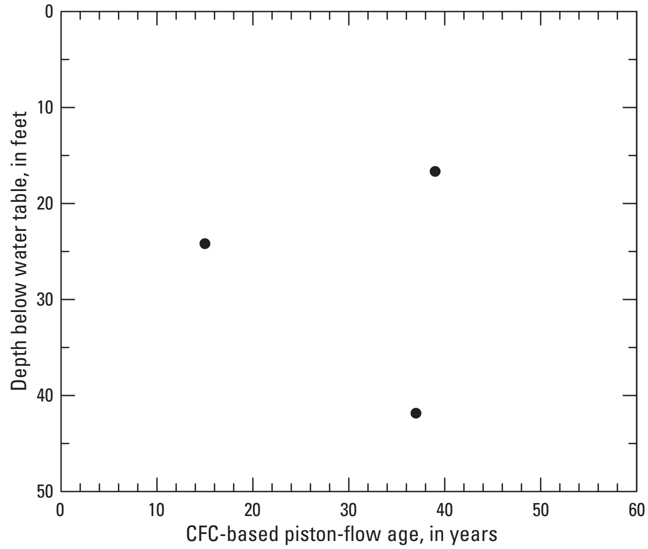


Figure G54. Age gradient for dated sites from the LUSAG3 and REFFO1 networks in the WILL Study Unit.

Advantages associated with these samples:

Major dissolved-gas data were available for all 18 sites.

Although these were supply wells, the open intervals were moderately short (median saturated open interval = 10 feet).

Disadvantages associated with these samples:

No tracers other than CFCs.

Reducing conditions were common. The median field O_2 was 0.3 mg/L, and CH_4 was commonly detected (8 detections, between 0.0010 and 0.1458 mg/L, with median of the 8 = 0.0114 mg/L).

Depth to water (can affect tracer transport to water table):

Median: 16.05 feet
Mean: 20.47 feet
Minimum: 3.30 feet
Maximum: 60.33 feet

Brief analysis:
The age gradient is composed of only 3 data points (fig. G54). Nevertheless, to be consistent with the approach taken with other networks, the age gradient is shown.

YELL LUSOT1

Samples from 28 sites in the YELL Study Unit were collected during 2001 for CFCs (network and, in parentheses, number of sites):

LUSOT1 (28) (low-density residential land use)
See table G40.

The aquifer is composed of sediments.

The procedure was to assume that recharge elevation was equal to the elevation of the water table, to estimate recharge temperature and excess air at oxic sites based upon major dissolved-gas data, and to constrain recharge temperature and excess air at suboxic sites using median excess air at oxic sites. (At one site in this network, major dissolved-gas data were available but tracer data were not available; interpretation of the major dissolved-gas data for this site was included in this appendix.)

Advantages associated with these samples:

Major dissolved-gas data were available for all sites that had CFC analyses.

These monitoring wells had short saturated open intervals (all saturated open intervals $\leq$10 feet).

The median penetration of the center of the open interval into the water table was 4.66 feet (for the 28 wells sampled for CFCs) (sampling close to the water table, potentially minimizing mixing).

Monitoring wells, therefore low pumping stress.

Mostly oxic (median field O_2 = 3.0 mg/L, for the 28 wells sampled for CFCs); only one sample contained detectable CH_4 (at 0.0011 mg/L).

Disadvantages associated with these samples:

Four of the datable sites also had ^{3}H data, but multiple tracers were otherwise lacking.

Depth to water (can affect tracer transport to water table) (calculated for the 28 sites with CFC data):

Median: 6.48 feet
Mean: 12.42 feet
Minimum: 0.93 feet
Maximum: 48.20 feet

Brief analysis:

The age gradient for this network (fig. G55) shows little structure, in part because these wells represent only the uppermost 9 feet of the aquifer. However, the overall pattern of relatively young groundwater from sampling points near the water table in recharge areas is consistent with the network design.

Four of the datable sites had ^{3}H data. The reconstructed ^{3}H plot is shown in figure G56. The ^{3}H data could be consistent with these four samples being relatively unmixed and approximating piston-flow transport.

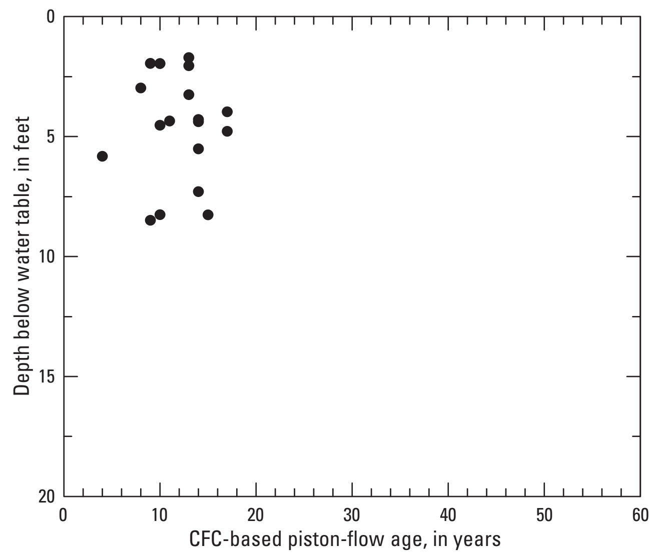


Figure G55. Age gradient for dated sites from the LUSOT1 network in the YELL Study Unit.

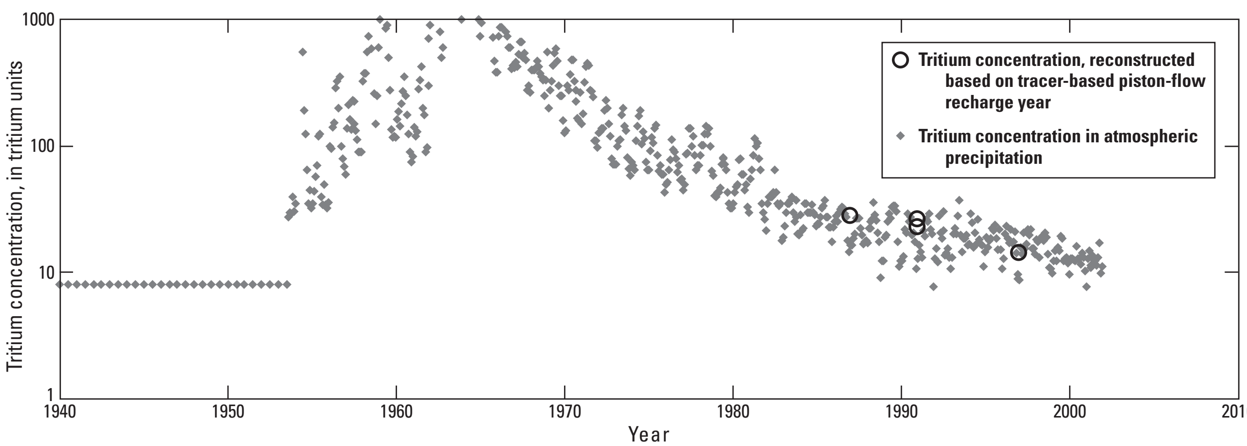


Figure G56. Reconstructed tritium concentrations and tritium in atmospheric precipitation for the LUSOT1 network, YELL Study Unit.

References Cited in Appendix G

Anderholm, S.K., 1996, Water-quality assessment of the Rio Grande Valley, Colorado, New Mexico, and Texas—Shallow ground-water quality of a land-use area in the San Luis Valley, south-central Colorado, 1993: U.S. Geological Survey Water-Resources Investigations Report 96-4144, 94 p.

Busenberg, Eurybiades, and Plummer, L.N., 2000, Dating young groundwater with sulfur hexafluoride: Natural and anthropogenic sources of sulfur hexafluoride: Water Resources Research, v. 36, no. 10, p. 3011–3030.

Bush, P.W., Ardis, A.F., Fahlquist, Lynne, Ging, P.B., Hornig, C.E., and Lanning-Rush, Jennifer, 2000, Water Quality in South-Central Texas, Texas, 1996–98: U.S. Geological Survey Circular 1212, 32 p.

Cook, P.G., and Böhlke, J.K., 2000, Determining timescales for groundwater flow and solute transport, *in* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, p. 1–30.

Ebbert, J.C., and Moon, H.K., 1998, Relation between irrigation method, sediment yield, and losses of pesticides and nitrogen: Journal of Environmental Quality, v. 27, p. 372–380.

International Atomic Energy Agency, 2006, Use of chlorofluorocarbons in hydrology—A guidebook: Vienna, Austria, International Atomic Energy Agency (IAEA), 277 p.

Jones, J.L., and Wagner, R.J., 1995, Water-quality assessment of the central Columbia Plateau in Washington and Idaho—Analysis of available nutrient and pesticide data for ground water, 1942-92: U.S. Geological Survey Water-Resources Investigations Report 94-4258, 119 p.

Rademacher, L.K., Clark, J.F., Hudson, G.B., Erman, D.C., and Erman, N.A., 2001, Chemical evolution of shallow groundwater as recorded by springs, Sagehen basin; Nevada County, California: Chemical Geology, v. 179, p. 37-51.

Starn, J.J., and Brown, C.J., 2007, Simulations of ground-water flow and residence time near Woodbury, Connecticut: U.S. Geological Survey Scientific Investigations Report 2007-5210, 45 p.

Wassenaar, L.I., Hendry, M.J., and Harrington, N., 2006, Decadal geochemical and isotopic trends for nitrate in a transboundary aquifer and implications for agricultural beneficial management practices: Environmental Science and Technology, v. 40, p. 4626-4632.

Description of Data Files in Appendix G

These data files are organized by Study Unit (see figure 1 in the body of the report, and table A1 in appendix A) and Network (see table A1 in appendix A).

Each file contains a "Summary" table that includes USGS site identification numbers, dates of sample collection, tracer-based piston-flow ages and tracer-based piston-flow recharge dates, selected environmental tracer data, and ancillary data such as well-construction data and basic geochemical data. The sources of these data and interpretations were described in the body of the report.

Each file also contains a "Raw Tracer Data" table. This table contains detailed information on environmental tracer concentrations. The sources of these data were described in the body of the report.

For Networks where major dissolved-gas data were collected, a "Major Dissolved Gases" table is included. This table contains detailed information on major dissolved-gas concentrations. The source of these data was described in the body of the report.

Appendix G tables can be accessed and downloaded at URL http://pubs.usgs.gov/sir/2010/5229/data/sir20105229_apps.zip.

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Hinkle and others— **Estimates of Tracer-Based Piston-Flow Ages of Groundwater from Selected Sites, 1992–2005**—Scientific Investigations Report 2010–5229