Prepared in cooperation with the U.S. Department of the Army

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Scientific Investigations Report 2010–5178

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

Front cover: Illustration adapted from a photograph of Big Creek facing west and downstream near well JPG-DU-02I at the former Jefferson Proving Ground, near Madison, Indiana (photograph by David C. Lampe, June 21, 2007).

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Conversion Factors, Water-Quality Units, and Abbreviations

Inch/Pound to Metric (SI) units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	0.254	millimeter (mm)
inch (in.)	2.54×10^{-4}	micrometer (μm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	259	hectare (ha)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	3.785×10^{3}	milliliter (mL) or cubic centimeter (cm^3)
gallon (gal)	3.785×10^{6}	microliter (μL)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)

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

$$°C= (°F-32)/1.8$$

Metric (SI) to Inch/Pound units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	3.937×10^{-2}	inch (in.)
micrometer (µm)	3.937×10^{-5}	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
milliliter (mL)	2.642×10^{-4}	gallon (gal)
microliter (µL)	2.642×10^{-7}	gallon (gal)
	Flow rate	
liter per second (L/s)	951	gallon per minute (gal/min)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound, avoirdupois (lb)
	Pressure	
pascal (Pa)	9.869×10^{-6}	atmosphere, standard (atm)
pascal (Pa)	1×10^{-5}	bar

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

$$°F= (1.8\times°C) +32$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) unless otherwise noted. Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83), unless otherwise noted. Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviated water-quality and other units used in this report

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), or picograms per liter (pg/L). Chemical concentrations and water temperature are given in metric units.

A **milligram per liter** (mg/L) is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. For water with dissolved-solids concentrations less than 7,000 mg/L, the numerical value for milligrams per liter is the same as for concentrations in parts per million.

A concentration of 1,000 **micrograms per liter** (µg/L) is equivalent to 1 milligram per liter. For water with dissolved-solids concentrations less than 7,000 mg/L, the numerical value for micrograms per liter is the same as for concentrations in parts per billion.

A concentration of 1 million **picograms per liter** (pg/L, also picograms per kilogram of pg/kg) is equivalent to 1 milligram per liter.

The unit **millimole per liter** (mmol/L) expresses the concentration of chemical constituents in solution as the weight of a chemical substance, in milligrams (10^{-3} g), in a liter of water, divided by the atomic weight of one atom or molecule of its composition elements, in grams (one mole). A **micromole per liter** (µmol/L) is a unit expressing the concentration of chemical constituents in solution as the weight of a chemical substance, in micrograms (10^{-6} g), in a liter of water, divided by the atomic weight of one atom or molecule of its composition elements, in grams. A **nanomole per kilogram** (nmol/kg) is a unit expressing the concentration of chemical constituents in solution as the weight of a chemical substance, in nanograms (10^{-9} g), in one kilogram of water, divided by the atomic weight of one atom or molecule of its composition elements, in grams. These units are used in this report to describe concentrations of dissolved gases and constituents in a water sample.

Concentrations of the dissolved gases helium and neon are also reported in units of **cc x 10^9/g of water at STP**; this corresponds to 10^9 cubic centimeters of a dissolved gas per gram of water at standard temperature (25 degrees Celsius) and pressure (760 millimeters of mercury).

A **Formazin Nephelometric Ratio Unit** or **FNRU** is a unit of measure used to report the turbidity of water. Turbidity is a measure of the cloudiness of water and is measured by the amount of light that is scattered and absorbed instead of transmitted through the water by a standard light measuring device, or nephelometer.

One **tritium unit** (TU) is equivalent to a concentration of 3.2 picocuries per liter.

Hydraulic conductivity is given in units of feet per day.

Other abbreviations or acronyms used in this report

Acronym or abbreviation	Full name of acronym or abbreviation
Army	U.S. Department of the Army
CFC	Chlorofluorocarbon compound
CFC-11	Trichlorofluoromethane or $CFCl_3$
CFC-113	Trichlorotrifluoroethane or $C_2F_3Cl_3$
CFC-12	Dichlorodifluoromethane or CF_2Cl_2
CH_4	Methane
CO_2	Carbon dioxide
DU	Depleted uranium
FNRU	Formazin Nephelometric Ratio Units
He	Helium
JPG	Jefferson Proving Ground
NTU	Nephelometric Turbidity Unit
NWQL	National Water Quality Laboratory
O	Oxygen
pptv	Part per trillion by volume
PVC	Polyvinyl chloride
QA	Quality assurance
QC	Quality control
RPD	Relative percent difference
SAIC	Science Applications International Corporation
SC	Specific conductance
TU	Tritium unit
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UXO	Unexploded ordnance

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Abstract

During 2007–08, the U.S. Geological Survey, in cooperation with the U.S. Department of the Army, conducted a study to evaluate the relative age of groundwater in Pre-Wisconsinan till and underlying shallow and deep carbonate bedrock units in and near an area at Jefferson Proving Ground (JPG), southeastern Indiana, which was used during 1984–94 to test fire depleted uranium (DU) penetrators. The shallow carbonate unit includes about the upper 40 feet of bedrock below the bedrock-till surface; the deeper carbonate unit includes wells completed at greater depth. Samples collected during April 2008 from 15 wells were analyzed for field water-quality parameters, dissolved gases, tritium, and chlorofluorocarbon (CFC) compounds; samples from 14 additional wells were analyzed for tritium only.

Water-level gradients in the Pre-Wisconsinan till and the shallow carbonate unit were from topographically higher areas toward Big Creek and Middle Fork Creek, and their tributaries. Vertical gradients were strongly downward from the shallow carbonate unit toward the deep carbonate unit at 3 of 4 paired wells where water levels recovered after development; indicating the general lack of flow between the two units. The lack of post development recovery of water levels at 4 other wells in the deep carbonate unit indicate that parts of that unit have no appreciable permeability.

CFC and tritium-based age dates of Pre-Wisconsinan till groundwater are consistent with infiltration of younger (typically post-1960 age) recharge that "mixes" with older recharge from less permeable or less interconnected strata. Part of the recharge to three till wells dated from the early to mid-1980s (JPG-DU-03O, JPG-DU-09O, and JPG-DU-10O). Age dates of young recharge in water from two till wells predated 1980 (JPG-DU-04O and JPG-DU-06O). Tritium-based age dates of water from seven other till wells indicated post-1972 age recharge. Most wells in the Pre-Wisconsinan till have the potential to produce groundwater that partially was recharged during or after DU penetrator testing; their water quality can indicate the presence of DU-related contaminants.

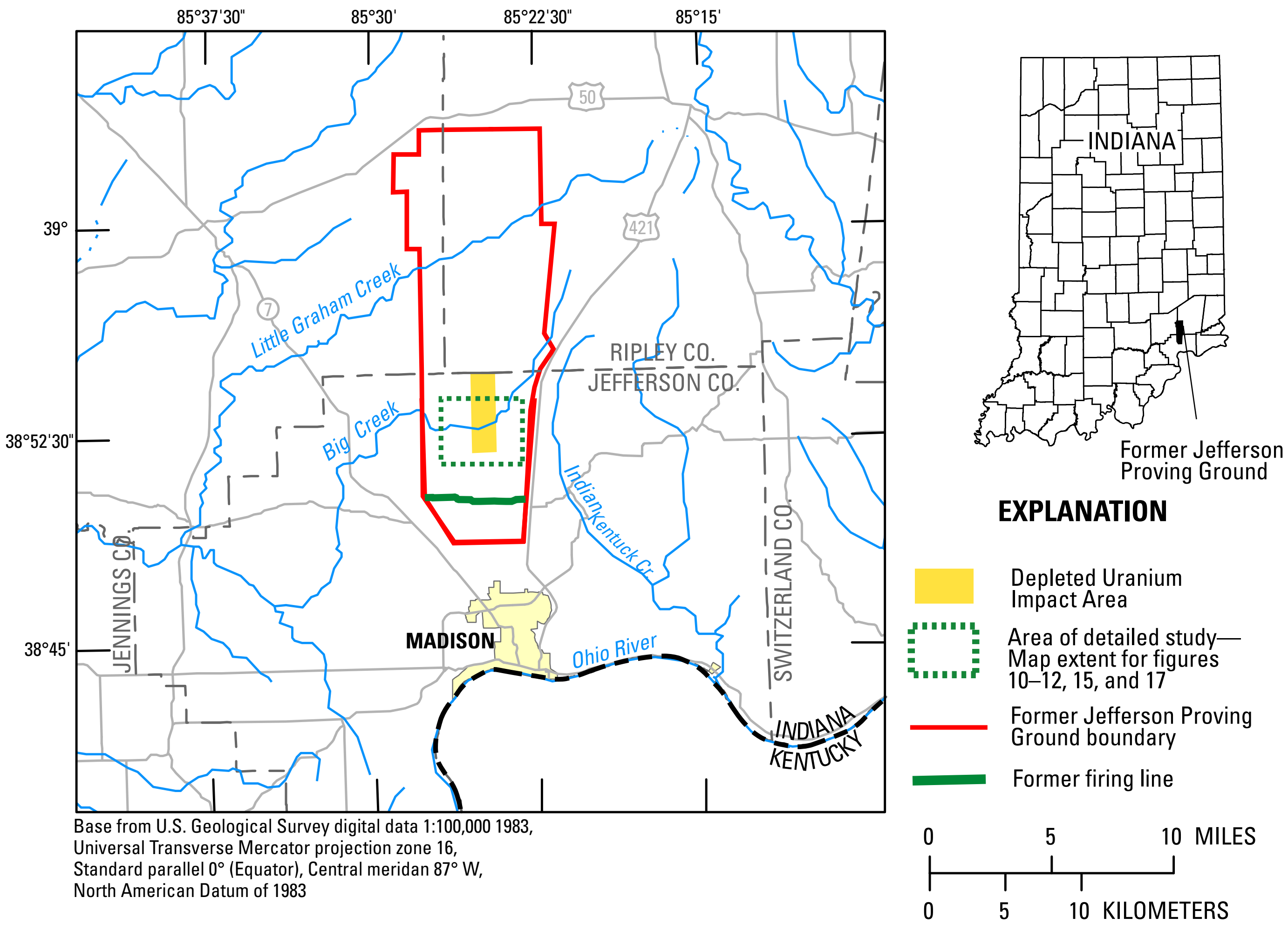
The shallow carbonate unit near Big Creek is a karst flow system that may be recharged in part from areas with smaller thicknesses of overlying till or through more permeable parts of the till. This is indicated by CFC- and tritium-based piston-flow (non-mixing) model age dates of early-1980s for water from JPG-DU-02I, similar tritium-based ages of water produced from nearby wells MW-5 and MW-11, and cave development along the creek. The CFC and tritium-based age dates indicate that water samples from JPG-DU-01I and JPG-DU-03I were best described as mixtures of post-1984 modern recharge and submodern (1953 or older) recharge. These five wells produced groundwater that was recharged, at least partially, during or after DU-penetrator testing and are within or downgradient from the DU Impact Area with respect to groundwater flow directions inferred from water-level contours. Wells with groundwater age dates that are near to or after the onset (1984) of DU penetrator testing and that have a plausible connection to a contaminant source can be used to indicate the presence or absence of contaminants from DU penetrator or DU-related corrosion products in groundwater.

Groundwater-age dates indicate that the ages of recharge sampled from shallow carbonate unit wells JPG-DU-04I, JPG-DU-05I, JPG-DU-06I, JPG-DU-09I, and JPG-DU-10D in easternmost (upgradient) and southernmost wells in the shallow carbonate unit are submodern (1953 or older) and predate the DU testing by at least 30 or more years. Water-quality data from these five wells are not likely to represent effects from DU-projectile testing or corrosion for years.

Well JPG-DU-09D in the deep carbonate unit produced groundwater samples with a submodern (1953 or older) age date. The slow recovery of water levels in most wells in the deep carbonate unit is consistent with slow rates of groundwater flow and very old groundwater ages in that unit.

Introduction

Jefferson Proving Ground (JPG), located in southeastern Indiana, is a facility of approximately 86 mi^2 (fig. 1) that was operated by the U.S. Department of the Army (Army) from 1940 to 1995 for testing conventional ammunition, other ordnance items, and propellant-based ammunition and weapons systems (U.S. Department of the Army, 2005). The



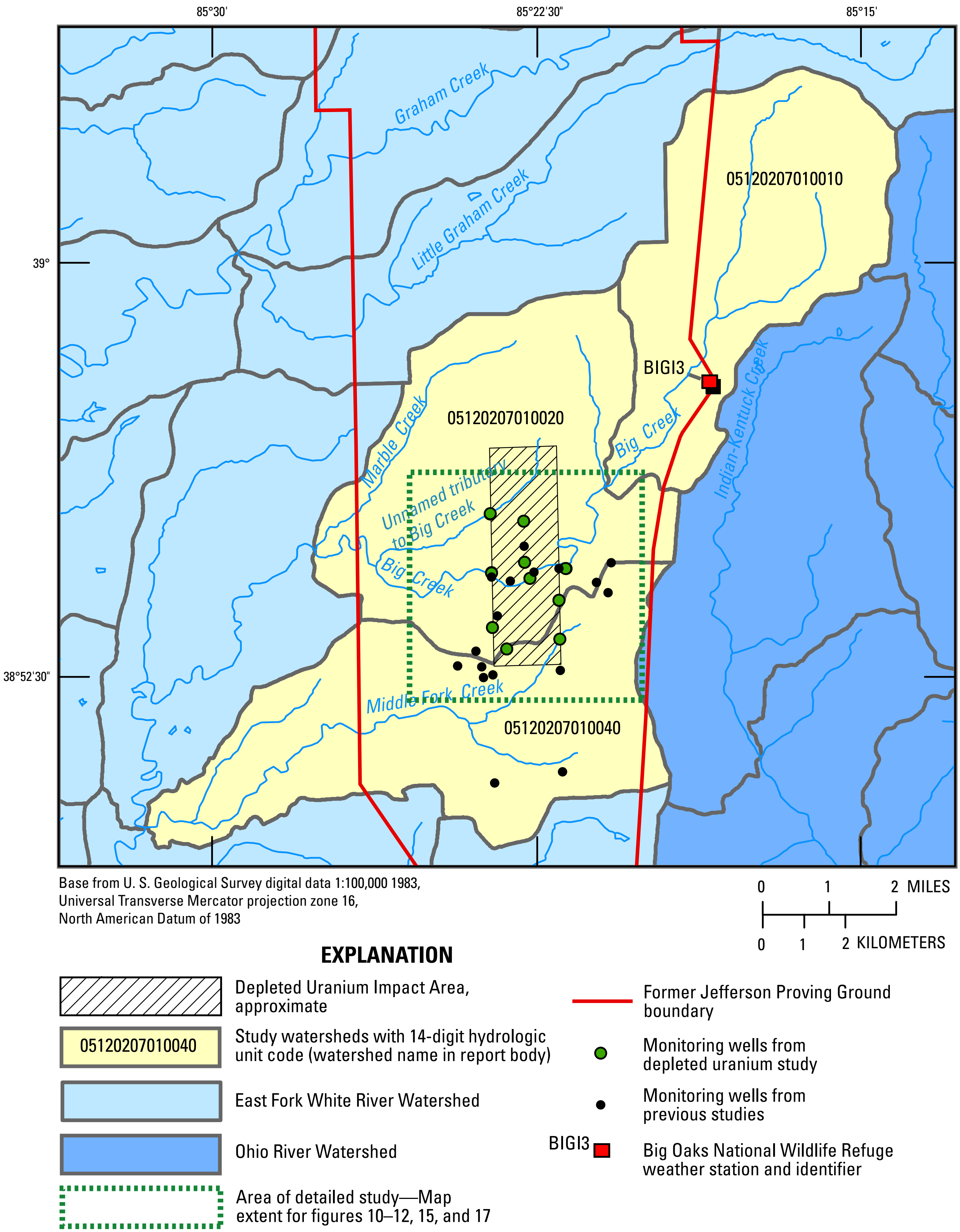
Base from U.S. Geological Survey digital data 1:100,000 1983,
Universal Transverse Mercator projection zone 16,
Standard parallel 0° (Equator), Central meridan 87° W,
North American Datum of 1983

Figure 1. Study area and Depleted Uranium Impact Area, Jefferson Proving Ground, southeastern Indiana.

facility consisted of a northern firing range area (about 80 mi^2; 51,000 acres) and a southern cantonment area, separated by an east-west oriented firing line. During 1984–94, the Army test fired depleted uranium (DU) projectiles (“penetrators”) from three positions along the firing line into an approximately 3.3 mi^2 (about 2,100 acres) area north of the firing line, known as the DU Impact Area (fig. 1). Possession and test firing of DU penetrators into the DU Impact Area were done under a license issued by the Nuclear Regulatory Commission (NRC) (License SUB-1435, Docket 040-08838).

The potential contaminant sources examined during this investigation are the possible leaching of DU from remaining penetrators and corrosion products from the penetrators into groundwater in and around the vicinity of the DU Impact Area. The potential transport of DU and its corrosion products in groundwater and surface water and their environmental fate is a matter of concern to the Army, the NRC, and local residents. Natural uranium is composed of three radioactive isotopes of uranium (U); the isotopes are identified by their atomic mass numbers ^{238}U (99.2745 percent by mass), ^{235}U (0.7200 percent by mass), and ^{234}U (0.0055 percent by mass) (Smith, 2001, p. iii; Grossblatt, 2008). DU is the fraction of uranium that remains after natural uranium is processed to preferentially remove one of its isotopes (uranium-235).

The Army has petitioned the NRC to decommission the DU Impact Area. In 2006, the Army and its contractor, Science Applications International Corporation (SAIC), began investigating the hydrology and hydrogeologic framework of parts of the area north of the firing line to better understand the nature and extent of possible groundwater contaminants from DU-penetrator testing and processes that would affect their fate and transport. The Army and SAIC installed observation wells in 2007 in unconsolidated glacial till overburden (Pre-Wisconsinan till) and in shallow and deeper units within carbonate bedrock (“shallow carbonate unit” and “deep carbonate unit”) in and around the DU Impact Area (fig. 2). The Army and SAIC also monitored surface-water stage in the Big Creek and Middle Fork Creek drainage areas and springflow at gaged sites located within and at the upgradient and downgradient boundaries of the DU Impact Area; however, those sites and results are not discussed in this report. The hydrologic data were collected to provide information to further refine the



Base from U. S. Geological Survey digital data 1:100,000 1983,
Universal Transverse Mercator projection zone 16,
North American Datum of 1983

Figure 2. Approximate extent of Depleted Uranium Impact Area relative to watersheds, monitoring wells, and a weather station, Jefferson Proving Ground, southeastern Indiana.

conceptual site model (CSM) of site hydrogeology and to identify locations that are best suited for sampling groundwater and monitoring groundwater levels in these zones.

Prior studies in other carbonate aquifers have identified how understanding the age of groundwater since it recharged to an aquifer (“age dating”), in combination with conventional hydrogeologic methods, can help define groundwater-flow mechanisms and factors that affect transport of possible contaminants (Lindsay and others, 2003, 2009). Groundwater age is defined as an estimated number of years since infiltrating water reached the water table and recharged the aquifer. Application of multiple age-dating tracers, such as tritium and chlorofluorocarbon compounds, can assist in the verification of dates of groundwater age and identify likely mixtures involving waters of different ages since recharge (Plummer and others, 2003). This knowledge can be used to evaluate whether wells produce water that recharged before or after the introduction of a possible contaminant source or that represent a “mixture” of water with those ages. Estimates of the groundwater age from observation wells also can be helpful in interpreting the groundwater-flow system, groundwater-chemistry data, and geochemical modeling of potential DU-constituent transport.

As part of the overall hydrologic investigation, the U.S. Geological Survey (USGS), in cooperation with the Army and in coordination with SAIC, began an investigation in 2007 to characterize the age of water from wells developed in the Pre-Wisconsinan till, shallow carbonate, and deep carbonate hydrogeologic units in and near the DU Impact Area. Age dates of groundwater can assist with the interpretation of groundwater chemistry and of subsurface processes affecting transport of corrosion products from DU-penetrator testing. Dates of groundwater age can aid in the identification of which wells produce water whose recharge dates from before about 1984. Wells with age dates predating the penetrator testing can be used to assess background pre-testing water-chemistry conditions. These wells, by definition, sample parts of the hydrogeologic units that were not susceptible to DU contamination when the sampling was done. Wells with age dates after the onset (1984) of DU-penetrator testing and that have a plausible connection to a contaminant source can be used to indicate the presence or absence of contaminants from DU penetrator or DU-related corrosion products in groundwater.

Purpose and Scope

This report describes the results of an investigation to identify the age of groundwater in Pre-Wisconsin till, shallow, and deeper carbonate bedrock units in and near the DU Impact Area at Jefferson Proving Ground, Indiana, using analyses of tritium, chlorofluorocarbon (CFC) compounds, and dissolved gases. The dates of groundwater age were used to evaluate whether recharge dating from the onset of DU-projectile testing (1984) or later had reached the sampled intervals of the hydrogeologic units and thereby classify the suitability of wells to monitor groundwater quality for effects related to leaching of DU penetrator or DU-related corrosion products. The report also describes basic information about the hydrogeologic framework of water-bearing units sampled in the study area, with special emphasis on differences between groundwater levels in the unconsolidated Pre-Wisconsinan till, and in the shallow and deeper parts of carbonate bedrock formations. The water-level data also were used in the selection of wells for sampling and analysis and to estimate recharge altitudes for CFC-based age-dating analysis. Dissolved-gas analyses of groundwater were interpreted to estimate the temperature of water at the time it infiltrated below the water table and into groundwater; the recharge temperatures are used to estimate the atmospheric mixing ratios of CFCs that are used for age dating.

Groundwater ages that were younger than about 1980 (1984 being the onset of DU-projectile testing) were used to indicate wells that produce water potentially capable of indicating water-quality conditions affected by DU-projectile testing and the subsequent potential leaching of DU and corrosion products into groundwater. Groundwater ages older than about 1980 were used to classify wells that were not immediately susceptible to contamination from DU penetrator or DU-related corrosion products.

Description of the Study Area

The part of the study area that encompasses the sampled wells, the “area of detailed study,” includes about 12.7 mi^2 of Jefferson Proving Ground in central Jefferson County, southeastern Indiana (fig. 2). The DU Impact Area is within area of detailed study; the DU Impact Area is about 3.3 mi^2 (fig. 2). The study area includes the watersheds of streams that flow to the west and southwest across the study area including Middle Fork Creek and unnamed tributaries (within 14-digit hydrologic unit 05120207010040—Middle Fork Creek—Jefferson) and Big Creek and unnamed tributaries (within 14-digit hydrologic unit 05120207010020—Big Creek-Marble Creek; fig. 2; DeBroka and Cohen, 1999). The drainage areas of these hydrologic units extend both upstream and downstream from the DU Impact Area; surface water from these areas drains to the Muscatatuck River and then to the East Fork White River. East of the study area, streams flow to the east, then south to the Ohio River.

Land-surface altitudes are highest in the flat upland areas between drainages and range from about 880 to 890 ft above the vertical datum (U.S. Geological Survey, 1959, 1992). Land-surface altitudes are lowest in the valleys of streams that cross the study area, about 770 ft above the vertical datum, about 1.5 mi west and downstream from where Big Creek leaves the DU Impact Area; 810 to 820 ft above the vertical datum in the valley of a tributary to Middle Fork Creek, about 0.75 mi downstream from where it flows out of the DU Impact Area; and about 830 ft above the vertical datum where an unnamed tributary of Big Creek flows to the southwest, about 1.5 west of the DU Impact Area (U.S. Geological Survey, 1959, 1992).

The climate of Jefferson Proving Ground area is continental and is characterized by strongly marked seasons (Scheeringa, 2002). The study area is in the transition zone between cool polar air to the north and warm, tropical moisture-laden air masses from the south. Summers are hot and humid; winters are cold and damp. Temperatures range from an average high/low of 3.7/-5.2°C in January to a high/low of 30.3/19.1°C in July, based on weather data for Madison, Indiana, for 1971–2000 (Midwestern Regional Climate Center, 2009a). The average annual temperature for Madison was 12.6°C during 1971–2000 (Midwestern Regional Climate Center, 2009a). Average monthly precipitation for Madison typically ranges from 2.92 in. in September to 4.96 in. in May (Midwestern Regional Climate Center, 2009b). The average annual precipitation for Madison during 1971–2000 was 46.09 in./year (Midwestern Regional Climate Center, 2009b). Precipitation is greatest during March–August but is received each month of the year.

Uses of areas north of the firing line are chiefly forested land, grassed land, and wetlands. Areas north of the firing line contain unexploded ordnance and residue from testing of nonexplosive ordnance and projectiles. The U.S. Fish and Wildlife Service has managed the wildlife resources of JPG since 1996 and for most of JPG north of the firing line (including the DU Impact Area) as an overlay refuge named “Big Oaks National Wildlife Refuge” since June 2000. The U.S. Fish and Wildlife Service manages the refuge under a 25-year agreement in which the Army retains ownership of JPG.

Hydrogeologic Framework

The hydrogeologic framework is summarized in terms of the water-bearing units that were sampled and their relation to physiography and geology. The study area is in the southeastern part of the Muscatatuck Plateau physiographic division of the Southern Hills and Lowlands region of Indiana (Gray, 2000, plate 1). The area is part of the westernmost extent of the Vernon Segment hydrogeologic terrain (Fleming and others, 1995), a west to southwest sloping set of gently rolling to flat erosional surfaces that have been incised and dissected by streams that are tributary to the Muscatatuck River.

The area is south and outside the limit of Wisconsin glaciation; this report refers to the till and related unconsolidated overburden (soil and loess) in the study area as Pre-Wisconsinan till. Till surfaces generally are flat to gently sloping on upland areas but are deeply dissected and completely removed along the most deeply incised stream channels along Big Creek, Middle Fork Creek, and other tributaries. The till is described as a poor aquifer because of the abundance of clay and silt and the lack of coarse grained aquifer units (Greeman, 1981); these characteristics would also make the Pre-Wisconsinan till a poor medium for contaminant transport. Recharge to water-bearing units below the fine grained till occurs slowly but is thought to be more rapid where the till is thinnest or removed by erosion.

The Pre-Wisconsinan till is underlain by near-surface carbonate rocks that are part of the lower limestone and dolomite sequence of Silurian Age and the Whitewater Formation of Ordovician Age, as described by Greeman (1981). The bedrock surface is described as dipping westward at about 20 ft/mi (Schneider, 1966). The lower limestone and dolomite sequence beneath the study area likely includes lower parts of the Salamonie Dolomite and the Brassfield Limestone (Gray, 1972; Shaver and others, 1986). The Salamonie Dolomite is described as argillaceous limestone, dolomitic limestone with shale partings, and ranges in thickness from 0 to about 80 ft in and near JPG (Shaver and others, 1986; Greeman, 1981). The Brassfield Limestone is described as ranging in thickness from 0 to 20 ft and generally as a medium- to coarse-grained fossiliferous limestone with some dolomite. The Whitewater Formation is characterized as thinly interbedded limestone, argillaceous limestone and shale beds, with shale beds increasing with depth.

Sizeable areas of the Vernon segment hydrogeologic terrain in southeastern Indiana include carbonate bedrock that exhibits karst solution features, including sinkholes, solution enlarged joints and fractures, and a few small caves (Fleming and others, 1995). The principal karst development in the carbonate rock in this physiographic division typically is restricted to narrow areas close to the entrenched streams (Gray, 2000, p. 11), although some karst development beneath thin drift deposits is possible. In this area, the upland surface between areas of incised drainage slopes westward at a rate somewhat less than the regional dip of Silurian strata. The easternmost part of the study area borders parts of the western extent of the Newpoint Plain, a largely plateau area east of the study area and JPG.

Fracture-trace analysis (Greeman, 1981; Science Applications International Corporation, 2007a) and surface geophysical surveys (electrical imaging; Science Applications International Corporation, 2007a) indicated evidence of karst features and preferential flow pathways in the subsurface beneath and adjacent to the DU Impact Area. The SAIC electrical-imaging survey also provided data that indicated a paleokarst surface that may have appreciable relief (from about 20 to 100 ft) beneath the Pre-Wisconsinan till; that surface indicated by resistivity of about 450 ohm-meters or more. Caves have been mapped in limestone exposures in JPG along Big Creek (19 caves) and Middle Fork Creek (2 caves), although not all had active flowing groundwater (Sheldon, 1997). The uppermost 20 to 30 ft of the carbonate bedrock at sites south of the firing line contributed water to vertical flowmeter tests of aquifer properties by Wilson and others (2001). Although similar data are not available for wells north of the firing line, many wells installed by SAIC and during prior hydrogeologic investigations were screened or open to permeable zones within about 1 to 40 ft below the till-bedrock interface.

Based on the above descriptions, the water-bearing units sampled for this study have been divided for the purpose of this investigation into the following preliminary hydrogeologic framework: Pre-Wisconsinan till, shallow carbonate unit, and deep carbonate unit (table 1). Wells classified as producing groundwater from Pre-Wisconsinan till have well screens that are open to overburden deposits above the bedrock surface. Wells classified as producing groundwater from the shallow carbonate unit have well screens that are open to the carbonate bedrock within about 1 to 40 ft below the bedrock surface. The shallow carbonate unit is not a true stratigraphic classification; it represents a zone of fractures, paleokarst, and other dissolution-modified features within the upper 40 ft of carbonate bedrock. The deep carbonate unit is defined by wells that are completed at depths of more than 40 ft below the bedrock surface or are isolated by zones of very low permeability. The deep carbonate unit represents a less transmissive and less productive sequence of the carbonate bedrock and may be characterized by longer groundwater flow paths and older recharge.

Methods of Data Collection and Analysis

Fifteen observation wells were selected to sample and analyze groundwater for concentrations of several dissolved gases, tritium, and CFCs. These 15 wells were selected from among the 23 wells installed in 2007 by SAIC as part of evaluating the hydrogeologic framework of the DU Impact Area (fig. 3); they are identified with the prefix “JPG-DU.” These 23 wells were installed in areas where, according to background data collection, active, water-saturated zones in the hydrogeologic units were most likely to be encountered by drilling. Additional samples were collected from 14 wells installed for prior studies at JPG but that were open to the same hydrogeologic units sampled in the DU Impact Area; those wells are identified with the prefixes “MW” and “MW-RS.” The 14 wells are within the DU Impact Area and in adjacent areas of JPG; water sampled from those wells was analyzed for concentrations of tritium only. Geologic and well-construction information about these well locations is summarized in table 2 (at end of report). The JPG-DU wells were accessible by previously cleared roads and are at sites that have been examined for DU and unexploded ordnance. The MW and MW-RS wells were in areas with more limited examination and access; those samples were collected for USGS by SAIC personnel.

Several criteria were used to indicate the suitability of wells to sample for dissolved gases and age-dating constituents:.

Slow water-level recovery. If water levels in a well did not recover since post-installation pumping and development or did not recover after pre-sampling measurement of field properties and collection of water samples by SAIC, no dissolved gas or age-dating samples were collected.

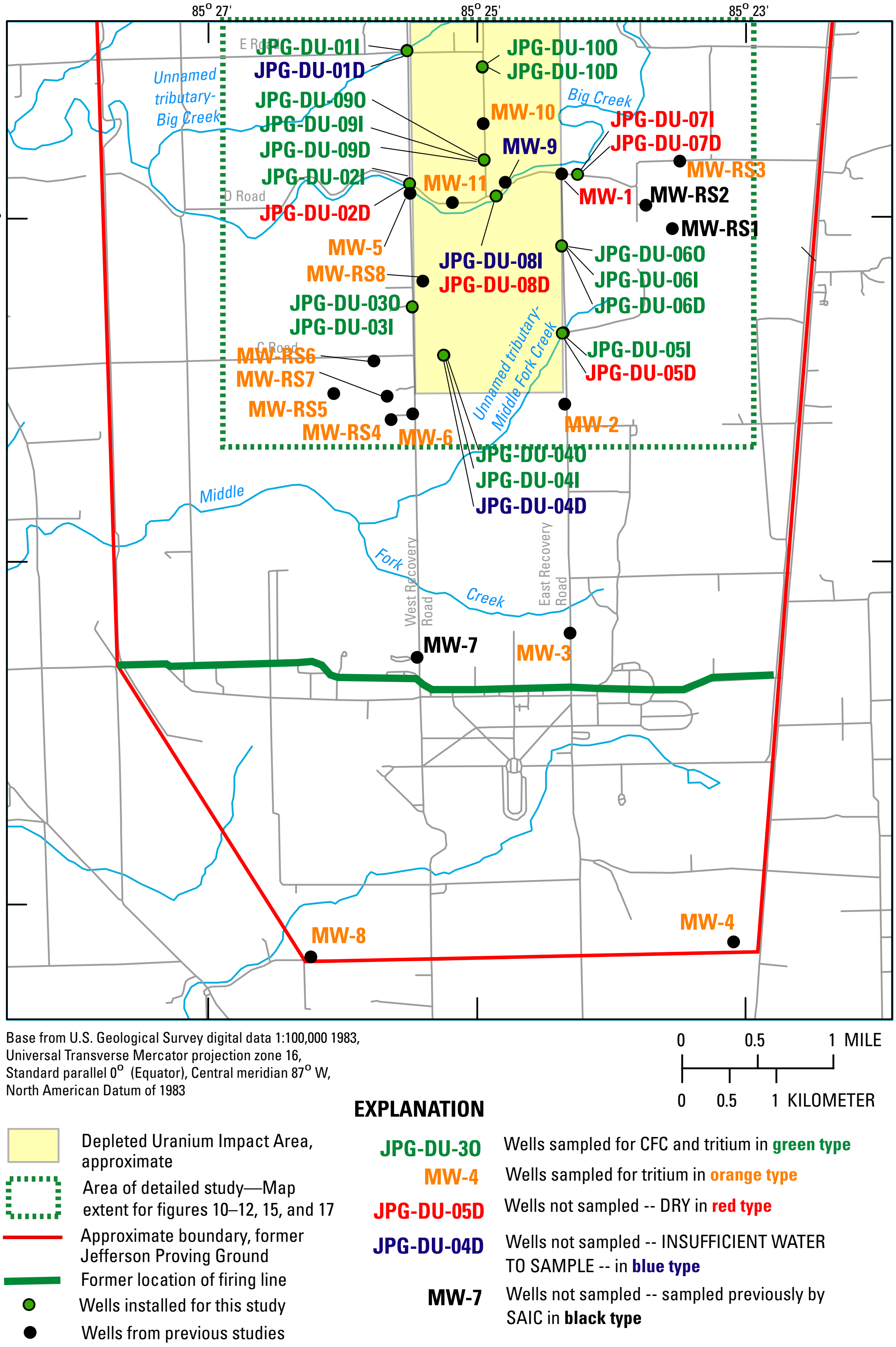
Some water-level recovery. If water levels in a well recovered since post-installation pumping and development, collection of dissolved gas and age-dating sampling was attempted. This criterion assumes that water-level recovery indicates that the well produced groundwater from a saturated part of a hydrogeologic unit.

Variable water-levels. Sampling of water representative of the aquifer and young-age dates were considered possible if groundwater levels varied by more than 1 ft in periodic measurements. This criterion assumes that the fluctuation was a function of infiltration of recharge to the aquifer and an possible expression of younger age groundwater in the well or interconnection with relatively younger flow paths in the hydrogeologic units. Dissolved gas and age-dating samples were collected from those wells.

Based on the above criteria, water from 5 JPG-DU series wells from the Pre-Wisconsinan till unit were sampled for dissolved gases, tritium, and CFCs and water from 8 wells from prior studies in that unit were sampled for tritium only (fig. 3; table 3). Water from 8 JPG-DU series wells in the shallow carbonate unit were sampled for dissolved gases, tritium, and CFCs and water from 6 wells from prior studies in that unit were sampled for tritium only (fig. 3; table 3). Two wells in the shallow carbonate unit could not be sampled because of poor water level recovery and three wells from prior studies were not sampled because they had been visited and sampled prior to the USGS sampling in April 2008. Only two wells from the deep carbonate unit were sampled for dissolved gases, tritium, and CFCs; seven other wells in the deep carbonate unit could not be sampled because of poor water level recovery (fig. 3; table 3).

Sampling and Analyses of Groundwater Chemistry

Water samples for age-dating analysis were collected at wells sampled by SAIC in April 2008. Observation wells sampled for this investigation were developed by SAIC about 1 month or more before sampling, using procedures described in Field Sampling Plan Addendum 4 (Science Applications International Corporation, 2007b). Samples from monitoring wells were collected with a portable, positive displacement, low-capacity gear-driven submersible pump (Fultz Pumps, Inc.). The pump used Teflon rotors in a stainless steel pump cavity and housing to push water through a stainless steel discharge adaptor fitting that split flow to two tubes. The pump was lowered nearly to the bottom of each sampled well, then raised about 3 ft for operation during measurements of field properties and sample collection. Groundwater flow from the adaptor fitting was routed to land surface through one of two tubes: (1) a 0.5 in. outside diameter tube used by SAIC for measurement of field water-quality parameters and (2) a 0.18 in. inside diameter nylon tube that was used for



Base from U.S. Geological Survey digital data 1:100,000 1983,
Universal Transverse Mercator projection zone 16,
Standard parallel 0° (Equator), Central meridian 87° W,
North American Datum of 1983

Figure 3. Monitoring wells in the study area, Jefferson Proving Ground, southeastern Indiana.

Table 1. Generalized hydrogeologic framework of water-bearing units sampled for this study, Jefferson Proving Ground, southeastern Indiana.

[ft, feet; NAVD 88, North American Vertical Datum of 1988]

Lithostratigraphic descriptions	Hydrogeologic framework characteristics		
	Unit name in this report	Characteristic	Range of depths for bottom of well screen below land or bedrock surface (ft below NAVD 88)
Pre-Wisconsinan till, commonly weathered, with silts, silty clay, with infrequent sand and gravel bodies. May also include a veneer of late-Wisconsinan loess and silty colluvium	Pre-Wisconsinan till	Confining unit for shallow carbonate unit, groundwater flow considered principally to be vertical and slow relative to the shallow carbonate unit. Some horizontal groundwater flow can be expected along small sand and gravel lenses and weathered zones.	Depth of top of well screen below land surface for sampled wells: about 5 ft to about 58 ft Depth of bottom of well screens: about 12 ft to about 68 ft
Carbonate bedrock, substantially of rocks of Silurian and Ordovician age	Shallow carbonate unit	Parts of carbonate aquifer, where fractured or dissolution modified.	Depth of bottom of well screen below bedrock surface for sampled wells: about 9 ft to about 40 ft
Shale and carbonate rocks of Ordovician age	Deep carbonate unit	Aquifer, where fractured or dissolution modified Generally massive unfractured, unmodified carbonate in places, non-water bearing in places	Depth of bottom of well screen below bedrock surface for sampled wells: about 49 ft to about 131 ft

dissolved gases, tritium, and CFC sampling. Flow from the larger diameter tubing was routed to a flow cell connected to a multiparameter instrument (Horiba model U-22), which was used to collect field measurements of water-quality parameters. Water-quality parameters were measured until they stabilized to ±0.1 standard units for pH, ±25 μS/cm for specific conductance, ±0.2 mg/L for dissolved oxygen, and <50 Nephelometric Turbidity Units (NTU) for turbidity. The convention NTU is used in this report to report turbidity data to be consistent with the procedures used to measure water-quality parameters; those are described in Field Sampling Plan Addendum 5 (Science Applications International Corporation, 2008).

After water samples were collected by SAIC for analysis of other constituents, groundwater discharge was routed through the 0.18 in. inside diameter nylon tube to collect the dissolved gases, tritium, and CFC samples. The pump was operated at variable flow rates, 0.5 L/min or less, during this sampling.

Unfiltered samples of groundwater for tritium analysis were collected directly from the discharge end of the nylon tubing into pre-cleaned, 1-L polyethylene bottles, sealed with a polyseal cap, with the cap taped in place using a strip of standard electrical tape. Samples were shipped in sealed coolers to the USGS Isotope Tracers Project Laboratory, Menlo Park, Calif. The samples were analyzed for concentration of tritium by counting the rate of tritium decay by beta (electron) emissions from neutron decay to stable helium using a standard electrolytic enrichment, liquid scintillation method (Thatcher and others, 1977) with a detection limit of 0.1 tritium units (TU) (table 4). For comparison to other work, 3.2 picocuries of tritium per liter is equal to 1 TU. A TU equals 1 tritium atom for every 1018 atoms of hydrogen. For 1 L of water, 1 TU is equivalent to 0.12 tritium atom disintegrations per second (Lucas and Unterweger, 2000).

Unfiltered samples of water were collected in the field in pre-weighed 150-mL serum bottles that were filled without headspace for analyses of dissolved gas, including oxygen,

Table 3. Number of wells sampled and not sampled for this study from each hydrogeologic unit.

[USGS, U.S. Geological Survey; SAIC, Science Applications International Corporation]

Hydrogeologic unit name	Number of wells sampled, by type of analysis		Number of wells not sampled, with reason	
	Dissolved gases, chlorofluorocarbon compounds, and tritium	Tritium only	Poor water level recovery	Visited prior to USGS sampling by SAIC, not sampled
Pre-Wisconsinan till	5	8	0	0
Shallow carbonate	8	6	2	3
Deep carbonate	2	0	7	0

Table 4. Analytical methods used for groundwater samples collected for analyses of dissolved gases and age dating at the Jefferson Proving Ground, southeastern Indiana.

[--, not available or not known; USGS, U.S. Geological Survey; GC-MS, gas chromatography-mass spectometry;]

Constituent or property name	Reporting unit	Reporting limit	Source of analysis	Analytical method description
		Dissolved gases		
Dissolved gases, unfiltered (oxygen, nitrogen, argon, carbon dioxide, and methane)	milligrams per liter	--	USGS Dissolved Gas Laboratory, Reston, Va.	GC-MS, Thermal conductivity detector (oxygen, nitrogen, argon) and flame ionization detector (carbon dioxide and methane); U.S Geological Survey (2009a); Busenberg and others (1998); and *http://water.usgs.gov/lab/dissolved-gas/lab/analytical_procedures/*
Dissolved gases, unfiltered (helium and neon)	milligrams per liter	--	USGS Dissolved Gas Laboratory, Reston, Va.	Thermal conductivity detector; Busenberg and others (2000); U.S. Geological Survey (2009c); and *http://water.usgs.gov/lab/dissolved-gas/lab/helium.html*
Chlorofluorocarbon compounds (CFC-12, CFC-11, and CFC-113)	picograms per liter	0.5–1.0 picogram per liter	USGS Chlorofluorocarbon Laboratory, Reston, Va.	U.S. Geological Survey (2009b) and *http://water.usgs.gov/lab/chlorofluorocarbons/lab/analytical_procedures/*
		Isotope		
Tritium, unfiltered	tritium unit	.1 tritium unit	USGS Isotope Tracers Project Laboratory, Menlo Park, Calif.	Electrolytic enrichment, liquid scintillation method, R-1174-76 (Thatcher and others, 1977; USGS Techniques of Water Resources Investigations book 5, chapter A5)

nitrogen, argon, carbon dioxide, methane, helium, and neon; then stored on ice after collection, and in a refrigerator at 4°C in the laboratory before their analysis. Water samples were collected and analyzed for dissolved gases using methods in U.S. Geological Survey (2009a) and Busenberg and others (1998, 2000) (table 4). Sequential replicate samples were collected and analyzed for oxygen, nitrogen, argon, carbon dioxide, and methane but not for helium and neon. Samples were shipped on ice to the USGS Dissolved Gas Laboratory in Reston, Virginia, for analysis.

The analyses of argon and nitrogen are checked at the lab by analyzing standard samples prepared at known temperatures in equilibrium with air and using those results to compute the air-water equilibrium temperature. The concentrations of argon and nitrogen for these analyses yielded computed air-water equilibrium temperatures within 0.5°C of their preparation temperature in all 12 of the standard samples analyzed (Peggy Widman, U.S. Geological Survey, written commun., 2009). The precision of the analytical results for helium and neon are 5 to 10 and 10 to 20 percent, respectively.

Unfiltered samples of water were collected to analyze the concentrations of chlorofluorocarbon compounds (CFCs), dichlorodifluoromethane (CFC-12 or CF_2Cl_2), trichlorofluoromethane (CFC-11 or $CFCl_3$), and trichlorotrifluoroethane (CFC-113 or $C_2F_3Cl_3$) in water and compute estimates of groundwater ages. Water for analysis of CFC was collected in 125-mL (4 oz) clear-glass bottles ("sample vials") with aluminum-foil lined bottle caps; five sample vials of groundwater were collected using methods in U.S. Geological Survey (2009b). Water samples were analyzed for concentrations of CFCs by the USGS Chlorofluorocarbon Laboratory in Reston, Virginia, with a purge-and-trap extraction, followed by compound separation with a gas chromatograph, and compound detection with an electron-capture detector (Busenberg and Plummer, 1992) (table 4). Two or three sample vials from each well were selected by laboratory personnel and analyzed for concentrations of CFCs, with a detection limit of about 1 picogram per liter (pg/L) of water.

Quality-Assurance Sampling and Analyses

Field quality assurance (QA) components included collection of QA samples and data to evaluate the reproducibility of the sampling and analysis methods for selected dissolved gases and chlorofluorocarbon compounds (sequential replicate samples). Replicate samples were collected sequentially for analysis of CFC and selected dissolved gases and used to evaluate the overall variability of the sampling and analysis procedures. A sequential replicate is a sample collected in immediate succession to the water sample from the same source, using the same equipment and methods, and submitted to the same laboratories as the water sample for identical analyses. The variability between analyses from a water sample and a sequential replicate was evaluated by calculating the relative percent difference (RPD) of concentrations of each analyte that was detected in both the water sample and sequential replicate (Olsen and Spencer, 2000; U.S. Army Corps of Engineers, 2008).

$$RPD = \left|(SR-WS)/((SR+WS)/2)\right| \times 100$$

where

RPD is the relative percent difference,
SR is the concentration in the sequential replicate, and
WS is the concentration in the water sample.

The RPD describes the difference in concentrations between two samples that were identical in their handling and analysis and that should be identical in composition. If the RPD of an analysis was within 25 percent, the sample result met the precision objectives of this study. If the RPD was greater than 25 percent, the sample result was reported, but the concentration for that analysis was flagged with the letter “Q” in data tables to indicate that the concentration is an estimate. The RPD precision objective used in this study exceeds the variability typically allowed for environmental analyses (50 percent; U.S. Army Corps of Engineers, 2008).

Estimates of Groundwater Age Using Tritium

Estimates of groundwater age were made by comparing the activity of tritium in water to its decay-adjusted activity in precipitation samples from the Ohio River Basin, expressed as a range of groundwater age or the age of recharge to groundwater. Tritium is a radioactive isotope of hydrogen; each tritium atom has a mass of 3 atomic mass units and a half-life of 12.33 years (Lucas and Unterweger, 2000). Tritium is produced naturally by the bombardment of nitrogen in the atmosphere by cosmic radiation (Grosse and others, 1951) and is added to the atmosphere by the solar wind. Atmospheric tritium and oxygen then combine to form water, which enters the groundwater system through infiltration of precipitation. Although few measurements are available, the natural concentration of tritium in precipitation before 1953 was estimated to be about 6 to 8 TU (Thatcher, 1962) and the estimated concentration of tritium in Ohio River Basin precipitation before 1952 was about 6–8 TU (Michel, 2004). As a consequence of radioactive decay, a tritium concentration of 8 TU in a water sample collected in 1952 would decrease to about 0.3 TU by April 2008, the sampling date for this study.

Concentrations of tritium were used to classify groundwater-age dates to distinguish between aquifer recharge from precipitation that was 1953 or older (submodern), recharge from precipitation that was younger than 1953 (modern), and mixtures of the two. Concentrations of tritium in precipitation greatly increased from about 1954 through 1980 because of the release of bomb-related tritium from testing of atmospheric thermonuclear devices, the greatest release happening from 1953 through 1962 (fig. 4; Clark and Fritz, 1997; International Atomic Energy Agency, 2006). For example, concentrations of tritium in Ottawa, Canada precipitation, a station with a long data record, were quite variable between samples but increased from about 20 TU in August 1953 to about 5,800 TU in June 1963. By about 1990, bomb-related tritium largely had been removed from the atmosphere and concentrations of tritium in precipitation had returned to near natural levels (fig. 4).

Tritium in precipitation varies with latitude; therefore, monthly estimates of concentrations of tritium in Ohio River Basin precipitation were used for age-dating estimates (fig. 4; Robert Michel, U.S. Geological Survey, written commun., 2009; Michel, 2004). Estimated concentrations of tritium for the Ohio River Basin were based on, but generally less than, the Ottawa, Canada data; they increased from about 15 TU in August 1953 to about 2,600 TU in May 1963 and then gradually decreased to about 7 TU by December 2001 (Robert Michel, U.S. Geological Survey, written commun., 2009; Michel, 2004; International Atomic Energy Agency, 2006).

Concentrations of tritium for the Ohio River Basin were estimated by averaging concentrations of tritium in precipitation from sites at Chicago, Illinois, and St. Louis, Missouri, as indicated in Michel (2004). Although the uncertainty of estimates of concentrations of tritium in Ohio River Basin precipitation have not been evaluated, the correlation coefficients of annual average concentrations of tritium in Ottawa, Canada precipitation, after weighting the data to account for differences in precipitation amounts, were 0.99 with concentrations of tritium from Chicago and 0.93 with concentrations of tritium from St. Louis (International Atomic Energy Agency, 1981).

Groundwater-age dates were evaluated for concentrations of tritium in groundwater by comparing them with annual averages of concentrations of tritium in precipitation, corrected for decay to the date of sample collection. When tritium in precipitation falls and infiltrates into groundwater, it continues to undergo decay during its residence time in groundwater until it is sampled. To create a record of concentrations of tritium in precipitation that were comparable to the already decayed concentrations in groundwater, the concentrations of tritium in Ohio River Basin precipitation were annually averaged and decay corrected to the date of sampling (April 2008) using a standard decay equation (Clark and Fritz, 1997, p. 181) and half-life of tritium (12.33 years; Lucas and Unterweger, 2000). Decay corrected, annual average concentrations of tritium estimated for Ohio River Basin precipitation increased from 0.8 TU in 1953 to about 119 TU in 1963, but then decreased to about 8.5 TU by 1972 and to about 4 to 5 TU since 1986 (fig. 5).

The following ranges of concentrations of tritium were used to qualitatively classify groundwater-age dates. These

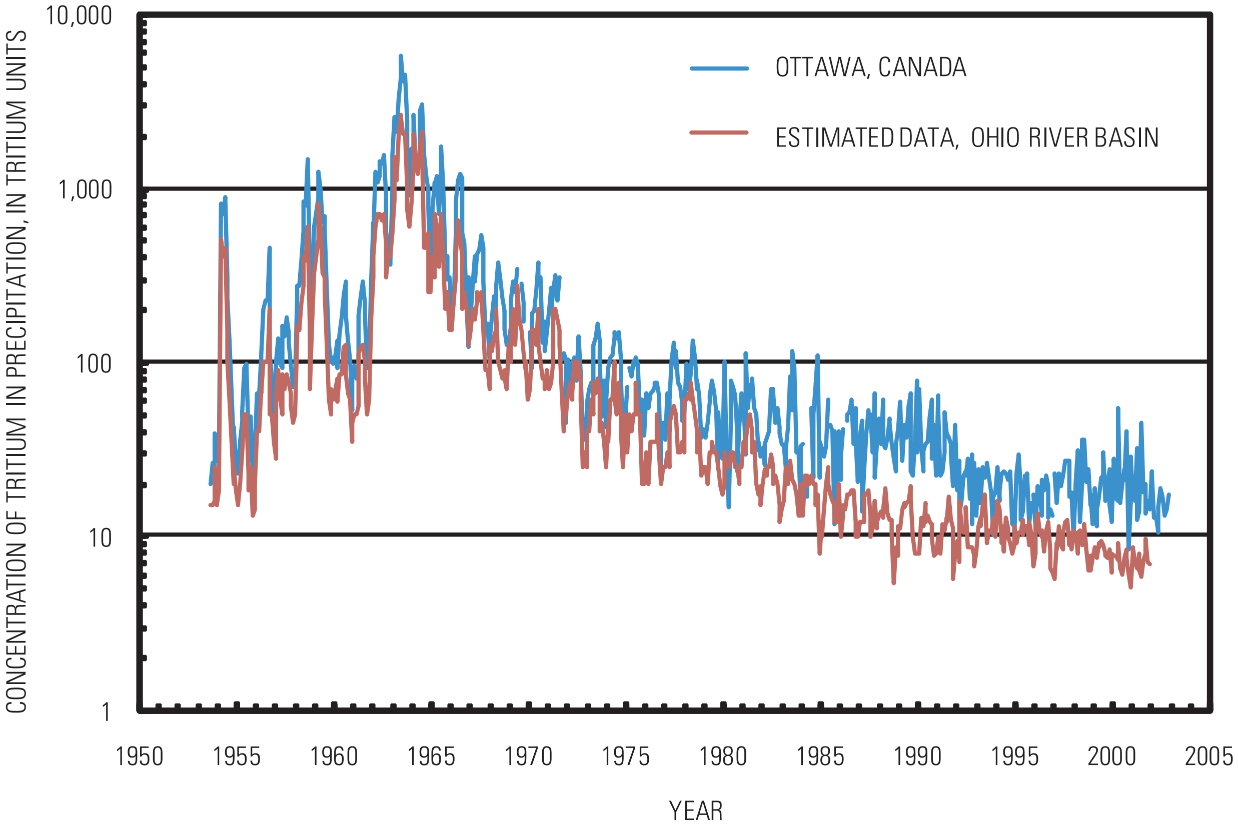


Figure 4. Average monthly concentration of tritium in precipitation in samples collected from Ottawa, Canada, 1953–2002 (International Atomic Energy Agency, 2006) and monthly estimates of concentrations of tritium in precipitation for the Ohio River Basin (Robert Michel, U.S. Geological Survey, written commun., 2009; Michel, 2004).

classifications were modified from Clark and Fritz (1997, p. 185) and adapted to the record of decay-corrected concentrations of tritium in Ohio River Basin precipitation.

1. Submodern: Less than or equal to about 0.8 TU—Groundwater substantially recharged before or during 1953.
2. Submodern-modern mix: About 0.9 to less than 4 TU—Groundwater is a mixture of pre-recharge from before or during 1953 with recent, post-1953 recharge. The mixture classification explains cases when groundwater represents a mixture of submodern water from slower subsurface flow paths and modern groundwater from faster subsurface flow paths to a well.
3. Substantially modern: About 4 TU to about 15 TU—Water represents substantially modern recharge (post-1953). In addition, water in this range with about 4 to 8 TU may be a mixture of post-1972 recharge. Smaller concentrations of tritium in this range can also indicate mixing of modern recharge with submodern groundwater.

The analytical precision of concentrations of tritium was added to the tritium concentration of a sample to evaluate the uncertainty of tritium-based estimates of groundwater age. Concentrations of tritium have an associated decay-counting uncertainty referred to as “Tritium, 2-sigma precision.” Radioactive decay of tritium is a random process; to account for the randomness while obtaining a precise result, counting is done until a precise number of counts are obtained (Thatcher and others, 1977, p. 69–71). The counting uncertainty (standard deviation or sigma) includes uncertainties in decay counts and other analytical factors and is computed using methods described in Thatcher and others (1977, p. 70 and 71, equations 1–5). The 2-sigma precision indicates that the concentration of tritium reported for a sample has a 95-percent probability of being within plus or minus one standard deviation of the reported concentration. Age classifications that changed when the 2-sigma precision statistic values were added to tritium concentrations were compared with the CFC-based age date to verify the final groundwater-age classification for those samples.

Estimates of Groundwater Age Using Chlorofluorocarbon Compounds

Concentrations of the three CFC compounds—CFC-12, CFC-11, and CFC-113—were used to estimate groundwater age for samples collected in and near the DU Impact Area

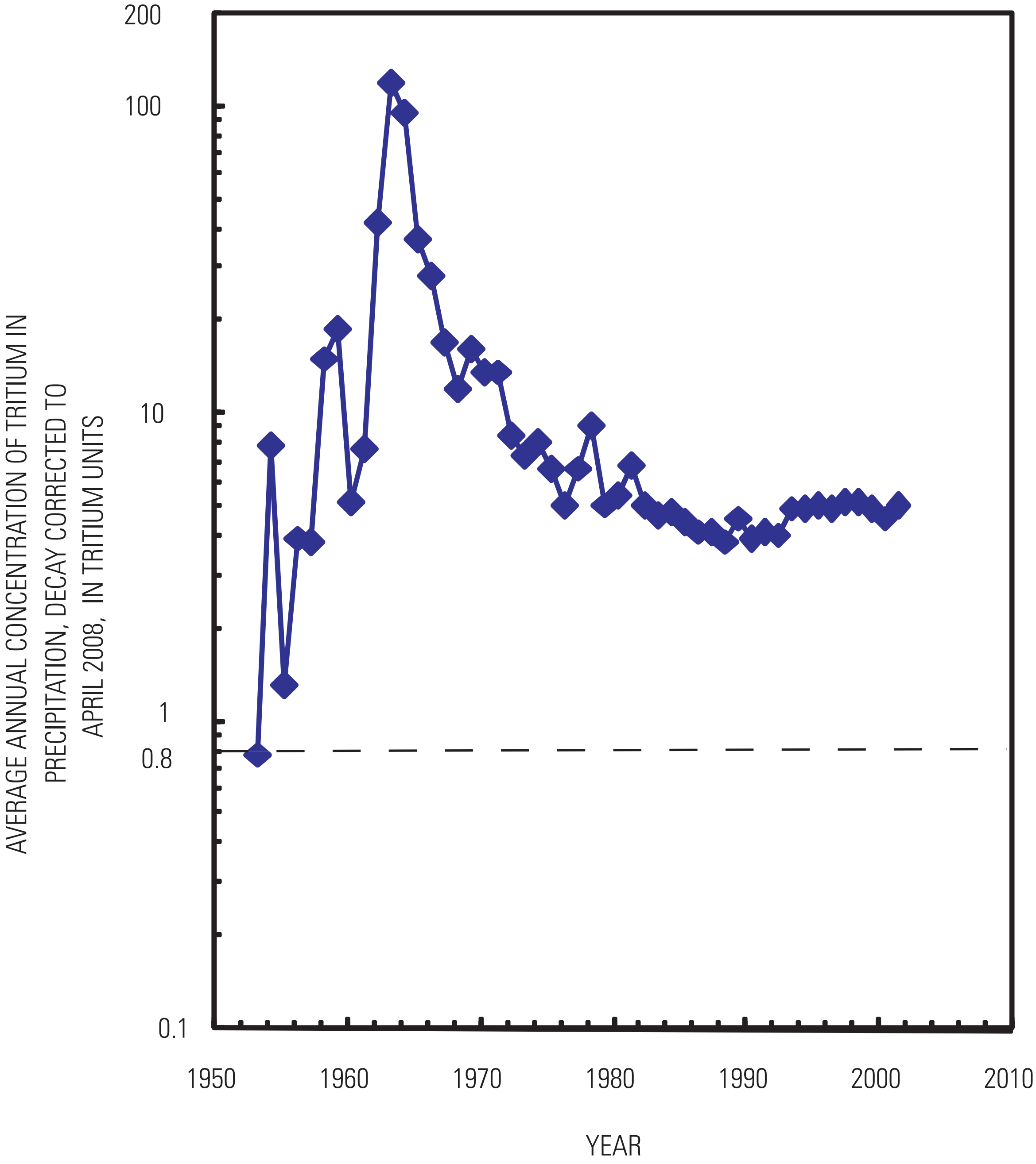


Figure 5. Average annual concentration of tritium in precipitation for the Ohio River Basin, 1953-2001, as corrected for decay to April 2008 when groundwater was sampled. Concentrations were computed using monthly estimates of concentrations of tritium in precipitation for the Ohio River Basin from Robert Michel (U.S. Geological Survey, written commun., 2009; Michel, 2004).

from the Pre-Wisconsinan till, shallow carbonate unit, and deep carbonate units. Estimates of groundwater age are apparent ages and are based on interpretations of measured concentrations of CFCs in groundwater and processes affecting the CFCs from entry into the aquifer with recharge until they are sampled. The following description of CFC-based groundwater-age dating methods and their interpretation are paraphrased from International Atomic Energy Agency (2006) and Rowe and others (1999).

CFC-12, CFC-11, and CFC-113 are stable, synthetic, halogenated alkanes that were developed as refrigerants. Production of CFC-12 began in 1931, followed by CFC-11 in 1936, and CFC-113 in about 1943. Precipitation that dates from about 1940 is assumed to contain one or more of these CFCs; therefore, precipitation that infiltrated into groundwater at JPG after about 1940 is assumed to have contained one or more of these CFCs. Water that contains no CFCs is presumed to represent pre-1940 recharge. The concentrations of the

CFCs in the atmosphere of North America and in recharge have changed through time (fig. 6); these changes can be used to indirectly estimate groundwater age.

To compute the age of a groundwater sample, concentrations of each CFC compound are divided by the appropriate Henry's Law constant. This result gives the partial pressure of the compound in air from the unsaturated or "vadose" zone above the water table when water infiltrated below the water table and became isolated from the atmosphere. The solubility (C_D) of a CFC compound (D) relates to the equilibrium between gas and water phases, as described by Henry's Law:

$$C_{\mathrm{D}} = K_{\mathrm{D\,(T,S)}} \times P_{\mathrm{D}},$$

where

$K_{\mathrm{D\,(T,S)}}$ is the Henry's law constant for the CFC compound (D) at a defined average recharge temperature (T) and salinity (S) and

P_{D} is the partial pressure, under atmospheric conditions (Schwarzenbach and others, 1993), of the CFC compound (D).

The solubility of dissolved gases (such as CFCs, argon, and nitrogen) depends on the average recharge temperature of the groundwater sample. Recharge temperatures were estimated with the ratio of dissolved nitrogen to argon gas in water samples (Rowe and others, 1999). The concentrations of nitrogen and argon in water infiltrating below the water table may be expected to be in equilibrium with the atmosphere at the prevailing surface pressure and temperature (Heaton and Vogel, 1981). Concentrations of nitrogen and argon were normalized using an assumed recharge altitude to a pressure of 760 mm of mercury to limit altitude effects on comparison of gas solubility. The recharge altitude is the altitude at which water infiltrates below the water table and becomes isolated from equilibrium with the atmosphere. Recharge altitudes used for recharge temperature and CFC-based groundwater-age computations generally were assumed to be similar to measured water levels at a well or to inferred water levels upgradient from a well to represent recharge from upgradient sources.

Concentrations of nitrogen and argon in groundwater also were corrected for the "excess air" introduced into

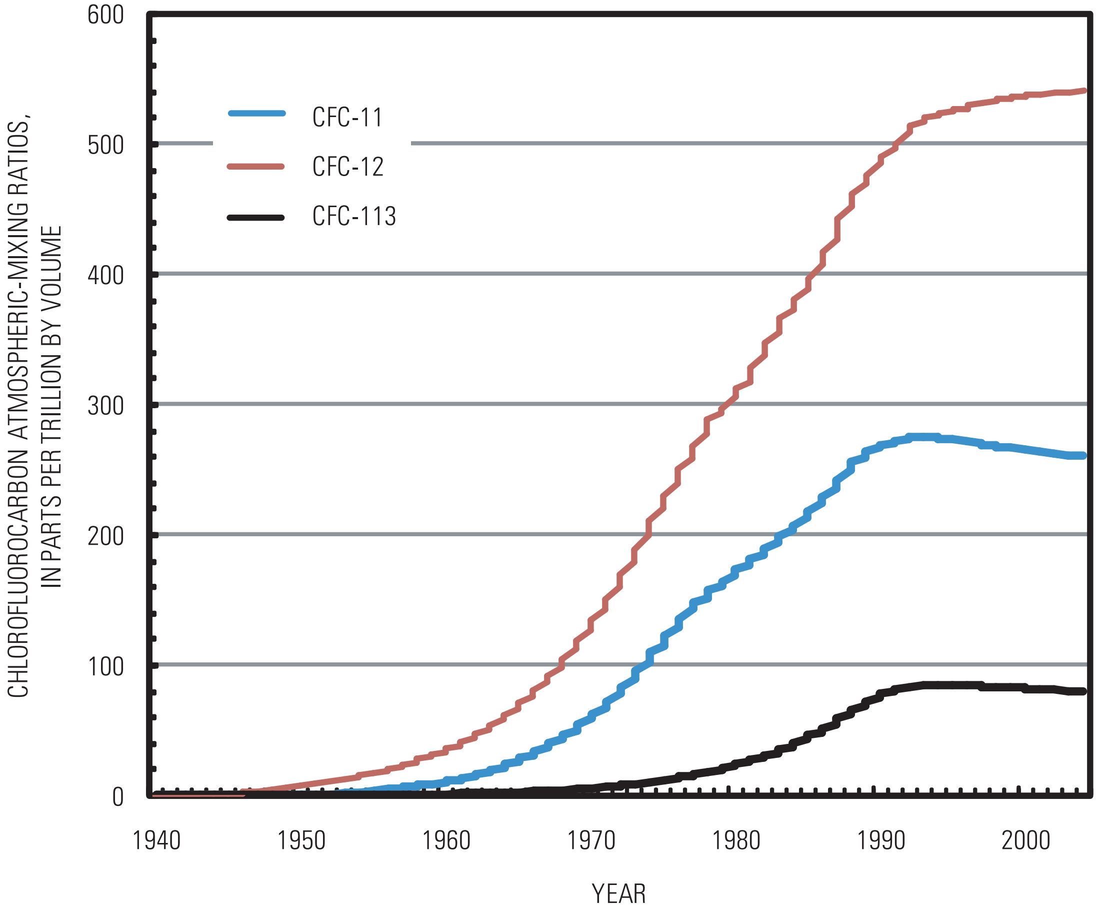
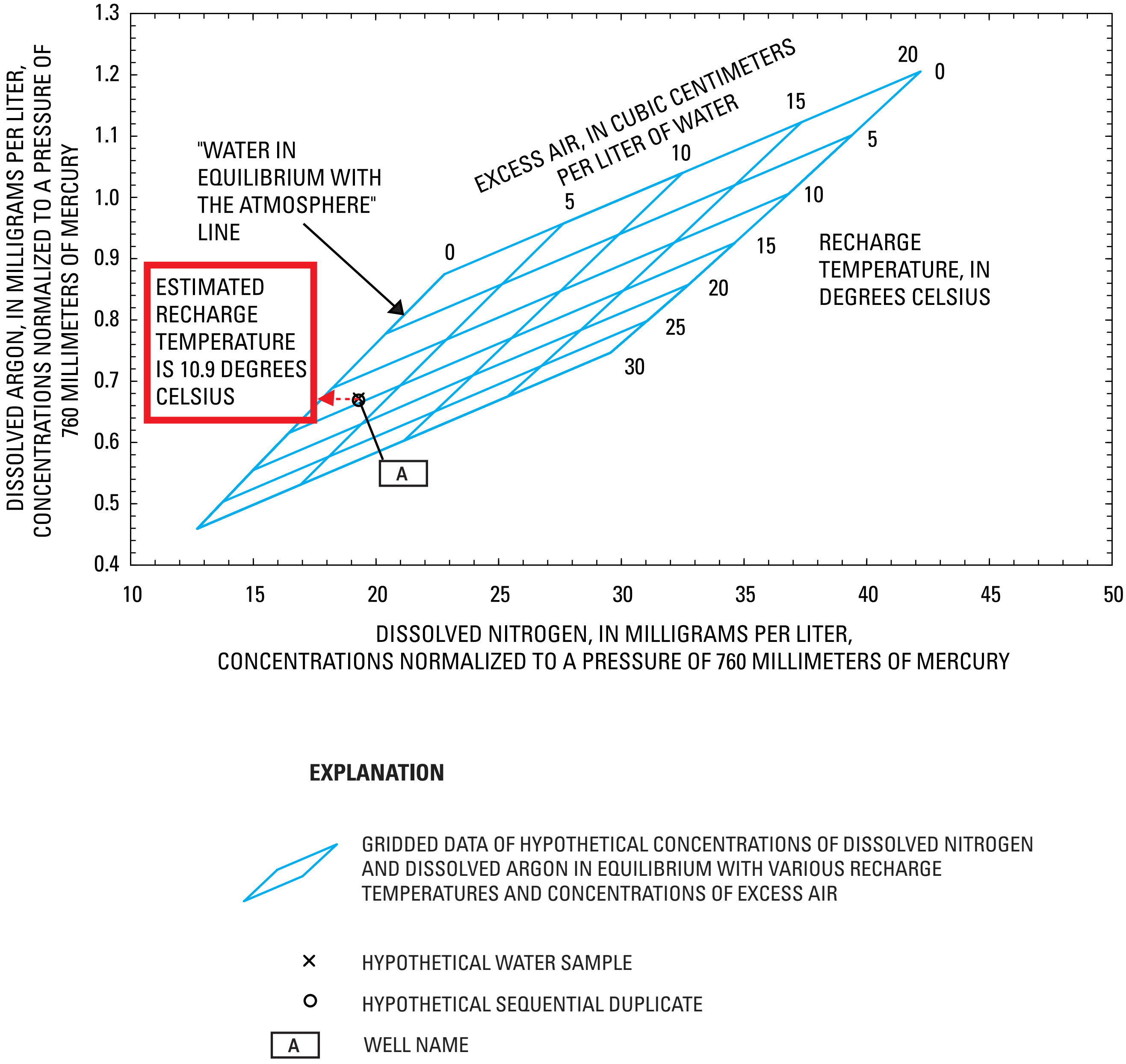


Figure 6. Atmospheric-mixing ratios of dichlorodifluoromethane (CFC-12), trichlorofluoromethane (CFC-11), and trichlorotrifluoromethane (CFC-113) for air in North America (Eurybiades Busenberg and L.N. Plummer, U.S. Geological Survey, written commun., 2006). Data before 1976 were reconstructed from chlorofluorocarbon production data, as referenced and described in Plummer and Busenberg (2000).

groundwater during infiltration. Infiltrating water can entrap air bubbles that when carried below the water table, dissolve and are incorporated into dissolved gases (Heaton and Vogel, 1981). Excess air refers to the volume of dissolved gas in a liter of groundwater in excess of that predicted by equilibrium of infiltrating water with the atmosphere. Excess air is trapped and dissolved under increased hydrostatic pressure in groundwater at the capillary fringe or in fractures as the water table rises. Introduction of excess air adds CFCs to groundwater and, if not accounted for in age interpretation, causes a young-age bias. Recharge temperatures were estimated as shown on figure 7 for a hypothetical data point by comparing the corrected concentrations of nitrogen and argon gas with a plot of nitrogen-argon solubility in water at 760 mm of



Gridded data from Julian Wayland (U.S. Geological Survey, written commun., 2003), as computed using methods from Weiss, R.F., 1970, The solubility of nitrogen, oxygen, and argon in water and seawater: Deep Sea Research, v. 17, no. 4, p. 721–735.

Figure 7. Recharge temperature grid with hypothetical concentrations of dissolved nitrogen and dissolved argon at various recharge temperatures and concentrations of excess air in water samples.

mercury with excess air contents ranging from 0 to 20 cm^3/kg of water (Heaton and Vogel, 1981) using gas-solubility data from Weiss (1970).

"Excess nitrogen," if present in a sample, was subtracted from concentrations of nitrogen gas during the computation of corrected concentrations of nitrogen gas that were used in estimation of recharge temperature. Excess nitrogen can originate from biogeochemical processes in an aquifer, such as denitrification, that produce more nitrogen gas than would be dissolved in water in equilibrium with soil gas during recharge; it cannot exceed the total amount of excess air in a sample. Excess nitrogen was estimated by comparing the nitrogen gas in the sample with the amount that should be present if the water sample were in equilibrium with atmospheric nitrogen at the estimated recharge temperature. Excess nitrogen in a water sample can create unrealistically high estimates of recharge temperatures and introduce errors in the CFC-based estimate of groundwater age.

The calculated partial pressures of CFCs in each water sample, corrected for the amount of excess air in the sample, were compared with the atmospheric mixing ratios of the three CFC compounds from 1940 to 2005 (fig. 6) to infer the age of each water sample (Eurybiades Busenberg and L.N. Plummer, U.S. Geological Survey, written commun., 2006; International Atomic Energy Agency, 2006). Interpretations of groundwater age depend on the assumption that concentrations of CFCs are in equilibrium with gases in the soil and that concentrations of CFCs in infiltrating water are equal to those in the atmosphere (International Atomic Energy Agency, 2006).

A water sample from a well represents a mixture of groundwater from all the flow paths and age dates that contribute to the well screen (Plummer and others, 2003). Interpretation of groundwater-age dates and the potential transport of associated contaminants are affected by the source of recharge to the contributing flow paths and the hydraulic conductivity and porosity characteristics of an aquifer (International Atomic Energy Agency, 2006). Two models, piston flow and binary mixing, were used to represent some of the variation in age dates in groundwater. Computation of reliable groundwater ages requires that all concentrations of CFCs are reliable, they have not been decreased through degradation, and they have not increased to anomalously large values by introduction of contamination.

In some cases, a groundwater sample can be described as flowing along a discrete path and is unaffected by mixing processes from where it recharges an aquifer to where it is sampled from the screened interval of the well; this situation is called "piston flow" (International Atomic Energy Agency, 2006, p. 6). A determination that a piston-flow model describes the flow of groundwater from recharge to the well also assumes that the well screen is short and does not produce water from a variety of recharge sources and flow paths. Interpretation of groundwater-age dates is simpler with a piston-flow model because the concentration of the age-dating tracer also is assumed to be unaffected by mixing or other processes that would change the concentration of the tracer. Piston flow is most likely to occur when recharge occurs in a small area, such as through a sinkhole or through a thinner part of a confining-till unit, and when an aquifer is very thin or composed of conduit-like or fractured-and-solution-enhanced flow paths. For example, flow through a network of discrete or interconnected fractures or solution-modified features, such as in fractured or dissolution-modified carbonate rock or karst (Smart and Hobbs, 1986) could be described by piston flow.

Another type of model, binary mixing, represents a groundwater sample as a mixture of old (pre-CFC or CFC-free) water and young water that infiltrated to the aquifer after CFCs were introduced to the environment. The simple dilution of young water with old, CFC-free water enables the age of the young water to be computed using the atmospheric ratios of two CFCs in the water sample (Plummer and others, 2003).

Examples of interpreting age dates of groundwater samples using the concentration of three CFC compounds relative to piston-flow and binary-mixing models are shown in figure 8 and described below; this discussion is modified and partly reproduced from Plummer and others (2003) and International Atomic Energy Agency (2006). A sample of groundwater that is not affected by mixing with groundwater of different ages (point X, fig. 8A) would plot along piston-flow curves for pairs of CFC atmospheric-mixing ratios. The correspondence of the atmospheric-mixing ratios in groundwater—point X—to the typical atmospheric composition of the CFC compounds at various times—the piston-flow curve—indicates the age of the groundwater since it infiltrated below the water table. Point X depicts the concentrations of CFC-11 and CFC-12 in a hypothetical groundwater sample collected in 2008 with an age of 22 years that infiltrated below the water table in 1986. Samples that plot off the piston-flow curves and within the area defined by the dashed lines shown in figure 8 can be defined by binary mixtures. For example, point Y plots along a dashed line that represents a binary mixture between young 1985 water (with concentrations of CFC-12 and CFC-113 similar to the 1985 atmosphere) and old, CFC-free water (point Y, fig. 8B). In a binary mixture, the age of the young water, for this study, also represents the minimum age of activities and contamination that could be associated with that water. The proportions of the young and old waters that correspond to the position of point Y on the mixing line are estimated by the lever rule (Levine, 1978, p. 294).

Water samples with concentrations of CFCs that have been affected by processes such as sorption, biotransformation, or contamination will plot outside the areas of piston-flow and binary-mixing models. For example, point Y on figure 8A indicates a smaller concentration of CFC-11 relative to CFC-12; it is below the piston-flow and binary-mixing areas. Because CFC-12 typically is more stable and less affected by processes such as sorption or biotransformation, the relative depletion of CFC-11 in the composition represented by point Y would be attributed to degradation in the aquifer by biogeochemical processes. In comparison, point X on figure 8B contains a larger concentration of CFC-113 relative to CFC-12 and plots above the piston-flow and binary-mixing areas. The

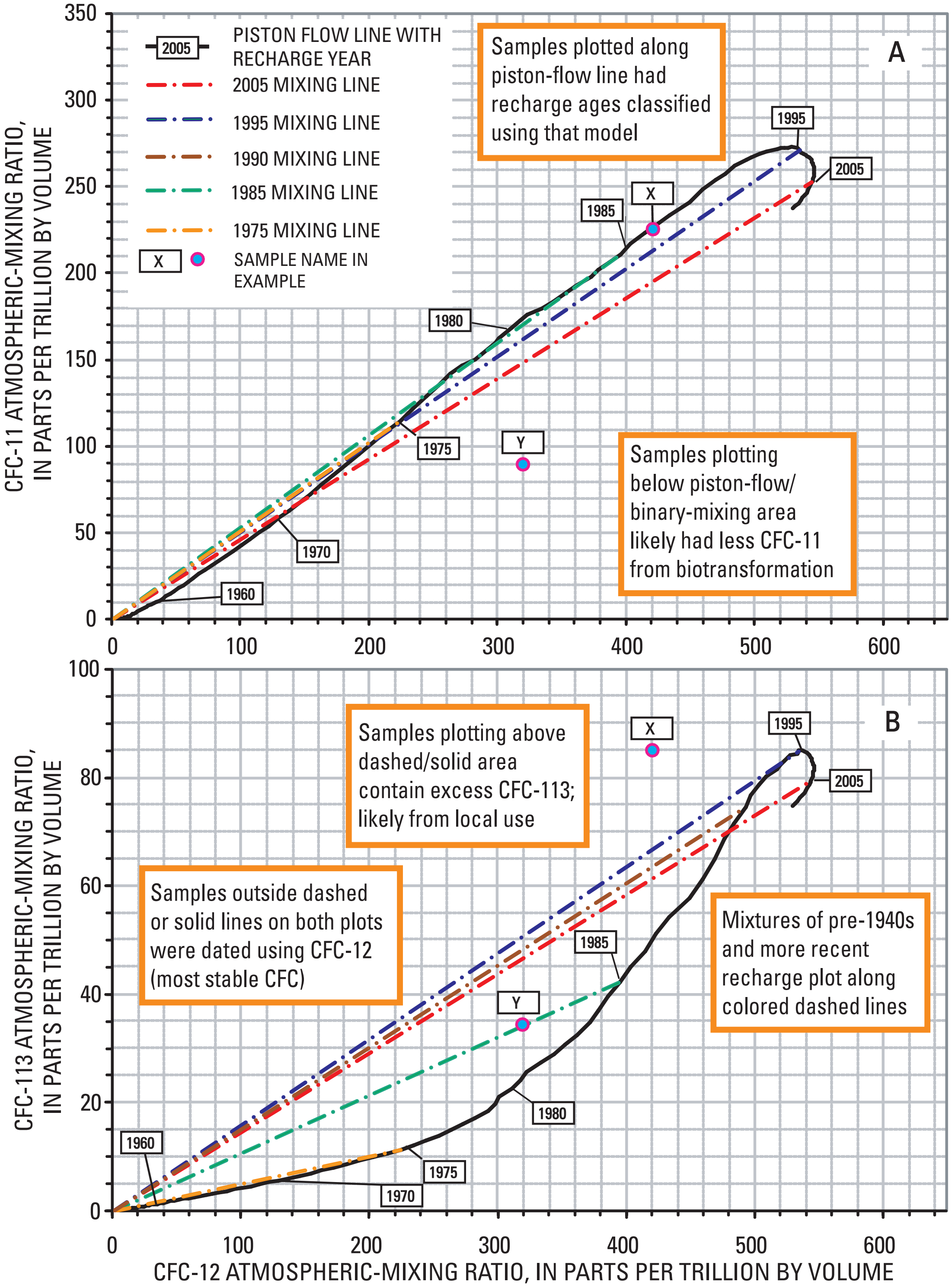


Figure 8. Examples of interpreting age dates of groundwater samples using the atmospheric-mixing ratios of chloroflurocarbon (CFC) compounds relative to piston-flow and binary-mixing models: A. CFC-11 and CFC-12 and B. CFC-113 and CFC-12. Abundances of CFC-11, CFC-12, and CFC-113 are shown as continuous curves corresponding to different groundwater-mixing models: (1) Thin solid lines (including point "X") indicate compositions of discrete water parcels with single ages (corresponds to the "piston-flow" or no-mixing model); (2) Dashed lines of different colors (including point "Y") indicate compositions of binary mixtures with varying fractions of "young" water with recharge compositions of 2005, 1995, 1990, 1985, and 1975 and "old" water that has no detectable CFC compounds (pre-1940 water). Dates (years) indicated along the piston-flow line (1) correspond to atmospheric-mixing ratios of CFC-11, CFC-12, and CFC-113 in precipitation from the identified years.

apparent excess of CFC-113 in the composition represented by point X on figure 8B would be attributed to contamination from an external source.

Preliminary Hydrogeologic Framework of Till and Carbonate Bedrock Hydrogeologic Units

This section presents a preliminary description of the hydrogeologic framework of the till and carbonate bedrock hydrogeologic units and groundwater flow to provide a context for presentation and interpretation of the age-dating results. A more comprehensive presentation and analysis of geologic and hydrologic data collected to describe the detailed hydrogeologic framework of the DU Impact Area is in preparation as of April 2009 by the Army and Science Applications International Corporation. That effort may modify some of these preliminary observations on that framework.

A synoptic groundwater level measurement was made by SAIC personnel on April 7, 2008, immediately before the collection of groundwater samples described in this investigation (table 5, at end of report). Groundwater levels also were occasionally collected from many of these wells by USGS personnel during June 2007–August 2008 (table 5). March through August are locally the months with the largest average precipitation, ranging from about 4.1 in/month in August to 4.96 in/month in May (Midwestern Regional Climate Center, 2009b). Precipitation at a Big Oaks National Wildlife Refuge weather station (BIGI3), about 2 mi northwest of the study area (fig. 2), was 13.42 in. during the March that preceded sampling (National Weather Service, 2008); this was considerably wetter than the normal average precipitation for March of 4.26 in. (1971–2000 period, Midwestern Regional Climate Center, 2009b) and wetter than any other month during the September 2007–September 2008 period (fig. 9).

Groundwater-flow directions and vertical gradients between water-bearing intervals were interpreted to provide a preliminary framework to estimate groundwater ages and water-chemistry data. Water-level contours were compiled from a set of synoptic groundwater level measurements made on April 7, 2008, from wells in the Pre-Wisconsinan till, shallow carbonate unit, and deep carbonate unit (figs. 10–12) to interpret water-level gradients and the directions of flow potentials (the direction of the water-level gradient) that prevailed immediately before sampling.

The water table in the Pre-Wisconsinan till is contoured in discontinuous parts because the till was encountered in upland areas between incised stream valleys and is not present or thin along several stream valleys (fig. 10). Groundwater-level gradient directions generally were toward the local surface-water drainage. North of Big Creek, the gradient directions are westward toward a tributary of Big Creek and southward toward Big Creek. Groundwater-gradient directions in the Pre-Wisconsinan till south of Big Creek are south and southwestward toward Middle Fork Creek and northward toward Big Creek (fig. 10).

Vertical gradients generally were downward from the Pre-Wisconsinan till into the shallow carbonate unit at paired wells JPG-DU-04O and JPG-DU-04I, JPG-DU-06O and JPG-DU-06I, and JPG-DU-09O and JPG-DU-09I (table 6, at end of report). Vertical gradients most often were upward from the shallow carbonate unit into the Pre-Wisconsinan till at paired wells JPG-DU-03O and JPG-DU-03I and at paired wells JPG-DU-10O and JPG-DU-10D (table 6).

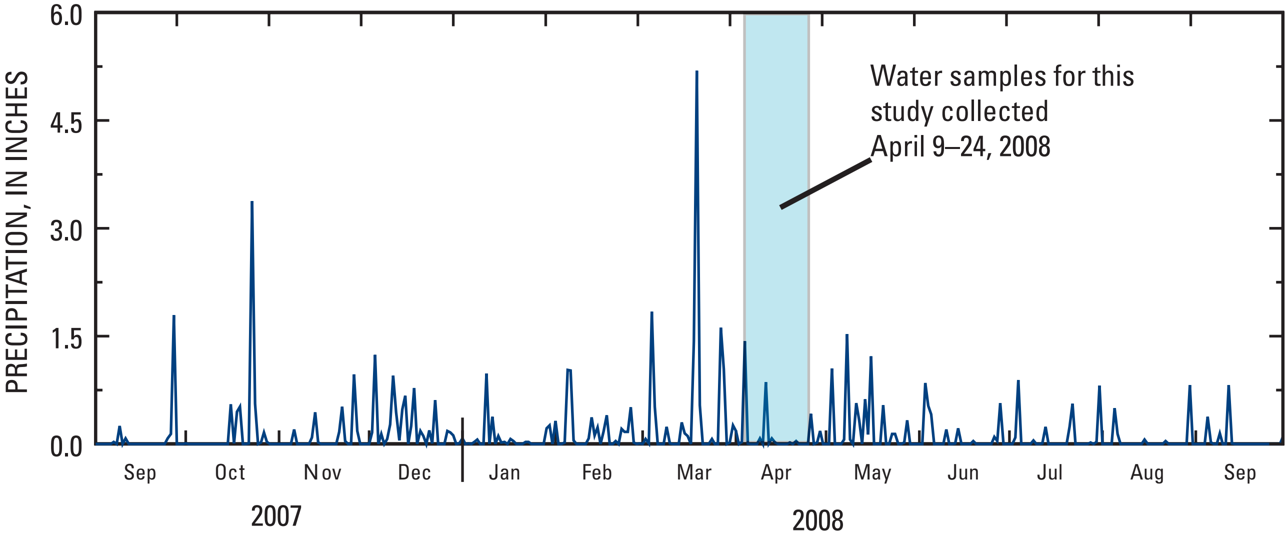
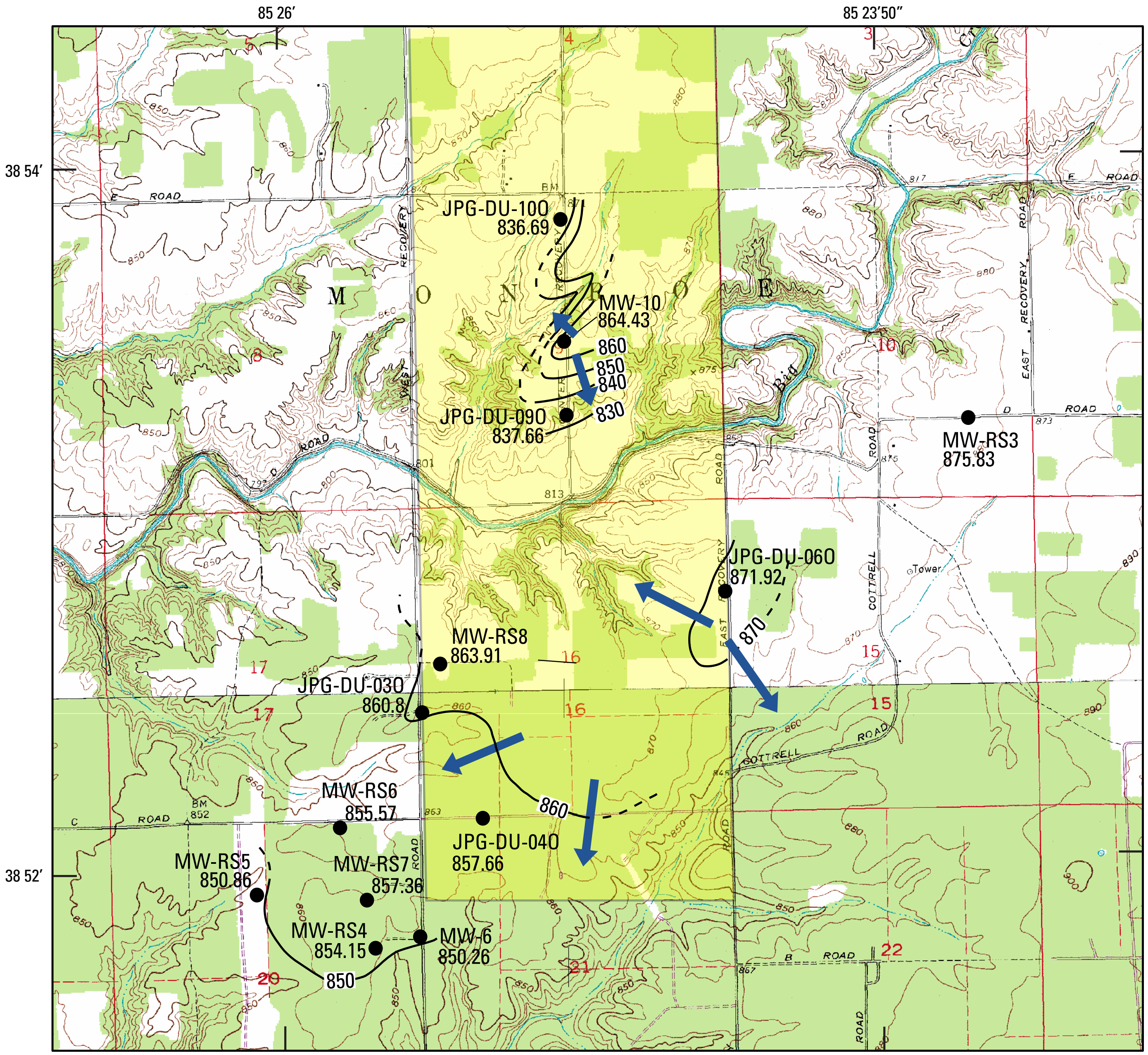


Figure 9. Precipitation at a Big Oaks National Wildlife Refuge weather station about 5 miles northwest of the study area at Jefferson Proving Ground, southeastern Indiana, September 2007 to September 2008.



Base from U.S. Geological Survey Digital Raster Graphic (DRG) 1:24,000;
San Jacinto, Ind., 1959, minor revision 1994, also Clifty Falls, Ind., 1995,
Universal Transverse Mercator projection, Zone 16, North American Datum
of 1927. Vertical datum of the DRG is the National Geodetic Vertical Datum of 1929

EXPLANATION

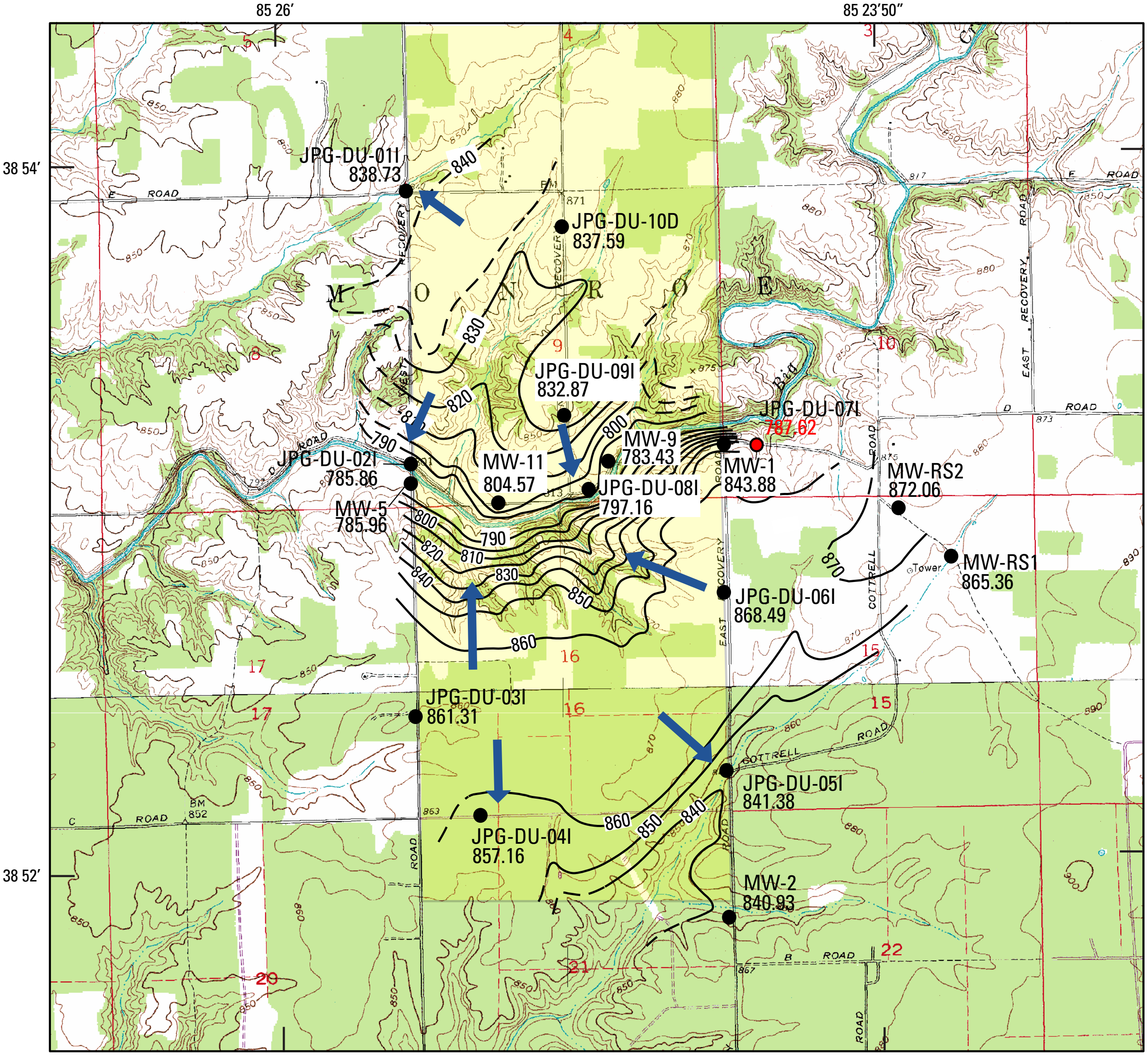
🟨 DEPLETED URANIUM IMPACT AREA—Approximate extent

— 860 — WATER-LEVEL CONTOUR—Approximate altitude of the water level in the Pre-Wisconsinan till, April 7, 2008, in feet above North American Vertical Datum of 1988. Dashed where approximately located. Contour interval 10 feet

MW-RS4
854.15 ● GROUNDWATER OBSERVATION WELL--With well identifier and water level in the Pre-Wisconsinan till, April 7, 2008, in feet above North American Vertical Datum of 1988.

← INFERRED DIRECTION OF WATER-LEVEL GRADIENT IN THE PRE-WISCONSINAN TILL

Figure 10. Altitude of the water table in the Pre-Wisconsinan till, April 7, 2008, at the Jefferson Proving Ground, southeastern Indiana.



Base from U.S. Geological Survey Digital Raster Graphic (DRG) 1:24,000;
San Jacinto, Ind., 1959, minor revision 1994, also Clifty Falls, Ind., 1995,
Universal Transverse Mercator projection, Zone 16, North American Datum
of 1927. Vertical datum of the DRG is the National Geodetic Vertical Datum of 1929

EXPLANATION

🟨 DEPLETED URANIUM IMPACT AREA—Approximate extent

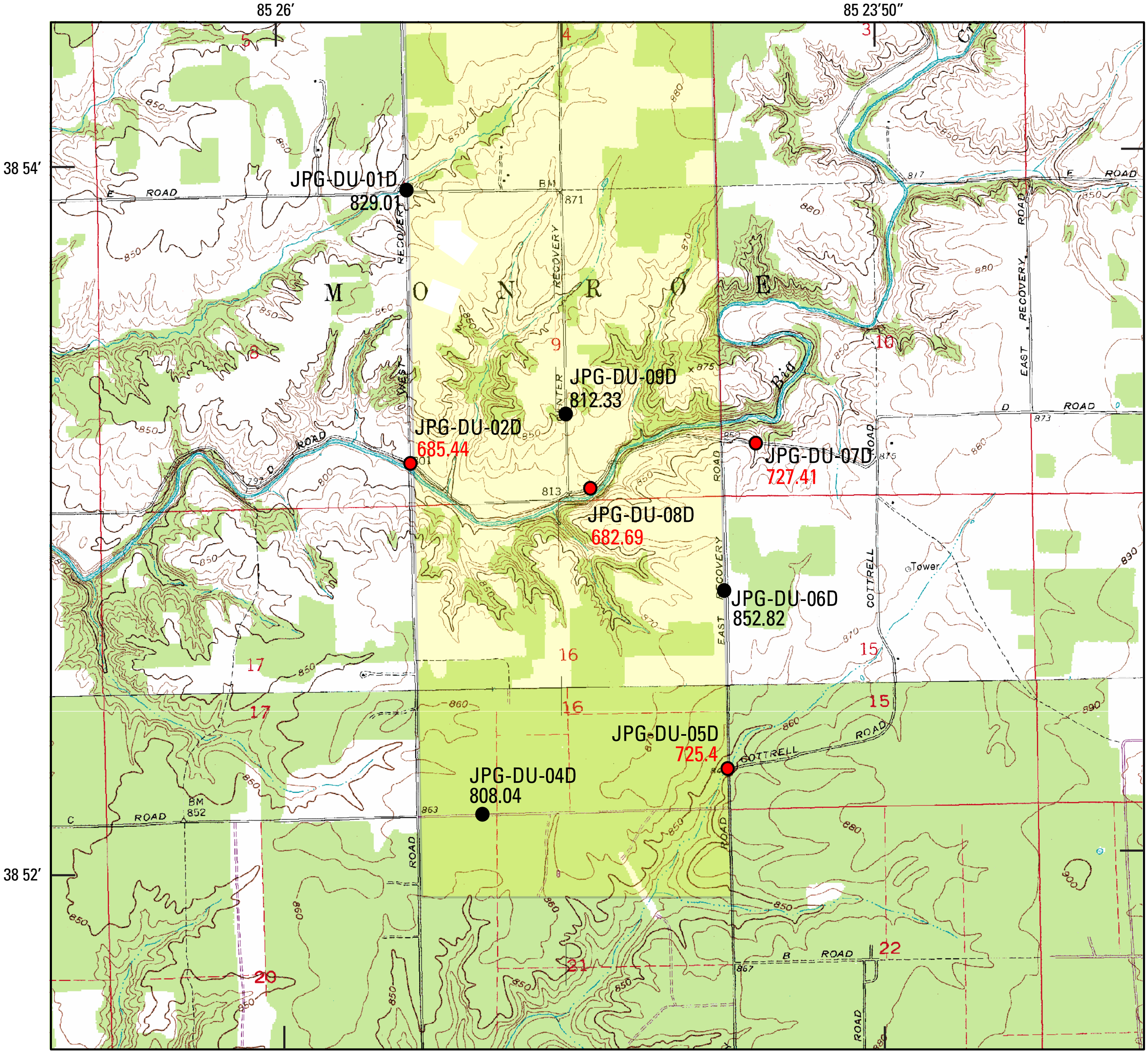
— 830 — WATER-LEVEL CONTOUR—Approximate altitude of the water level in the shallow carbonate unit, April 7, 2008, in feet above North American Vertical Datum of 1988. Dashed where approximately located. Contour interval 10 feet.

JPG-DU-01I 838.73 ● GROUNDWATER OBSERVATION WELL--With well identifier and water level in the shallow carbonate unit, April 7, 2008, in feet above North American Vertical Datum of 1988.

JPG-DU-07I 787.62 🔴 GROUNDWATER OBSERVATION WELL--With well identifier and water level in well in the shallow carbonate unit indicating dry condition, April 7, 2008, in feet above North American Vertical Datum of 1988.

← INFERRED DIRECTION OF WATER-LEVEL GRADIENT--Direction of groundwater flow may differ because of irregular distribution of interconnected porosity in the shallow carbonate unit

Figure 11. Altitude of groundwater levels in the shallow carbonate unit, April 7, 2008, at the Jefferson Proving Ground, southeastern Indiana.



Base from U.S. Geological Survey Digital Raster Graphic (DRG) 1:24,000;
San Jacinto, Ind., 1959, minor revision 1994, also Clifty Falls, Ind., 1995,
Universal Transverse Mercator projection, Zone 16, North American Datum
of 1927. Vertical datum of the DRG is the National Geodetic Vertical Datum of 1929

0 0.5 1 MILE

0 0.5 1 KILOMETER

EXPLANATION

🟨	DEPLETED URANIUM IMPACT AREA—Approximate extent
● JPG-DU-04D 808.04	GROUNDWATER OBSERVATION WELL—With well identifier and water level in the deep carbonate unit, April 7, 2008, in feet above North American Vertical Datum of 1988.
🔴 JPG-DU-05D 725.4	GROUNDWATER OBSERVATION WELL—With well identifier and water level in well screened in the deep carbonate unit indicating dry condition, April 7, 2008, in feet above North American Vertical Datum of 1988.

Figure 12. Altitude of groundwater levels in the deep carbonate unit, April 7, 2008, at the Jefferson Proving Ground, southeastern Indiana.

Groundwater-level gradient directions in the shallow carbonate unit were toward local surface-water drainages and generally from areas of higher groundwater levels in interstream areas toward discharge areas near Big Creek, Middle Fork Creek, and their tributaries (fig. 11). The April 7, 2008, water levels in the shallow carbonate unit are contoured as a continuous surface, although the distribution of conductive fractures and dissolution modified zones in the unit is considered by this study to be heterogeneous and discontinuous.

Vertical gradients from the shallow carbonate unit toward the deep carbonate unit at 3 of 4 paired wells and slow or no recovery of water levels in wells at 4 other sites in the deep carbonate unit indicate a resistance to and lack of flow between the two units and that the directions of flow in the shallow carbonate unit principally are horizontal (table 6). Vertical gradients were downward from the shallow carbonate unit toward the deep carbonate unit at two sites with paired wells with relatively stable water levels; at JPG-DU-06I and JPG-DU-06D and at JPG-DU-09I and JPG-DU-09D (tables 5 and 6). The gradients at these sites ranged from 0.106 ft/ft downward between wells JPG-DU-06I and JPG-DU-06D to 0.655 ft/ft downward between wells JPG-DU-06I and JPG-DU-06D for data collected between January and August of 2008.

Vertical gradients were also likely downward between wells JPG-DU-04I and JPG-DU-04D (table 6). Because water levels did not fully stabilize between sampling-related changes in well JPG-DU-04D (table 5), the magnitude of the long-term vertical gradients between these wells cannot be evaluated with available data. In contrast, as water levels recovered from 35.23 to -0.58 ft below the land surface datum in JPG-DU-01D from January through August 2008, vertical gradients gradually changed from downward to slightly upward between paired wells JPG-DU-01I and JPG-DU-01D (tables 5 and 6). The slow recovery or non-recovery of water levels in most wells in the deep carbonate unit however, was consistent with a very low horizontal hydraulic conductivity in most parts of that unit.

Water levels in deep wells at three other well pairs, notably JPG-DU-02D, JPG-DU-05D, and JPG-DU-08D, did not substantially recover after groundwater was withdrawn during initial well development (fig. 3 and table 5). The vertical hydraulic gradients between well pairs JPG-DU-02I and JPG-DU-02D, JPG-DU-05I and JPG-DU-05D, and JPG-DU-08I and JPG-DU-08D indicate a poor hydraulic connection between the shallow and deep carbonate units. The lack of post development recovery of water levels at wells JPG-DU-02D, JPG-DU-05D, JPG-DU-07D, and JPG-DU-08D in the deep carbonate unit indicate that parts of that unit have little or no permeability.

Groundwater-flow directions in the deep carbonate unit could not be determined because of the heterogeneous distribution of permeable zones, as indicated by the several dry wells in this unit (fig. 12) and the slow recovery of water levels at several wells. The heterogeneous distribution of permeable zones in the deep carbonate encountered during well drilling indicate that groundwater occurrence and flow may be limited to sparse, poorly connected joints and bedding plane separations with little solution enhancement. The slow recovery of water levels after post drilling development in wells open to the deep carbonate unit indicate these water bearing zones have a low hydraulic conductivity and collectively contribute little to groundwater transmission laterally across the deep carbonate.

Recharge to wells screened in Pre-Wisconsinan till was assumed principally to represent vertical flow to the saturated zone sampled by the well. Groundwater level measurements and land-surface altitudes were used to assign a recharge altitude to water from each well for recharge temperature and CFC-based age-dating computations (table 5). The recharge altitudes of water from wells screened in Pre-Wisconsinan till were assumed to be similar to the observed groundwater levels from those wells, rounded to the nearest 5 ft; these recharge altitudes ranged from 840 ft above the vertical datum for well JPG-DU-09O to 870 ft above the vertical datum for well JPG-DU-06O (table 5).

Groundwater recharge to wells that were open to the shallow and deep carbonate units likely occurred upgradient from the well and at higher water-level altitudes than the sampled depth. Recharge altitudes used for dissolved gas and CFC-based groundwater-age computations for water from wells in the shallow carbonate unit ranged from 810 ft above the vertical datum for well JPG-DU-02I to 870 ft above the vertical datum for well JPG-DU-06I (table 5). Recharge altitudes for water from two wells in the deep carbonate unit were assigned to be similar to those used for adjacent wells in the shallow carbonate unit; they were 840 ft above the vertical datum for well JPG-DU-09D and 870 ft above the vertical datum for well JPG-DU-06D (table 5).

General Groundwater Chemistry and Evaluation of Oxidation-Reduction Conditions

Field water-quality parameters were measured by SAIC representatives during the sampling of 15 wells in and near the DU Impact Area (table 7). The values of these parameters are reported to provide a context for the USGS samples analyzed for dissolved gases, tritium, and CFCs. The data reported here represent a one-time sampling of the wells; other sampling was done in 2008 and 2009 by SAIC. Water-quality parameters measured in water from wells sampled for tritium only are not presented in this report.

Water from wells in the deep carbonate unit generally had less dissolved oxygen than water from the wells in the Pre-Wisconsinan till or the shallow carbonate unit. Field measurements of dissolved oxygen ranged from <0.1 mg/L in water from wells JPG-DU-09D and JPG-DU-02I to 1.7 mg/L in water from well JPG-DU-10O (table 7). Three of 5 samples from the Pre-Wisconsinan till and 6 of 8 samples from the shallow carbonate unit had concentrations of dissolved oxygen that ranged from 0.7 mg/L to 1.7 mg/L. These concentrations

Table 7. Values of field-determined water-quality parameters in groundwater samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; °C, degrees Celsius; µS/cm, microsiemens per centimeter; NTU, Nephelometric Turbidity Units, as reported by Science Applications International Corporation; mV, millivolt; mg/L, milligrams per liter; <, less than]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Turbidity (NTU[1])	Redox potential (mV)	Dissolved oxygen (mg/L)
Groundwater samples from the Pre-Wisconsinan till								
JPG-DU-03O	04/09/08	1055	11.1	999	7.55	32	-32	0.6
JPG-DU-04O	04/15/08	0830	11.7	1,160	8.01	42	-148	.7
JPG-DU-06O	04/15/08	1530	11.2	990	7.64	30	78	.4
JPG-DU-09O	04/13/08	1650	11.3	999	8.00	26	-105	1.2
JPG-DU-10O	04/13/08	1250	12.0	1,440	8.01	374	-161	1.7
Groundwater samples from the shallow carbonate unit								
JPG-DU-01I	04/10/08	0915	12.0	3,130	7.71	16	-110	.8
JPG-DU-02I	04/14/08	1355	11.4	702	7.98	0	-82	<.1
JPG-DU-03I	04/09/08	1500	12.7	1,280	7.96	14	6	1.6
JPG-DU-04I	04/15/08	1015	12.4	1,130	7.77	49	-126	.9
JPG-DU-05I	04/15/08	1315	12.1	910	7.98	16	-28	.9
JPG-DU-06I	04/20/08	1630	13.0	1,010	7.75	32	-176	.8
JPG-DU-09I	04/14/08	0830	10.1	999	7.74	16	14	1.0
JPG-DU-10D	04/10/08	1355	14.8	926	7.74	2	-248	.1
Groundwater samples from the deep carbonate unit								
JPG-DU-06D	04/21/08	1115	14.0	1,630	7.80	61	-249	.3
JPG-DU-09D	04/14/08	1100	11.8	85,600	7.17	0	38	<.1

[1] Turbidity values were determined using a Horiba model U-22XD multiparameter unit. That unit was calibrated to report turbidity data in Nephelometric Turbidity Units (NTU; Horiba, Ltd., 2001). U.S. Geological Survey methods described in Anderson (2005) have revised criteria to report turbidity data in Formazin Nephelometric Ratio Units from equipment, such as the model used here, that have a scattered light receptor that is not oriented at 90 degrees to the light source. These data are reported here in units of NTU to be consistent with other reporting of the data by Science Applications International Corporation (2008).

are considered for this study to be sufficiently oxic to support aerobic bacterial processes (Bradley and others 2008; Gossett, 2010); CFC compounds are generally stable under oxic conditions (International Atomic Energy Agency, 2006). Except for water from wells JPG-DU-02I and JPG-DU-10O, concentrations of dissolved oxygen in water from the shallow carbonate unit ranged from 0.8 to 1.6 mg/L. Water from wells JPG-DU-02I, JPG-DU-10D, and JPG-DU-09D had concentrations of dissolved oxygen that were 0.1 mg/L or less, which was an indication that they may support anaerobic microbial conditions (Bradley and others, 2008); those conditions, if sufficiently reduced, have the potential to biotransform and decrease concentrations of some CFCs—particularly CFC-11 and CFC-113 (International Atomic Energy Agency, 2006).

Specific-conductance (SC) values were highest in water from one well in the deep carbonate unit (JPG-DU-09D, 85,600 µS/cm) and the shallow carbonate unit (well JPG-DU-01I, 3,130 µS/cm; table 7). The groundwater level in well JPG-DU-01I generally was above land surface, indicating that the well potentially was developed in a discharge area or a confined part of the shallow carbonate unit. The source of the large SC values in water from well JPG-DU-01I cannot be distinguished using these data. SC values were smallest in water from the shallow carbonate unit (wells JPG-DU-02I, 702 µS/cm and JPG-DU-05I, 910 µS/cm); these wells are located next to streams that are incised into carbonate bedrock and have less than 5 ft of overlaying soil or Pre-Wisconsinan till deposits. SC measures the fluid electrical conductivity; SC values relate to the types and quantities of dissolved substances in water, but there is no universal linear relation between concentrations of dissolved solids and SC (Radtke and others, 2005).

The pH values of the 15 groundwater samples reported in table 7 were alkaline. The pH of groundwater in the study area ranged from 7.17 at a well (JPG-DU-09D) in the deep carbonate unit to 8.01 at two wells (JPG-DU-04O and JPG-DU-10O) in the Pre-Wisconsinan till. No trends in pH with depth or across the study area were noted.

Concentrations of Dissolved Gas and Estimated Average Recharge Temperatures

Estimated average recharge temperatures of groundwater indicate that most recharge to groundwater in the study area occurs during the cooler months of fall, winter, and spring seasons when evapotranspiration typically is smallest. Estimated average recharge temperatures of groundwater ranged from 1.5°C at well JPG-DU-04O to 11.7°C at well JPG-DU-3I; the median recharge temperature was 7.1°C (table 8). These estimated average recharge temperatures were less than 12.6°C, the mean monthly air temperature at Madison, Indiana (Midwestern Regional Climate Center, 2009a). Most wells had estimated average recharge temperatures that were 8.6°C or less; these corresponded to the range of monthly average air temperatures at Madison, Indiana, from November to March (-0.7°C to 7.4°C; Midwestern Regional Climate Center, 2009a) and indicated that most recharge occurred during the cooler, non-growing months. Absolute differences between the estimated average recharge temperatures computed for groundwater samples (table 8) and sequential replicate samples (table 9, at end of report) were very small; they ranged from no difference for well JPG-DU-03I to 0.7°C for well JPG-DU-3I. Excess concentrations of air in water from 13 of 15 wells sampled for dissolved gases ranged from 1.7 cm^3/L in water from well JPG-DU-02I to 13.7 cm^3/L in water from well JPG-DU-04I (table 8). Recharge altitudes in table 5 were used to normalize the concentrations of argon and nitrogen gas to standard pressure (760 mm of mercury).

Nitrogen and argon concentrations for wells JPG-DU-06D and JPG-DU-09D produced estimated average recharge temperatures of 16.9 and 13.7, which were greater than the mean monthly air temperature of 12.6°C at Madison, Indiana. Concentrations of argon in groundwater from wells JPG-DU-06D and JPG-DU-09D were the smallest of all groundwater sampled during this investigation (table 8). These recharge temperatures assume that excess nitrogen, relative to the smaller concentrations of argon, is present in water from the two wells; 3.8 mg/L for well JPG-DU-06D and 11.5 mg/L for well JPG-DU-09D. Water from well JPG-DU-06D had the largest concentration of methane of any sample collected during this study (11.4 mg/L as CH_4; table 8) and a small concentration of carbon dioxide (17.1 mg/L as CO_2), indicating the likely prevalence of reduced, methanogenic conditions that also could have generated excess nitrogen. Water from well

Table 8. Concentrations of selected dissolved gases in water samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligrams per liter; cm^3/L, cubic centimeters per liter; °C, degrees Celsius; Q, estimated concentration; --, not computed]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Methane (mg/L)	Carbon dioxide (mg/L)	Argon (mg/L)	Nitrogen (mg/L)	Argon, normalized to 760 mm mercury (mg/L)	Nitrogen, normalized to 760 mm mercury (mg/L)	Excess air concentration (cm^3/L)	Excess nitrogen concentration (mg/L)	Estimated average recharge temperature (°C)
Groundwater samples from the Pre-Wisconsinan till											
JPG-DU-03O	04/08/08	1500	Q0.0013	81.4	0.84	26.1	0.87	27	7.6	--	7.2
JPG-DU-04O	04/15/08	0830	.033	58.5	1.0	32.6	1.0	33.7	11.5	--	1.5
JPG-DU-06O	04/15/08	1530	.0054	65.8	.78	23.5	.81	24.3	5.5	--	8.5
JPG-DU-09O	04/13/08	1650	.022	34.9	.82	25.6	.85	26.5	7.6	--	8.3
JPG-DU-10O	04/13/08	1250	2.0	38.8	.79	23.2	.82	23.9	4.3	--	6.7
Groundwater samples from the shallow carbonate unit											
JPG-DU-01I	04/10/08	915	.023	42.6	.86	26.2	.88	27.1	7.1	--	5.3
JPG-DU-02I	04/14/08	1355	Q.0016	21.7	.74	20.4	.77	21	1.7	--	7.1
JPG-DU-03I	04/09/08	1055	.0079	25.3	.76	24.1	.79	24.9	7.4	--	11.7
JPG-DU-04I	04/15/08	1015	.025	54.4	1.0	33.5	1.0	34.5	13.7	--	4.2
JPG-DU-05I	04/15/08	1315	Q.00048	23.5	.85	27.7	.88	28.5	9.8	--	8.6
JPG-DU-06I	04/20/08	1630	.019	59.5	.82	24.4	.84	25.2	5.5	--	6.4
JPG-DU-09I	04/14/08	0830	Q.00080	42.2	.81	23.8	.83	24.6	5.0	--	6.7
JPG-DU-10D	04/10/08	1355	.013	26.1	.84	26.5	.87	27.3	8.1	--	7.7
Groundwater samples from the deep carbonate unit											
JPG-DU-06D	04/21/08	1115	11.4	17.1	.57	19	.59	19.7	1.0	3.8	16.9
JPG-DU-09D	04/14/08	1100	.018	16.7	.46	23.7	.48	24.5	.5	11.5	13.7

Quality assurance data, including analyses of sequential replicate samples, are included in table 12 (at end of report).

JPG-DU-09D had less than 0.1 mg/L of dissolved oxygen, an indication of anaerobic microbial conditions that could generate excess nitrogen through a process such as nitrate reduction if sufficient nitrate was present.

All groundwater samples collected during this study contained more terrigenic helium (helium of mineralogic origin) than would permit reliable estimation of groundwater-age dates using the ratio of tritium to the isotope helium-3 ($^3H/^3He$) in water (table 10). Therefore, age dating by the $^3H/^3He$ method was not attempted. Dating of groundwater samples that are mixtures of very old water with submodern recharge by the $^3H/^3He$ method can be complicated if a sample contains a large excess (50 percent or greater) of terrigenic helium from the old fraction (Plummer and others, 2000). Concentrations of dissolved helium in groundwater samples collected during this investigation ranged from 82 x 10^{-9} ccSTP/g water to 109,500 x 10^{-9} ccSTP/g (table 10). Modern water in equilibrium with air normally contains less helium, about 46x10^{-9} ccSTP/g water. The concentrations of helium in groundwater samples collected during this study are substantially greater than the equilibrium concentration plus 50 percent (about 70 x 10^{-9} ccSTP/g water), indicating the likelihood of substantial uncertainties if age estimates of the young fraction of mixed groundwater were computed. In a mixture, the $^3He/^4He$ ratio of the terrigenic helium must be known for the particular sample within about 1 percent or better to permit reliable $^3H/^3He$ dating of the young fraction.

Estimates of Groundwater Age from Till and Carbonate Bedrock Hydrogeologic Units

Estimates of groundwater age were developed from concentrations of tritium (table 11) and from concentrations of CFCs using concentrations of excess air and recharge temperatures determined from dissolved-gas data (tables 9 and 10). In addition, ratios of CFC compounds were used to indicate whether a single, largely unmixed source of water (piston flow) to the well was a feasible explanation for concentrations of CFCs and tritium from a well, as compared with mixing of old (pre-CFC) and young (binary mixing) recharge (tables 12 and 13, at end of report). The sum of the concentrations of tritium and the associated 2-sigma precision of concentrations of tritium in groundwater samples were used to assess the potential for analytical uncertainty to affect tritium-based groundwater age estimates, similar to the procedure used by Bartolino (1997, p. 16). Details of the groundwater-age estimates and the implications for water-quality sampling are presented in the following sections.

Tritium-Based Groundwater Ages

Samples from two wells, one in the shallow carbonate unit (JPG-DU-10D) and one in the deep carbonate unit

Table 10. Concentrations of helium and neon in water samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; nmol/kg, nanomole per kilogram; cc x 10^{-9}/g of water at STP, 10^{-9} cubic centimeters of a dissolved gas per gram of water at standard temperature (25 degrees Celsius) and pressure (760 millimeters of mercury); ND, neon concentrations not determined owing to interfering concentrations of helium generally larger than 1,000 nanomoles per kilogram of water; NA, not analyzed]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Helium (nmol/kg in water)	Helium ([cc x 10^{-9}]/g of water at STP)	Neon (nmol/kg in water)	Neon ([cc x 10^{-9}]/g of water at STP)
Groundwater samples from the Pre-Wisconsinan till						
JPG-DU-03O	04/08/08	1500	5.1	115	16.0	359
JPG-DU-04O	04/15/08	0830	6.4	142	19.5	436
JPG-DU-06O	04/15/08	1530	3.6	82	15.0	335
JPG-DU-09O	04/13/08	1650	3.7	83	15.4	345
JPG-DU-10O	04/13/08	1250	4.3	97	8.0	179
Groundwater samples from the shallow carbonate unit						
JPG-DU-01I	04/10/08	0915	1,277	28,600	ND	ND
JPG-DU-02I	04/14/08	1355	11.0	246	10.0	223
JPG-DU-03I	04/09/08	1055	18.8	422	14.1	316
JPG-DU-04I	04/15/08	1015	28.9	647	14.4	322
JPG-DU-05I	04/15/08	1315	15.1	338	10.8	243
JPG-DU-09I	04/14/08	0830	6.1	136	15.1	338
JPG-DU-10D	04/10/08	1355	2,949	66,100	ND	ND
Groundwater samples from the deep carbonate unit						
JPG-DU-06D	04/21/08	1115	NA	NA	NA	NA
JPG-DU-09D	04/14/08	1100	4,885	109,500	ND	ND

Table 11. Concentrations of tritium in groundwater samples from observation wells at the Jefferson Proving Ground, southeastern Indiana, April 2008.

[TU, tritium unit; one tritium unit equals 3.2 picocuries per liter; well identifiers and data where concentrations of tritium were less than or equal to 0.8 TU are shown in **bold type**; estimated age of groundwater is classified from the concentration of tritium]

Project well identifier	Date sampled (month/day/year)	Tritium, water, unfiltered (tritium units)	Tritium, 2-sigma precision (tritium units)	Sum of tritium in water plus 2-sigma precision	Tritium-based estimate of groundwater age	Comments
Pre-Wisconsinan till unit						
WELL JPG-DU-03O	04/09/2008	4.1	0.5	4.6	Substantially modern	--
WELL JPG-DU-04O	**04/15/2008**	**.5**	**.4**	**.9**	**Submodern**	**Sum indicates may be submodern/modern mix**
WELL JPG-DU-06O	04/15/2008	4.6	.6	5.2	Substantially modern	--
WELL JPG-DU-09O	**04/13/2008**	**.5**	**.6**	**1.1**	**Submodern**	**Sum indicates may be submodern/modern mix**
WELL JPG-DU-10O	**04/13/2008**	**.7**	**.6**	**1.3**	**Submodern**	**Sum indicates may be submodern/modern mix**
WELL MW-6	04/15/2008	4.6	.6	5.2	Substantially modern	--
WELL MW-10	04/23/2008	3.3	.6	3.9	Submodern/modern mix	--
WELL MW-RS3	04/22/2008	5.5	.8	6.3	Substantially modern	--
WELL MW-RS4	04/15/2008	5.0	.6	5.6	Substantially modern	--
WELL MW-RS5	04/14/2008	6.6	.6	7.2	Substantially modern	--
WELL MW-RS6	04/14/2008	7.8	.8	8.6	Substantially modern	--
WELL MW-RS7	04/23/2008	8.7	.8	9.5	Substantially modern	--
WELL MW-RS8	04/24/2008	5.0	.6	5.6	Substantially modern	--
Shallow carbonate unit						
WELL JPG-DU-01I	**04/10/2008**	**.2**	**.4**	**.6**	**Submodern**	**--**
WELL JPG-DU-02I	04/14/2008	5.1	.6	5.7	Substantially modern	--
WELL JPG-DU-03I	04/09/2008	2.6	.5	3.1	Submodern/modern mix	--
WELL JPG-DU-04I	**04/15/2008**	**.4**	**.4**	**.8**	**Submodern**	**--**
WELL JPG-DU-05I	**04/15/2008**	**.3**	**.4**	**.7**	**Submodern**	**--**
WELL JPG-DU-06I	**04/20/2008**	**.3**	**.4**	**.7**	**Submodern**	**--**
WELL JPG-DU-09I	**04/14/2008**	**.5**	**.6**	**1.1**	**Submodern**	**Sum indicates may be submodern/modern mix**
WELL JPG-DU-10D	**04/10/2008**	**.1**	**.6**	**.7**	**Submodern**	**--**
WELL MW-2	04/22/2008	3.9	.6	4.5	Submodern/modern mix	May be substantially modern
WELL MW-3	04/22/2008	5.0	.6	5.6	Substantially modern	--
WELL MW-4	04/15/2008	5.3	.8	6.1	Substantially modern	--
WELL MW-5	04/25/2008	3.7	.6	4.3	Submodern/modern mix	May be substantially modern
WELL MW-8	04/15/2008	4.4	.6	5.0	Substantially modern	--
WELL MW-11	04/23/2008	4.9	.6	5.5	Substantially modern	--
Deep carbonate unit						
WELL JPG-DU-06D	04/21/2008	3.3	.6	3.9	Submodern/modern mix	--
WELL JPG-DU-09D	**04/14/2008**	**<.1**	**.4**	**.5**	**Submodern**	**--**

(JPG-DU-09D), had the smallest concentrations of tritium for any samples collected during this study, less than or equal to 0.1 TU (fig. 13; table 11). The tritium-based age dates indicate that the sources of recharge to these wells was submodern and predated 1954. The age dates for these two wells also indicate that water quality from these wells is not affected by the post-1984 presence of DU penetrators because recharge from those years has not reached the geologic intervals sampled by the wells.

Four wells in the shallow carbonate unit: JPG-DU-01I, JPG-DU-04I, JPG-DU-05I, and JPG-DU-06I, had concentrations of tritium that were greater than 0.1 but less than or equal to 0.4 TU (fig. 13), indicating that the predominant sources of recharge to these wells also have a submodern age. The range of concentrations of tritium for these four wells, computed by addition or subtraction of the 2-sigma precision with the concentrations of tritium, also were less than or equal to 0.8 TU (table 11). These data indicate that water sampled from these four wells reflect recharge from 1953 or earlier and would not be affected by the post-1984 presence of DU penetrators. A potential presence of modern water in the samples from wells JPG-DU-01I, JPG-DU-04I, and JPG-DU-05I was indicated by the CFC-based age dates; these age classifications are discussed later in this report.

Three wells in the Pre-Wisconsinan till, JPG-DU-04O, JPG-DU-09O, and JPG-DU-10O, and one well in the shallow carbonate unit JPG-DU-09I, had concentrations of tritium that were less than 0.8 TU (fig. 13). However, the sum of concentrations of tritium and the 2-sigma precision of those concentrations for these four wells, overlapped the classification between submodern and submodern/modern mixture age classifications. Although the concentrations of tritium in the samples from these four wells were small (<0.8 TU) and are similar to that of decay-corrected 1953 and earlier precipitation, the possibility of their mixing with submodern water could not be ruled out using analyses of tritium only. Tritium-based age dates from these four wells were verified using CFC-based age dates.

Concentrations of tritium in groundwater samples from 19 wells ranged from 2.6 to 8.7 TU (table 11), indicating that some or most recharge to these wells, and presumably the associated sources of potential contaminants, reflect activities that post-date 1953 (fig. 13). These samples were classified as having groundwater ages that were substantially modern or a submodern/modern mix. The range of concentrations of tritium in these wells also was slightly less than or nearly equal to the range of annual average decay-corrected concentrations of tritium in post-1972 precipitation from the Ohio River Basin of 3.9 to 8.1 TU (fig. 13). Water from well MW-10 in the Pre-Wisconsinan till unit, wells JPG-DU-03I, MW-2, and MW-5 in the shallow carbonate unit, and JPG-DU-06D in the deep carbonate unit had concentrations of tritium that were slightly less than the decay-corrected post-1972 precipitation. Tritium concentrations in water from these five wells likely represent a mixture of modern water with some fraction of submodern, tritium-depleted water. The possibility of 1984 and later recharge contributing to the modern component of recharge classified in several JPG-DU wells is evaluated later in this report using CFC-based age dates.

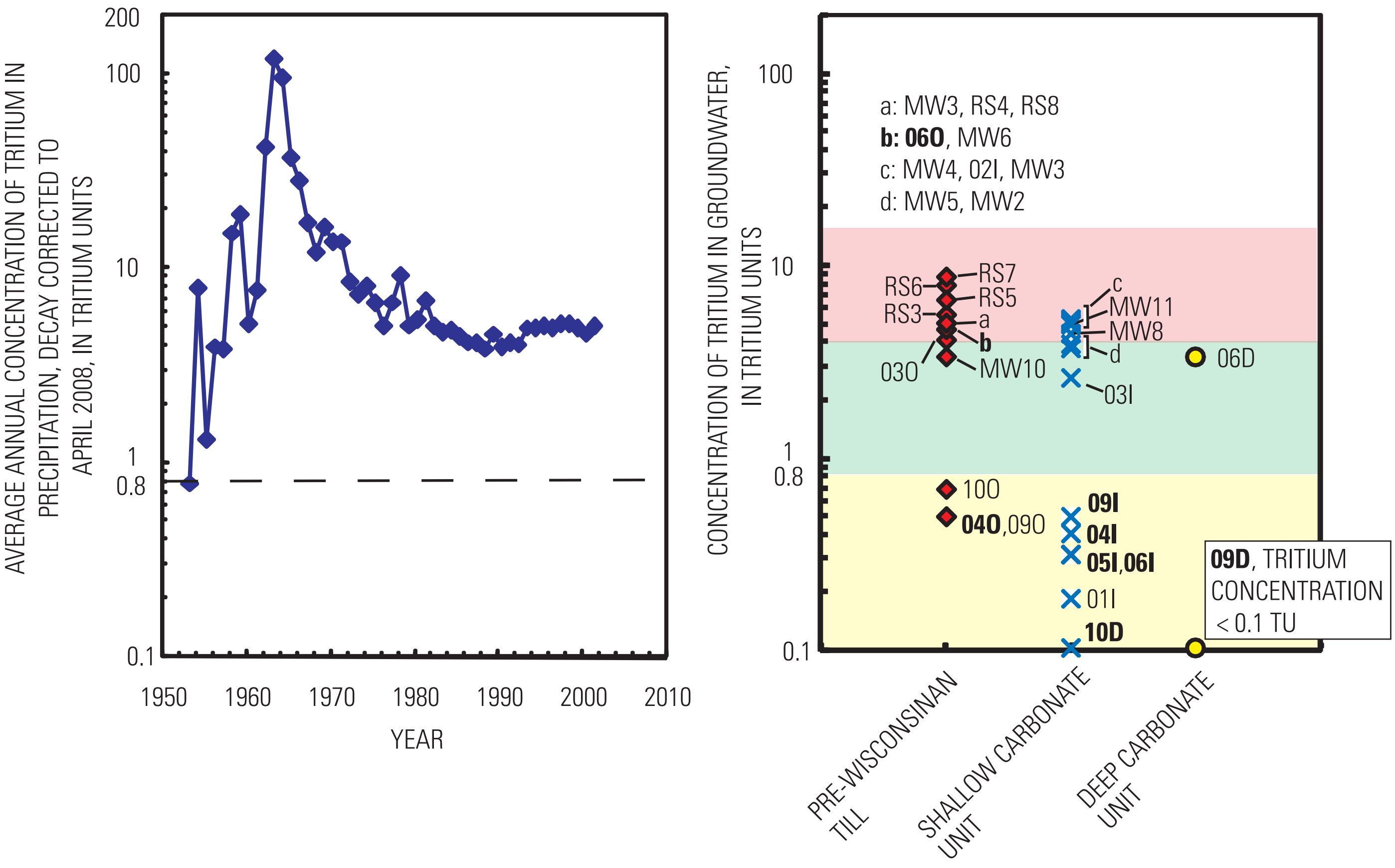
The possibility that the MW and MW-RS series wells could produce groundwater containing recharge from the 1984 and later period affected by DU testing cannot be ruled out solely using tritium data. MW and MW-RS series wells were sampled for tritium and were not sampled for CFCs; these wells have age classifications that include some modern recharge. Tritium-based age classifications therefore indicate that water quality from the post-1984 testing period of DU penetrators could be monitored from these wells.

Chlorofluorocarbon-Based Groundwater Ages

Chlorofluorocarbon-based groundwater ages were computed using two hypothetical flow scenarios; a piston-based model that assumes no mixing during groundwater flow between recharge and the well screen and a binary-mixing hypothesis that represents the final water composition as a mixture between pre-CFC age (pre-1940) and post-1940 or younger groundwater (tables 12 and 13). CFC-based estimates of groundwater age in several samples from wells in the shallow carbonate and deep carbonate units indicated piston-flow and binary mixtures that predated the use of DU penetrators at JPG. Results from other wells indicated the presence of water with groundwater ages that were partially or entirely from, during, or after about 1980 (table 13). Results of these estimates can be used to evaluate groundwater monitoring targeted to identify water-quality effects dating from or after 1984.

Pre-Wisconsinan Till Groundwater-Age Dates

The CFC-based age dates of groundwater samples from five wells in the Pre-Wisconsinan till could be explained best as binary mixtures of young (mid-1970s or more recent in age) and old, pre-1940, pre-CFC recharge (figs. 14 and 15; table 13). For example, water from wells JPG-DU-03O and JPG-DU-06O were best represented as binary mixtures of recharge from about 1984 and 1979, respectively, and pre-1940 recharge, based on atmospheric-mixing ratios of CFC-113 and CFC-12 (fig. 14). The contribution of mid-1980s era recharge to the computed binary mixture was about 70 percent of the sample from well JPG-DU-03O (fig. 15; table 13). The contribution of late-1970s era recharge to the computed binary mixture was about 30 percent of the sample from well JPG-DU-06O (fig. 15; table 13). The CFC-based age estimates of these two samples were consistent with their tritium-based age estimates (table 13); they indicate that wells JPG-DU-03O and JPG-DU-06O may produce groundwater that partly includes recharge that is close in time to the early period of DU-projectile testing at JPG. Based on the CFC-age dates and their locations relative to the DU Impact Area, wells JPG-DU-03O and JPG-DU-06O are suitable to monitor



EXPLANATION

Groundwater-age classification based on tritium concentrations

🟥	Substantially modern—Concentrations of tritium ranging from 4 to 15 tritium units (TU). Indicates groundwater is predominantly post-1953 recharge, If tritium ranges from 4 to 8 TU, may be mostly post-1972 recharge
🟩	Submodern-modern mix—Concentrations of tritium ranging from 0.9 to less than 4 TU. Indicates groundwater is a mixture of submodern recharge with modern, post-1953 recharge
🟨	Submodern—Concentrations of tritium ranging from <0.1 to 0.8 tritium units. Indicates groundwater is predominantly composed of 1953 or earlier recharge

Groundwater sample—Plotted with last 3 to 4 characters and numbers of local well identifier, as in table 2. Well identifiers in bold font (**10D**) indicate that the chlorofluorocarbon-based groundwater age of the water sample from the well substantially predates depleted uranium projectile firing at Jefferson Proving Ground (pre-1984).

◆ 030	Sample from Pre-Wisconsinan till
× **100**	Sample from shallow carbonate unit
○ **09D**	Sample from deep carbonate unit

Figure 13. Estimates of the average annual concentration of tritium in precipitation for the Ohio River Basin, 1953–2002, corrected for radioactive decay to April 2008, as compared with concentrations of tritium in groundwater samples in the study area at Jefferson Proving Ground, southeastern Indiana, 2008.

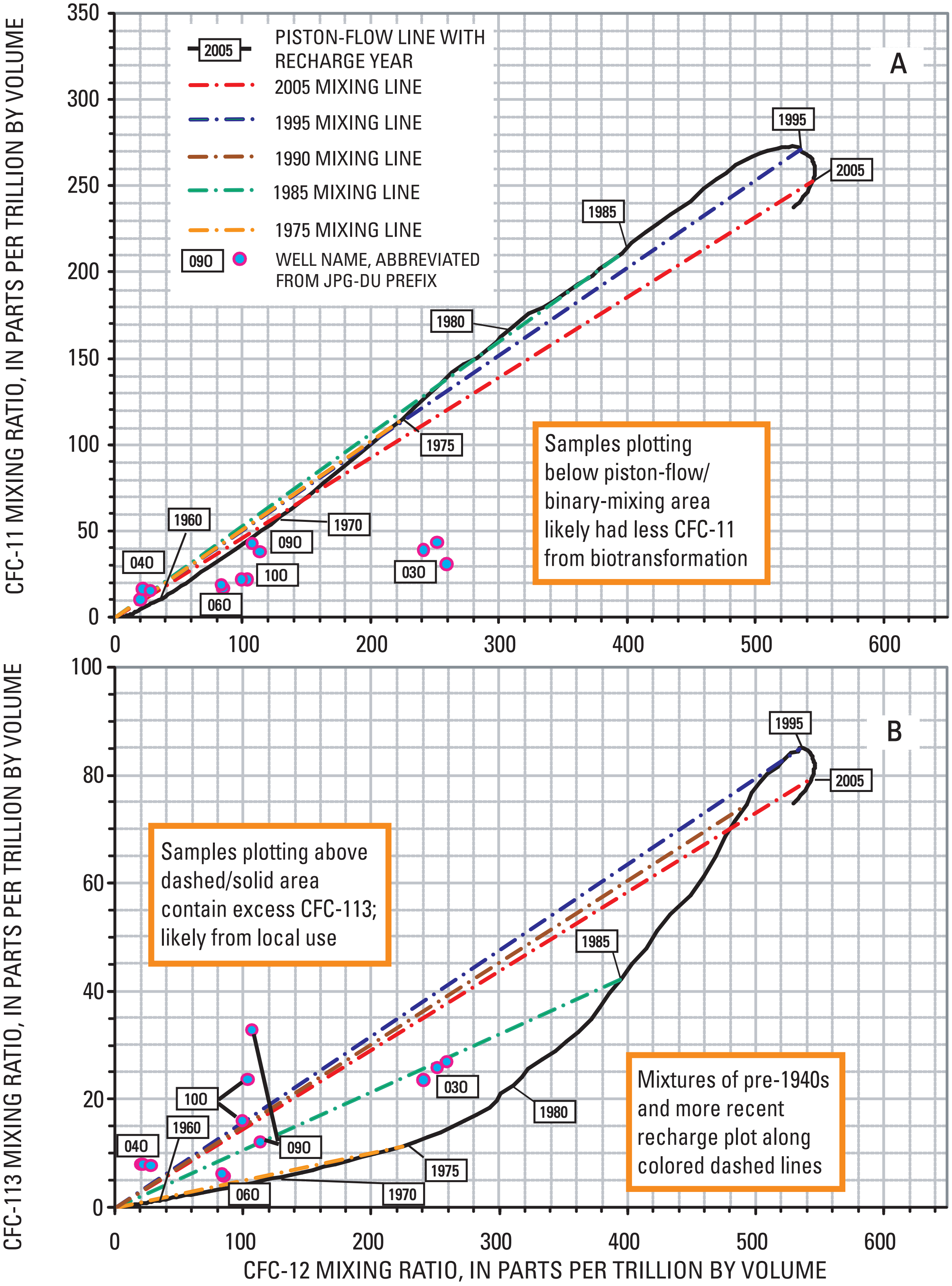
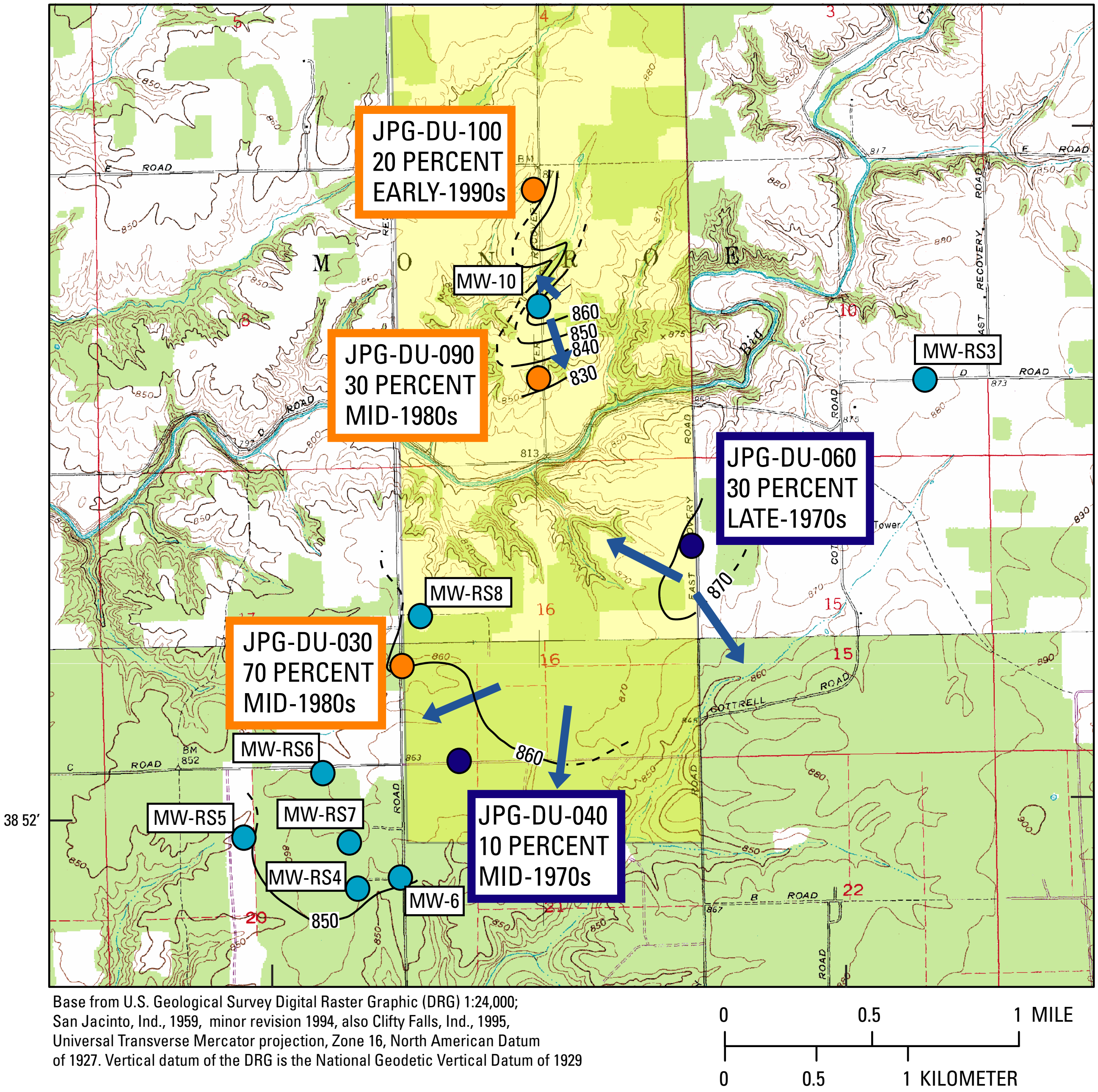


Figure 14. Relation between atmospheric-mixing ratios of chloroflurocarbon compounds in water from wells screened in Pre-Wisconsinan till, Depleted Uranium Impact Area, Jefferson Proving Ground, southeastern Indiana, April 2008. A. CFC-11 and CFC-12; B. CFC-113 and CFC-12. Model lines are included for piston flow and binary mixing of 1975–2005 age water with old (pre-CFC) water.



Base from U.S. Geological Survey Digital Raster Graphic (DRG) 1:24,000;
San Jacinto, Ind., 1959, minor revision 1994, also Clifty Falls, Ind., 1995,
Universal Transverse Mercator projection, Zone 16, North American Datum
of 1927. Vertical datum of the DRG is the National Geodetic Vertical Datum of 1929

EXPLANATION

🟨 DEPLETED URANIUM IMPACT AREA—Approximate extent

— 860 — WATER-LEVEL CONTOUR—Approximate altitude of the water level in the Pre-Wisconsinan till, April 7, 2008, in feet above National Geodetic Vertical Datum of 1929. Dashed where approximately located. Contour interval 10 feet

← INFERRED DIRECTION OF WATER-LEVEL GRADIENT IN THE PRE-WISCONSINAN TILL

🟠 WELL WITH PARTIALLY OR ALL POST-1980 GROUNDWATER AGE FROM CHLOROFLUOROCARBON COMPOUND ANALYSIS—with estimated percentage and age of young groundwater in sample

● WELL WITH PRE-1980 GROUNDWATER AGE FROM CHLOROFLUOROCARBON COMPOUND ANALYSIS —with estimated percentage and age of young groundwater in sample

🔵 POST-1953 AND POSSIBLY POST-1972 GROUNDWATER AGE; TRITIUM ANALYSIS

Figure 15. Groundwater-age classifications of water sampled from wells screened in Pre-Wisconsinan till, Depleted Uranium Impact Area, Jefferson Proving Ground, southeastern Indiana, April 2008.

groundwater quality for effects related to DU-penetrator testing.

Atmospheric-mixing ratios of CFC-11 and CFC-12 in water from two of three sample vials collected from well JPG-DU-04O were best represented as a binary mixture of about 90 percent pre-1940 water and about 10 percent recent recharge from the mid-1970s (figs. 14 and 15; table 13). The CFC-based age estimate for well JPG-DU-04O was consistent with a tritium-based age estimate for the sample from that well (table 13). These data indicate that groundwater samples from well JPG-DU-04O in April 2008 produced groundwater composed of recharge that predates 1984 and were not of a suitable age to monitor water quality for effects related to DU-penetrator testing.

Atmospheric-mixing ratios of CFC-113 and CFC-12 in water from two other wells from the Pre-Wisconsinan till (JPG-DU-09O and JPG-DU-10O), when interpreted with tritium data, indicated that their composition could be derived partially from post-1980s recharge to groundwater (figs. 14 and 15; table 13). A sample from well JPG-DU-09O (sample vial 2; table 12) and a sequential replicate from well JPG-DU-10O (sample vial 5; table 12) with the smallest CFC-113 atmospheric-mixing ratios plotted near binary-mixing curves of about 1985 and 1990 recharge, respectively, with pre-1940 recharge (fig. 14). Hypothetical mixtures of pre-1940s recharge with (a) about 30 percent of 1985 recharge to water from well JPG-DU-09O or (b) about 20 percent of 1991 recharge to water from well JPG-DU-10O, respectively, could explain the CFC-113 and CFC-12 atmospheric-mixing ratios and the concentration of tritium in these samples (fig. 15; table 13). The CFC-age dates indicate that wells JPG-DU-09O and JPG-DU-10O produce groundwater that includes recharge from the time of DU-penetrator testing at JPG; the wells are capable of producing water with groundwater-quality effects dating from that time.

One sample vial each from wells JPG-DU-09O and JPG-DU-10O had atmospheric-mixing ratios of CFC-113 that indicated contamination of those samples by CFC-113 from an atmospheric or other source (fig. 14; table 12). A sequentially collected replicate from well JPG-DU-09O (sample vial 3) and the initial sample from well JPG-DU-10O (sample vial 4) had CFC-113 atmospheric-mixing ratios that were from about 50 to 170 percent greater than their sequential replicate, respectively (table 12). These data indicate the potential for CFC-113 to have been used locally and introduced into recharge; CFC-113 has had a wide variety of uses, including as an aerosol propellant; as a cleaning agent for electrical and electronic components; and in the production of foam for plastics, packaging, and insulation (Merck and Co., 1989). The agreement of other results from these wells with tritium-based age dates indicate that these specific sample vials represented isolated sample contamination. These results also indicate the need for caution when interpreting CFC-based age dates without corroboration from tritium or other age-dating methods.

The sensitivity of CFC-based age dates to changes in recharge altitude and recharge temperature was evaluated for a sample from well JPG-DU-03O (sample bottle 1); this well was screened in the Pre-Wisconsinan till and had a CFC-based age date which was a mixture that included some recharge from the 1980s (table 14). Sensitivity of age dates was assessed by (1) increasing or decreasing the recharge altitude by 20 ft while holding recharge temperature constant and (2) increasing the recharge temperature by 5°C while holding recharge altitude constant. These changes represent possible variability of these properties based on local temperature and land-surface topography.

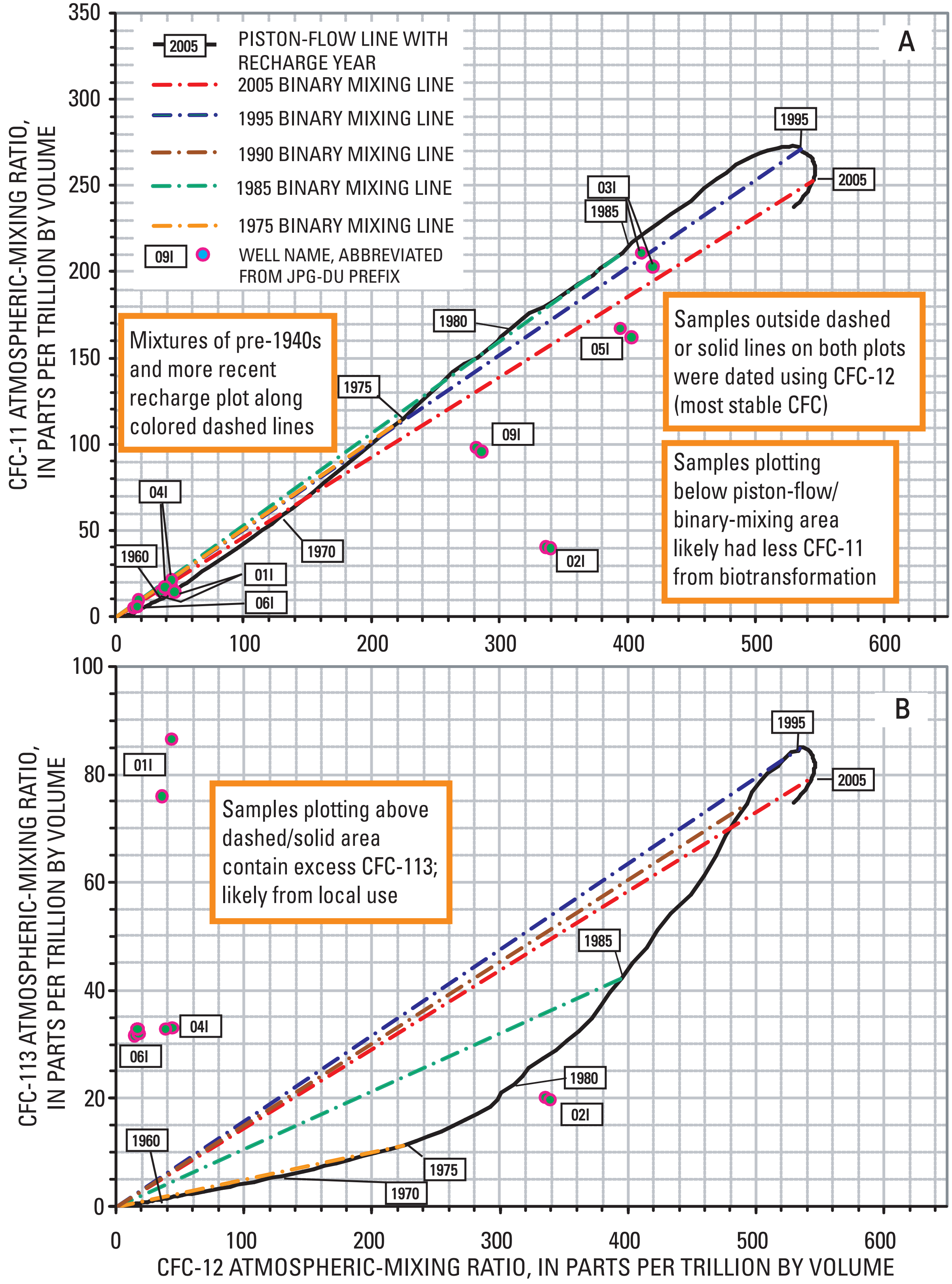
Increasing the recharge temperature by 5°C resulted in a 3-year decrease in the piston-flow-based groundwater age; the same decrease in recharge temperature increased the piston-flow-based groundwater age by 4 years (table 14). The difference between the two adjustments arises from rounding of the age-date year to an even number. Increasing the recharge temperature by 5°C resulted in a 1-year decrease in the age and a 15-percent decrease in the fraction of young recharge in a binary mixture. Decreasing the recharge temperature by 5°C resulted in a 1-year increase in the age and an 11-percent increase in the fraction of young recharge in a binary mixture.

An increase or decrease in recharge altitude by 20 ft had no effect on the computed piston-flow age date or the age and fraction of young groundwater in a binary mixture (table 14). These sensitivities to changes in recharge temperature and recharge altitude are consistent with those reported by Plummer and Busenberg (2000, p. 24 and 25). Plummer and Busenberg (2000) specified that a recharge temperature uncertainty of ±2°C leads to uncertainty in apparent CFC ages of 1 year or less for water recharged prior to the mid-1970s but larger uncertainties for groundwater recharged after 1990 because the rate of increase in CFC-11, CFC-12, and CFC-113 in the atmosphere slows after 1990.

Shallow Carbonate Unit Groundwater-Age Dates

Atmospheric-mixing ratios of CFC-11 and CFC-12 and tritium data in water from two wells in the shallow carbonate unit (JPG-DU-01I and JPG-DU-03I) indicated that their composition could be derived partially from mixtures of modern, post-2000 age recharge with pre-1940s age recharge (figs. 16 and 17). The fractions of younger recharge computed for water from these wells using CFC-11/CFC-12 atmospheric ratios were about 10 percent of water sampled from well JPG-DU-01I and about 80 percent of water sampled from well JPG-DU-03I (table 13). The ages of these CFC-based mixtures in water from wells JPG-DU-01I and JPG-DU-03I were consistent with hypothetical tritium-based mixtures for samples from those wells (table 13). The CFC-based age dates indicate that portions of water sampled from wells JPG-DU-01I and JPG-DU-03I originated as post-1984 modern recharge; these wells therefore could be expected to produce groundwater with some water quality in the sample that dates from after the onset of DU-projectile testing.

Water from well JPG-DU-02I had a CFC-based age date that was best described by a piston-flow (no mixing) based



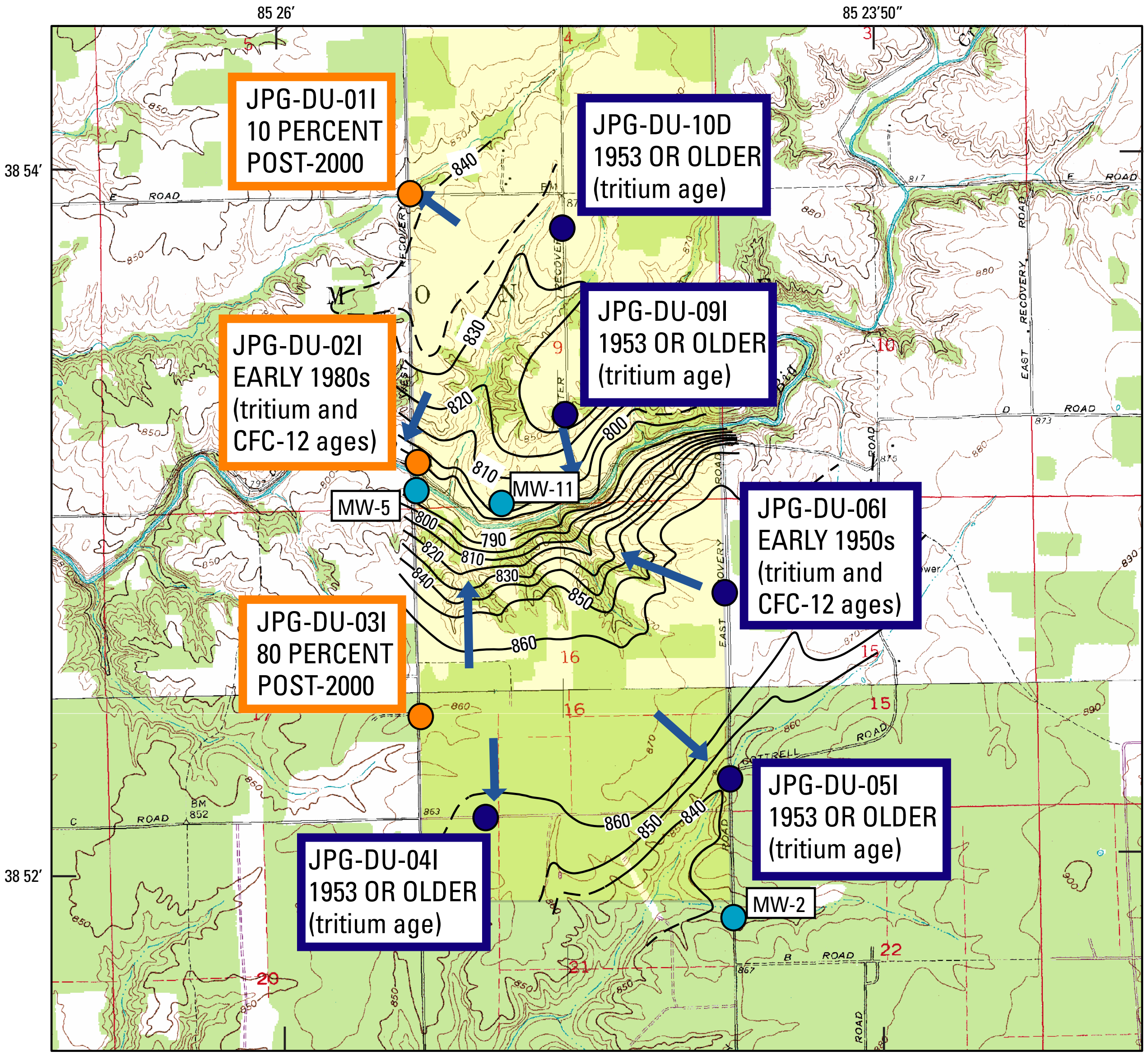
Mixtures of pre-1940s and more recent recharge plot along colored dashed lines

Samples outside dashed or solid lines on both plots were dated using CFC-12 (most stable CFC)

Samples plotting below piston-flow/binary-mixing area likely had less CFC-11 from biotransformation

Samples plotting above dashed/solid area contain excess CFC-113; likely from local use

Figure 16. Relation between atmospheric-mixing ratios of chloroflurocarbon compounds in groundwater samples from the shallow carbonate unit in and near the Depleted Uranium Impact Area, Jefferson Proving Ground, southeastern Indiana, April 2008. A. CFC-11 and CFC-12; B. CFC-113 and CFC-12. Model lines are included for piston flow and binary mixing of 1975–2005 age water with old (pre-CFC) water.



Base from U.S. Geological Survey Digital Raster Graphic (DRG) 1:24,000;
San Jacinto, Ind., 1959, minor revision 1994, also Clifty Falls, Ind., 1995,
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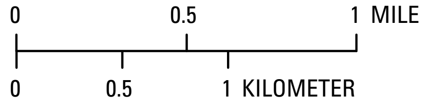
of 1927. Vertical datum of the DRG is the National Geodetic Vertical Datum of 1929



EXPLANATION

🟨 DEPLETED URANIUM IMPACT AREA—Approximate extent

— 830 — WATER-LEVEL CONTOUR—Approximate altitude of the water level in the shallow carbonate unit, April 7, 2008, in feet above National Geodetic Vertical Datum of 1929. Dashed where approximately located. Contour interval 10 feet.

← INFERRED DIRECTION OF WATER-LEVEL GRADIENT--Direction of groundwater flow may differ because of irregular distribution of interconnected porosity in the shallow carbonate unit

● WELL WITH PARTIALLY OR ALL POST-1980 GROUNDWATER AGE FROM CHLOROFLUOROCARBON COMPOUND ANALYSIS—with estimated percentage and age of young groundwater in sample

● WELL WITH PRE-1980 GROUNDWATER AGE FROM CHLOROFLUOROCARBON COMPOUND OR TRITIUM ANALYSIS —with estimated percentage and age of young groundwater in sample

● POST-1953 AND POSSIBLY POST-1972 GROUNDWATER AGE; TRITIUM ANALYSIS

Figure 17. Groundwater-age classifications of water sampled from wells screened in the shallow carbonate unit in and near the Depleted Uranium Impact Area, Jefferson Proving Ground, southeastern Indiana, April 2008.

Table 14. Sensitivity of CFC-based age dates to changes in recharge temperature and altitude computed for a sample from well JPG-DU-03O, Jefferson Proving Ground, southeastern Indiana, April 2008.

[The most reliable groundwater-age dates are in **bold type**; mm/dd/yy, month/day/year; °C, degrees Celsius; ft-VD, altitude in feet above North American Vertical Datum of 1988; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoromethane; pptv, part per trillion by volume; --, not computed]

Well name	Date sampled (mm/dd/yy)	Type of sensitivity adjustment	Estimated recharge temperature (°C)	Estimated recharge altitude (ft-VD)	Sample bottle	Calculated atmospheric mixing ratio			Groundwater-age dates, no mixing (piston flow) assumed			Difference in median groundwater age since recharge, no mixing assumed (years)	CFC-12/ CFC-113 atmospheric mixing ratio (pptv/ pptv)	Difference in estimated CFC-based age of young recharge in binary mixture	CFC-based estimated fraction of young recharge in mixture
						CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	CFC-11	CFC-12	CFC-113				
JPG-DU-03O	04/09/08	Original data	7.2	860	1	38.5	238.9	23.3	1967	1976	1980	--	0.097	0 (1984)	0.67
		Decrease temperature by 5°C	2.2	860	1	28.4	183.9	16.9	1965	1973	1978	-3	.92	-1 (1983)	.52
		Increase temperature by 5°C	12.2	860	1	50.7	302.3	31.1	1969	1980	1983	+4	.103	+1 (1985)	.78
		Decrease recharge altitude by 20 feet	7.2	840	1	38.4	238.8	23.3	1967	1976	1980	0	.097	0 (1984)	.67
		Increase recharge altitude by 20 feet	7.2	880	1	38.5	239.1	23.3	1967	1976	1980	0	.097	0 (1984)	.67

model of recharge and groundwater flow in the shallow carbonate unit (table 13). A piston-flow based estimate indicated that recharge to well JPG-DU-02I dated from about 1981, or close to the period of DU-projectile testing (table 12). The validity of largely unmixed flow contributing recharge to well JPG-DU-02I also was corroborated by the similarity of the concentration of tritium in the April 2008 water sample, 5.1 ± 0.6 TU, and the decay-corrected concentration of tritium in 1981 precipitation, 6.8 TU (fig. 14; table 13). The CFC- and tritium-age dates indicate that well JPG-DU-02I produces groundwater of a suitable age to monitor water quality for effects related to DU-penetrator testing.

A karst (fractured-and-solution-enhanced) flow system in the shallow carbonate unit also may occur beneath areas mantled by Pre-Wisconsinan till. Piston- or unmixed-flow models of the CFC-12 atmospheric-mixing ratio and concentration of tritium in water sampled from well JPG-DU-06I both yield age dates from the early 1950s. These data indicate that the age of groundwater produced from well JPG-DU-06I was submodern and was not of a suitable age to monitor water quality for changes related to DU-penetrator testing. Piston flow through a network of heterogeneous and discontinuous fractures and solution openings would make for longer, more tortuous flow paths through the shallow carbonate unit and thereby increase the age of groundwater as compared with more direct flow paths.

Four wells, JPG-DU-04I, JPG-DU-05I, JPG-DU-09I, and JPG-DU-10D, that produce groundwater from the shallow carbonate unit had “discordant” age dates; their CFC-12-based piston-flow age dates were substantially younger than their corresponding tritium-based age dates (table 13). The small concentrations of tritium in these samples (0.1 to 0.5 TU) indicate that nearly all or a substantial percentage of the samples originate as submodern (1953 or older) recharge. The modern CFC-12-based age dates from JPG-DU-04I, JPG-DU-05I, JPG-DU-09I, and JPG-DU-10D, however, indicate an unknown source of CFC-12 in the sample.

Plausible explanations for the coincidence of submodern tritium-based age dates and modern CFC-based age dates of water from wells JPG-DU-04I, JPG-DU-05I, JPG-DU-09I, and JPG-DU-10D all indicate that tritium is the reliable indicator of age dates of water sampled from these wells. For example, mixing of modern recharge with elevated concentrations of CFCs with submodern recharge has been ruled out as a cause; it also would increase concentrations of tritium above submodern concentrations in the resulting mixed groundwater. Explanations of coincident modern CFC-12 and submodern tritium-age dates in samples from these four wells involve addition of gaseous CFC to the sample, either during its flow in groundwater, by gas entrainment in groundwater during well development, or by leakage into the samples between collection and analysis. Contamination by CFC leakage into the sample vial between collection and analysis is unlikely because of the reproducibility of the CFC-12 and CFC-11 analytical results from groundwater samples and their sequential replicates from these four wells (table 15, at end of report).

It is more likely that the concentrations of CFCs and age dates of samples from wells JPG-DU-04I, JPG-DU-05I, JPG-DU-09I, and JPG-DU-10D were reset by entrainment of modern CFC into groundwater during well development. In this hypothesis, atmospheric gases with modern concentrations of CFCs are introduced to groundwater during well development. If water levels were lowered below the top of the well screen during the withdrawal of groundwater, atmospheric gases, including modern concentrations of CFCs could enter the formation and dissolve into groundwater (Plummer and others, 2000). Atmospheric concentrations of vadose gases also can be introduced into unsaturated, fractured, or dissolution-modified rock by barometric pressure changes and exposure to otherwise submodern-age groundwater (Plummer and others, 2000). Tritium results indicate that water samples from these four wells had submodern age dates that are too old to monitor groundwater quality for effects from DU-penetrator testing.

Deep Carbonate Unit Groundwater-Age Dates

The CFC-12 piston-flow-based estimate of recharge age for the April 2008 water sample from well JPG-DU-09D indicated a mid-1960s age of recharge (table 12). This recharge age, however, is considerably younger than the tritium-based age estimates for samples from the same well that indicates submodern (1953 or older) recharge. Although the CFC-12 and tritium-recharge estimates are discordant, both age estimates predate the testing of DU penetrators by 20 or more years. The tritium-based groundwater-age date is the most reliable determination for this well, according to the explanations for discordant ages previously offered in this report. In addition, the slow recovery of water levels in most wells in the deep carbonate unit is consistent with slow rates of groundwater flow and very old groundwater ages in that unit.

The CFC-based and tritium-based age dates of water samples from well JPG-DU-06D are strongly suspect as to whether they represent conditions in the deep carbonate unit. The CFC-12 based recharge age estimate for the sequential replicate sample (sample vial 5) of groundwater from JPG-DU-06D was modern (early 2000s) but an age estimate could not be computed for the water sample (sample vial 4) because of apparent contamination with respect to CFC-12 (table 12). The validity of the CFC-12 age estimate from the sequential replicate sample is indicated by the similarity of the concentration of tritium in the associated water sample to the decay-corrected average annual concentration of tritium in 2001 precipitation—the last year of the data record used by this study (table 13). These data indicate that water sampled from well JPG-DU-06D is younger than the water samples from adjacent well JPG-DU-06O in the Pre-Wisconsinan till and is considerably younger than the sample from adjacent well JPG-DU-06I in the shallow carbonate unit. Given the greater depth of well JPG-DU-06D (98 ft below land surface datum; table 2) relative to neighboring shallow wells and the overall low permeability of the deep carbonate unit presumed from very low yield during well development (Joseph Skibinski, written commun., Science Applications International Corporation, 2010), it is unlikely for modern age water to have naturally reached the screened interval of this well. Incomplete development prior to sampling or leakage of modern water to the well screen along the well casing during development and sampling also could explain the sampling of modern recharge in water from well JPG-DU-06D; data collected during this study are not sufficient to resolve which explanation is correct.

Vulnerability of Groundwater to Contamination Relative to the Hydrogeologic Framework

Groundwater-age dates from wells in the Pre-Wisconsinan till are consistent with a conceptual-flow model of vertical infiltration of younger recharge that “mixes” with older recharge from less permeable or less interconnected units within the till. Water sampled from the Pre-Wisconsinan till at five JPG-DU series wells represented a mixture of old, pre-1940s recharge that predates JPG operation and young recharge dating from just before DU-projectile testing (JPG-DU-04O and JPG-DU-06O) or from after testing began (JPG-DU-03O, JPG-DU-09O, and JPG-DU-10O) (table 13). The concentrations of chemical constituents that are potential tracers of post-1984 recharge also would be diluted by this mixing; post-1984 recharge has not completely replaced pre-CFC (pre-1940s) groundwater where sampled from the till. In addition, tritium-based groundwater ages from 11 MW and MW-RS series wells that produce water from the Pre-Wisconsinan till ranged from mixtures of submodern (1953 and older) and modern (post-1953) groundwater to substantially modern (post-1953 and possibly post-1972) groundwater. These data also indicate that infiltration of younger recharge is an important process of groundwater flow in the Pre-Wisconsinan till in and near the DU Impact Area.

Wells MW-6, MW-RS4, MW-RS5, MW-RS6, and MW-RS7 are outside of and downgradient from the DU Impact Area (fig. 15). These wells had tritium-based groundwater ages that were substantially modern (post-1953 and possibly post-1972). These ages and flow directions indicate that these wells, and well JPG-DU-03O, may be well positioned to monitor for groundwater-quality effects of DU-projectile testing.

Groundwater-age dates indicate that the shallow carbonate unit adjacent to Big Creek is largely a fairly transmissive but heterogeneous fractured-and-solution-enhanced karst flow system that may be recharged in part from areas with smaller thicknesses of overlying till. Well JPG-DU-02I had CFC- and tritium-based age dates that were best explained by a piston-flow model (table 13). The likely recharge area for JPG-DU-02I included an area of the shallow carbonate unit with the thinnest layer amount of overlying till or soil overburden, as indicated by the shallow depth to bedrock (table 2). Recharge to well JPG-DU-02I dated from the early to mid-1980s indicates that the source of flow to the well at the time of sampling was from upgradient and upwatershed parts of the shallow carbonate unit. Recent water from bank storage during higher flows in Big Creek, or from vertical recharge into the aquifer adjacent to the well where the till is thin or absent, was not identified in the age date from well JPG-DU-02I (table 13). Wells MW-5 and MW-11 are nearby to JPG-DU-02I and in similar settings along Big Creek, have similar concentrations of tritium and age dates (table 11), and likely have similar recharge sources. The contribution of unmixed recharge to wells JPG-DU-02I, MW-5, and MW-11 through a locally, more conduit-dominated karst flow system is indicated by cave development in the shallow carbonate unit immediately adjacent to Big Creek (Sheldon, 1997).

The thickness or permeability of Pre-Wisconsinan till is an important factor in how quickly modern recharge reaches the shallow carbonate unit. Two wells in the shallow carbonate unit that locally have thin soil or till cover (JPG-DU-01I; table 2) or that are closer to surface expressions of fracturing or linear karst features in the subsurface (JPG-DU-03I) had age dates that were best explained as mixtures of young recharge and some old, pre-1940 recharge. The large part of post-2000 age recharge contributing to water produced from well JPG-DU-03I indicates the likely proximity of this well to recharge features. Well JPG-DU-01I locally has a thin cover of till or soil overburden (20 ft; table 2) but also is downgradient from parts of the shallow carbonate unit that presumably receive less recent recharge because of thicker overlying till deposits (fig. 11). This combination of hydrogeologic framework near the well corroborates the interpretation of the groundwater age of water from well JPG-DU-01I as a mixture of a small part (about 10 percent) of post-2000 age local recharge with about 90 percent of old, pre-CFC, pre-1940 recharge from upwatershed areas with thicker till deposits over the shallow carbonate unit.

Groundwater flow directions, as inferred from water-level contours, in combination with groundwater-age dates also assist in identifying which wells in the shallow carbonate unit may be susceptible to water-quality effects from activities in the DU Impact Area. Wells JPG-DU-01I, JPG-DU-02I, and JPG-DU-03I are located within or downgradient from the DU Impact Area based on the inferred groundwater flow directions in the shallow carbonate unit (fig. 11). These wells also produced some part of their groundwater from recharge that dated from about 1980 or later. Two MW-series wells in this area have similar concentrations of tritium to that from well JPG-DU-02I; their age dates represent mixtures of submodern and modern water (MW-5) or substantially modern water (MW-11). MW-5 and MW-11 are downgradient with respect to groundwater levels from upland parts of the Big Creek watershed in the DU Impact Area (fig. 11). Regional gradients likely are overall expressions of groundwater-flow directions although flow directions within the shallow carbonate unit would reflect the complex interconnections of open fractures and dissolution-modified features within the unit. The complexity of local groundwater-flow directions within similar formations to the shallow carbonate unit was previously described for wells south of the firing line (Wilson and others, 2001). These data indicate that wells JPG-DU-01I, JPG-DU-02I, MW-5, MW-11, and possibly JPG-DU-03I potentially are the most useful sampling points at which to evaluate the presence of groundwater quality affected by DU-projectile testing.

Wells with older age dates that predate the penetrator testing can also be used to assess background water chemistry conditions in each water bearing unit. The submodern ages of groundwater from wells JPG-DU-04I, JPG-DU-05I, JPG-DU-06I, JPG-DU-09I, and JPG-DU-10D in the shallow carbonate unit indicate that their sources of recharge are from upgradient areas capped by thicker or less permeable deposits of Pre-Wisconsinan till; water from these wells was composed of recharge that predated DU-projectile testing. These five wells each produced adequate amounts of water for sampling; they were installed on or near surface indications of fractures and (or) subsurface indications of permeable features in the bedrock. The distribution of groundwater-age dates (fig. 17) indicates that the easternmost (upgradient) and southernmost parts of the shallow carbonate unit under the DU Impact Area may derive recharge from slower flow paths through karst features that are more isolated from land surface as compared with wells along the western DU Impact Area boundary and along Big Creek. Age dating indicates that the age of recharge sampled from these five wells predates the DU testing by about 30 or more years; therefore, water quality from these wells is not likely to reflect effects from DU-projectile testing or residual-corrosion products for years.

Data collected during this investigation are not sufficient to resolve whether the hydrogeologic framework or well-construction factors provide a better explanation for the modern water sampled from the deep carbonate unit at well JPG-DU-06D. Water sampled from the deep carbonate unit at well JPG-DU-06D had CFC- and tritium-based age dates that indicated modern groundwater; much younger than water produced from adjacent well JPG-DU-06I in the shallow carbonate unit (table 13). The young age of water sampled from well JPG-DU-06D could represent a very direct source of modern recharge to the well. Water produced by well JPG-DU-06D must recharge to a 40 ft greater depth into the carbonate bedrock, and conceivably along a longer flow path, than water produced by well JPG-DU-06I (table 2). Plausible human-affected explanations for the detection of modern water from JPG-DU-06D include the possibility that water sampled from this well could be (a) from modern water used for well construction or (b) from vertical leakage of recharge along the well bore past the grout seal separating the screened interval from land surface.

Implications and Limitations of the Age-Dating Technique

The use of multiple constituents to classify groundwater age improved the ability of this analysis to identify groundwater samples that potentially contained some fraction of post-1953 recharge. Groundwater samples from several wells had concentrations of tritium that were less than 0.8 TU, the common threshold used to distinguish submodern-age, 1953 or older recharge from water that contains some volume of post-1953 recharge (Clark and Fritz, 1997). When CFC data also were used to interpret the age dates for samples from wells JPG-DU-04O, JPG-DU-09O, and JPG-DU-10O, the sample age indicated mixtures containing 20 to 30 percent modern recharge.

The proportions of young and old groundwater in samples that are best described as binary mixtures may vary owing to hydrologic condition; this sampling represents one event in time. The sensitivity analysis of the CFC-based age date for water from well JPG-DU-03O indicates that the relative percentage of modern water in a binary mixture was sensitive to recharge temperature; a difference of 5°C in recharge temperature produced about a 10 to 15 percent change in the fraction of modern groundwater contributing to the sample (table 14). The binary mixtures were therefore reported to the nearest 10 percent. Within these limits, however, the explanation of age dates as binary mixtures of modern and submodern water indicate that concentrations of constituents derived from modern activities at land surface also would be affected—either diluted or enriched in the resulting groundwater—by the mixing with older water.

Several limitations of the age dating methods were described in this report in connection with interpretations of groundwater age dates. The effect of the laboratory precision of tritium on groundwater age classifications was evaluated by including the 2-sigma precision of those analyses in the classification. Limitations with CFC-based age classifications reported by this study included possible issues with well construction (such as for JPG-DU-06D), subareal exposure of groundwater and incorporation of CFCs into otherwise submodern age groundwater (such as identified for the sample from JPG-DU-05I), and potential introduction of excess CFC from local atmospheric sources into groundwater. Each of the potential limitations on CFC-based age dates would bias the estimates toward younger ages. The effect of these limitations was identified and in most cases removed from the age-date interpretation by comparing the CFC-based age dates to the tritium-based age classification, tritium being less susceptible to several of the causes of interferences with CFC age dates.

The post-1995 decrease of atmospheric mixing ratios of CFC-11 and CFC-113 (fig. 6) can affect the classification of groundwater age dates involving a mixture with some part of modern, post-1995 recharge using piston flow and binary mixing models. CFC-based groundwater age dates from wells JPG-DU-10O, JPG-DU-01I, and JPG-DU-03I all involved mixtures with post-1990 groundwater (table 13). After 1995, the piston flow curve inverts to a downward slope for both CFC-11 and CFC-113 relative to CFC-12 concentrations. The inversion creates the possibility that CFC-based mixtures that involve some part of 1990 to 2005 age groundwater can have two possible initial concentrations of CFC-11 and CFC-113, one from the 1990-1995 rising part of the piston flow curve and one from the 1995-2005 falling part of the curve.

Several strategies were used to interpret which age estimate was appropriate for the young fraction of recharge in these mixtures. In the case of a sample from well JPG-DU-03I, the atmospheric mixing ratios of CFC-11 and CFC-12 plotted in an area of figure 16 whose position could only be explained by binary mixtures of groundwater recharge from about 1995 to 2000 with CFC-free groundwater. In the case of a sample from well JPG-DU-01I, the atmospheric mixing ratios of CFC-11 and CFC-12 in the groundwater sample could be explained by binary mixtures of groundwater recharge from about either 2005 or from about 1965 with CFC-free groundwater (fig. 16). However, the tritium concentration of a hypothetical mixture (14.4 TU) of a 50 percent 1965-age recharge (28 TU, fig. 5) with 50 percent submodern recharge (0.8 TU) was substantially greater than the tritium concentration of the water sample from that well plus its 2-sigma uncertainty (0.6 TU). Therefore, the mixture of 2005 age recharge and CFC-free recharge was deemed the most plausible explanation for the CFC-11 and CFC-12 concentrations in the samples from well JPG-DU-01I. The atmospheric mixing ratios of CFC-113 and CFC-12 in a sample from well JPG-DU-10O (fig. 14) could be explained by a mixture of groundwater recharge from about either 1992 or 1996 with CFC-free groundwater. The age of recharge contributing to the young part of this mixture could not be distinguished using the tritium technique.

Methods used by this study could not distinguish whether mixtures of submodern and modern groundwater identified with age dating constituents occurred in the formation or in the well itself. Several wells had concentrations of age dating constituents that were best explained as binary mixtures of submodern and modern age groundwater. In-formation mixing could occur along the convergence of flow paths to a well screen. In-well mixing could arise if the well screen intersected geologically separate flowpaths with different groundwater ages. The potential for in-well mixing is generally increased by use of progressively longer well screens.

Summary and Conclusions

During 1984–94, the U.S. Department of the Army test fired depleted uranium (DU) projectiles (“penetrators”) under the authority of a Nuclear Regulatory Commission license into an area of approximately 2,080 acres north of the firing line, known as the DU Impact Area, at Jefferson Proving Ground (JPG) in southeastern Indiana. The Army and its contractor, Science Applications International Corporation (SAIC), began in 2006 an investigation of the hydrologic and hydrogeologic framework of a Pre-Wisconsinan till and underlying shallow and deep carbonate bedrock units in an around the DU Impact Area to understand processes that could affect the fate and transport of possible contaminants. The U.S. Geological Survey, in cooperation with the Army, evaluated the relative age of groundwater in Pre-Wisconsinan till and underlying shallow and deep carbonate bedrock units from in and near an area at the JPG that was used during 1984–94 to test fire DU penetrators. Wells with younger age dates from after the onset (1984) of DU penetrator testing and that have a plausible connection to a contaminant source can be used to indicate the presence or absence of contaminants from DU penetrator or DU-related corrosion products in groundwater. Wells with older age dates that predate the penetrator testing can also be used to assess background water chemistry conditions in each water bearing unit.

Samples collected during April 2008 from 15 wells were analyzed for field water-quality parameters, dissolved gases, and the age-dating constituents: tritium and chlorofluorocarbon (CFC) compounds; samples from 14 additional wells were analyzed for tritium only. The hydrogeologic framework was classified as a Pre-Wisconsinan till, an underlying shallow carbonate unit that represents a zone of fractures, paleokarst, and other dissolution-modified features within the upper 40 feet of carbonate bedrock, and a deeper carbonate unit that groups wells that produce from depths that are more than about 40 feet below the bedrock surface. Water-level gradients in the Pre-Wisconsinan till and the shallow carbonate unit were from topographically high parts of the study area toward major streams, Big Creek and Middle Fork Creek, and their tributaries. Regional flow directions in the deep carbonate unit could not be defined. Vertical gradients between the Pre-Wisconsinan till and the shallow carbonate unit were downward at three sites (well pairs JPG-DU-04O and 04I, JPG-DU-06O and 06I, and JPG-DU-09O and 09I) and upward at two sites (well pairs JPG-DU-03O and 03I, and JPG-DU-10O and 10D). Vertical gradients were strongly downward from the shallow carbonate unit toward the deep carbonate unit at 3 of 4 paired wells where water levels recovered after development; indicating the general lack of flow between the two units. The lack of post development recovery of water levels at 4 other wells in the deep carbonate unit indicate that parts of that unit have no appreciable permeability.

Groundwater level measurements and land-surface altitudes were used to assign a recharge altitude to water from each well for recharge temperature and CFC-based age-dating computations. The recharge altitudes of water from wells screened in Pre-Wisconsinan till were assumed to be similar to the observed groundwater levels from those wells, rounded to the nearest 5 feet; these recharge altitudes ranged from 840 feet above the vertical datum for well JPG-DU-09O to 870 feet above the vertical datum for well JPG-DU-06O. Groundwater recharge to wells that were open to the shallow and deep carbonate units likely occurred upgradient from the well and at higher water-level altitudes than the sampled depth. Recharge altitudes used for dissolved gas and CFC-based groundwater-age computations for water from wells in the shallow carbonate unit ranged from 810 feet above the vertical datum for well JPG-DU-02I to 870 feet above the vertical datum for well JPG-DU-06I.

Analyses of dissolved gas in groundwater were interpreted to estimate the temperature of water at the time it infiltrated below the water table and into groundwater. Estimated average recharge temperatures of groundwater indicate that most recharge to groundwater in the study area occurs during the cooler months of fall, winter, and spring seasons when evapotranspiration typically is smallest. Estimated average recharge temperatures of groundwater ranged from 1.5 degrees Celsius (°C) at well JPG-DU-04O to 11.7°C at well JPG-DU-3I; the median recharge temperature was 7.1°C. Most wells had recharge temperatures that were 8.6°C or less; these corresponded to the range of monthly average air temperatures at Madison, Indiana, from November to March (-0.7°C to 7.4°C), indicating that most recharge occurred during the cooler, non-growing months.

Groundwater-age dates from wells in the Pre-Wisconsinan till are consistent with a conceptual-flow model of vertical infiltration of younger (typically post-1960 age) recharge that “mixes” with older recharge from less permeable or less interconnected strata within the till. The CFC- and tritium-based age dates of groundwater samples from five wells in the Pre-Wisconsinan till could be explained best as binary mixtures of young, post-CFC and 1953 or older recharge. Part of the mixture of recharge that contributed to water samples from three wells in the Pre-Wisconsinan till, JPG-DU-03O, JPG-DU-09O, and JPG-DU-10O, dated from the early to mid-1980s. These age dates indicate the potential for water samples from wells in the Pre-Wisconsinan till to detect water quality modified by activities associated with DU-penetrator testing at JPG. The age-dating information also indicates that concentrations of chemical constituents, which are potential tracers of post-1984 recharge, will be diluted by this mixing; post-1984 recharge had not completely replaced pre-1940s groundwater, where sampled from the till. No wells in the Pre-Wisconsinan till produced entirely submodern recharge, although age dates of groundwater that contributed to mixtures produced from wells JPG-DU-04O and JPG-DU-06O predated 1980.

In addition, water from wells MW-6, MW-10, MW-RS3, MW-RS4, MW-RS5, MW-RS6, and MW-RS7 in the Pre-Wisconsinan till also had tritium-based age dates that indicated the possible presence of post-1972 age recharge. Water from these seven MW and MW-RS series wells also may produce water samples that could indicate water quality modified by activities associated with DU-penetrator testing at JPG. The possibility that the MW and MW-RS series wells could produce groundwater containing recharge from the 1984 and later period affected by DU testing cannot be ruled out solely by use of tritium data; therefore, water quality from the post-1984 testing period of DU penetrators could be monitored from these wells.

Groundwater-age dates indicate that the shallow carbonate unit adjacent to Big Creek largely is a fairly transmissive but heterogeneous karst (fractured-and-solution-enhanced) flow system that may be recharged in part from areas with smaller thicknesses of overlying till. The till is thin or absent near Big Creek at wells JPG-DU-02I, MW-5, and MW-11. A CFC- and tritium-based piston-flow based age date of the early 1980s for water produced from well JPG-DU-02I, similar concentrations of tritium and tritium-based ages of water produced from well JPG-DU-02I and from nearby wells MW-5 and MW-11, and evidence of cave development along Big Creek together indicate the importance of local, conduit-based, karst flow systems in the shallow carbonate unit near the creek.

Piston flow in the shallow carbonate unit also may occur beneath Pre-Wisconsinan till. CFC- and tritium-based piston-flow models of water sampled from well JPG-DU-06I both yielded age dates of recharge contributing to the well from the early 1950s. The data indicate that groundwater produced from well JPG-DU-06I had recharged more than 30 years before the initial testing of DU penetrators; water quality from the well would not exhibit effects related to DU-penetrator testing or later leaching of residual-corrosion products.

The thickness or permeability of Pre-Wisconsinan till affects the time that modern recharge takes to infiltrate to the shallow carbonate unit. Part or all of the groundwater from wells JPG-DU-01I , JPG-DU-02I, and JPG-DU-03I in the shallow carbonate unit included recharge dating from about 1980 or later. The CFC- and tritium-based age dates indicate that water sampled from wells JPG-DU-01I and JPG-DU-03I was best described as a mixture of post-1984 modern recharge and submodern (1953 or older) recharge.

Four wells in the shallow carbonate unit, JPG-DU-04I, JPG-DU-05I, JPG-DU-09I, and JPG-DU-10D, and well JPG-DU-09D in the deep carbonate unit produced groundwater samples with old (submodern, 1953 or older) tritium-based age dates and young (modern, 1960s to 1980s) CFC-based age dates. The disagreement likely arises by the exposure of submodern groundwater, well after recharge and during groundwater flow, to atmospheric concentrations of CFCs. Concentrations of tritium were therefore used to compute age dates for water from these wells; their groundwater-age dates were submodern (1953 or older). Water quality sampled from these four wells should represent background conditions; this groundwater should not exhibit effects related to DU-penetrator testing or later leaching of residual-corrosion products for at least 30 years after this sampling.

The submodern ages of groundwater from wells JPG-DU-04I, JPG-DU-05I, JPG-DU-06I, JPG-DU-09I, and JPG-DU-10D in the shallow carbonate unit indicate that their sources of recharge are from upgradient areas capped by thicker or less permeable deposits of Pre-Wisconsinan till; water from these wells was composed of recharge that predated DU-projectile testing. The distribution of groundwater-age dates (fig. 17) indicates that the easternmost (upgradient) and southernmost parts of the shallow carbonate unit under the DU Impact Area may derive recharge from slower flow paths through karst features that are more isolated from land surface as compared with wells along the western DU Impact Area boundary or along Big Creek. Age dating indicates that the age of recharge sampled from these five wells predates the DU testing by about 30 or more years; therefore, water quality from these wells is not likely to reflect effects from DU-projectile testing or residual-corrosion products for years.

Incomplete removal of water from drilling by development prior to sampling or leakage of modern water to the well screen along the well casing before or during development and sampling also could explain the sampling of recent, post-2000 recharge in water from well JPG-DU-06D. The age date of water sampled from this well could not be reliably determined.

Based on water-level contours and age dates, water quality from several wells in the shallow carbonate unit may partially represent recharge affected by activities in the DU Impact Area. Wells JPG-DU-01I, JPG-DU-02I, and JPG-DU-03I are within or downgradient from the DU Impact Area, with respect to water levels, and produce some part of their groundwater from recharge that dated from about 1980 or later. Water from wells MW-5 and MW-11 have similar concentrations of tritium and presumably similar age dates to water from well JPG-DU-02I and are downgradient from parts of the DU Impact Area. Although flow paths to wells JPG-DU-01I, JPG-DU-02I, JPG-DU-03I, MW-5, and MW-11 may be complex and not directly along the water-level gradient, their age dates and hydrogeologic information indicate that these five wells potentially are the most useful for sampling the shallow carbonate unit to identify possible water-quality effects from DU-related contaminants in groundwater.

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Table 2. Selected characteristics of observation wells considered for sampling at the Jefferson Proving Ground, southeastern Indiana, 2007–08. (Well construction data provided by Science Applications International Corporation.)

[USGS, U.S. Geological Survey; mm, month; dd, day; yyyy, year; NAVD 88, vertical datum is North American Vertical Datum of 1988; USA, U.S. Department of the Army; NA, bedrock not encountered by boring; UK, unknown; negative distance to measuring point from land surface indicates that measuring point is below land surface]

USGS well name	USGS Agency code and site identifier	Date installed (mm/dd/ yyyy)	Land surface altitude (feet above NAVD 88)	Top of well casing—reference mark—altitude (feet above NAVD 88)	Well depth (feet below land surface)	Well screen length (feet)	Well screen and riser diameter (inches)	Well screen slot size (inches)	Depth to top and bottom of well screen (feet below land surface)	Altitude of top and bottom of well screen (feet above NAVD 88)
Depleted Uranium Impact Area characterization wells										
WELL JPG-DU-01I	USA 385355085253201	06/15/2007	838.06	841.23	41.7	10	2	0.01	31.4–41.4	806.66–796.66
WELL JPG-DU-01D	USA 385355085253202	06/14/2007	838.26	841.15	113.1	10	2	.01	102.8–112.8	735.46–725.46
WELL JPG-DU-02I	USA 385308085253201	05/21/2007	800.93	803.94	29.2	10	2	.01	18.8–28.8	782.13–772.13
WELL JPG-DU-02D	USA 385308085253202	05/20/2007	800.92	803.83	119.3	10	2	.01	108.95–118.95	691.97–681.97
WELL JPG-DU-03O	USA 385226085253101	12/12/2007	862.10	865.54	24.3	10	2	.01	14–24	848.1–838.1
WELL JPG-DU-03I	USA 385226085253102	12/12/2007	862.14	865.60	60.9	10	2	.01	50.6–60.6	811.54–801.54
WELL JPG-DU-04O	USA 385209085251701	12/04/2007	864.11	867.28	47.0	20	2	.01	26.8–46.8	837.31–817.31
WELL JPG-DU-04I	USA 385209085251702	12/03/2007	864.32	867.38	65.5	10	2	.01	55.1–65.1	809.22–799.22
WELL JPG-DU-04D	USA 385209085251703	11/29/2007	864.18	867.13	100.4	10	2	.01	90–100	774.18–764.18
WELL JPG-DU-05I	USA 385215085242401	11/27/2007	843.71	847.21	34.9	10	2	.01	24.5–34.5	819.21–809.21
WELL JPG-DU-05D	USA 385215085242402	11/19/2007	843.67	847.26	130.7	10	2	.01	120.45–130.45	723.22–713.22
WELL JPG-DU-06O	USA 385243085242503	11/13/2007	872.56	876.02	20.4	10	2	.01	10–20	862.56–852.56
WELL JPG-DU-06I	USA 385243085242501	06/18/2007	872.91	875.65	48.2	10	2	.01	37.8–47.8	835.11–825.11
WELL JPG-DU-06D	USA 385243085242502	06/17/2007	872.79	875.76	98.3	10	2	.01	88–98	784.79–774.79
WELL JPG-DU-07I	USA 385311085241601	11/18/2007	842.39	846.33	60.4	10	2	.01	50.05–60.05	792.34–782.34
WELL JPG-DU-07D	USA 385311085241602	11/15/2007	842.58	846.53	120.4	10	2	.01	110–120	732.58–722.58
WELL JPG-DU-08I	USA 385305085245101	05/24/2007	815.44	818.59	36.0	10	2	.01	25.65–35.65	789.79–779.79
WELL JPG-DU-08D	USA 385305085245102	05/23/2007	815.36	818.58	136.7	10	2	.01	126.28–136.28	689.08–679.08
WELL JPG-DU-09O	USA 385319085245801	06/03/2007	846.63	849.63	34.0	10	2	.01	23.7–33.7	822.93–812.93
WELL JPG-DU-09I	USA 385319085245802	06/02/2007	846.45	849.38	49.4	10	2	.01	39–49	807.45–797.45
WELL JPG-DU-09D	USA 385319085245803	06/02/2007	846.10	849.07	83.4	10	2	.01	73–83	773.1–763.1
WELL JPG-DU-10O	USA 385336085245801	06/07/2007	870.39	873.51	68.3	10	2	.01	58–68	812.39–802.39
WELL JPG-DU-10D	USA 385336085245802	06/06/2007	870.71	873.64	88.3	10	2	.01	78–88	792.71–782.71

Table 2. Selected characteristics of observation wells considered for sampling at the Jefferson Proving Ground, southeastern Indiana, 2007–08. (Well construction data provided by Science Applications International Corporation.)—Continued

[USGS, U.S. Geological Survey; mm, month; dd, day; yyyy, year; NAVD 88, vertical datum is North American Vertical Datum of 1988; USA, U.S. Department of the Army; NA, bedrock not encountered by boring; UK, unknown; negative distance to measuring point from land surface indicates that measuring point is below land surface]

USGS well name	USGS Agency code and site identifier	Date installed (mm/dd/ yyyy)	Land surface altitude (feet above NAVD 88)	Top of well casing—reference mark—altitude (feet above NAVD 88)	Well depth (feet below land surface)	Well screen length (feet)	Well screen and riser diameter (inches)	Well screen slot size (inches)	Depth to top and bottom of well screen (feet below land surface)	Altitude of top and bottom of well screen (feet above NAVD 88)
Wells from prior studies										
WELL JPG MW-1	USA 385311085242401	12/06/1983	851.75	853.58	33.2	4.8	2	0.006	8.3–13.1 and 28.4–33.2	843.45–838.65 and 823.35–818.55
WELL JPG MW-2	USA 385151085242401	12/13/1983	848.25	850.49	23.7	10	2	.006	13.7–23.7	834.55–824.55
WELL JPG MW-3	USA 385032085242401	12/13/1983	870.96	873.64	42.8	10	2	.006	32.8–42.8	838.16–828.16
WELL JPG MW-4	USA 384843085231301	12/14/1983	898.92	902.19	28.0	5	2	.006	8.5–13.5 and 23–28	890.42–885.42 and 875.92–870.92
WELL JPG MW-5	USA 385306085253201	12/07/1983	801.91	804.36	33.4	10	2	.006	23.4–33.4	778.51–768.51
WELL JPG MW-6	USA ‘385149085253201	12/17/1983	858.44	861.22	40.0	10	2	.006	30–40	828.44–818.44
WELL JPG MW-7	USA 385024085253201	12/08/1983	850.99	853.70	53.7	10	2	.006	43.7–53.7	807.29–797.29
WELL JPG MW-8	USA 384841085262101	12/09/1983	838.97	841.28	28.2	10	2	.006	18.2–28.2	820.77–810.77
WELL JPG MW-9	USA 385309085244901	09/09/1988	819.85	819.96	38.0	20	2	UK	18–38	801.85–781.85
WELL JPG MW-10	USA 385329085245801	09/18/1988	865.91	866.14	41.3	20	2	UK	21.3–41.3	844.61–824.61
WELL JPG MW-11	USA 385302085251301	09/19/1988	809.49	809.89	41.9	30	2	UK	11.9–41.9	797.59–767.59
WELL JPG MW-RS1	USA 385252085233501	08/20/2002	865.39	867.78	13.5	8	2	.01	5.5–13.5	859.89–851.89
WELL JPG MW-RS2	USA 385252085233501	08/16/2002	873.28	875.83	25.2	10	2	.01	15.2–25.2	858.08–848.08
WELL JPG MW-RS3	USA 385315085233101	08/17/2002	879.19	881.57	12.5	5	2	.01	7.5–12.5	871.69–866.69
WELL JPG MW-RS4	USA 385147085254201	08/19/2002	858.21	860.85	14.8	9	2	.01	5.8–14.8	852.41–843.41
WELL JPG MW-RS5	USA 385156085260701	08/18/2002	851.42	853.98	13.1	8	2	.01	5.0–13.1	846.42–838.32
WELL JPG MW-RS6	USA 385248085254901	08/18/2002	858.24	860.68	14.4	9	2	.01	5.4–14.4	852.84–843.84
WELL JPG MW-RS7	USA 385155085254301	08/19/2002	859.42	862.02	12.5	5	2	.01	7.5–12.5	851.92–846.92
WELL JPG MW-RS8	USA 385235085252601	08/21/2002	865.03	867.14	15.7	10	2	.01	5.7–15.7	859.33–849.33

Table 2. Selected characteristics of observation wells considered for sampling at the Jefferson Proving Ground, southeastern Indiana, 2007–08. (Well construction data provided by Science Applications International Corporation.)—Continued

[USGS, U.S. Geological Survey; mm, month; dd, day; yyyy, year; NAVD 88, vertical datum is North American Vertical Datum of 1988; USA, U.S. Department of the Army; NA, bedrock not encountered by boring; UK, unknown; negative distance to measuring point from land surface indicates that measuring point is below land surface]

USGS well name	Depth to top of bedrock (feet below land surface)	Altitude of top of bedrock (feet above NAVD 88)	Depth of top of well screen below top of bedrock (feet below land surface)	Depth of base of well screen below top of bedrock (feet below land surface)	Lithology opposite well screen interval	Hydrogeologic unit	Sampling criteria
Depleted Uranium Impact Area characterization wells							
WELL JPG-DU-01I	20.0	818.06	11.7	21.7	Limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-01D	19.5	818.76	83.6	93.6	Limestone	Deep carbonate unit	Poor recovery during pre-sample pumping, not sampled
WELL JPG-DU-02I	16.0	784.93	3.2	13.2	Limestone, shale	Shallow carbonate unit	Sampled for tritium, CFCs, dissolved gases
WELL JPG-DU-02D	0.7	800.27	108.65	118.7	Limestone	Deep carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-03O	NA	NA	NA	NA	Clay, sand, and gravel	Pre-Wisconsinan till	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-03I	40.6	821.54	10.3	20.3	Limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-04O	NA	NA	NA	NA	Gravel and clay	Pre-Wisconsinan till	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-04I	47.0	817.32	8.5	18.5	Limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-04D	46.2	817.98	44.2	54.2	Limestone	Deep carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-05I	5.8	837.91	19.1	29.1	Limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-05D	5.7	837.97	115	125.0	Fossiliferous Limestone	Deep carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-06O	NA	NA	NA	NA	Not reported, above bedrock	Pre-Wisconsinan till	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-06I	35.4	837.51	2.8	12.8	Limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-06D	35.7	837.09	52.6	62.6	Limestone	Deep carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-07I	5.6	836.79	44.8	54.8	Limestone	Deep carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-07D	5.7	836.88	104.7	114.7	Fossiliferous Limestone	Deep carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-08I	6.0	809.44	20	30.0	Limestone, dolomite, shale	Shallow carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-08D	6.0	809.36	120.7	130.7	Limestone	Deep carbonate unit	Poor water-level recovery, not sampled
WELL JPG-DU-09O	NA	NA	NA	NA	Clay with sand and gravel	Pre-Wisconsinan till	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-09I	34.0	812.45	5.4	15.4	Limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-09D	34.0	812.10	39.4	49.4	Limestone	Deep carbonate unit	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-10O	71.8	798.59	NA	NA	Sand, silt, clay	Pre-Wisconsinan till	Sampled for dissolved gases, tritium, CFCs
WELL JPG-DU-10D	72.5	798.21	5.8	15.8	Limestone, shaley limestone	Shallow carbonate unit	Sampled for dissolved gases, tritium, CFCs

Table 2. Selected characteristics of observation wells considered for sampling at the Jefferson Proving Ground, southeastern Indiana, 2007–08. (Well construction data provided by Science Applications International Corporation.)—Continued

[USGS, U.S. Geological Survey; mm, month; dd, day; yyyy, year; NAVD 88, vertical datum is North American Vertical Datum of 1988; USA, U.S. Department of the Army; NA, bedrock not encountered by boring; UK, unknown; negative distance to measuring point from land surface indicates that measuring point is below land surface]

USGS well name	Depth to top of bedrock (feet below land surface)	Altitude of top of bedrock (feet above NAVD 88)	Depth of top of well screen below top of bedrock (feet below land surface)	Depth of base of well screen below top of bedrock (feet below land surface)	Lithology opposite well screen interval	Hydrogeologic unit	Sampling criteria
					Wells from prior studies		
WELL JPG MW-1	8.0	843.75	20.4	25.2	Limestone	Shallow carbonate unit	Visited prior to USGS sampling by SAIC, not sampled
WELL JPG MW-2	9.0	839.25	4.7	14.7	Limestone	Shallow carbonate unit	Sampled by SAIC for tritium
WELL JPG MW-3	NA	NA	NA	NA	Limestone	Shallow carbonate unit	Sampled by SAIC for tritium
WELL JPG MW-4	12.9	886.02	10.1	15.1	Siltstone/Limestone	Shallow carbonate unit	Sampled by SAIC for tritium
WELL JPG MW-5	13.5	788.41	9.9	19.9	Limestone	Shallow carbonate unit	Sampled by SAIC for tritium
WELL JPG MW-6	NA	NA	NA	NA	Silty Clay	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-7	14.3	836.69	29.4	39.4	Limestone	Shallow carbonate unit	Not sampled for this study; water levels only
WELL JPG MW-8	14.8	824.17	3.4	13.4	Limestone	Shallow carbonate unit	Sampled by SAIC for tritium
WELL JPG MW-9	NA	NA			Limestone & Shale	Shallow carbonate unit	Poor recovery, not sampled
WELL JPG MW-10	NA	NA	NA	NA	Sandy to Clayey Silt	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-11	NA	NA	NA	NA	Limestone & Shale	Shallow carbonate unit	Sampled by SAIC for tritium
WELL JPG MW-RS1	4.5	860.89	1	9.0	Limestone & Clayey Silt	Shallow carbonate unit	Visited by SAIC prior to this sampling, not sampled
WELL JPG MW-RS2	7.0	866.28	8.2	18.2	Limestone	Shallow carbonate unit	Visited by SAIC prior to this sampling, not sampled
WELL JPG MW-RS3	18.5	860.69	NA	NA	Silty Clay	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-RS4	10.0	848.21	NA	NA	Silty Clay & Fine Sand	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-RS5	5.6	845.82	NA	NA	Silty Clay & Fine Sand	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-RS6	NA	NA	NA	NA	Silty Clay & Sand	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-RS7	26.5	832.92	NA	NA	Silty Clay & Sand	Pre-Wisconsinan till	Sampled by SAIC for tritium
WELL JPG MW-RS8	14.5	850.53	NA	NA	Silty Clay & Sand	Pre-Wisconsinan till	Sampled by SAIC for tritium

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; mm/dd/yyyy, month/day/year; hh, hours; mm, minutes; -, negative depths to water indicate water levels above land surface; NR, not reported; SAIC, Science Applications International Corporation; NA, no recharge altitude estimated because no age-dating samples were collected from well; Dry, no water in well at time of measurement; --, no value]

USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385355085253201	WELL JPG-DU-01I	838.06	-0.48	838.54	06/20/2007	16:24	USGS	850
			-.96	839.02	09/12/2007	09:57	USGS	
			-.89	838.95	09/12/2007	14:04	USGS	
			-1.05	839.11	01/07/2008	NR	USGS	
			-1.06	839.12	01/09/2008	12:46	USGS	
			-.67	838.73	04/07/2008	11:20	SAIC	
			-1.40	839.46	05/05/2008	12:57	USGS	
			-1.53	839.59	05/09/2008	08:17	USGS	
			-1.58	839.64	05/13/2008	15:50	USGS	
			-1.78	839.84	05/16/2008	09:22	USGS	
			-1.76	839.82	05/17/2008	13:02	USGS	
			-1.71	839.77	07/14/2008	12:10	SAIC	
			-1.06	839.12	08/18/2008	10:22	USGS	
			-.87	838.93	08/22/2008	12:15	USGS	
USA 385355085253202	WELL JPG-DU-01D	838.26	109.94	727.77	06/21/2007	NR	USGS	NA
			77.28	760.43	09/12/2007	09:57	USGS	
			77.18	760.53	09/12/2007	14:04	USGS	
			35.23	802.48	01/07/2008	NR	USGS	
			34.66	803.05	01/09/2008	12:46	USGS	
			9.25	829.01	04/07/2008	11:18	SAIC	
			6.86	830.85	05/05/2008	12:59	USGS	
			5.19	832.52	05/09/2008	08:22	USGS	
			3.65	834.06	05/13/2008	15:51	USGS	
			2.79	834.92	05/16/2008	09:25	USGS	
			2.49	835.22	05/17/2008	13:02	USGS	
			-1.62	839.88	07/14/2008	12:11	SAIC	
			-.61	838.32	08/18/2008	10:24	USGS	
			-.58	838.29	08/22/2008	12:15	USGS	
USA 385308085253201	WELL JPG-DU-02I	800.93	16.33	783.85	06/21/2007	09:35	USGS	810
			16.96	783.22	09/12/2007	09:27	USGS	
			16.97	783.21	09/12/2007	14:17	USGS	
			Dry	--	01/07/2008	11:26	USGS	
			Dry	--	01/09/2008	12:18	USGS	
			15.07	785.86	04/07/2008	12:23	SAIC	
			15.66	784.52	05/05/2008	12:51	USGS	
			14.20	785.98	05/09/2008	09:13	USGS	
			14.72	785.46	05/13/2008	14:46	USGS	
			9.61	790.57	05/16/2008	08:00	USGS	
			13.25	786.93	05/17/2008	12:35	USGS	
			16.20	784.73	07/14/2008	13:30	SAIC	
			16.42	783.76	08/18/2008	10:14	USGS	
			16.48	783.70	08/22/2008	11:45	USGS	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; mm/dd/yyyy, month/day/year; hh, hours; mm, minutes; -, negative depths to water indicate water levels above land surface; NR, not reported; SAIC, Science Applications International Corporation; NA, no recharge altitude estimated because no age-dating samples were collected from well; Dry, no water in well at time of measurement; --, no value]

USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385308085253202	WELL JPG-DU-02D	800.92	116.77	683.46	06/21/2007	NR	USGS	NA
			116.15	684.08	09/12/2007	09:27	USGS	
			116.15	684.08	09/12/2007	14:17	USGS	
			115.78	684.45	01/07/2008	11:26	USGS	
			116.78	683.45	01/09/2008	12:18	USGS	
			115.48	685.44	04/07/2008	12:21	SAIC	
			116.31	683.92	05/05/2008	12:48	USGS	
			116.31	683.92	05/09/2008	09:20	USGS	
			116.30	683.93	05/13/2008	14:46	USGS	
			116.23	684.00	05/16/2008	10:16	USGS	
			116.24	683.99	05/17/2008	12:35	USGS	
			116.08	684.84	07/14/2008	13:27	SAIC	
			117.79	682.44	08/18/2008	10:13	USGS	
			117.76	682.47	08/22/2008	11:45	USGS	
USA 385226085253101	WELL JPG-DU-03O	862.10	3.89	857.66	01/07/2008	12:25	USGS	860
			2.58	858.97	01/08/2008	07:48	USGS	
			2.78	858.77	01/09/2008	11:56	USGS	
			1.30	860.80	04/07/2008	10:47	SAIC	
			1.87	859.68	05/05/2008	12:06	USGS	
			1.34	860.21	05/09/2008	09:37	USGS	
			1.44	860.11	05/13/2008	14:26	USGS	
			1.18	860.37	05/16/2008	08:31	USGS	
			.98	860.57	05/17/2008	11:34	USGS	
			3.89	858.21	07/14/2008	11:50	SAIC	
			9.29	852.26	08/18/2008	11:14	USGS	
			9.74	851.81	08/22/2008	12:32	USGS	
USA 385226085253102	WELL JPG-DU-03I	862.14	18.80	842.77	01/08/2008	07:48	USGS	865
			16.03	845.54	01/09/2008	11:56	USGS	
			.83	861.31	04/07/2008	10:49	SAIC	
			1.56	860.01	05/05/2008	12:09	USGS	
			1.11	860.46	05/09/2008	09:36	USGS	
			.95	860.62	05/13/2008	14:25	USGS	
			1.01	860.56	05/16/2008	08:34	USGS	
			.93	860.64	05/17/2008	11:34	USGS	
			6.69	855.45	07/14/2008	11:51	SAIC	
			6.74	854.83	08/18/2008	11:17	USGS	
			6.67	854.90	08/22/2008	12:33	USGS	
USA 385209085251701	WELL JPG-DU-04O	864.11	8.27	855.37	01/07/2008	NR	USGS	860
			8.28	855.36	01/09/2008	07:40	USGS	
			6.45	857.66	04/07/2008	10:32	SAIC	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

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USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385209085251701—Continued			7.06	856.58	05/05/2008	12:20	USGS	
			6.74	856.90	05/09/2008	07:53	USGS	
			6.91	856.73	05/16/2008	08:42	USGS	
			6.68	856.96	05/17/2008	11:43	USGS	
			8.69	855.42	07/14/2008	11:41	SAIC	
			1.18	853.46	08/18/2008	11:28	USGS	
			1.37	853.27	08/22/2008	10:51	USGS	
USA 385209085251702	WELL JPG-DU-04I	864.32	9.93	853.98	01/07/2008	NR	USGS	865
			9.28	854.63	01/09/2008	07:37	USGS	
			7.16	857.16	04/07/2008	10:33	SAIC	
			7.67	856.24	05/05/2008	12:18	USGS	
			7.51	856.40	05/09/2008	07:48	USGS	
			7.57	856.34	05/13/2008	13:17	USGS	
			8.55	855.36	05/16/2008	08:44	USGS	
			7.46	856.45	05/17/2008	11:43	USGS	
			9.63	854.69	07/14/2008	11:40	SAIC	
			11.10	852.81	08/18/2008	11:27	USGS	
			11.24	852.67	08/22/2008	10:51	USGS	
USA 385209085251703	WELL JPG-DU-04D	864.18	8.80	782.81	01/07/2008	NR	USGS	NA
			8.27	783.34	01/09/2008	07:35	USGS	
			56.14	808.04	04/07/2008	10:41	SAIC	
			58.81	804.80	05/05/2008	12:24	USGS	
			57.95	805.66	05/09/2008	07:42	USGS	
			57.13	806.48	05/13/2008	13:23	USGS	
			56.54	807.07	05/16/2008	08:47	USGS	
			56.22	807.39	05/17/2008	11:43	USGS	
			46.97	817.21	07/14/2008	11:39	SAIC	
			52.01	811.60	08/18/2008	11:25	USGS	
			51.43	812.18	08/22/2008	10:52	USGS	
USA 385215085242401	WELL JPG-DU-05I	843.71	2.47	840.68	01/07/2008	NR	USGS	860
			1.41	841.74	01/09/2008	09:27	USGS	
			2.33	841.38	04/07/2008	11:03	SAIC	
			2.87	840.28	05/05/2008	13:59	USGS	
			1.62	841.53	05/09/2008	06:35	USGS	
			1.94	841.21	05/13/2008	13:42	USGS	
			.54	842.61	05/16/2008	08:54	USGS	
			1.44	841.71	05/17/2008	11:52	USGS	
			3.35	840.36	07/14/2008	11:24	SAIC	
			3.94	839.21	08/18/2008	11:37	USGS	
			4.04	839.11	08/22/2008	11:21	USGS	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

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USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385215085242402	WELL JPG-DU-05D	843.67	118.11	725.02	01/07/2008	NR	USGS	NA
			118.18	724.95	01/09/2008	09:30	USGS	
			118.27	725.40	04/07/2008	11:02	SAIC	
			121.12	722.01	05/05/2008	14:00	USGS	
			121.11	722.02	05/09/2008	06:41	USGS	
			121.12	722.01	05/13/2008	13:43	USGS	
			121.13	722.00	05/16/2008	08:58	USGS	
			12.99	722.14	05/17/2008	11:52	USGS	
			12.98	722.69	07/14/2008	11:22	SAIC	
			121.28	721.85	08/18/2008	11:39	USGS	
			121.29	721.84	08/22/2008	11:21	USGS	
USA 385243085242503	WELL JPG-DU-06O	872.56	2.11	869.83	01/07/2008	NR	USGS	870
			2.10	869.84	01/09/2008	11:30	USGS	
			.64	871.92	04/07/2008	10:52	SAIC	
			1.14	870.80	05/05/2008	14:10	USGS	
			.67	871.27	05/09/2008	10:10	USGS	
			.84	871.10	05/13/2008	13:53	USGS	
			.57	871.37	05/16/2008	09:08	USGS	
			.37	871.57	05/17/2008	11:58	USGS	
			5.08	867.48	07/14/2008	11:31	SAIC	
			7.12	864.82	08/18/2008	11:44	USGS	
			7.41	864.53	08/22/2008	11:13	USGS	
USA 385243085242501	WELL JPG-DU-06I	872.91	8.31	864.23	06/21/2007	NR	USGS	870
			1.23	862.31	07/18/2007	15:11	USGS	
			12.45	860.09	09/11/2007	15:56	USGS	
			12.33	860.21	09/12/2007	08:40	USGS	
			12.52	860.02	09/12/2007	13:26	USGS	
			7.98	864.56	01/07/2008	NR	USGS	
			7.91	864.63	01/09/2008	11:30	USGS	
			4.42	868.49	04/07/2008	10:50	SAIC	
			4.35	868.19	05/05/2008	14:10	USGS	
			4.06	868.48	05/09/2008	10:16	USGS	
			4.09	868.45	05/13/2008	13:52	USGS	
			3.99	868.55	05/16/2008	09:02	USGS	
			3.87	868.67	05/17/2008	11:59	USGS	
			8.59	864.32	07/14/2008	11:35	SAIC	
			1.90	861.64	08/18/2008	11:49	USGS	
			11.16	861.38	08/22/2008	11:13	USGS	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

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USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385243085242502	WELL JPG-DU-06D	872.79	11.42	860.69	06/21/2007	NR	USGS	870
			37.17	834.94	07/18/2007	15:11	USGS	
			21.73	850.38	09/11/2007	15:56	USGS	
			21.68	850.43	09/12/2007	08:40	USGS	
			21.67	850.44	09/12/2007	13:26	USGS	
			2.24	851.87	01/07/2008	NR	USGS	
			2.18	851.93	01/09/2008	11:30	USGS	
			19.97	852.82	04/07/2008	10:51	SAIC	
			58.39	813.72	05/05/2008	14:11	USGS	
			53.12	818.99	05/09/2008	10:14	USGS	
			48.38	823.73	05/13/2008	13:54	USGS	
			45.45	826.66	05/16/2008	09:06	USGS	
			44.29	827.82	05/17/2008	11:59	USGS	
			22.36	850.43	07/14/2008	11:33	SAIC	
			47.25	824.86	08/18/2008	11:48	USGS	
			43.15	828.96	08/22/2008	11:13	USGS	
USA 385311085241601	WELL JPG-DU-07I	842.39	56.62	784.94	01/07/2008	13:57	USGS	NA
			56.59	784.97	01/09/2008	11:39	USGS	
			54.77	787.62	04/07/2008	10:22	SAIC	
			55.75	785.81	05/05/2008	14:21	USGS	
			55.67	785.89	05/09/2008	10:26	USGS	
			55.60	785.96	05/13/2008	14:03	USGS	
			55.56	786.00	05/16/2008	09:13	USGS	
			55.44	786.12	05/17/2008	12:07	USGS	
			54.56	787.83	07/14/2008	11:56	SAIC	
			54.28	787.28	08/18/2008	11:57	USGS	
			54.24	787.32	08/22/2008	11:06	USGS	
USA 385311085241602	WELL JPG-DU-07D	842.58	116.33	725.73	01/07/2008	NR	USGS	NA
			116.35	725.71	01/09/2008	11:39	USGS	
			115.17	727.41	04/07/2008	10:23	SAIC	
			117.10	724.96	05/05/2008	14:21	USGS	
			117.06	725.00	05/09/2008	10:32	USGS	
			117.03	725.03	05/13/2008	14:02	USGS	
			116.99	725.07	05/16/2008	09:16	USGS	
			116.89	725.17	05/17/2008	12:06	USGS	
			116.28	726.30	07/14/2008	12:01	SAIC	
			116.02	726.04	08/18/2008	11:58	USGS	
			115.97	726.09	08/22/2008	11:06	USGS	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

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USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385305085245101	WELL JPG-DU-08I	815.44	Dry	--	06/20/2007	NR	USGS	NA
			21.57	793.16	01/07/2008	NR	USGS	
			21.42	793.31	01/09/2008	12:23	USGS	
			18.28	797.16	04/07/2008	12:31	SAIC	
			35.74	778.99	05/05/2008	13:25	USGS	
			35.28	779.45	05/09/2008	08:59	USGS	
			35.41	779.32	05/13/2008	15:17	USGS	
			35.22	779.51	05/16/2008	09:55	USGS	
			35.18	779.55	05/17/2008	12:42	USGS	
			32.88	782.56	07/14/2008	14:00	SAIC	
			34.65	780.08	08/18/2008	10:54	USGS	
			34.46	780.27	08/22/2008	11:53	USGS	
USA 385305085245102	WELL JPG-DU-08D	815.36	134.53	679.97	06/20/2007	NR	USGS	NA
			133.13	681.37	01/07/2008	NR	USGS	
			133.12	681.38	01/09/2008	12:23	USGS	
			132.67	682.69	04/07/2008	12:36	SAIC	
			134.45	680.05	05/05/2008	13:26	USGS	
			134.42	680.08	05/09/2008	09:04	USGS	
			134.41	680.09	05/13/2008	15:39	USGS	
			134.35	680.15	05/16/2008	10:00	USGS	
			134.34	680.16	05/17/2008	12:42	USGS	
			134.20	681.16	07/14/2008	14:02	SAIC	
			135.29	679.21	08/18/2008	10:52	USGS	
			135.26	679.24	08/22/2008	11:53	USGS	
USA 385319085245801	WELL JPG-DU-09O	846.63	11.76	834.24	06/20/2007	15:55	USGS	840
			1.25	835.75	07/18/2007	08:13	USGS	
			8.42	837.58	01/09/2008	12:32	USGS	
			8.97	837.66	04/07/2008	11:35	SAIC	
			9.16	836.84	05/05/2008	13:12	USGS	
			8.96	837.04	05/09/2008	08:42	USGS	
			17.91	828.09	05/13/2008	15:11	USGS	
			8.72	837.28	05/16/2008	09:49	USGS	
			8.72	837.28	05/17/2008	12:51	USGS	
			8.84	837.79	07/14/2008	12:32	SAIC	
			9.37	836.63	08/18/2008	10:46	USGS	
			9.45	836.55	08/22/2008	12:00	USGS	
USA 385319085245802	WELL JPG-DU-09I	846.45	2.27	825.55	06/20/2007	15:57	USGS	845
			14.24	831.58	07/18/2007	08:13	USGS	
			13.61	832.21	01/09/2008	12:32	USGS	
			13.58	832.87	04/07/2008	11:36	SAIC	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

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USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385319085245802—Continued			14.40	831.42	05/05/2008	13:18	USGS	
			14.32	831.50	05/09/2008	08:43	USGS	
			14.29	831.53	05/13/2008	15:11	USGS	
			14.11	831.71	05/16/2008	09:46	USGS	
			13.99	831.83	05/17/2008	12:51	USGS	
			14.60	831.85	07/14/2008	12:33	SAIC	
			14.92	830.90	08/18/2008	10:44	USGS	
			14.91	830.91	08/22/2008	12:00	USGS	
USA 385319085245803	WELL JPG-DU-09D	846.10	52.03	793.49	06/20/2007	16:00	USGS	850
			36.36	809.16	07/18/2007	08:13	USGS	
			34.25	811.27	01/07/2008	NR	USGS	
			34.21	811.31	01/09/2008	12:32	USGS	
			33.77	812.33	04/07/2008	11:39	SAIC	
			35.76	809.76	05/05/2008	13:18	USGS	
			35.22	810.30	05/09/2008	08:52	USGS	
			34.86	810.66	05/13/2008	15:12	USGS	
			34.66	810.86	05/16/2008	09:42	USGS	
			34.64	810.88	05/17/2008	12:51	USGS	
			34.21	811.89	07/14/2008	12:34	SAIC	
			37.08	808.44	08/18/2008	10:42	USGS	
			36.40	809.12	08/22/2008	12:01	USGS	
USA 385336085245801	WELL JPG-DU-10O	870.39	35.09	834.67	06/20/2007	16:10	USGS	840
			35.20	834.56	07/18/2007	08:01	USGS	
			35.28	834.48	01/09/2008	12:39	USGS	
			33.70	836.69	04/07/2008	11:25	SAIC	
			33.86	835.90	05/05/2008	13:05	USGS	
			33.73	836.03	05/09/2008	08:29	USGS	
			33.69	836.07	05/13/2008	15:00	USGS	
			33.54	836.22	05/16/2008	09:30	USGS	
			34.29	835.47	05/17/2008	13:09	USGS	
			34.88	835.51	07/14/2008	12:16	SAIC	
			36.12	833.64	08/18/2008	10:36	USGS	
			34.48	835.28	08/22/2008	12:08	USGS	
USA 385336085245802	WELL JPG-DU-10D	870.71	34.82	835.27	06/20/2007	16:15	USGS	845
			32.72	837.37	07/18/2007	08:01	USGS	
			33.63	836.46	01/07/2008	NR	USGS	
			33.59	836.50	01/09/2008	12:39	USGS	
			33.12	837.59	04/07/2008	11:29	SAIC	
			33.36	836.73	05/05/2008	13:08	USGS	
			33.26	836.83	05/09/2008	08:33	USGS	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; mm/dd/yyyy, month/day/year; hh, hours; mm, minutes; -, negative depths to water indicate water levels above land surface; NR, not reported; SAIC, Science Applications International Corporation; NA, no recharge altitude estimated because no age-dating samples were collected from well; Dry, no water in well at time of measurement; --, no value]

USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385336085245802—Continued			33.30	836.79	05/13/2008	14:59	USGS	
			33.21	836.88	05/16/2008	09:32	USGS	
			33.26	836.83	05/17/2008	12:14	USGS	
			33.51	837.20	07/14/2008	12:17	SAIC	
			34.53	835.56	08/18/2008	10:33	USGS	
			36.44	833.65	08/22/2008	12:08	USGS	
USA 385311085242401	WELL JPG MW-1	851.75	7.87	843.88	04/07/2008	10:26	SAIC	NA
			9.19	842.56	07/14/2008	11:39	SAIC	
USA 385151085242401	WELL JPG MW-2	848.25	7.32	840.93	04/07/2008	11:13	SAIC	NA
			9.35	838.90	07/14/2008	11:16	SAIC	
USA 385032085242401	WELL JPG MW-3	870.96	6.32	864.64	04/07/2008	10:08	SAIC	NA
			9.27	861.69	07/14/2008	11:22	SAIC	
USA 384843085231301	WELL JPG MW-4	898.92	.44	898.48	04/07/2008	09:46	SAIC	NA
			5.10	893.82	07/14/2008	10:42	SAIC	
USA 385306085253201	WELL JPG MW-5	801.91	15.95	785.96	04/07/2008	11:09	SAIC	NA
			17.00	784.91	07/14/2008	13:34	SAIC	
USA ‘385149085253201	WELL JPG MW-6	858.44	1.43	857.01	04/07/2008	10:27	SAIC	NA
			8.18	850.26	07/14/2008	11:33	SAIC	
USA 385024085253201	WELL JPG MW-7	850.99	6.11	844.88	04/07/2008	10:19	SAIC	NA
			8.25	842.74	07/14/2008	11:26	SAIC	
USA 384841085262101	WELL JPG MW-8	838.97	21.02	817.95	04/07/2008	09:57	SAIC	NA
			21.33	817.64	07/14/2008	10:55	SAIC	
USA 385309085244901	WELL JPG MW-9	819.85	36.42	783.43	04/07/2008	12:44	SAIC	NA
			36.58	783.27	07/14/2008	13:54	SAIC	
USA 385329085245801	WELL JPG MW-10	865.91	1.48	864.43	04/07/2008	11:32	SAIC	NA
			6.93	858.98	07/14/2008	12:29	SAIC	
USA 385302085251301	WELL JPG MW-11	809.94	5.37	804.57	04/07/2008	12:27	SAIC	NA
			1.37	799.57	07/14/2008	13:45	SAIC	
USA 385252085233501	WELL JPG MW-RS1	865.39	.03	865.36	04/07/2008	10:04	SAIC	NA
			.88	864.51	07/14/2008	12:23	SAIC	

Table 5. Groundwater levels measured by the U.S. Geological Survey and Science Applications International Corporation (selected dates) in wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; mm/dd/yyyy, month/day/year; hh, hours; mm, minutes; -, negative depths to water indicate water levels above land surface; NR, not reported; SAIC, Science Applications International Corporation; NA, no recharge altitude estimated because no age-dating samples were collected from well; Dry, no water in well at time of measurement; --, no value]

USGS agency code and site identifier	USGS well name	Land surface altitude (feet above NAVD 88)	Water level (feet below land surface)	Water-level altitude (feet above NAVD 88)	Measurement date (mm/dd/yyyy)	Measurement time (hhmm)	Measurement source	Estimated recharge altitude (feet above NAVD 88)
USA 385252085233501	WELL JPG MW-RS2	873.28	1.22	872.06	04/07/2008	10:12	SAIC	NA
			5.42	867.86	07/14/2008	12:13	SAIC	
USA 385315085233101	WELL JPG MW-RS3	879.19	3.36	875.83	04/07/2008	10:16	SAIC	NA
			5.83	873.36	07/14/2008	12:06	SAIC	
USA 385147085254201	WELL JPG MW-RS4	858.21	4.06	854.15	04/07/2008	11:54	SAIC	NA
			5.82	852.39	07/14/2008	12:58	SAIC	
USA 385156085260701	WELL JPG MW-RS5	851.42	.56	850.86	04/07/2008	12:20	SAIC	NA
			6.79	844.63	07/14/2008	13:11	SAIC	
USA 385248085254901	WELL JPG MW-RS6	858.24	2.67	855.57	04/07/2008	12:13	SAIC	NA
			6.08	852.16	07/14/2008	13:04	SAIC	
USA 385155085254301	WELL JPG MW-RS7	859.42	2.06	857.36	04/07/2008	12:00	SAIC	NA
			4.27	855.15	07/14/2008	12:50	SAIC	
USA 385235085252601	WELL JPG MW-RS8	865.03	1.12	863.91	04/07/2008	10:52	SAIC	NA
			7.52	857.51	07/14/2008	11:49	SAIC	

Table 6. Vertical water-level gradients between paired shallow and deep observation wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.

[mm/dd/yyyy, month/day/year; -, negative water-level-gradient values indicate downward gradients; positive water-level-gradient values indicate upward gradients]

Well name of shallow well	Well name of deep well	Measurement date (mm/dd/yyyy)	Vertical hydraulic gradient (feet)[1]	Direction of vertical gradient
WELL JPG-DU-01I (Shallow carbonate unit)	WELL JPG-DU-01D (Deep carbonate unit)	06/20/2007	1.474	Downward
		09/12/2007	1.096	Downward
		09/12/2007	1.094	Downward
		01/07/2008	.507	Downward
		01/09/2008	.499	Downward
		04/07/2008	.137	Downward
		05/05/2008	.113	Downward
		05/09/2008	.092	Downward
		05/13/2008	.071	Downward
		05/16/2008	.061	Downward
		05/17/2008	.057	Downward
		07/14/2008	-.002	Upward
		08/18/2008	.004	Downward
		08/22/2008	.001	Downward
WELL JPG-DU-02I (Shallow carbonate unit)	WELL JPG-DU-02D (Deep carbonate unit)	06/21/2007	1.068	Downward
		09/12/2007	1.058	Downward
		09/12/2007	1.058	Downward
		04/07/2008	1.075	Downward
		05/05/2008	1.073	Downward
		05/09/2008	1.088	Downward
		05/13/2008	1.083	Downward
		05/16/2008	1.137	Downward
		05/17/2008	1.098	Downward
		07/14/2008	1.066	Downward
		08/18/2008	1.072	Downward
		08/22/2008	1.071	Downward
WELL JPG-DU-03O (Pre-Wisconsinan till)	WELL JPG-DU-03I (Shallow carbonate unit)	01/08/2008	.441	Downward
		01/09/2008	.360	Downward
		04/07/2008	-.014	Upward
		05/05/2008	-.010	Upward
		05/09/2008	-.007	Upward
		05/13/2008	-.014	Upward
		05/16/2008	-.006	Upward
		05/17/2008	-.002	Upward
		07/14/2008	.075	Downward
		08/18/2008	-.071	Upward
		08/22/2008	-.085	Upward
WELL JPG-DU-04O (Pre-Wisconsinan till)	WELL JPG-DU-04I (Shallow carbonate unit)	01/07/2008	.063	Downward
		01/09/2008	.034	Downward
		04/07/2008	.022	Downward
		05/05/2008	.017	Downward
		05/09/2008	.024	Downward
		05/16/2008	.062	Downward

Table 6. Vertical water-level gradients between paired shallow and deep observation wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

[mm/dd/yyyy, month/day/year; -, negative water-level-gradient values indicate downward gradients; positive water-level-gradient values indicate upward gradients]

Well name of shallow well	Well name of deep well	Measurement date (mm/dd/yyyy)	Vertical hydraulic gradient (feet)[1]	Direction of vertical gradient
WELL JPG-DU-04O—Continued		05/17/2008	0.025	Downward
		07/14/2008	.032	Downward
		08/18/2008	.031	Downward
		08/22/2008	.029	Downward
WELL JPG-DU-04I	WELL JPG-DU-04D	01/07/2008	2.027	Downward
(Shallow carbonate unit)	(Deep carbonate unit)	01/09/2008	2.030	Downward
		04/07/2008	1.402	Downward
		05/05/2008	1.463	Downward
		05/09/2008	1.443	Downward
		05/13/2008	1.418	Downward
		05/16/2008	1.374	Downward
		05/17/2008	1.396	Downward
		07/14/2008	1.070	Downward
		08/18/2008	1.172	Downward
		08/22/2008	1.151	Downward
WELL JPG-DU-05I	WELL JPG-DU-05D	01/07/2008	1.205	Downward
(Shallow carbonate unit)	(Deep carbonate unit)	01/09/2008	1.217	Downward
		04/07/2008	1.208	Downward
		05/05/2008	1.228	Downward
		05/09/2008	1.241	Downward
		05/13/2008	1.238	Downward
		05/16/2008	1.252	Downward
		05/17/2008	1.242	Downward
		07/14/2008	1.222	Downward
		08/18/2008	1.218	Downward
		08/22/2008	1.217	Downward
WELL JPG-DU-06O	WELL JPG-DU-06I	01/07/2008	.201	Downward
(Pre-Wisconsinan till)	(Shallow carbonate unit)	01/09/2008	.199	Downward
		04/07/2008	.125	Downward
		05/05/2008	.104	Downward
		05/09/2008	.111	Downward
		05/13/2008	.106	Downward
		05/16/2008	.112	Downward
		05/17/2008	.115	Downward
		07/14/2008	.115	Downward
		08/18/2008	.125	Downward
		08/22/2008	.124	Downward
WELL JPG-DU-06I	WELL JPG-DU-06D	06/21/2007	.064	Downward
(Shallow carbonate unit)	(Deep carbonate unit)	07/18/2007	.535	Downward
		09/11/2007	.186	Downward
		09/12/2007	.187	Downward
		09/12/2007	.183	Downward

Table 6. Vertical water-level gradients between paired shallow and deep observation wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

[mm/dd/yyyy, month/day/year; -, negative water-level-gradient values indicate downward gradients; positive water-level-gradient values indicate upward gradients]

Well name of shallow well	Well name of deep well	Measurement date (mm/dd/yyyy)	Vertical hydraulic gradient (feet)[1]	Direction of vertical gradient
WELL JPG-DU-06I—Continued		01/07/2008	0.245	Downward
		01/09/2008	.245	Downward
		04/07/2008	.310	Downward
		05/05/2008	1.070	Downward
		05/09/2008	.972	Downward
		05/13/2008	.877	Downward
		05/16/2008	.821	Downward
		05/17/2008	.801	Downward
		07/14/2008	.274	Downward
		08/18/2008	.720	Downward
		08/22/2008	.634	Downward
WELL JPG-DU-07I	WELL JPG-DU-07D	01/07/2008	.998	Downward
(Shallow carbonate unit)	(Deep carbonate unit)	01/09/2008	.998	Downward
		04/07/2008	1.004	Downward
		05/05/2008	1.012	Downward
		05/09/2008	1.012	Downward
		05/13/2008	1.012	Downward
		05/16/2008	1.012	Downward
		05/17/2008	1.012	Downward
		07/14/2008	1.015	Downward
		08/18/2008	1.015	Downward
		08/22/2008	1.015	Downward
WELL JPG-DU-08I	WELL JPG-DU-08D	01/07/2008	1.072	Downward
(Shallow carbonate unit)	(Deep carbonate unit)	01/09/2008	1.073	Downward
		04/07/2008	1.102	Downward
		05/05/2008	.990	Downward
		05/09/2008	.993	Downward
		05/13/2008	.992	Downward
		05/16/2008	.992	Downward
		05/17/2008	.993	Downward
		07/14/2008	1.003	Downward
		08/18/2008	1.000	Downward
		08/22/2008	1.001	Downward
WELL JPG-DU-09O	WELL JPG-DU-09I	06/20/2007	.561	Downward
(Pre-Wisconsinan till)	(Shallow carbonate unit)	07/18/2007	.269	Downward
		01/09/2008	.347	Downward
		04/07/2008	.309	Downward
		05/05/2008	.350	Downward
		05/09/2008	.358	Downward
		05/13/2008	-.222	Upward
		05/16/2008	.360	Downward
		05/17/2008	.352	Downward
		07/14/2008	.384	Downward
		08/18/2008	.370	Downward
		08/22/2008	.364	Downward

Table 6. Vertical water-level gradients between paired shallow and deep observation wells in the Pre-Wisconsinan till and in the shallow and deep carbonate units at the Jefferson Proving Ground, southeastern Indiana, 2007–08.—Continued

[mm/dd/yyyy, month/day/year; -, negative water-level-gradient values indicate downward gradients; positive water-level-gradient values indicate upward gradients]

Well name of shallow well	Well name of deep well	Measurement date (mm/dd/yyyy)	Vertical hydraulic gradient (feet)[1]	Direction of vertical gradient
WELL JPG-DU-09I	WELL JPG-DU-09D	06/20/2007	0.935	Downward
(Shallow carbonate unit)	(Deep carbonate unit)	07/18/2007	.654	Downward
		01/09/2008	.610	Downward
		04/07/2008	.598	Downward
		05/05/2008	.632	Downward
		05/09/2008	.619	Downward
		05/13/2008	.609	Downward
		05/16/2008	.608	Downward
		05/17/2008	.611	Downward
		07/14/2008	.581	Downward
		08/18/2008	.655	Downward
		08/22/2008	.636	Downward
WELL JPG-DU-10O	WELL JPG-DU-10D	06/20/2007	-.030	Upward
(Pre-Wisconsinan till)	(Shallow carbonate unit)	07/18/2007	-.140	Upward
		01/09/2008	-.101	Upward
		04/07/2008	-.045	Upward
		05/05/2008	-.041	Upward
		05/09/2008	-.040	Upward
		05/13/2008	-.036	Upward
		05/16/2008	-.033	Upward
		05/17/2008	-.068	Upward
		07/14/2008	-.085	Upward
		08/18/2008	-.096	Upward
		08/22/2008	.082	Downward

[1] Vertical gradients were computed between water levels in wells, using the formula

vertical gradient = (WLs - WLd)/(ALTs -ALTd)

where

WLs is the water-level altitude in the shallow well or the surface-water stage;

WLd is the water-level altitude in the deep well;

ALTs is one of the following values. When the water table was in the screened interval in the shallow well, ALTs was the altitude of the midpoint between the water-table altitude and the altitude of the base of the shallow well screen. When the water table was above the screened interval of the shallow well, ALTs was the altitude of the midpoint between the top and base of the shallow well screen; and

ALTd is one of the following values. When the water table was in the screened interval in the deep well, ALTd was the altitude of the midpoint between the water-table altitude and the altitude of the base of the deep well screen. When the water table was above the screened interval of the deep well, ALTd was the altitude of the midpoint between the top and base of the deep well screen.

Table 9. Concentrations of selected dissolved gases in sequential replicate groundwater samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.

[mm/dd/yy, month/day/year; hhmm, hours and minutes; mg/L, milligrams per liter; RPD, relative percent difference with concentration in water sample; °C, degrees Celsius]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Methane (mg/L)	RPD[1] (percent)	Carbon dioxide (mg/L)	RPD[1] (percent)	Oxygen (mg/L)	RPD[1] (percent)	Argon (mg/L)	RPD[1] (percent)	Nitrogen (mg/L)	RPD[1] (percent)	Estimated average recharge temperature (°C)
						Quality-assurance samples (sequential replicates)							
Pre-Wisconsinan till water samples													
JPG-DU-03O	04/08/08	1505	0.00073	60.0	80.4	1.2	0.25	24.6	0.84	0.0	26.3	0.8	7.7
JPG-DU-04O	04/15/08	0835	.029	12.9	55.1	6.0	.29	24.2	.99	1.0	31.8	2.5	2.0
JPG-DU-06O	04/15/08	1535	.0051	5.7	66.2	.6	.23	4.4	.78	.0	23.5	.0	9.0
JPG-DU-09O	04/13/08	1655	.020	9.5	35.2	.9	.18	28.6	.82	.0	25.5	.4	8.4
JPG-DU-10O	04/13/08	1255	2.1	4.9	39.3	1.3	.23	12.2	.80	1.3	23.2	.0	6.3
Shallow carbonate unit samples													
JPG-DU-01I	04/10/08	0920	.023	.0	42.5	.2	.27	16.9	.85	1.2	26.3	.4	5.6
JPG-DU-02I	04/14/08	1400	.0012	28.6	21.6	.5	.23	14.0	.74	.0	20.5	.5	7.6
JPG-DU-03I	04/09/08	1100	.0076	3.9	26.1	3.1	.18	36.4	.77	1.3	24.5	1.6	11.7
JPG-DU-04I	04/15/08	1020	.024	4.1	55.0	1.1	.31	17.5	.99	1.0	33.6	.3	4.9
JPG-DU-05I	04/15/08	1320	.00033	37.0	23.9	1.7	.32	16.9	.87	2.3	28.5	2.8	8.2
JPG-DU-06I	04/20/08	1635	.018	5.4	59.1	.7	.22	4.7	.81	1.2	24.3	.4	6.6
JPG-DU-09I	04/14/08	0835	.0012	40.0	43.0	1.9	.25	24.6	.82	1.2	24.2	1.7	6.2
JPG-DU-10D	04/10/08	1400	.014	7.4	25.1	3.9	.24	28.6	.83	1.2	25.9	2.3	8.1
Deep carbonate unit samples													
JPG-DU-06D	04/21/08	1120	12	8.7	17.7	3.4	.13	14.3	.57	.0	19.1	.5	17.1
JPG-DU-09D	04/14/08	1105	.019	5.4	16.8	.6	.25	43.9	.46	.0	23.6	.4	13.6

[1] The RPDs were computed for the paired water sample and sequential replicate as

RPD = |(SD-WS)/((SD+WS)/2)| x 100,

where
RPD is the relative percent difference,
SD is the concentration in the sequential replicate, and
WS is the concentration in the water sample.

Table 12. Concentrations of chlorofluorocarbon compounds and piston-flow based estimates of groundwater age for water samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.

[The most reliable dates of groundwater age are in **bold type**; dates of groundwater age based on estimated concentrations are *italicized*; mm/dd/yy, month/day/year; hhmm, hours and minutes; °C, degrees Celsius; ft-VD, altitude in feet above North American Vertical Datum of 1988; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoromethane; pg/L, picogram per liter; pptv, part per trillion by volume; Q, estimated concentration; Contam., calculated atmospheric mixing ratio indicates chlorofluorocarbon concentration in water sample affected by addition of excess chlorofluorocarbon to that predicted to be in the atmosphere; --, not computed]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Estimated recharge temperature (°C)	Estimated recharge altitude (ft-VD)	Sample vial	Concentration in water sample			Calculated atmospheric mixing ratio			Dates of groundwater age, no mixing (piston flow) assumed			Median age of groundwater since recharge, no mixing assumed (years)	Alternate mixing model feasible
						CFC-11 (pg/L)	CFC-12 (pg/L)	CFC-113 (pg/L)	CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	CFC-11	CFC-12	CFC-113		
Pre-Wisconsinan till water samples																
JPG-DU-03O	04/09/08	1500	7.2	860	1	127.2	184.7	33.9	38.5	238.9	23.3	1967	**1976**	1980	**32**	Yes
					2	142.5	193.1	37.2	43.1	249.7	25.5	1968	**1976**	1981	**32**	Yes
					4	100.8	198.6	38.9	30.5	256.9	26.7	1966	**1977**	1981	**31**	Yes
JPG-DU-04O	04/15/08	0830	1.5	860	2	Q47.5	21.5	16.9	Q10.1	20.2	7.9	***1960***	**1956**	1972	**52**	Yes
					3	Q76.4	23.3	16.7	Q16.2	21.9	7.8	***1962***	**1957**	1972	**49**	Yes
					4	Q70.8	Q29.3	16.4	Q15.0	Q27.5	7.6	***1962***	***1958***	1972	**48**	Yes
JPG-DU-06O	04/15/08	1530	8.5	870	2	50.8	59.8	7.6	16.6	83.7	5.7	**1963**	**1967**	1970	**43**	Yes
					3	56.2	58.7	8.1	18.4	82.2	6.1	**1963**	**1967**	1970	**43**	Yes
JPG-DU-09O	04/13/08	1650	8.3	840	2	117.9	83.2	Q16.5	37.9	113.4	12.1	**1967**	**1969**	1975	**40**	Yes
					3	132.0	78.5	Q44.9	42.5	107.1	32.9	**1968**	**1968**	1983	**40**	No
JPG-DU-10O	04/13/08	1250	6.7	840	4	75.1	81.1	Q35.5	22.2	104.6	24.0	1964	**1968**	1980	**40**	No
					5	74.7	77.9	Q23.9	22.1	100.4	16.2	1964	**1968**	1978	**40**	Yes
Shallow carbonate unit samples																
JPG-DU-01I	04/10/08	0915	5.3	850	1	64.6	36.8	140.8	17.5	43.3	86.0	**1963**	**1962**	1996	**46**	Yes
					2	53.6	30.4	123.5	14.5	35.8	75.4	**1962**	**1960**	1990	**47**	Yes
JPG-DU-02I	04/14/08	1355	7.1	810	2	131.7	248.5	28.3	40.0	332.9	19.9	1968	**1981**	1979	**27**	No
					3	129.0	251.3	27.6	39.2	336.6	19.5	1967	**1982**	1979	**26**	No
JPG-DU-03I	04/09/08	1055	11.7	865	1	523.0	262.1	756.4	203.1	420.3	676.3	**1984**	**1986**	Contam.	**23**	Yes
					3	543.1	256.8	764.2	210.9	411.8	683.3	**1985**	**1986**	Contam.	**23**	Yes
JPG-DU-04I	04/15/08	1015	4.2	865	2	82.3	40.2	58.4	20.6	43.0	32.2	**1964**	**1962**	1983	**45**	Yes
					3	66.4	35.4	58.1	16.7	37.9	32.0	**1963**	**1961**	1983	**46**	Yes

Table 12. Concentrations of chlorofluorocarbon compounds and piston-flow based estimates of groundwater age for water samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.—Continued

[The most reliable dates of groundwater age are in **bold type**; dates of groundwater age based on estimated concentrations are *italicized*; mm/dd/yy, month/day/year; hhmm, hours and minutes; °C, degrees Celsius; ft-VD, altitude in feet above North American Vertical Datum of 1988; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoromethane; pg/L, picogram per liter; pptv, part per trillion by volume; Q, estimated concentration; Contam., calculated atmospheric mixing ratio indicates chlorofluorocarbon concentration in water sample affected by addition of excess chlorofluorocarbon to that predicted to be in the atmosphere; --, not computed]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Estimated recharge temperature (°C)	Estimated recharge altitude (ft-VD)	Sample vial	Concentration in water sample			Calculated atmospheric mixing ratio			Dates of groundwater age, no mixing (piston flow) assumed			Median age of groundwater since recharge, no mixing assumed (years)	Alternate mixing model feasible
						CFC-11 (pg/L)	CFC-12 (pg/L)	CFC-113 (pg/L)	CFC-11 (pptv)	CFC-12 (pptv)	CFC-113 (pptv)	CFC-11	CFC-12	CFC-113		
Shallow carbonate unit samples—Continued																
JPG-DU-05I	04/15/08	1315	8.6	860	2	518.6	292.9	169.1	169.2	399.2	124.5	1980	**1985**	Contam.	**23**	Yes
					3	502.4	299.3	181.9	163.9	407.9	134.0	1980	**1986**	Contam.	**22**	Yes
JPG-DU-06I	04/20/08	1630	6.4	870	3	18.2	11.3	47.5	5.3	14.3	31.4	**1956**	**1954**	1983	**55**	Yes
					4	Q32.8	14.0	48.0	9.5	17.7	31.7	***1960***	**1955**	1983	**53**	Yes
					5	19.5	13.3	49.4	5.6	16.8	32.7	**1957**	**1955**	1983	**52**	Yes
JPG-DU-09I	04/14/08	0830	6.7	845	3	338.6	222.9	284.3	99.9	286.1	191.8	1974	**1978**	Contam.	**30**	No
					5	330.4	226.3	277.2	97.5	290.5	187.0	1974	**1978**	Contam.	**30**	No
JPG-DU-10D	04/10/08	1355	7.7	845	2	45.7	34.6	184.3	14.2	45.7	129.9	**1962**	**1962**	Contam.	**46**	No
					5	51.3	28.2	166.9	16.0	37.2	117.6	**1962**	**1961**	Contam.	**47**	Yes
Deep carbonate unit samples																
JPG-DU-06D	04/21/08	1115	16.9	870	4	458.0	323.7	818.5	235.6	695.9	1029	1987	Contam.	Contam.	--	No
					5	399.6	265.5	772.8	205.6	570.7	971.3	1984	**Modern**	Contam.	--	No
JPG-DU-09D	04/14/08	1100	13.7	850	2	80.0	39.8	663.4	35.1	74.6	701.8	**1967**	**1966**	Contam.	**42**	Yes
					5	86.6	35.6	664.9	38.0	72.9	703.5	**1967**	**1966**	Contam.	**42**	Yes

Quality assurance data, including analyses of sequential replicate sample vials, are reproduced with relative percent difference statistics in table 13.

Table 13. Comparison of concentrations of tritium in groundwater samples, April 2008, to hypothetical concentrations of tritium from chlorofluorocarbon-based piston-flow model age dates and hypothetical models of binary mixtures of recharge with pre-1940 recharge, Jefferson Proving Ground, southeastern Indiana, 2008.

[CFC, chlorofluorocarbon; pptv, part per trillion by volume; NA, none computed or used; hypothetical concentration of tritium of young recharge assumed to equal the estimated concentration of tritium in Ohio River Basin recharge for the same year as the estimated CFC-based age of young recharge in binary mixture or of recharge in piston-flow model; <, less than]

Well name	Tritium water, unfiltered (tritium units)	Tritium, 2-sigma precision (tritium units)	Concentration of tritium plus 2-sigma precision (tritium units)	Model type and concentration of CFC or atmospheric mixing ratio used for age date	CFC atmospheric mixing ratio (pptv/pptv)	Estimated CFC-based age of young recharge in binary mixture or of recharge in piston flow model	Concentration of tritium in young recharge in binary mixture or in piston flow, decay corrected to April 2008 (tritium units)	CFC-based estimated fraction of young recharge in mixture	Hypothetical concentration of tritium from piston flow or binary mixing models (tritium units)	Classification of groundwater age	Comments
Pre-Wisconsinan till water samples											
JPG-DU-03O	4.1	0.5	4.6	Binary mixture using CFC-113/CFC-12 ratio	0.097 CFC-113/CFC-12	1984	4.7	0.67	3.4	Mixture of about 70 percent of mid-1980s recharge with about 30 percent pre-1940 recharge	Concentration of tritium in groundwater is similar to that produced from binary mixture using CFC data
JPG-DU-04O	.5	.4	.9	Binary mixture using CFC-11/CFC-12 ratio	.5 CFC-11/CFC-12	1974	7.4	.11	1.3	Mixture of about 10 percent of mid-1970s recharge with pre-1940 recharge	Concentration of tritium in groundwater is similar to that produced from binary mixture using CFC data
JPG-DU-06O	4.6	.6	5.2	Binary mixture using CFC-113/CFC-12 ratio	.069 CFC-113/CFC-12	1979	7.1	.29	2.4	Mixture of about 30 percent of late-1970s recharge with pre-1940 recharge	Concentration of tritium is slightly less than that produced from binary mixture using CFC ratio

Table 13. Comparison of concentrations of tritium in groundwater samples, April 2008, to hypothetical concentrations of tritium from chlorofluorocarbon-based piston-flow model age dates and hypothetical models of binary mixtures of recharge with pre-1940 recharge, Jefferson Proving Ground, southeastern Indiana, 2008.—Continued

[CFC, chlorofluorocarbon; pptv, part per trillion by volume; NA, none computed or used; hypothetical concentration of tritium of young recharge assumed to equal the estimated concentration of tritium in Ohio River Basin recharge for the same year as the estimated CFC-based age of young recharge in binary mixture or of recharge in piston-flow model; <, less than]

Well name	Tritium water, unfiltered (tritium units)	Tritium, 2-sigma precision (tritium units)	Concentration of tritium plus 2-sigma precision (tritium units)	Model type and concentration of CFC or atmospheric mixing ratio used for age date	CFC atmospheric mixing ratio (pptv/pptv)	Estimated CFC-based age of young recharge in binary mixture or of recharge in piston flow model	Concentration of tritium in young rcharge in binary mixture or in piston flow, decay corrected to April 2008 (tritium units)	CFC-based estimated fraction of young recharge in mixture	Hypothetical concentration of tritium from piston flow or binary mixing models (tritium units)	Classification of groundwater age	Comments
					Pre-Wisconsinan till water samples—Continued						
JPG-DU-09O (sample vial 4)	0.5	0.6	1.1	Piston flow; CFC-12	NA	1969	12.1	1.00	12.1	Discordant date: Mid-1950s (tritium) or late-1960s (CFC-12)	Concentration of tritium is much less than that predicted by piston-flow recharge model using CFC-12 data
				Binary mixture; CFC-113/ CFC-12 ratio	0.106 CFC-113/ CFC-12	1985	4.8	.30	1.8	Mixture of about 30 percent of mid-1980s recharge with pre-1940 recharge	Concentration of tritium in groundwater is similar to that produced from binary mixture using CFC data; result not replicated by sequential replicate sample due to slight CFC-113 contamination
JPG-DU-10O (sample vial 4)	.7	.6	1.3	Piston flow; CFC-12	NA	1968	12.1	1.00	12.1	Discordant date: Early to mid-1950s (tritium) or late-1960s (CFC-12) recharge	Concentration of tritium in groundwater is much less than that predicted by piston-flow recharge model using CFC-12 data
				Binary mixture using CFC-113/ CFC-12 ratio	.161 CFC-113/ CFC-12	1992	4.1	.20	1.2	Mixture of about 20 percent of early-1990s recharge with pre-1940 recharge	Concentration of tritium in groundwater is similar to that produced from binary mixture using CFC data from sequential replicate.

Table 13. Comparison of concentrations of tritium in groundwater samples, April 2008, to hypothetical concentrations of tritium from chlorofluorocarbon-based piston-flow model age dates and hypothetical models of binary mixtures of recharge with pre-1940 recharge, Jefferson Proving Ground, southeastern Indiana, 2008.—Continued

[CFC, chlorofluorocarbon; pptv, part per trillion by volume; NA, none computed or used; hypothetical concentration of tritium of young recharge assumed to equal the estimated concentration of tritium in Ohio River Basin recharge for the same year as the estimated CFC-based age of young recharge in binary mixture or of recharge in piston-flow model; <, less than]

Well name	Tritium water, unfiltered (tritium units)	Tritium, 2-sigma precision (tritium units)	Concentration of tritium plus 2-sigma precision (tritium units)	Model type and concentration of CFC or atmospheric mixing ratio used for age date	CFC atmospheric mixing ratio (pptv/pptv)	Estimated CFC-based age of young recharge in binary mixture or of recharge in piston flow model	Concentration of tritium in young recharge in binary mixture or in piston flow, decay corrected to April 2008 (tritium units)	CFC-based estimated fraction of young recharge in mixture	Hypothetical concentration of tritium from piston flow or binary mixing models (tritium units)	Classification of groundwater age	Comments
Shallow carbonate unit samples											
JPG-DU-01I	0.2	0.4	0.6	Binary mixture using CFC-11/ CFC-12 ratio	0.404 CFC-11/ CFC-12	2005	5.1	0.08	0.9	Mixture of about 10 percent of post-2000 recharge with pre-1940 recharge	Concentration of tritium in groundwater is similar to that produced from binary mixture using CFC data
JPG-DU-02I	5.1	.6	5.7	Piston flow; CFC-12	NA	1981	6.8	1.00	6.8	Early 1980's recharge	Concentration of tritium is concordant with piston-flow recharge model predicted by CFC-12 data
JPG-DU-03I	2.6	.5	3.1	Binary mixture using CFC-11/ CFC-12 ratio	.483 CFC-11/ CFC-12	2000	4.75	.77	3.8	Mixture of about 80 percent of post-2000 recharge with pre-1940 recharge	Concentration of tritium in groundwater is similar to that produced from binary mixture using CFC data
JPG-DU-04I	.4	.4	.8	Binary mixture using CFC-11/ CFC-12 ratio	.479 CFC-11/ CFC-12	1972	11.1	.27	3.4	Discordant date: tritium date (1953 or older recharge) is the age date of this sample	Concentration of tritium in groundwater is much less than that produced from binary mixture using CFC data

Table 13. Comparison of concentrations of tritium in groundwater samples, April 2008, to hypothetical concentrations of tritium from chlorofluorocarbon-based piston-flow model age dates and hypothetical models of binary mixtures of recharge with pre-1940 recharge, Jefferson Proving Ground, southeastern Indiana, 2008.—Continued

[CFC, chlorofluorocarbon; pptv, part per trillion by volume; NA, none computed or used; hypothetical concentration of tritium of young recharge assumed to equal the estimated concentration of tritium in Ohio River Basin recharge for the same year as the estimated CFC-based age of young recharge in binary mixture or of recharge in piston-flow model; <, less than]

Well name	Tritium water, unfiltered (tritium units)	Tritium, 2-sigma precision (tritium units)	Concentration of tritium plus 2-sigma precision (tritium units)	Model type and concentration of CFC or atmospheric mixing ratio used for age date	CFC atmospheric mixing ratio (pptv/pptv)	Estimated CFC-based age of young recharge in binary mixture or of recharge in piston flow model	Concentration of tritium in young recharge in binary mixture or in piston flow, decay corrected to April 2008 (tritium units)	CFC-based estimated fraction of young recharge in mixture	Hypothetical concentration of tritium from piston flow or binary mixing models (tritium units)	Classification of groundwater age	Comments
Shallow carbonate unit samples—Continued											
JPG-DU-05I	0.3	0.4	0.7	Piston flow; CFC-12	NA	1985	4.8	1.00	4.8	Discordant date: tritium date (1953 or older recharge) is the age date of sample	Concentration of tritium is much less than that predicted by piston-flow recharge model using CFC-12 data
JPG-DU-06I	.3	.4	.7	Piston flow; CFC-12	NA	1954	.8	1.00	.8	1953 or older recharge or early-1950's recharge	Concentration of tritium is similar to that predicted by piston-flow recharge model using CFC-12 data
JPG-DU-09I	.5	.6	1.1	Piston flow; CFC-12	NA	1978	6.7	1.00	6.7	Discordant date: tritium date (1953 or older recharge) is the age date of sample	Concentration of tritium is much less than that predicted by piston-flow recharge model using CFC-12 data
JPG-DU-10D	.1	.6	.7	Piston flow; CFC-12	NA	1962	24.7	.30	7.8	Discordant date: tritium date (pre-1953 recharge) is the age date of this sample	Concentration of tritium is much less than that predicted by piston-flow recharge model using CFC-12 data

Table 13. Comparison of concentrations of tritium in groundwater samples, April 2008, to hypothetical concentrations of tritium from chlorofluorocarbon-based piston-flow model age dates and hypothetical models of binary mixtures of recharge with pre-1940 recharge, Jefferson Proving Ground, southeastern Indiana, 2008.—Continued

[CFC, chlorofluorocarbon; pptv, part per trillion by volume; NA, none computed or used; hypothetical concentration of tritium of young recharge assumed to equal the estimated concentration of tritium in Ohio River Basin recharge for the same year as the estimated CFC-based age of young recharge in binary mixture or of recharge in piston-flow model; <, less than]

Well name	Tritium water, unfiltered (tritium units)	Tritium, 2-sigma precision (tritium units)	Concentration of tritium plus 2-sigma precision (tritium units)	Model type and concentration of CFC or atmospheric mixing ratio used for age date	CFC atmospheric mixing ratio (pptv/pptv)	Estimated CFC-based age of young recharge in binary mixture or of recharge in piston flow model	Concentration of tritium in young recharge in binary mixture or in piston flow, decay corrected to April 2008 (tritium units)	CFC-based estimated fraction of young recharge in mixture	Hypothetical concentration of tritium from piston flow or binary mixing models (tritium units)	Classification of groundwater age	Comments
Deep carbonate unit samples											
JPG-DU-06D	3.3	0.6	3.9	Piston flow; CFC-12	NA	2005	5.1	1.00	5.1	Modern, post-2005 recharge	Concentration of tritium is similar to that predicted by piston-flow recharge model using CFC-12 data
JPG-DU-09D	<.1	.4	.5	Piston flow; CFC-12	NA	1967	39	.28	10.9	Discordant date: tritium date (pre-1953 recharge) is the age date of sample	Concentration of tritium is much less than that predicted by piston-flow recharge model using CFC-12 data

Table 15. Concentrations of chlorofluorocarbon compounds in sequential replicate groundwater samples from the Jefferson Proving Ground, southeastern Indiana, April 2008.

[The most reliable dates of groundwater age are in **bold**; mm/dd/yy, month/day/year; hhmm, hours and minutes; CFC-11, trichlorofluoromethane; pg/L, picogram per liter; RPD, relative percent difference; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoromethane]

Well name	Date sampled (mm/dd/yy)	Time sampled (hhmm)	Sample vial	Concentration in water sample					
				CFC-11 (pg/L)	RPD[1] (percent)	CFC-12 (pg/L)	RPD[1] (percent)	CFC-113 (pg/L)	RPD[1] (percent)
Pre-Wisconsinan till water samples									
JPG-DU-03O	04/09/08	1500	2	142.5	11.3	193.1	4.4	37.2	9.3
JPG-DU-03O	04/09/08	1500	4	100.8	23.2	198.6	7.3	38.9	13.7
JPG-DU-04O	04/15/08	0830	3	76.4	**46.7**	23.3	8.0	16.7	1.2
JPG-DU-04O	04/15/08	0830	4	70.8	**39.4**	29.3	**30.7**	16.4	3.0
JPG-DU-06O	04/15/08	1530	3	56.2	10.1	58.7	1.7	8.1	6.4
JPG-DU-09O	04/13/08	1650	3	132.0	11.3	78.5	5.8	44.9	**92.5**
JPG-DU-10O	04/13/08	1250	5	74.7	.5	77.9	4.0	23.9	**39.1**
Shallow carbonate unit samples									
JPG-DU-01I	04/10/08	0915	2	53.6	18.6	30.4	18.8	123.5	13.1
JPG-DU-02I	04/14/08	1355	3	129.0	2.0	251.3	1.1	27.6	2.5
JPG-DU-03I	04/09/08	1055	3	543.1	3.8	256.8	2.0	764.2	1.0
JPG-DU-04I	04/15/08	1015	3	66.4	21.4	35.4	12.7	58.1	.5
JPG-DU-05I	04/15/08	1315	3	502.4	3.2	299.3	2.2	181.9	7.3
JPG-DU-06I	04/20/08	1630	4	32.8	**57.3**	14.0	21.3	48.0	1.0
JPG-DU-06I	04/20/08	1630	5	19.5	6.9	13.3	16.3	49.4	3.9
JPG-DU-09I	04/14/08	0830	5	330.4	2.5	226.3	1.5	277.2	2.5
JPG-DU-10D	04/10/08	1355	5	51.3	11.8	28.2	20.4	166.9	9.9
Deep carbonate unit samples									
JPG-DU-06D	04/21/08	1115	5	399.6	13.6	265.4	19.8	772.8	5.7
JPG-DU-09D	04/14/08	1100	5	86.5	7.8	38.9	2.3	664.9	.2

[1] The RPDs were computed for the paired water sample (table 10) and sequential replicate as

$$RPD = |(SD-WS)/((SD+WS)/2)| \text{ x } 100,$$

where

RPD is the relative percent difference,
SD is the concentration in the sequential replicate, and
WS is the concentration in the water sample.

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