DOE/ID-22246

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

Geochemistry of Groundwater in the Eastern Snake River Plain Aquifer, Idaho National Laboratory and Vicinity, Eastern Idaho

Professional Paper 1837–A

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

Cover: Big Lost River, southeastern edge of the Lost River Range, and Naval Reactors Facility. Photograph by U.S. Geological Survey INL Project Office, December 6, 2017.

Geochemistry of Groundwater in the Eastern Snake River Plain Aquifer, Idaho National Laboratory and Vicinity, Eastern Idaho

By Gordon W. Rattray

DOE/ID-22246
Prepared in cooperation with the U.S. Department of Energy

Professional Paper 1837–A

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2018

Suggested citation:
Rattray, G.W., 2018, Geochemistry of groundwater in the eastern Snake River Plain aquifer, Idaho National Laboratory and vicinity, eastern Idaho: U.S. Geological Survey Professional Paper 1837–A (DOE/ID-22246), 198 p., https://doi.org/10.3133/pp1837A.

ISSN 2330-7102 (online)

Contents

Contents—Continued

Contents—Continued

Geochemistry of Surface Water and Groundwater—Continued

Temporally Variable Water Chemistry—Continued

Figures

Figures—Continued

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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 National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

Supplemental Information

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 either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of carbon-14 in water are given in percent modern carbon (pmC).

Abbreviations

ATRC	Advanced Test Reactor Complex
AVH	axial volcanic highland
BC	Birch Creek
BLR	Big Lost River
CFA	Central Facilities Area
DOE	U.S. Department of Energy
ESRP	eastern Snake River Plain
INL	Idaho National Laboratory
INEL	Idaho National Engineering Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IQR	Inner quartile range
ISU	Idaho State University Chemistry Laboratory
LLR	Little Lost River
LMWL	local meteoric water line
MFC	Materials and Fuels Complex
NAD	North American Datum or normalized absolute difference
NGL	Noble Gas Laboratory
NRF	Naval Reactors Facility
NWIS	U.S. Geological Survey National Water Information System
NWQL	U.S. Geological Survey National Water Quality Laboratory
pmC	percent modern carbon
QC	quality control
RESL	Radiological and Environmental Sciences Laboratory
RPD	relative percent difference
RSD	relative standard deviation
RWMC	Radioactive Waste Management Complex
SITL	U.S. Geological Survey Stable Isotope and Tritium Labs
STP	standard temperature and pressure
TAN	Test Area North
USGS	U.S. Geological Survey

Geochemistry of Groundwater in the Eastern Snake River Plain Aquifer, Idaho National Laboratory and Vicinity, Eastern Idaho

By Gordon W. Rattray

Abstract

Nuclear research activities at the U.S. Department of Energy (DOE) Idaho National Laboratory (INL) in eastern Idaho produced radiochemical and chemical wastes that were discharged to the subsurface, resulting in detectable concentrations of some waste constituents in the eastern Snake River Plain (ESRP) aquifer. These waste constituents may pose risks to the water quality of the aquifer. In order to understand these risks to water quality the U.S. Geological Survey, in cooperation with the DOE, conducted a study of groundwater geochemistry to improve the understanding of hydrologic and chemical processes in the ESRP aquifer at and near the INL and to understand how these processes affect waste constituents in the aquifer.

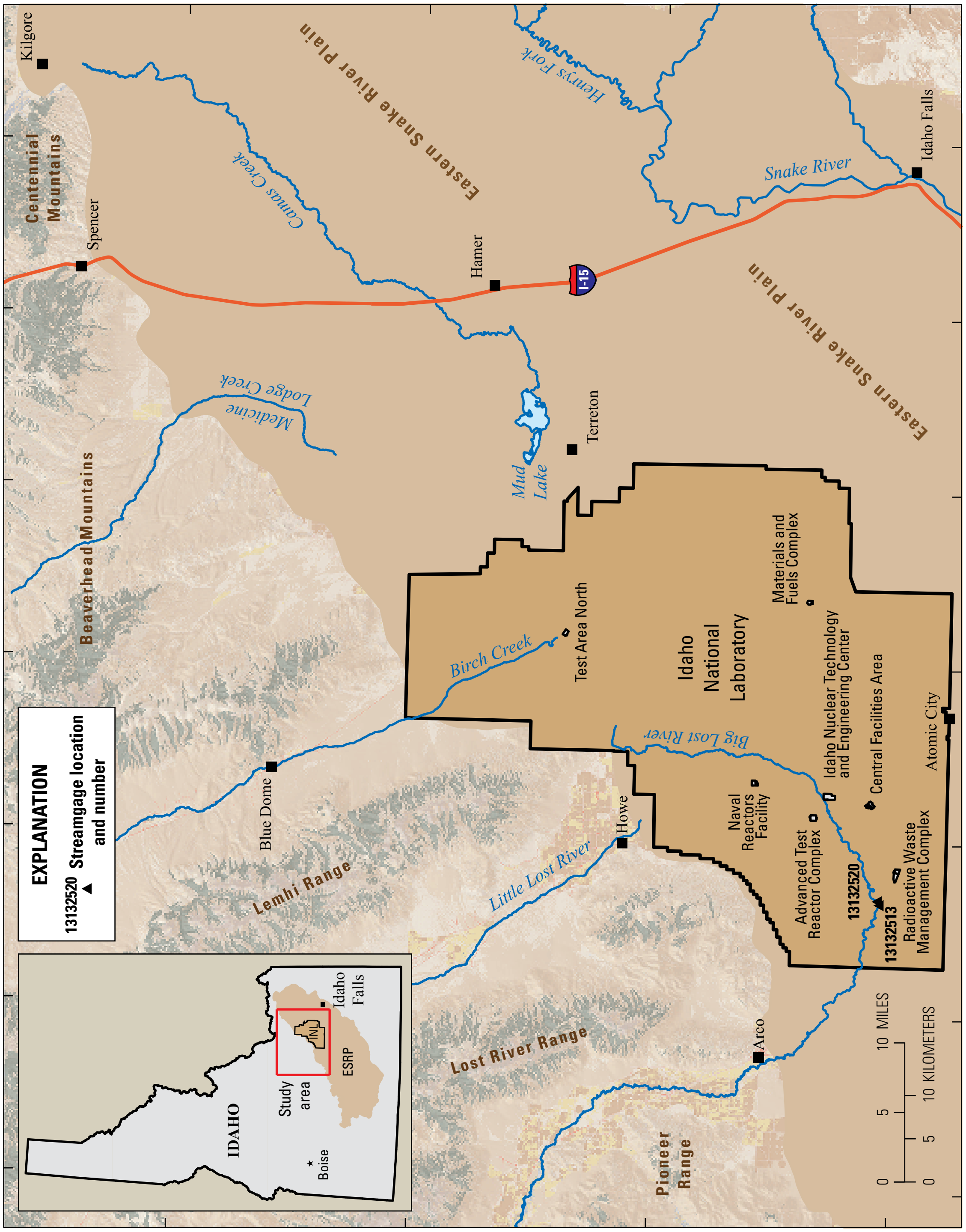
Geochemistry data were used to identify sources of recharge, mixing of water, and directions of groundwater flow in the ESRP aquifer at the INL. The geochemistry data were analyzed from 167 sample sites at and near the INL. The sites included 150 groundwater, 13 surface-water, and 4 geothermal-water sites. The data were collected between 1952 and 2012, although most data collected at the INL were collected from 1989 to 1996. Water samples were analyzed for all or most of the following: field parameters, dissolved gases, major ions, dissolved metals, isotope ratios, and environmental tracers.

Sources of recharge identified at the INL were regional groundwater, groundwater from the Little Lost River (LLR) and Birch Creek (BC) valleys, groundwater from the Lost River Range, geothermal water, and surface water from the Big Lost River (BLR), LLR, and BC. Recharge from the BLR that may have occurred during the last glacial epoch, or paleorecharge, may be present at several wells in the southwestern part of the INL. Mixing of water at the INL primarily included mixing of surface water with groundwater from the tributary valleys and mixing of geothermal water with regional groundwater. Additionally, a zone of mixing between tributary valley water and regional groundwater, trending southwesterly, extended from near the northeastern boundary of the INL to the southern boundary of the INL. Groundwater flow directions for regional groundwater were southwesterly, and flow directions for tributary groundwater were southeasterly upon entering the ESRP, but eventually began to flow southwesterly in a direction parallel with regional groundwater.

Several discrepancies were identified from comparison of sources of recharge determined from geochemistry data and backward particle tracking with a groundwater-flow model. Some discrepancies observed in the particle tracking results included representation of recharge from BC near the north INL boundary, groundwater from the BC valley not extending far enough south, regional groundwater that extends too far west in the southern part of the INL, and no representation of recharge from geothermal water in model layer 1 or recharge from the BLR in the southwestern part of the INL.

Introduction

The eastern Snake River Plain (ESRP) aquifer is an important resource for the State of Idaho because it supplies water for industry, to irrigate approximately 900,000 acres of farmland, and is the sole source of drinking water for approximately 200,000 people (Idaho Department of Environmental Quality, 2015). Nuclear research activities at the Idaho National Laboratory (INL), a U.S. Department of Energy (DOE) site established on the ESRP in eastern Idaho in 1949, produced liquid and solid radiochemical and chemical wastes that were disposed to the subsurface at various INL facilities (fig. 1). The disposal of these wastes resulted in detectable concentrations of some waste constituents in the ESRP aquifer (Davis and others, 2013).



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 1. Geographic features and facilities at the Idaho National Laboratory (INL) and vicinity, eastern Idaho.

The presence of radiochemical and chemical wastes in the ESRP aquifer may pose risks to the water quality of the aquifer, which is a concern of the State of Idaho, DOE, and the public. To understand these risks to water quality, the U.S. Geological Survey, in cooperation with the DOE, is conducting geochemistry studies, in coordination with groundwater-flow and contaminant-transport modeling, to improve the understanding of hydrologic and chemical processes in the ESRP aquifer at and near the INL and determine how these processes affect waste constituents in the aquifer.

Geochemistry studies are useful for investigating various hydrologic and chemical processes and also can provide information that may be used to evaluate, improve, and (or) calibrate groundwater-flow and contaminant-transport models. For example, inorganic chemistry data are helpful for identifying the spatial extent of similar water types and the chemical reactions occurring in the aquifer, the isotope ratios of water are useful for identifying **sources of recharge**[1] and mixing of water, and **environmental tracers** are useful for determining groundwater ages and velocities (Pearson and White, 1967; Thorstenson and others, 1979; Knobel and others, 1998; Busenberg and others, 2001; Rattray, 2015). Identifying sources of recharge, mixing of water, and groundwater flow directions and velocities in the aquifer may be possible from both an integrated analysis of all of the geochemistry data as well as using select geochemistry data as groundwater tracers (Gerla, 1992; Uliana and Sharp, 2001; Weyhenmeyer and others, 2002; Larsen and others, 2003; Plummer and others, 2004a, 2004b). Geochemistry data have been used to evaluate, improve, and (or) calibrate groundwater-flow models of the Middle Rio Grande Basin (Sanford and others, 2003; Plummer, Sanford, and others, 2004; Sanford and others, 2004), a small watershed in Wisconsin (Keating and Bahr, 1998), and the ESRP aquifer (Fisher and others, 2012) and to calibrate a groundwater-flow and contaminant-transport model of an alluvial aquifer system in Denmark (Troldborg and others, 2007).

Several geochemistry studies completed at the INL have used some combination of inorganic chemistry, isotope chemistry, environmental tracers, and the mineralogy of the aquifer to investigate the source and extent of water types (Robertson and others, 1974), the estimated ages of the **young fraction of groundwater** (Busenberg and others, 2001), and plausible chemical reactions occurring in the aquifer (Knobel and others, 1997). Several recent studies investigated the geochemistry of sources of recharge to the ESRP aquifer at the INL (Carkeet and others, 2001; Swanson and others, 2002, 2003; Ginsbach, 2013; Rattray and Ginsbach, 2014; Rattray, 2015) or investigated the presence of preferential groundwater-flow paths at the INL (Johnson and others, 2000; Luo and others, 2000; Roback and others, 2001; McLing and Roback, 2007) from ratios of strontium-87/strontium-86 ($^{87}Sr/^{86}Sr$), uranium-234/uranium-238 ($^{234}U/^{238}U$), or both.

This study was undertaken because the recent availability of the geochemical characterization of source waters to the INL and $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios provided new, valuable geochemistry data and information for understanding hydrologic and chemical processes at the INL. Possible future geochemistry studies include geochemical mass-balance modeling and identifying chemical reactions in the ESRP aquifer at the INL. The results of this, and future, geochemistry studies will be used to evaluate, and possibly calibrate, groundwater-flow and contaminant-transport models at the INL (Ackerman and others, 2010; Fisher and others, 2012).

Purpose and Scope

This study provides a comprehensive investigation of the geochemistry of surface water and groundwater in the region encompassing the mountains north and northeast of the INL and the ESRP at and east of the INL (fig. 1). The objectives of the study were to identify sources of recharge, mixing of water, and groundwater flow directions in the shallow (upper 250 feet [ft]) ESRP aquifer at the INL. The objectives of this study were achieved through analysis of a comprehensive suite of geochemistry data (inorganic, isotopic, and environmental tracer) and of the land use, geology, and hydrology of the study area.

The geochemistry data compiled for this report represent a large number of water samples collected from sites at and near the INL. This compilation is more comprehensive and encompasses a larger spatial area (including all suspected areas of source water) than previous studies that investigated the geochemistry of **groundwater at the INL** (Olmsted, 1962; Robertson and others, 1974; Busenberg and others, 2001). The data were compiled from existing data, include water-quality data collected from 167 sample sites, and were from water samples collected between 1952 and 2012. Data include measured or calculated values for field parameters (temperature, pH, specific conductance, and alkalinity); dissolved gases (dissolved oxygen [DO], carbon dioxide [CO_2], and helium [He]); major ions (calcium [Ca], magnesium [Mg], sodium [Na], potassium [K], bicarbonate [HCO_3], carbonate [CO_3], chloride [Cl], sulfate [SO_4], fluoride [F], and nitrate [NO_3]); silica [SiO_2]; dissolved metals (aluminum [Al], barium [Ba], boron [B], chromium [Cr], iron [Fe], lithium [Li], manganese [Mn], strontium [Sr],

---

[1] Definitions of sources of recharge and other selected terms used in this report are in the "Glossary".

and uranium [U]); isotope ratios[2] (hydrogen-2/hydrogen-1 [δ^2H],[3] oxygen-18/oxygen-16 [$\delta^{18}O$], carbon-13/carbon-12 [$\delta^{13}C$], sulfur-34/sulfur-32 [$\delta^{34}S$], nitrogen-15/nitrogen-14 [$\delta^{15}N$], helium-3/helium-4 [δ^3He], strontium-87/strontium-86 [$^{87}Sr/^{86}Sr$], and uranium-234/uranium-238 [$^{234}U/^{238}U$]); and environmental tracers (tritium [^3H], terrigenic helium [He_{terr}], chlorofluorocarbon-11 [CFC-11], chlorofluorocarbon-12 [CFC-12], chlorofluorocarbon-113 [CFC-113], sulfur hexafluoride [SF_6], tritium/helium-3 [$^3H/^3He$][4], and carbon-14 [^{14}C]).

Previous Investigations

Several previous geochemical studies included interpretations of the sources of groundwater in the ESRP aquifer at the INL. In a study of the physical and chemical character of groundwater at the INL, Olmsted (1962) noted that Na, K, and SiO_2 concentrations in groundwater from the northwestern part of the INL were smaller than concentrations of these constituents in groundwater from the southeastern part of the INL. Olmsted proposed that the concentrations of these constituents reflect different water-rock interaction in the groundwater source areas; small concentrations result from reaction with carbonate rocks in the Little Lost River (LLR) and Birch Creek (BC) drainage basins northwest of the INL (type A groundwater) and large concentrations result from reaction with silicic volcanic rocks in the Beaverhead and Centennial Mountains north and northeast of the INL (type B groundwater; Olmsted, 1962, p. 37–38). Olmsted (1962, p. 39) also noted that a top layer of dilute groundwater (as much as 50 ft thick) may reflect infiltration of precipitation and local runoff on the plain and that groundwater in the eastern part of the INL with larger dissolved solids and Cl and smaller HCO_3 concentrations was derived from return flow of irrigation water from the Mud Lake area northeast of the INL (fig. 1).

Schoen (1972) and Robertson and others (1974) evaluated the chemical composition of groundwater at the INL, the chemical composition of potential recharge, and water-rock interaction in potential areas of source water. Like Olmsted (1962), they determined that groundwater in the northwestern part of the INL was chemically distinct from groundwater in the southeastern part of the INL. They suggested that groundwater in the northwestern part of the INL was recharged with Ca-Mg-HCO_3 water from tributary valleys northwest of the INL and that groundwater in the southeastern part of the INL was recharged with Ca-Na-HCO_3 groundwater (with relatively high F, SO_4, and SiO_2 contents) originating in mountains to the northeast. Schoen (1972) and Robertson and others (1974) also suggested that a narrow zone of mixing of the two water types extended northeast to southwest approximately bisecting the INL, that thermal water may contribute small amounts of recharge to the aquifer, and that irrigation water could be recognized by high water temperature, high dissolved-solids content, and high levels of fertilizer-based constituents such as NO_3. Mann (1986), McLing and others (2002), and Rattray (2015) suggested that a small amount of recharge at or adjacent to the INL may be from **geothermal water** upwelling from below the ESRP aquifer.

In studies estimating the age of the young fraction of groundwater at the INL, Busenberg and others (1993, 2001) evaluated the sources of groundwater from concentrations of F, Li, dissolved gases (including calculated groundwater recharge temperatures and concentrations of He_{terr}), and ^3H. They showed that Li concentrations in groundwater were smaller in the northwestern than the southeastern part of the INL and, similar to other geochemical methods used by Olmsted (1962), Schoen (1972), and Robertson and others (1974), were useful for identifying recharge from water originating in tributary valleys to the northwest and recharge from underflow of **regional groundwater** from the northeast. Recharge temperatures, He_{terr}, and ^3H were used to identify tributary and regional water as well as areas where recharge from precipitation may have occurred. Concentrations of He and F were used by Busenberg and others (2001, p. 70–73) to define three groundwater types at the INL:

1. Groundwater in the western part of the INL that contained small concentrations of He (near air-water saturation) and F and that represents recharge from tributary valleys northwest of the INL;
2. Groundwater in the northeastern part of the INL that contained large concentrations of He (more than three times air-water saturation) and F and that represents recharge of regional groundwater northeast of the INL; and
3. Groundwater in the southeastern part of the INL that contained moderate concentrations of He (as much as three times air-water saturation) and large concentrations of F, and that represents recharge of regional groundwater east of the INL.

---

[2] Isotope ratios were measured from water (δ^2H and $\delta^{18}O$), dissolved inorganic carbon ($\delta^{13}C$), sulfate ($\delta^{34}S$), and nitrate ($\delta^{15}N$).

[3] The delta (δ) notation for isotope ratios, and most other equations used in this report, are described in appendix 2 (eq. 2-2).

[4] Helium-3 and carbon-14 are radioactive isotopes used for dating groundwater (Clark and Fritz, 1997). CFCs, SF_6, and $^3H/^3He$ were used to estimate the age of the young fraction of groundwater (Busenberg and others, 2001).

Additionally, flow velocity vectors for groundwater were produced by Busenberg and others (2001, fig. 25) for the western part of the INL from $^3H/^3He$ ages of groundwater and the probable locations of recharge.

Geochemical mass-balance and mixing models were used by McLing (1994) and Schramke and others (1996) to identify sources of water at the INL. McLing modeled a north-to-south flow path extending across the INL using the chemistry of surface water from BC and groundwater from the Atomic City well as flow-path end members. A successful mixing model, with limited water-rock interaction (primarily precipitation of calcite and cation exchange), was generated that included surface water from BC, regional groundwater (referred to as Mud Lake water), and geothermal water (Heise Hot Springs, about 40 miles [mi] east of the INL) as sources of water at the Atomic City well. Schramke and others (1996) created models of two north-to-south flow paths, with the paths originating at wells near the mouths of the LLR or BC drainage basins and terminating at wells in the central part of the INL. Their most reasonable models included some water-rock interaction (primarily precipitation of calcite and montmorillonite and dissolution of silica, plagioclase, halite, and kaolinite) and mixing of surface water from the Big Lost River (BLR) and the LLR and groundwater from the LLR and BC drainage basins.

The geochemistry and evolution of groundwater recharging the INL from the north and east were investigated in several studies using geochemical mass-balance models. Geochemical mass-balance models of the BLR (north of Arco), LLR, and BC drainage basins (fig. 2) were developed by Carkeet and others (2001) and Swanson and others (2002, 2003). Groundwater in all these drainage basins was a Ca-Mg-HCO_3-type water. Results from the geochemical mass-balance models indicated that the chemistry of the groundwater was controlled primarily by carbonate reactions and, at some wells, silicate reactions, dissolution of gypsum/anhydrite, and dissolution of fertilizer from nearby agriculture. The geochemistry of the Camas and Medicine Lodge Creek drainage basins, which includes the southern parts of the Beaverhead and Centennial Mountains and the ESRP east of the INL (including the Mud Lake area), was investigated by Ginsbach (2013), Rattray and Ginsbach (2014), and Rattray (2015). Non-geothermal groundwater from the mountains was either a Ca-HCO_3 or a Ca-Mg-HCO_3 type water. Groundwater from the ESRP was a Ca-Mg-HCO_3-type water or, if from the Mud Lake area, was various combinations of Ca-, Mg-, and (or) Na-HCO_3-type water and one Ca-Cl-HCO_3-type water. Geochemical mass-balance modeling indicated that the chemistry of groundwater in the (1) mountains was controlled by carbonate and silicate reactions plus dissolution of gypsum; (2) ESRP east of the Mud Lake area was controlled by these reactions plus dissolution of halite and cation exchange; and (3) ESRP in the Mud Lake area was controlled by carbonate, silicate, and redox reactions, dissolution of evaporite minerals and fertilizer, and cation exchange.

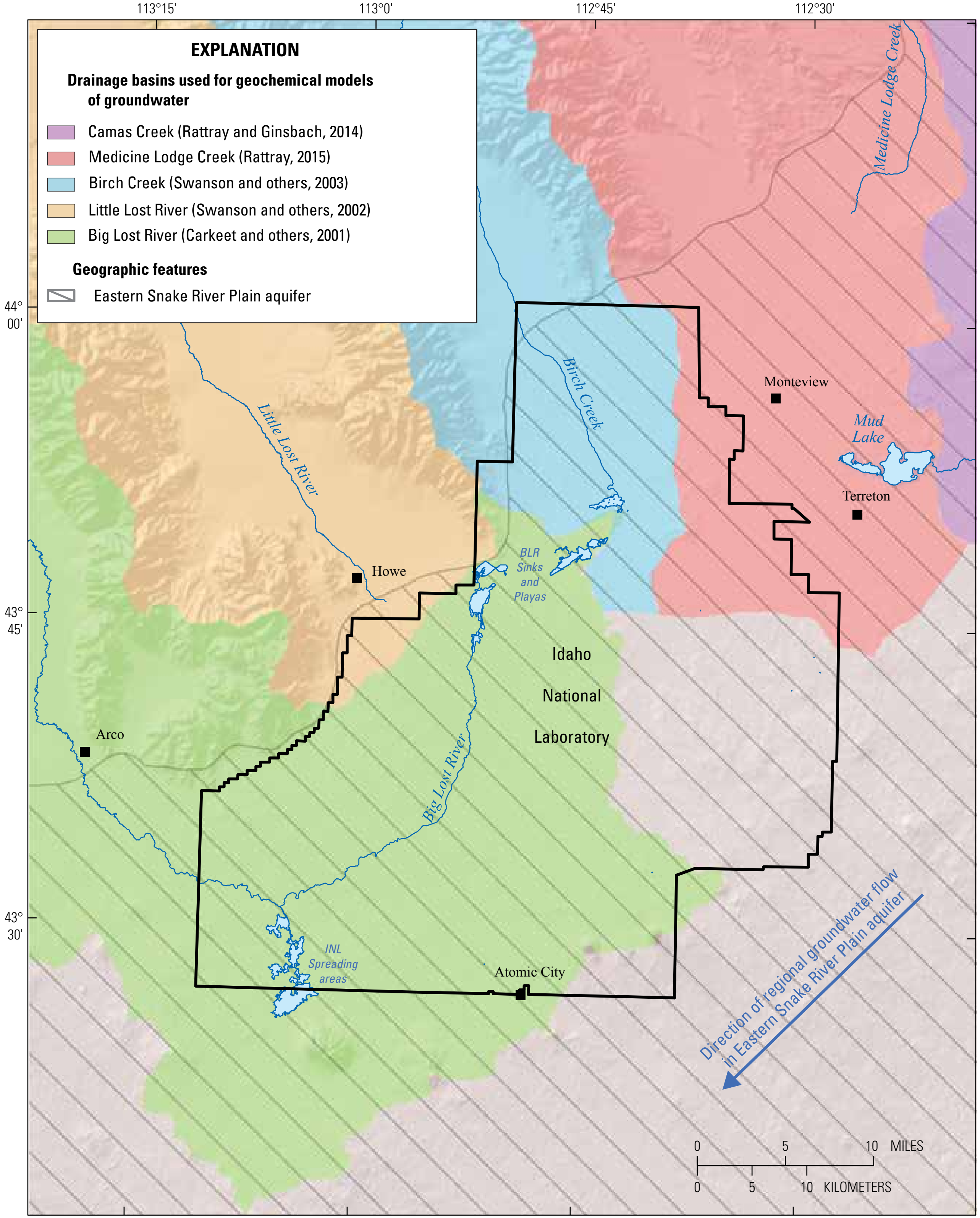
Studies by Johnson and others (2000), Luo and others (2000), Roback and others (2001), and McLing and Roback (2007) used the radioisotopes of uranium, thorium, radium, radon, and (or) strontium to understand water-rock interaction and the age, flow directions, and sources of groundwater at the INL. Conclusions from these studies were that dissolution rates of basalt were about 70–800 milligrams per liter per year ([mg/L]/yr), that the age of groundwater ranged from less than 10–100 years, that preferential flow paths extended south-southeast from the LLR and BC valleys, and that stagnant flow zones were present in the central and western parts of the INL.

The direction of groundwater flow in the aquifer was inferred in numerous reports from the direction of movement of wastes discharged to the aquifer (Mann and others, 1988; Mann and Cecil, 1990; Mann and Beasley, 1994; Sorenson and others, 1996; Bartholomay, 2009, 2013; Davis and others, 2013). The movement of wastes indicated that the direction of groundwater flow was generally south-southeast near Test Area North (TAN, fig. 1) and south-southwest in the southwestern part of the INL.

Description of Study Area

Geography, Climate, and Land Use

The study area encompasses approximately 5,000 square miles (mi^2) of eastern Idaho (fig. 1). The southeastern part of the study area includes the 890-mi^2 INL and includes approximately 2,200 mi^2 of the ESRP, which is a relatively flat topographic depression. The northwestern part of the study area includes approximately 2,800 mi^2 of the rugged, north- to northwest-trending mountains of the Pioneer, Lost River, and Lemhi Ranges and the Beaverhead Mountains. The mountains are bisected by the BLR, LLR, and BC valleys. Altitudes range from a low of about 4,800 ft at the BLR sinks and Mud Lake to a maximum of 12,655 ft in the Lost River Range (figs.1 and 2).



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 2. Drainage basins adjacent to the Idaho National Laboratory where the chemistry of groundwater was investigated with geochemical mass-balance models, eastern Idaho.

The climate is semi-arid on the ESRP and continental in the mountains. Mean annual temperatures and mean annual precipitation are 5.7 °C and 8.4 inches (in.) at the INL on the ESRP (period of record 1950–2014, National Oceanic and Atmospheric Administration, 2015) and about 0.0–2.2 °C and 32–36 in. (mostly as snow) in the higher areas of the mountains (period of record 1981–2010; Prism Climate Group [2015]).

Land use and cover in the mountains and valleys is forest or bare rock at higher elevations, shrub and grassland in the valleys, with extensive irrigated agriculture (as indicated by the distribution of cultivated crops in figure 3) in the BLR and LLR valleys, particularly in the lower parts of the valleys, and minimal irrigated agriculture in the BC valley (fig. 3). Land cover on the ESRP is primarily shrub, bare rock, and grassland, with areas of irrigated agriculture east of the INL and wetlands within the Mud Lake Wildlife Management Area and Camas National Wildlife Refuge (fig. 3*B*). At the INL, land use includes industrial facilities and waste disposal areas, such as wastewater infiltration or evaporation ponds, wastewater ditches, and waste burial sites (Davis and others, 2013).

Geology

The geology of the study area can be divided into mountainous terrain and the ESRP, which are part of the northern Basin and Range province and the Snake River Plain-Yellowstone Plateau volcanic province (Link and Janecke, 1999; Morgan and McIntosh, 2005), respectively. The western Centennial Mountains[5] (fig. 1) are included in the geologic discussion of the mountains because much of the groundwater northeast of the INL originates in these mountains. Sediment overlies rocks of these provinces throughout much of the study area (Lewis and others, 2012).

Mountains

The mountains are largely composed of Paleozoic and Mesozoic miogeosynclinal sedimentary rocks (uplifted during basin and range tectonism) with some Tertiary intermediate and silicic volcanic rocks (the Challis Volcanic Group and the Heise volcanic field) and Quaternary sediments (fig. 4; Link and Janecke, 1999). The miogeosynclinal rocks consist primarily of marine limestone and dolostone, but also include marine and continental sandstone, shale, siltstone, mudstone, quartzite, chert, conglomerate, and phosphorite (Lewis and others, 2012). The Challis Volcanic Group is comprised of rhyolite, dacite, and andesite, the Heise volcanic field is composed of rhyolite, and the sediments are largely alluvial deposits of gravel, sand, and silt (Lewis and others, 2012) composed of quartz, feldspar, calcite, clays, dolomite, pyroxene, and biotite (Bartholomay and others, 1989; Bartholomay and Knobel, 1989).

There are significant differences in the geology of the mountain ranges, even though the mountains are largely composed of Paleozoic carbonate rocks (Lewis and others, 2012). The core of the Pioneer Range is composed of Paleozoic carbonate rocks, but much of these carbonate rocks are overlain by Tertiary volcanic rocks from the Challis Volcanic Group (Crosthwaite and others, 1970). The Lost River Range also is largely composed of Paleozoic carbonate rocks, but includes Paleozoic and Cenozoic sandstone, shale, mudstone, and chert, and Tertiary volcanic rocks from the Challis Volcanic Group. The Lemhi Range and the western part of the Beaverhead Mountains (Skipp and others, 1979; Abplanalp and others, 2008) have a similar geology as the Lost River Range, but also include Proterozoic and Paleozoic quartzite and Tertiary rhyolite from the Heise volcanic field. The central and eastern parts of the Beaverhead Mountains and the western Centennial Mountains have a core of Paleozoic carbonate rocks (almost entirely overlain by Mesozoic and Cenozoic sandstone, shale, mudstone, and chert), Tertiary rhyolite from the Heise volcanic field, and small amounts of Tertiary volcanic rocks from the Challis Volcanic Group (Kirkham, 1927; Stearns and others, 1939; Witkind, 1980).

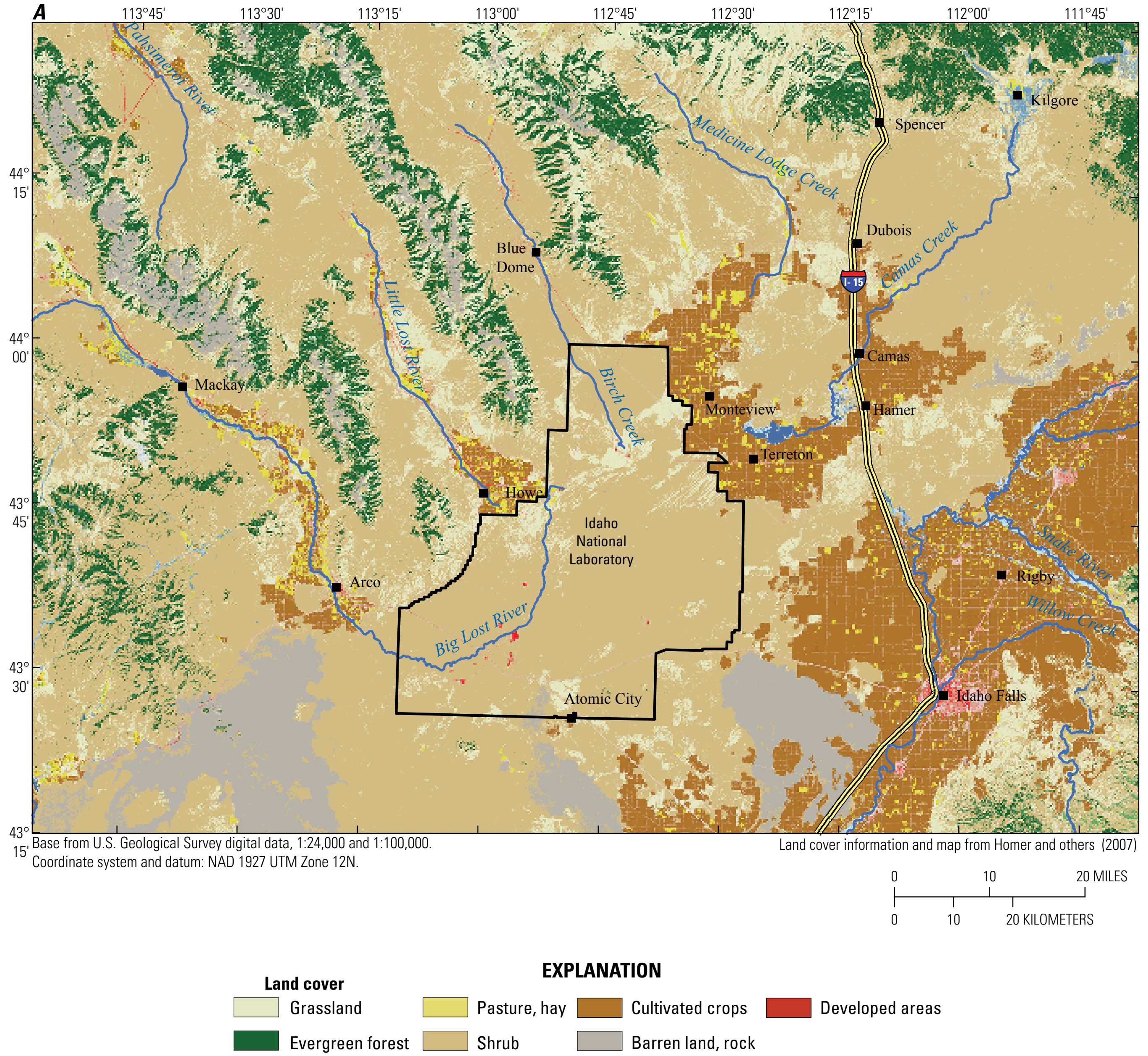
Eastern Snake River Plain

The ESRP is a bimodal volcanic province in which massive eruptions of rhyolites were followed by voluminous eruptions of basalt. On the ESRP in the vicinity of the INL, these eruptions resulted in late Tertiary–early Quaternary rhyolites that are overlain by a thick accumulation of numerous subhorizontal Quaternary basalt flows (Ackerman and others, 2006) plus surficial and interbed sediments (fig. 4; Doherty and others, 1979; Anderson and Liszewski, 1997). Interbed sediments are located in interflow zones that consist of the highly fractured basalt and rubble at the top of the underlying basalt flow, the base of the overlying basalt flow, and any interbed sediment between the basalt flows (Whitehead, 1992; Welhan, Johannesen, and others, 2002).

Rhyolite is composed primarily of glass, potassium feldspar, plagioclase, quartz, opaque oxides, and pyroxene with lesser amounts of apatite and biotite and basalt is composed primarily of plagioclase, olivine, pyroxene, and iron oxide with lesser amounts of apatite and glass (Nace and others, 1956; Bartholomay and others, 1989; Knobel and others, 1997; Morgan and McIntosh, 2005; Rattray and Ginsbach, 2014). Surficial and interbed sediments were deposited by alluvial, eolian, fluvial, and lacustrine processes.

---

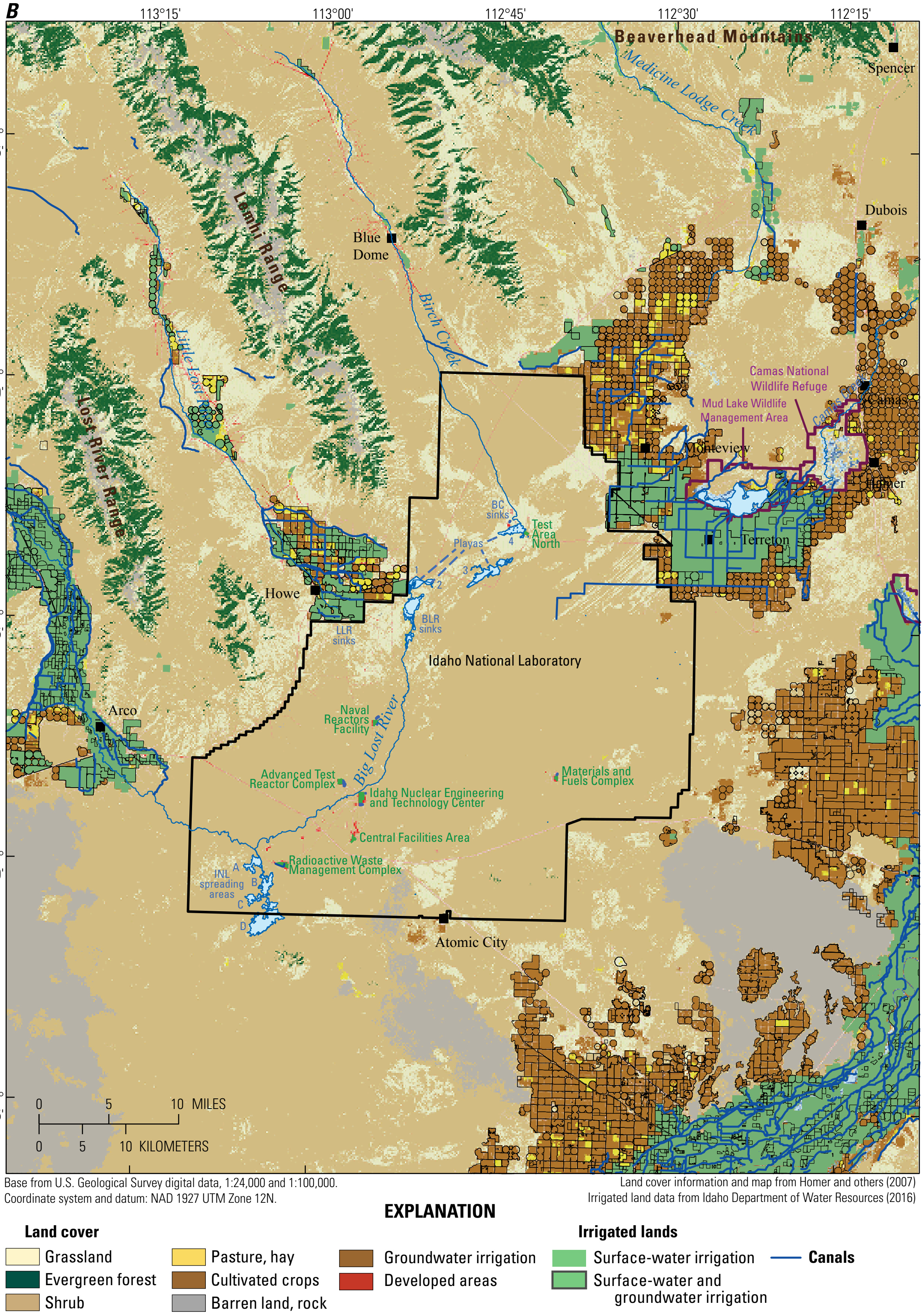
[5] As defined by Witkind (1980).



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Land cover information and map from Homer and others (2007)

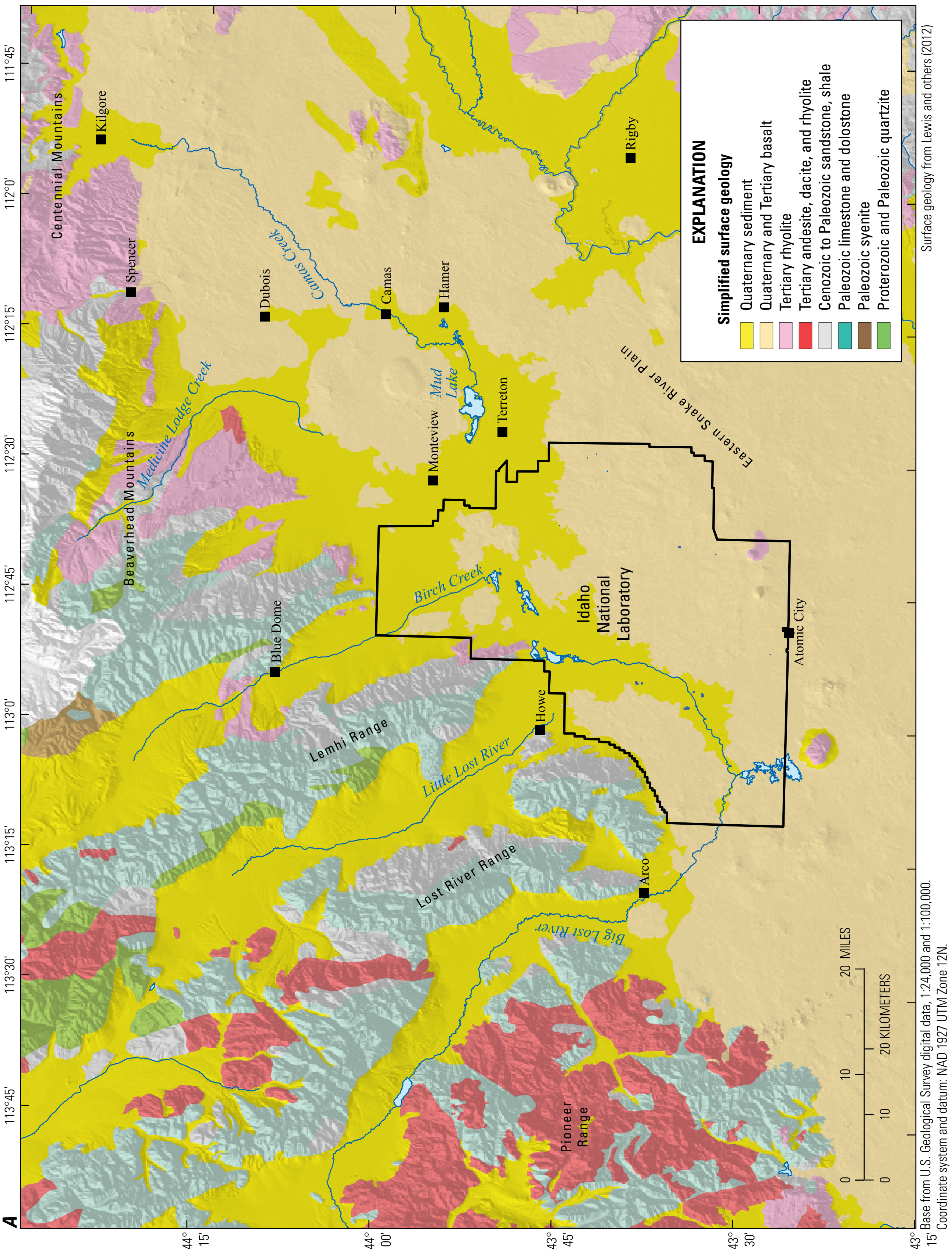
Figure 3. Land cover and use at the Idaho National Laboratory (INL) and vicinity, eastern Idaho. (*A*) Land use and cover throughout the study area. (*B*) Land use and cover, highways, canals, surface-water features, and industrial facilities at the INL and vicinity.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Land cover information and map from Homer and others (2007)
Irrigated land data from Idaho Department of Water Resources (2016)

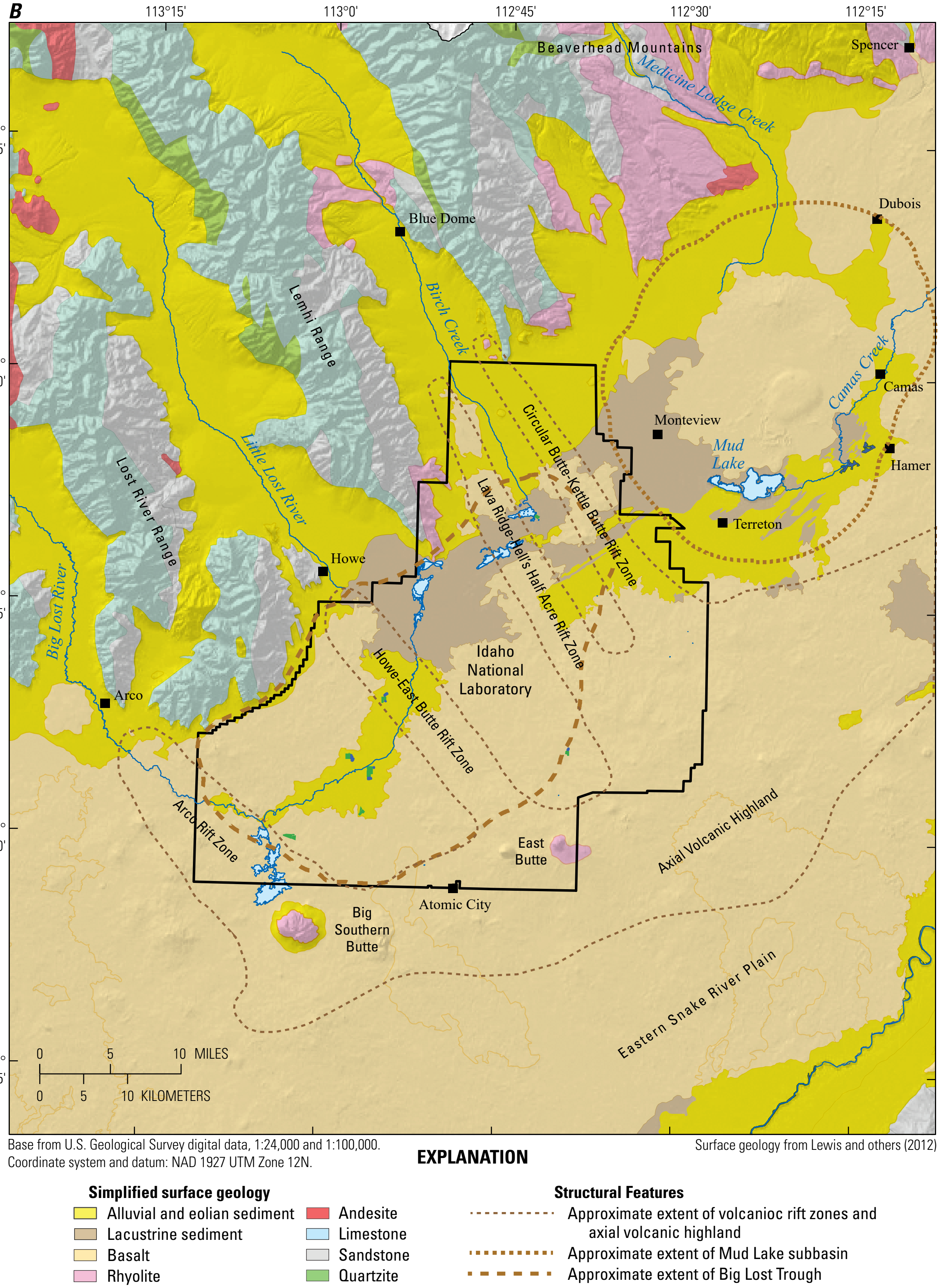
Figure 3.—Continued



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Surface geology from Lewis and others (2012)

Figure 4. Surface geology at the Idaho National Laboratory (INL) and vicinity, eastern Idaho. (*A*) Surface geology throughout the study area. (*B*) Surface geology, Big Lost Trough, Mud Lake subbasin, Axial Volcanic Highland, rift zones, and rhyolitic buttes at the INL and vicinity.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Surface geology from Lewis and others (2012)

Figure 4.—Continued

These sediments consist of gravel, sand, silt, and clay (Nace and others, 1975) and are composed primarily of quartz, calcite, feldspar, clays, pyroxene, dolomite, and biotite (Bartholomay and others, 1989; Bartholomay and Knobel, 1989; Reed and Bartholomay, 1994). Gypsum observed in some lacustrine sediments (fig. 4*B*) may indicate that evaporite deposits are locally present (Blair, 2002; Geslin and others, 2002).

Structural features in the ESRP (fig. 4*B*) include (1) the Axial Volcanic Highland (AVH), a broad linear topographic highland trending southwest-to-northeast formed from the accumulation of lava flows from basaltic volcanoes centered along the AVH and uplift associated with emplacement of rhyolite domes (Kuntz and others, 1992); (2) volcanic rift zones, which are broad belts of focused volcanism that generally trend northwestward and are perpendicular to the AVH and the direction of regional ground-water flow (figs. 2 and 4*B*) (Kuntz and others, 1992); (3) vent corridors, which are narrow zones in and near volcanic rift zones that contain known or inferred volcanic vents, dikes, and fissures (Anderson and others, 1999); (4) caldera boundaries and (potentially) buried faults (Ginsbach, 2013); and (5) the Big Lost Trough and Mud Lake subbasins, long-lived sedimentary basins that encompassed Pleistocene Lake Terreton (Gianniny and others, 2002).

Hydrology

Surface Water

Surface water at and near the INL includes the BLR, LLR, BC, Camas Creek, and Mud Lake. There are also several man-made water conveyance, wastewater discharge, and flood control structures at and near the INL, such as irrigation canals, wastewater ponds and ditches, and the INL spreading areas (fig. 3*B*).

The streams originate in the mountains northwest (BLR), north (LLR, BC), and northeast (Camas Creek) of the INL and typically are perennial in the mountain valleys and ephemeral on the ESRP. Much of the flow in the BLR and LLR, and most of the flow in BC, arises from groundwater inflow (Mundorff, 1962; Mundorff and others, 1963; Crosthwaite and others, 1970). Annual discharge in the BLR (fig. 5), LLR, and Camas Creek varies significantly depending on the amount of annual precipitation in the surrounding mountains (Mundorff and others, 1963; Ackerman and others, 2006; U.S. Geological Survey, 2014), but annual discharge in BC is relatively uniform because most of the flow is from groundwater inflow (Mundorff, 1962).

Water from all these streams is diverted for irrigation, with large amounts of water diverted for irrigation throughout the BLR and LLR valleys, from BC to the ESRP north of the INL, and on the ESRP from Camas Creek (fig. 3). Small amounts of water from BC and the LLR frequently flowed onto, or adjacent to, the INL and terminated in sinks and playas in either the northern part of, or just north of, the INL (Mundorff and others, 1963; Kjelstrom and Berenbrock, 1996; Swanson and others, 2003). During wet years (that is, years with above average precipitation) large amounts of water from the BLR flowed onto the INL and occasionally reached playa 4 (figs. 3*B* and 5) (Bennett, 1990). Camas Creek generally flows as far as Camas (fig. 3) in spring and flows into Mud Lake during wet years.

Beginning in 1965, water from the BLR began to be diverted to the INL spreading areas in the southwestern corner of the INL (figs. 3*B* and 5) (Mundorff and others, 1963; Crosthwaite and others, 1970; Bennett, 1990; Kjelstrom and Berenbrock, 1996), and since 1969, no water from BC has reached the BC sinks or playa 4 (fig. 3) because of construction of diversion channels used to divert most of the water north of the INL for power or irrigation (although some water is diverted to gravel pits on the INL northeast of playa 4) (Kjelstrom and Berenbrock, 1996; Bennett, 1990). Some water from the BLR reaching the ESRP is lost to evaporation, but most of the water recharges the ESRP aquifer by infiltrating through the river channel, sinks, playas, and spreading areas (Bennett, 1990). Rates of infiltration are variable and depend on pressure head and the permeability of geologic materials in the unsaturated zone. However, rapid vertical and horizontal flow of infiltrating water may occur in localized areas, such as the BLR sinks and the INL spreading areas, when a significant amount of water is available for infiltration through permeable geologic materials (Nimmo and others, 2002).

Sources of water at Mud Lake are streamflow from Camas Creek, groundwater inflow, and pumped groundwater. Discharge from Mud Lake occurs as evapotranspiration, water transported through canals to irrigate land on the ESRP northeast of the INL, and seepage through the lakebed (Spinazola, 1994).

Wastewater ponds are present at the Advanced Test Reactor Complex (ATRC), Idaho Nuclear Technology and Engineering Center (INTEC), Materials and Fuels Complex (MFC), and TAN and wastewater ditches are present at the MFC and the Naval Reactors Facility (NRF) (Davis and others, 2013). Most wastewater in the ditches and evaporation or infiltration ponds at the INL originates as groundwater pumped from the ESRP aquifer (precipitation runoff also may provide some water to ditches and ponds), and discharge from the ponds is from evaporation or downward infiltration.

Groundwater

Aquifers in the study area include alluvial aquifers in the BLR, LLR, and BC valleys and the basalt aquifer underlying the ESRP. The alluvial aquifers are homogeneous and unconfined and are recharged by groundwater inflow from adjacent mountains and infiltration of precipitation, streamflow, and irrigation water. Discharge from the alluvial aquifers is through consumptive use for domestic and agricultural use and groundwater outflow to the ESRP aquifer.

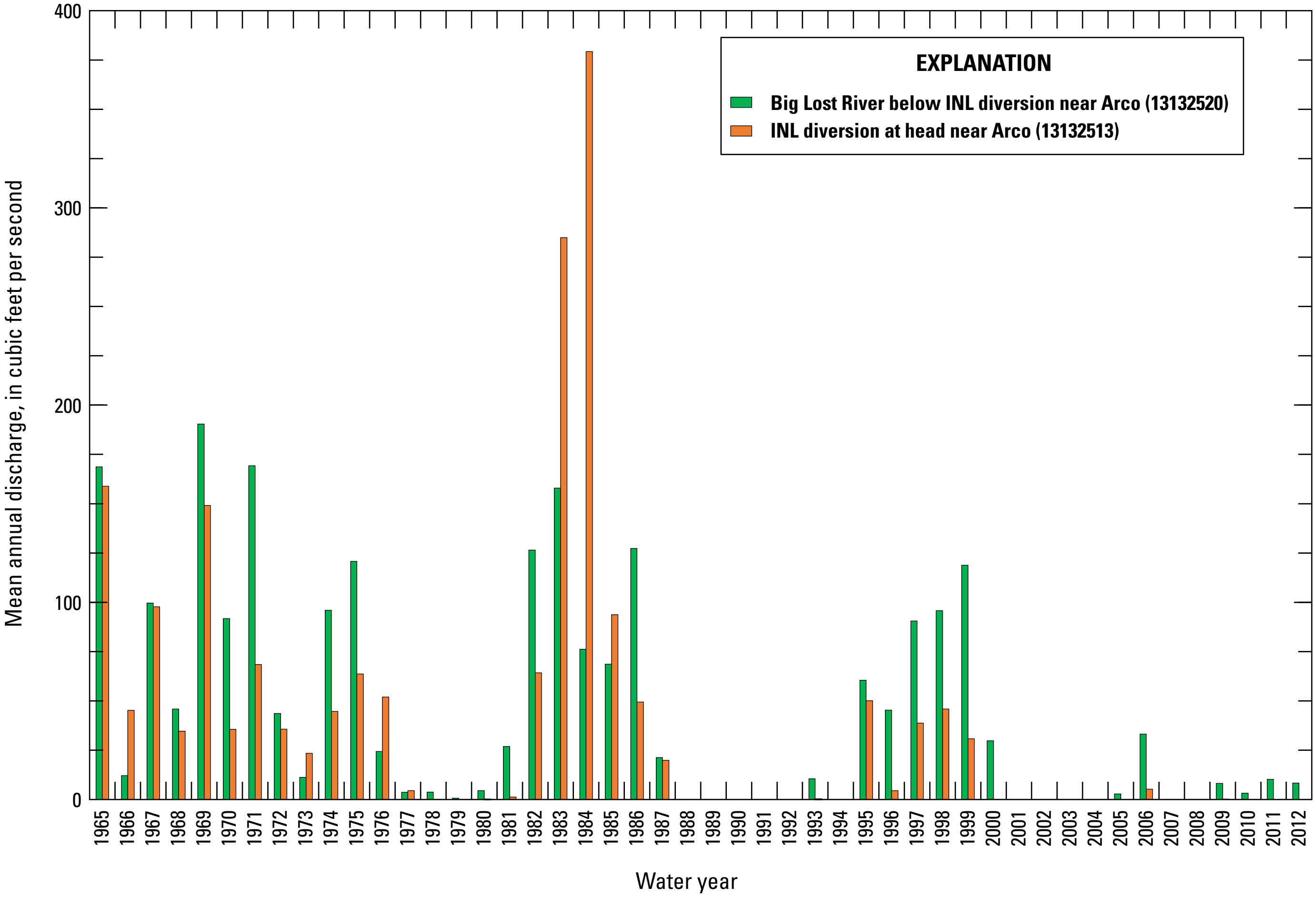


Figure 5. Mean annual discharge of the Big Lost River and INL diversion at the Idaho National Laboratory, eastern Idaho. Streamgage locations are shown in figure 1.

The ESRP aquifer at and near the INL is a heterogeneous, unconfined, fractured-basalt aquifer. The aquifer thickness ranges from several hundred to several thousand feet, the thickness of the unsaturated zone ranges from about 200 to 1,000 ft, and the thickness of both the aquifer and unsaturated zone generally increase in a north-to-south direction (Whitehead, 1992; Ackerman and others, 2006; Bartholomay and others, 2017). The aquifer includes hundreds of interfingered layers of basalt and sediment, with the thickness of individual basalt flows estimated to range from 2 to 100 ft (Anderson and Liszewski, 1997). Most groundwater flow in the aquifer is horizontal and occurs in the rubble- and sediment-filled interflow zones between basalt flows (Whitehead, 1992), although dikes associated with volcanic rift zones and vent corridors may impede horizontal flow (Anderson and others, 1999). Upward and downward vertical groundwater movement occurs in the aquifer (Mann, 1986; Ackerman and others, 2006), but significant vertical movement is probably constrained to areas where vertical fractures are abundant (Whitehead, 1992) or vertically oriented fissures and dikes associated with volcanic rift zones or vent corridors are present. Fissures and dikes that extend to significant depths may facilitate the upward movement of geothermal water (Anderson and others, 1999) through rhyolite and basalt.

Recharge to the ESRP aquifer in the vicinity of the INL occurs as underflow of regional groundwater from the ESRP aquifer northeast of the INL (Ackerman and others, 2006), groundwater underflow from the alluvial aquifers in the tributary valleys (Mundorff and others, 1963; Crosthwaite and others, 1970; Kjelstrom and Berenbrock, 1996), infiltration from the BLR, LLR, BC, precipitation, irrigation water, and Mud Lake (Bennett, 1990; Spinazola, 1994; Ackerman and others, 2006), wastewater discharge (Davis and others, 2013), and upward flow of geothermal water across the base of the aquifer (Mann, 1986; McLing and others, 2002; Rattray, 2015). A small amount of recharge may occur as groundwater underflow from the mountain fronts of the Lost River Range, Lemhi Range, and Beaverhead Mountains (Ackerman and others, 2006).

Estimates of 1980 recharge rates to the ESRP aquifer at the INL (for the area of a groundwater-flow model at and near the INL; Ackerman and others, 2006) indicate that regional underflow of groundwater contributes the most recharge (1,225 cubic feet per second [ft^3/s]), followed by groundwater underflow from the BLR (367 ft^3/s), LLR (226 ft^3/s), and BC (102 ft^3/s) valleys and total recharge from irrigation (120 ft^3/s; table 1). Most recharge from irrigation occurs in the Mud Lake area northeast of the INL (fig. 3*B*). Recharge from infiltration of the BLR (95 ft^3/s) is locally important because of the episodic and spatially concentrated nature of the recharge (Ackerman and others, 2006), with significant amounts of recharge at the INL spreading areas, BLR sinks, and BLR playas (Bennett, 1990). Recharge from infiltration of precipitation (80 ft^3/s) is spatially diffuse and generally contributes only a minimal amount of recharge to the aquifer at any location (Ackerman and others, 2006), although recharge from precipitation may be locally important in small basins where precipitation may collect or in areas of bare basalt where precipitation may infiltrate rapidly (Garabedian, 1992; Busenberg and others, 2001). Recharge from upward flow of geothermal water (50 ft^3/s), infiltration from Mud Lake (15 ft^3/s), and wastewater discharge (6 ft^3/s) is small, but may be important locally due to the concentrated areas of this recharge (Spinazola, 1994; Anderson and others, 1999; Davis and others, 2013; Rattray, 2015).

Perched groundwater zones have formed beneath the ATRC, INTEC, and Radioactive Waste Management Complex (RWMC) due to localized infiltration of water from the BLR and wastewater infiltration ponds and low permeability geologic materials impeding the downward movement of water (Cecil and others, 1991; Bartholomay and Tucker, 2000; Davis and others, 2013). Perched water zones persist as long as the source of the infiltrating water remains; when the source of infiltrating water is removed, the perched water zone dissipates (Davis and others, 2013).

Water-table contours for April 1989[6] for the ESRP aquifer (fig. 6), interpolated from 481 water-level measurements (405 of the measurements were made in April; appendix 1, table 1-1) using the natural neighbor technique (Sibson, 1981), indicate that groundwater in the aquifer generally flows south and southwest across the INL and that hydraulic gradients are relatively flat throughout the INL and relatively steep along the northwestern and northeastern boundaries of the INL and southwest of the INL. The steep hydraulic gradient northeast of the INL may reflect a decrease in hydraulic conductivity due to deposition of fine-grained sediments along the boundary of the Mud Lake subbasin (Ackerman and others, 2006) or impermeable volcanic structures associated with volcanic rift zones (fig. 4*B*) or vent corridors (Kuntz and others, 1992; Anderson and others, 1999; Kuntz and others, 2002).

Temporal, local changes to the water table occur at the INL. In the western part of the INL the water table rises or declines non-uniformly due to either episodic, or a lack of, infiltration from the BLR in response to short-term (3–8 years) wet or dry climate cycles (Ackerman and others, 2006). In the eastern part of the INL the water table fluctuates seasonally (Bartholomay and Twining, 2015) in response to pumping of groundwater for irrigation (throughout the Mud Lake area) and infiltration of surface water used for irrigation (west and south of Mud Lake; fig. 3*B*) (Idaho Department of Water Resources, 2016).

Porosity of the fractured basalts ranged from 0.05 to 0.27 percent, although these values were dependent on scale and the methods used to determine them (Ackerman and others, 2006). However, porosity and permeability generally are small in the massive interiors of basalt flows and large in the interflow zones (Welhan, Clemo, and Grego, 2002; Welhan, Johannesen, and others, 2002; Ackerman and others, 2006). Hydraulic conductivities (K) estimated from single-well aquifer tests indicate that the aquifer has extreme heterogeneity in K, with K ranging more than six orders of magnitude (log K of -2.00 to 4.38 ft/d; fig. 7).

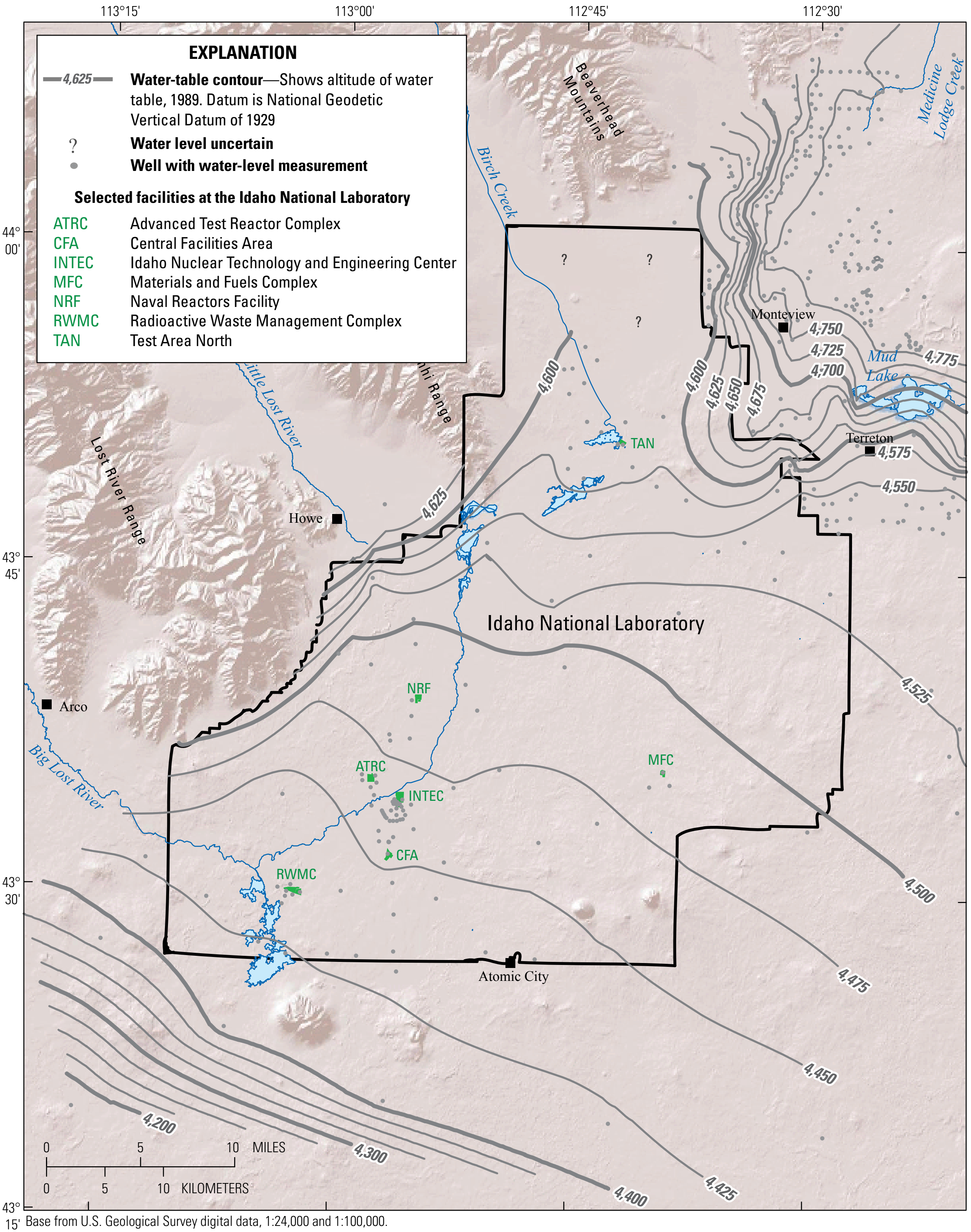
Table 1. Estimated rates of recharge to the eastern Snake River Plain aquifer for selected water-budget components, Idaho National Laboratory and vicinity, eastern Idaho, 1980.

[Estimated rates of recharge are from Ackerman and others (2006), Spinazola (1994), or were estimated using methods described in Ackerman and others (2006). ft^3/s, cubic foot per second]

Water-budget component	Estimated rate of recharge (ft^3/s)
Infiltration	
Precipitation	80
Big Lost River	95
Mud Lake	15
Irrigation-Mud Lake area	100
Irrigation-Howe area	20
Groundwater underflow	
Regional, from northeast	1,225
Big Lost River valley	367
Little Lost River valley	226
Birch Creek valley	102
Wastewater discharge	6
Upward flow of geothermal water	50

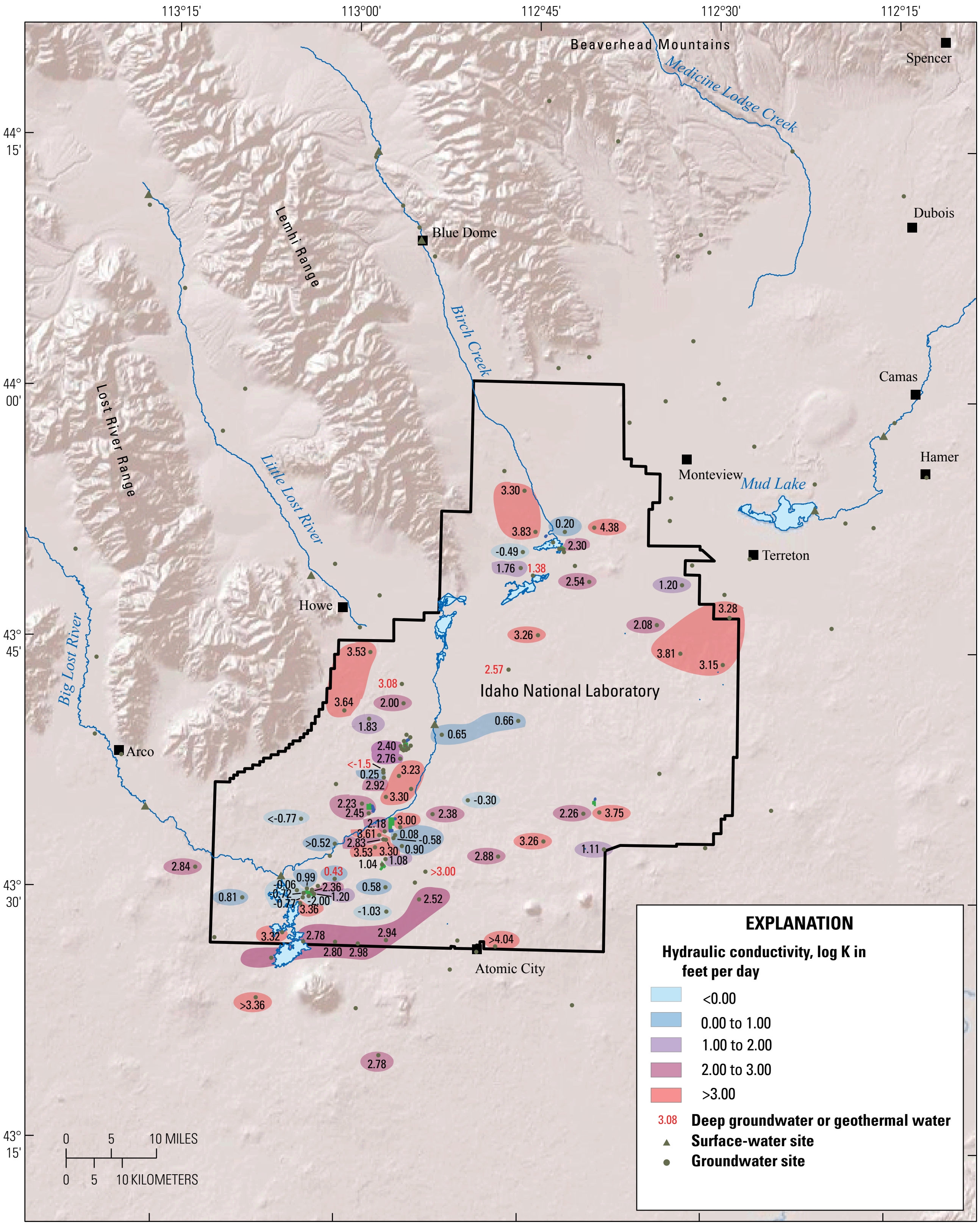
---

[6] Water-table contours were prepared for April 1989 because this period was close to the time when most of the chemistry data were collected, and the large number of water-level measurements made that month provided the best resolution of water-table contours.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 6. Locations of wells with water-level measurements and 1989 water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 7. Hydraulic conductivities estimated from single-well aquifer tests, Idaho National Laboratory and vicinity, eastern Idaho.

Most hydraulic conductivities exceed log K values of 2 ft/d (Anderson and others, 1999), and most of the log K values of less than 1 ft/d were measured from wells in the central and southwestern parts of the INL. Average linear flow velocities of about 2–20 ft/d (Ackerman and others, 2006) were estimated from model ages of environmental tracers (Busenberg and others, 2001) and assumed first-arrival times of contaminants in groundwater (Barraclough and others, 1981; Pittman and others, 1988; Mann and Beasley, 1994; Cecil and others, 2000).

Irrigation

Extensive irrigation adjacent to the INL occurs in the Howe area of the LLR valley and the Mud Lake area (fig. 3). Surface water from the LLR and groundwater are used for irrigation in the Howe area, groundwater is used for irrigation in areas north of Mud Lake, groundwater and surface water are used for irrigation in areas west of Mud Lake, and either surface water or groundwater is the primary source of irrigation water in areas south of Mud Lake (Idaho Department of Water Resources, 2016).

Geochemistry Data

Data Sources

The geochemistry data in this report are primarily from previously published data, but also include some data from the U.S. Geological Survey (USGS) National Water Information System (NWIS) database (accessible at http://maps.waterdata.usgs.gov/mapper/) (table 10 [at back of report]). A few dissolved oxygen data are from written notes in USGS INL Project Office field notebooks. For most water samples data from several sources were required to provide a comprehensive suite of geochemistry data.

Data for 83 of the 167 sample sites were primarily from Busenberg and others (2000), and data for 21 of the sites were primarily from Rattray (2015). Data for most of the other sample sites were from Knobel and others (1992, 1999a, 1999b), Carkeet and others (2001), Swanson and others (2002, 2003), Mann (1986), Robertson and others (1974), and the U.S. Geological Survey (2014). Data for three sites equipped with multi-level-monitoring systems (wells Middle 2051, USGS 134, and USGS 135) were from Bartholomay and Twining (2010) and Bartholomay and others (2015).

Chlorofluorocarbon, sulfur hexafluoride, tritium/helium-3, and most tritium and carbon-14 data were from Busenberg and others (1998, 2000, 2001). Other sources of tritium data were Rattray (2015), Knobel and others (1992, 1999a, 1999b), Carkeet and others (2001), Swanson and others (2002, 2003), Bartholomay and Twining (2010), and Bartholomay and others (2015), and some carbon-14 data were from and Mann (1986) and Schramke and others (1996). Uranium isotopic data were from Johnson and others (2000), and strontium isotopic data were from Roback and others (2001) and McLing and others (2002). Some of the hydrogen and oxygen stable isotope data were from Ott and others (1994), the sulfur and nitrogen stable isotope data were from Knobel and others (1999a), Wood and Low (1988), and Bartholomay and others (1994, 1995), and some dissolved metal data were from Liszewski and Mann (1993).

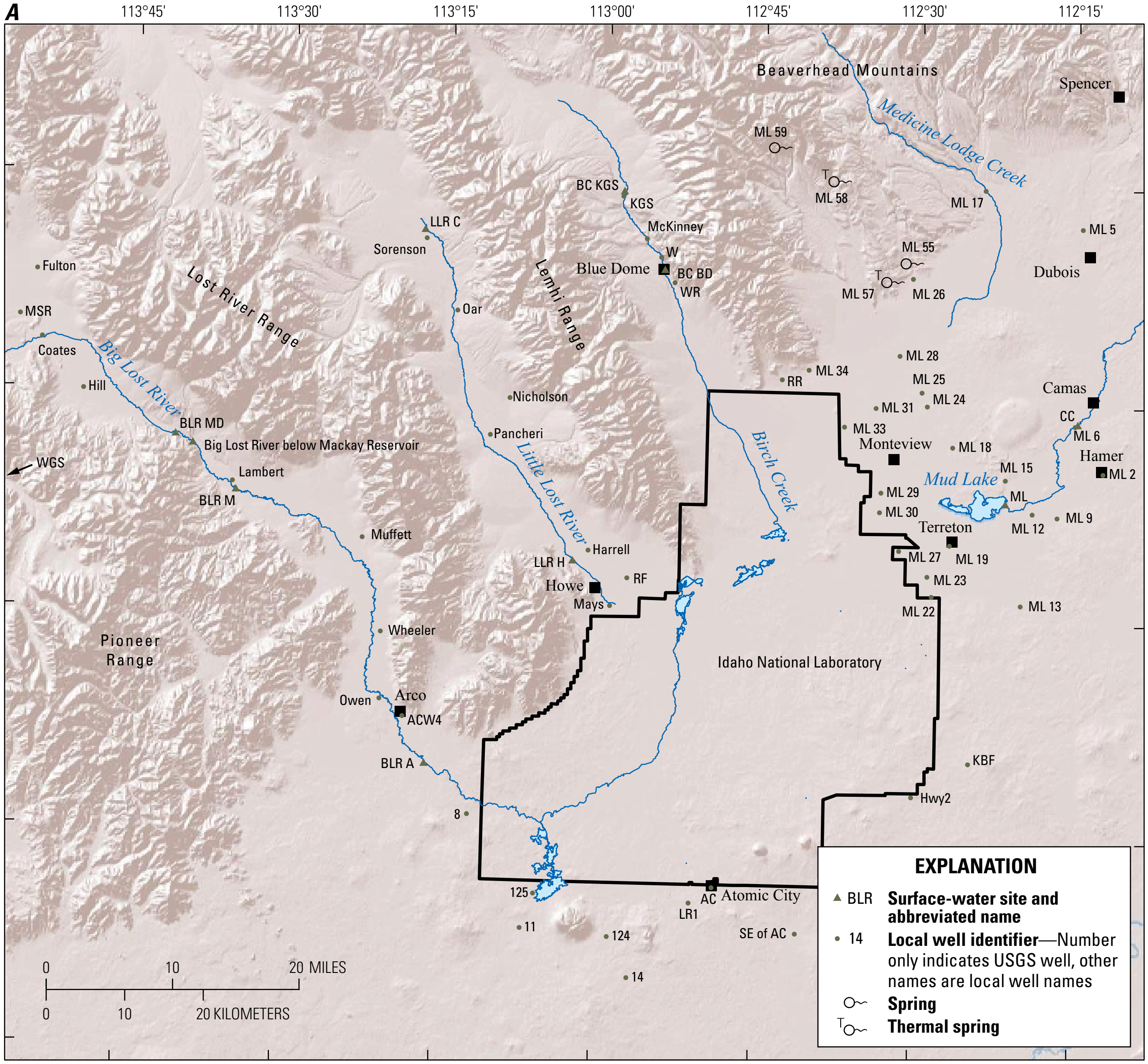
Sample Locations

Of the 167 sample sites, 154 are groundwater sites and 13 are surface-water sites (fig. 8). Groundwater sites (table 11 [at back of report]) include 129 wells and 2 sites from a deep test hole (INEL-1) in the basalt ESRP aquifer, 19 wells in alluvium aquifers in tributary valleys (9 from the BLR valley, 5 from the LLR valley, and 4 from the BC valley) or mountain fronts (Reno Ranch), and 4 springs in the Beaverhead Mountains (Blue Spring, Heart Spring, Lidy Hot Springs, and Warm Spring)[7]. Surface-water sites include seven sites from the BLR, two sites each from the LLR and BC, and one site each from Camas Creek and Mud Lake. Ninety-five of the wells in the ESRP aquifer are inside the INL and include 76 monitoring, 13 production, 5 disposal, and 1 domestic well (table 11). Thirty-four of the wells in the ESRP aquifer are outside of the INL and include 15 domestic, 11 irrigation, 4 monitoring, and 2 each production and stock wells.

Well construction information for the 129 wells (table 11) in the ESRP basalt aquifer indicate that most of the wells have large open intervals. Consequently, withdrawal of groundwater by pumping may collect and mix water from different aquifer depths. For the three wells equipped with multi-level monitoring systems (instrumented with Westbay™ packer sampling systems), water samples were collected from several discrete well intervals of varying depths. However, only samples collected from the shallowest zone in each multi-level monitoring well (Bartholomay and Twining, 2010; Bartholomay and others, 2015), which represents the shallow part of the ESRP aquifer, were included in this report. Based on the well construction information, 119 of the wells tap water exclusively or nearly exclusively from the shallow part of the ESRP aquifer and 9 wells pump water from deeper depths (that is, more than 250 ft below the water table). The depth that water was pumped from well ML 34 is unknown.

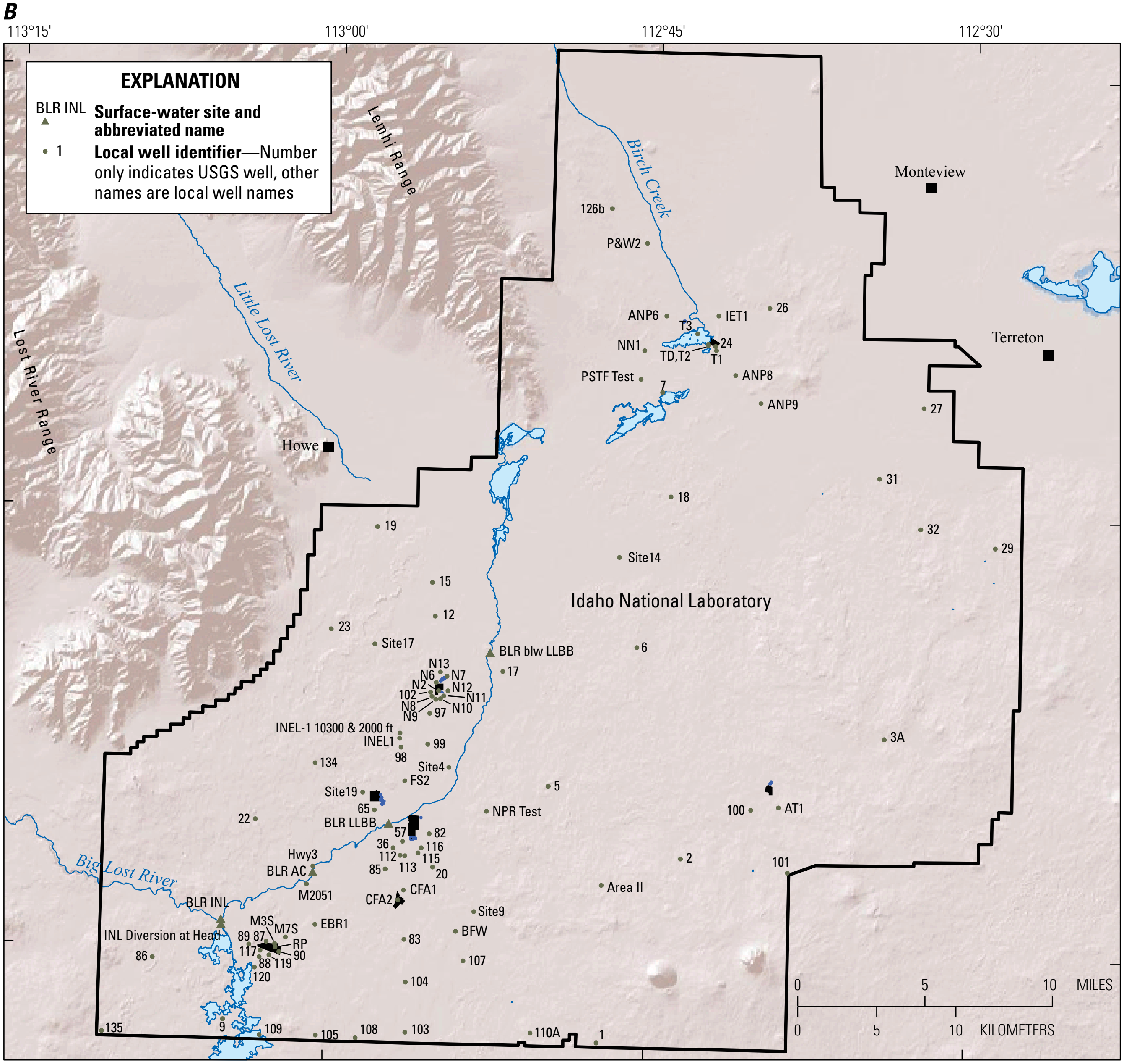
---

[7] The lowest-altitude sites in each of the tributary valleys are on the ESRP, and the two lowest-altitude sites for the BC valley, P&W 2 and USGS 126b, also are within the INL boundary (fig. 8*B*). Water-quality samples collected from two cold springs (ML 55/Blue Spring and ML 59/Heart Spring; fig. 8*A*) in the Beaverhead Mountains are discussed with the tributary valley samples because the chemistry of these spring waters is representative of groundwater in the mountains that provide recharge to the tributary valleys.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 8. Location of water-quality sample collection sites (*A*) outside and (*B*) within the Idaho National Laboratory, eastern Idaho. Site names and abbreviated names are shown in table 10.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 8.—Continued

The chemistry of water samples collected from well ML 34 and the four shallowest deep wells (ML 15, ML 22, No Name 1, and Site 19, with maximum well open interval depths ranging from about 290 to 371 ft below the water table), was similar and spatially consistent with the chemistry of samples collected from nearby wells penetrating only the shallow aquifer. Consequently, 124 of the 129 water samples from wells in the ESRP aquifer seem to be representative of the chemistry of the active, shallower part of the aquifer. The chemistry of water samples from the five deepest wells (wells EBR 1, Site 9, Site 14, USGS 7, and USGS 15[8]), which have maximum well open interval depths ranging from 284 to 626 ft below the water table, is probably representative of groundwater from the deeper part of aquifer. Two geothermal water samples were collected from test hole INEL-1 at depth intervals of 1,511–2,206 and 4,210–10,333 ft below the water table.

Sample Collection and Analysis

Surface-water and spring samples were collected as grab samples, except for the sample collected at BLR below INL Diversion (June 2, 1995), which was collected using equal width increments. Three groundwater samples were collected with bailers from wells equipped with multi-level monitoring systems (wells Middle 2051, USGS 134, and USGS 135), and all other groundwater samples were collected at wells with either dedicated or portable pumps. Sample collection followed procedures and guidelines documented in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated) and USGS INL Project Office Quality Assurance Plans that were in place at the time of collection (Mann, 1996; Knobel and others, 2008). Additional sample collection information, as well as analytical method information, are presented in the reports from which the geochemistry data set was compiled (Robertson and others, 1974; Knobel and others, 1992, 1999a, 1999b; Busenberg and others, 1993, 1998, 2000; Liszewski and Mann, 1993; Ott and others, 1994; Schramke and others, 1996; Johnson and others, 2000; Carkeet and others, 2001; Roback and others, 2001; McLing and others, 2002; Swanson and others, 2002, 2003; Bartholomay and Twining, 2010; Ginsbach, 2013; Rattray and Ginsbach, 2014; Bartholomay and others, 2015; Rattray, 2015).

Water samples were collected from 160 of the 167 sample sites between 1989 and 2012 (table 12 [at back of report]). Samples collected at the seven other sites included two groundwater samples collected in 1952 (from wells Highway 2 and USGS 3A), two surface-water samples collected between 1965 and 1981 (BLR near Atomic City[9] and BLR near Arco), two geothermal samples collected in 1979 from INEL-1, and one groundwater sample collected in 1984 from the Highway 3 well. Data from these seven samples were included with the more recent data to aid geochemical interpretation.

The 101 (nongeothermal) groundwater samples collected at or downgradient of the INL were collected between 1952 and 2010 (table 12 and fig. 8). One sample was collected in 1952 (USGS 3A), 1 sample was collected in 1984 (Highway 3), 12 samples were collected in 1989, 4 samples were collected in 1991, 79 samples were collected during 1995 and 1996, 1 sample was collected in 2000 (USGS 126b), 2 samples were collected in 2008 (Middle 2051, USGS 134), and 1 sample was collected in 2010 (USGS 135).

Samples were analyzed for all or most[10] of the following: field parameters, dissolved gases[11], major ions, dissolved metals, isotope ratios, and environmental tracers. The concentrations of CO_3 and the partial pressures of CO_2 were determined from speciation calculations with PHREEQC (Parkhurst and Appelo, 2013), the δ^3He values and concentrations of He_{terr} were calculated from helium concentrations, and the model ages for the young fraction of groundwater were estimated from concentrations and (or) ratios of CFCs, SF_6, and $^3H/^3He$ (Busenberg and others, 2000, 2001).

Bicarbonate concentrations were calculated from field alkalinity measurements using the equation (appendix 2, eq. 2-1) in Hem (1992). This calculation provides a good estimate of bicarbonate because alkalinity in the ESRP aquifer is primarily from carbonate alkalinity. Only bicarbonate concentrations were reported in Busenberg and others (2000), however, and the original alkalinity measurements were not archived in NWIS; therefore, alkalinity (as $CaCO_3$) from these samples was back calculated from the reported bicarbonate concentrations.

Historical data were used for time series analyses of bicarbonate, chloride, and nitrate concentrations and the stable isotope ratios of hydrogen and oxygen. The stable isotope ratios were from water samples collected during 1991–92 from the BLR below Mackay Reservoir, LLR near Howe,

---

[8] Well USGS 15 was drilled to a depth of 1,497 ft below land surface in 1951. The well caved to 610 ft below land surface (approximately 214 ft below the water table) sometime between 1952 and 1960. The chemistry of water pumped from this well is not representative of groundwater from the shallow aquifer. Consequently, some water pumped from this well probably originates from depths greater than 610 ft below land surface.

[9] Some samples are composite samples. For example, the data for BLR near Atomic City includes field parameters and some major ions measured from a sample collected in 1965, a chloride measurement from a sample collected in 1985, and other major ions, trace metals, and isotopes measured from samples collected in 1997.

[10] Only measurements of the stable isotope ratios of hydrogen and oxygen were included in this report for the site BLR below Mackay Reservoir.

[11] Dissolved-oxygen values were not measured during collection of many samples used in this report. In these cases, the DO values reported in table 12 for a particular site were the mean of all measurements of DO in the USGS NWIS database (U.S. Geological Survey, 2014) for that site through 2015. The ESRP aquifer generally was well oxygenated, with a relatively stable DO content, so these estimated values should adequately represent the DO at a particular site.

BC at Blue Dome, and Mud Lake near Terreton (Ott and others, 1994). Bicarbonate and nitrate concentrations were measured in surface water samples collected from the BLR near Arco, LLR near Howe, and Mud Lake near Terreton between 1965 and 1981 and were retrieved from NWIS. Chloride and nitrate concentrations measured in groundwater samples from 17 and 7 wells, respectively, were also retrieved from NWIS.

Various laboratories were used for analysis of specific chemical constituents, although most analyses of major ions, dissolved metals, stable isotopes, and environmental tracers were completed by the USGS National Water Quality Laboratory (NWQL) or other USGS laboratories (table 2). Analyses of ^{14}C were completed at the University of Arizona and the Rafter Radiocarbon Laboratory at the Institute of Geological and Nuclear Sciences in New Zealand, analyses of ^{87}Sr/^{86}Sr and ^{234}U/^{238}U were completed at the USGS Metal and Metaloid Laboratory and Los Alamos National Laboratory, and analyses of helium isotopes were completed at the USGS Chlorofluorocarbon Laboratory and the Noble Gas Laboratory (NGL) at the Lamont-Doherty Earth Observatory.

Several laboratories, with differing analytical methods and analytical uncertainties, were used for the measurement of tritium activity. The NWQL and DOE Radiological and Environmental Sciences Laboratory (RESL) used liquid scintillation counting to measure tritium activities. Analytical uncertainties (1σ) typically were about ±13 pCi/L for NWQL and generally ranged from ±150 to ±200 pCi/L for RESL (Knobel and others, 1992, 1999a, 1999b; Carkeet and others, 2001; Swanson and others, 2002, 2003). Low-level tritium activity was measured using electrolytic enrichment liquid scintillation counting by the NWQL and the USGS Stable Isotope and Tritium Labs (SITL) and ^{3}He in-growth mass spectrometry by the NGL. Analytical uncertainties (1σ) were approximately 1.0 pCi/L for analyses by NWQL and NGL (Busenberg and others, 2000) and ranged from 1.9 to 2.5 pCi/L for analyses by SITL (Ginsbach, 2013; Rattray and Ginsbach, 2014).

Table 2. Laboratories that completed water-quality analyses.

[**Laboratory:** CFC, U.S. Geological Survey (USGS) Chlorofluorocarbon Laboratory, Reston, Virginia; CUL, USGS Common-Use Laboratory, Reston, Virginia; ISU, Idaho State University Chemistry Laboratory; LANL, Los Alamos National Laboratory, Los Alamos, New Mexico; NGL, Noble Gas Laboratory, Lamont-Doherty Geological Observatory, Palisades, New York; MMIL, USGS Metal and Metalloid Isotope Laboratory, Menlo Park, California; NGL, Noble Gas Laboratory, Lamont-Doherty Earth Observatory, Columbia University, New York, New York; NWQL, USGS National Water Quality Laboratory, Denver, Colorado; RESL, Department of Energy Radiological and Environmental Sciences Laboratory; RRL, Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, New Zealand; SIL, USGS Stable Isotope Laboratory, Reston, Virginia; SITL, USGS Stable Isotope and Tritium Labs, Menlo Park, California; UA, University of Arizona, Tuscon, Arizona. **Abbreviations:** CFC, chlorofluorocarbon; He, helium; ^{3}He, helium-3; SF$_6$, sulfur hexafluoride; –, not applicable]

Data source	Chemical constituent analyzed at laboratory					
	Major ions, metals, nitrate	**Stable isotopes**	**Tritium**	**He, ^{3}He, CFCs, SF$_6$**	**Carbon-14**	**Strontium and uranium isotopes**
Bartholomay and Twining, 2010	NWQL	NWQL	NWQL, RESL	–	–	–
Bartholomay and others, 2015	NWQL	NWQL	NWQL, RESL	–	–	–
Busenberg and others, 1993	–	–	–	CFC	–	–
Busenberg and others, 1998	–	–	–	CFC	–	–
Busenberg and others, 2000	CUL	SIL, CFC, NGL	NWQL, NGL	CFC, NGL	RRL	–
Carkeet and others, 2001	NWQL, ISU	NWQL	NWQL	–	–	–
Ginsbach, 2013	NWQL	SIL	SITL	CFC	–	–
Johnson and others, 2000	–	–	–	–	–	MMIL
Knobel and others, 1992	NWQL	–	NWQL, RESL	–	–	–
Knobel and others, 1999a	NWQL	NWQL	NWQL	–	–	–
Knobel and others, 1999b	NWQL	–	NWQL	–	–	–
Liszewski and Mann, 1993	NWQL	–	–	–	–	–
Mann, 1986	NWQL	–	–	–	–	–
McLing and others, 2002	–	–	–	–	–	MMIL
Ott and others, 1994	–	NWQL	–	–	–	–
Rattray, 2015	NWQL	NWQL	–	–	–	–
Rattray and Ginsbach, 2014	NWQL	SIL	SITL	CFC	–	–
Roback and others, 2001	LANL	–	–	–	–	LANL, MMIL
Robertson and others, 1974	Unknown	–	–	–	–	–
Schramke and others, 1996	–	–	–	–	UA	–
Swanson and others, 2002	NWQL, ISU	NWQL	NWQL	–	–	–
Swanson and others, 2003	NWQL, ISU, CUL	NWQL	NWQL	–	–	–
U.S. Geological Survey, 2014	NWQL	NWQL	NWQL	–	–	–

Analytical Results

Analytical results for surface-water and groundwater samples are presented in tables 12–17 (at back of report). Values for field parameters and dissolved gases are shown in table 12, concentrations of major ions, silica, and the charge balance for each water sample are shown in table 13 (at back of report), and concentrations of selected dissolved metals are shown in table 14 (at back of report). Isotope ratios are shown in tables 15 and 16 (at back of report), and activities of the radioisotopes ^{3}H and ^{14}C, the approximate age of the water based on ^{3}H activity, the percentage of He_{terr}, and the apparent age of the young fraction of groundwater are shown in table 17 (at back of report). The CFC, SF_6, and $^{3}H/^{3}He$ data used to estimate the apparent age of the young fraction of groundwater were presented in tables in Busenberg and others (1998, 2000, 2001). Stable isotope ratios of hydrogen and oxygen and concentrations of bicarbonate and nitrate used for time series analysis of surface water sites are shown in tables 3 and 4, respectively.

The geochemistry data in tables 12–17 were grouped by water type (surface water, geothermal water) and geographic location (**tributary valley groundwater**, regional groundwater, **groundwater at the INL**)[12] .Surface water, tributary valley groundwater, regional groundwater, and geothermal water are all sources of recharge to groundwater at the INL. Groundwater at the INL includes **deep groundwater** (water depths more than 250 ft below the water table), groundwater probably influenced by industrial wastewater discharge (herein referred to as **contaminated groundwater**), and **natural groundwater** (shallow groundwater [water depths less than 250 ft below the water table]) probably not influenced (with respect to inorganic and radiochemical constituents) by industrial wastewater discharge.

---

[12] Definitions of these water groups are in the Glossary, and expanded descriptions of these water groups are in appendix 3. Tributary valley groundwater includes water from two cold springs, ML 55 and ML 59, in the Beaverhead Mountains because the chemistry of water from these springs is representative of groundwater in the mountains that provides recharge to the tributary valleys.

Table 3. Stable isotope ratios of hydrogen and oxygen for the Big Lost River below Mackay Reservoir, Little Lost River near Howe, Birch Creek at Blue Dome, and Mud Lake near Terreton, Idaho National Laboratory and vicinity, eastern Idaho, 1991–92.

[Data from Ott and others (1994). Location of sites shown in figures 8–9. **Abbreviations:** $\delta^{2}H$ and $\delta^{18}O$, delta notations for the stable isotopes of hydrogen and oxygen, respectively; nd, not determined; ±, plus or minus]

Date sampled	Big Lost River below Mackay Reservoir		Little Lost River near Howe		Birch Creek at Blue Dome		Mud Lake near Terreton	
	$\delta^{2}H\pm1.5$ (permil)	$\delta^{18}O\pm0.15$ (permil)	$\delta^{2}H\pm1.5$ (permil)	$\delta^{18}O\pm0.15$ (permil)	$\delta^{2}H\pm1.5$ (permil)	$\delta^{18}O\pm0.15$ (permil)	$\delta^{2}H\pm1.5$ (permil)	$\delta^{18}O\pm0.15$ (permil)
03-28-91	-138.0	-18.00	-137.0	-18.10	-143.0	-18.70	-132.0	-17.75
05-02-91	-135.0	-17.85	-136.0	-18.10	-140.0	-18.55	-133.0	-17.60
05-31-91	-135.0	-17.75	-137.0	-18.05	-141.0	-18.60	-134.0	-17.85
07-02-91	-129.0	-17.20	-137.0	-18.00	-140.0	-18.75	-131.0	-17.75
07-30-91	-129.0	-17.05	-138.0	-18.00	-142.0	-18.65	-133.0	-17.70
08-29-91	-133.0	-17.30	-137.0	-17.80	-141.0	-18.70	-134.0	-17.85
10-02-91	-135.0	-17.80	-139.0	-18.15	-142.0	-18.70	-135.0	-17.75
11-04-91	-136.0	-18.00	-139.0	-18.25	-142.0	-18.55	-133.0	-17.30
12-06-91	nd	nd	-139.0	-18.10	-142.0	-18.55	-129.0	-16.70
01-03-92	-136.0	-17.85	-139.0	-18.20	-142.0	-18.75	-130.0	-16.90
02-07-92	-136.0	-17.95	-139.0	-18.20	-142.0	-18.70	-135.0	-17.50
03-06-92	-136.0	-18.00	-139.0	-18.25	-142.0	-18.75	-122.0	-15.55
04-06-92	-136.0	-17.80	-138.0	-18.00	-142.0	-18.60	-133.0	-17.60
04-30-92	-137.0	-17.75	-137.0	-17.85	-142.0	-18.70	-135.0	-17.70
06-18-92	-134.0	-17.45	-137.0	-18.10	-142.0	-18.65	-134.0	-17.80

Table 4. Concentrations of bicarbonate and nitrate for selected periods for the Big Lost River near Arco, Little Lost River near Howe, and Mud Lake near Terreton, Idaho National Laboratory and vicinity, eastern Idaho.

[Location of sites shown in figures 8–9. **Abbreviations:** mg/L, milligram per liter; N, nitrogen; nd, not determined]

Big Lost River near Arco			Little Lost River near Howe			Mud Lake near Terreton		
Date	Bicarbonate (mg/L)	Nitrate (mg/L as N)	Date	Bicarbonate (mg/L)	Nitrate (mg/L as N)	Date	Bicarbonate (mg/L)	Nitrate (mg/L as N)
10-01-65	209	0.16	04-02-65	203	0.23	04-01-68	139	0.29
12-01-65	247	0.54	09-28-67	194	0.18	10-14-68	144	0.18
01-10-66	227	0.38	11-15-68	191	0.18	04-02-69	145	0.29
02-15-66	230	0.38	05-30-69	130	0.18	12-24-69	159	0.59
03-28-66	219	0.29	09-17-69	196	nd	04-13-70	150	0.36
05-04-66	234	0.45	12-14-69	224	0.27	09-18-70	144	0.36
06-09-66	223	0.09	05-14-70	187	0.27	05-27-71	151	0.25
07-08-66	240	0.02	06-04-70	95	0.25	10-27-71	164	0.58
08-25-66	291	0.05	08-13-70	184	0.16	04-18-72	183	0.18
09-30-66	256	nd	05-22-71	149	0.18	09-25-72	150	1.30
11-01-66	270	0.02	02-28-72	233	4.10	05-24-73	150	0.88
12-05-66	251	0.18	07-12-72	177	0.06	10-25-73	148	0.48
01-04-67	285	0.34	09-19-72	191	0.11	05-15-74	132	0.71
02-06-67	268	0.27	07-18-73	201	0.18	09-27-74	103	0.09
03-15-67	282	0.18	09-18-73	149	7.50	07-31-75	126	0.03
04-17-67	277	0.14	05-14-74	138	0.25	09-12-75	90	0.06
05-25-67	214	0.11	09-24-74	190	0.33	10-05-76	100	0.12
06-14-67	180	0.18	07-23-75	164	0.11	06-30-77	110	nd
07-07-67	172	0.14	03-03-76	143	1.20	10-26-77	150	0.43
08-24-67	255	0.25	05-25-76	123	0.14	07-20-78	nd	0.04
09-26-67	230	0.18	07-16-76	167	0.18	08-22-78	120	0.33
12-08-67	248	0.59	10-20-76	170	0.13			
02-12-68	252	0.50	08-26-77	190	0.09			
03-18-68	240	0.43	05-08-78	160	nd			
04-23-68	168	0.27	09-22-78	170	0.47			
05-28-68	249	0.05	08-28-79	nd	0.13			
08-05-68	235	0.20	12-04-79	nd	0.45			
09-06-68	232	0.18	05-18-80	nd	0.24			
10-11-68	257	0.41	10-30-80	nd	0.15			
11-16-68	233	0.29	06-05-81	130	0.11			
05-30-69	174	0.27	07-21-81	nd	0.03			
08-20-69	227	0.09						
05-13-70	240	0.27						
06-05-70	268	0.16						
08-12-70	269	0.38						

The geochemistry of natural groundwater varies spatially in response to numerous, but chemically distinct, sources of recharge. Consequently, the 58 natural groundwater samples were grouped into spatially defined areas based on their similarity of potential source waters and chemical and isotopic compositions (tables 12–17). Spatially defined areas for natural groundwater were defined as the North, Northeast, Southeast, Central, Northwest, and Southwest INL Areas (fig. 9).

Data Quality

The data quality of environmental samples was evaluated from quality control (QC) samples collected to estimate the variability and contamination bias of chemical and radiochemical constituents in groundwater samples (no QC samples were collected for surface-water samples) and the charge balance of surface-water and groundwater samples. Variability and contamination bias were estimated from analysis of field replicates and field or equipment blanks (table 5), respectively. Replicate samples also were collected for interlaboratory comparison of analytical results from the NWQL and Idaho State University (ISU) laboratories.

Many laboratories were used for analysis of chemical and radiochemical constituents (table 2). Except for tritium and the samples collected in 1952[13] (table 12), the methods used by the different laboratories for analysis of specific chemical and radiochemical constituents had similar detection limits and precision. Consequently, all replicate and blank results for specific chemical and radiochemical constituents were evaluated collectively and the results were considered representative of groundwater samples except for analyses of tritium, samples collected in 1952, replicates collected for interlaboratory comparison, and the three groundwater samples collected with bailers.

Variability

A total of 101[14] replicates were collected with the groundwater samples and were used to evaluate variability for every chemical constituent presented in this report except for $^{87}Sr/^{86}Sr$, ^{14}C, He, δ^3He, CFCs, and SF_6 (table 5). All replicates were collected as duplicates. Of these replicates, 64 were used to evaluate the variability of chemical constituents in pumped groundwater samples, 24 were used to evaluate the variability of chemical constituents in samples collected with bailers from wells equipped with multi-level monitoring systems, and 13 were used for comparison of analytical results from the NWQL and ISU laboratories.

Multiple sample bottles were collected for 149 CFC samples, 6 He samples, and 5 δ^3He samples (Busenberg and others, 1998, 2000). These samples were treated as replicates, generally were collected as duplicates or triplicates, but also included higher number replicates.

Variability for each chemical constituent, as well as the variability of chemical constituents analyzed by both the NWQL and ISU, was evaluated by calculating the reproducibility of chemical constituents from replicates. Reproducibility of chemical constituents was calculated as normalized absolute difference (NAD),[15] relative standard deviation (RSD), or relative percent difference (RPD) (table 5; appendix 2, eqs. 2-3–2-8). Acceptable reproducibility (acceptance criteria) for a chemical constituent from an individual replicate was defined as an NAD less than or equal to 1.96, RSD less than 14 percent, or RPD less than 20 percent (Rattray, 2012, 2014; Bartholomay and others, 2015). Acceptable reproducibility for the collective set of replicates was defined as a chemical constituent having acceptable reproducibility in greater than or equal to 90 percent of all replicates from which the constituent was analyzed (Rattray, 2012, 2014). Replicate data, statistical calculations of reproducibility, and (or) a discussion of quality assurance was presented in each of the reports listed in table 5.

Replicates were used to evaluate the reproducibility of 29 chemical constituents (table 5). The acceptance criteria for reproducibility for an individual replicate was exceeded for 12 constituents for pumped groundwater samples, 4 constituents for bailed groundwater samples, and 1 constituent for interlaboratory comparison (table 6).

Reproducibility for Pumped Groundwater Samples

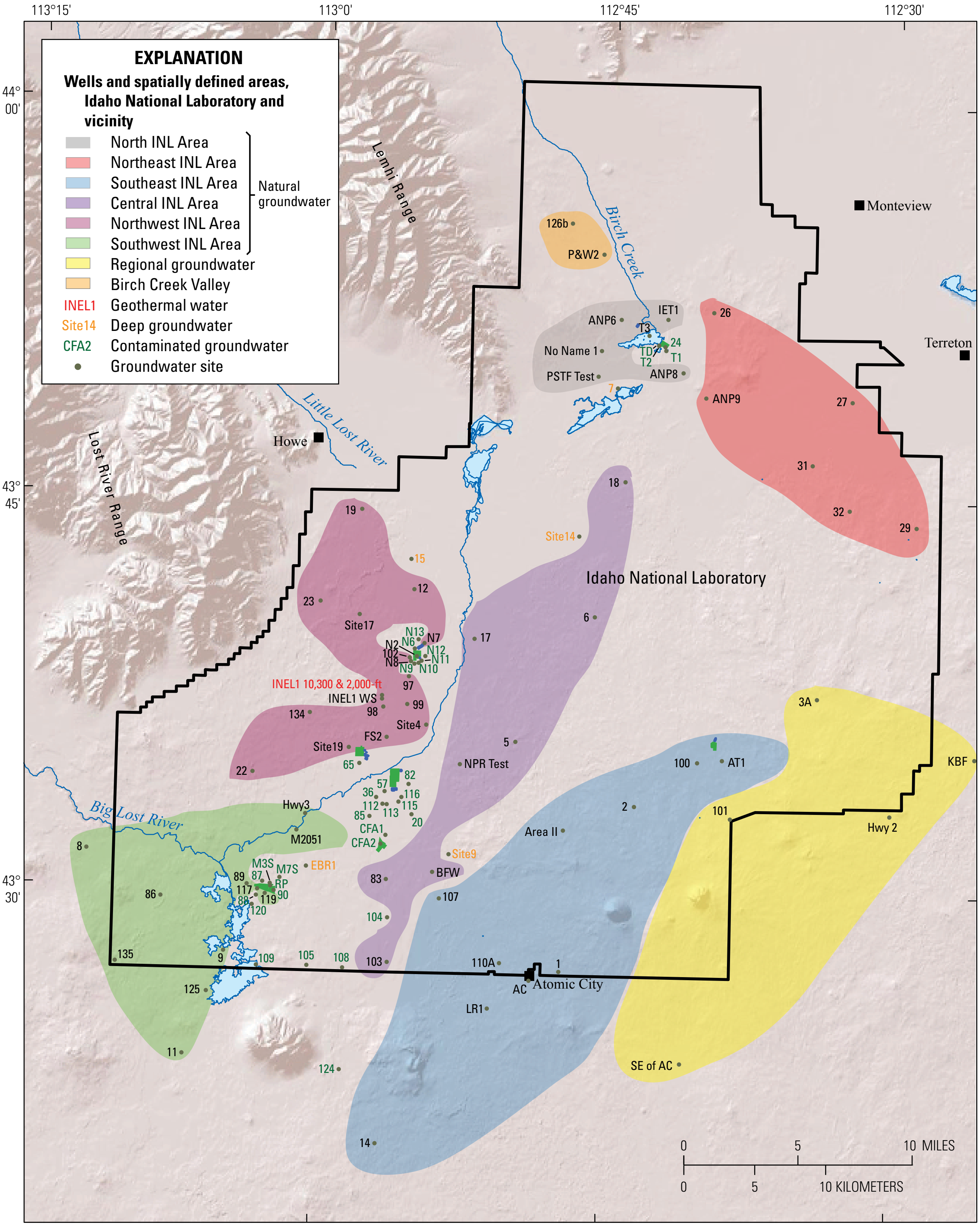
The 12 constituents with a result that exceeded the acceptance criteria for reproducibility in pumped groundwater samples were Cl, SO_4, F, Al, Cr, Fe, $\delta^{15}N$, ^3H, δ^3He, CFC-11, CFC-12, and CFC-113. The percentage of acceptable results for these 12 constituents was 93 percent for Cl and SO_4, 83 percent for ^3H and CFC-12, 81 percent for Cr and CFC-11, 75 percent for F and $\delta^{15}N$, 73 percent for Al, 60 percent for δ^3He, 53 percent for Fe, and 40 percent for CFC-113 (table 6). Ten of these constituents did not meet the acceptance criteria for percentage of acceptable results for the collective set of replicates (≥90 percent).

---

[13] Chemical analyses (particularly for pH, alkalinity, and iron) from water samples collected in 1952 were less accurate than analyses from the 1980s through 2010s. A discussion of the accuracy and uncertainty of these analyses is presented in Robertson and others (1974).

[14] Ott and others (1994) collected four replicates of groundwater samples. However, only surface-water data were used from that report, so the replicates of groundwater were not included in the data-quality assessment presented herein.

[15] NAD is referred to as the Z-value in Knobel and others (1992, 1999a, 1999b), Carkeet and others (2001), Swanson and others (2002, 2003), Bartholomay and Twining (2010), and Bartholomay and others (2015).



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 9. Wells and spatially defined areas at the Idaho National Laboratory and vicinity, eastern Idaho.

Table 5. Quality-control samples collected at Idaho National Laboratory and vicinity, eastern Idaho.

[Shaded rows indicate bailed samples. **Report:** Includes only those reports that collected quality-control data discussed in this report. For example, replicates were collected for groundwater samples by Ott and others (1994), but only surface-water results from Ott and others (1994) are discussed in this report. Consequently, the replicate data from Ott and others (1994) are not discussed. **Constituents analyzed from replicates:** Ca, calcium; Cl, chloride; F, fluoride; Mg, magnesium; NO_3, nitrate; K, potassium; SiO_2, silica; Na, sodium; SO_4, sulfate; Al, aluminum; Ba barium; B, boron; Cr, chromium; Fe, iron; Li, lithium; Mn, manganese; Sr, strontium; ^3H, tritium; CFC, chlorofluorocarbon; He, helium; δ^3He, helium-3/helium-4; δ^2H, hydrogen-2/hydrogen-1; $\delta^{18}O$, oxygen-18/oxygen-16; $\delta^{13}C$, carbon-13/carbon-12; $\delta^{34}S$, sulfur-34/sulfur-32; $\delta^{15}N$, nitrogen-15/nitrogen-14; U, uranium; $^{234}U/^{238}U$, uranium-234/uranium-238. Numbers in parentheses indicate number of replicates from which the constituent was analyzed. **Abbreviations:** RPD, relative percent difference; RSD, relative standard deviation; NAD, normalized absolute difference (reported as a z-value in many of the reports referenced); NWQL, U.S. Geological Survey National Water Quality Laboratory; RESL, U.S. Department of Energy Radiological and Environmental Sciences Laboratory]

Report	Number of replicate samples	Number of blank samples	Constituents analyzed from replicates	Statistical method used for calculating reproducibility
Knobel and others, 1992	[1]3	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,Cr,Fe,Li,Mn,Sr,^3H	RPD, NAD
Liszewski and Mann, 1993	[2]47	4	F(34), Cr(22), Ba(3), Fe(3), Mn(3), Sr(3), Al(2), Li(1)	RPD
Busenberg and others, 1998, 2000	[3]149	0	CFC-11, CFC-12, CFC-113	RSD
Busenberg and others, 2000	[4]6	0	He, δ^3He	RSD, NAD
Knobel and others, 1999a	4	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,Cr,Fe,Li,Mn,Sr,δ^2H,$\delta^{18}O$, $\delta^{13}C$,$\delta^{34}S$,$\delta^{15}N$,^3H	NAD
Knobel and others, 1999b	4	1	Ca,Mg,Na,K,Cl,SO_4,NO_3,Al,Ba,Cr,Fe,Mn,^3H	NAD
Carkeet and others, 2001	1	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,Cr,Fe,Li,Mn,Sr,δ^2H,$\delta^{18}O$, $\delta^{13}C$,^3H	NAD
Carkeet and others, 2001	[5]5	0	Ca,Mg,Na,K,SiO_2,Al,Ba,Cr,Fe,Mn,Sr	NAD
Roback and others, 2001	1	[6]2+	U, $^{234}U/^{238}U$	NAD
Swanson and others, 2002	[5]4	1	Ca,Mg,Na,K,SiO_2,Ba,Fe,Mn,Sr	NAD
Swanson and others, 2003	1	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Ba,Cr,Fe,Mn,Sr,δ^2H,$\delta^{18}O$,$\delta^{13}C$,^3H	NAD
Swanson and others, 2003	[5]4	0	Ca,Mg,Na,K,SiO_2,Ba,Cr,Fe,Mn,Sr	NAD
Bartholomay and Twining, 2010	[7]8	2	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,Cr,Fe,Li,Mn,Sr,δ^2H,$\delta^{18}O$, $\delta^{13}C$,^3H	RPD, NAD
Rattray and Ginsbach, 2014	1	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Fe,Mn	RSD
Rattray and Ginsbach, 2014	1	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,B,Cr,Fe,Li,Mn,Sr,δ^2H, $\delta^{18}O$,$\delta^{13}C$,^3H	RSD, NAD
Bartholomay and others, 2015	[8]16	7	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,Cr,Fe,Li,Mn,Sr,δ^2H,$\delta^{18}O$,$\delta^{13}C$,^3H	RPD, NAD
Rattray, 2015	[9]1	0	Ca,Mg,Na,K,SiO_2,Cl,SO_4,F,NO_3,Al,Ba,B,Cr,Fe,Li,Mn,Sr,δ^2H, $\delta^{18}O$,$\delta^{13}C$,^3H	RSD, NAD

[1] Two replicates were only of ^3H. Four ^3H results were obtained from the three replicates, two each from the NWQL and RESL (table 2).

[2] Does not include bailed samples (Mann, 1996) or four samples from Knobel and others (1999a).

[3] Only includes replicate data for sites in table 12 and excludes contaminated data (Busenberg and others, 2001).

[4] Only five replicates for δ^3He.

[5] Replicate used for interlaboratory comparison.

[6] Multiple, but unknown number, of field blanks were collected and analyzed.

[7] Only three replicates for $\delta^{13}C$ and ^3H.

[8] Only five replicates for δ^2H and $\delta^{18}O$, three for ^3H, and two for $\delta^{13}C$.

[9] Also discussed two replicates from Rattray and Ginsbach (2014).

Table 6. Chemical constituents with a replicate result exceeding the acceptance criteria.

[Chemical constituents in **bold** did not meet the acceptance criteria for the collective set of replicates. **Abbreviations:** CFC, chlorofluorocarbon; NWQL, U.S. Geological Survey National Water Quality Laboratory; LSC, liquid scintillation counting]

Chemical constituent	Total number of replicate results	Number of replicate results exceeding acceptance criteria	Replicate results meeting acceptance criteria (percent)
Magnesium (Mg)[1]	13	1	92
Fluoride (F)[2]	24	1	96
Aluminum (Al)[2]	**24**	**3**	**88**
Iron (Fe)[2]	24	1	96
Manganese (Mn)[2]	24	2	92
Chloride (Cl)	14	1	93
Sulfate (SO_4)	14	1	93
Fluoride	44	11	**75**
Aluminum	15	4	**73**
Chromium (Cr)	36	7	**81**
Iron	17	8	**53**
Nitrogen-15/nitrogen-14 ($\delta^{15}N$)	4	1	**75**
Tritium (^3H) (NWQL, LSC)	12	2	**83**
Helium-3/helium-4 (δ^3He)	5	2	**60**
CFC-11	145	28	**81**
CFC-12	120	21	**83**
CFC-113	112	67	**40**

[1] Replicates used for interlaboratory comparison.

[2] Replicates collected with bailers from wells equipped with multi-level monitoring system.

The replicate results for F probably did not meet the acceptance criteria due to the generally small concentrations of F in replicates, because relative variability generally increases as concentrations decrease. Replicate results for Al, Cr, and Fe exceeded the acceptance criteria in several reports, and the poor reproducibility of these constituents indicates that they generally have a large variability compared to most other constituents. One of four replicates had a result for $\delta^{15}N$ that exceeded the acceptance criteria for individual replicates, but these are too few results to confidently assess the variability of $\delta^{15}N$.

Tritium results for two replicates, analyzed by liquid scintillation counting by NWQL, exceeded the acceptance criteria for individual replicate samples. One result had a NAD of 2.12 that was only slightly larger than the acceptance criteria (≤1.96). The other tritium result was for samples with activities of 27,600 and 29,600 pCi/L and analytical uncertainties (1σ) of 220 and 450 pCi/L. Although the NAD for these tritium activities is large (NAD = 4.0), the RPD of measurements of these large activity samples is relatively small (RPD = 7 percent). Consequently, even though tritium results exceeded the acceptance criteria for the collective set of replicates, the reproducibility of tritium seems to be quite good.

The percentage of acceptable replicate results was 60 percent for δ^3He (table 6), which was less than the acceptance criteria (≥90 percent) for the collective set of replicates. Although the variability in replicate measurements of δ^3He was larger than the acceptance criteria, the effect of this variability on interpretation of δ^3He values was insignificant. The δ^3He values were used to calculate R_s/R_a values (appendix 2, eq. 2-11), where R_s is the $^3He/^4He$ of an environmental sample and R_a is the $^3He/^4He$ of air, and the maximum variability of R_s/R_a values for replicate samples was less than 1.8 percent.

The percentage of acceptable replicate results was 81 and 83 percent for CFC-11 and CFC-12, respectively, and 40 percent for CFC-113 (table 6). The standard deviation of repeated measurements for the instrument used to measure CFCs was less than 3 percent (Busenberg and others, 1998). This indicates that the low reproducibility of the CFC samples probably was due to difficulties in sample collection, storage, and (or) shipping. Analytical precision for measurement of CFCs was about 50 percent at the detection limits of about 1 picogram per kilogram (pg/kg) and about 3 percent for concentrations greater than 25 pg/kg (Busenberg and others, 1998). Most concentrations of CFC-113 were less than 25 pg/kg and many were near the detection limit. These low concentrations were probably the reason that CFC-113 had such low reproducibility.

Reproducibility for Bailed Groundwater Samples

The four constituents with a result that exceeded the acceptance criteria for reproducibility in bailed groundwater samples were F, Al, Fe, and Mn. The percentage of acceptable results for these four constituents was 96 percent for F and Fe, 92 percent for Mn, and 88 percent for Al (table 6). Aluminum was the only constituent that did not meet the acceptance criteria for reproducibility for the collective set of replicates and, as stated above, reproducibility is smaller and variability is larger for Al than for most other constituents.

Interlaboratory Comparison

Replicates collected for interlaboratory comparison of analytical results from the NWQL and ISU laboratories (Carkeet and others, 2001; Swanson and others, 2002, 2003) were analyzed for 11 chemical constituents (cations, silica, and metals) (table 5). All replicate results met the acceptance criteria for an individual replicate except for one result for Mg, which had an NAD of 2.03 that slightly exceeded the acceptance criteria of less than or equal to 1.96. However, the percentage of replicate results for Mg that met the acceptance criteria was 92 percent (table 6), which meets the acceptance criteria for the collective set of replicates. These results indicate that there was minimal variability and good reproducibility between the analytical results from NWQL and ISU.

Bias

Field blanks were collected with pumped and bailed groundwater samples and equipment blanks were collected with bailed groundwater samples. Field blanks were prepared at the sample site and included any contamination from the source solution, sample bottles, filter capsules and preservatives (if required), ambient conditions, and sample storage. Equipment blanks included all sources of contamination associated with field blanks plus any contamination from portable sampling equipment (Rattray, 2012, 2014). The frequency and magnitude of contamination bias in the environmental samples was evaluated using order statistics and the binomial probability distribution (appendix 2, eq. 2-9).

Pumped Groundwater Samples

Analytical results for six field blanks collected with pumped groundwater samples and for multiple field blanks collected with U samples were reported (table 5). Ba and Cr were analyzed from three blanks, Ca, Mg, Na, K, F, Fe, and Mn were analyzed from two blanks, and SiO_2, Cl, SO_4, NO_3, Al, and Sr were analyzed from one blank (Liszewski and Mann, 1993; Knobel and others, 1999b; Swanson and others, 2002). Concentrations of U in field blanks were small, and concentrations of all other chemical constituents in blanks were less than the reporting level except for one result each for Ca (2.9 mg/L), Ba (2 µg/L), and Cr (0.6 µg/L).

A statistical analysis was not possible for those constituents with only one measurement from the blank samples, but for constituents with two (Ca, Mg, Na, K, Fe, Mn) or three measurements (Ba, Cr) a statistical analysis was done using order statistics and the binomial probability distribution (Rattray, 2012, 2014). The analysis indicated that at a confidence level of 78 percent (Ba, Cr) or 64 percent (Ca, Mg, Na, K, Fe, Mn) at least 60 percent of the pumped groundwater samples had a contamination bias less than the largest measurement from a blank sample. The largest measurements from blank samples were 2.9 mg/L for Ca, 2 µg/L for Ba, and 6 µg/L for Cr and the analytical reporting levels for Mg, Na, K, Fe, and Mn. These results indicate that some pumped groundwater samples may have a small contamination bias for Ca, Ba, and Cr. The maximum contamination bias for U was reported as less than 0.3 percent (Roback and others, 2001).

Bailed Groundwater Samples

Four field and five equipment blanks were collected with the bailed groundwater samples (table 5). Four field blanks were analyzed for Na, Cl, SO_4, Cr, and NO_3 and two field blanks were also analyzed for Ca, Mg, K, SiO_2, F, Al, Ba, Fe, Li, Mn, Sr, and U. Results for all chemical constituents analyzed from the field blanks were less than the reporting level except for two results each for Na (0.215 and 0.415 mg/L), Cl ([16]E0.16 and 0.328 mg/L), and SiO_2 (1.01 and 1.29 mg/L). Five equipment blanks were analyzed for Na, Cr, and NO_3, four equipment blanks were analyzed for Cl, two equipment blanks were analyzed for SO_4, and one equipment blank was analyzed for Li. Results for all chemical constituents analyzed from the equipment blanks were less than the reporting level (Bartholomay and others, 2015).

For statistical analysis, the equipment blanks were treated as field blanks. A statistical analysis was not possible for those constituents with only one measurement from the blank samples, but for constituents with two (Ca, Mg, K, SiO_2, F, Al, Ba, Fe, Mn, Sr, and U), three (Li), six (SO_4), eight (Cl), or nine (Na, NO_3, Cr) measurements, a statistical analysis was done using order statistics and the binomial probability distribution (Rattray, 2012, 2014). The analysis indicated that, at a confidence level of 78 percent (Li) or 64 percent (Ca, Mg, K, SiO_2, F, Al, Ba, Fe, Mn, Sr, U), at least 60 percent of the bailed groundwater samples had a contamination bias less than the largest measurement from a blank sample, and at a confidence level of 96 (Na, NO_3, Cr), 94 (Cl), or 88 (SO_4) percent at least 70 percent of the bailed groundwater samples had a contamination bias less than the largest measurement

---

[16] E indicates an estimated result.

from a blank sample. The largest measurements from blank samples were 0.415 mg/L for Na, 0.328 mg/L for Cl, and 1.29 for SiO_2 and were less than the analytical reporting levels for Ca, Mg, K, SO_4, NO_3, F, Al, Ba, Cr, Fe, Li, Mn, Sr, and U. These results indicate that some bailed groundwater samples may have a small contamination bias for Na, Cl, and SiO_2.

Charge Balance

Calculation of the charge balance of a sample provides an indication of the accuracy of major ion analyses for that sample. The charge balance of samples was calculated (appendix 2, eq. 2-10) from concentrations, in milliequivalents per liter (meq/L), of the major ions. Charge balance errors of 5 percent or less (absolute value) are generally considered acceptable for analyses of water samples (Freeze and Cherry, 1979), although larger errors may be acceptable if the sum of ions is less than 5 meq/L (Hem, 1992). Charge balance errors exceeding 5 percent may indicate analytical errors or omission of important ionic species from analysis (Freeze and Cherry, 1979).

Of the 165 water samples with a complete suite of major ion analyses, 160 had charge balance errors of less than 5 percent (table 13). The five water samples with charge balance errors larger than 5 percent were from NRF 13, USGS 87, USGS 90, TDD 3, and USGS 134, and three of these samples were contaminated groundwater (NRF 13, USGS 87, and USGS 90). The charge balance errors for samples from USGS 87, USGS 90, TDD 3, and USGS 134 ranged from 6.5 to 7.8 percent (absolute value). These errors are slightly larger than the 5 percent criteria for charge balance errors, but are acceptable for the purposes of this report. The sample collected from NRF 13 had a charge balance error of 18.8 percent, which makes the major ion chemistry of this sample suitable only for identifying the distribution of wastes in the ESRP aquifer at NRF.

Sources of Chemical and Isotopic Constituents

The geochemistry of groundwater in the ESRP aquifer at the INL reflects the sources of chemical and isotopic constituents, which includes the chemistry of the various sources of recharge and any physical and chemical processes occurring in the aquifer. The chemistry of recharge sources and the physical and chemical processes influencing chemical and isotopic compositions in the aquifer must be understood in order to make reliable interpretations, based on their compositions in surface water and groundwater, about sources of recharge, mixing of water, and groundwater flow directions.

Some important physical and chemical processes include solution of gases, mixing of water, evaporation, alpha (α) recoil, water-rock interaction, isotope fractionation, and radioactive decay. Redox reactions may be important in some areas, either from oxidation of minerals with iron and (or) sulfur in a reduced state (Wood and Low, 1988), upwelling of anoxic geothermal water (Rattray, 2015), or mixing with anoxic water in wetlands (Rattray and Ginsbach, 2014). These physical and chemical processes provide sources (and sinks) of dissolved gases and inorganic chemicals, affect stable and radioactive isotope compositions, control the percentage of He_{terr} in groundwater, and influence the compositions of environmental tracers used to estimate the age of groundwater.

Sources of Inorganic Chemical Constituents

Dissolved Gases

Sources of dissolved gases in the ESRP aquifer may include exchange of gases between the aquifer and the atmosphere, soil zone, or unsaturated zone; release of gases into groundwater from the aquifer matrix; recharge of surface water that equilibrated with atmospheric, soil zone, or unsaturated zone gases; upward movement of geothermal water; and chemical or biological reactions in the aquifer (Busenberg and others, 2001; Rattray and Ginsbach, 2014).

Carbon-14 activities and DO, CO_2, ^{3}He, ^{4}He, CFCs, and SF_6 concentrations in the ESRP aquifer typically were not in equilibrium with current atmospheric, soil zone, or unsaturated zone gas concentrations and provided evidence that the aquifer at the INL generally behaved as a closed system (Busenberg and others, 1993; Schramke and others, 1996; Busenberg and others, 2001). Geochemical modeling of the ESRP aquifer upgradient of the INL generally supported this interpretation, but also demonstrated that the aquifer behaved as an open system, with respect to some gases, in areas where recharge from geothermal or surface water occurred (Rattray and Ginsbach, 2014; Rattray, 2015). Recharge of surface water, as infiltration from lakes, ponds, irrigation water, or streams, potentially may add He, CFCs, SF_6, and oxygen from the atmosphere and unsaturated zone, as well as CO_2 produced in the soil zone, to groundwater. Upward movement of geothermal water may be a source of anoxic water, helium, methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S).

Chemical, biological, and physical processes and reactions may affect the concentrations of dissolved gases in the aquifer. Such processes and reactions include anaerobic degradation of CFCs under reducing conditions, microbial reduction of NO_3^- to N_2 under anoxic conditions (Busenberg and others, 2001), consumption of oxygen through oxidation-reduction reactions, consumption of CO_2 through silicate and carbonate reactions (Rattray and Ginsbach, 2014), production of ^{3}He as a daughter product of radioactive decay of ^{3}H, and release of ^{4}He from the aquifer matrix by α-particle decay of ^{238}U, ^{235}U, and ^{232}Th and their daughter products (Solomon, 2000; Solomon and Cook, 2000).

The ESRP aquifer is a well-oxygenated system, so reducing and anoxic conditions occur only locally in the ESRP aquifer. The rate of most silicate reactions is extremely slow, but because silicate rocks are so abundant in the ESRP aquifer silicate reactions may affect the partial pressure of CO_2. Consequently, modification of dissolved gas concentrations in the ESRP aquifer from chemical, biological, or physical processes and reactions is largely from consumption of CO_2 from carbonate and silicate reactions, the production of He from radioactive decay, and downward transport of atmospheric, soil zone, or unsaturated zone gases to the aquifer in infiltrating surface water.

Major Ions and Dissolved Metals

Potential sources of inorganic chemical constituents in the ESRP aquifer, excluding stream and shallow groundwater sources of recharge, include water-rock interaction, anthropogenic inputs, and geothermal water (table 7). Water-rock interaction, which may be a source or sink of inorganic chemical constituents, refers to the dissolution or precipitation of minerals or other solid phases and ion exchange processes. Plausible water-rock interactions in the ESRP aquifer include carbonate and silicate reactions, dissolution of evaporite minerals, oxidation of pyrite, and cation exchange (Wood and Low, 1988; McLing, 1994; Schramke and others, 1996; Knobel and others, 1997; Busenberg and others, 2001; Rattray and Ginsbach, 2014; Rattray, 2015). However, except for volcanic glass, which is reactive, silicate reactions may be a small source of inorganic chemical constituents in the ESRP aquifer because most silicate minerals dissolve slowly in groundwater due to the kinetics of a rate-limiting reaction step or steps (Lasaga and others, 1994). This interpretation is supported by petrographic analyses that show most mineral grains in basalt, in the shallow part of the ESRP aquifer, appear fresh and unaltered (Nace and others, 1956). Geochemical modeling also indicated only small amounts of silicate phases need to dissolve to produce the chemistry of groundwater in the shallow ESRP aquifer (Busenberg and others, 2001; Rattray and Ginsbach, 2014; Rattray, 2015).

Anthropogenic inputs primarily are derived from irrigated areas adjacent to the INL and industrial waste disposal from sites at the INL. Anthropogenic sources of chemical and isotopic constituents include industrial wastes disposed at the INL, agricultural wastes from fertilizer, cattle manure, and legume crops tilled under at the end of the growing season (Rupert, 1996), road salt and salt brine (Ken Hahn, Idaho Transportation Department, oral commun., October 6, 2015; U.S. Department of Energy, 2011), and atmospheric deposition of tritium, carbon-14, and other environmental tracers. Anthropogenic inputs from domestic septic system wastes are negligible (Rupert, 1996). The predominant waste constituents disposed at the INL have been Na, Cl, SO_4, NO_3, and ^3H (Davis and others, 2013). The disposal methods, years of disposal, and wastes disposed for various facilities at the INL are shown in table 8. Agricultural wastes may be significant sources of NO_3, K, and Cl (Rupert, 1996; Appelo and Postma, 2005; Shakhashiri, 2015), and road salt and road deicing salt brine may be sources Ca, Na, Mg, and Cl (U.S. Department of Energy, 2011). Deposition of environmental tracers that were or are anthropogenic in origin include ^3H, ^{14}C, CFCs, and SF_6 (Michel, 1989; Plummer and others, 1993; Busenberg and Plummer, 2000).

Geothermal water beneath the ESRP aquifer is anoxic and has large concentrations of HCO_3, Na, SO_4, B, Fe, and Li (INEL-1 10,300 ft, tables 12–14). Consequently, a small amount of upwelling geothermal water that mixes with shallow ESRP groundwater can produce redox reactions and noticeable changes in major ion and dissolved metal chemistry (Rattray, 2015).

Classification of Water Types

Water types, or hydrochemical facies, of water samples may be used to indicate broad differences in the major ion chemistry of water samples, the chemical evolution of groundwater, and as an indicator of mixing of source waters. Water at the INL and vicinity was classified into hydrochemical facies based on the relative percentage of individual cations and anions. For example, cation (Ca^{+2}, Mg^{+2}, and $Na^+ + K^+$) and anion ($HCO_3^- + CO_3^{-2}$, Cl^-, and SO_4^{-2}) concentrations (in units of milliequivalents per liter) of water samples were plotted on trilinear (Piper) diagrams (Plummer and others, 2004b), with the cations and anions plotted as a percentage of the total cation or total anion concentrations (fig. 10*A*). The Na-HCO_3 hydrochemical facies was defined as water in which $Na^+ + K^+$ makes up 50 percent or more of the total cations and $HCO_3^- + CO_3^{-2}$ makes up 50 percent or more of the total anions (Rattray and Ginsbach, 2014). Similarly, the Mixed Cation-Mixed Anion hydrochemical facies is defined by water in which no cation makes up 50 percent or more of the total cations and no anion makes up 50 percent or more of the total anions.

Table 7. Potential sources of inorganic chemical constituents to the eastern Snake River Plain aquifer, Idaho National Laboratory and vicinity, eastern Idaho.

[The sources of inorganic chemical constituents are based on information in Barraclough and others (1967); Schoen (1972); Roberson and Schoen (1973); Robertson and others (1974); Parliman (1983); Deer and others (1983); Mann (1986); Wood and Low (1988); Hem (1992); McLing (1994); Knobel and others (1997); McNutt (2000); Osmond and Cowart (2000); Busenberg and others (2001); Rattray and Ginsbach (2014); Rattray (2015); Shakhashiri (2015). **Abbreviations:** ATRC, Advanced Test Reactor Complex; INTEC, Idaho Nuclear Engineering and Technology Center; MFC, Materials and Fuels Complex; NRF, Naval Reactors Facility; RWMC, Radioactive Waste Management Complex; TAN, Test Area North; >, greater than]

Inorganic chemical constituent	Potential sources of inorganic chemical constituents
Calcium	Dissolution of carbonate (calcite, aragonite, dolomite), silicate (primarily from basaltic glass and plagioclase, minor amounts from pyroxene), evaporite (gypsum, anhydrite), fluoride (fluorite), and phosphate (apatite, fluorapatite) minerals; agricultural soil amendments (inorganic fertilizer, gypsum, lime); discharge of wastewater at the ATRC.
Magnesium	Dissolution of carbonate (magnesium-calcite, dolomite) and silicate (primarily from basaltic glass, minor amounts from olivine and pyroxene) minerals; agricultural soil amendments (lime); discharge of wastewater (at ATRC); road deicing salt brine.
Sodium	Dissolution of silicate (primarily from rhyolitic glass, basaltic glass, and plagioclase) and evaporite (halite) minerals; agricultural soil amendments (inorganic fertilizer, manure); sewage; road salt; ion exchange reactions; discharge of wastewater; geothermal water.
Potassium	Dissolution of silicate (primarily from rhyolitic and basaltic glass, possibly minor amounts from potassium feldspar and biotite) and evaporite (sylvite) minerals; agricultural soil amendments (inorganic fertilizer, manure); sewage; geothermal water.
Silica	Dissolution of silicate (primarily from rhyolitic glass, basaltic glass, and plagioclase, minor amounts from olivine, pyroxene, and possibly potassium feldspar and biotite) minerals.
Bicarbonate and carbonate	Dissolution of carbonate (calcite, dolomite) and silicate (primarily from rhyolitic glass, basaltic glass, and plagioclase, minor amounts from olivine, pyroxene, and possibly potassium feldspar) minerals; agricultural soil amendments (lime); discharge of wastewater (from decomposition of organic compounds or sewage); geothermal water; dissociation of carbonic acid.
Chloride	Dissolution of evaporite (halite) minerals; agricultural soil amendments (inorganic fertilizer, manure); sewage; road salt and road deicing salt brine; discharge of wastewater; atmospheric deposition.
Sulfate	Dissolution of evaporite (gypsum, anhydrite) minerals; oxidation of sulfide minerals (pyrite); agricultural soil amendments (inorganic fertilizer, gypsum); discharge of wastewater (at MFC, NRF, ATRC, and INTEC); geothermal water; atmospheric deposition.
Fluoride	Dissolution of silicate (possibly from rhyolitic glass, minor amounts from micas) minerals, fluoride (fluorite), and phosphate (fluorapatite) minerals; discharge of wastewater (at INTEC); geothermal water.
Nitrate	Agricultural soil amendments (inorganic fertilizer, manure); sewage; animal waste; legumes; plant debris; discharge of wastewater; atmospheric deposition.
Aluminum	Dissolution of silicate (primarily from rhyolitic glass, basaltic glass, and plagioclase, possibly minor amounts from potassium feldspar and biotite) minerals.
Barium	Dissolution of carbonate (witherite) and sulfate (barite) minerals; discharge of wastewater (at ATRC).
Boron	Dissolution of evaporite (borax) minerals; agricultural soil amendments (inorganic fertilizer); geothermal water.
Chromium	Discharge of wastewater (ATRC and MFC) and leaching of solid wastes (RWMC).
Iron	Dissolution of silicate (primarily from basaltic glass, minor amounts from olivine and pyroxene) minerals, oxidation of sulfide (pyrite) minerals; agricultural soil amendments (inorganic fertilizer); geothermal water; relatively insoluble in oxic water.
Lithium	Dissolution of silicate (mica) minerals; geothermal water.
Manganese	Small amounts in carbonate rocks (limestone, dolostone) and a significant constituent of basalt; agricultural soil amendments (inorganic fertilizer); geothermal water.
Strontium	Dissolution of carbonate rocks (limestone, dolostone) and silicate (primarily from plagioclase and potassium feldspar) minerals; discharge of wastewater or leaching of solid waste (particularly at INTEC, but also TAN, MFC, ATRC, and RWMC).
Uranium	Dissolves in minor amounts from most rocks, with greater abundance in igneous (felsic > mafic) than sedimentary rocks; discharge of wastewater or leaching of solid waste (at MFC, INTEC, CFA, and RWMC); relatively insoluble in anoxic water.

Table 8. Waste constituents disposed to the subsurface, Idaho National Laboratory, eastern Idaho.

[Information from Davis and others (2013), U.S. Department of Energy (2011), Lenhard and others (2004), Fromm (1995) and Busenberg and others (2001). Locations of site facilities shown on figure 3*B*. **Waste constituents disposed:** Includes only constituents that are discussed in this report. **Abbreviations:** Ba, barium; Ca, calcium; Cl, chloride; CFC, chlorofluorocarbon; Cr, chromium; F, fluoride; ^{3}H, tritium; Mg, magnesium; Na, sodium; NO_3, nitrate; SO_4, sulfate; Sr, strontium; U, uranium]

Site facility	Historical and current disposal methods	Years	Waste constituents disposed
Advanced Test Reactor Complex	Wells, infiltration, and evaporation ponds	1952 to present	Ca, Mg, Na, Cl, SO_4, NO_3, Cr, Ba, ^{3}H, ^{90}Sr, CFCs
Central Facilities Area	Drain field, ponds, landfills[1]	1952 to present	Na, Cl, NO_3, U isotopes
Idaho Nuclear and Technology Engineering Center	Wells, infiltration ponds and trenches, buried waste	1952 to present	Na, Cl, SO_4, F, NO_3, ^{3}H, ^{90}Sr, U isotopes, CFCs
Materials and Fuels Complex	Ditches, lagoons, canals, pit	1960 to present	Na, Cl, SO_4, N, Cr, ^{90}Sr, ^{238}U
Naval Reactors Facility	Ponds, ditch	1953 to present	Na, Cl, SO_4, NO_3, ^{3}H, CFCs
Radioactive Waste Management Complex	Burial in landfill, trenches, and pits;[1] septic systems	1952 to present	Na, Cl, NO_3, Cr, organic compounds, ^{14}C, ^{90}Sr, U isotopes, CFCs
Test Area North (includes the Technical Support Facility)	Well, infiltration ponds	1953 to 2007	Na, Cl, organic compounds, ^{3}H, ^{90}Sr

[1] Solid waste.

The hydrochemical facies of surface water and groundwater samples from the study area were plotted on a trilinear diagram (fig. 10*A*), and oval areas representing most natural groundwater at the INL were included on this figure to compare where various source waters or other groundwater at the INL plot relative to natural groundwater. The spatial distribution of the hydrochemical facies of surface water and groundwater in the study area is shown in figure 10*B*.

Interpretation of Isotope Ratios

Geochemistry data from groundwater at and near the INL include stable and radioactive isotope data. Isotopic data were reported as isotope ratios using delta notation (δ^2H, δ^{18}O, δ^{13}C, δ^{34}S, δ^{15}N, δ^3He), mass ratios (^{87}Sr/^{86}Sr, ^{3}He/^{4}He), activity ratio (^{234}U/^{238}U), and activities (^{3}H, ^{14}C). Differences in stable isotope ratios result from isotope fractionation and exchange, and differences in radioisotopes result primarily from radioactive decay (the spontaneous emission of particles and radiant energy from the unstable nuclei of a radioactive atom or isotope; Faure, 1986) and (or) mixing of water with different radioisotope activities. Radioactive, or parent, isotopes that decay may become less abundant in the aquifer or aquifer matrix, whereas the daughter isotopes produced by the decay of parent isotopes may increase in abundance. For example, rubidium-87 (^{87}Rb), ^{238}U, ^{234}U, ^{3}H, and ^{14}C are all unstable isotopes that undergo radioactive decay in the aquifer and ^{87}Sr, ^{234}U, ^{3}He, and ^{4}He are some of the daughter isotopes produced by radioactive decay. Isotope ratios can be used to identify sources of water and chemical elements, and radioisotopes reported as activities typically are used to estimate the age of groundwater (that is, the time since the groundwater was recharged).

Hydrogen and Oxygen

The stable isotope ratios of hydrogen and oxygen in groundwater are inherited from the sources of groundwater, although evaporation or mixing of water can modify the isotope ratios. Groundwater in the study area originates largely from precipitation in the mountains (Rattray and Ginsbach, 2014; Rattray, 2015), and in precipitation the stable isotopes of hydrogen and oxygen reflect the origin of the air mass and the conditions under which precipitation occurs (Benjamin and others, 2004). For example, in a continental air mass that undergoes numerous precipitation events, the δ^2H and δ^{18}O values of the water vapor in the air mass (or cloud) become progressively depleted (lighter, smaller, or more negative) as fractionation and Rayleigh-type distillation causes precipitation to be isotopically enriched (heavier, larger, or less negative; Clark and Fritz, 1997). This rainout effect causes precipitation to become progressively lighter along the path of the air mass. Precipitation also may become progressively depleted as temperature decreases, which can occur due to changes in latitude, altitude, or seasons. Changes in latitude across the study area are not large enough to effect a change in temperature or the δ^2H and δ^{18}O values of precipitation.

However, colder temperatures and relatively lighter δ^2H and $\delta^{18}O$ values in precipitation occur in the study area at high elevations in the mountains and during winter.

In water undergoing evaporation, δ^2H and $\delta^{18}O$ values in the residual water body become enriched due to isotope mass fractionation. This effect is readily identified on a δ^2H–$\delta^{18}O$ diagram (fig. 11), where the progressive increase of δ^2H and $\delta^{18}O$ values in the evaporated water body plots along a lower slope than the slope of local meteoric water lines (Clark and Fritz, 1997). For example, a linear regression of δ^2H and $\delta^{18}O$ values from Mud Lake water samples produced an evaporation line with a slope ($\delta^2H = 5.35\ \delta^{18}O + 38.9$, $r^2 = 0.88$) that may be characteristic for surface water on the ESRP near the INL (fig. 11). Local meteoric water lines (LMWL) for summer and winter precipitation in the mountains east, north, and west of the study area were developed by Benjamin and others (2004), and these LMWL, and the δ^2H and $\delta^{18}O$ values for surface-water and groundwater samples collected from the study area (table 15), are shown in figure 11. An oval region representing most natural groundwater at the INL also was included in figure 11 to compare where various potential source waters, and other groundwater at the INL, plot on the graph relative to natural groundwater.

Carbon

The stable isotopes of dissolved inorganic carbon in groundwater are initially influenced by recharge water moving through the soil and unsaturated zones. This recharge is influenced by the decay of organic matter, which has typical $\delta^{13}C$ values of soil CO_2 (of C_3-type plants typical in temperate, high-latitude regions) estimated to range from about -24 to -30 permil (Clark and Fritz, 1997), although Wood and Low (1988, p. 22) estimated that $\delta^{13}C$ values of soil CO_2 in upland tributary basins to the INL were about -22 permil. On the ESRP at the INL, Wood and Low (1988) noted that the $\delta^{13}C$ values of CO_2 in soil gas averaged -14 permil and Conrad and DePaolo (2004) measured background (uncontaminated) $\delta^{13}C$ values from the shallow (30–230 ft depth) unsaturated zone at the RWMC and determined an average $\delta^{13}C$ value for soil CO_2 of -18.2 permil.

As water enters and moves through the soil and unsaturated zones, CO_2 dissolves in groundwater and fractionation of the carbon isotopes produces a $\delta^{13}C$ value for bicarbonate that is enriched by about 9 permil relative to the soil or unsaturated zone CO_2 (Clark and Fritz, 1997). Water-rock interaction with carbonate rocks in the soil, unsaturated, and saturated zones may also influence $\delta^{13}C$ values. Marine carbonate rocks typically have $\delta^{13}C$ values near zero (Clark and Fritz, 1997), and reported $\delta^{13}C$ values of microbial limestone in the Beaverhead Mountains had $\delta^{13}C$ values ranging from -2.8 to 5.1 permil (Hodges, 2006). Consequently, dissolution of carbonate rocks will cause $\delta^{13}C$ values in groundwater to become heavier. Because $\delta^{13}C$ values fractionate to slightly heavier values in calcite precipitating from groundwater (Clark and Fritz, 1997), $\delta^{13}C$ values in the residual groundwater will be lighter.

Upwelling of geothermal water may also influence $\delta^{13}C$ values in the ESRP aquifer. Carbon dioxide in the mantle has $\delta^{13}C$ values that range from about -10 to -2 permil (Clark and Fritz, 1997). These values are similar to or heavier than $\delta^{13}C$ values in natural groundwater at the INL, indicating that upwelling geothermal water that mixes with natural groundwater may cause the $\delta^{13}C$ values in some natural groundwater to become slightly heavier.

Sulfur

The stable isotopes of sulfur can be used to determine sources of sulfur and, if sources of sulfur vary across the study area, to identify sources of water. Potential sources of sulfur in the study area include dissolution of calcium sulfate (anhydrite or gypsum in evaporite deposits, soil amendments, or associated with limestone), iron sulfide (pyrite) minerals, and volcanic sulfur. Typical ranges of $\delta^{34}S$ values for calcium sulfate are about 10–30 permil in Paleozoic and Cenozoic evaporites and about 0–25 permil for calcium sulfate associated with limestone, and the typical range for volcanic sulfur is about 2–15 permil (Clark and Fritz, 1997). A single measurement of pyrite from a vesicle in a sample of ESRP basalt yielded a value of -8.9 permil (Wood and Low, 1988). The stable isotopes of sulfur from the Snake and Boise Rivers, at locations where they drain Permian sulfate deposits and pyritized granite, respectively, had $\delta^{34}S$ values of 14.9 and -6.6 permil (Wood and Low, 1988).

Nitrogen

The stable isotopes of nitrogen may be used to determine whether nitrogen (as nitrate) in groundwater was derived from inorganic fertilizer, manure, septic systems, or underwent denitrification. Ranges typical of $\delta^{15}N$ values for these inputs are -5 to 5 permil for inorganic fertilizer and 10 to 20 permil for manure or septic systems (Clark and Fritz, 1997). The $\delta^{15}N$ value for the residual fraction of nitrate that underwent denitrification (the nitrate remaining after N_2 gas produced from denitrification leaves the system) increases as the residual fraction of nitrate decreases; $\delta^{15}N$ values for the residual fraction have been reported to be as much as 80 permil (Clark and Fritz, 1997).

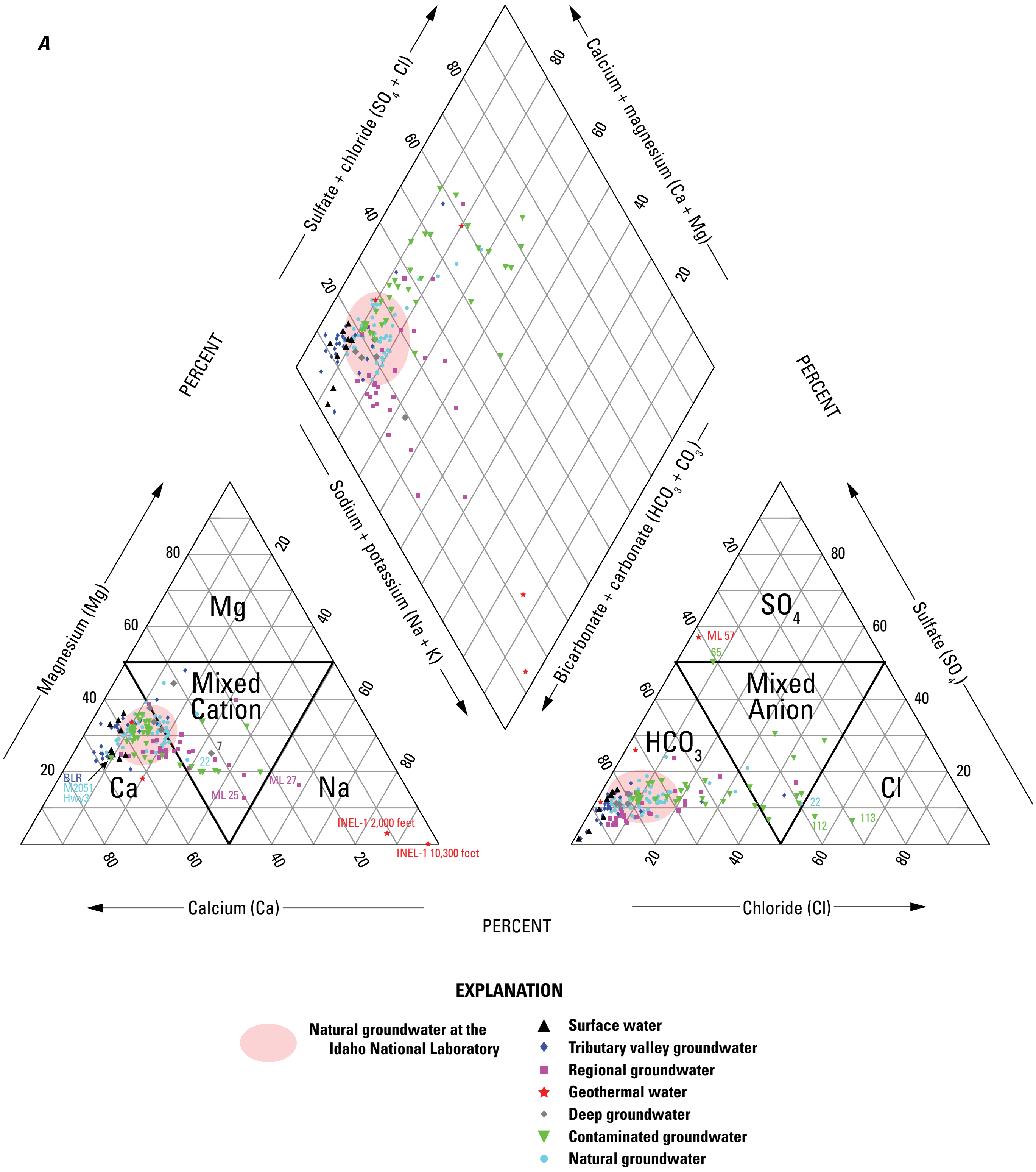
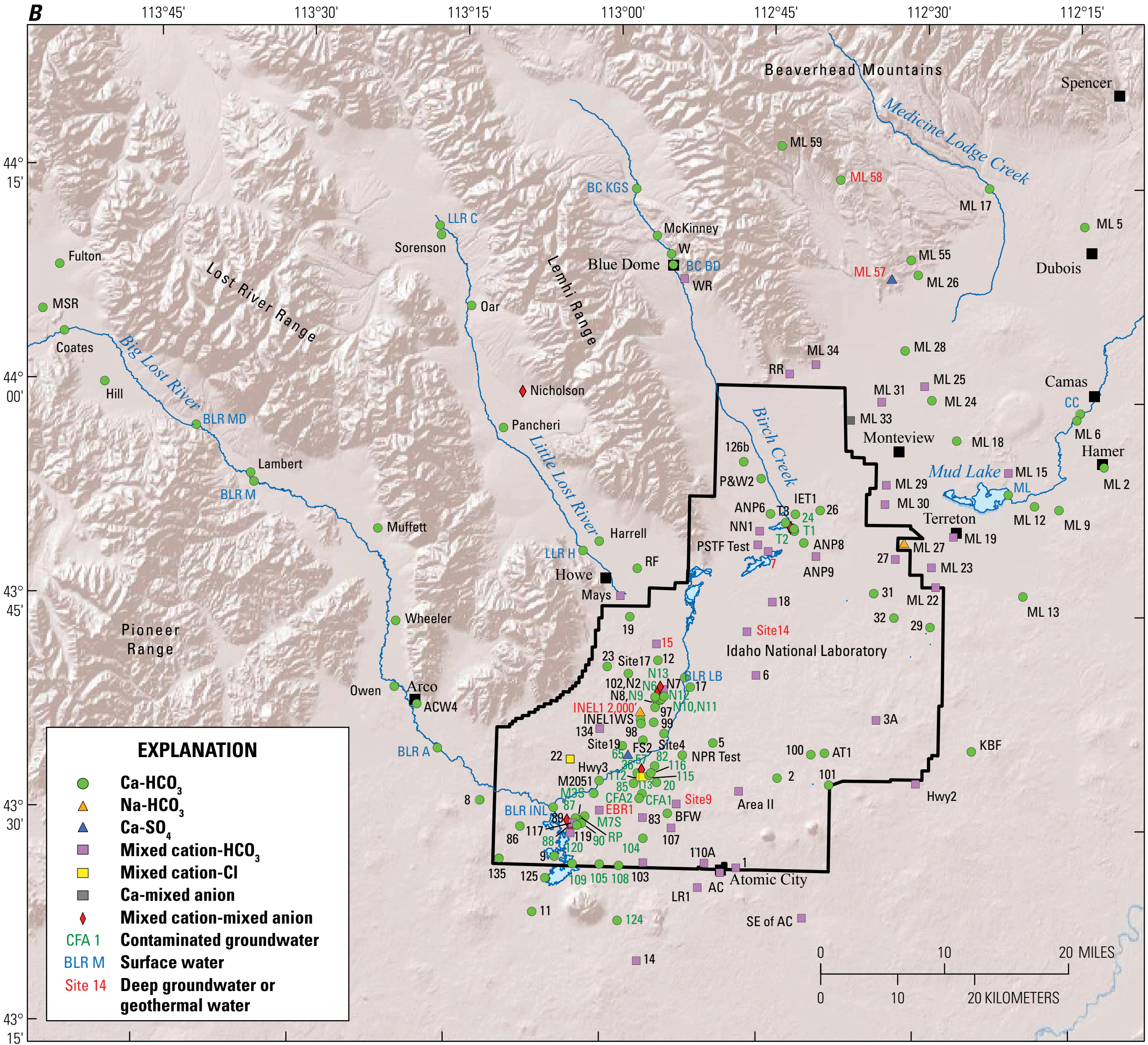


Figure 10. Hydrochemical facies of surface water and groundwater in the study area, Idaho National Laboratory and vicinity, eastern Idaho. (*A*) Trilinear diagram showing hydrochemical facies of surface-water and groundwater samples. (Oval areas represent where most natural groundwater plots on the diagram, and triangular fields represent defined cation and anion hydrochemical facies.) (*B*) Spatial distribution of hydrochemical facies of surface-water and groundwater samples.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 10.—Continued

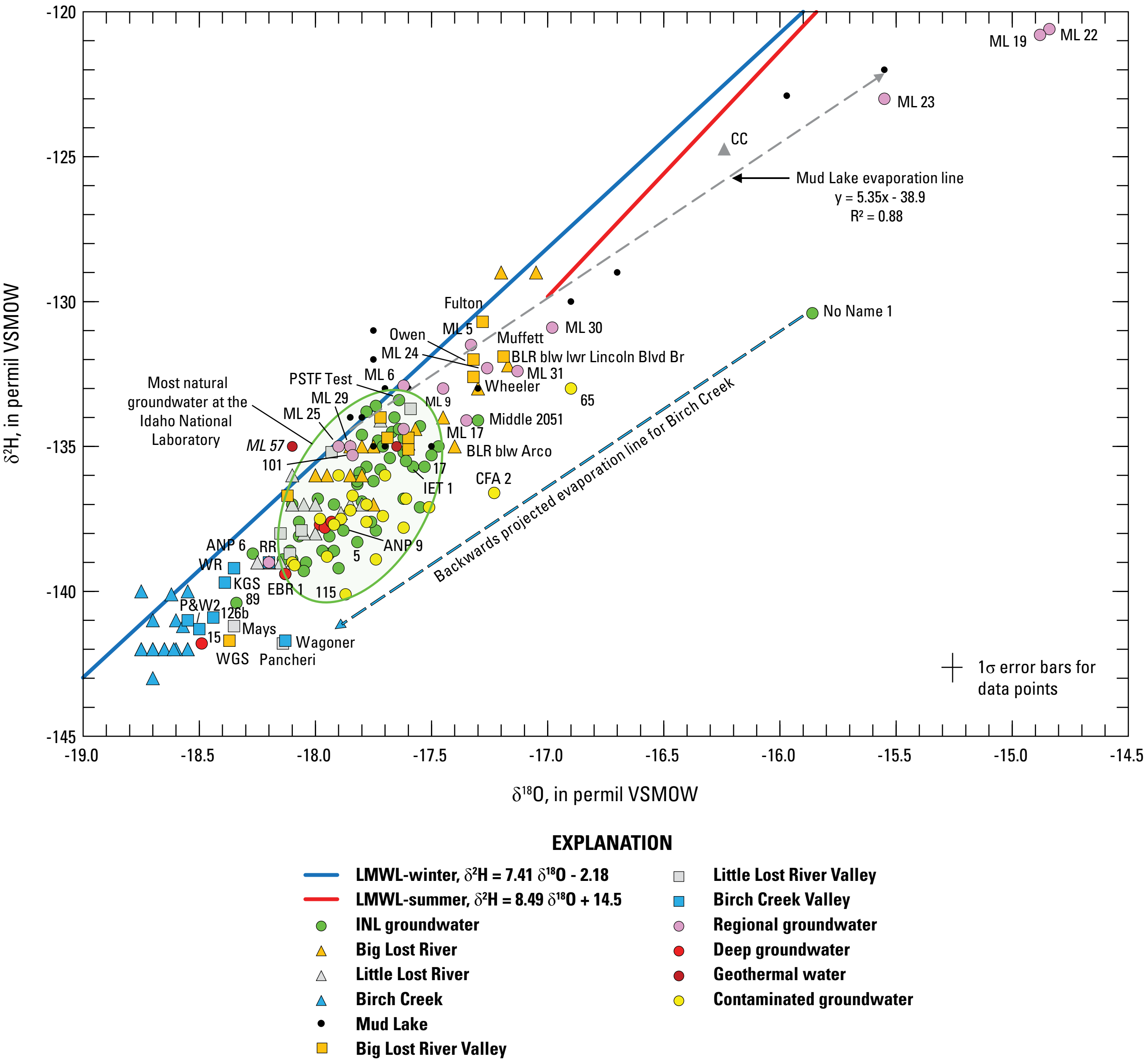


Figure 11. Local meteoric water lines for summer and winter precipitation, stable isotope ratios of hydrogen and oxygen (δ^2H and $\delta^{18}O$, respectively) for surface-water and groundwater samples collected from the study area, evaporation lines, and the region that represents most δ^2H and $\delta^{18}O$ (Vienna Standard Mean Ocean Water [VSMOW]) values in natural groundwater at the Idaho National Laboratory, eastern Idaho. Actual values are shown in tables 3 and 15; abbreviated site names are shown in table 10.

Helium

Helium, a noble gas, is chemically inert, has two stable isotopes (^{3}He and helium-4 [^{4}He]) that accumulate in aquifer materials through different processes (such as radioactive decay of U and Th in aquifer minerals and upward fluxes from deeper units, including the mantle), and ^{4}He may be released slowly, and at a steady rate, from the aquifer matrix into groundwater. The unreactive chemistry of helium, the unique helium concentrations and ^{3}He/^{4}He isotopic ratios, or R (calculated from δ^3He values in table 15 and eq. 2-11 for calculating R_s/R_a in appendix 2, where R_s is the R of an environmental sample and R_a is the R of air), of various waters, and the steady release rate of ^{4}He to the groundwater allows helium concentrations and isotopic ratios in groundwater to be used to identify sources of water and to estimate groundwater ages. However, complications in using helium for these purposes may arise from transport of helium across aquifer boundaries due to upward diffusion of helium from the mantle or deep crust (Stute and others, 1992; Clark and Fritz, 1997) and (or) enhanced release of ^{4}He from aquifers containing recently eroded sediments (Solomon and others, 1996; Solomon, 2000).

Concentrations of helium are about 4.5×10^{-8} cm^3 at standard temperature and pressure per gram of fluid or solid (STP/g) in surface water, 10^{-7}–10^{-4} cm^3 STP/g in crustal fluids, and as large as 2.7×10^{-5} cm^3 STP/g in mantle fluids (Clark and Fritz, 1997). Basalts of the ESRP near the INL have helium concentrations ranging from about 1×10^{-9} to 7×10^{-9} cm^3 STP/g (of rock; Graham and others, 2009). Typical concentrations of helium in groundwater at the INL that was saturated with air, or that contained small amounts of excess air, were about 4.5×10^{-8}–6.5×10^{-8} cm^3 STP/g (Busenberg and others, 2001).

Helium in air has an R of 1.384×10^{-6} (R_a), and helium dissolved in surface water is slightly fractionated to a smaller R of 1.360×10^{-6} (R_{sw}). Helium derived from the crust is enriched in ^{4}He because U and Th isotopes (described in section, "Uranium") in crustal rocks go through numerous α-particle decay steps in the process of decaying to their final daughter product, and α particles are ^{4}He molecules (Clark and Fritz, 1997). Crustal helium that accumulates in groundwater, therefore, is enriched in ^{4}He, has an R of about 10^{-9}–10^{-7} (R_c) (Solomon, 2000), and an R_c/R_a ranging from about 0.0007 to 0.07. Helium derived from the mantle is enriched in ^{3}He, relative to R_a, and has an R of about 1.0×10^{-5}–3.0×10^{-5} (R_m) and an R_m/R_a ranging from about 7 to 21 (Clark and Fritz, 1997; Solomon, 2000). Increased ^{3}He concentrations in groundwater also may occur from radioactive decay of natural or anthropogenic ^{3}H in the groundwater, producing tritiogenic ^{3}He with an R (R_t) in groundwater that will increase as long as significant amounts of ^{3}H are present. Sources of significant amounts of tritiogenic ^{3}He in the ESRP aquifer at the INL include recharge from streams and surface water used for irrigation during the 1950s–1970s and discharge of tritium in wastewater at the INL.

The various sources of helium produce different evolutions of helium concentrations and R_s/R_a ratios in groundwater. These differences were illustrated for groundwater samples at the INL by plotting R_s/R_a ratios compared to helium concentrations in figure 12. Helium in surface water or groundwater that is in equilibrium with helium in air has an R_s/R_a ratio of approximately 1 and small helium concentrations, although samples containing excess air (No Name 1; Busenberg and others, 2001) have larger helium concentrations. Groundwater containing crustal helium has helium concentrations that increase, and R_s/R_a ratios that decrease, with increasing groundwater residence time, and groundwater containing mantle helium has helium concentrations and R_s/R_a ratios that increase with increasing amounts of mantle helium. The R_s/R_a ratios also increase in groundwater affected by tritiogenic helium. However, even though tritiogenic and mantle helium may both have large R_s/R_a ratios, they can be differentiated from each other because tritiogenic helium produces much smaller increases in helium concentrations than mantle helium.

Helium may completely or partially re-equilibrate with atmospheric helium in groundwater used for irrigation. Under these conditions, helium concentrations in the groundwater may decrease and, depending on the R_s/R_a ratios in the groundwater prior to use for irrigation, R_s/R_a ratios may decrease, increase, or stay the same.

Basalts of the ESRP were derived from the mantle, so the basalts contained helium enriched in ^{3}He. Basalts near the INL have an R ranging from 2.2×10^{-5} to 2.4×10^{-5} (R_b) and R_b/R_a ratios of about 15–17 (Graham and others, 2009), although dissolution of basalt adds very small amounts of helium to groundwater. Consequently, helium added to groundwater from dissolution of basalt should slightly increase the R_s/R_a ratios of the groundwater without a significant increase in helium concentrations (fig. 12). Additionally, accumulation of helium in groundwater from dissolution of basalt is limited to groundwater undersaturated with respect to the minerals in the basalt, and once groundwater reaches chemical equilibrium with these minerals this source of helium ceases. Only recharge from precipitation, streams, and groundwater from the tributary valleys, and surface water used for irrigation, all of which should be undersaturated with silica, should dissolve significant amounts of basalt.

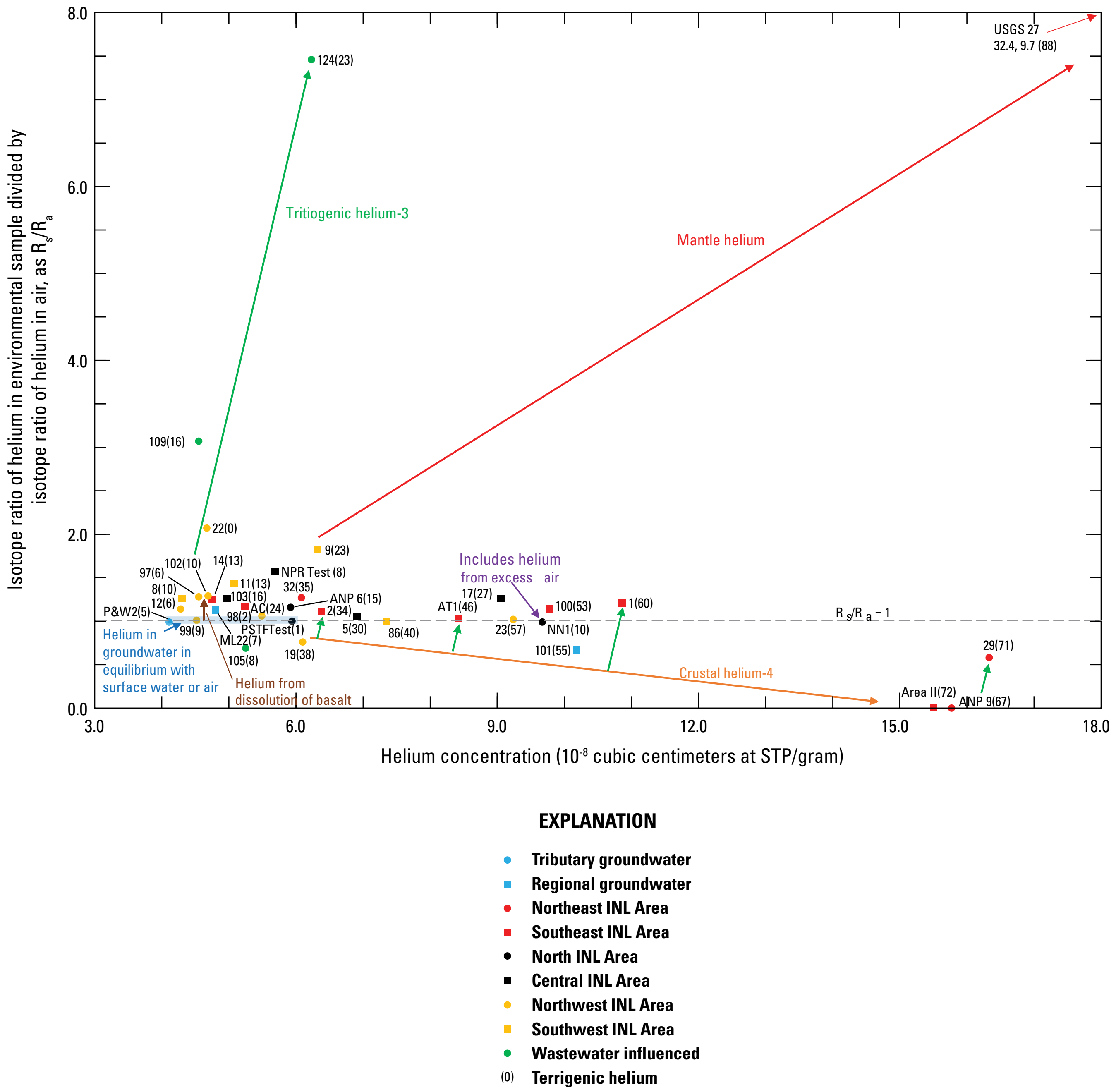


Figure 12. Helium concentrations and the isotope ratios of helium (as the isotope ratio of sample to air, R_s/R_a) for groundwater samples, Idaho National Laboratory and vicinity, eastern Idaho. Arrows indicate how helium concentrations and ratios evolve for various sources of helium. STP, standard temperature and pressure.

Strontium

The isotope ratio, $^{87}Sr/^{86}Sr$, can be used in groundwater studies to identify groundwater source areas, flow directions, and mixing (Johnson and others, 2000) because Sr is readily soluble in groundwater, $^{87}Sr/^{86}Sr$ values often are relatable to specific geologic terranes, and fractionation of the Sr isotopes is generally negligible (McNutt, 2000). The current amount of Sr in the environment is the sum of primordial Sr plus any ^{87}Sr resulting from radioactive decay of ^{87}Rb (with a half-life of 4.88×10^{10} years).

Atmospheric deposition of Sr is generally quite low and, compared to dissolution of minerals, generally is not a significant source of Sr in water (Graustein, 1989). Consequently, Sr in water primarily is derived from water-rock interaction between groundwater and the geologic terranes of the source areas and matrix of an aquifer. An anthropogenic source of strontium occurs at the INL, however, where ^{90}Sr was discharged to the subsurface at some INL facilities (table 7) and a plume of elevated ^{90}Sr activities is present in groundwater downgradient of the INTEC (Bartholomay, Tucker, and others, 2000; Davis and others, 2013). Strontium-90 decays to daughter products yttrium-90 and zircon-90 (stable daughter) and thus has no effect on the $^{87}Sr/^{86}Sr$ in groundwater at the INL.

Strontium and rubidium (Rb) may substitute for Ca and K, respectively, in minerals. Calcium is abundant in many minerals in the study area, such as carbonate (calcite, aragonite, and dolomite), evaporite (gypsum and anhydrite), and silicate (plagioclase, amphiboles, pyroxenes, micas, and clays) minerals, so Sr should be abundant in the study area, whereas potassium is present only in a few silicate (potassium feldspar, micas, and clays) and evaporite (sylvite) minerals in the study area, so Rb should not be abundant in the study area. The $^{87}Sr/^{86}Sr$ value of a mineral reflects the relative abundance of Sr and Rb in the mineral and the age of the mineral. For instance, if Sr is abundant in a mineral and Rb is not, then the $^{87}Sr/^{86}Sr$ value of that mineral will change only slightly over time. Conversely, if Rb is abundant in a mineral and Sr is not, then the $^{87}Sr/^{86}Sr$ value of that mineral will increase through time due to decay of ^{87}Rb to ^{87}Sr.

Because Ca is abundant in many minerals in the study area, and K is not, Sr typically is more abundant than Rb in most of the rock types in the study area, although Rb is generally more abundant than Sr in sandstone and rhyolite. For example, average concentrations (in parts per million) typical for rock types in the study area are 610 and 3 for carbonate rocks, 300 and 140 for shale, 465 and 30 for basalt, and 20 and 60 for sandstone for Sr and Rb, respectively (Faure, 1986). Strontium and Rb concentrations range from about 50 to 1,000 and 50 to 500 for dacite and 600 to 1,200 and 10 to 100 for andesite, respectively (Hedge, 1966). The Sr and Rb concentrations measured from 123 basalt core samples (from 7 coreholes) from the ESRP at the INL ranged from 176 to 392 and 1.0 to 34 and had mean concentrations of 281 and 10.7, respectively (Knobel and others, 1995; Reed and others, 1997). Concentrations measured in rhyolitic tuffs of the Heise volcanic field ranged from 22 to 58 for Sr and 220 to 240 for Rb (Morgan and others, 1984).

Typical $^{87}Sr/^{86}Sr$ values of various types of geologic terranes are 0.7030 for young, mantle-derived, volcanic rocks, 0.7068–0.7092 for marine carbonate rocks, and as much as 0.7500 or more for old ($>10^9$ years) igneous or metamorphic rocks (Graustein, 1989). The $^{87}Sr/^{86}Sr$ values of various types of volcanic terranes at and near the study area were 0.7056–0.7080 (mean of 0.7069) for Cenozoic olivine basalts on the ESRP, 0.7110–0.7134 for silicic volcanic rocks on the ESRP, and 0.7061–0.7085 for Cenozoic basalts from Yellowstone National Park and vicinity (Leeman and Manton, 1971; Graham and others, 2009).

Uranium

The uranium isotope ratio, $^{234}U/^{238}U$, can be used in groundwater studies to identify groundwater sources, flow directions, mixing, and the age of old (tens to hundreds of thousands of years; Clark and Fritz, 1997) groundwater because U is readily soluble in oxic groundwater, has natural variations in groundwater, and the isotopes have long half-lives (Roback and others, 2001). Uranium-234 is a daughter product of the ^{238}U decay series, where ^{238}U undergoes α-decay (with a half-life of 4.47×10^9 years) to thorium-234 (^{234}Th), and ^{234}U is produced from ^{234}Th by two short-lived beta decay events. Uranium-234 is also radioactive (with a half-life of 2.48×10^5 years) and eventually decays to the stable isotope lead-206 after numerous intermediate daughter steps (Clark and Fritz, 1997; Osmond and Cowart, 2000). In rocks sufficiently old (approximately 10^6 years) the parent and daughter isotopes of the ^{238}U decay series will reach secular equilibrium (that is, the activity of the parent isotope is identical to its daughters), with an activity ratio for $^{234}U/^{238}U$ of 1 (Luo and others, 2000).

The activity ratio of $^{234}U/^{238}U$ in groundwater usually is greater than 1 because the mobility of ^{234}U is enhanced by physical factors associated with α-decay recoil. Alpha-recoil acts to increase the ^{234}U activity in groundwater because α-decay of ^{238}U displaces ^{234}Th about 20 nanometers in the mineral or rock, resulting in microfracturing of the mineral lattice and, in some cases, ejection of ^{234}Th into the groundwater solution (Osmond and Cowart, 2000). The physical damage to the mineral lattice from the decay of ^{238}U also may allow ^{234}Th or ^{234}U to preferentially etch, leach, or dissolve from the rock relative to ^{238}U. These physical processes cause the $^{234}U/^{238}U$ ratio in groundwater to increase with increasing length of time that the groundwater is in contact with geologic materials (although very long contact times may cause the ratio to decrease to secular equilibrium as mineral sites with leachable ^{234}U become exhausted).

Uranium is present in most rocks in small concentrations, and generally will be more abundant in crystalline or felsic rocks than in sedimentary or mafic rocks (Osmond and Cowart, 2000). Typical average uranium concentrations (in parts per million) for rock types in the study area were 1.9 for carbonate rocks, 1.4 for sandstone, 3.2 for shale, and 0.43 for basalt (Faure, 1986). In the ESRP basalt aquifer at the INL, uranium concentrations measured from 95 basalt core samples (from 5 coreholes) ranged from 0.02 to 2.4 ppm with a mean concentration of 0.7 ppm (Knobel and others, 1995; Reed and others, 1997). Due to the larger uranium concentration and solubility of carbonate rocks relative to basalt, uranium concentrations and $^{234}U/^{238}U$ ratios in groundwater that flows from carbonate aquifers north of the INL into the ESRP basalt aquifer are likely to persist in the basalt aquifer for a considerable time unless the ratios are modified by mixing with surface water or other groundwater.

The activity ratio of $^{234}U/^{238}U$ in groundwater at the INL also may be influenced by anthropogenic sources of uranium. Uranium isotopes were discharged to the subsurface at some INL facilities (table 8), and anthropogenic uranium was present in groundwater downgradient of the INTEC (Beasley and others, 1998). Groundwater samples within or near the contaminant plume extending downgradient from the INTEC, and from which $^{234}U/^{238}U$ ratios were collected and measured (table 16), were examined for the presence of anthropogenic and non-natural uranium isotopes, but no anthropogenic or non-natural uranium isotopes were detected in the samples (Roback and others, 2001).

Environmental Tracers

Tritium

Large quantities of ^3H, the radioactive isotope of hydrogen, were introduced into the atmosphere by thermonuclear bomb testing in the 1950s and 1960s (Solomon and Cook, 2000). Because ^3H is readily incorporated into water molecules in the atmosphere and is rapidly removed from the atmosphere in meteoric precipitation, the large peak and subsequent decrease of ^3H concentrations in the atmosphere make ^3H a useful tracer for determining the age of water. Because the half-life of ^3H is only 12.34 years, ^3H is currently most useful for qualitatively estimating the residence time of water as older or as younger than the year (1952) when thermonuclear bomb testing in the atmosphere began.

Approximately 31,620 curies (Ci) of ^3H was discharged to the subsurface at the INTEC and ATRC between 1952 and 1998 (Bartholomay, Tucker, and others, 2000), with approximately 21,135 Ci of the ^3H discharged at the INTEC (Davis, 2006; Davis and others, 2013). This has resulted in elevated activities of ^3H, and a ^3H plume, in groundwater downgradient of the ATRC and INTEC (Bartholomay, Tucker, and others, 2000; Davis and others, 2013). The ^3H derived from wastewater cannot be used to estimate the age of groundwater at the INL, although with ^3H-^3He age dating wastewater ^3H may be used to estimate the age of wastewater disposal and average linear groundwater velocities (Busenberg and others, 2001; Ackerman and others, 2006).

The age of groundwater was qualitatively estimated, by plotting the ^3H activity of a water sample and the date of sample collection, as **old groundwater**, **young groundwater**, a mixture of young and old groundwater, or groundwater containing ^3H from wastewater (fig. 13). Old groundwater was defined as a ^3H activity equal to or less than the line on figure 13*A* representing the radioactive decay (the equation for radioactive decay of ^3H is presented in appendix 2, eq. 2-12) of ^3H in water recharged in 1952, using a pre-bomb 1952 ^3H activity in precipitation of 48 pCi/L (Morris and others, 1963). Young groundwater (and surface water) was defined as a ^3H activity within an area approximated by a line on figure 13*A* representing the decay of ^3H in groundwater recharged from precipitation during the mid-1960s (upper bound) and the activity of ^3H in precipitation at the INL[17] from the late 1980s through 2012 (lower bound). Groundwater plotting between the lower bound for young water and the line representing the decay of ^3H in precipitation recharge from 1952 likely is a mixture of young and old groundwater, although this groundwater also could be young recharge from the mid-1950s. Groundwater plotting above the upper bound for young water probably is contaminated with ^3H from discharge of wastewater. Groundwater containing ^3H from wastewater also may plot between the upper bound for young water and the activity of ^3H in precipitation at the INL, so water plotting in this area may be either young groundwater or groundwater contaminated with ^3H from wastewater.

The definitions of young and old groundwater do not preclude that these waters also could be mixtures of young and old groundwater. For example, groundwater that was a mixture of 50 percent 1970 recharge (tritium activity of approximately 1,000 pCi/L) with 50 percent old groundwater (with zero tritium activity) would have a tritium activity of about 125 pCi/L in the mid-1990s and would appear to be young groundwater.

---

[17] The estimated monthly activity of ^3H in precipitation at the INL was calculated for 1953 through 1983 from data in Michel (1989), for 1984 through 2001 from data provided by R.L. Michel (U.S. Geological Survey, written commun., 2012), and was estimated for 2002 through 2012 from a regression ($R^2 = 0.91$; appendix 2, eq. 2-13) of calculated monthly ^3H activities from data provided by R.L. Michel with measured ^3H activities in precipitation measured at Vienna (International Atomic Energy Agency/World Meteorological Organization, 2015) for 1990 through 2001.

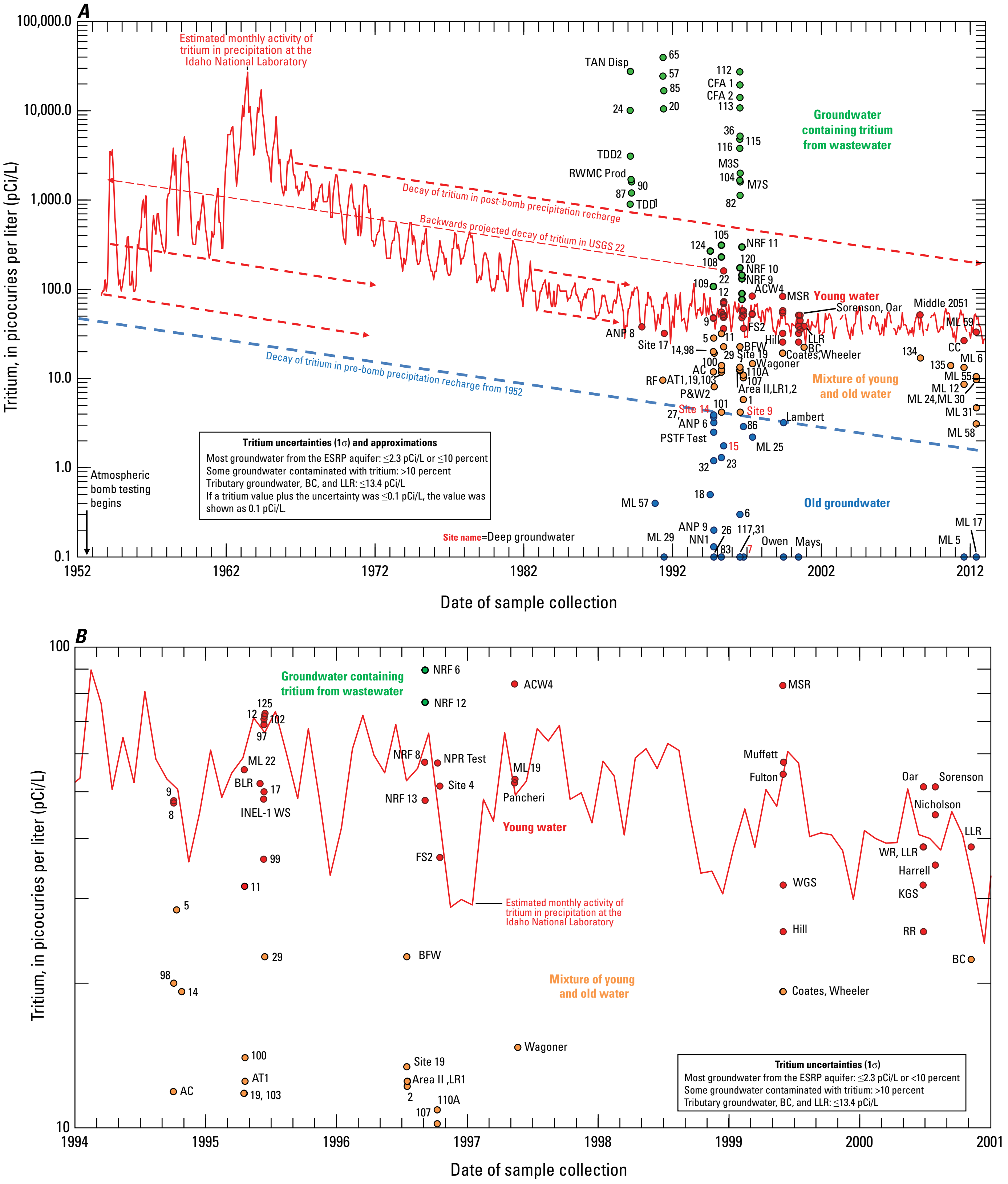


Figure 13. Activity of tritium in surface water and groundwater, the estimated monthly activity of tritium in precipitation, decay curves representing the possible evolution of tritium activities in pre-bomb and post-bomb recharge from precipitation, and areas on the graph representing old groundwater, young water, mixtures of young and old water, and wastewater, Idaho National Laboratory and vicinity, eastern Idaho. (*A*) Tritium activities of water samples collected between 1952 and 2012. (*B*) Water samples collected between 1994 and 2001 with tritium activities between 10 and 100 picocuries per liter.

Similarly, groundwater that was a mixture of 5 percent 1983 recharge (tritium activity of approximately 100 pCi/L) with 95 percent old groundwater (with zero tritium activity) would have a tritium activity of about 2.5 pCi/L in the mid-1990s and would appear to be old groundwater.

Terrigenic Helium

Terrigenic helium (He_{terr}) consists of the helium in groundwater that was derived from the crust and mantle ($He_{terr} = He_{crust} + He_{mantle}$) and is represented as a percentage of the total amount of helium in the groundwater. The He_{terr} in a groundwater sample can be calculated by rearranging the mass balance equation for helium and solving for He_{terr}. The rearranged mass balance equation is (Busenberg and others, 2001)

$$He_{terr} = He_{tot} - He_{eq} + He_{air} + He_{trit}, \tag{1}$$

where

He_{terr} is the terrigenic helium,

He_{tot} is the measured helium in the water sample,

He_{eq} is the helium in solution in equilibrium with air,

He_{air} is the helium in solution derived from excess air in solution, and

He_{trit} is the helium in solution produced by radioactive decay of ^3H (tritiogenic helium).

The He_{terr} equation can be used to estimate the recharge source and relative age of groundwater in the ESRP aquifer at the INL to indicate whether the groundwater consists of **recent recharge**; regional, and presumably older, groundwater; or contains some old, deep groundwater with some mantle helium. Recent recharge refers to groundwater that has been in contact with air or the unsaturated-zone atmosphere within the past several hundred years and has not mixed with regional groundwater, and recent recharge generally has a He_{terr} of about 0–10 percent (Busenberg and others, 2001). Regional groundwater, which has been in contact with the aquifer matrix for a longer period (several hundred years or more), contains a significant amount of crustal helium. Busenberg and others (2001) observed that regional groundwater at and near the INL, and unaffected by recent recharge, generally has a He_{terr} of about 80–90 percent and that thermal springs in the area, which contain mantle helium, had a He_{terr} exceeding 95 percent.

For this report, however, ranges of He_{terr} values indicating specific sources for helium and water were reinterpreted for the ESRP aquifer based on how helium concentrations and ratios evolve (fig. 12) and He_{terr} values compared to ^3H activities (fig. 14). The ranges of ^3H activities indicated young groundwater (typically 30–75 pCi/L for groundwater at the INL), old groundwater (typically <4 pCi/L), or a mixture of young and old groundwater (4–30 pCi/L). The He_{terr} values equal to or less than 10 percent were interpreted to represent recent recharge containing helium in equilibrium with air, between 10 and 50 percent represent crustal helium in regional or tributary groundwater that has mixed with a large amount of recent recharge, 50–80 percent represent crustal helium in regional or tributary groundwater that has mixed with a small amount of recent recharge, and that exceed 80 percent represent mantle helium either in geothermal water or in regional or tributary groundwater containing some geothermal water (figs. 12 and 14). The He_{terr} values that exceeded 80 percent were interpreted to represent some contribution from mantle helium because (1) He_{terr} values of 88–89 percent were present in groundwater from ML 25 and USGS 27, and these wells were interpreted to contain geothermal water (with mantle helium) based on geochemical modeling (Rattray, 2015) or a large R_s/R_a ratio (9.70; fig. 12), respectively; and (2) He_{terr} values of 82–91 percent (and helium concentrations exceeding 20×10^{-8} cm^3 STP/g) were present in either deep groundwater (Site 14, USGS 15) or in groundwater (Site 14, USGS 18, USGS 26, USGS 31) immediately downgradient of sites (ML 27, ML 29, USGS 7, USGS 27) containing geothermal water. Identification of sites containing geothermal water was based on geochemical modeling (ML 27 and ML 29; Rattray, 2015), a large He_{terr} value (97 percent) and helium concentration (149×10^{-8} cm^3 STP/g) (USGS 7), and a large R_s/R_a ratio (USGS 27).

In combination with tritium activities, He_{terr} also may be used to determine the mechanism of recharge (Busenberg and others, 2001, p. 70–72). Rapid, focused recharge or recharge through a thin unsaturated zone has small He_{terr} concentrations (<10 percent) and measurable tritium activities, while slow, diffuse recharge through a thick unsaturated zone also has small He_{terr} concentrations (<10 percent) but little or no tritium (fig. 14).

Tritium/Helium-3, Chlorofluorocarbons, and Sulfur Hexafluoride

The environmental tracers $^3H/^3He$, CFCs, and SF_6 were used to estimate the age of the young fraction of groundwater in the ESRP aquifer at the INL. These tracers were useful for estimating the age of young groundwater that recharged since about 1940–70 (Busenberg and others, 2001).

The $^3H/^3He$ age-dating method is based on the fact that the daughter product from radioactive decay of ^3H is ^3He. This leads to an ingrowth of ^3He with time in groundwater containing ^3H (see ingrowth equation in appendix 2, eq. 2-14).

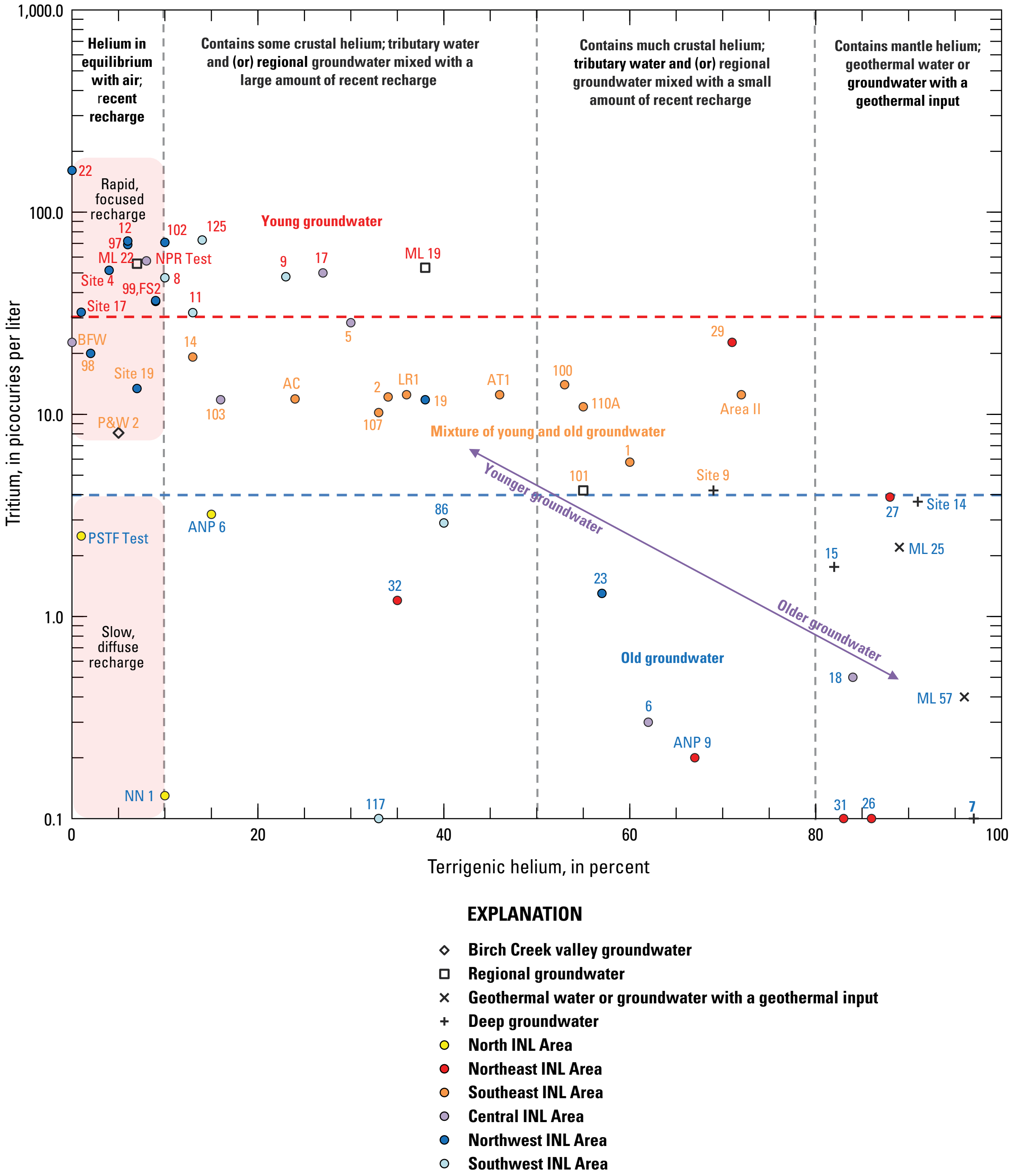


Figure 14. Activity of tritium and percent terrigenic helium, ranges of tritium activities that indicate the qualitative age of groundwater, and ranges of terrigenic helium that were interpreted to represent specific sources of helium and water, Idaho National Laboratory and vicinity, eastern Idaho.

By combining the equations for radioactive decay of ^{3}H and ingrowth of ^{3}He, the age of the groundwater may be determined from the measured activities of ^{3}H and ^{3}He (Clark and Fritz, 1997; Solomon and Cook, 2000).

Complications to age dating with ^{3}H-^{3}He arise due to the various sources of ^{3}H and ^{3}He (sources of ^{3}H and ^{3}He are discussed in the sections, "Tritium" and "Helium"). Determining the amount of ingrown ^{3}He requires that all other sources of ^{3}He be subtracted from the measured concentration of ^{3}He. This requires solving the ^{3}He mass balance equation for ingrown, or tritiogenic, ^{3}He. The rearranged mass balance equation is (Busenberg and others, 2001)

$$^3\mathrm{He}_{\mathrm{trit}} = {}^3\mathrm{He}_{\mathrm{total}} - {}^3\mathrm{He}_{\mathrm{eq}} - {}^3\mathrm{He}_{\mathrm{air}} - {}^3\mathrm{He}_{\mathrm{man}} - {}^3\mathrm{He}_{\mathrm{rad}}, \qquad (2)$$

where

$^3\mathrm{He}_{\mathrm{trit}}$ is the ingrown helium-3 produced by radioactive decay of tritium,

$^3\mathrm{He}_{\mathrm{total}}$ is the measured helium-3 in the groundwater sample,

$^3\mathrm{He}_{\mathrm{eq}}$ is the helium-3 in solution in equilibrium with air,

$^3\mathrm{He}_{\mathrm{air}}$ is the helium-3 in solution derived from excess air in solution,

$^3\mathrm{He}_{\mathrm{man}}$ is the helium-3 introduced from mantle fluids, and

$^3\mathrm{He}_{\mathrm{rad}}$ is the helium-3 produced by radioactive decay of uranium, thorium, and lithium in crustal rocks.

At the INL, some groundwater could not be dated with ^{3}H/^{3}He due to large amounts of $^3\mathrm{He}_{\mathrm{man}}$, $^3\mathrm{He}_{\mathrm{rad}}$, and contamination of groundwater with ^{3}H from industrial wastewater disposal. Where wastewater ^{3}H was present, the travel time of the water from the disposal site was determined, not the age of the young fraction of groundwater (Busenberg and others, 2001).

CFCs are halogenated gases that initially were developed in the 1930s for use in refrigeration. They are volatile compounds, so they quickly entered the atmosphere and then the hydrosphere. CFCs are a useful age-dating tool of young groundwater because the atmosphere was free of these compounds until the 1930s, release of CFCs to the atmosphere has caused atmospheric mixing ratios to increase from 1940 to 1990, the atmospheric mixing ratios of CFCs are known or have been reconstructed, the Henry's Law solubilities of CFCs in water are known, and accurate measurements can be made from water samples with low CFC concentrations (Plummer and Busenberg, 2000). The mixing ratios of CFC-11, CFC-12, and CFC-113 in the atmosphere increased at different rates, so groundwater ages may be estimated from individual CFC mixing ratios or from ratios of two CFC mixing ratios (Busenberg and others, 2001).

The calculated groundwater age from CFC concentrations refers to the time elapsed since the recharge water was isolated from the unsaturated-zone atmosphere and assumes that water recharging an aquifer was in equilibrium with the unsaturated-zone atmosphere (Busenberg and Plummer, 2000; Plummer and Busenberg, 2000). The term "model age" is used in reference to CFC ages because there are numerous physical and chemical processes that can influence the calculated age. Some physical and chemical processes that may affect the calculated model ages of groundwater include the estimated recharge temperature at the air-groundwater interface, the elevation at which recharge occurred, the amount of excess air in the groundwater, the method of recharge through the unsaturated zone, gas transport processes in the unsaturated zone, mixing of water, hydrodynamic dispersion, degradation of CFCs, and CFC contamination from local anthropogenic sources (Plummer and Busenberg, 2000; Busenberg and others, 2001).

In calculating the model age of the young fraction of groundwater at the INL, Busenberg and others (2001) used several simplifying assumptions and noble gas concentrations in groundwater to estimate recharge temperature and elevation, excess air, and method of recharge. They used conceptual models to define some other processes. For instance, recharge was modeled through the unsaturated zone as occurring either slowly or rapidly, and groundwater in the aquifer was modeled as either unmixed or as a mixture of young and old water. If mixing was modeled, then the fraction of young groundwater in the sample needed to be estimated. These estimates were made based on the mixing ratio of a CFC compound in air at the time of recharge and the concentration of the same CFC in the water sample, chemical and isotopic concentrations in the water sample, or geochemical modeling.

The application of SF_6 for age dating young groundwater is similar to that for CFCs. SF_6 is a stable, volatile gas that began to be produced for industrial purposes in the 1950s. Substantial production began in the 1960s, atmospheric mixing ratios rose rapidly beginning in the late 1970s, and age dating with SF_6 is possible back to about 1970 (Busenberg and Plummer, 2000).

Like CFCs, the model age of groundwater calculated from SF_6 concentrations refers to the time elapsed since the recharge water was isolated from the unsaturated-zone atmosphere and assumes that the water recharging an aquifer is in equilibrium with the unsaturated-zone atmosphere. Most of the same physical and chemical processes that affect CFC concentrations also affect SF_6, although SF_6 does not seem to degrade and is less likely to be from local contamination. There is a natural source for SF_6 in groundwater, because many igneous rocks contain low concentrations of SF_6. Water can be dated with SF_6 when the igneous component of SF_6 is small relative to other sources of SF_6 (Busenberg and Plummer, 2000; Busenberg and others, 2001).

Busenberg and others (2001) calculated the model age of groundwater from SF_6 concentrations using the same assumptions and models described for modeling CFCs. Procedures to correct for natural, or igneous, SF_6 have not been developed, so no correction was made to model ages calculated from SF_6 concentrations. Some groundwater samples from the INL could not be dated with SF_6 because they had SF_6 concentrations larger than modern air-water equilibrium, indicating a significant source of SF_6 from igneous rocks (Busenberg and others, 2001).

The estimated model ages of young groundwater from a site, based on methods using $^3H/^3He$, individual CFCs and SF_6, and ratios of CFCs and SF_6, varied considerably (Busenberg and others, 2001). Difficulties in the age dating methods may be caused by variability in the analytical data, the complexity of estimating groundwater ages in groundwater at the INL with environmental tracers (Busenberg and others, 2001), and using models to calculate the age of young groundwater that are dependent on an assumption of binary mixing. Young groundwater at the INL generally consists of numerous episodic surface-water-recharge events that have occurred since the 1940s, so much of the groundwater at the INL may be a mixture of more than two sources of water. Due to these difficulties in estimating the age of young groundwater, Busenberg and others (2001) stated that the results should be used with caution. However, a conservative interpretation of data from Busenberg and others (2001) is that water samples containing CFCs and SF_6 contain some young groundwater.

Carbon-14

Carbon-14 can be used for dating groundwater as old as 50,000 years, identifying sources of recharge, and evaluating groundwater mixing because ^{14}C undergoes radioactive decay with a relatively long half-life (5,730 years), carbon is ubiquitous in groundwater, and there are numerous sources and sinks of carbon (Clark and Fritz, 1997). Carbon-14 is naturally produced in the atmosphere, but also was introduced into the atmosphere by thermonuclear bomb testing in the 1950s and 1960s. Carbon-14 in the atmosphere also has been diluted during the industrial age by combustion of fossil fuel. In the atmosphere, ^{14}C quickly oxidizes to CO_2 and subsequently assimilates into the biosphere (through photosynthesis) and hydrosphere (through exchange reactions with meteoric waters and the ocean; Clark and Fritz, 1997; Kalin, 2000).

Carbon-14 enters groundwater through gas exchange of CO_2 with the atmosphere, soil zone, or unsaturated zone and dissolution of carbonate minerals containing geologically young carbon (Kalin, 2000). Marine carbonates on continents are geologically old, so they no longer contain any ^{14}C (that is, "dead" carbon). Carbon, and therefore ^{14}C, is present in groundwater as dissolved organic (DOC) or inorganic (DIC) carbon. Concentrations of DIC are much larger in groundwater at the INL than concentrations of DOC, and measurements of ^{14}C in groundwater from the INL are made from DIC.

The **modern activity of ^{14}C**[18] is reported relative to an international "modern carbon" standard, based on the 1950 concentration of ^{14}C in the atmosphere, in units of percent modern carbon (pmC) (Clark and Fritz, 1997). Since the modern activity is referenced to the 1950 activity of ^{14}C in the atmosphere (that is, the 1950 ^{14}C activity in the atmosphere = 100 pmC), values of pmC greater than 100 indicate a post-1950 age of groundwater and pmC values less than 100 indicate a pre-1950 age of groundwater (Kalin, 2000). However, sources of "dead" carbon may reduce the activity of ^{14}C in groundwater, so the age of groundwater with pmC values less than 100 is ambiguous.

Quantitative determination of the radiocarbon ages of groundwater can be calculated from the equation for radioactive decay (analogous to the equation for radioactive decay of ^3H in appendix 2, eq. 2-12). However, determining the initial activity of ^{14}C in groundwater is complicated from the varying activities of ^{14}C in the atmosphere through time, fractionation of carbon during phase transformations, and the potentially numerous sources of carbon with different ^{14}C activities. Corrections for these processes are complex, but are routinely performed (Clark and Fritz, 1997; Kalin, 2000). Radiocarbon ages were not calculated for this report because most of the groundwater in the ESRP aquifer at the INL contains measurable tritium and is therefore too young to allow for reliable determination of radiocarbon ages (Plummer and others, 1993).

Geochemistry of Surface Water and Groundwater

The geochemistry of groundwater at the INL was influenced by different sources of recharge, physical and chemical processes occurring in the ESRP aquifer, and temporal variability. The geochemistry of different sources of recharge, and the physical and chemical processes occurring in the ESRP aquifer, was determined by comparing the chemistry of each water group and relating differences in chemistry to differences in land use, geology, and hydrology. The geochemistry of some groundwater at the INL undergoes temporal variability, and understanding the causes of these temporal changes was essential for fully understanding the influence of different sources of recharge, and the physical and chemical processes occurring in the ESRP aquifer, on groundwater geochemistry at the INL.

---

[18] Modern in this context refers to groundwater recharged after 1950.

Sources of recharge with the most potential to influence the geochemistry of groundwater at the INL included (1) concentrated sources of dilute recharge, such as infiltration of the BLR through the INL spreading areas and the BLR channel, sinks, and playas (Bennett, 1990; Bartholomay and others, 2012); (2) the largest sources of recharge, such as underflow of regional groundwater from the Mud Lake area east of the INL and underflow of tributary valley groundwater from the LLR and BC valleys north of the INL (table 1); and (3) sources of recharge with large concentrations of chemical or radiochemical constituents, such as return flows of irrigation water in the Mud Lake area and the LLR valley that contain agricultural wastes (Swanson and others, 2002; Rattray, 2015), upward flow of brackish geothermal water (Mann, 1986; Rattray, 2015), and industrial wastewater discharge at the INL (Davis and others, 2013).

Precipitation, industrial wastewater discharge, and geothermal water provided recharge to the ESRP aquifer near the INL in small amounts at localized areas (table 1) (Bartholomay, Tucker, and others, 2000; Ackerman and others, 2006; Rattray, 2015). Precipitation was chemically dilute and recharge of precipitation would only dilute nearby groundwater. In contrast, relatively small amounts of recharge of industrial wastewater and geothermal water (table 1), which contained large concentrations of some chemical and radiochemical constituents (tables 13–14 and 17), mixed with comparatively dilute groundwater in the ESRP aquifer, thereby constraining these sources of chemical or radiochemical constituents to a local influence on groundwater geochemistry that diminishes noticeably with distance from the point source (Davis and others, 2013). The chemistry of recharge from irrigation water and industrial wastewater was not available, so the effect these recharge sources had on groundwater chemistry was evaluated indirectly from the chemistry of affected groundwater. For example, the effect on groundwater geochemistry from irrigation return flows and wastewater discharge was indirectly evaluated from the chemistry of groundwater in irrigated areas and contaminated groundwater, respectively.

Interpretations about sources of recharge for groundwater at the INL primarily were made from the statistical and spatial distribution of concentrations or values of chemical and isotopic constituents. These distributions were presented in box-and-whisker plots (herein called boxplots) (figs. 27*A*–*LL* [at back of report]) and maps (figs. 28*A*–*DD* [at back of report]). Other graphical methods used to make interpretations about sources of water and groundwater at the INL, such as trilinear (fig. 10*A*) and δ^2H-δ^{18}O diagrams (fig. 11), were described in the section, “Sources of Chemical and Isotopic Constituents.”

Boxplots were used to compare and contrast the chemistry of different sources of water and groundwater from spatially defined areas at the INL (fig. 9). The box height represents the variation or range of the inner two quartiles of data (second and third quartiles, also inner quartile range [IQR]) and is divided into two halves by the median. The relative heights of the box halves indicate the skewness of the inner quartile data, the lines (or whiskers) show the minimum and maximum data points (excluding outliers) and indicate variability of the outer two quartiles (1st and 4th quartiles) of data, and individual points represent outlier data (Helsel and Hirsch, 2002). Outliers consist of data points that exceed 1.5 times the IQR. Chemistry data that were censored (<, less than; >, greater than, >>, much greater than), included remarks (E, estimated; ?, uncertain), ranges of values (10–20 years before the sampling date), or that included uncertainty estimates (value ± uncertainty) were included in boxplots using the censored value (<1 µg/L was included as 1 µg/L), the value without the remark (E4.7 µg/L was included as 4.7 µg/L), the midpoint of the range of values (10–20 years before the sampling date was included as 15 years before the sampling date), and the value without the uncertainty (22.4 ± 12.8 pCi/L was included as 22.4 pCi/L). Thirteen tritium activities with uncertainties that equaled or exceeded the absolute value of the reported activity, and with uncertainties that exceeded 9.5 pCi/L (for example, 12.8 ± 12.8 pCi/L), were excluded from the boxplot for tritium activities (fig. 27*II*). Estimated ages of the young fraction of groundwater include a remark, “old,” for USGS 23 (table 17), and in the boxplot for the estimated age of the young fraction of groundwater the remark “old” was set to 55 years before the sampling date (fig. 27*KK*).

Chemical and Isotopic Constituents

Field Parameters

Water temperatures ranged from 6 to 57 °C (table 12). Groundwater in the tributary valleys generally had colder temperatures than regional groundwater, and the warmest groundwater temperatures were in geothermal water (fig. 27*A*). Numerous factors influenced the difference in temperatures between tributary valley and regional groundwater. For instance, tributary valley groundwater originated mainly as snowmelt at high elevations, which produced cold groundwater. Regional groundwater, probably had longer groundwater residence times than tributary valley groundwater (based on tritium activities in figure 28*BB*), was warmed by the large geothermal gradient in the ESRP (Blackwell and others, 1992), and may include geothermal water that moved vertically upward (Mann, 1986; Rattray, 2015). These influences on groundwater temperatures were apparent at the INL, as recharge from tributary water (streams and groundwater) and regional groundwater produced temperatures that were colder in groundwater in the northwestern part of the INL than the southeastern part (fig. 28*A*).

The pH ranged from nearly neutral (7.1) to slightly alkaline (8.6) (table 12). Tributary valley and regional groundwater pH values generally were smaller than groundwater at the INL, whereas pH values in surface water generally were larger (fig. 27*B*). Most pH in natural (as well as deep and contaminated) groundwater ranged from 7.8 to 8.3, with slightly larger pH values in groundwater from the southern parts of the INL (Southeast, Central, and Southwest INL Areas) than in the northern parts (North, Northeastern, and Northwestern INL Areas). The slightly larger pH in the southern parts of the INL may be due to consumption of CO_2 from dissolution of silicate minerals in the ESRP aquifer (Rattray and Ginsbach, 2014).

Specific conductance ranged from 147 to 1,878 µS/cm at 25 °C (table 12). Specific conductance in tributary valley and regional groundwater ranged from 180 to 1,100 µS/cm at 25 °C, with larger specific conductance in groundwater from irrigated areas. Specific conductance values generally were less than 400 µS/cm at 25 °C in surface water, deep groundwater, and natural groundwater from the North, Southeast, Central, and Southwest INL Areas, and more than 400 µS/cm at 25 °C in geothermal water, contaminated groundwater, and natural groundwater from the Northeast and Northwest INL Areas (fig. 27*C*). The large specific conductance values in groundwater from the Northeast and Northwest INL Areas were due to irrigation in the upgradient Mud Lake and Howe areas (fig. 28*B*), respectively.

Alkalinity ranged from 71 to 740 mg/L as $CaCO_3$ (table 12). However, except for geothermal water from test hole INEL-1 10,300 feet (740 mg/L as $CaCO_3$) and irrigation-influenced regional groundwater from ML 30 (384 mg/L as $CaCO_3$), alkalinity was less than or equal to 279 mg/L as $CaCO_3$. Natural groundwater, except from the Northwest INL Area, had small alkalinity (84–165 mg/L as $CaCO_3$) (fig. 27*D*). Larger alkalinity concentrations in groundwater from the Northwest INL Area may be due to irrigation in the upgradient Howe area, where infiltration of irrigation water transported soil CO_2 downward to the alluvial aquifer, and the increased CO_2 in the aquifer enhanced dissolution of carbonate minerals in the aquifer matrix (Rattray, 2015). The smallest alkalinity concentration was from USGS 22, which is also from the Northwest INL Area. Busenberg and others (2001, p. 90), in evaluating the age of the fraction of young groundwater at USGS 22, suggested that groundwater at this site represented recent infiltration of precipitation. The small alkalinity of this groundwater probably was due to the short residence time of this groundwater in the ESRP basalt aquifer; therefore, the time available for carbonate and silicate reactions to proceed was limited.

Dissolved Gases

Dissolved-oxygen concentrations ranged from 0.1 to 12.2 mg/L (table 12, figs. 27*E* and 28C). Most surface water was saturated with DO (≥8.4 mg/L), most tributary valley, regional, deep, contaminated, and natural groundwater was either saturated or slightly undersaturated (≥6 mg/L), and geothermal water was considerably undersaturated (<6 mg/L) or anoxic (INEL-1 10,300 feet; anoxic interpretation was based on large iron and small uranium concentrations; table 14). Anoxic (<0.5 mg/L) groundwater was measured from four other sites (Wildhorse Guard Station, Kaufman Guard Station, ML 25, TAN Disposal), and these anoxic conditions probably were due to confined aquifers at the headwaters of the BLR and BC valleys, mixing of regional groundwater with anoxic geothermal water and subsequent oxidation-reduction reactions (Rattray, 2015), and oxidation of organic compounds discharged in wastewater at TAN (U.S. Department of Energy, 2011).

The partial pressure of CO_2 ranged from -3.7 to -1.8 (as log PCO_2) (table 12). The largest partial pressures of CO_2 were in geothermal water, tributary valley groundwater, and regional groundwater and the smallest partial pressures were from surface water and natural groundwater in the southern part of the INL (Southeast, Central, and Southwest INL Areas) (figs. 27*F* and 28*D*). The larger partial pressures of CO_2 in tributary valley and regional groundwater were from the downward transport of soil CO_2 associated with natural and anthropogenic sources of recharge, and the smaller partial pressures of CO_2 in groundwater from southern part of the INL were from infiltration of the BLR on the ESRP (where rapid, focused recharge prevented infiltration recharge from equilibrating with soil CO_2; Busenberg and others, 2001) and consumption of CO_2 from dissolution of silicate and carbonate minerals in the ESRP aquifer (Rattray, 2015).

Helium concentrations ranged from 4.0×10^{-8} to 149×10^{-8} cm^3 STP/g (table 12). Helium measurements from source waters were few in number, but they did show that different source waters have distinctive helium concentrations. No measurements of helium concentrations were made in surface water, but surface water should be in equilibrium with air and have a helium concentration of about 4.5×10^{-8} cm^3 STP/g (Clark and Fritz, 1997). Helium concentrations in other source waters ranged from 4.1×10^{-8} to 10×10^{-8} cm^3 STP/g in tributary valley groundwater, 4.8×10^{-8} to 41.8×10^{-8} cm^3 STP/g in regional groundwater, and was 120×10^{-8} cm^3 STP/g in geothermal water from ML 57 (fig. 28*E*). Helium concentrations in deep groundwater ranged from 5.5×10^{-8} to 149×10^{-8} cm^3 STP/g, with the largest concentration, from USGS 7, indicating that this groundwater contained either some geothermal water or helium from the mantle. Helium concentrations ranged from 4.5×10^{-8} to 11.5×10^{-8} cm^3 STP/g in contaminated groundwater and 4.0×10^{-8} to 32.4×10^{-8} cm^3 STP/g in natural groundwater. Excluding outliers, helium concentrations in contaminated groundwater and natural groundwater from the North, Northwest, and Southwest INL Areas were similar to concentrations in surface water and tributary valley groundwater (fig. 27*G*), indicating that surface water and tributary valley groundwater probably were the sources of water to these Areas. Helium concentrations in natural groundwater from the Northeast, Southeast, and Central INL Areas that were larger than measured for tributary valley groundwater indicate that regional groundwater probably was a source of water to these Areas, although four helium concentrations greater than 20×10^{-8} cm^3 STP/g (USGS 18 in the Central INL Area and USGS 26, USGS 27, and USGS 31 from the Northeast INL Area) also may contain some helium from geothermal water or deep groundwater.

Major Ions

Statistical and Spatial Distribution

Concentrations of calcium, magnesium, and bicarbonate ranged from 7.3 to 130, 0.5 to 45, and 87 to 900 mg/L (table 13), respectively. Most calcium, magnesium, and bicarbonate concentrations were larger in tributary valley groundwater than in regional groundwater (figs. 27*H*–27*J*), although irrigation produced some large concentrations of these constituents in regional groundwater. Compared to natural groundwater, surface water and deep groundwater generally had smaller calcium, magnesium, and bicarbonate concentrations, contaminated groundwater generally had larger concentrations, and geothermal water from INEL-1 had smaller concentrations of calcium and magnesium and larger concentrations of bicarbonate. Concentrations of calcium, magnesium, and bicarbonate in natural groundwater from the Northwest INL Area extended over a wide range of concentrations and had larger concentrations than other natural groundwater; these larger concentrations probably were due to irrigation in the LLR valley (figs. 28*F*–*H*).

Concentrations of sodium, potassium, fluoride, and silica ranged from 2.8 to 390, 0.6 to 13.6, less than 0.1 to 13, and 5.2 to 62 mg/L, respectively. Concentrations of these constituents in water reflect the chemistry of the geologic terranes that the water originates in (Olmsted, 1962; Robertson and others, 1974; Busenberg and others, 2000; Carkeet and others, 2001; Swanson and others, 2002, 2003; Rattray and Ginsbach, 2014; Rattray, 2015). Surface water originates, and tributary valley groundwater resides, in carbonate terrane, whereas regional groundwater and geothermal water from INEL-1 reside in silicate terrane that includes basalt and rhyolite. Consequently, regional groundwater and geothermal water from INEL-1 had larger concentrations of sodium, potassium, fluoride, and silica (table 7) than surface water or tributary valley groundwater (figs. 27*K*–*N*). Irrigation also influenced sodium and potassium concentrations, and produced larger concentrations of sodium in irrigated areas of the LLR valley and larger concentrations of sodium and potassium in the Mud Lake area (figs. 28*I*–*J*). The larger concentrations of sodium, potassium, fluoride, and silica in natural groundwater from the Northeast and Southeast INL Areas, relative to natural groundwater from the North, Central, Northwest, and Southwest INL Areas, indicate that recharge primarily was from regional groundwater, and possibly some upwelling geothermal water, in the Northeast and Southeast INL Areas and from surface water and (or) tributary valley groundwater in the North, Central, Northwest, and Southwest INL Areas. Deep and contaminated groundwater had sodium, potassium, fluoride, and silica concentrations that were similar to natural groundwater, although larger concentrations of these constituents in deep groundwater from USGS 7 probably were due to upwelling geothermal water and larger concentrations of sodium in some contaminated groundwater were due to wastewater discharge.

Concentrations of chloride and nitrate ranged from 1.0 to 240 mg/L and less than 0.02 to 8.5 mg/L as N, respectively (table 13). Regional groundwater generally had larger concentrations of chloride and nitrate than surface water, tributary valley groundwater uninfluenced by irrigation, geothermal water, and deep groundwater (figs. 27*O*–*P*), all of which had concentrations of chloride and nitrate that were generally less than 20 mg/L and less than 1 mg/L as N, respectively. Irrigation or wastewater discharge produced larger chloride (>20 mg/L) and (or) nitrate (>1 mg/L as N) concentrations in some groundwater from the BLR and LLR valleys and most contaminated groundwater (figs. 28*M*–*N*). In natural groundwater, the generally larger chloride and nitrate concentrations in groundwater from the Northeast, Southeast, and Northwest INL Areas were due to irrigation, whereas the smaller concentrations in groundwater from the North, Central, and Southwest INL Areas indicate that this groundwater was uninfluenced or minimally influenced by irrigation.

Concentrations of sulfate ranged from 1.4 to 200 mg/L (table 13). Sulfate concentrations greater than or equal to 30 mg/L were measured in LLR valley and regional groundwater influenced by irrigation, geothermal water,[19] and most contaminated groundwater and concentrations less than 30 mg/L were measured in surface water, most tributary valley groundwater, regional groundwater uninfluenced by irrigation, and deep groundwater (figs. 27*Q* and 28*O*). Most sulfate concentrations were greater than or equal to 24 mg/L in natural groundwater from the North and Northeast INL Areas, less than or equal to 26 mg/L in natural groundwater from the Southeast, Central, and Southwest INL Areas, and ranged from 14 to 40.4 mg/L in natural groundwater from the Northwest INL Area. The larger concentrations in the Northeast and Northwest INL Areas may be due to irrigation in the Mud Lake and Howe areas, respectively. However, the larger

---

[19] Sulfur in anoxic groundwater, such as geothermal water from INEL-1 10,300 feet, should be in a reduced state as bisulfide (HS^-) under alkaline conditions (Drever, 1997, fig. 7–11). However, the sample was analyzed for sulfate, not bisulfide, because any bisulfide in the sample would have become oxidized during collection and storage of the water sample.

concentrations in the North INL Area, where no irrigation occurs, indicates that the Beaverhead Mountains may contain a greater amount of sulfur-bearing minerals, such as anhydrite and gypsum, than the Pioneer, Lost River and Lemhi Ranges.

Hydrochemical Facies

Trilinear diagrams were used to indicate the major ion compositions of water samples (fig. 10*A*). Water samples were categorized into hydrochemical facies based on their plotted location in the trilinear diagrams, and the hydrochemical facies of water samples were plotted on a map to illustrate spatial differences in major ion concentrations across the INL (fig. 10*B*).

Surface water and tributary valley groundwater, both of which originate in carbonate rocks in the mountains north of the INL, were primarily Ca-HCO_3 hydrochemical facies, and regional groundwater, which resides in silicate rocks and was influenced by irrigation, was typically Ca-HCO_3 or mixed cation-HCO_3 hydrochemical facies. However, regional groundwater from ML 25 and ML 27 (mixed cation-HCO_3 and Na-HCO_3 hydrochemical facies, respectively) plots between geothermal water from INEL-1 (Na-HCO_3 hydrochemical facies) and most regional groundwater on the cation part of figure 10*A*, consistent with the interpretation that groundwater at ML 25 and ML 27 was a mixture of geothermal water and regional groundwater (Rattray, 2015).

The hydrochemical facies of contaminated groundwater samples was primarily Ca-HCO_3, although Ca-mixed anion and mixed cation-mixed anion water types also were common. A Ca-SO_4 water type for groundwater from USGS 65 indicates that sulfur was a significant waste constituent at ATRC, and a mixed cation-Cl water type at USGS 112 and USGS 113 indicates that chloride was a significant waste constituent at INTEC.

The hydrochemical facies of natural groundwater in the northwestern part of the INL was primarily Ca-HCO_3, and the hydrochemical facies of natural groundwater in the southeastern part of the INL was either Ca-HCO_3 or mixed cation-HCO_3 (fig. 10*B*). This spatial distribution of hydrochemical facies reflects the influence of recharge from surface water and tributary valley groundwater in the northwestern part of the INL and regional groundwater in the southeastern part of the INL.

The hydrochemical facies of natural groundwater from USGS 22, in the Northwest INL Area, was mixed cation-Cl, with chloride and sodium comprising much larger percentages of total anions and cations, respectively, than other natural groundwater (fig. 10*A*). USGS 22 is located about 0.37 mi northeast of State Highway 26, and the larger amounts of chloride and sodium in this groundwater may be due to solution of road salt applied to the highway in precipitation that subsequently infiltrates to the aquifer.

Dissolved Metals

Concentrations of aluminum (dissolved and total recoverable)[20] ranged from less than 1 to 1,400 µg/L (table 14). Concentrations generally were less than or equal to 20 µg/L in groundwater, although several total recoverable aluminum concentrations were greater than or equal to 40 µg/L, and concentrations ranged from 1 to 116 µg/L in surface water (table 14; fig. 27*R*). The generally small concentrations of aluminum were because of the small solubility of aluminum in oxic water (Hem, 1992).

Concentrations of barium ranged from 10 to 342 µg/L (table 14). Tributary valley groundwater had slightly larger barium concentrations than regional groundwater, indicating that barium was probably more abundant in the carbonate rocks in the mountains than the silicate rocks in the ESRP (fig. 27*S*). However, the largest (>90 µg/L) barium concentrations were in contaminated groundwater, tributary valley and regional groundwater that were influenced by irrigation, and natural groundwater from the Northwest INL Area downstream of irrigated areas in the LLR valley. The smallest barium concentrations were in regional and natural groundwater not influenced or minimally influenced by irrigation (fig. 28*P*). Barium probably was more abundant in irrigated areas due to solution of barium-bearing agricultural soil amendments, sediment, and (or) rock as irrigation water infiltrated through the unsaturated zone to the aquifer.

Concentrations of boron ranged from 8 to 900 µg/L (table 14). Boron concentrations were largest in geothermal water and were larger in regional groundwater than surface water or tributary valley groundwater (fig. 27*T*). As a result, boron concentrations increased across the INL in a northwest-to-southeast direction (fig. 28*Q*), with larger concentrations in the Northeast and Southeast INL Areas than in the North, Central, Northwest, and Southwest INL Areas.

Concentrations of chromium ranged from 0 to 190 µg/L (table 14). Chromium concentrations were generally less than or equal to 20 µg/L (fig. 27*U*), and these small concentrations were a result of the small abundance of chromium in the minerals in the carbonate and silicate rocks of the study area (Deer and others, 1983; Morgan and others, 1984; Kuntz and others, 1992; Lewis and others, 2012). The largest concentration of chromium, in contaminated groundwater at USGS 65, was from wastewater discharge from ATRC (tables 7–8).

---

[20] Concentrations of metals in groundwater from NRF 6, NRF 7, NRF 8, NRF 9, NRF 10, NRF 11, NRF 12, and NRF 13 were for total recoverable metals.

Concentrations of iron ranged from 0 to 1,700 µg/L (table 14). Iron concentrations in surface water ranged from less than 10 to 100 µg/L and most concentrations in groundwater were less than 100 µg/L, although some concentrations greater than 125 µg/L were measured from geothermal, contaminated, and anoxic groundwater (fig. 27*V*). Iron concentrations in natural groundwater generally were larger than in tributary valley and regional groundwater, probably because of dissolution of iron-bearing minerals in the ESRP basalt aquifer (Schramke and others, 1996; Knobel and others, 1997; Busenberg and others, 2001; Swanson and others, 2003; Rattray and Ginsbach, 2014).

Concentrations of lithium ranged from 1.0 to 280 µg/L[21] (table 14). Lithium concentrations generally were less than 10 µg/L in surface water and tributary valley groundwater and greater than 10 µg/L in regional groundwater and geothermal water (fig. 27*W*). These sources of water produced lithium concentrations at the INL that generally increased in a northwest-to-southeast direction. For example, lithium concentrations were less than 10 µg/L in natural groundwater from the North, Central, Northwest, and Southwest INL Areas and greater than 10 µg/L in natural groundwater from the Northeast and Southeast INL Areas (fig. 28*R*). This distribution of lithium concentrations indicates that recharge in the Northeast and Southeast INL Areas primarily was from regional groundwater, whereas recharge in the North, Central, Northwest, and Southwest INL Areas primarily was from tributary streams and tributary valley groundwater.

Concentrations of manganese ranged from 0 to 140 µg/L (table 14). Most concentrations were less than or equal to 20 µg/L (fig. 27*X*), although concentrations in anoxic or nearly anoxic (0.7 mg/L DO) groundwater ranged from 18 to 140 µg/L due to the higher solubility of manganese under reduced conditions (Hem, 1992).

Concentrations of strontium ranged from 61 to 1,000 µg/L (table 14). Strontium concentrations generally were smaller in surface water than groundwater (fig. 27*Y*), and strontium concentrations in groundwater generally were larger in areas influenced by irrigation or wastewater discharge (fig. 28*S*).

Concentrations of uranium ranged from 0.02 to 3.59 µg/L (table 14; fig. 28*T*). These small concentrations were due to the low abundance of uranium in crustal rocks (Emsley, 1989). Uranium concentrations in groundwater generally were greater than 1.0 µg/L, and concentrations greater than 2.0 µg/L probably were due to longer groundwater residence times, irrigation, and (or) wastewater discharge (fig. 27*Z*). Concentrations less than 1.0 µg/L were present in groundwater with a short aquifer residence time, such as USGS 22, and due to the lower solubility of uranium in anoxic groundwater.

Isotope Ratios

Stable Isotope Ratios of Hydrogen and Oxygen

The δ^2H and $\delta^{18}O$ values in water samples ranged from -143.0 to -120.6 and -18.75 to -14.84 permil, respectively (tables 3 and 15). Most of the δ^2H and $\delta^{18}O$ values plot slightly below and approximately parallel to the LMWL for winter, indicating that snow, the primary source of meteoric water in the study area during winter, was the source of most of the water (fig. 11).

The δ^2H and $\delta^{18}O$ values in surface water and tributary valley groundwater extend over a wide range (figs. 27*AA*–*BB*) because water evaporates from the BLR, BC, and Mud Lake, producing large δ^2H and $\delta^{18}O$ values (fig. 11), and δ^2H and $\delta^{18}O$ values decrease in a southwest-to-northeast direction in streams and groundwater from the tributary valleys north of the INL (fig. 28*U*). The directional decrease in δ^2H and $\delta^{18}O$ values may be due to altitude and (or) rainout effects in precipitation as air masses travel in a southwest-to-northeast direction over the Lost River and Lemhi Ranges (Benjamin and others, 2004). The importance of these effects was evaluated by plotting the $\delta^{18}O$ values of streams and groundwater from the tributary valleys against the elevation of the sampling site (fig. 15). If the altitude effect was important, the $\delta^{18}O$ values in streams and groundwater water from a tributary valley would decrease with increasing elevation, and if the rainout effect was important, the $\delta^{18}O$ values would decrease in the direction that the storms travel. Linear regression showed that $\delta^{18}O$ values in groundwater decreased with increased elevation for the BLR valley (mean gradient of -0.47‰ $\delta^{18}O$ per 1,000-ft increase in elevation; $R^2 = 0.49$) but not the LLR and BC valleys, so the altitude effect influenced the $\delta^{18}O$ values in the BLR valley but not the LLR or BC valleys. However, the successive decrease of δ^2H and $\delta^{18}O$ values in water from the BLR, LLR, and BC valleys indicates that the rainout effect influenced the δ^2H and $\delta^{18}O$ values in the LLR and BC valleys, probably due to increased precipitation as air masses traveled over 12,000-ft high peaks in the Lost River and Lemhi Ranges (fig. 28*U*).

Natural groundwater from the North INL Area had a wide range of δ^2H and $\delta^{18}O$ values (fig. 28*U*). This large range was due to recharge of groundwater from the BC valley with small δ^2H and $\delta^{18}O$ values (ANP 6) and recharge of surface water from BC with δ^2H and $\delta^{18}O$ values that became enriched during evaporation in playa 4 (No Name 1, fig. 11). In addition, δ^2H and $\delta^{18}O$ values from PSTF Test were similar to values from the BLR (fig. 11), but not BC or groundwater from the BC valley, which indicates that groundwater at PSTF Test was from infiltration recharge of the BLR at playas 3 and (or) 4 (fig. 3*B*).

---

[21] The lithium concentration for INEL-1 10,300 feet was approximated as 280 µg/L, the lithium concentration in geothermal water sampled from INEL-1 from the depth interval 3,559–4,878 feet below land surface. This approximation appeared reasonable because of the similarity of temperatures and concentrations of major ions and dissolved metals in groundwater from INEL-1 10,300 feet and from the sampling depth interval of 3,559–4,878 feet below land surface (Mann, 1986).

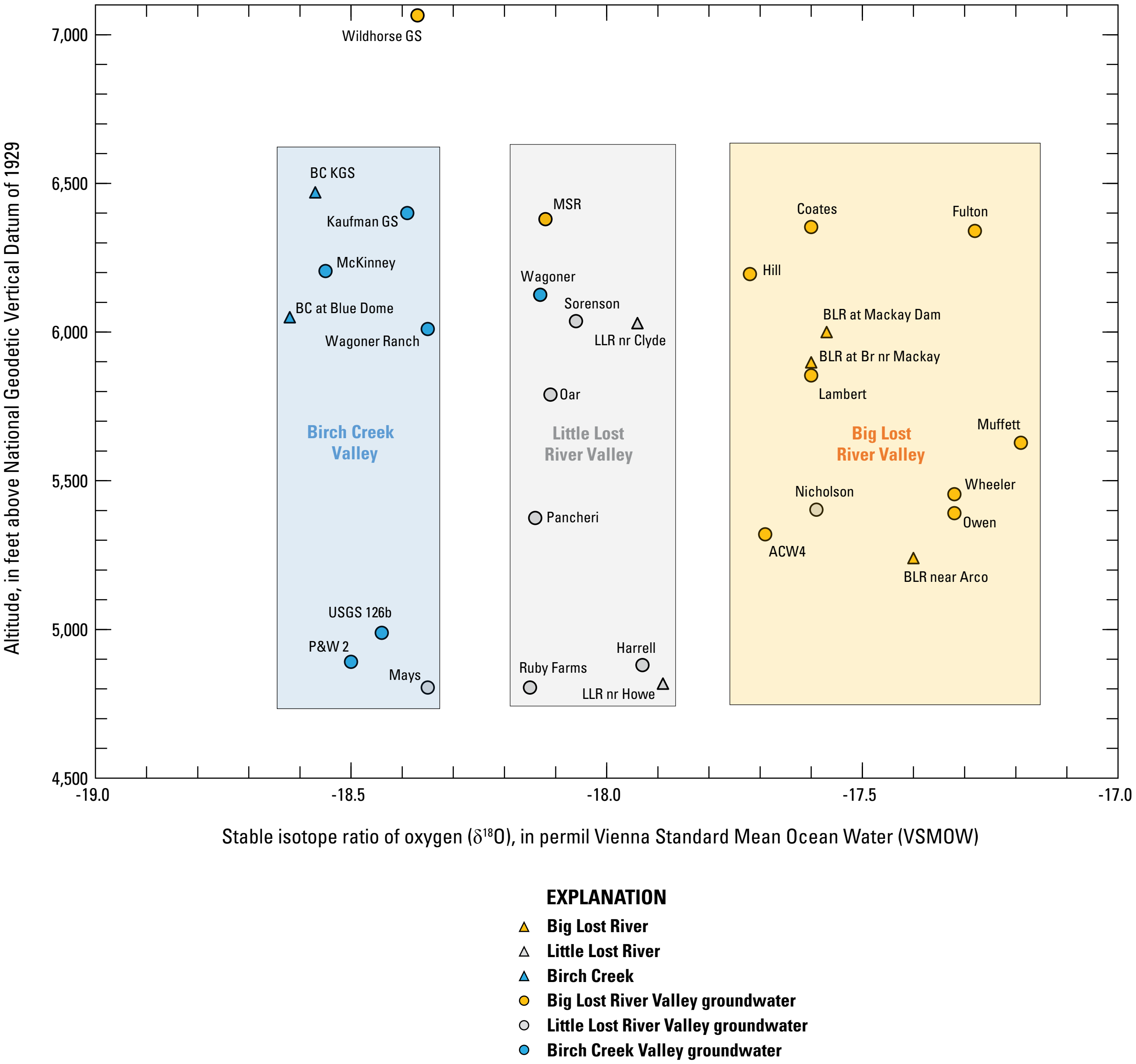


Figure 15. Stable isotope ratios of oxygen ($\delta^{18}O$) at different elevations for surface water and groundwater from the Birch Creek, Little Lost River, and Big Lost River valleys, eastern Idaho.

Regional groundwater generally had larger δ^2H and $\delta^{18}O$ values, with much larger δ^2H and $\delta^{18}O$ values in regional groundwater from wells ML 19, ML 22, and ML 23 southwest of Mud Lake due to recharge of evaporated surface water used for irrigation (fig. 11), than streams and groundwater from the LLR and BC valleys (figs. 27*AA–BB* and 28*U*). Mixing of BC valley groundwater, regional groundwater, and recharge of water from BC and (or) the BLR that underwent evaporation caused most δ^2H and $\delta^{18}O$ values in natural groundwater from the Northeast, Southeast, and northern part of the Central INL Areas to be intermediate between the δ^2H and $\delta^{18}O$ values in BC valley and regional groundwater (fig. 28*U*). Similarly, most δ^2H and $\delta^{18}O$ values in natural groundwater from the Northwest, Southwest, and southern part of the Central INL Areas were either similar to δ^2H and $\delta^{18}O$ values in groundwater from the LLR valley or between δ^2H and $\delta^{18}O$ values for groundwater from the LLR valley and the BLR, indicating that most groundwater in this part of the INL was either groundwater from the LLR valley or a mixture of groundwater from the LLR valley and infiltration recharge from the BLR.

Stable Isotope Ratios of Carbon

The $\delta^{13}C$ values, measured from dissolved inorganic carbon, ranged from -15 to -3.9 permil (table 15). The $\delta^{13}C$ values in the study area reflected the competing influence of dissolution of carbonate minerals with large $\delta^{13}C$ values and infiltration recharge from streams and irrigation water that transported soil CO_2 with small $\delta^{13}C$ values from the unsaturated zone to the aquifer. Consequently, $\delta^{13}C$ values are useful for identifying where these processes have influenced the chemistry of groundwater. For example, the large $\delta^{13}C$ values in geothermal water (figs. 27*CC* and 28*V*) from the Beaverhead Mountains were due to significant dissolution of carbonate minerals, the smaller $\delta^{13}C$ values in regional groundwater probably were due to infiltration of irrigation water, and the intermediate values in tributary valley groundwater were due to dissolution of carbonate minerals and, where irrigation occurs, infiltration of irrigation water.

The $\delta^{13}C$ values in natural groundwater from the North INL Area were larger than values in most other natural groundwater (fig. 27*CC*) because the source of water to this Area was BC and groundwater from the BC valley, both of which had large $\delta^{13}C$ values (fig. 28*V*), and there was no irrigation in the BC valley to facilitate transport to the aquifer of soil CO_2 with small $\delta^{13}C$ values. Natural groundwater in the Northeast, Central, Northwest, and Southwest INL Areas had $\delta^{13}C$ values that were similar to $\delta^{13}C$ values in tributary valley groundwater and larger than $\delta^{13}C$ values in regional groundwater. The complex carbon system in these Areas probably was influenced by dissolution of carbonate minerals, transport of soil CO_2 to the aquifer through infiltration of the BLR, and mixing of tributary valley groundwater with either regional groundwater or surface water from the BLR. The $\delta^{13}C$ values in natural groundwater from the Southeast INL Area were generally smaller than $\delta^{13}C$ values in tributary valley groundwater, larger than $\delta^{13}C$ values in regional groundwater, and increased in the downgradient direction (fig. 28*V*). Lithium concentrations indicate that the source of groundwater in the Southeast INL Area was regional groundwater (fig. 28*R*), so the increasing $\delta^{13}C$ values in groundwater as it flows southeastward may be due to continual dissolution of carbonate minerals in the aquifer matrix or increased mixing with tributary valley groundwater.

Small, outlier $\delta^{13}C$ values were measured in groundwater from USGS 22 and USGS 89, in the Northwest and Southwest INL Areas, respectively. These small $\delta^{13}C$ values may have resulted from transport of soil CO_2 from the unsaturated zone to the aquifer during infiltration recharge of precipitation (USGS 22) or the BLR (USGS 89).

Stable Isotope Ratios of Sulfur

The $\delta^{34}S$ values measured from sulfate in water from 47 sites ranged from 1.6 to 16.0 permil (table 15; fig. 28*W*). These values included measurements from two wells (USGS sites 433852112165201 and 431857112405501) from Wood and Low (1988) that were included in figure 28*W* to provide additional information about $\delta^{34}S$ values in regional groundwater.

The statistical distribution of $\delta^{34}S$ values (fig. 27*DD*) shows that $\delta^{34}S$ values generally were larger in regional groundwater than in surface water or tributary valley groundwater, the median $\delta^{34}S$ value was larger in surface water than tributary valley groundwater, natural groundwater from the Northeast and Southeast INL Areas had $\delta^{34}S$ values similar to regional groundwater, and natural groundwater from the North, Central, Northwest, and Southwest INL Areas had $\delta^{34}S$ values similar to surface water and tributary valley groundwater. The spatial distribution of $\delta^{34}S$ values (fig. 28*W*), however, provided a different, and more informative analysis because a limited number of $\delta^{34}S$ values from sources of recharge to the INL (BLR, tributary valley groundwater, regional groundwater) were available. Therefore, $\delta^{34}S$ values in natural groundwater were used to identify representative $\delta^{34}S$ values from sources of recharge.

Regional groundwater contained four large $\delta^{34}S$ values (ranging from 11.6 to 16.0 permil) and, at sites influenced by geothermal water (ML 29) or irrigated with surface water (Reno Ranch, ML 22), three smaller $\delta^{34}S$ values (ranging from 5.1 to 8.3 permil). Consequently, there is uncertainty about typical $\delta^{34}S$ values in regional groundwater. However, $\delta^{34}S$ values in natural groundwater from the Northeast and Southeast INL Areas, where recharge is primarily from regional groundwater, ranged from 9.0 to 11.9 permil and were larger than $\delta^{34}S$ values in surface water, tributary valley groundwater, and other natural groundwater. Thus, most regional groundwater entering the INL must have $\delta^{34}S$ values greater than 9 permil and probably greater than 10 permil (fig. 28*W*).

The $\delta^{34}S$ values in groundwater from the BLR, LLR, and BC valleys were (or ranged from) 1.6, 1.8 to 3.3, and 7.6 to 7.7 permil, respectively. The small $\delta^{34}S$ values from the BLR and LLR valleys were from groundwater that was influenced by irrigation, so sulfur in soil amendments may have lowered the $\delta^{34}S$ values in the groundwater. The $\delta^{34}S$ values in natural groundwater from the North and Northwest INL Areas, directly south of the BC and LLR valleys, ranged from 6.1 to 8.6 permil (fig. 28*W*). These $\delta^{34}S$ values indicate that groundwater entering the ESRP aquifer from the LLR and BC valleys probably had $\delta^{34}S$ values of about 7 to 8 permil.

Natural groundwater from the Central and Southwest INL Areas had $\delta^{34}S$ values that ranged from 5.2 to 5.8 permil. These $\delta^{34}S$ values were smaller than $\delta^{34}S$ values in the hydrologically upgradient North and Northwest INL Areas, indicating that groundwater in the Central and Southwest INL Areas was a mixture of upgradient groundwater and another source of water with smaller $\delta^{34}S$ values. The $\delta^{34}S$ values in groundwater from the Central and Southwest INL Areas were from sites located near or hydrologically downgradient of the BLR channel or INL spreading areas (figs. 3*B* and 28*W*). A water sample collected from the BLR near Arco had a fairly small $\delta^{34}S$ value of 4.4 permil, so water in the Central and Southwest Areas probably was a mixture of upgradient groundwater and water from the BLR.

Stable Isotope Ratios of Nitrogen

The $\delta^{15}N$ values, measured from nitrate in groundwater from 38 sites, ranged from 4.7 to 9.5 permil (table 15). Most of the $\delta^{15}N$ values were from natural groundwater, although there were some $\delta^{15}N$ values in groundwater from the LLR and BC valleys (6.0–7.0 permil), regional groundwater northwest of Mud Lake (6.9 and 9.5 permil), regional groundwater southwest of Mud Lake (4.7 and 5.1 permil), and deep groundwater (5.8 to 6.3 permil) (figs. 27*EE* and 28*X*). No $\delta^{15}N$ values were measured from surface water.

The $\delta^{15}N$ values in natural groundwater from the eastern part of the INL were larger in the north ($\delta^{15}N$ values greater than or equal to 6.3 permil) than in the south (less than or equal to 5.4 permil). These $\delta^{15}N$ values were consistent with recharge in the northern and southern regions of regional groundwater northwest and southwest of Mud Lake, respectively. The $\delta^{15}N$ values were greater than or equal to 5.9 permil in natural groundwater from the North, Central, and Northwest INL Areas, which was consistent with recharge of groundwater from the LLR and (or) BC valleys. The $\delta^{15}N$ values in natural groundwater from the Southwest INL Area extended over a wide range (5.4 to 8.1 permil), but these $\delta^{15}N$ values were not used to identify sources of recharge to this Area because $\delta^{15}N$ values were not available for several potential sources of recharge (BLR, groundwater from the BLR valley, and groundwater from the Lost River Range).

Isotope Ratios of Helium

The R_s/R_a ratios, measured in groundwater from 37 sites, ranged from 0.001 to 9.70 (table 15; fig. 28*Y*). These ratios included a measurement from USGS 121 (1.75; fig. 28*Y*), from Busenberg and others (2001), that was included with the basic data set (table 15) to provide additional information about R_s/R_a ratios in natural groundwater from the Northwest INL Area.

Most of the R_s/R_a ratios were from natural groundwater, although there were a few R_s/R_a ratios from tributary valley groundwater, regional groundwater, and contaminated groundwater. Most natural groundwater had R_s/R_a ratios that ranged from 0.99 to 2.07, although groundwater from ANP 9 and Area II had R_s/R_a ratios of 0.001 and 0.003, respectively, and groundwater from USGS 27 had an R_s/R_a ratio of 9.70 (figs. 27*FF* and 28*Y*). One R_s/R_a ratio was measured from tributary valley groundwater (0.99 from P&W2), two R_s/R_a ratios were measured from regional groundwater (1.13 and 0.67 from ML 22 and USGS 101, respectively), and three R_s/R_a ratios were measured from contaminated groundwater (0.69–7.46).

Identification of the sources of helium in groundwater provided information about sources of water to the groundwater, and figure 12 illustrates the changes in helium concentrations and R_s/R_a ratios in groundwater depending on whether helium was derived from the atmosphere, mantle, crust, radioactive decay of tritium (tritiogenic helium), or from dissolution of basalt. For example, natural groundwater from ANP 6, No Name 1, and PSTF Test in the North INL Area, plus P&W2 at the mouth of the BC valley, had helium concentrations (except for No Name 1 which contains excess air; Busenberg and others, 2001) and R_s/R_a ratios similar to values in the atmosphere, which suggested that recent recharge from BC (or the BLR at PSTF Test) was the primary source of water at these wells. Likewise, helium concentrations and R_s/R_a ratios in regional groundwater from ML 22 were similar to values in the atmosphere, indicating that surface water used for irrigation was the likely source of recharge at this well.

Helium concentrations and R_s/R_a ratios in groundwater from the Northeast INL Area indicated that sources of helium were from the atmosphere (USGS 32), mantle (USGS 27), crust (ANP 9, USGS 29), and radioactive decay of tritium (USGS 29, USGS 32). Thus, sources of recharge at these wells probably included surface water used for irrigation in the Mud Lake area (from the 1960s to the 1970s when large quantities of tritium were in the atmosphere) at USGS 32, upwelling geothermal water (USGS 27), regional groundwater (ANP 9), and regional groundwater plus surface water used for irrigation in the Mud Lake area (USGS 29).

Following the same logic for other natural groundwater, sources of recharge in the

1. Southeast INL Area included the BLR (USGS 14), groundwater used for irrigation that equilibrated with the atmosphere (Atomic City), and regional groundwater plus surface water used for irrigation in the Mud Lake area (Arbor Test 1, Area II, USGS 1, USGS 2, USGS 100);
2. Central INL Area included the BLR (USGS 103, NPR Test) and the BLR plus groundwater from the LLR and (or) BC valleys (USGS 5, USGS 17);
3. Northwest INL Area included the BLR plus groundwater from the LLR valley (most sites), groundwater from the LLR valley (USGS 19), groundwater from the Lost River Range (and perhaps precipitation) at USGS 23, and recent recharge from precipitation (USGS 22); and
4. Southwest INL Area included the BLR plus groundwater from the BLR and LLR valleys and (or) the Lost River Range (all sites).

Stable Isotope Ratios of Strontium and Radioisotope Ratios of Uranium

The $^{87}Sr/^{86}Sr$ ratios, measured in water from 57 sites, ranged from 0.70935 to 0.71434 and $^{234}U/^{238}U$ activity ratios, measured in water from 51 sites, ranged from 1.54 to 3.14 (table 16; figs. 28*Z*–*AA*). These ratios included $^{87}Sr/^{86}Sr$ ratios from three wells (Howe City well, well 52098-1, and well 52098-2; fig. 28*Z*) from Johnson and others (2000) and a $^{234}U/^{238}U$ activity ratio from the Crooked Creek well (fig. 28*AA*) from Roback and others (2001). These ratios were included with the basic data set (table 16) and in boxplots (figs. 27*GG*–*HH*) to provide additional information about $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios in tributary valley and (or) regional groundwater.

The $^{87}Sr/^{86}Sr$ ratios in surface water varied widely (fig. 27*GG*), with larger ratios from the LLR (0.71256) and BC (0.71198) and a smaller ratio from the BLR (0.71056). The $^{234}U/^{238}U$ activity ratios from surface water were available only at two sites from the BLR, and these $^{234}U/^{238}U$ activity ratios were smaller than ratios in most other water in the study area (fig. 27*HH*). The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios in streams may fluctuate seasonally depending on the relative percentages of surface water (that is, tributary creeks, overland runoff, and direct precipitation) and groundwater inflow that contributed to stream discharge.

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios were larger in tributary valley groundwater than in regional groundwater (figs. 27*GG*–*HH*). Consequently, natural groundwater from the northern part of the INL generally had the largest $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios due to recharge from streams and groundwater from the tributary valleys. Natural groundwater from the eastern-to-south-central part of the INL (figs. 28*Z*–*AA*) had $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios that generally increased in the downgradient direction, probably due to mixing between tributary valley and regional groundwater. Natural groundwater from the western part of the INL that was near or downgradient of the BLR had $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios that were similar to or slightly smaller than ratios from the BLR, probably due to recharge from the BLR. Groundwater from USGS 22, in the Northwest INL Area, had the smallest $^{234}U/^{238}U$ activity ratio (1.54) and concentration of uranium (0.43 µg/L) in oxic groundwater, probably because the source of water at USGS 22 was precipitation and therefore all of the uranium in this groundwater was from the dissolution of basalt minerals.

The interpretation that the distribution of $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios was largely explained by mixing of tributary valley groundwater with regional groundwater and (or) recharge from the BLR differs from the interpretations of preferential flow paths of Johnson and others (2000) and Roback and others (2001). They based their interpretations on contours of $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios, with the contours delineating north-to-south trending zones consisting of alternating low and high isotope-ratio zones. Johnson and others (2000, p. 873) argued that recharge from the BLR did not cause the two low isotope-ratio zones because the $^{87}Sr/^{86}Sr$ ratio of the BLR (0.71056) was larger than the ratios in the low isotope-ratio zones (0.70951–0.71047; fig. 28*Z*), whereas Roback and others (2001, p. 1,139) argued that mixing did not readily explain the shape or location of the high or low isotope-ratio zones. No isotopic data separated the two low-isotope zones (Roback and others, 2001, fig. 2), however, so different contours could easily be drawn that merge the two low isotope-ratio zones into a single low isotope-ratio zone that follows the channel of the BLR, similar to the ranges of isotope ratios in figure 28*AA*, for example. Additionally, the smallest $^{87}Sr/^{86}Sr$ ratio (0.70951), from USGS 22, represented the $^{87}Sr/^{86}Sr$ ratio in recharge from precipitation (Busenberg and others, 2001). This $^{87}Sr/^{86}Sr$ ratio was smaller than the $^{87}Sr/^{86}Sr$ ratio from the BLR (0.71056), which was collected prior to peak runoff (U.S. Geological Survey, 2014), and shows that the $^{87}Sr/^{86}Sr$ ratio in the BLR could easily be smaller when snowmelt is at a maximum during periods of peak runoff and recharge.

Environmental Tracers

Tritium and Terrigenic Helium

Tritium activities ranged from -190±70 to 39,600±380 pCi/L, although the largest tritium activity in uncontaminated groundwater was 160.9±0.4 pCi/L (table 17).

The He_{terr} values ranged from 0 to 97 percent (table 17) and generally had an inverse relation with tritium activities; small tritium activities corresponded to large He_{terr} values and large tritium activities corresponded to small He_{terr} values (fig. 14). For example, geothermal water and most deep groundwater had small tritium activities but large He_{terr} values, results that were consistent with old groundwater, and regional groundwater had smaller tritium activities and larger He_{terr} values than tributary valley groundwater (figs. 27*II*–*JJ*), results that were consistent with regional groundwater that had an older mean groundwater age than tributary valley groundwater. The tritium activities in surface water indicated that surface water consists primarily of young water (figs. 13*A*–*B* and 27*II*).

Natural groundwater from the Northeast INL Area generally had small tritium activities and large He_{terr} values, consistent with old groundwater and, at wells USGS 26, USGS 27, and USGS 31, some geothermal water, whereas natural groundwater from the Northwest INL Area generally had large tritium activities and small He_{terr} values, consistent with rapid, focused recent recharge (figs. 14 and 28*BB*–*CC*). Tritium activities and He_{terr} values indicated that natural groundwater from the (1) Southeast INL Area was a mixture of young and old groundwater that consisted of various amounts of recent recharge and regional groundwater and (2) Central INL Area was either (a) young groundwater or a mixture of young and old groundwater that contained large amounts of recent recharge or (b) old groundwater that contained small amounts of recent recharge and, at USGS 18, some geothermal water. Tritium activities in natural groundwater from the Southwest INL Area indicated that this was young groundwater and He_{terr} values of 10–40 percent indicated that large amounts of recent recharge mixed with old groundwater that probably originated in the LLR valley. Natural groundwater from the North INL Area had small tritium activities and He_{terr} values, in contrast to the inverse relation of these chemical constituents in other water, and indicated that this Area contained old groundwater that consisted of slow, diffuse recent recharge (fig. 14). Although rapid, focused recharge was the more common method of recharge in the fractured basalt ESRP aquifer at the INL, slow, diffuse recharge may have occurred in the North INL Area where surface water seeped through thick accumulations of sediment (Whitehead, 1992) and fine-grained lacustrine sediment at playas 3 and 4 (figs. 3*B* and 4*B*).

Tritium activities in natural groundwater from several wells did not conform to the general distribution of tritium. For example, tritium activities indicated that groundwater from USGS 29, in the Northeast INL Area, was not old groundwater but a mixture of young and old groundwater (fig. 14). The young groundwater at USGS 29 was probably from recent recharge of surface water used for irrigation in the Mud Lake area. Tritium activities also indicated that old groundwater, instead of young groundwater or a mixture of young and old groundwater, was present at wells USGS 23, USGS 86, USGS 117, and possibly USGS 119 (table 17) in the Northwest and Southwest INL Areas. The presence of old groundwater at these wells may be due to (1) recharge of old groundwater from the Lost River Range (USGS 23), (2) a location (USGS 86) that received minimal young recharge from the BLR (Bennett, 1990), or (3) small hydraulic conductivities (0.01–6.5 ft/d; log K values of -2.00–0.81 ft/d in table 11) that restricted throughflow of groundwater (USGS 86, USGS 117, USGS 119).

Tritium/Helium-3, Chlorofluorocarbons, and Sulfur Hexafluoride

Based on concentrations and (or) ratios of $^3H/^3He$, CFCs, and SF_6, the estimated age of the young fraction of groundwater ranged from 2–5 to much greater than (>>) 55 (or “old”)[22] years before the sampling date (table 17). The estimated age of the young fraction of groundwater in tributary valley and regional groundwater was determined at five sites, and each of the sites contained some young groundwater. Concentrations of CFCs and SF_6 in deep groundwater, and natural groundwater from USGS 6 and USGS 23, were either zero or small. These concentrations, and the small tritium activities in groundwater from these wells, indicated that deep groundwater, and natural groundwater from USGS 6 and USGS 23, consisted primarily of old groundwater. The absence of young groundwater at USGS 6 and USGS 23 was probably due to the 8–10-mi distance of USGS 6 downgradient from sources of young recharge at playas 3 and 4 (figs. 3*B* and 9) and groundwater at USGS 23 consisting of old groundwater from the Lost River Range (Busenberg and others, 2001). All other natural groundwater with concentrations and (or) ratios of $^3H/^3He$, CFCs, and SF_6 were estimated to contain some young groundwater, even if only in small amounts. For example, natural groundwater from the Northeast INL Area had the youngest estimated age of the young fraction groundwater (fig. 27*KK*). However, the small tritium activities and large He_{terr} values in groundwater from the Northeast INL Area indicated that only a small fraction of this groundwater was young groundwater.

---

[22] The difference between estimated ages >>55 years before the sampling date and “old” was that no CFCs were detected in groundwater samples with estimated ages >>55 years, and thereby could be determined to predate the release of CFCs to the atmosphere, whereas “old” groundwater contained CFCs that, based on small tritium activities in the groundwater, was presumed to be from advective and diffusive transport of CFCs through the unsaturated zone (Busenberg and others, 2001).

Carbon-14

Carbon-14 age dating indicated that geothermal water from INEL-1 10,300 feet was about 35,000 years old (Mann, 1986). Carbon-14 ages were not determined for other groundwater in the study area because tritium, an indicator of recent recharge, was present in nearly all other groundwater. Carbon-14 activities, however, may be useful for identifying sources of recharge. For example, modern carbon-14 activities (>100 pmC) should be present in recent recharge of surface water (with an estimated percent modern carbon of 120; fig. 27*LL*), plus any CO_2 in the unsaturated zone in equilibrium with the atmosphere that was transported to the aquifer in infiltrating surface water. Conversely, marine carbonates in the mountains, or in sediment in the unsaturated zone or ESRP aquifer, typically have carbon-14 activities of 0 pmC (Clark and Fritz, 1997, table 8-1), and dissolution of marine carbonates will reduce the carbon-14 activity in groundwater. For example, the small carbon-14 activities in natural groundwater from the northern part of the INL, 21–37 pmC (fig. 28*DD*), were due to dissolution of marine carbonates.

The relation between carbon-14 activity and the mean age of natural groundwater was evaluated from a plot of carbon-14 and tritium activities (fig. 16), with larger tritium activities corresponding to a younger mean age and smaller tritium activities corresponding to an older mean age. The $\delta^{13}C$ values also were included to provide information about the sources of carbon in the groundwater. Natural groundwater plots along two trends in figure 16, with groundwater from the Northeast and Southeast INL Areas plotting along a steeper slope, and generally having a smaller tritium activity and $\delta^{13}C$ value for a given carbon-14 activity, than groundwater from the North, Central, Northwest, and Southwest INL Areas. These two trends indicated that groundwater from the Northeast and Southeast INL Areas had a different origin than groundwater

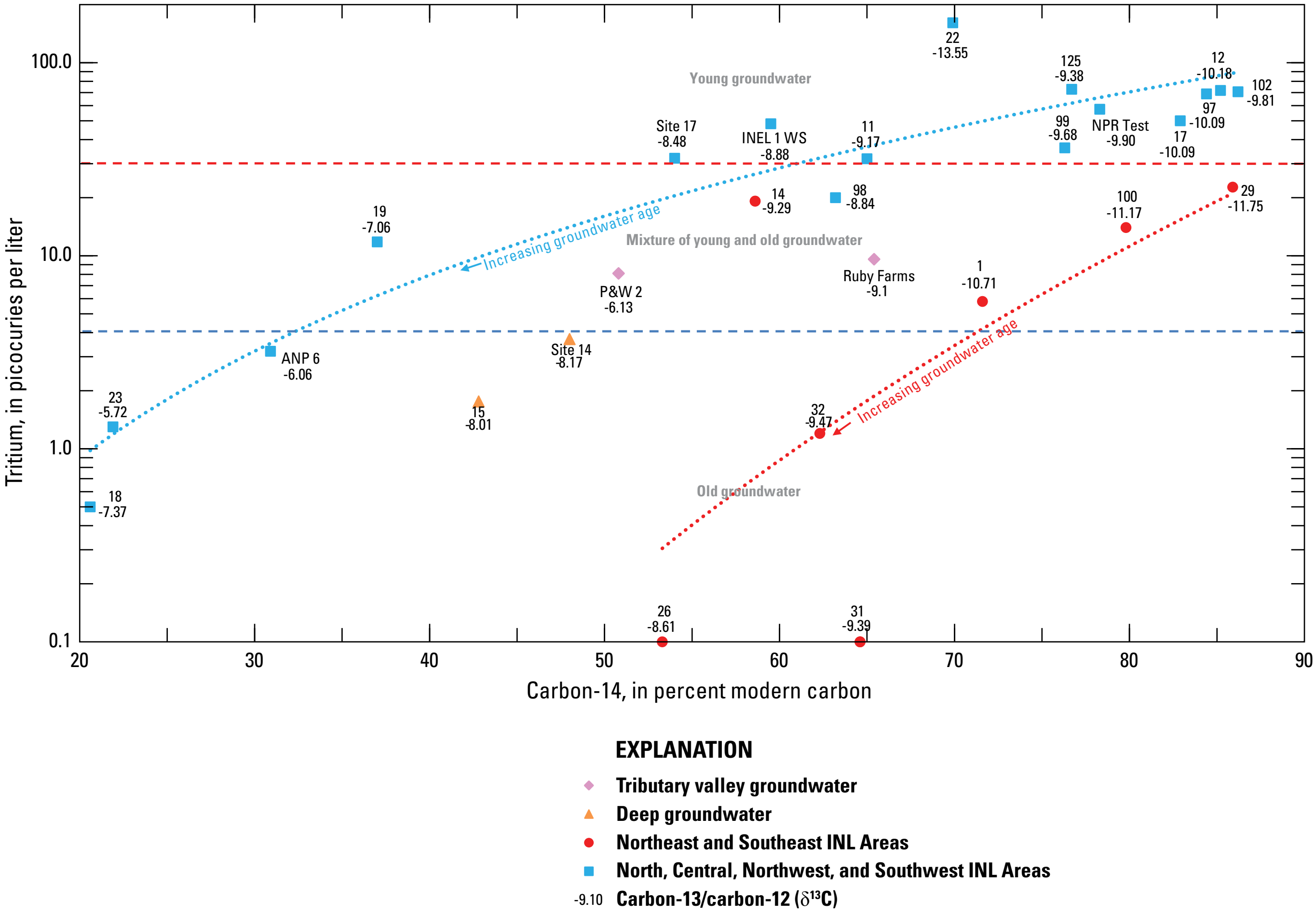


Figure 16. Carbon-14 activities, tritium activities, and carbon-13/carbon-12 ($\delta^{13}C$) values in groundwater, Idaho National Laboratory and vicinity, eastern Idaho.

from the North, Central, Northwest, and Southwest INL Areas, a conclusion that was consistent with the interpretation from lithium concentrations that groundwater from these Areas was from regional groundwater and tributary valley water, respectively. Along each of the trends, $\delta^{13}C$ values also generally increased as tritium and carbon-14 activities decreased. These results indicated that dissolution of marine carbonates in interbed sediment occurs throughout the ESRP aquifer at the INL.

Distinguishing Chemical and Isotopic Characteristics for Each Water Group

Knowledge of the distinguishing chemical and isotopic characteristics for each water group will help identify the sources of water at the INL. This synopsis of the chemical and isotopic constituents that distinguish each of the water groups is based on the analysis of the chemical and isotopic constituents presented above and the data presented in figures 27*A–LL* and 28*A–DD*.

Surface Water

Surface water generally was dilute, had small concentrations of helium, major ions, boron, and lithium, and was a $Ca\text{-}HCO_3$ water type. Surface water generally was young water characterized by large tritium activities, and infiltration recharge of surface water may transport soil CO_2 with light $\delta^{13}C$ values to the aquifer. The $\delta^{2}H$ and $\delta^{18}O$ values in surface water ranged from heavy to light, with the heaviest values in Camas Creek and Mud Lake, intermediate values in the BLR and LLR, and lighter values in BC. The LLR and BC had large $^{87}Sr/^{86}Sr$ ratios, although the $^{87}Sr/^{86}Sr$ ratio from the BLR was much smaller.

Tributary Valley Groundwater

Tributary groundwater was cold, had small concentrations of potassium, fluoride, silica, boron, and lithium, and primarily was a $Ca\text{-}HCO_3$ type water. Because of the influence of agriculture, groundwater in the lower parts of the BLR and LLR valleys had relatively large specific conductance values and nitrate concentrations. The $\delta^{2}H$ and $\delta^{18}O$ values in tributary valley groundwater ranged from heavy to light, with heavy, intermediate, and light $\delta^{2}H$ and $\delta^{18}O$ values in groundwater from the BLR, LLR, and BC valleys, respectively. The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios in groundwater from the LLR and BC valleys were large.

Regional Groundwater

The chemistry of regional groundwater can be categorized into three groups—groundwater that was either extensively (North, West, and Southwest Mud Lake Areas; table 10) or slightly (East Mud Lake and Southeast INL Boundary Areas) influenced by agricultural inputs and groundwater that was influenced by upwelling geothermal water (groundwater with geothermal input). Groundwater extensively influenced by agricultural inputs typically was a mixed cation-HCO_3 water type with large specific conductance, large concentrations of CO_2, major ions (except for fluoride), barium, boron, lithium, strontium, and uranium, heavy $\delta^{2}H$ and $\delta^{18}O$ values, and was young water or a mixture of young and old water. Groundwater slightly influenced by agricultural inputs was typically a $Ca\text{-}HCO_3$ water type with small specific conductance, small concentrations of calcium, magnesium, bicarbonate, chloride, sulfate, barium, boron, and strontium, large concentrations of fluoride and silica, and was old water or a mixture of young and old water. Groundwater influenced by upwelling geothermal water was a mixed cation-HCO_3 or $Na\text{-}HCO_3$ water type, was anoxic or undersaturated with oxygen, had small specific conductance, small concentrations of CO_2, calcium, chloride, sulfate, nitrate, strontium, and uranium, large concentrations of sodium, potassium, fluoride, silica, and lithium, and was old water. Regional groundwater can be distinguished from tributary valley groundwater by warmer groundwater temperatures, larger concentrations of sodium, potassium, fluoride, silica, boron, and lithium, and, compared with groundwater from the LLR and BC valleys, heavier $\delta^{2}H$ and $\delta^{18}O$ values, lighter $\delta^{13}C$ values, and smaller $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios.

Geothermal Water

Geothermal water consisted of three distinct water types. Site ML 58 (Warm Spring), located high in the Beaverhead Mountains, was a $Ca\text{-}HCO_3$ type water with a large fluoride concentration, a large $\delta^{13}C$ value, an extremely large $^{87}Sr/^{86}Sr$ ratio, and was a mixture of young and old water. Site ML 57 (Lidy Hot Springs), located in the foothills of the Beaverhead Mountains, was a $Ca\text{-}SO_4$ type water with large specific conductance, large calcium, potassium, sulfate, fluoride, boron, lithium, and strontium concentrations, a large $\delta^{13}C$ value, $\delta^{2}H$ and $\delta^{18}O$ values that plot to the left of the LMWL (fig. 11), and consisted of old water. Water from borehole INEL-1, deep below the ESRP, was a $Na\text{-}HCO_3$ type water with large specific conductance, large sodium, potassium, fluoride, silica, boron, and lithium concentrations, small calcium and magnesium concentrations, small $^{87}Sr/^{86}Sr$ ratios, and, for water from site INEL-1 10,300 feet, was anoxic and very old.

Deep Groundwater

Deep groundwater generally had small specific conductance, small concentrations of DO, chloride, and nitrate, small $\delta^{18}O$ and large $\delta^{13}C$ values, was a mixed cation-HCO_3 water type, and, based on small tritium activities, was primarily old groundwater. However, some important chemical differences existed between deep groundwater from different sites. For example, deep groundwater from Site 14 and USGS 7 had large temperatures (16.3 and 18.8 °C), large concentrations of helium (38.4 and 149 cm^3 STP/g × 10^{-8}), large percentages of He_{terr} (91 and 97 percent), and USGS 7 plots between natural groundwater and geothermal water from INEL-1 on a trilinear diagram (fig. 10*A*), all of which indicated that some mantle helium, in upwelling geothermal water (fig. 14), was present in deep groundwater from these two wells. Site EBR 1, on the other hand, had a small helium concentration (5.5 cm^3 STP/g × 10^{-8}), a fairly small He_{terr} (27 percent), and a tritium activity (-3.2±13 pCi/L) consistent with either old groundwater or a mixture of young and old groundwater (table 17). The small helium concentration and percentage of He_{terr} indicated that deep groundwater at EBR 1 contained some recent recharge. The location of EBR 1 (fig. 9) indicates that the source of recent recharge probably was the BLR, and the estimated age of the young fraction of groundwater indicated that the recent recharge occurred at least 45 years prior to collection of the water sample in 1996 (Busenberg and others, 2001, table 9).

Contaminated Groundwater

Potential sources of recharge to contaminated groundwater included wastewater discharged at site facilities as well as tributary groundwater and infiltration of the BLR and, at TAN, BC. These potential sources of water resulted in a wide variety of hydrochemical facies for contaminated groundwater, although most contaminated groundwater was a Ca-HCO_3 water type (fig. 10*A*–*B*). Concentrations of fluoride, silica, and lithium were small, and discharge of wastewater resulted in large specific conductance, large calcium, sodium, chloride, and sulfate concentrations, and large tritium activities. Infiltration of wastewater or the BLR caused some contaminated groundwater to have helium concentrations similar to air-water equilibrium concentrations, light $\delta^{13}C$ values, and slightly evaporated $\delta^{2}H$ and $\delta^{18}O$ values (in groundwater south of the INTEC infiltration ponds).

Discharge of large amounts of certain waste constituents in wastewater from specific site facilities resulted in contaminated groundwater with distinct chemical characteristics at each site facility. For example, contaminated groundwater at ATRC had large calcium, sulfate, and chromium concentrations, large tritium activities, and was a Ca-SO_4 water type. Contaminated groundwater at INTEC had large magnesium, sodium, chloride, and barium concentrations, large tritium activities, and included some groundwater that was a mixed cation-Cl water type, whereas groundwater at NRF had large calcium, magnesium, sodium, chloride, and sulfate concentrations and included some groundwater that was a mixed cation-mixed anion water type. Contaminated groundwater at RWMC had large sulfate concentrations and large tritium activities, contaminated groundwater at TAN had small DO concentrations, large sodium and chloride concentrations, and large tritium activities, and some contaminated groundwater from RWMC and TAN was a mixed cation-mixed anion water type.

Natural Groundwater

Natural groundwater generally was well oxygenated, indicating that widespread oxidation-reduction reactions do not occur in groundwater at the INL. Other chemical characteristics in natural groundwater typically varied across the INL due to the chemical diversity of the source waters. For example, specific conductance was largest in natural groundwater downgradient of irrigated lands in the Mud Lake area and the LLR valley. Most major ion, and some dissolved metal, concentrations in natural groundwater also followed a general pattern of either increasing or decreasing concentrations in a southeast-to-northwest direction across the INL in response to recharge from carbonate and silicate terranes north and east of the INL, respectively. Agricultural inputs prevented these patterns of increasing or decreasing concentrations from being entirely consistent. However, three elements, fluoride, silica, and lithium, show a consistent decrease in concentrations in a southeast-to-northwest direction across the INL because these elements primarily were derived from dissolution of silicate minerals east of the INL and concentrations of these elements were not affected by agricultural inputs. Although major ion and dissolved metal concentrations varied across the INL, the dominant anion in groundwater was bicarbonate. As a result, the hydrochemical facies of natural groundwater was either a Ca-HCO_3 or a mixed cation-HCO_3 water type.

The $\delta^{2}H$ and $\delta^{18}O$ values in natural groundwater also varied widely across the INL because of the widely different values in sources of recharge. For example, for the three primary sources of recharge to the INL, $\delta^{18}O$ values were typically less than -17.90 permil in groundwater from the LLR and BC valleys, were probably about -17.4 or -17.17 permil in the BLR (on the ESRP), and ranged from -17.90 to -14.84 permil in regional groundwater (fig. 11).

About one-half of the R_s/R_a ratios in natural groundwater were at or slightly larger than 1.0, consistent with helium from young recharge. Ratios less than 1.0 were present in some natural groundwater from the Northeast and Southeast INL Areas, consistent with groundwater containing crustal helium and having a long aquifer residence time, and an R_s/R_a ratio of 9.70 for a groundwater sample (USGS 27) from the Northeast INL Area indicated that this groundwater contains geothermal water. Tritium activities indicated that natural groundwater in the North and Northeast INL Areas and the northern part of the Central INL Area consisted primarily of old groundwater, the Southeast INL Area consisted of a mixture of young and old groundwater, and the Northwest and Southwest INL Areas and the southern part of the Central INL Area consisted primarily of young groundwater or a mixture of young and old groundwater.

Temporally Variable Water Chemistry

Temporally variable groundwater chemistry occurs at many locations at the INL (Robertson and others, 1974; Bartholomay and others, 2012; Davis and others, 2015) due to temporally variable natural and anthropogenic sources of recharge. Temporally variable sources of recharge include (1) episodic recharge of surface water with different, and variable, chemical compositions than groundwater at the INL; (2) changing wastewater disposal practices at site facilities; and (3) changing irrigation practices north (tributary valley groundwater) and east (regional groundwater) of the INL. Examples of temporally variable sources of recharge include (1) episodic recharge from the BLR (Bennett, 1990), LLR, and BC; (2) changes in method of discharge of wastewater from injection wells to infiltration ponds and relocation of infiltration ponds (Davis and others, 2013); and (3) increased use of groundwater for irrigation (Goodell, 1988) and changing from flood to sprinkler irrigation (Idaho Department of Environmental Quality, 2006).

Long-term trends (trends that occur over decades) in groundwater chemistry at the INL, which includes the influence of irrigation water and wastewater discharge, were reported by Bartholomay and others (2012) and Davis and others (2015). The long-term trends showed that for groundwater unaffected by wastewater disposal (that is, natural groundwater), changes to groundwater chemistry because of anthropogenic inputs was generally gradual and of small magnitude. In contrast, wet and dry climate periods produce highly variable infiltration from surface water sources of recharge that influence the natural chemistry of groundwater at the INL.

Infiltration of surface water produces changes in the chemistry of groundwater at the INL because surface water is generally more dilute than groundwater at the INL and may occur as focused, episodic recharge. The chemistry of surface water also varies in a seasonal manner in response to (1) the relative percentages of surface water inflow (that is, tributary creeks, overland runoff, and direct precipitation) and groundwater inflow that contributes to stream discharge and lake storage; (2) agricultural inputs; and (3) the amount of evaporation that the stream or lake has undergone. Surface water, therefore, has significant potential for producing temporally variable chemistry in groundwater at the INL. Consequently, the temporal variability of interest for this study are the temporal changes in the chemistry of surface water and the changes in groundwater geochemistry associated with focused, episodic recharge of surface water.

Surface Water

Time-series plots of bicarbonate, nitrate, and the stable isotopes of hydrogen and oxygen were prepared to identify changes in surface water chemistry and the primary cause of the change. Bicarbonate was used to identify the relative amounts of surface water and groundwater inflow to the streams and Mud Lake because groundwater in the study area has much larger concentrations of bicarbonate (table 13) than does meteoric water (Bartholomay and others, 2015; Busenberg and others, 2001). Nitrate was used to identify whether agricultural inputs influenced the chemistry of surface water, and the stable isotopes of hydrogen and oxygen were used to identify whether evaporation, which could affect the concentrations of dissolved constituents, occurs.

Bicarbonate and Nitrate

Concentrations of bicarbonate and nitrate (table 4), and monthly discharge or daily storage volume (U.S. Geological Survey, 2014), were plotted for the BLR near Arco, the LLR near Howe, and Mud Lake near Terreton (figs. 17*A*–*C*). The plotted data represent periods of record (1965 through 1970 for the BLR, 1965 through 1981 for the LLR, and 1968 through 1978 for Mud Lake) with a high frequency of data collection. A low frequency of data collection would make it difficult to identify the influence of surface water inflow relative to groundwater inflow or agricultural inputs on surface water chemistry. Data collection from sites on Birch Creek and Camas Creek were infrequent, so the influence of surface water inflow compared with groundwater inflow or agricultural inputs on surface water chemistry was not evaluated for these streams.

Concentrations of bicarbonate (in milligrams per liter) ranged from 168 to 291 for the BLR, from 95 to 233 for the LLR, and from 90 to 183 for Mud Lake. Conceptually, bicarbonate should decrease in the streams during spring snowmelt and runoff and should increase when the stream recedes to base flow. However, the timing of increases or decreases of bicarbonate concentrations in Mud Lake may not be directly relatable to snowmelt because water in Mud Lake was controlled by groundwater inflow, groundwater pumping, as well as surface-water inflow during spring runoff.

The correlation between bicarbonate concentrations and streamflow discharge or volume of lake storage was calculated to test whether the concentrations were related to stream discharge or volume of lake storage. Correlations of -0.70, -0.77, and 0.34 were calculated for the BLR, LLR, and Mud Lake, respectively. There was a moderately strong negative correlation for the streams, with smaller bicarbonate concentrations occurring during high volume discharge (spring runoff) and larger concentrations during low volume discharge (base flow). The correlation for Mud Lake was weak, probably because storage in Mud Lake was controlled by primarily by inflows and outflows that were not entirely related to snowmelt.

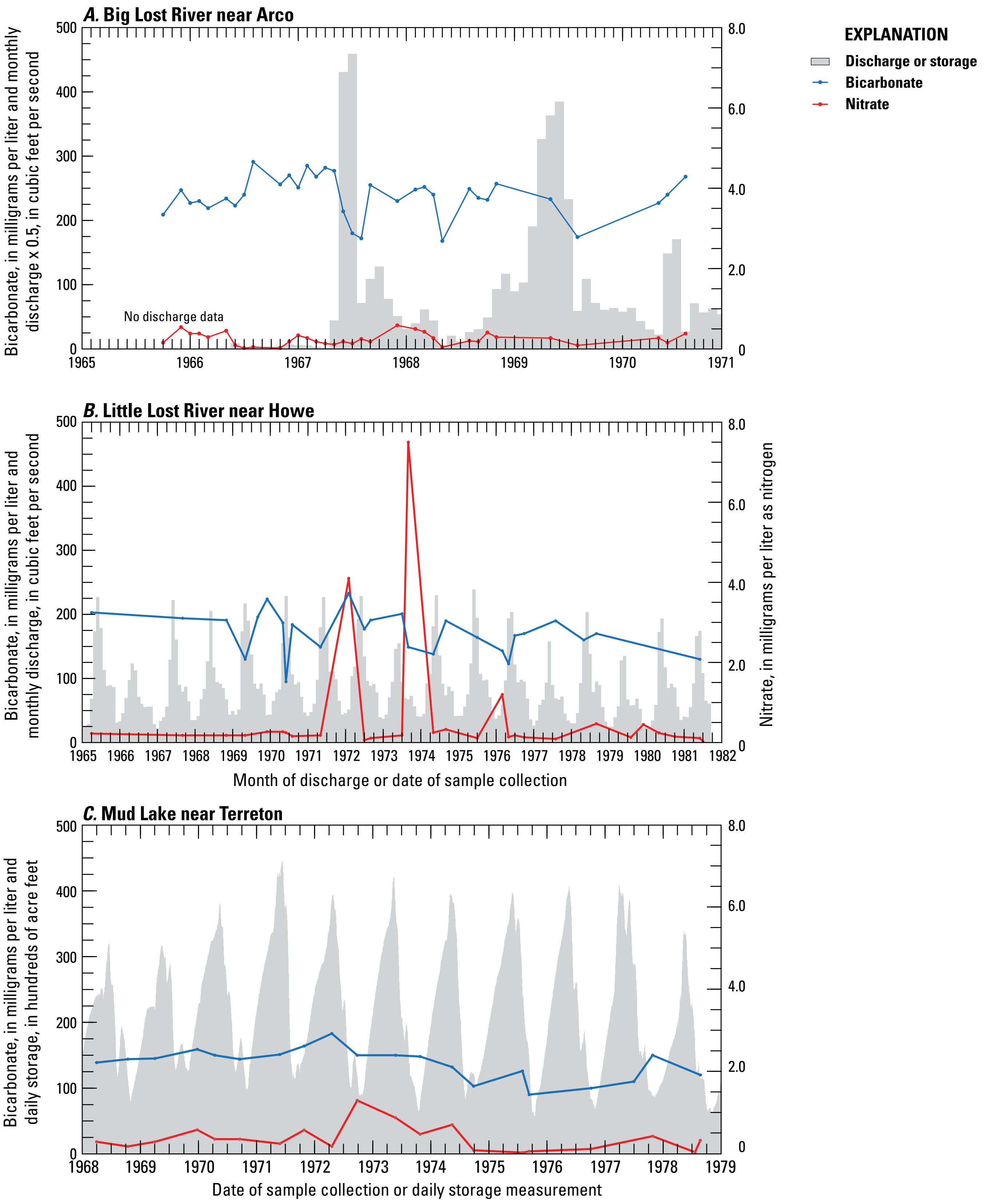


Figure 17. Bicarbonate and nitrate concentrations and monthly discharge or daily storage volume, Idaho National Laboratory and vicinity, eastern Idaho. (*A*) Concentrations and discharge for the Big Lost River near Arco, 1965 through 1970. (*B*) Concentrations and discharge for the Little Lost River near Howe, 1965 through 1981. (*C*) Concentrations and storage for Mud Lake near Terreton, 1968 through 1978.

Concentrations of nitrate (in milligrams per liter as nitrogen) ranged from 0.02 to 0.59 for the BLR, from 0.03 to 7.50 for the LLR, and from 0.03 to 1.30 for Mud Lake. The range of concentrations is quite large; however, only 10 of the 83 total nitrate measurements had nitrate concentrations exceeding 0.5 mg/L as N. These infrequent large nitrate concentrations indicate that fertilizer applied in irrigation areas was only occasionally a significant source of chemical constituents to surface water, and indicates that agricultural chemicals generally did not influence the chemistry of surface water in the study area.

Stable Isotopes of Hydrogen and Oxygen

The δ^2H and δ^{18}O values were measured from monthly water samples, collected between March 1991 and June 1992, from the BLR at Mackay Reservoir, the LLR near Howe, BC at Blue Dome, and Mud Lake near Terreton (table 3). The δ^{18}O values ranged from -18.00 to -17.05 permil for the BLR, -18.25 to -17.80 permil for the LLR, -18.75 to -18.55 permil for BC, and -17.85 to -15.55 permil for Mud Lake. The range between large and small δ^{18}O values, 0.20 permil for BC, 0.45 permil for the LLR, 0.95 permil for the BLR, and 2.30 permil for Mud Lake, shows that δ^{18}O values were mostly uniform in BC, slightly variable in the LLR, moderately variable in the BLR, and highly variable in Mud Lake. Part of the variability of the δ^2H and δ^{18}O values may be due to the location of the sampling site. For example, Birch Creek at Blue Dome, at an altitude of 6,050 ft (table 11), is likely to be less influenced by evaporation than Mud Lake near Terreton at an altitude of 4,775 ft.

The δ^{18}O values were plotted on a time series graph (figs. 18*A*–*B*), along with the daily discharge in the BLR and LLR (discharge data were not available for BC) and the daily storage volume of Mud Lake (U.S. Geological Survey, 2014). The δ^{18}O values of the streams, during 1991 and 1992, ranged from heavy to light in a southwest-to-northeast direction (that is, δ^{18}O values for the BLR were heavier than for the LLR and δ^{18}O values for the LLR were heavier than for BC) and the δ^{18}O values from Mud Lake were as heavy, or heavier, than those from the BLR (fig. 18).

The δ^{18}O values from BC do not show any evidence of evaporation (figs. 11 and 18*A*). The δ^{18}O values from the LLR are slightly heavier in summer than winter, which indicates that a small amount of evaporation of the LLR may occur during summer. The δ^{18}O values from the BLR are significantly heavier in the summer than winter, and some of the heavier δ^{18}O values from the BLR plot along the lower extent of the Mud Lake evaporation line (fig. 11). This indicates that water in the BLR has undergone evaporation, and the positive correlation between δ^{18}O values and discharge in the BLR below Mackay Reservoir (r=0.97) shows that the evaporation occurred to water stored in Mackay Reservoir. Two of the heavier δ^{18}O values from the BLR also plot near the LMWL for winter, not the Mud Lake evaporation line, and these heavier values may be due to summer precipitation, not evaporation.

Heavier δ^{18}O values occurred in Mud Lake during both summer and winter, and these heavier δ^{18}O values plotted along the Mud Lake evaporation line (fig. 11), indicating that the heavier values were due to evaporation. Heavy δ^{18}O values may occur during both summer and winter in Mud Lake because it is a shallow lake with a large surface area (area of about 4,000 acres and maximum storage of 61,000 acre-ft; Spinazola, 1994). In the heat of summer, the large surface area promotes significant evaporation of the lake, which enriches the δ^{18}O values. During the cold winter months, the large surface area still promotes evaporation, although much less than in summer. However, this smaller amount of winter evaporation still enriches the δ^{18}O values of the lake because of the much smaller volume of storage in the lake during winter (fig. 18*B*) and, because water from the lake is not being used for irrigation, the longer residence time of water in the lake during winter relative to summer.

Natural Groundwater

At wells located near or slightly downgradient of areas where episodic recharge of surface water occurs, water levels measured at the wells, as well as groundwater geochemistry, may rapidly respond to the episodic recharge. Thus, episodic recharge of surface water may produce patterns of peaks and valleys in time series plots of water levels and chemical concentrations. Because the surface-water recharge from streams is typically more dilute than the groundwater (table 12), chemical concentrations in groundwater decrease as water levels increase. Consequently, episodic recharge of surface water may produce an inverse correlation between rising and declining water levels and concentrations of major ions in a well (Bartholomay and others, 2012). At wells some distance from areas of episodic recharge of surface water, the groundwater containing the episodic recharge may not reach the well at all or may take several years or more to flow to the well. Under these conditions, there may be no inverse correlation between water levels and chemical concentrations, or the inverse correlation may be offset by a lag period that depends on the rates at which hydraulic pressure heads influence water levels in a well and the time it takes for groundwater containing the episodic recharge to reach the well.

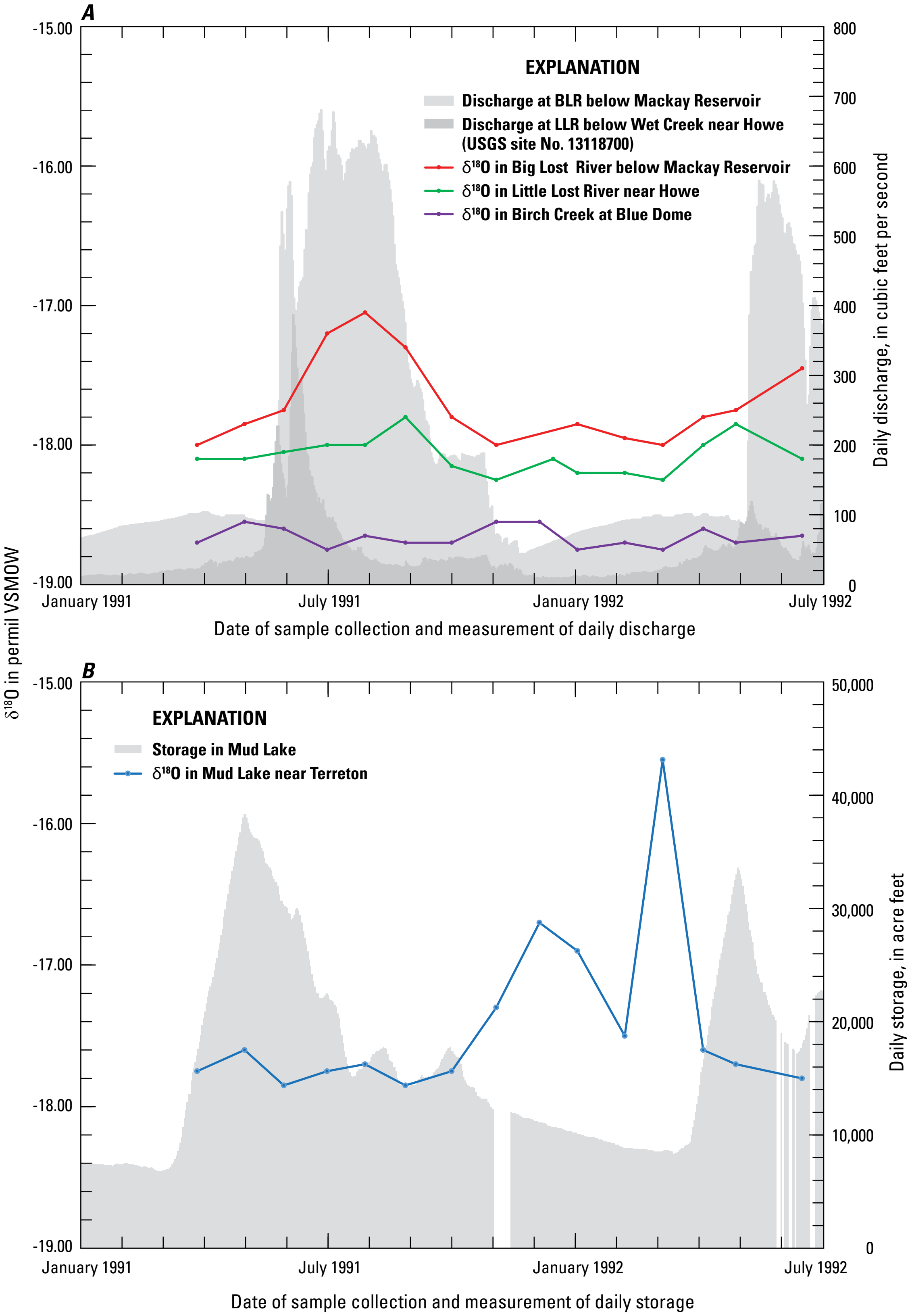


Figure 18. Monthly stable isotope ratios of oxygen ($\delta^{18}O$) for surface water from the (*A*) Big Lost River (BLR), Little Lost River (LLR), Birch Creek, and Mud Lake and the daily discharge of the BLR and LLR and (B) storage of water in Mud Lake from January 1991 to July 1992, Idaho National Laboratory and vicinity, eastern Idaho.

Episodic infiltration recharge from the BLR produces an extensive temporal influence on groundwater geochemistry at the INL because the BLR channel extends across the western part of the INL (fig. 3*B*), discharge of the BLR at the INL ranges from hundreds of cubic feet per second during wet climate cycles to zero during dry climate cycles[23] (fig. 5), surface water may rapidly infiltrate to the aquifer (Nimmo and others, 2002), and the water in the BLR ranges from slightly to significantly more dilute than most groundwater in the western part of the INL (fig. 28*B;* Bartholomay and others, 2012). The distribution and amount of water in the BLR at the INL affects the location and amount of infiltration recharge. For example, during 1965–87, 50 percent of the water in the BLR at the INL was diverted to the INL spreading areas, 9 percent infiltrated between the INL diversion and Lincoln Boulevard (fig. 8*B*), and 41 percent either infiltrated below Lincoln Boulevard or flowed into playas 1, 2, or 3 (fig. 3*B*) (Bennett, 1990). Infiltration rates from the BLR channel were small (≤4 [ft^3/s]/mi) at small discharge volumes (37–118 ft^3/s at streamgage BLR near Arco); however, at a large discharge volume (372 ft^3/s at streamgage BLR near Arco; May 6–8, 1985) infiltration rates were about 1–9 (ft^3/s)/mi from the BLR channel and 28 (ft^3/s)/mi from the BLR sinks (Bennett, 1990, fig. 12). Episodic infiltration recharge from the BLR caused generalized water level rises and declines of ±6–10 ft in the western part of the INL during the 1980s and 1990s (Ackerman and others, 2006, fig. 22).

The temporal variability of groundwater geochemistry at the INL was evaluated by plotting time series of water levels and chloride concentrations in selected wells distributed throughout the INL (figs. 19*A*–*Q*). Chloride concentrations were selected to represent changes in groundwater geochemistry because chloride was routinely sampled, is nonreactive in solution, and has smaller concentrations in surface water (1–5 mg/L) than in natural (4.9–66.6 mg/L) or contaminated (11.9–240 mg/L) groundwater (fig. 27*O*, table 13). In addition, time series of nitrate concentrations were plotted for wells where irrigation may influence groundwater geochemistry.

North INL Area

Water levels and chloride concentrations are plotted in figures 19*A*–*C* for three wells, P&W 2, ANP 6, and No Name 1, in or near the North INL Area. These wells had annual or more frequent measurements of water levels and chloride concentrations beginning in 1980, 1992, and 1991. P&W 2 and ANP 6 are located about 0.6 and 0.9 mi west of BC and No Name 1 is located about 0.8 mi southwest of playa 4 (figs. 3*B* and 9).

Water-level patterns at P&W 2, ANP 6, and No Name 1 were similar and included annual water-level fluctuations of 1–5 ft in response to seasonal recharge of streamflow, water-level fluctuations of 5–26 ft in response to wet and dry climate cycles (Ackerman and others, 2006), and a long-term steep decline in water levels of 33–35 ft between 1988 and 2014.

Chloride concentrations ranged from 5 to 25 mg/L at P&W 2, 11 to 21.8 mg/L at ANP 6, and 18 to 23 mg/L at No Name 1 (fig. 19*A*–*C*), and increased in the downgradient direction (that is, chloride concentrations at P&W 2 < ANP 6 < No Name 1). Chloride concentrations at P&W 2 and ANP 6 had a pattern of peaks and valleys, which indicates that groundwater at this location may include episodic recharge of surface water associated with wet and dry climate cycles. The estimated age of the fraction of young water at P&W2 and ANP 6 were 4–16 and 20–30 years (Busenberg and others, 2001), respectively, indicating that peak chloride concentrations probably lag peak water levels. The smaller chloride concentrations probably occur from dilution of groundwater in response to greater amounts of recharge from BC during wet climate cycles, whereas the larger chloride concentrations probably reflect relatively undiluted groundwater (Bartholomay and others, 2012). The nearly uniform chloride concentrations at No Name 1 indicated that the old groundwater (tritium concentration of 0.13±0.03 pCi/L; table 17) at this well does not include variable surface-water recharge (although groundwater at No Name 1 probably did include variable recharge from BC prior to construction of diversion channels in 1969).

Northeast INL Area

Water levels, chloride concentrations, and nitrate concentrations were plotted in figures 19*D*–*F* for three wells, USGS 26, USGS 31, and USGS 32, in the Northeast INL Area. These wells had annual or more frequent measurements of water levels and chloride concentrations beginning in 1991[24]. Site USGS 26 is about 2.8 mi east of BC and USGS 31 and USGS 32 are about 11 mi southwest of Mud Lake (figs. 3*B* and 9).

Water-level patterns at USGS 26 were similar to the water-level patterns at P&W2, ANP 6, and No Name 1. Water-level patterns in USGS 31 and USGS 32 included annual water-level fluctuations of 1–6 ft because of groundwater pumping for irrigation (Young and Norvitch, 1984) in the Mud Lake area, water-level fluctuations of 3–14 ft in response to wet and dry climate cycles, and a long-term decline in water levels of 18 and 24 ft between 1988 and 2014.

---

[23] For the purposes of this report, wet (and dry) climate cycles consisted of two or more consecutive years with more than (or less than) 25 ft^3/s discharge in the BLR below INL diversion near Arco Idaho (USGS site number 13132520). Based on figure 5, for the 50-year period of record between 1965 and 2012, each wet or dry climate cycle lasted from 4 to 12 years.

[24] Annual water-level measurements at some wells, such as USGS 26, began decades prior to beginning annual measurements of chloride concentrations.

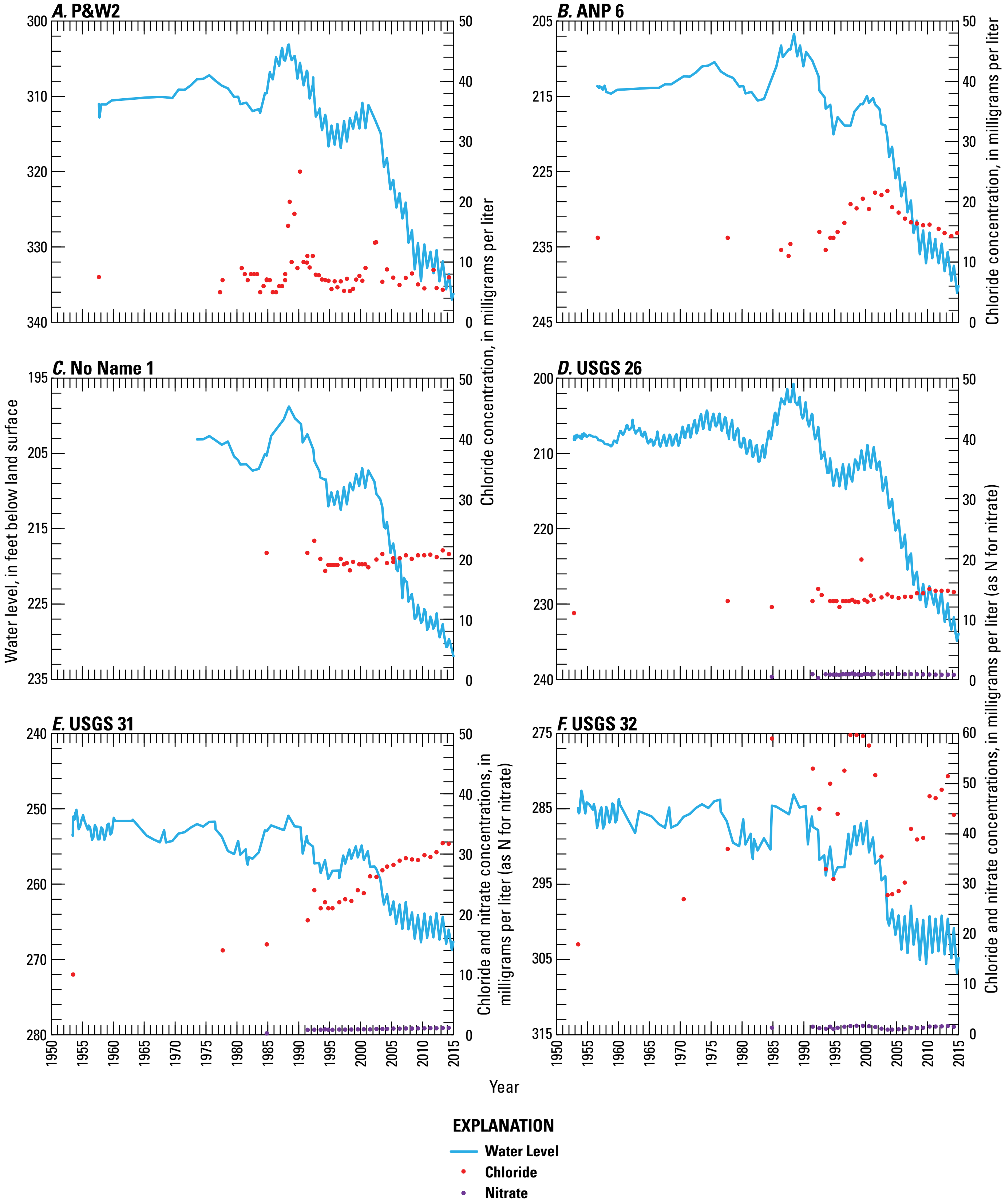


Figure 19. Water levels and chloride and nitrate concentrations for selected wells, Idaho National Laboratory and vicinity, eastern Idaho.

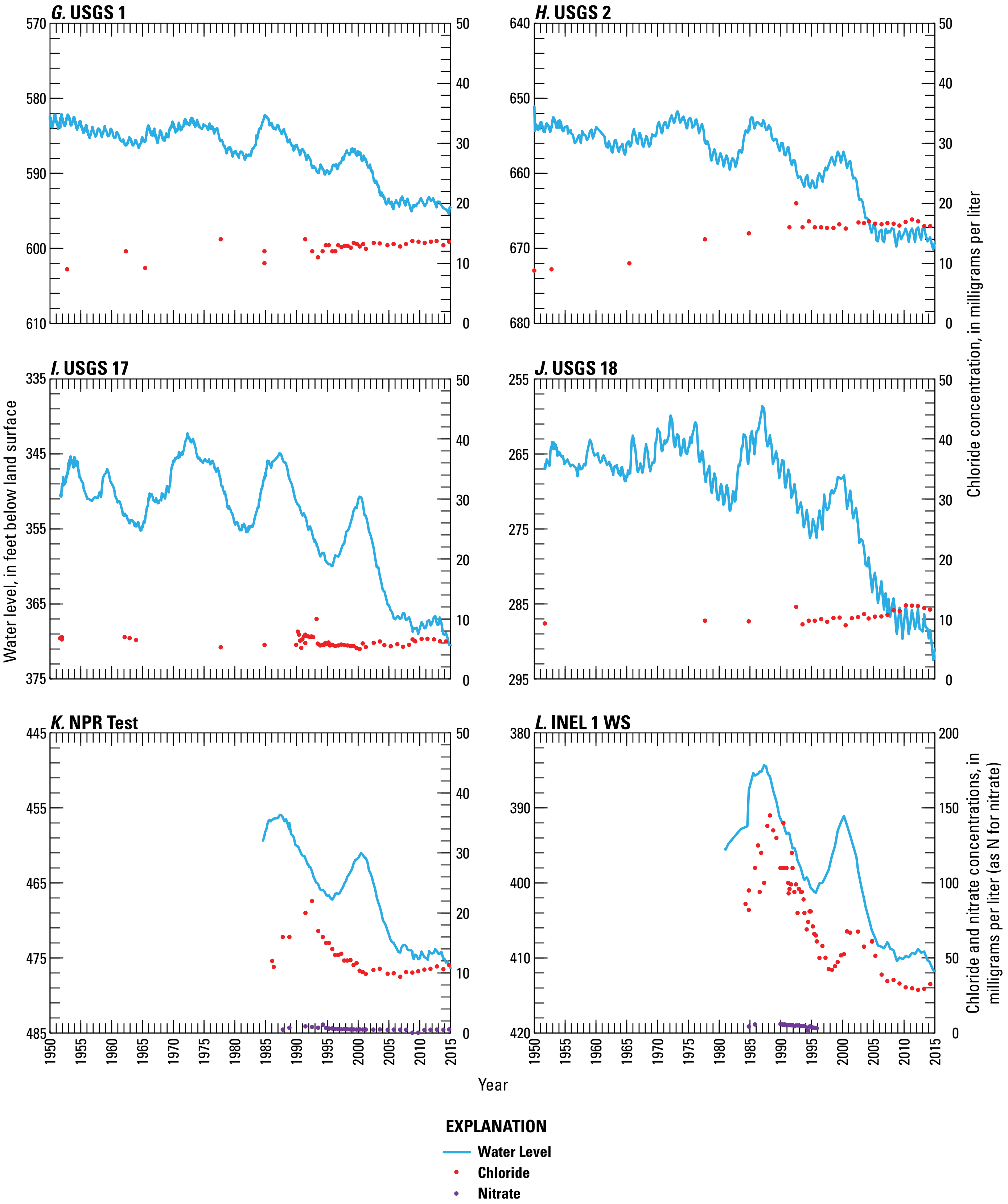


Figure 19.—Continued

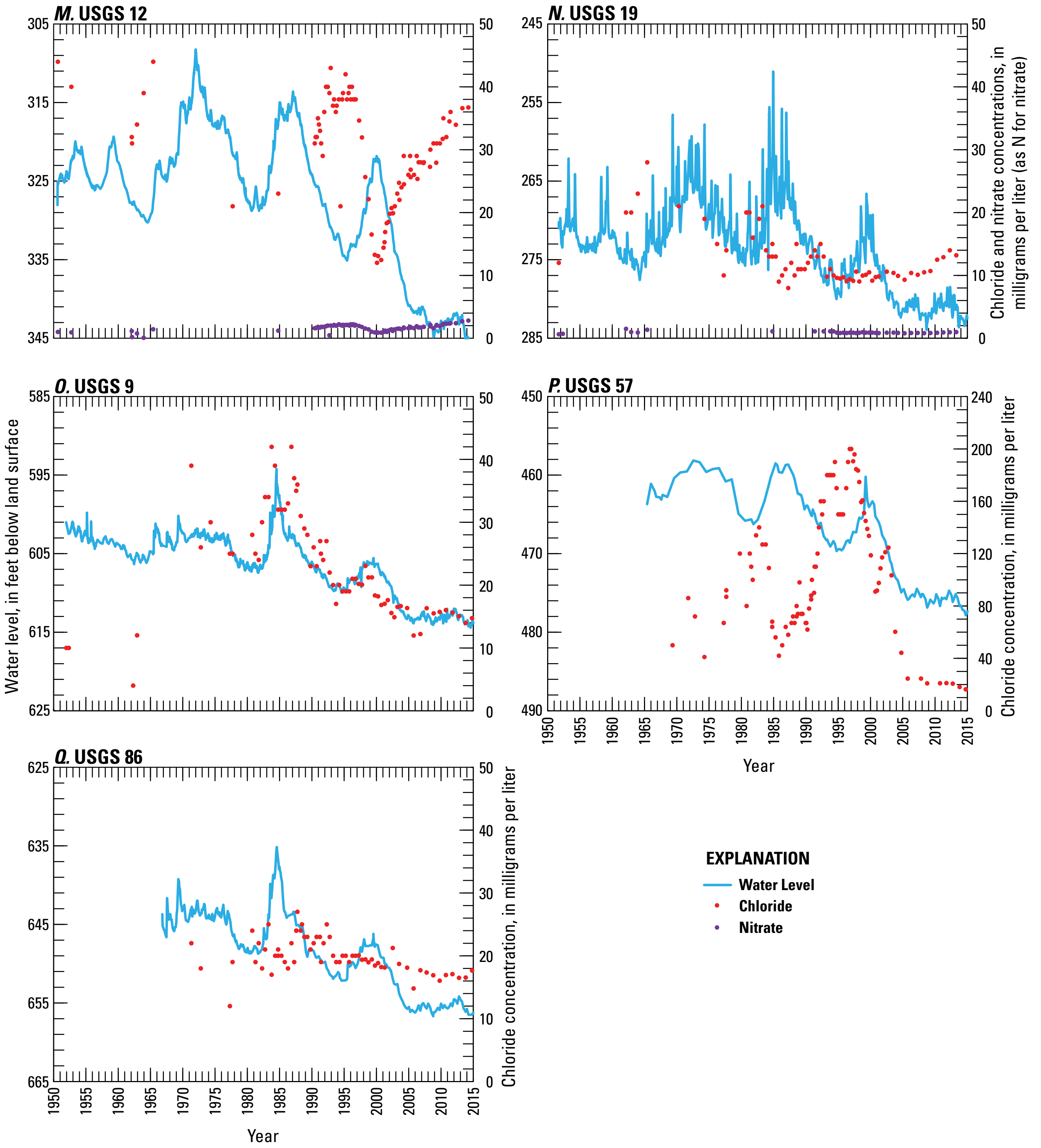


Figure 19.—Continued

Excluding one outlier chloride concentration[25] (19.9 mg/L in 1999), chloride concentrations at USGS 26 ranged from 11 to 15 mg/L. Like chloride concentrations at No Name 1, the chloride concentrations at USGS 26 were nearly uniform. Nitrate concentrations also were nearly uniform, and generally ranged between 0.73 and 0.97 mg/L as N. Consequently, groundwater at this well does not include episodic recharge of surface water, but probably does include a small amount of groundwater influenced by irrigation.

Chloride concentrations at USGS 31 ranged from 10 to 31.8 mg/L and increased throughout the period of record (1953–2014). Nitrate concentrations also steadily increased (period of record 1984–2014), from 0.81 to 1.14 mg/L as N. The absence of peaks and valleys in the chloride concentrations indicates that episodic recharge of surface water did not influence groundwater at this location, and the larger than background concentration of nitrate[26] indicates that groundwater at this location includes a small amount of groundwater influenced by irrigation. The steadily increasing chloride and nitrate concentrations may result from anthropogenic influences (Bartholomay and others, 2012), such as application of agricultural products to the land coupled with recycling of groundwater used for irrigation (Plummer and others, 2000) and more efficient irrigation methods (that is, transitioning from flood to sprinkler irrigation), or a long-term trend of decreasing recharge.

Chloride and nitrate concentrations at USGS 32 ranged from 18 to 59.7 mg/L for chloride and 1.0 to 1.8 mg/L as N for nitrate. Measurements of chloride and nitrate were sparse prior to 1984, but concentrations of chloride and nitrate have a pattern of peaks and valleys between 1977 and 2003 that indicates that groundwater at this location includes episodic recharge of surface water associated with wet and dry climate cycles. In addition, the nitrate concentrations indicate that the groundwater was influenced by irrigation. USGS 32 is located near areas in the Mud Lake area that are irrigated with both surface water and groundwater, and the variability in chloride and nitrate concentrations at this well may reflect temporally changing relative amounts of surface water and groundwater used for irrigation in response to wet and dry climate cycles. The steadily increasing chloride and nitrate concentrations between 2003 and 2013 may be due to anthropogenic influences or declining recharge.

Southeast INL Area

Water levels and chloride concentrations were plotted in figures 19*G*–*H* for two wells, USGS 1 and USGS 2, in the Southeast INL Area. These wells had annual or more frequent measurements of water levels and chloride concentrations beginning in 1991. USGS 1 and USGS 2 are about 1.3 mi northeast of Atomic City and about 4.3 mi southwest of the MFC (figs. 3*B* and 9), respectively.

Water-level patterns at USGS 1 and USGS 2 were similar. They had annual water-level fluctuations of 1–2 ft due to groundwater pumping for irrigation (from areas to the northeast, east, and southeast; figs. 3*B* and 8*B*), water-level fluctuations of 4–11 ft in response to wet and dry climate cycles, and a long-term decline in water levels of nearly 13–18 ft between 1984–85 and 2014.

Chloride concentrations at USGS 1 and USGS 2 ranged from 9 to 14 and 8.8 to 20 mg/L, respectively, were nearly uniform at USGS 1, slightly increased from 1950 to 1992 in USGS 2, and were nearly uniform in USGS 2 after 1992. These slightly increasing or nearly uniform chloride concentrations indicate that groundwater at these wells does not include episodic recharge of surface water.

Central INL Area

Groundwater levels and chloride concentrations were plotted in figures 19*I*–*K* for three wells, USGS 17, USGS 18, and NPR Test, in the Central INL Area. These wells had annual or more frequent measurements of water levels and chloride concentrations beginning in 1989, 1992, and 1991. USGS 17 is located about 0.5 mi east of the BLR, USGS 18 is located about 3.1 mi south of playa 4, and NPR Test is located about 1.6 and 5.6 mi southeast of the BLR and NRF (figs. 3*B* and 9), respectively.

Water-level patterns at USGS 17 and NPR Test were similar. They had annual water-level fluctuations of less than 1 ft, water-level fluctuations of 4–16 ft in response to wet and dry climate cycles, and a long-term decline in water levels of 21–25 ft between 1987 and 2014. Water-level patterns in USGS 18 were similar to water-level patterns in the North INL Area.

Chloride concentrations ranged from 5.0 to 10 mg/L at USGS 17, 8.9 to 12.2 mg/L at USGS 18, and 9.4 to 22 mg/L at NPR Test. Chloride concentrations at USGS 17 and USGS 18 were nearly uniform, indicating that groundwater at these wells may not include episodic recharge of surface water.

---

[25] Outlier chloride concentrations may be due to dilution of groundwater with drilling fluids, accidental switching of water-quality sample bottles during sample processing (Rattray, 2012), or some unidentified cause (Rattray, 2014).

[26] The background concentration of nitrate was assumed to be equal to or less than 0.5 mg/L as nitrogen. This assumption was based on nitrate concentrations in BC valley groundwater, where irrigation did not influence the concentration of nitrate in groundwater.

However, the large changes in water levels in response to wet and dry climate cycles at USGS 17, plus the close proximity of this well to the BLR, indicates that groundwater at USGS 17 was significantly influenced by episodic recharge from the BLR. Chloride concentrations at USGS 17 were nearly uniform because the water at this well, and thus the chloride, is derived primarily from the BLR. This interpretation is consistent with chloride concentrations at USGS 17 that were similar to chloride concentrations in the BLR (BLR near Arco, Idaho [13132500]); between 1965 and 2013, and based on 94 chloride measurements, the BLR near Arco had a mean (plus or minus standard deviation) chloride concentration of 5.9 ± 2.2 mg/L (data available at https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=13132500).

Chloride concentrations at well NPR Test had a pattern of peaks and valleys (fig. 19*K*) during 1986–2001 and a slight increasing concentration trend from 2001 to 2014. The peaks and valleys indicate that groundwater at this site includes episodic recharge of surface water associated with wet and dry climate cycles, whereas the increasing trend may be due to the overall trend of decreasing recharge.

The peak chloride concentration at NPR Test, 22 mg/L, was much larger than the peak chloride concentration in groundwater from USGS 5 (13 mg/L in 1977; data available at http://maps.waterdata.usgs.gov/mapper/), the closest well north of NPR Test in a direction toward the BC valley. Consequently, a source for the larger chloride concentrations at well NPR Test may be episodic recharge from the BLR sinks that pushes irrigation- and wastewater-influenced groundwater near NRF, with large chloride concentrations, southeastward toward NPR Test. Comparison of peak water level and chloride concentrations suggests that there is about a 5-year time lag for recharge from the BLR to reach NPR Test, which is consistent with the presence of young groundwater at NPR Test (based on a tritium concentration of 57.4±0.2 pCi/L; table 17). The interpretation was also consistent with nitrate concentrations that increased and decreased in unison with the chloride concentrations (fig. 19*K*) and with the orientation of contours of water-level changes resulting from episodic recharge from the BLR in response to wet climate cycles (Ackerman and others, 2006, fig. 22).

Northwest INL Area

Water levels, chloride concentrations, and nitrate concentrations were plotted in figures 19*L*–*N* for three wells, INEL 1 WS, USGS 12, and USGS 19, in the Northwest INL Area. These wells had annual or more frequent measurements of water levels and chloride concentrations beginning in 1984, 1990, and 1980. INEL 1 WS and USGS 12 are about 2.6 and 2.4 mi west of the BLR, respectively, and USGS 19 is about 1.9 mi south of the LLR sinks (figs. 3*B* and 9).

Water-level patterns at INEL 1 WS and USGS 12 were similar. They had annual water-level fluctuations of less than 1 ft, water-level fluctuations of 6–20 ft in response to wet and dry climate cycles, and a long-term steep decline in water levels of 27–31 ft between 1987 and 2014. Water-level patterns in USGS 19 had annual water-level fluctuations ranging from 1 to 20 ft, water-level fluctuations of 6–13 ft in response to wet and dry climate cycles, and a long-term decline in water levels of 21 ft between 1984 and 2014. The wide range of annual water-level fluctuations in USGS 19 probably was due to several surface water sources of recharge, such as infiltration recharge from the LLR channel and sinks and surface water used for irrigation, and groundwater pumping for irrigation in the Howe area of the LLR valley (fig. 3*B*) (Bartholomay and others, 2012; Bartholomay and Twining, 2015).

Chloride and nitrate concentrations ranged from 28.7 to 145 mg/L (excluding two large concentration outliers of 210 and 230 mg/L) and 1.4 to 5.9 mg/L as N at well INEL 1 WS, 12 to 44 mg/L and 0.18 to 2.7 mg/L as N at USGS 12, and 8 to 28 mg/L (excluding a small concentration outlier of 1 mg/L) and 0.64 to 1.5 mg/L as N at USGS 19. Patterns of chloride and nitrate concentrations at all three wells consisted of peaks and valleys, which indicates that groundwater at these wells includes episodic recharge of surface water associated with wet and dry climate cycles. The nitrate concentrations at all three wells shows that groundwater at these locations included groundwater from the LLR valley that was influenced by irrigation.

Water levels and chloride concentrations at USGS 12 were inversely related (fig. 19*M*). This pattern suggests that recharge from the BLR during wet climate cycles was rapidly diluting chloride concentrations. This interpretation was consistent with the tritium concentration of 71.9±0.7 pCi/L at USGS 12 (table 17), which shows that this well contains very recent recharge from the BLR, perhaps within the past 3–5 years (Busenberg and others, 2001; Bartholomay and others, 2012). Peak water levels and chloride concentrations at INEL 1 WS and USGS 19 are offset. This indicates that there is a time lag between when recharge occurred and when the recharge water reached these wells.

Southwest INL Area

Water levels and chloride concentrations were plotted in figures 19*O*–*Q* for three wells, USGS 9, USGS 57, and USGS 86, in the Southwest INL Area. These wells had annual or more frequent measurements of water levels and chloride concentrations beginning in 1979–80. USGS 9 is adjacent to INL spreading area C and about 3.2 mi southwest of RWMC, USGS 57 is about 0.8 and 0.3 mi south of the BLR and southwest of INTEC, respectively, and USGS 86 is about 2.5 mi south of the BLR (figs. 3*B* and 9).

Water-level patterns at USGS 9 and USGS 86 were similar. They had annual water-level fluctuations of 1–7 ft, water-level fluctuations of 4–14 ft in response to wet and dry climate cycles, and a long-term steep decline in water levels of 20–21 ft between 1984 and 2014. The annual water-level fluctuations were due to the combination of infiltration recharge from the BLR channel at the INL and the use of both surface water and groundwater for irrigation in the BLR valley and on the ESRP near Arco (fig. 3*B*). Water-level patterns in

USGS 57 had annual water-level fluctuations of 1.5 ft or less, water-level fluctuations of 7–16 ft in response to wet and dry climate cycles (and diversions to the INL spreading areas), and a long-term decline in water levels of 19 ft between 1987 and 2014.

Chloride concentrations ranged from 10 to 42 mg/L (excluding a concentration outlier of 4 mg/L) at USGS 9, 16.3 to 200 mg/L at USGS 57, and 12 to 27 mg/L at USGS 86. Patterns of chloride concentrations at USGS 9 and USGS 57 consisted of peaks and valleys, which indicates that groundwater at these wells includes episodic recharge of surface water associated with wet and dry climate cycles. A pattern of peaks and valleys was present in chloride concentrations at USGS 86 between 1971 and 1992, but the nearly annual frequency of the peaks and valleys indicate that the chloride concentrations were probably not related to variable recharge associated with wet-dry climate cycles.

Water levels and chloride concentrations at USGS 9, after 1980, rise and fall nearly uniformly. This may be because episodic recharge from the BLR north of the RWMC pushes contaminated groundwater at the RWMC south toward USGS 9. An exception to the nearly uniform pattern of rising and falling water levels and chloride concentrations occurred during 1984–85, when enough water was diverted from the BLR to reach, and subsequently infiltrate from, INL spreading area C. This infiltrating water diluted chloride concentrations at USGS 9 during 1984–85.

Chloride concentrations at USGS 86 varied enough to suggest that some seasonal recharge, either from the BLR or irrigation return flows, influenced the geochemistry of groundwater at this well. At USGS 57, chloride concentrations were influenced by the amount of chloride discharged in wastewater at INTEC as well as from episodic recharge from the BLR. For example, the decrease in chloride concentrations during 1995 resulted from a decrease in chloride discharged at INTEC, and the decrease of chloride concentrations from 2003 onward resulted from relocation in 2002 of the INTEC infiltration ponds to a location 1.4 mi west of USGS 57 (Davis and others, 2013).

Discussion

Temporally variable recharge from the BLR, LLR, BC, and of surface water used for irrigation produced temporal variability in the geochemistry of groundwater at the INL. The temporal variability of groundwater geochemistry due to variable recharge from the LLR, BC, and surface water irrigation was limited to small areas adjacent to these sources of recharge. In contrast, episodic recharge from the BLR produced temporally variable geochemistry across most of the western part of the INL. These results show that the ESRP aquifer is a mostly static system in the eastern part of the INL and largely a dynamic system in the western part of the INL.

Geochemical Implications for Hydrology

Sources of Recharge

Sources of recharge were identified at both large and small scales. At the large scale, groundwater at the INL was divided into areas where recharge from tributary water or regional groundwater primarily resides, and at the small scale, sources of recharge for specific Areas and wells at the INL were identified. Recharge that may have occurred during the last glacial epoch, or paleorecharge, may be present at seven wells in the southwestern part of the INL.

Tributary or Regional Water

Lithium concentrations of less than and greater than 5 µg/L were previously used to divide the INL into areas that consisted primarily of tributary or regional groundwater (Ackerman and others, 2006; Fisher and others, 2012; Bartholomay and Hall, 2016). The spatial distribution of lithium, and silica concentrations (figs. 28*L* and *R*) were good indicators of where tributary water or regional groundwater reside in the aquifer because

1. The chemistry of tributary water was influenced primarily by carbonate rocks (Carkeet and others, 2001; Swanson and others, 2002, 2003) and the chemistry of regional groundwater was influenced by carbonate and volcanic (rhyolite and basalt) rocks, (Rattray and Ginsbach, 2014; Rattray, 2015);
2. The abundance of lithium and silica in the carbonate rocks was either small or zero;
3. Silica was present in abundance in volcanic rocks; and
4. Lithium may substitute for aluminum in biotite (Deer and others, 1983), a mineral present in rhyolite (Rattray and Ginsbach, 2014).

Therefore, regional groundwater should have larger lithium and silica concentrations than tributary water. Concentrations of lithium and silica were plotted on a graph (fig. 20)[27] to evaluate whether lithium concentrations of 5 µg/L, or some other concentration, best differentiated areas where tributary valley water (groundwater and surface water) and regional groundwater reside in the shallow ESRP aquifer at the INL.

Increasing lithium concentrations (fig. 20) represent increasing dissolution of rhyolite and increasing silica concentrations represent increasing dissolution of basalt and (or) rhyolite. Surface water and groundwater from the tributary valleys, except groundwater from ML 55 (in the Beaverhead Mountains) and Kaufman Guard Station

---

[27] Silica and lithium concentrations for contaminated groundwater were not plotted in figure 20, but contaminated groundwater had a maximum lithium concentration of 9 µg/L (table 14) which indicates that tributary water was the primary source of recharge at sites consisting of contaminated groundwater.

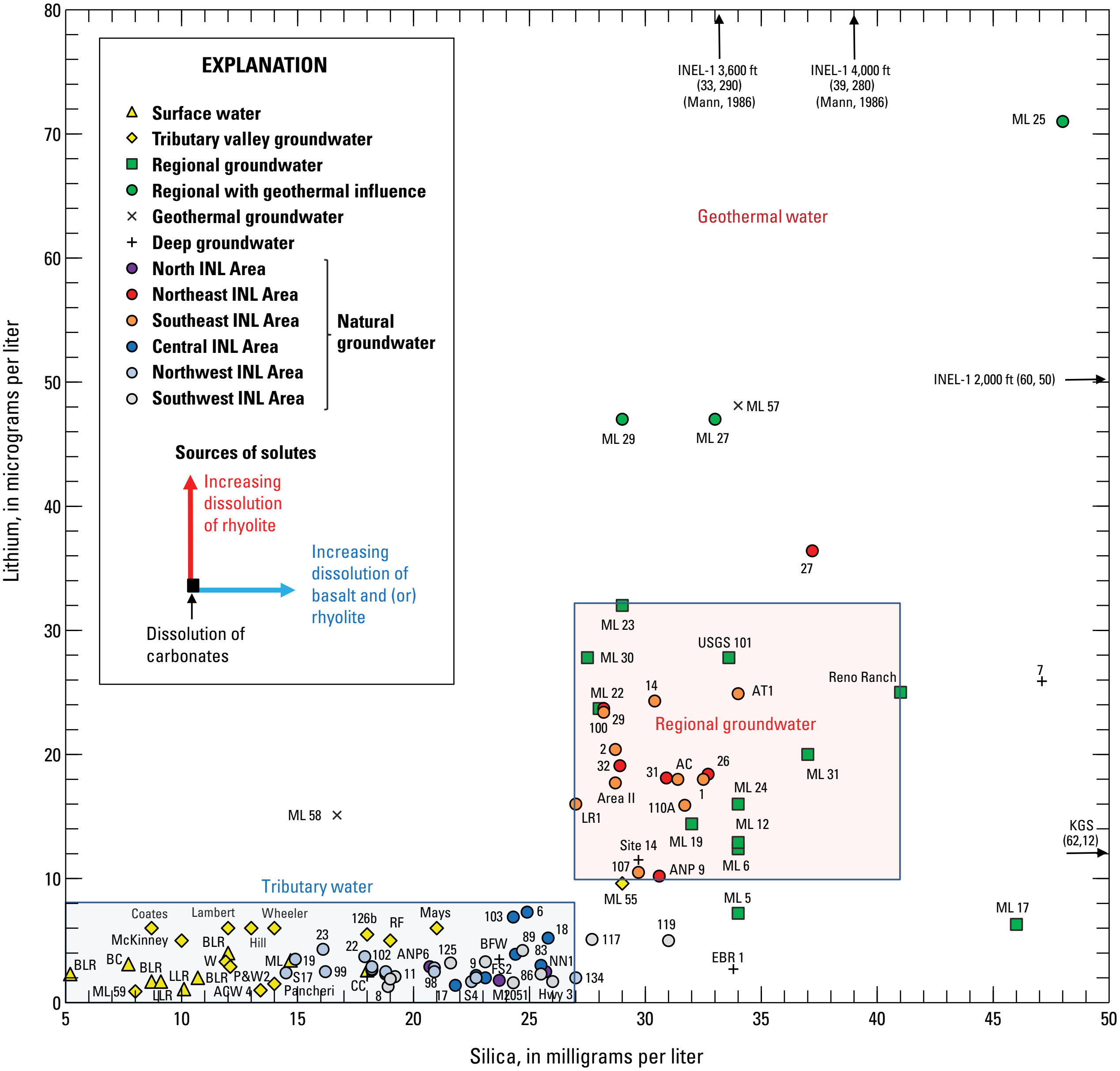


Figure 20. Concentrations of silica and lithium for surface water and groundwater, Idaho National Laboratory and vicinity, eastern Idaho.

(KGS), have concentrations of less than or equal to 6 µg/L for lithium and 21 mg/L for silica. Regional groundwater, except from ML 5 and ML 17 and wells with a geothermal influence (ML 25, ML 27, ML 29), has concentrations ranging from 12.4 to 32 µg/L for lithium and 27 to 41 mg/L for silica. The lithium and silica concentrations in some of the excepted wells were influenced by dissolution of rhyolite (ML 55, Kaufman Guard Station) or recharge in the northeastern Mud Lake area (ML 5 and ML 17) from carbonate rocks in the Beaverhead Mountains. Upwelling geothermal water rises through rhyolite basement rock underlying the thick accumulation of basalt on the ESRP so geothermal water (except for ML 58, which is geothermal water in the Beaverhead Mountains) and geothermally influenced groundwater (ML 25, ML 27, ML 29) have lithium concentrations exceeding those in most regional groundwater. Considering the lithium and silica concentrations representative of tributary water and regional groundwater, figure 20 indicates that there is a clear demarcation in these concentrations between natural groundwater at the

INL consisting primarily of tributary water or regional groundwater, with lithium and silica concentrations of less than or equal to 8 µg/L and 27 mg/L consisting primarily of tributary water and concentrations greater than or equal to 10 µg/L and 27 mg/L consisting primarily of regional groundwater.

Groundwater from five wells at the INL (USGS 103, USGS 124, USGS 126b, USGS 6, and USGS 18) that would be classified as regional groundwater using the 5 µg/L lithium division have lithium concentrations of more than 5 µg/L but less than 8 µg/L; this groundwater was reclassified as tributary water in this report (fig. 21). These slightly elevated lithium concentrations were due to (1) a mixture of mostly tributary water with a small amount of regional groundwater at USGS 103; (2) dissolution of rhyolite on or adjacent to the INL (figs. 4*B* and 21) at USGS 124 and USGS 126b; and (3) upwelling of geothermal water at or upgradient of USGS 6 and USGS 18 (figs. 9, 28*A*, *K*, and *CC*). Under the revised concentration ranges for tributary water and regional groundwater, shallow groundwater composed primarily of regional groundwater resided in the Northeast and Southeast INL Areas and shallow groundwater composed primarily of tributary water resided the North, Central, Northwest, and Southwest INL Areas.

Sources of Recharge at Specific Areas and Wells

Sources of recharge for specific Areas and wells at and near the INL were identified by evaluating all of the geochemical data previously presented. However, $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios were particularly useful for identifying sources of recharge and mixing of water. These isotope ratios often provide unique fingerprints for different sources of water that were not dependent on elemental concentrations, and the unique fingerprints may be retained in the groundwater across significant distances of transport (Roback and others, 2001). These qualities of the isotope ratios make them useful for identifying sources of recharge and mixing of water far from their location of recharge. Consequently, sources of recharge at the INL were most easily identified by plotting $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for surface and groundwater samples on a graph and evaluating where the samples plot on the graph relative to binary mixing lines between various potential sources of recharge (figs. 22*A*–*B*) (Roback and others, 2001).

Binary mixing lines between different recharge sources (and basalt) at the INL were calculated (eq. 2-15) from strontium and uranium concentrations and isotope ratios (tables 14 and 16; Mann, 1986; Johnson and others, 2000; Roback and others, 2001; McLing and others, 2002). Representative $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios were available for recharge from regional groundwater (USGS 101), groundwater representative of surface water used for irrigation in the Mud Lake Area (ML 22), groundwater representative of water from the LLR (USGS 19) and BC valleys (P&W 2), the BLR (BLR near Atomic City), geothermal water (INEL-1 10,300 ft), and deep groundwater in the central part of the INL (Site 14). Representative $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios were not available for recharge from the LLR or groundwater from the BLR valley and Lost River Range. Representative $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for basalt were used that were equal to the mean value for Cenozoic olivine basalts on the ESRP for $^{87}Sr/^{86}Sr$ (0.7069) and the $^{234}U/^{238}U$ activity ratio in groundwater from USGS 22 (1.54).[28] Although binary mixing lines proved to be useful for identifying sources of recharge and mixing, $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for groundwater that consists of more than two sources of strontium and uranium, from recharge and dissolution of basalt, probably will not plot on a binary mixing line.

A second $^{234}U/^{238}U$ ratio from the BLR was available (BLR below INL diversion, table 16). This $^{234}U/^{238}U$ ratio (fig. 22*A–B,* $^{87}Sr/^{86}Sr$ ratio for the BLR near Atomic City) was smaller than the $^{234}U/^{238}U$ ratio for the BLR near Atomic City. These variable $^{234}U/^{238}U$ ratios probably result from temporally variable relative percentages of young surface water (that is, water from tributary creeks, overland flow, and direct precipitation) and older groundwater inflow that contribute to stream discharge, with the $^{234}U/^{238}U$ ratio decreasing as the percentage of young surface water increases. Both BLR samples were collected at flows well below peak spring runoff (U.S. Geological Survey, 2014); consequently, these samples of BLR water may represent a large amount of groundwater base flow. During peak spring runoff, a greater percentage of young surface water would contribute to stream discharge, resulting in $^{234}U/^{238}U$ ratios in the BLR that could be smaller than indicated on figures 22*A*–*B*. Because most recharge from the BLR at the INL occurs during spring runoff (Bennett, 1990), much of the recharge at the INL from the BLR may have smaller $^{234}U/^{238}U$ ratios than indicated in figures 22*A*–*B*. The value for USGS 17 plots below values for the BLR in figure 22*B* and, due to its location adjacent to the BLR, probably consists primarily of recharge from the BLR. Consequently, a hypothetical binary mixing line between the BLR, as represented by USGS 17, and groundwater from the Little Lost River valley was shown on figure 22*B*.

---

[28] Roback and others (2001, fig. 3), in their binary mixing model for $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ in groundwater at the INL, used the same $^{87}Sr/^{86}Sr$ value for basalt, but used a value of 1 (secular equilibrium) for $^{234}U/^{238}U$. In this report, the $^{234}U/^{238}U$ value from USGS 22, 1.54, was considered representative of the $^{234}U/^{238}U$ in groundwater from dissolution of basalt because the source of water at USGS 22 was precipitation, which means that all of the uranium in groundwater at USGS 22 was from dissolution of minerals in the host basalt.

Roback and others (2001) plotted $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios to evaluate sources and mixing of water at the INL. They determined that BC valley groundwater and regional groundwater mixed in the eastern part of the INL and that the BLR was an important source of recharge in the central and western parts of the INL. They also suggested that incongruent dissolution of basalt, accompanied by removal of uranium from solution through precipitation and (or) ion exchange, played an important role in modifying uranium concentrations and isotopic ratios in groundwater. Dissolution of basalt will alter some $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios in groundwater (such that they plot to the left of their sources of recharge in figure 22*A*–*B*). However, significant dissolution of basalt, even of readily soluble basalt glass (Rattray and Ginsbach, 2014), occurs only when water undersaturated with silica, such as tributary valley groundwater, infiltration of the BLR, and infiltration of precipitation, provides recharge to the ESRP aquifer. Significant dissolution of basalt, therefore, is not ubiquitous but is concentrated in areas where recharge that is undersaturated with silica occurs. Such recharge occurs as groundwater from the tributary valleys enters the ESRP aquifer at the mouths of the LLR and BC valleys, water from BC infiltrates through the BC channel, sinks, and playa 4, and water from the BLR infiltrates through the BLR channel, sinks, and playas and at the INL spreading areas.

North INL Area

Lithium and silica concentrations indicated that natural groundwater in the North INL Area consisted primarily of tributary water (figs. 20–21), with BC and groundwater from the BC valley as possible sources of recharge throughout the area and the BLR a possible source of water at playas 3 and 4 (fig. 3*B*). Isotopic data were not available for ANP 8 and TDD 3, except for tritium activity at TDD 3, so the discussion of sources of recharge for this area was based primarily on data from ANP 6, No Name 1, IET 1 Disposal, and PSTF Test as well as P&W 2 from the mouth of the BC valley (fig. 21). The major ion chemistry of groundwater from ANP 8 and TDD 3 was similar to ANP 6 (table 13, figs. 28*F*–*O*), so these wells were presumed to have the same sources of recharge as ANP 6.

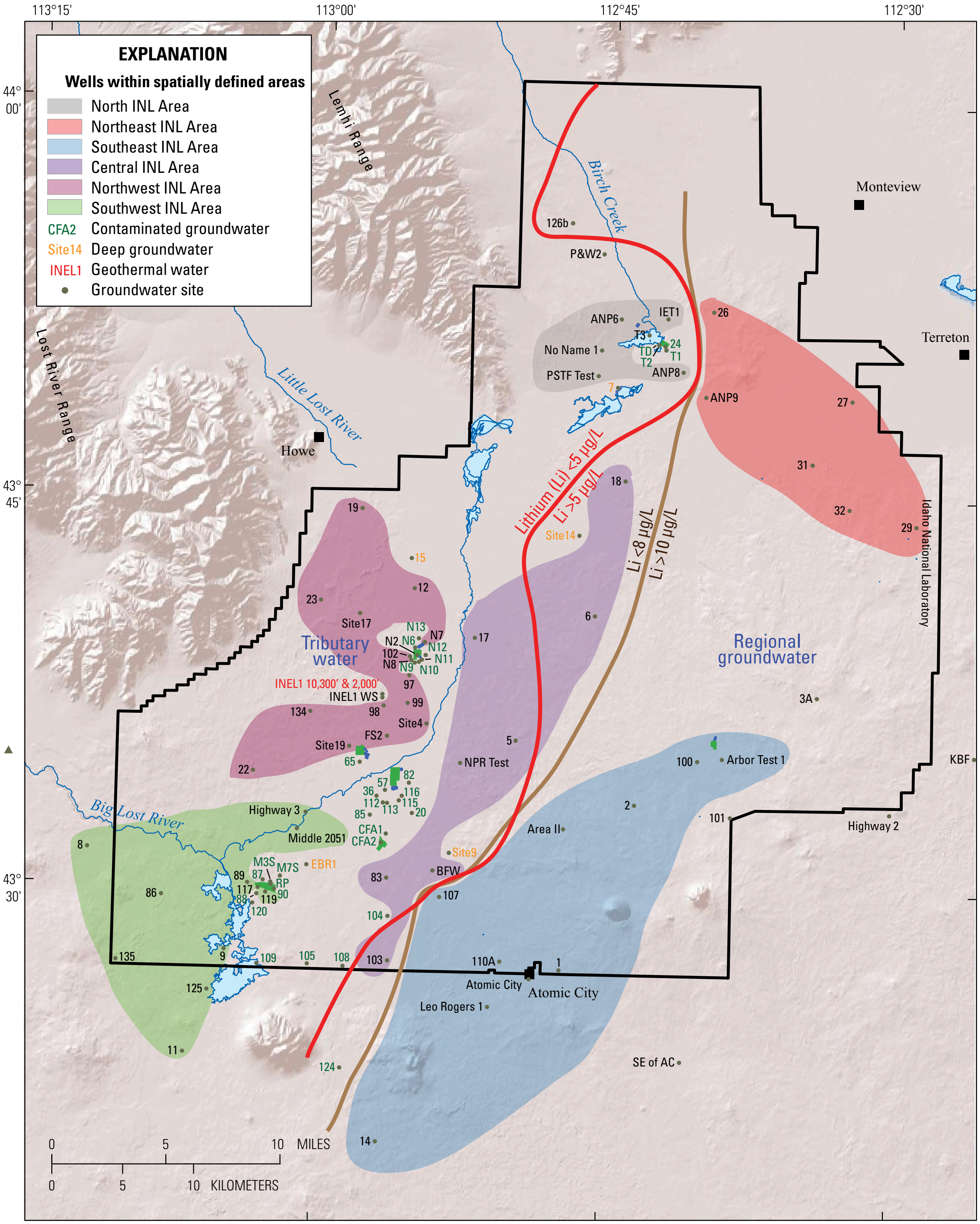
Light δ^2H and $\delta^{18}O$ values measured in groundwater from P&W 2 (-141.3 and -18.50 permil) and ANP 6 (-138.7 and -18.27 permil) were similar to values for BC or groundwater from the BC valley (fig. 11). P&W 2 had a small helium concentration, an R_s/R_a ratio of 0.99, and a He_{terr} value of 5 percent (fig. 12), all of which suggest that this groundwater consisted largely of water from BC. ANP 6 had a slightly larger helium concentration, an R_s/R_a ratio of 1.16, and a He_{terr} value of 15 percent. ANP 6 is older and more evolved chemically than P&W 2, so these data were consistent with recharge from BC that has had a long enough groundwater residence time for some crustal helium and tritiogenic ^3He to accumulate in the groundwater (fig. 12). Additionally, ANP 6 plots along a binary mixing line for BC valley groundwater (P&W 2) and basalt, with the location of ANP 6 along the mixing line indicating that at least 10 percent of the strontium and uranium in the groundwater is from dissolution of basalt (fig. 22*A*).

Heavy δ^2H and $\delta^{18}O$ values (-130.4 and -15.86 permil) were measured in groundwater from No Name 1 and indicated that groundwater at this well consisted mostly or entirely of evaporated surface water. No Name 1 is about 0.8 mi southwest of playa 4 (fig. 3*B*), which may receive water from either the BLR or BC, and one or both of these streams must be the source of evaporated water. An evaporation line projected backwards from No Name 1 in figure 11 indicated that this groundwater may originate from BC. However, the $^{87}Sr/^{86}Sr$ ratio at No Name 1 (0.71037) was similar to the ratio from the BLR (0.71056) but much smaller than the ratio from BC (0.71198). The He_{terr} value of this groundwater (10 percent) was consistent with recharge largely from the BLR or BC with a small amount of groundwater from the BC valley (fig. 14). However, because this was old groundwater (tritium activity of 0.13±0.03 pCi/L; fig. 13*A*) recharge consisting solely of surface water could have had a long enough groundwater residence time to accumulate some crustal and tritiogenic helium.

PSTF Test is located between playas 3 and 4 and IET 1 Disposal is located northeast of playa 4 (figs. 3*B* and 9). The BLR occasionally flows into playas 3 and 4 (Bennett, 1990), and BC occasionally flowed into playa 4 prior to 1969, so either stream could be a source of recharge. However, the δ^2H and $\delta^{18}O$ values from PSTF Test (-133.4 and -17.64 permil) and IET 1 Disposal (-135.7 and -17.58 permil) in figure 11 were consistent with either recharge from the BLR or a mixture of recharge from BC and the BLR. The He_{terr} values were 1 and 18 percent at PSTF Test and IET 1 Disposal (fig. 14), respectively. The small He_{terr} value at PSTF Test, plus the R_s/R_a ratio of 1.00, small helium concentration (fig. 12), and small tritium activity (2.5±0.1 pCi/L), indicated that this water probably consisted primarily of pre-1952 recharge of surface water. The larger He_{terr} value at IET 1 Disposal could indicate that this water contains some groundwater from the BC valley, but the small helium concentration at this well was similar to the small concentrations at ANP 6 and PSTF Test (fig. 28*E*) and indicated that this water also was recharged primarily by surface water.

Northeast INL Area

Lithium and silica concentrations indicated that the six natural groundwater samples from the Northeast INL Area consisted primarily of regional groundwater (figs. 20–21).



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 21. Wells within spatially defined areas and the division of tributary water and regional groundwater based on a 5 microgram per liter (µg/L) lithium concentration (Ackerman and others, 2006; Fisher and others, 2012; Bartholomay and Hall, 2016) and lithium concentrations less than 8 µg/L and greater than 10 µg/L, Idaho National Laboratory and vicinity, eastern Idaho.

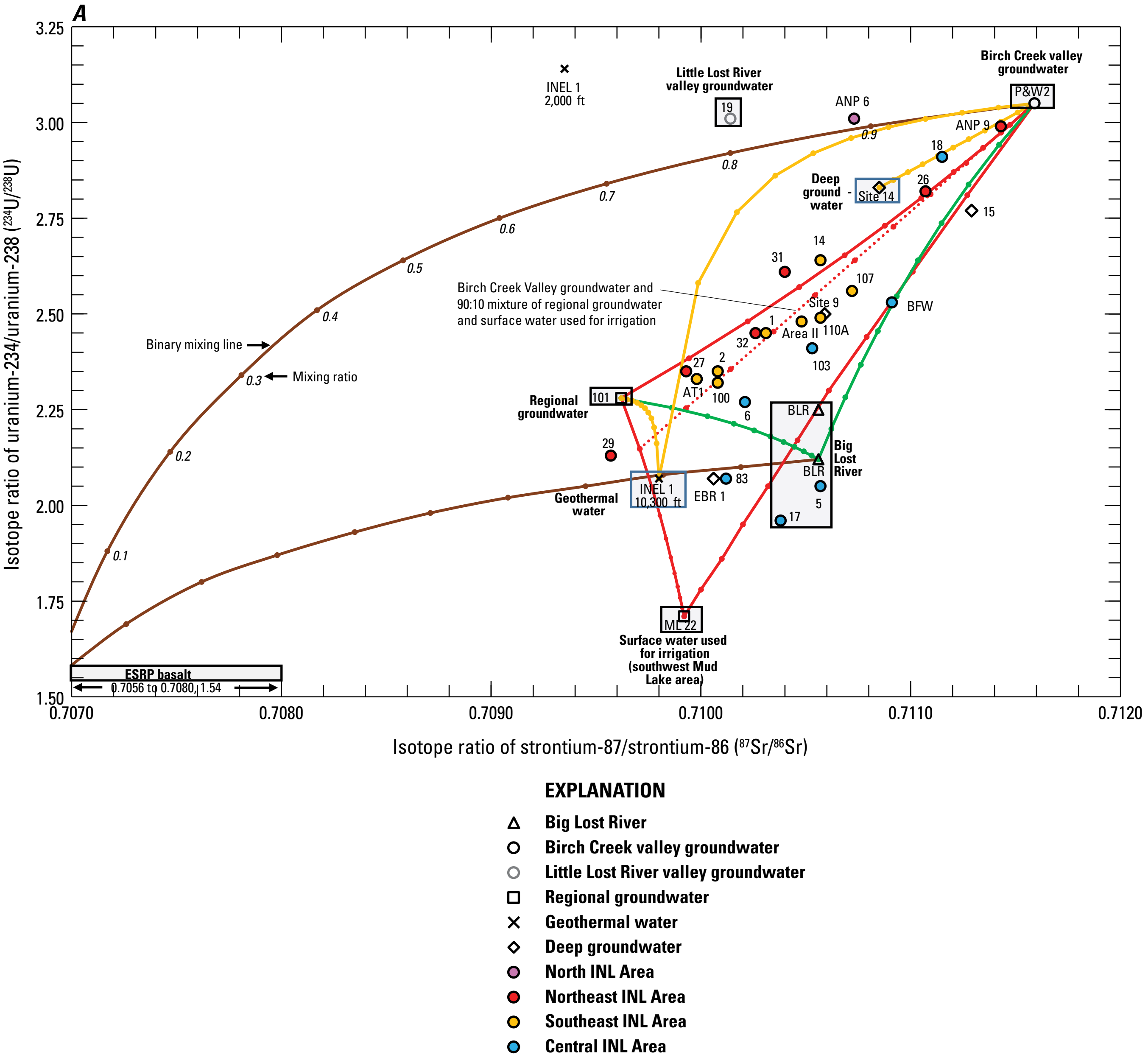


Figure 22. Strontium ($^{87}Sr/^{86}Sr$) and uranium ($^{234}U/^{238}U$) isotope ratios in surface water and groundwater and binary mixing lines between various sources of recharge (and basalt), Idaho National Laboratory and vicinity, eastern Idaho. (*A*) $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for the North, Northeast, Southeast, and Central INL Areas. (*B*) $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for the North, Central, Northwest, and Southwest INL Areas.

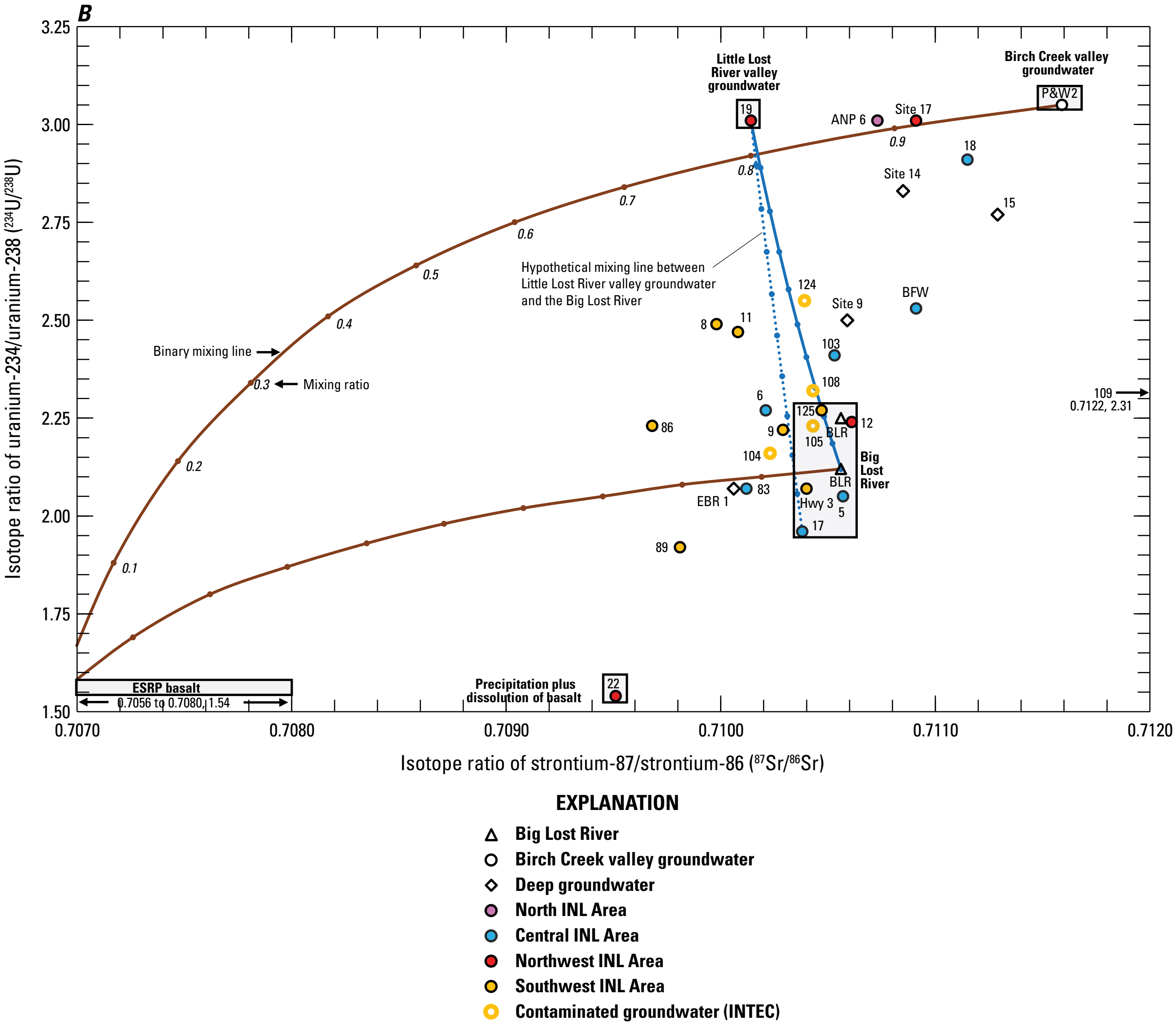


Figure 22.—Continued

However, both tributary water and regional groundwater could be sources of recharge to this area, with possible sources of recharge consisting of BC, groundwater from the BC valley, regional groundwater, surface water used for irrigation, and geothermal water.

The inference, based on lithium and silica concentrations, that groundwater in the Northeast INL Area consisted primarily of regional groundwater was only partially supported by binary mixing lines between regional groundwater and (1) surface water in the Mud Lake area used for irrigation or (2) groundwater from the BC valley (fig. 22*A*). The mixing lines indicated that groundwater from USGS 29 was a mixture of about 90 percent regional groundwater and 10 percent surface water used for irrigation (plus some dissolution of basalt). Water from the other five wells was primarily a mixture of regional groundwater and water from the BC valley, with regional groundwater comprising about 10 percent of the groundwater at ANP 9, 40 percent at USGS 26, 70 percent at USGS 31, 80 percent at USGS 32, and 90 percent at USGS 27.

Other evidence was available that supported the interpretations based on the mixing lines. For example, the helium concentration and ratio at USGS 29 indicated that this water was old groundwater with a significant amount of tritiogenic ^{3}He (fig. 12) and the tritium activity indicated that this water was a mixture of young and old groundwater (fig. 13*A–B*). These data support the interpretation from the mixing lines that this groundwater was mostly regional groundwater with some recharge from surface water used for irrigation. Tritium activities at the other wells indicate that the water was old groundwater, consistent with the absence of surface water used for irrigation as a source of water at these wells. The δ^{2}H and δ^{18}O values also were lighter at ANP 9 than the other wells from the Northeast INL Area, consistent with larger percentages of tributary groundwater at ANP 9 and of regional groundwater at the other wells (fig. 28*U*).

The binary mixing lines (and δ^{2}H and δ^{18}O values for ANP 9) show that, in contrast to the interpretation based on lithium and silica concentrations, water from ANP 9 and USGS 26 consisted primarily of tributary water. The helium concentration and ratio for ANP 9 (fig. 12) shows that this groundwater does not contain geothermal water, so the elevated lithium and silica concentrations at this well (10.2 µg/L and 30.6 mg/L, respectively; fig. 20) were probably due to mixing with regional groundwater containing large lithium concentrations or dissolution of rhyolite or rhyolitic debris originating from the southern extent of the Beaverhead Mountains (fig. 4*A*). The presence of some geothermal water at USGS 26, USGS 27, and USGS 31 was supported by the warm water temperatures (14.9–15.8 °C; figs. 27*A* and 28*A*), large helium concentrations (20.6–32.4 cm^{3} STP/g × 10^{-8}; figs. 27*G* and 28*E*), large R_s/R_a ratio (9.70, for USGS 27; figs. 12 and 28*Y*), and large He_{terr} values (83–88 percent; figs. 14 and 28*CC*). The geothermal water represents upwelling of water from beneath the aquifer and indicates that some upward movement of water has occurred. The interpretation of upward flow was consistent with an intra-borehole measurement of flow at USGS 31 and another well southeast of TAN (Ackerman and others, 2006). Although geothermal water in the Northeast INL Area could result directly from upwelling geothermal water, it also could result indirectly as geothermally influenced shallow groundwater from the Mud Lake area (Rattray, 2015) moves downgradient through the Northeast INL Area.

Southeast INL Area

The ten natural groundwater samples collected from the Southeast INL Area all had lithium and silica concentrations that indicated this groundwater consisted primarily of regional groundwater (figs. 20–21). There were many potential sources of recharge to this area, however, such as the BLR, BC, groundwater from the LLR and BC valleys, regional groundwater, and surface water used for irrigation.

Tritium activities of 10–19 pCi/L (fig. 13*A–B*) and nitrate concentrations of 0.9–1.5 mg/L as N (fig. 28*N*) indicate that all these waters were mixtures of young and old water and that they contain some recharge of surface water, groundwater influenced by irrigation, or both. The ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios were measured for eight of the samples, which generally plot along a binary mixing line for BC valley groundwater and a 90:10 mixture of regional groundwater and surface water used for irrigation (fig. 22*A*). The mixing line indicates that BC valley groundwater comprises about 15–20 percent of groundwater at Arbor Test 1, USGS 2, and USGS 100, 30 percent at USGS 1, 35–40 percent at Area II, USGS 14, and USGS 110A, and 45 percent at USGS 107.

Groundwater from USGS 107 and USGS 110A plots slightly below the mixing line for BC valley groundwater and the 90:10 mixture of regional groundwater and surface water, in a direction toward the ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios for the BLR. These two wells plus groundwater from Leo Rogers 1 and USGS 14, all located in the southwestern part of the Southeast INL Area ( ), had slightly heavier δ^{18}O values than other groundwater from this Area, indicating that these four wells may contain a small amount of recharge from the BLR.

Central INL Area

Lithium and silica concentrations for the eight natural groundwater samples from the Central INL Area indicated that these samples consisted primarily of tributary water (figs. 20–21). However, the locations of these samples extends about 24 mi in a northeast-to-southwest direction along the transition zone between tributary water and regional groundwater, so potential sources of recharge included the BLR, BC, groundwater from the LLR and BC valleys, regional groundwater, surface water used for irrigation in the Mud Lake area, and geothermal water. In addition, USGS 83 may consist of paleorecharge (see section, "Paleorecharge").

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios indicated that groundwater from the Badging Facility Well was about a 50:50 mixture of recharge from the BLR and groundwater from the BC valley and that groundwater from USGS 18 consisted of about 40 percent deep groundwater similar in composition to Site 14 and 60 percent groundwater from the BC valley (fig. 22*A*). The deep groundwater at Site 14 consisted primarily of groundwater from the BC valley (based on the location of Site 14 relative to the mouth of the BC valley; fig. 21) with some geothermal water (based on the warm water temperature of 16.3 °C and large helium concentration of 38.4 cm^3 STP/g x 10^{-8}; table 12), so USGS 18 contained a small amount of geothermal water, but consisted primarily of groundwater from the BC valley.

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for USGS 5 and USGS 17 plot below the ratios for the BLR on figure 22*A*–*B*, indicating that the BLR may be the only source of recharge at these wells. However, the presence of He_{terr} values of 30 and 27 percent (fig. 14) and $\delta^{18}O$ values (-17.82 and -17.53 permil; fig. 28*U*) that were lighter than $\delta^{18}O$ values for the BLR below lower Lincoln Blvd Br (-17.17 permil) shows that some tributary groundwater probably was present at USGS 5 and USGS 17. The tritium activity at USGS 5 (28.4±0.4 pCi/L; fig. 13*B*) indicated that this groundwater was a mixture of young and old water, and the warm temperature (14.9 °C; fig. 28*A*) and relatively light δ^2H and $\delta^{18}O$ values (-138.3 and -17.82 permil; fig. 11) in this water indicated that the BC valley was the source of old groundwater at this well. The large tritium activity at USGS 17 (50.0±0.5 pCi/L) suggests that this groundwater was entirely young water. However, this tritium activity could occur if some recharge from the BLR during the 1950s to 1960s, when the tritium activity in the BLR was very large, mixed with old groundwater. The relatively heavy δ^2H and $\delta^{18}O$ values (-135.7 and -17.53 permil; fig. 11) in water from USGS 17 were more consistent with the LLR valley than the BC valley, as the source of old groundwater at this well.

NPR Test was not analyzed for $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios, but the large tritium activity (57.4±0.2 pCi/L), small He_{terr} value (8 percent), and helium concentration and R_s/R_a ratio (fig. 12) all indicated that the BLR is the primary source of recharge at this well. However, the δ^2H and $\delta^{18}O$ values (-137.6 and -17.76 permil) were lighter than values for the BLR below lower Lincoln Blvd Br., indicating that some tributary valley groundwater probably was present in this water. As described in section, "Temporally Variable Water Chemistry," groundwater from the LLR valley may flow to NPR Test during periods of surface water recharge at the BLR sinks. The groundwater sample at NPR Test was collected in October 1996, and a significant amount of discharge in the BLR, and recharge to the BLR sinks, occurred at the INL during 1995–96 (fig. 5). In comparison to USGS 5, which received recharge of groundwater from the BC valley, groundwater from NPR Test was slightly cooler (12.2 °C; fig. 28*A*), had heavier δ^2H and $\delta^{18}O$ values, and had more dissolved ions (fig. 28*B*). This was consistent with (1) cooler groundwater upgradient of NPR Test compared to USGS 5 (fig. 16), (2) heavier δ^2H and $\delta^{18}O$ values, and (3) due to agricultural activities, more dissolved ions in groundwater from the LLR valley compared to groundwater from the BC valley (fig. 28*B*). Based on this comparison and on the hydrologic conditions in 1995–96, some groundwater at NPR Test probably originated from the LLR valley.

USGS 6 and USGS 103 had lithium concentrations of 7.3 and 6.9 µg/L. These concentrations were slightly larger than other groundwater at the INL originating from the tributary valleys (fig. 20) because a small amount of geothermal water probably was present at USGS 6 and a small amount of regional groundwater probably mixed with tributary water at USGS 103. Groundwater from both wells have $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios that plot near the mixing lines for the BLR and groundwater from the LLR valley (fig. 22*B*). Groundwater at USGS 6 had a small tritium activity (0.3±0.8 pCi/L), a warm temperature (14.1 °C), small nitrate concentration (0.3 mg/L as N), and a large He_{terr} value (62 percent), all of which indicate that this water originated north of USGS 6. However, the heavy δ^2H and $\delta^{18}O$ values (-135.2 and -17.62 permil) at USGS 6 indicated that the primary northern source of recharge to this old groundwater was the BLR at playas 3 and 4. At USGS 103, a He_{terr} value of 16 percent and a tritium activity of 11.8±0.1 pCi/L indicated that the groundwater was composed of both young and old water, with the young water from the BLR and the old groundwater primarily from the LLR valley.

Northwest INL Area

Lithium and silica concentrations for the 17 natural groundwater samples from the Northwest INL Area indicated that these samples consisted primarily of tributary water (figs. 20–21). Potential sources of recharge from tributary water in this area included the BLR, groundwater from the LLR valley and Lost River Range, and precipitation. The LLR is an important source of recharge to groundwater in the LLR valley, but because the terminus of the LLR is just north of the INL, the LLR provides only indirect recharge to the INL.

Because ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios were analyzed only from four samples from the Northwest INL Area (fig. 22*B*), other geochemical data were required to identify the sources of recharge. The δ^{18}O and δ^{13}C values (fig. 23) were used to differentiate between the sources of recharge because δ^{18}O values in the LLR, the BLR (below lower Lincoln Blvd. Br.), and groundwater from the LLR valley were intermediate to light, heavy, and light (tables 3 and 15, fig. 28*U*), respectively, and δ^{13}C values for the same sources of recharge were heavy, light, and intermediate (fig. 28*V*). Tritium activities were a good indicator of young recharge in groundwater, with larger and smaller activities indicating greater and lesser amounts of young recharge from the BLR; tritium activities are shown in parentheses in figure 23. Additionally, groundwater that was heavily influenced by irrigation in the LLR valley, as indicated by nitrate concentrations greater than 1.0 mg/L as N, was detected in an area between the BLR and 2.5 mi west of the BLR, whereas groundwater with smaller nitrate concentrations, and apparently uninfluenced or lightly influenced by irrigation in the LLR valley, was detected in an area generally 3 or more miles west of the BLR (fig. 28*N*).

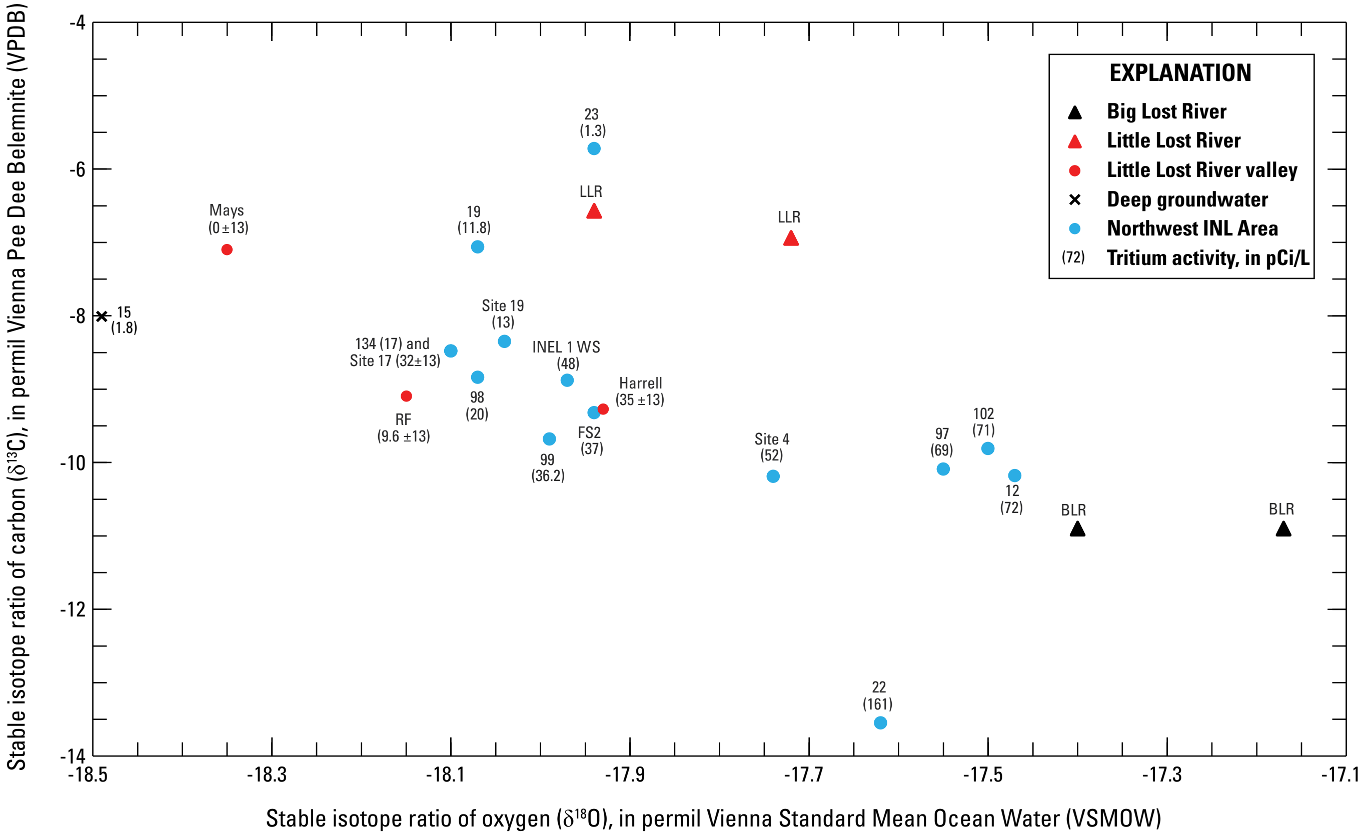


Figure 23. Stable isotope ratios of oxygen and carbon (δ^{18}O and δ^{13}C) for selected surface-water and groundwater sites, Idaho National Laboratory and vicinity, eastern Idaho.

Groundwater from the Northwest INL Area, except USGS 22 and USGS 23, plots between or near data representing the BLR and groundwater from the LLR valley (fig. 23). USGS 22 had a small estimated hydraulic conductivity (0.68 ft/d; log K of <-0.17 ft/d; table 11), small DO, large sodium, potassium, and chloride concentrations, small bicarbonate and uranium concentrations, a distinctive hydrochemical facies (fig. 10*B*), a light δ^{13}C value, a ^{234}U/^{238}U ratio approaching the value for basalt (fig. 22*B*), a large tritium activity (160.9±0.4 pCi/L; fig. 13*A*), and a small He_{terr} value (0 percent; fig. 28*CC*). All of these chemical characteristics were consistent with young water consisting of rapid, focused vertical recharge (fig. 14) from precipitation that dissolved evaporite (possibly road salt) and silicate minerals. Projecting the tritium activity at USGS 22 backward in time (fig. 13*A*) shows that the precipitation recharge occurred sometime between 1954 and 1981. USGS 23 had warm groundwater (15.4 °C; fig. 28*A*, table 12), a heavy δ^{13}C value and, because it had a small tritium activity and a moderately large He_{terr} value (1.3±0.1 pCi/L and 57 percent, respectively; fig. 14), consisted of old groundwater. However, the relatively small silica concentration (16.1 mg/L; fig. 28*L* and table 13) in this groundwater indicates that it has not had a long residence time in the ESRP aquifer. Based on these geochemical characteristics, and due to the close proximity of USGS 23 to the Lost River Range, groundwater from the Lost River Range was probably the primary source of water at USGS 23.

The δ^{18}O, δ^{13}C values, and tritium activities (fig. 23) indicated that (1) USGS 12, USGS 97, and USGS 102 consisted largely of recharge from the BLR with some groundwater from the LLR valley; (2) Site 4 was a relatively even mixture of these two sources of water; (3) Fire Station 2, INEL 1 WS, and USGS 99 consisted largely of groundwater from the LLR valley with some recharge from the BLR; (4) Site 17, Site 19, USGS 98, and USGS 134 consisted largely of groundwater from the LLR valley; and (5) USGS 19 consisted largely of groundwater from the LLR valley with some recharge from either the LLR, groundwater from the Lost River Range, or both. The ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios for USGS 12 were consistent with groundwater consisting primarily of recharge from the BLR, but the ratios for Site 17 indicate that there probably was another source of recharge at this well besides groundwater from the LLR valley (fig. 22*B*).

The only isotopic data available for NRF 2, NRF 7, and NRF 8 were tritium activities from NRF 7 and NRF 8. However, the major ion chemistry of NRF 2 and NRF 8 was similar to the chemistry of USGS 12 (table 13), indicating that these wells may have the same sources of recharge. Groundwater at NRF 7 was dilute (table 12; also, specific conductance ranged from 202 to 268 µS/cm at 25 °C from 1991 to 2014; U.S. Geological Survey, 2014), and the only plausible sources of this dilute water were the BLR and precipitation. The tritium activity was 12.8±12.8 pCi/L at NRF 7 in 1996 (table 17), but 35 low-level tritium analyses of less than 5 pCi/L from 1997–2015[29] (Bartholomay, Knobel, and others, 2000; Bartholomay and others, 2001; Bartholomay and others, 2002; U.S. Geological Survey, 2014) show that water at this well is old groundwater. Consequently, water at NRF 7 probably consists mostly of old recharge from the BLR.

Southwest INL Area

Lithium and silica concentrations for the 11 natural groundwater samples from the Southwest INL Area indicated that these samples consisted primarily of tributary water (figs. 20–21). Potential sources of recharge from tributary water in this area included the BLR and groundwater from the BLR valley, LLR valley, and Lost River Range. Four of the groundwater samples, collected from USGS 86, USGS 89, USGS 117, and USGS 119, seemed to consist of paleorecharge (see section, “Paleorecharge”).

The ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios were available for five groundwater samples (that were not paleorecharge) (fig. 22*B*). Five contaminated groundwater samples collected from wells in the Southwest INL Area (USGS 104, USGS 105, USGS 108, USGS 109, and USGS 124) had ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios (fig. 22*B*), so these data also were used to identify sources of recharge to the Southwest INL Area. The contaminated groundwater samples were believed to have uncontaminated ^{87}Sr/^{86}Sr and ^{234}U/^{238}U ratios because (1) although ^{90}Sr is discharged in wastewater at the INL, radioactive decay of ^{90}Sr does not produce ^{87}Sr or ^{86}Sr as daughter products and (2) no anthropogenic or non-natural uranium isotopes were detected in the contaminated groundwater samples (Roback and others, 2001). However, USGS 109 had a large, unexplained ^{87}Sr/^{86}Sr ratio, and therefore was not used for identifying sources of recharge. Additionally, USGS 104 seemed to consist of paleorecharge and will be discussed in the section “Paleorecharge.”

---

[29] Three low-level tritium values measured in water from NRF 7 ranged from 23 to 57 pCi/L, but these measurements appear to be associated with analytical problems (Bartholomay, Knobel, and others, 2000; Bartholomay and others, 2001).

Middle 2051 and Highway 3 are located near each other and the BLR (fig. 21). Middle 2051 had a large tritium activity (fig. 28*BB*) and heavy δ^2H and $\delta^{18}O$ values (fig. 11), consistent with recharge from the BLR. Ratios of $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ from Highway 3 indicated that this groundwater consisted primarily of water from the BLR (fig. 22*B*), and both these sites plot in the same area on a trilinear diagram as the BLR (fig. 10*A*). This evidence shows that groundwater at Middle 2051 and Highway 3 consisted primarily of water from the BLR.

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios from USGS 9, USGS 105, USGS 108, and USGS 125 indicated that the BLR was the primary source of recharge at these wells with groundwater from the LLR valley a possible minor contributor of recharge (fig. 22*B*). Large tritium activities at USGS 9 and USGS 125 (fig. 28*BB*) support the interpretation that the BLR is the source of recharge, and δ^2H and $\delta^{18}O$ values for these four wells that were lighter than the δ^2H and $\delta^{18}O$ values for the BLR near Arco support the presence of some recharge from a source with lighter δ^2H and $\delta^{18}O$ values, such as groundwater from the LLR valley (fig. 28*U*).

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios from USGS 124 indicated that recharge at this well was about a 50:50 mixture of the BLR and groundwater from the LLR valley (fig. 22*B*). Slightly lighter δ^2H and $\delta^{18}O$ values at USGS 124 than at USGS 9 and USGS 125 (fig. 28*U*) support the interpretation that groundwater at USGS 124 consisted of a larger amount of groundwater recharge from the LLR valley than did groundwater at USGS 9 and USGS 125.

USGS 8, USGS 11, and USGS 135 are all located at or near the southwestern corner of the INL and extend in a northwest-to-southeast direction away from the mouth of the BLR valley (figs. 8*A–B*). The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for USGS 8 and USGS 11 plot near, but slightly left of, the 50:50 mixing point on the mixing line between the BLR and groundwater from the LLR valley (fig. 22*B*). Recharge of groundwater from the BLR valley or dissolution of basalt may cause these data points to plot slightly left of the mixing line. It is possible that groundwater from the BLR valley was a source of recharge to USGS 8, because USGS 8 is the closest well in the Southwest INL Area to the BLR valley. The closest well in the BLR valley to USGS 8 was the Arco City Well 4 (fig. 8*A*), which had a tritium activity of 83.8±2.9 pCi/L (fig. 28*BB*) and a $\delta^{18}O$ value of -17.69 permil (fig. 28*U*). The tritium activity at USGS 8 (47.4±0.5 pCi/L) could be consistent with recharge from the BLR and groundwater from the BLR valley, but the $\delta^{18}O$ value at USGS 8 (-17.78 permil) was much lighter than the $\delta^{18}O$ value in the BLR near Arco (-17.4 permil) and indicated that USGS 8 was probably a mixture of recharge from the BLR and groundwater from the LLR valley. Tritium activities at USGS 135 and USGS 11 were 14±1.9 and 31.8±0.2 pCi/L, respectively, and $\delta^{18}O$ value for both wells was -17.92 permil. The slightly lighter $\delta^{18}O$ values, relative to USGS 8, indicates that groundwater at these wells may consist of a larger amount of recharge from the LLR valley, and the larger tritium activity at USGS 11, relative to USGS 135, may be due to diversion of, and more recent recharge from, the BLR at the INL spreading areas (figs. 3*B* and 5).

Comparison with Recharge Sources Simulated with a Groundwater-Flow Model

The sources of recharge at the INL are summarized in table 9 and figure 24*A–B*. The areas delineating recharge from specific source waters at the INL (fig. 24*A–B*), determined from geochemistry data, were compared to source water areas determined from backward particle tracking for model layer 1 of a three-dimensional, steady-state groundwater-flow model (fig. 25; from Fisher and others, 2012, fig. 15*A*). The geochemistry data primarily represented conditions from 1995–96, at the beginning of a wet period when the BLR flowed onto the INL (fig. 5), and the steady-state model represented 1980 conditions, at the end of a dry period when the BLR did not flow onto the INL. Thus, the hydrologic conditions should cause the areas delineating recharge from the BLR on figures 24–25 to differ, although the areas delineating other, more stable, sources of recharge should be similar for both 1980 and 1995–96 conditions.

Several differences were identified between source water areas determined from geochemistry and flow modeling. These differences included (1) recharge from BC near the north INL boundary in the flow model that was not supported by geochemistry, (2) groundwater from the BC valley in the flow model did not extend far enough south, (3) regional groundwater in the flow model that extended too far west in the southern part of the INL, (4) recharge in model layer 1 from deeper groundwater or geothermal water was not represented in the flow model, and (5) recharge from the BLR in the southwestern part of the INL was not represented in the flow model.

Paleorecharge

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios in groundwater from USGS 83, USGS 86, USGS 89, and USGS 104 (contaminated groundwater), and EBR 1 (deep well), all located in the southwestern part of the INL, indicated that this groundwater consisted primarily of recharge from the BLR, perhaps some groundwater from the LLR valley, and post-recharge dissolution of basalt (fig. 22*B*). The chemistry of groundwater from four of these wells (excludes USGS 104, which had some contamination from wastewater discharge), and USGS 117 and USGS 119, was slightly different from other groundwater in the southwestern part of the INL. For example, groundwater from these six wells, compared to nearby groundwater, generally had smaller specific conductance and concentrations of CO_2, Ca, and HCO_3 (figs. 28*D, F, H*) and larger concentrations of SiO_2 (fig. 28*L*). The differences in concentrations at these wells were consistent with groundwater that had dissolved less carbonate rocks and more silicate rocks, which would occur if this groundwater, relative to surrounding groundwater, consisted of greater amounts of recharge from the BLR and lesser amounts of recharge of groundwater from the tributary valleys. The BLR also provided either all or nearly all of the recharge at two nearby wells, Highway 3 and Middle 2051, but the chemistry of the groundwater at these wells was similar to most groundwater in the southwestern part of the INL. This suggests that the BLR must have been more dilute when providing recharge to the six wells with the different chemistry. The BLR was more dilute during spring runoff (see section, "Temporally Variable Water Chemistry"); consequently, the recharge from the BLR at the wells with different chemistry may have occurred during years with unusually large spring runoff. Alternatively, the dilute recharge could have occurred during wetter climatic conditions (Geslin and others, 2002) associated with the last glacial epoch.

Six of these wells have δ^2H and $\delta^{18}O$ values, and all six of the δ^2H and $\delta^{18}O$ values were much lighter ($\leq$-138.9 and $\leq$-18.05 permil) than the δ^2H and $\delta^{18}O$ values from the BLR on the ESRP ($\geq$-135.0 and $\geq$-17.4 permil), although some δ^2H and $\delta^{18}O$ values from winter samples of the BLR collected in the BLR valley at higher altitudes were nearly as light as in groundwater from these wells (tables 3 and 15; figs. 11, 15, and 18*A*). Considering that the BLR undergoes some evaporation, and that the higher altitude δ^2H and $\delta^{18}O$ values should become heavier as the BLR flows down valley and onto the ESRP during spring runoff, these higher altitude δ^2H and $\delta^{18}O$ values still do not explain the light δ^2H and $\delta^{18}O$ values in water collected from these six wells. The light δ^2H and $\delta^{18}O$ values in water from these wells may be due to recharge of paleowater (paleorecharge in fig. 24) during a colder, wetter period like the last glacial epoch. All seven of these wells are within, or adjacent to, the Big Lost Trough, an extensive depositional basin (Mark and Thackray, 2002), and their location in the southwestern extent of the Big Lost Trough (figs. 4*B* and 9) indicates that the BLR probably was a source of water at these wells. The He_{terr} values of 27–40 percent (fig. 28*CC*) support the presence of some old water at these wells, as does the tritium activity at USGS 86 (2.9±1.0 pCi/L). Large uncertainties associated with tritium activities in water from the other wells (and tritium from contamination at USGS 104) prevented determining if these wells consisted of old groundwater (table 17), although the uncertainties allow for the possibility that natural groundwater at each of these wells could be old groundwater. Age dating with low-level tritium, argon-39 (Hall and others, 2016), and carbon-14 could help determine if these wells contain old groundwater.

Paleorecharge currently may reside at these wells because of very slow travel times between current areas of recharge and the wells or, because rock units at these wells were largely impermeable, restricted horizontal groundwater flow to and from the wells. Considering the large range of hydraulic conductivities determined for the ESRP aquifer (0.01–24,000 ft/d; Ackerman and others, 2006), the hydraulic conductivities at these wells were either small (2.7–6.5 ft/d [log K of 0.43–0.81 ft/d] at EBR 1, USGS 83, and USGS 86) or very small (0.01–0.87 ft/d [log K of -2.00– -0.06 ft/d] at USGS 89, USGS 104, USGS 117, and USGS 119) (table 11; fig. 7). The very small hydraulic conductivities at wells USGS 89, USGS 117, and USGS 119 may be due to the close proximity of these wells to numerous volcanic vents. Areas near volcanic vents may contain dikes, alteration zones, and thick, tube-fed, pahoehoe flows, all of which may impede groundwater flow (Anderson and others, 1999). Regardless of the cause, wells with small hydraulic conductivities have restricted horizontal groundwater flow, and if horizontal flow was restricted then vertical flow, perhaps from ancient floods or meandering river courses of the BLR, may be the source of water at these wells.

The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios indicated that recharge from the BLR was the primary source of water at most of these wells (fig. 22*B*). Water at wells with small hydraulic conductivities either contained (USGS 86) or probably contained (EBR 1, USGS 83) some groundwater from the LLR valley (fig. 22*B*), and some recent recharge from the BLR at USGS 86 was indicated by the inverse relation at this well between water levels and chloride concentrations from 1975 to 1995 (fig. 19*Q*). The $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios in groundwater from a well with a very small hydraulic conductivity (USGS 89) indicated that recharge from the BLR, and probably precipitation, were sources of water at this well; this also may be true for other wells (USGS 117, USGS 119) with very small hydraulic conductivities. USGS 104 also had a very small hydraulic conductivity; paleorecharge from the BLR may be the primary source of water at this well, but the presence of waste constituents discharged from INTEC at USGS 104 indicated that some recent recharge also is a source of water to this well.

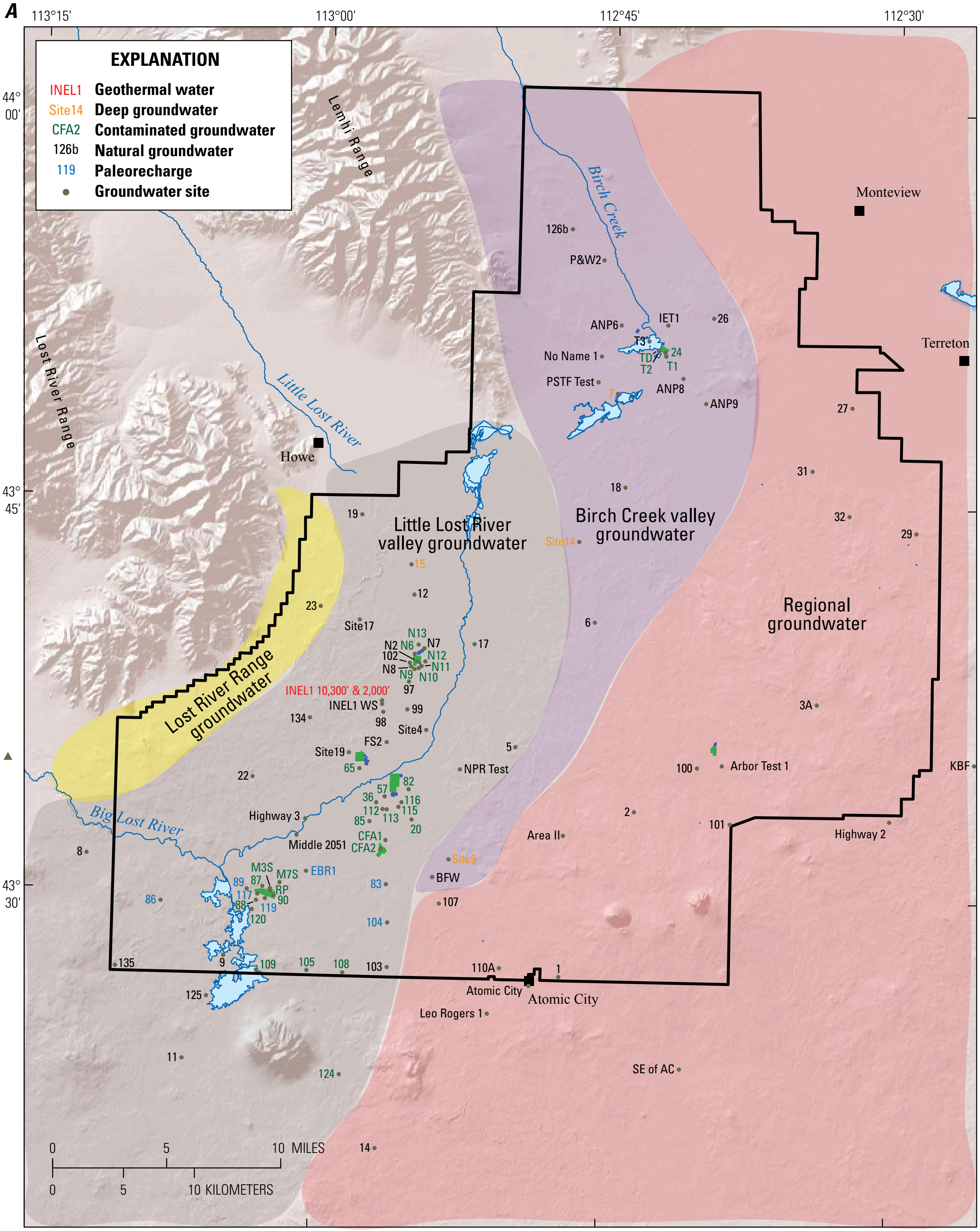
Table 9. Primary sources of recharge at groundwater sampling sites, Idaho National Laboratory and vicinity, eastern Idaho.

[Locations of sites shown in figures 8–9. **Site name:** Alternate names used in other reports shown in table 10. **Source of recharge:** Listed in order of probable largest contributing source to smallest contributing source. **Abbreviations:** INL, Idaho National Laboratory; sz, shallowest zone]

Site name	Source of recharge
North INL Area	
ANP 6	Birch Creek, Birch Creek valley groundwater
ANP 8	Birch Creek, Birch Creek valley groundwater
IET 1 Disposal	Birch Creek and (or) Big Lost River, Birch Creek valley groundwater
No Name 1	Big Lost River, Birch Creek, Birch Creek valley groundwater
P&W 2	Birch Creek, Birch Creek valley groundwater
PSTF Test	Big Lost River
TDD 3	Birch Creek, Birch Creek valley groundwater
Northeast INL Area	
ANP 9	Birch Creek valley groundwater, regional groundwater
USGS 26	Birch Creek valley groundwater, regional groundwater, geothermal water
USGS 27	Regional groundwater, Birch Creek valley groundwater, geothermal water
USGS 29	Regional groundwater, surface water irrigation (Southwest Mud Lake Area, tables 10–11)
USGS 31	Regional groundwater, Birch Creek valley groundwater, geothermal water
USGS 32	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
Southeast INL Area	
Arbor Test 1	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
Area II	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
Atomic City	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
Leo Rogers 1	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area), Big Lost River
USGS 1	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
USGS 2	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
USGS 14	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area), Little Lost River valley groundwater, Big Lost River
USGS 100	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area)
USGS 107	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area), Big Lost River
USGS 110A	Regional groundwater, Birch Creek valley groundwater, surface water irrigation (Southwest Mud Lake Area), Big Lost River
Central INL Area	
Badging Facility Well	Big Lost River, Birch Creek valley groundwater
NPR Test	Big Lost River, Little Lost River valley groundwater
USGS 5	Big Lost River (sinks and playas), Little Lost River valley groundwater
USGS 6	Big Lost River (playas 3 and 4), Little Lost River valley groundwater
USGS 17	Big Lost River, Little Lost River valley groundwater
USGS 18	Deep groundwater or geothermal water, Birch Creek valley groundwater
USGS 103	Big Lost River, Little Lost River valley groundwater, regional groundwater

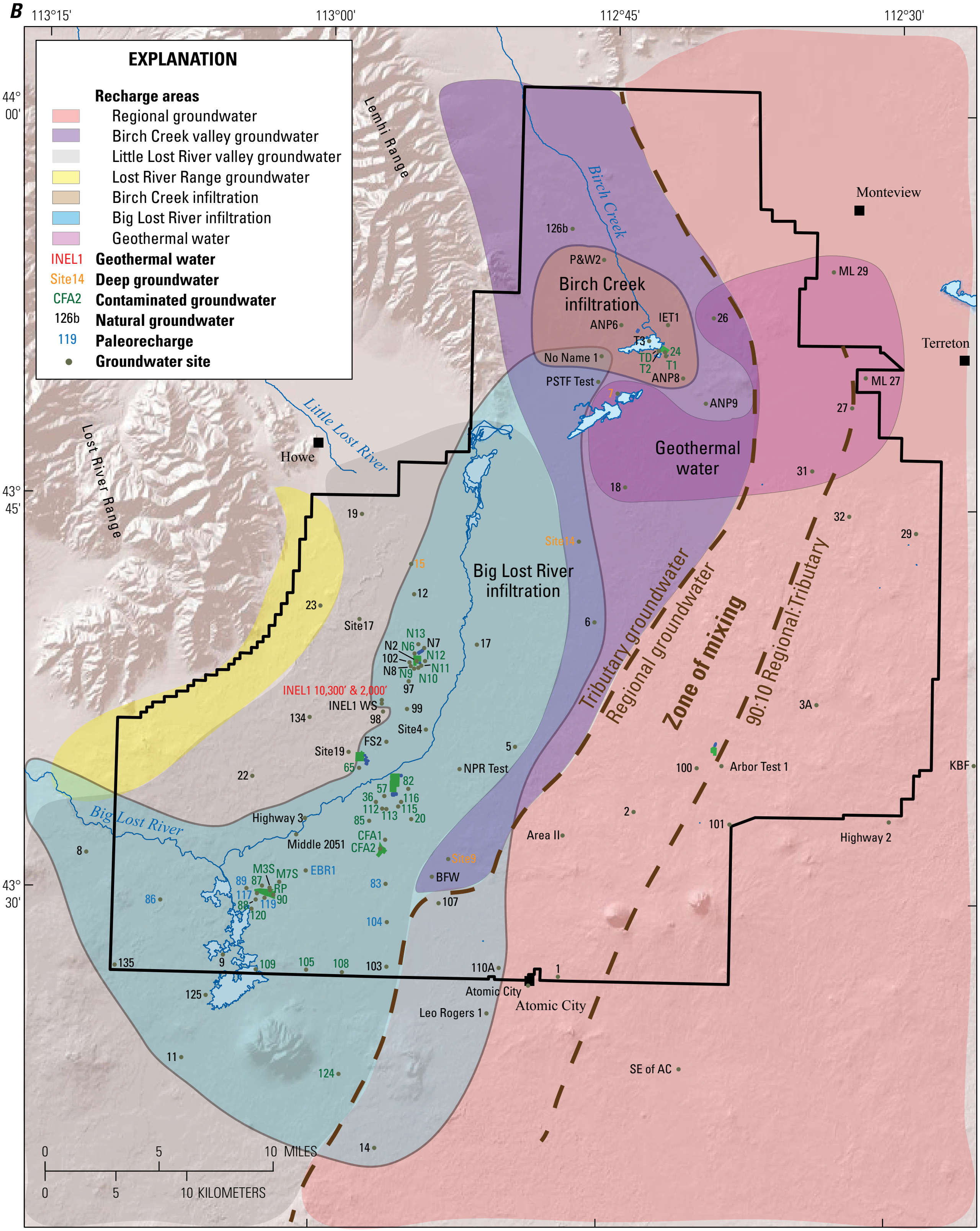
Table 9. Primary sources of recharge at groundwater sampling sites, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Source of recharge
	Northwest INL Area—Continued
Fire Station 2	Little Lost River groundwater, Big Lost River
INEL 1 WS	Little Lost River groundwater, Big Lost River
NRF 2	Big Lost River, Little Lost River valley groundwater
NRF 7	Big Lost River
NRF 8	Big Lost River, Little Lost River valley groundwater
Site 4	Little Lost River, Little Lost River valley groundwater, Big Lost River
Site 17	Little Lost River, Little Lost River valley groundwater
Site 19	Little Lost River, Little Lost River valley groundwater
USGS 12	Big Lost River, Little Lost River valley groundwater
USGS 19	Little Lost River valley groundwater, Little Lost River
USGS 22	Precipitation
USGS 23	Lost River Range groundwater
USGS 97	Big Lost River, Little Lost River valley groundwater
USGS 98	Little Lost River, Little Lost River valley groundwater
USGS 99	Little Lost River groundwater, Big Lost River
USGS 102	Big Lost River, Little Lost River valley groundwater
USGS 134 (sz)	Little Lost River, Little Lost River valley groundwater
	Southwest INL Area
Highway 3	Big Lost River
Middle 2051 (sz)	Big Lost River
USGS 8	Little Lost River valley groundwater, Big Lost River, Big Lost River valley groundwater
USGS 9	Big Lost River, Little Lost River groundwater
USGS 11	Little Lost River groundwater, Big Lost River
USGS 105	Big Lost River, Little Lost River groundwater
USGS 108	Big Lost River, Little Lost River groundwater
USGS 124	Big Lost River, Little Lost River groundwater
USGS 125	Big Lost River, Little Lost River groundwater
USGS 135 (sz)	Little Lost River groundwater, Big Lost River
	Paleorecharge
EBR 1	Big Lost River, Little Lost River groundwater
USGS 83	Big Lost River, Little Lost River groundwater
USGS 86	Big Lost River, Little Lost River groundwater
USGS 89	Big Lost River
USGS 104	Big Lost River, Little Lost River groundwater, contaminated groundwater from INTEC
USGS 117	Big Lost River
USGS 119	Big Lost River



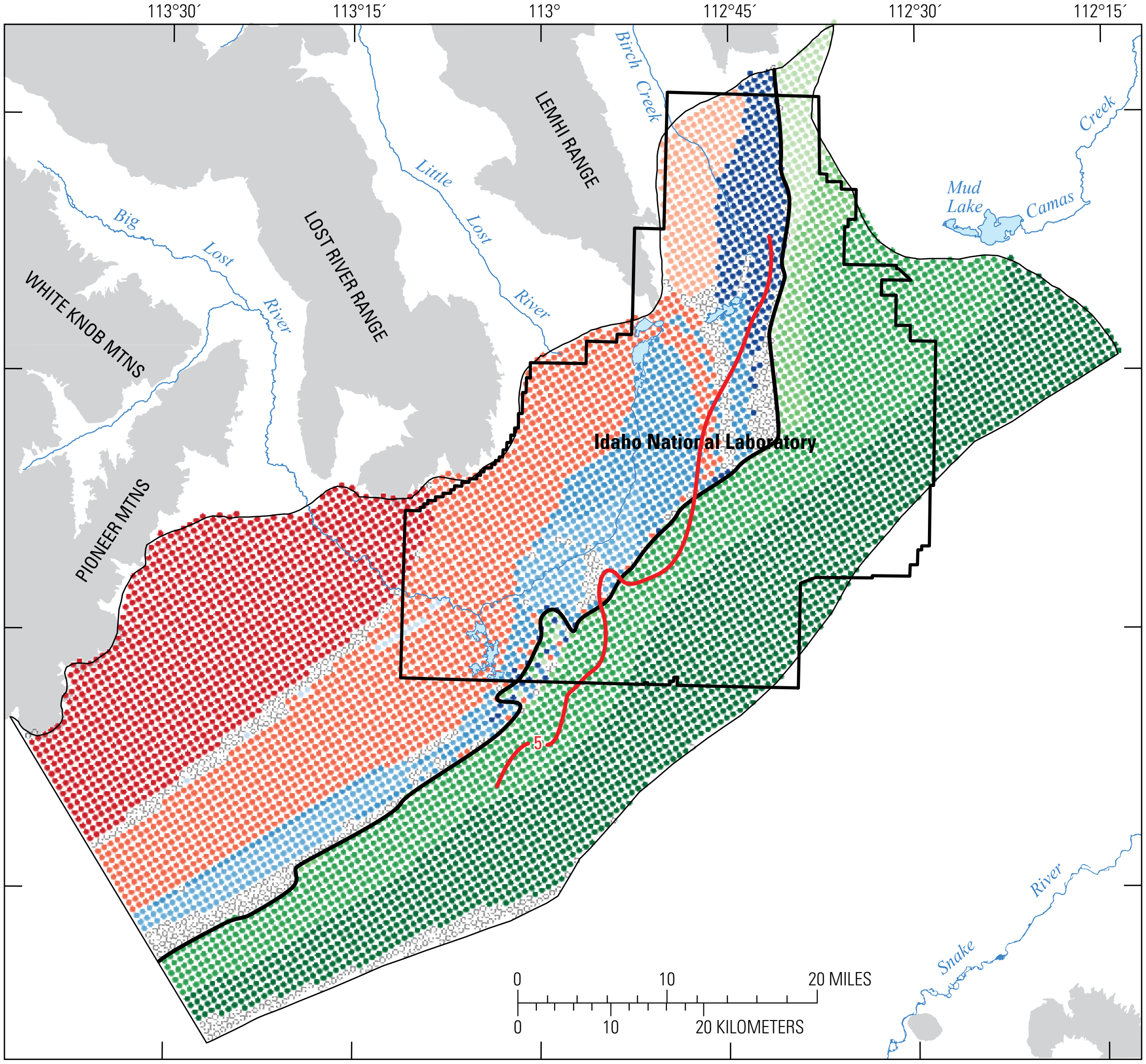
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 24. Sources of recharge and mixing of water, Idaho National Laboratory and vicinity, eastern Idaho. (*A*) Recharge of regional groundwater, groundwater from the tributary valleys and the Lost River Range, and location of sites influenced by paleorecharge. (*B*) Recharge from streams and geothermal water.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 24.—Continued



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000
Albers Equal-Area Conic projection, standard parallels 42°50′N, 44°10′N;
central meridian 113°00′W; North American Datum of 1927.

EXPLANATION

—— **Model area boundary**

—— **Major simulated interface between types A and B water**

—5— **5-microgram-per-liter lithium concentration isopleth**—Applies only to the upper 200 feet of the aquifer

Particles starting location and source area in model layer 1—layer is about 100 feet thick, varying with the water-table altitude. n is the number of particles that terminate in a designated source area.

Northwest mountain-front boundary source areas

- ● Big Lost River valley (n = 1,199)
- ● Little Lost River valley (n = 1,410)
- ● Birch Creek valley (n = 200)

Northeast regional-underflow boundary source areas

- ● Northeast boundary Reno section (n = 125)
- ● Northeast boundary Monteview section (n = 188)
- ● Northeast boundary Mud Lake section (n = 1,370)
- ● Northeast boundary Terreton section (n = 1,734)

Streamflow infiltration source areas

- ● Big Lost River stream reaches 600 and 601 (n = 15)
- ● Big Lost River spreading area, stream reaches 602 and 605 (n = 0)
- ● Big Lost River stream reaches 606 and 607 (n = 302)
- ● Big Lost River sinks and playas, stream reaches 608 and 610 (n = 461)
- ● Little Lost River stream reach 611 (n = 0)
- ● Birch Creek stream reach 612 (n = 270)

Orphans

- ○ Particles that did not terminate in one of the specified source areas (n = 4

Figure 25. Backward particle tracking starting locations and source water areas for particles released in model layer 1, Idaho National Laboratory and vicinity, eastern Idaho.

Mixing of Water

A mixing zone between tributary water and regional groundwater, delineated by two dashed lines in figure 24*B*, was present in the eastern and southeastern parts of the INL. One line separated areas at the INL that were dominantly tributary water or regional groundwater and the second line delineated the approximate location where a mixture of 90 percent regional groundwater and 10 percent tributary water occurred. The nearly uniform lithium concentrations in the area with dominantly tributary water (figs. 24*A* and 28*R*) indicated that this area consisted almost entirely of tributary water, which means that the line dividing tributary water and regional groundwater divided an area where mixing of tributary water and regional groundwater does not occur (tributary water) from an area where mixing does occur (regional groundwater). The 90:10 mixture ratio for tributary water and regional groundwater was approximated from mixing ratios shown in figure 22*A*. The zone of mixing extends in a northeast-to-southwest direction from the eastern boundary of the INL near USGS 27 to south of the southern boundary of the INL and Atomic City, and the width of the zone extends about 3 mi near USGS 31 to about 9 mi at the southern boundary of the INL.

Geothermal water was present in regional groundwater and groundwater from the BC valley along the northeastern boundary of the INL, in the Northeast INL Area, and in the northern part of the Central INL Area (fig. 24*B*). The area delineating geothermal water includes deep groundwater at USGS 7 that contained some geothermal water and wells ML 27 and ML 29 that are outside, but adjacent to, the INL because they were previously shown to be influenced by geothermal water (Rattray, 2015). The geothermal water probably moved upward from below the aquifer with a chemical composition similar to INEL 1 10,300 ft, an interpretation consistent with geochemical modeling by Rattray (2015) for groundwater from ML 27 and ML 29.

The upwelling geothermal water probably was facilitated by volcanic vent corridors and (or) volcanic rift zones (fig. 4*B*) that are present in the northeastern part of the INL and the Mud Lake area (Anderson and others, 1999; Rattray, 2015). The upward moving geothermal water and volcanic structures may produce geologic controls on hydraulic conductivity, such as alteration zones, dikes, and thick, tube-fed, pahoehoe flows that impede the horizontal movement of groundwater (Anderson and others, 1999). Restricted horizontal flow in this area, from either alteration zones, dikes, thick, tube-fed, pahoehoe flows, or perhaps fine-grained lacustrine sediment (fig. 4*B*), could explain why geochemistry data indicated that only small amounts of irrigation-influenced groundwater flowed into the INL from the Mud Lake area, across the northeastern INL boundary, even though the steep hydraulic gradient along this boundary (fig. 6) indicated that groundwater from the Mud Lake area should flow westerly into the INL.

Water from the BC channel, sinks, and playa 4 mixed with groundwater from the BC valley in the North INL Area. Tritium activities in groundwater from ANP 6 and No Name 1 (fig. 28*BB*) indicated that the groundwater was old, so infiltration and mixing of BC from the BC channel, sinks, and playa 4 probably had not occurred since 1969 when construction of diversion channels diverted most water from BC north of the INL.

The BLR flowed onto the INL during wet climate cycles, which included the mid-1990s (fig. 5), and recharge at the INL from the BLR during the mid-1990s occurred from the BLR channel, sinks, playas, and INL spreading areas. Recharge from the BLR was present in groundwater for a distance of about 37 mi in a north-to-south direction between playa 4 and USGS 14, with a width of about 7–8 mi in the Central and Northwest INL Areas, and recharge from the BLR was present in groundwater throughout the Southwest INL Area. Recharge from the BLR mixed with regional groundwater and groundwater from the BC and LLR valleys (fig. 24*B*).

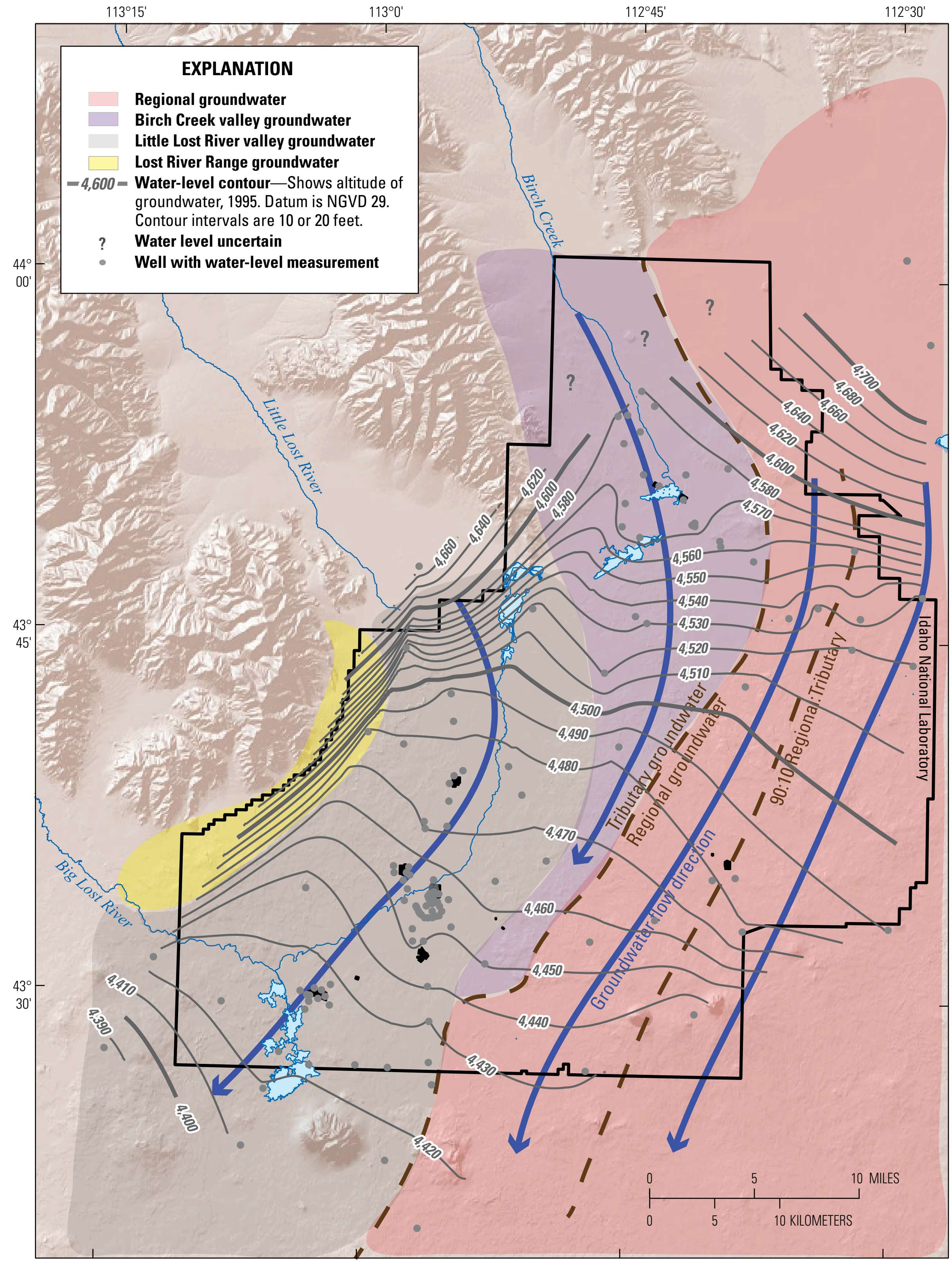
Groundwater Flow Directions

Areas indicating groundwater sources of recharge at the INL and water-table contours for April through mid-July 1995[30] are shown in figure 26. Arrows were drawn through the center of the areas representing groundwater sources of recharge from the LLR and BC valleys and approximately parallel to the line separating tributary water from regional groundwater and the line indicating a 90:10 mixture ratio of tributary water and regional groundwater. All these arrows are approximately perpendicular to water-table contours. This result provided confidence that the areas delineating groundwater sources of recharge were accurate because it showed that groundwater flow directions estimated from geochemistry data were consistent with groundwater flow directions estimated from potentiometric measurements.

The areas delineating groundwater sources of recharge indicated that groundwater from the LLR and BC valleys initially flows southeasterly onto the ERSP aquifer at the INL, generally following the alignment of their valleys, but eventually begins to flow southwesterly in a direction paralleling the general flow direction of regional groundwater (fig. 26). Regional groundwater seems to flow southerly in the northeastern part of the INL and then flows southwesterly through the southeastern part of the INL.

---

[30] The water-table contours for 1989 (fig. 6) were not used in figure 26 because most geochemistry data used to draw groundwater source areas were from the mid-1990s. The 1995 contours were constructed from 139 water-level measurements (U.S. Geological Survey, 2014) using the same procedures (described in section, “Groundwater”) for constructing the 1989 water table contours.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N.

Figure 26. Areas of recharge from tributary valley and regional groundwater, approximate location of groundwater that is a 90:10 mixture of regional groundwater and tributary valley groundwater, water-table contours for spring 1995, and approximate groundwater flow directions, Idaho National Laboratory and vicinity, eastern Idaho.

Flow directions in the northern part of the INL were uncertain because the limited spatial representation of water-level measurements in this area meant that the water-table contours were either non-existent or imprecise. Water-table contours also indicated that water from USGS 8, just west of the western INL boundary, primarily was from either the BLR valley or the Lost River Range, whereas the geochemistry data were interpreted as indicating that groundwater at USGS 8 was primarily from the LLR valley. The few water-level measurements from this area make the water-table contours uncertain, and because representative $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios were not available for groundwater from the BLR valley and the Lost River Range the source of water at USGS 8 determined from geochemistry data was also uncertain.

Summary and Conclusions

Groundwater sources of recharge to the ERSP aquifer at the Idaho National Laboratory (INL) included regional groundwater in the eastern and southeastern parts of the INL, groundwater from the Birch Creek (BC) valley in the northern and central parts of the INL, groundwater from the Little Lost River (LLR) valley over most of the western part of the INL, groundwater from the Lost River Range along the southern part of the northwestern INL boundary, and upward moving geothermal water in the northeastern part of the INL. Groundwater from the Big Lost River (BLR) valley does not appear to contribute any recharge to the INL. Surface water sources of recharge included BC in the northern part of the INL and the BLR over most of the western part of the INL. Paleorecharge from the BLR may have been present at seven wells in the southwestern part of the INL.

Mixing of water occurred throughout the INL. In the western part of the INL, which was a dynamic hydrologic system because of episodic recharge from the BLR, the BLR mixed with tributary valley groundwater. In the eastern part of the INL, which was a relatively static hydrologic system, surface water from BC mixed with groundwater from the BC valley in the northern part of the INL, geothermal water mixed with tributary valley and regional groundwater in the northeastern part of the INL, and tributary valley and regional groundwater mixed in the southeastern part of the INL.

Groundwater flow directions were estimated from areas representing recharge of groundwater from the tributary valleys, the line indicating a transition between dominantly tributary water and regional groundwater, and a line representing a 90:10 mixing ratio of regional groundwater to tributary water. Flow directions for regional groundwater were southwesterly, and flow directions for tributary groundwater were southeasterly upon entering the eastern Snake River Plain aquifer, in alignment with the tributary valleys, but eventually became southwesterly in a direction parallel with regional groundwater. These estimated flow directions were generally perpendicular to water-table contours, which indicated that the estimated flow directions were reasonably accurate.

Several discrepancies were identified from comparison of sources of recharge determined from geochemistry data and from backward particle tracking with a groundwater-flow model. Some discrepancies, described for the particle tracking results, were representation of recharge from BC near the north INL boundary, groundwater from the BC valley not extending far enough south, regional groundwater that extends too far west in the southern part of the INL, and recharge from the BLR not represented in the southwestern part of the INL. The particle tracking results also do not represent recharge from geothermal water in model layer 1.

Evaluation of sources of recharge, mixing of water, and groundwater flow directions at the INL could be improved by collecting some additional data. For example, the definition of the water table was poor in the northern part and west of the INL, leading to uncertainty about flow directions in the northern INL and sources of recharge at USGS 8 west of the INL. Collection of spatially distributed water-level measurements in these areas could provide information that would reduce these uncertainties. Helium concentrations and ratios were important data for identifying geothermal water, but helium ratios were available for only a few groundwater samples from the northeastern part of the INL. Collection of helium ratios from more wells in this area would provide a more accurate resolution of the spatial extent of geothermally influenced water at the INL.

Ratios of strontium and uranium ($^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$) provided the best information for identifying sources of recharge and mixing of water at the INL. However, these ratios were not available for some potential sources of recharge, such as BC, the LLR, the BLR during peak runoff, and groundwater from the BLR valley and the Lost River Range. Collection of $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ ratios for these potential source waters would improve confidence in geochemical interpretations of sources of recharge and mixing of water. Paleorecharge also may be present at some wells in the southwestern part of the INL; however, only one water sample from these wells had a measurement of age with enough accuracy to identify it as old water. Age dating, with low-level tritium, argon-39, and carbon-14, of groundwater from the other wells possibly containing paleorecharge could determine whether groundwater at these wells is old groundwater.

Acknowledgments

The author thanks Pete McMahon and Brian Marshall of the U.S. Geological Survey for providing technical reviews that significantly improved this manuscript.

References Cited

Abplanalp, J.M., Pink, C., Pope, M.C., and Watkinson, J.A., 2008, Geologic map of the southern Beaverhead Range (parts of Copper Mountain, Shamrock Gulch, Scott Butte, and Snaky Canyon quadrangles), Clark, Jefferson, and Lemhi Counties, east-central Idaho: Idaho Geological Society Technical Report 08-1, map scale 1:24,000.

Ackerman, D.J., Rattray, G.W., Rousseau, J.P., Davis, L.C., and Orr, B.R., 2006, A conceptual model of ground-water flow in the Eastern Snake River Plain aquifer at the Idaho National Laboratory and vicinity with implications for contaminant transport: U.S. Geological Survey Scientific Investigations report 2006-5122 (DOE/ID-22198), 62 p.

Ackerman, D.J., Rousseau, J.P., Rattray, G.W., and Fisher, J.C., 2010, Steady-state and transient models of ground-water flow and advective transport, Eastern Snake River Plain aquifer, Idaho National Laboratory and vicinity, Idaho: U.S. Geological Survey Scientific Investigations report 2010-5123 (DOE/ID-22209), 220 p.

Anderson, S.R., Kuntz, M.A., and Davis, L.C., 1999, Geologic controls of hydraulic conductivity in the Snake River Plain aquifer at and near the Idaho National Engineering and Environmental Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations report 99-4033 (DOE/ID-22155) 38 p., http://pubs.er.usgs.gov/publication/wri994033.

Anderson, S.R., and Liszewski, M.J., 1997, Stratigraphy of the unsaturated zone and the Snake River Plain aquifer at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 97-4183 (DOE/ID-22142), 65 p.

Appelo, C.J., and Postma, D., 2005, Geochemistry, groundwater, and pollution, 2nd ed.: Leiden, The Netherlands, A.A. Balkema Publishers, 649 p.

Barraclough, J.T., Lewis, B.D., and Jensen, R.G., 1981, Hydrologic conditions at the Idaho National Engineering Laboratory, Idaho, emphasis—1974–1978: U.S. Geological Survey Open-File Report 81-256 (IDO-22060), 116 p.

Barraclough, J.T., Teasdale, W.E., Robertson, J.B., and Jensen, R.G., 1967, Hydrology of the National Reactor Testing Station, Idaho, 1966: U.S. Geological Survey Open-File Report (IDO-22049), 95 p.

Bartholomay, R.C., 2009, Iodine-129 in the Snake River Plain aquifer at and near the Idaho National Laboratory, Idaho, 2003 and 2007: U.S. Geological Survey Scientific Investigations Report 2009-5088 (DOE/ID-22208), 28 p., http://pubs.usgs.gov/sir/2009/5088/.

Bartholomay, R.C., 2013, Iodine-129 in the Snake River Plain aquifer at and near the Idaho National Laboratory, Idaho, 2010–12: U.S. Geological Survey Scientific Investigations Report 2013-5195 (DOE/ID-22225), 22 p., http://pubs.usgs.gov/sir/2013/5195/.

Bartholomay, R.C., Davis, L.C., Fisher, J.C., Tucker, B.J., and Raben, F.A., 2012, Water-quality characteristics and trends for selected sites at and near the Idaho National Laboratory, Idaho, 1949–2009: U.S. Geological Survey Scientific Investigations Report 2012-5169 (DOE/ID-22219), 405 p.

Bartholomay, R.C., Edwards, D.D., and Campbell, L.J., 1994, Radionuclides, stable isotopes, inorganic constituents, and organic compounds in water from selected wells and springs from the southern boundary of the Idaho National Engineering Laboratory to the Hagerman area, Idaho, 1993: U.S. Geological Survey Open-File Report 94-503 (DOE/ID-22117), 35 p.

Bartholomay, R.C., and Hall, L.F., 2016, Evaluation of background concentrations of selected chemical and radiochemical constituents in water from n the Eastern Snake River Plain aquifer at and near the Idaho National Laboratory, Idaho: U.S. Geological Survey Scientific Investigations Report 2016-5056 (DOE/ID-22237), 19 p.

Bartholomay, R.C., Hopkins, C.B., and Maimer, N.V., 2015, Chemical constituents in groundwater from multiple zones in the Eastern Snake River Plain aquifer at the Idaho National Laboratory, Idaho, 2009–13: U.S. Geological Survey Scientific Investigations Report 2015-5002 (DOE/ID-22232), 109 p., http://pubs.er.usgs.gov/publication/sir20155002.

Bartholomay, R.C., and Knobel, L.L., 1989, Mineralogy and grain size of surficial sediment from the Little Lost River drainage and vicinity, with chemical and physical characteristics of geological materials from selected sites at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 89-384 (DOE/ID-22081), 74 p.

Bartholomay, R.C., Knobel, L.L., and Davis, L.C., 1989, Mineralogy and grain size of surficial sediment from the Big Lost River and Birch Creek drainages, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 89-385 (DOE/ID-22082), 19 p.

Bartholomay, R.C., Knobel, L.L., Tucker, B.J., and Twining, B.V., 2000, Chemical and radiochemical constituents in water from wells in the vicinity of the Naval Reactors Facility, Idaho National Engineering and Environmental Laboratory, Idaho, 1997-8: U.S. Geological Survey Open-File Report 00-236 (DOE/ID-22165), 52 p.

Bartholomay, R.C., Knobel, L.L., Tucker, B.J., and Twining, B.V., 2001, Chemical and radiochemical constituents in water from wells in the vicinity of the Naval Reactors Facility, Idaho National Engineering and Environmental Laboratory, Idaho, 1999: U.S. Geological Survey Open-File Report 010-27 (DOE/ID-22172), 37 p.

Bartholomay, R.C., Knobel, L.L., Tucker, B.J., and Twining, B.V., 2002, Chemical and radiochemical constituents in water from wells in the vicinity of the Naval Reactors Facility, Idaho National Engineering and Environmental Laboratory, Idaho, 2000: U.S. Geological Survey Open-File Report 02-148 (DOE/ID-22178), 34 p.

Bartholomay, R.C., Maimer, N.V., Rattray, G.W., and Fisher, J.C., 2017, An update of hydrologic conditions and distribution of selected constituents in water, eastern Snake River Plain aquifer and perched groundwater zones, Idaho National Laboratory, Idaho, emphasis 2012–15: U.S. Geological Survey Scientific Investigations Report 2017-5021 (DOE/ID-22242), 87 p.

Bartholomay, R.C., and Tucker, B.J., 2000, Distribution of selected radiochemical and chemical constituents in perched ground water, Idaho National Engineering and Environmental Laboratory, Idaho, 1996–98: U.S. Geological Survey Water-Resources Investigations Report 2000-4222 (DOE/ID-22168), 51 p., http://pubs.usgs.gov/wri/2000/4222/report.pdf.

Bartholomay, R.C., Tucker, B.J., Davis, L.C., and Greene, M.R., 2000, Hydrologic conditions and distribution of selected constituents in water, Snake River Plain aquifer, Idaho National Engineering and Environmental Laboratory, Idaho, 1996 through 1998: U.S. Geological Survey Water-Resources Investigations Report 00-4192 (DOE/ID-22167), 52 p.

Bartholomay, R.C., and Twining, B.V., 2010, Chemical constituents in groundwater from multiple zones in the Eastern Snake River Plain aquifer at the Idaho National Laboratory, Idaho, 2005–08: U.S. Geological Survey Scientific Investigations Report 2010-5116 (DOE/ID-22211), 81 p.

Bartholomay, R.C., and Twining, B.V., 2015, Hydrologic influences on water-level changes in the Eastern Snake River Plain aquifer at and near the Idaho National Laboratory, Idaho, 1949–2014: U.S. Geological Survey Scientific Investigations Report 2015-5085 (DOE/ID-22236), 37 p.

Bartholomay, R.C., Williams, L.M., and Campbell, L.J., 1995, Radionuclides, stable isotopes, inorganic constituents, and organic compounds in water from selected wells and springs from the southern boundary of the Idaho National Engineering Laboratory to the Hagerman area, Idaho, 1994: U.S. Geological Survey Open-File Report 95-718 (DOE/ID-22124), 37 p.

Beasley, T.M., Dixon, P.R., and Mann, L.J., 1998, ^{99}Tc, ^{236}U, and ^{237}Np in the Snake River Plain aquifer at the Idaho National Engineering Laboratory, Idaho Falls, Idaho: Environmental Science and Technology, v. 32, p. 3,875–3,881.

Benjamin, Lyn, Knobel, L.L., Hall, L.F., Cecil, L.D., and Green, J.R., 2004, Development of a local meteoric water line for southeastern Idaho, western Wyoming, and south-central Montana: U.S. Geological Survey Scientific Investigations Report 2004-5126 (DOE/ID-22191), 17 p.

Bennett, C.M., 1990, Streamflow losses and groundwater level changes along the Big Lost River at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 90-4067 (DOE/ID-22091), 49 p.

Blackwell, D.D., Kelly, S, and Steele, J.L., 1992, Heat flow modeling of the Snake River Plain, Idaho: U.S. Department of Energy contractor report no. EGG-NPR-10790, 109 p.

Blair, J.J., 2002, Sedimentology and stratigraphy of sediments of the Big Lost Trough subsurface from selected boreholes at the Idaho National Engineering and Environmental Laboratory, Idaho: Pocatello, Idaho State University, M.S. Thesis, 162 p., http://geology.isu.edu/thesis/Blair_James_2001.pdf.

Busenberg, Eurybiades, and Plummer, L.N., 2000, Dating young anthropogenic groundwater with sulfur hexafluoride: Natural and anthropogenic sources of sulfur hexafluoride: Water Resources Research, v. 36, no. 10, p. 3,011–3,030.

Busenberg, Eurybiades, Plummer, L.N., and Bartholomay, R.C., 2001, Estimated age and source of the young fraction of ground water at the Idaho National Engineering and Environmental Laboratory: U.S. Geological Survey Water-Resources Investigations Report 01-4265 (DOE/ID-22177), 144 p., http://pubs.er.usgs.gov/publication/wri014265.

Busenberg, Eurybiades, Plummer, L.N., Bartholomay, R.C., and Wayland, J.E., 1998, Chlorofluorocarbons, sulfur hexafluoride, and dissolved permanent gases in ground water from selected sites at and near the Idaho National Engineering and Environmental Laboratory, Idaho, 1994–97: U.S. Geological Survey Open-File Report 98-274 (DOE/ID-22151), 72 p., http://pubs.er.usgs.gov/publication/ofr98274.

Busenberg, Eurybiades, Plummer, L.N., Doughten, M.W., Widman, P.K., and Bartholomay, R.C., 2000, Chemical and isotopic composition and gas concentrations of ground water and surface water from selected sites at and near the Idaho National Engineering and Environmental Laboratory: U.S. Geological Survey Open-File Report 00-81 (DOE/ID-22164), 51 p., http://pubs.er.usgs.gov/publication/ofr0081.

Busenberg, Eurybiades, Weeks, E.P., Plummer, L.N., and Bartholomay, R.C., 1993, Age dating groundwater by use of chlorofluorocarbons (CCl_3F and CCl_2F_2), and distribution of Chlorofluorocarbons in the unsaturated zone, Snake River Plain aquifer, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 93-4054 (DOE/ID-22107), 47 p., http://pubs.er.usgs.gov/publication/wri934054.

Carkeet, Colleen, Rosentreter, J.J., Bartholomay, R.C., and Knobel, L.L., 2001, Geochemistry of the Big Lost River drainage basin, Idaho: U.S. Geological Survey Water-Resources Investigations Report 01-4031 (DOE/ID-22174), 31 p., http://pubs.er.usgs.gov/publication/wri014031.

Cecil, L.D., Orr, B.R., Norton, Teddy, and Anderson, S.R., 1991, Formation of perched ground-water zones and concentrations of selected chemical constituents in water, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4166 (DOE/ID-22100), 53 p., http://pubs.er.usgs.gov/publications/wri914166.

Cecil, L.D., Welhan, J.A., Green, J.R., Frape, S.K., and Sudicky, E.R., 2000, Use of chlorine-36 to determine regional-scale aquifer dispersivity, eastern Snake River Plain aquifer, Idaho/USA: Nuclear Instruments and Methods in Physics Research B 172, p. 679–687.

Childress, C.J.O., Foreman, W.T., Conner, B.F., and Maloney, T.J., 1999, New reporting procedures based on long-term method detection levels and some considerations for interpretations of water-quality data provided by the U.S. Geological Survey National Water Quality Laboratory: U.S. Geological Survey Open-File Report 99-193, 19 p., http://pubs.er.usgs.gov/publication/ofr99193/.

Clark, I.D., and Fritz, Peter, 1997, Environmental isotopes in hydrogeology: Boca Raton, Florida, Lewis Publishers, 328 p.

Conrad, M.E., and DePaolo, D.J., 2004, Carbon isotopic evidence for biodegradation of organic contaminants in the shallow vadose zone of the Radioactive Waste Management Complex: Vadose Zone Journal, v. 3, p. 143–153.

Crosthwaite, E.G., Thomas, C.A., and Dyer, K.L., 1970, Water resources in the Big Lost River basin, south-central Idaho: U.S. Geological Survey Open-File Report 70-93, 109 p., http://pubs.er.usgs.gov/publication/ofr7093.

Davis, L.C., 2006, An update of hydrologic conditions and distribution of selected constituents in water, Snake River Plain aquifer, Idaho National Laboratory, Idaho, emphasis 1999–2001: U.S. Geological Survey Scientific Investigations Report 2006-5088 (DOE/ID-22197), 48 p.

Davis, L.C., Bartholomay, R.C., Fisher, J.C., and Maimer, N.V., 2015, Water-quality characteristics and trends for selected wells possibly influenced by wastewater disposal at the Idaho National Laboratory, Idaho, 1981–2012: U.S. Geological Survey Scientific Investigations report 2015-5003 (DOE/ID-22233), 105 p.

Davis, L.C., Bartholomay, R.C., and Rattray, G.W., 2013, An update of hydrologic conditions and distribution of selected constituents in water, eastern Snake River Plain aquifer and perched groundwater zones, Idaho National Laboratory, Idaho, emphasis 2009–11: U.S. Geological Survey Scientific Investigations Report 2013-5214 (DOE/ID-22226), 89 p., http://pubs.er.usgs.gov/publication/sir20135214.

Deer, W.A., Howie, R.A., and Zussman, J., 1983, An introduction to the rock forming minerals: Longman House, Essex, England, 528 p.

Doherty, D.J., McBroome, L.A., and Kuntz, M.A., 1979, Preliminary geological interpretation and lithologic log of the exploratory geothermal test well (INEL-1), Idaho National Engineering Laboratory, eastern Snake River Plain, Idaho: U.S. Geological Survey Open-File Report 79-1248, 9 p.

Drever, J.I., 1997, The geochemistry of natural waters: Upper Saddle River, New Jersey, Prentice Hall, 436 p.

Emsley, John, 1989, The elements: Oxford, Clarendon Press, 256 p.

Faure, Gunter, 1986, Principles of Isotope Geology (2nd ed.): New York, NY, John Wiley & Sons, 589 p.

Fisher, J.C., Rousseau, J.R., Bartholomay, R.C., and Rattray, G.W., 2012, A comparison of U.S. Geological Survey three-dimensional model estimates of groundwater source areas and velocities to independently derived estimates, Idaho National Laboratory and vicinity, Idaho: U.S. Geological Survey Scientific Investigations Report 2012-5152 (DOE/ID-22218), 130 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Fromm, J.M., 1995, Characterizing aquifer hydrogeology and anthropogenic chemical influences on groundwater near the ICPP: Pocatello, Idaho State University, M.S. Thesis, 312 p.

Garabedian, S.P., 1992, Hydrology and digital simulation of the regional aquifer system, eastern snake River Plain, Idaho: U.S. Geological Survey Professional Paper 1408-F, 102 p., 10 pl.

Gerla, P.J., 1992, Pathline and geochemical evolution of ground water in a regional discharge area, Red River valley, North Dakota: Ground Water, v. 30, no. 5, p. 743–754.

Geslin, J.K., Link, P.K., Riesterer, J.W., Kuntz, M.A., and Fanning, C.M., 2002, Pliocene and Quaternary stratigraphic architecture and drainage systems of the Big Lost Trough, northeastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, Hydrogeology, and Environmental Remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 11–26., http://specialpapers.gsapubs.org/content/353/11.full.pdf+html.

Gianniny, G.L., Thackray, G.D., Kauffman, D.S., Forman, S.L., Sherbondy, M.J., and Findeisen, Delda, 2002, Late Quaternary highstands in the Mud Lake and Big Lost Trough subbasins of Lake Terreton, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, Hydrogeology, and Environmental Remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 77–90., http://specialpapers.gsapubs.org/content/353/77.full.pdf+html.

Ginsbach, M.L., 2013, Geochemical evolution of groundwater in the Medicine Lodge Creek drainage basin, eastern Idaho: Pocatello, Idaho State University, M.S. Thesis, 241 p., http://geology.isu.edu/thesis/Ginsbach.Michael.2013.pdf.

Goodell, S.A., 1988, Water use on the Snake River Plain, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-E, 51 p.

Graham, D.W., Reid, M.R., Jordan, B.T., Grunder, A.L., Leeman, W.P., and Lupton, J.E., 2009, Mantle source provinces beneath the northwestern USA delimited by helium isotopes in young basalts: Journal of Volcanology and Geothermal Research, v. 188, p. 128–140.

Graustein, W.C., 1989, ^{87}Sr/^{86}Sr ratios measure the sources and flow of strontium in terrestrial ecosystems: *in* Rundel, P.W., Ehleringer, J.R., and Nagy, K.A., eds., Stable Isotopes in Ecological Research: New York, Springer-Verlag Inc., p. 491–512.

Hall, Jeter, Aalseth, C.E., Bonicalzi, R.M., Brandenberger, J.M., Day, A.R., Humble, P.H., Mace, E.K., Panisko, M.E., and Seifert, Allen, 2016, ^{39}Ar/Ar measurements using ultra-low background proportional counters: Applied Radiation and Isotopes, v. 107, p. 187–190.

Hedge, C.E., 1966, Variations in radiogenic strontium found in volcanic rocks: Journal of Geophysical Research, v. 71, no. 24, p. 6,119–6,126.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 510 p.

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p., http://pubs.er.usgs.gov/publication/wsp2254.

Hodges, M.K.V., 2006, Tertiary stratigraphy of the Idaho Medicine Lodge Valley, Clark County, Idaho: Pocatello, Idaho State University, M.S. Thesis, 163 p., http://geology.isu.edu/thesis/Hodges_Mary_K.V._2006.pdf.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J., 2007, Completion of the 2001 national land cover database for the conterminous United States: Photographic Engineering and Remote Sensing, v. 73, no. 4, p. 337–341.

Idaho Department of Environmental Quality, 2006, State of Idaho Oversight Monitor—The Eastern Snake River Plain aquifer: Idaho Department of Environmental Quality Oversight Monitor, 6 p., https://www.deq.idaho.gov/media/462786-newsletter_0306.pdf.

Idaho Department of Environmental Quality, 2015, Sole source aquifers: Idaho Department of Environmental Quality Web site, accessed July 22, 2015, at http://deq.idaho.gov/water-quality/ground-water/sole-source-aquifers.aspx.

Idaho Department of Water Resources, 2014, Well driller reports: Idaho Department of Water Resources, accessed December 12, 2014, at http://www.idwr.idaho.gov/WaterManagement/WellInformation/DrillerReports/dr_default.htm.

Idaho Department of Water Resources, 2016, Eastern Snake River Plain: Irrigated Lands: 1996, accessed February 16, 2016, at http://research.idwr.idaho.gov/index.html#GIS_Data.

International Atomic Energy Agency/World Meteorological Organization, 2015, Global network of isotopes in precipitation database: International Atomic Energy Agency, accessed December 24, 2015, at http://www.iaea.org/water.

Johnson, T.M., Roback, R.C., McLing, T.L., Bullen, T.D., DePaolo, D.J., Doughty, C., Hunt, R.J., Smith, R.W., Cecil, L.D., and Murrell, M.T., 2000, Groundwater “fast paths” in the Snake River Plain aquifer—Radiogenic isotope ratios as natural groundwater tracers: Geology, v. 28, no. 10, p. 871–874.

Kalin, R.M., 2000, Radiocarbon dating of groundwater systems, *in* Cook, P.G., Herczeg, A.L., eds., Environmental Tracers in Subsurface Hydrology: Boston, Massachusetts, Kluwer Academic Publishers, p. 111–144.

Keating, E.H., and Bahr, J.M., 1998, Using reactive solutes to constrain groundwater flow models at a site in Northern Wisconsin: Water Resources Research, v. 34, p. 3,561–3,571.

Kirkham, V.R.D., 1927, A geologic reconnaissance of Clark and Jefferson and parts of Butte, Custer, Fremont, Lemhi, and Madison counties, Idaho: Idaho Bureau of Mines and Geology, Pamphlet no. 19, 47 p., 4 pls.

Kjelstrom, L.C., and Berenbrock, Charles, 1996, Estimates 100-year peak flows and flow volumes in the Big Lost River and Birch Creek at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 96-4163, 23 p., http://pubs.er.usgs.gov/publication/wri964163.

Knobel, L.L., Bartholomay, R.C., Cecil, L.D., Tucker, B.J., and Wegner, S.J., 1992, Chemical constituents in the dissolved and suspended fractions of ground water from selected sites, Idaho National Engineering Laboratory and vicinity, Idaho, 1989: U.S. Geological Survey Open-File Report 92-51 (DOE/ID-22101), 56 p., http://pubs.er.usgs.gov/publication/ofr9251.

Knobel, L.L., Bartholomay, R.C., and Orr, B.R., 1997, Preliminary delineation of natural geochemical reactions, Snake River Plain aquifer system, Idaho National Laboratory and vicinity, Idaho: U.S. Geological Survey Water-Resources Investigations Report 97-4093 (DOE/ID-22139), 52 p., http://pubs.er.usgs.gov/publication/wri974093.

Knobel, L.L., Bartholomay, R.C., Tucker, B.J., Williams, L.M., and Cecil, L.D., 1999a, Chemical constituents in ground water from 39 selected sites with an evaluation of associated quality assurance data, Idaho National Engineering and Environmental Laboratory and vicinity, Idaho: U.S. Geological Survey Open-File Report 99-246 (DOE/ID-22159), 58 p., http://pubs.er.usgs.gov/publication/ofr99246.

Knobel, L.L., Bartholomay, R.C., Tucker, B.J., Williams, L.M., 1999b, Chemical and radiochemical constituents in water from sites in the vicinity of the Naval Reactors Facility, Idaho National Engineering and Environmental Laboratory and vicinity, Idaho, 1996: U.S. Geological Survey Open-File Report 99-272 (DOE/ID-22160), 58 p., http://pubs.er.usgs.gov/publication/ofr99272.

Knobel, L.L., Cecil, L.D., and Wood, T.S., 1995, Chemical composition of selected core samples, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 95-748 (DOE/ID-22126), 59 p.

Knobel, L.L., Chapelle, F.H., and Meisler, Harold, 1998, Geochemistry of the northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404-L, 57 p., 8 pl.

Knobel, L.L., Tucker, B.J., and Rousseau, J.P., 2008, Field methods and quality-assurance plan for quality-of-water activities, U.S. Geological Survey, Idaho National Laboratory, Idaho: U.S. Geological Survey Open-File Report 2008-1165 (DOE/ID-22206), 36 p., http://pubs.usgs.gov/of/2008/1165/.

Kuntz, M.A., Anderson, S.A., Champion, D.E., Lanphere, M.A., and Grunwald, D.J., 2002, Tension cracks, eruptive fissures, dikes, and faults related to late Pleistocene-Holocene basaltic volcanism and implications for the distribution of hydraulic conductivity in the eastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, Hydrogeology, and Environmental Remediation: Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 111–133,

Kuntz, M.A., Covington, H.R., and Schorr, L.J., 1992, An overview of basaltic volcanism of the eastern Snake River Plain, Idaho, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of Eastern Idaho and Western Wyoming: Geological Society of America Memoir 179, p. 227–257, http://memoirs.gsapubs.org/content/179/227.full.pdf+html.

Larsen, Daniel, Gentry, R.W., and Solomon, D.K., 2003, The geochemistry and mixing of leakage in a semi-confined aquifer at a municipal well field, Memphis, Tennessee, USA: Applied Geochemistry, v. 18, p. 1,043–1,063.

Lasaga, A.C., Soler, J.M., Ganor, J., Burch, T.E., and Nagy, K.L., 1994, Chemical weathering rate laws and global geochemical cycles: Geochimica et Cosmochimica Acta, v. 58, p. 2,361–2,386.

Leeman, W.P., and Manton, W.I., 1971, Strontium isotopic composition of basaltic lavas from the Snake River Plain, southern Idaho: Earth and Planetary Science Letters, v. 11, p. 420–434.

Lenhard, R.J., Yonk, A.K., Wright, P.M., and Herzog, J.D., 2004, The Idaho National Engineering and Environmental Laboratory site—An overview of site history and soil and groundwater contamination issues: Vadose Zone Journal, v. 3, p. 1–5.

Lewis, R.S., Link, P.K., Stanford, L.R., and Long, S.P., 2012, Geologic map of Idaho: Idaho Geological Survey Map 9, scale 1:750,000, accessed September 14, 2015, at http://www.idahogeology.org/Products/reverselook.asp?switch=title&value=Geologic_Map_of_Idaho.

Link, P.K., and Janecke, S.U., 1999, Geology of east-central Idaho—Geologic roadlogs for the Big and Little Lost River, Lemhi, and Salmon River valleys, *in* Hughes, S.S., and Thackray, G.D., eds., Guidebook to the Geology of Eastern Idaho: Pocatello, Idaho Museum of Natural History, p. 295–334, http://imnh.isu.edu/digitalatlas/geo/gsa/gsafrm.htm.

Liszewski, M.J., and Mann, L.J., 1993, Concentrations of 23 trace elements in ground water and surface water at and near the Idaho National Engineering Laboratory, Idaho, 1988–91: U.S. Geological Survey Open-File Report 93-126 (DOE/ID-22110), 44 p., http://pubs.er.usgs.gov/publication/ofr93126.

Luo, Shangde, Ku, Teh-Lung, Roback, R.C., Murrell, M.T., and McLing, T.L., 2000, In-situ radionuclide transport and preferential groundwater flows at INEEL (Idaho): Decay-series disequilibrium studies: Geochimica et Cosmochimica Acta, v. 64, no. 5, p. 867–881, http://www.sciencedirect.com/science/journal/00167037/64/5.

Mann, L.J., 1986, Hydraulic properties of rock units and chemical quality of water for INEL-1—A 10,365-foot deep test hole drilled at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 86-4020 (DOE/ID-22070), 23 p., http://pubs.er.usgs.gov/publication/wri864020.

Mann, L.J., 1996, Quality-assurance plan and field methods for quality-of-water activities, U.S. Geological Survey, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 96-615 (DOE/ID-22132), 37 p., http://pubs.usgs.gov/of/1996/0615/.

Mann, L.J., and Beasley, T.M., 1994, Iodine-129 in the Snake River Plain aquifer at and near the Idaho National Engineering Laboratory, Idaho, 1990–91: U.S. Geological Survey Water-Resources Investigations Report 94-4053 (DOE/ID-22115), 27 p., http://pubs.er.usgs.gov/publication/wri944053.

Mann, L.J., and Cecil, L.D., 1990, Tritium in groundwater at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 90-4090 (DOE/ID-22090), 35 p., http://pubs.er.usgs.gov/publication/wri904090.

Mann, L.J., Chew, E.W. and Morton, J.S., 1988, Iodine-129 in the Snake River Plain aquifer at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 88-4165 (DOE/ID-22076), 27 p., http://pubs.er.usgs.gov/publication/wri884165.

Mark, L.E., and Thackray, G.D., 2002, Sedimentologic and hydrologic characterization of surficial sedimentary facies in the Big Lost Trough, Idaho National Engineering and Environmental Laboratory, *in* Link, P.K., and Mink, L.L., eds., Geology, Hydrogeology, and Environmental Remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, p. 61–76, http://specialpapers.gsapubs.org/content/353/77.full.pdf+html.

McLing, Travis, 1994, The pre-anthropogenic groundwater evolution at the Idaho National Engineering Laboratory, Idaho: Pocatello, Idaho State University, M.S. Thesis, 62 p., http://geology.isu.edu/thesis/McLing_Travis_1994.pdf.

McLing, T.L., and Roback, R.C., 2007, Use of aquifer temperature distribution and chemical/isotopic characteristics to define groundwater flow paths at the Idaho National Laboratory: *in* Hughes, S., Orr, B., Freiberg, D., and Boyack, D., eds., Proceedings of the Great Rift Science Symposium: Pocatello, Idaho, Idaho State University, p. 133–137.

McLing, T.L., Smith, R.W., and Johnson, T.M., 2002, Chemical characteristics of thermal water beneath the eastern Snake River Plain: *in* Link, P.K., and Mink, L.L. eds., Geology, Hydrogeology, and Environmental Restoration—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 205–211.

McNutt, R.H., 2000, Strontium isotopes, *in* Cook, P.G., Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Massachusetts, Kluwer Academic Publishers, p. 233–260.

Michel, R.L., 1989, Tritium deposition in the continental United States: U.S. Geological Survey Water-Resources Investigations Report 89-4072, 46 p.

Morris, D.A., Hogenson, G.M., Teasdale, W.E., and Shuter, E., 1963, Hydrology of waste disposal, National Reactor Testing Station, Idaho, annual progress report, 1962: U.S. Atomic Energy Commission, Idaho Operations Office Publication IDO-22044-USGS, 99 p.

Morgan, L.A., Doherty, D.J., and Leeman, P.L., 1984, Ignimbrites of the eastern Snake River Plain—Evidence for major caldera-forming eruptions: Journal of Geophysical Research, v. 89, no. B10, p. 8,665–8,678.

Morgan, L.A., and McIntosh, W.C., 2005, Timing and development of the Heise volcanic field, Snake River Plain, Idaho western USA: Geological Society of America Bulletin, v. 117, no. 3 and 4, p. 288–306.

Mundorff, M.J., 1962, Ground water in Birch Creek valley, Idaho: U.S. Geological Survey Open-File Report 62-93, 10 p.

Mundorff, M.J., Broom, H.C., and Kilburn, Chabot, 1963, Reconnaissance of the hydrology of the Little Lost River basin, Idaho: U.S. Geological Survey Water-Supply Paper 1539-Q, p. Q1–Q51., http://pubs.er.usgs.gov/publication/wsp1539Q.

Nace, R.L., Deutsch, Morris, and Voegli, P.T., 1956, Geography, geology, and water resources of the National Reactor Testing Station, Idaho—Part 2. Geography and geology: U.S. Geological Survey Open-File Report (IDO-22033), 225 p.

Nace, R.L., Voegli, P.T., Jones, J.R., and Deutsch, Morris, 1975, Generalized geologic framework of the National Reactor Testing Station, Idaho: U.S. Geological Survey Professional Paper 725–B, 49 p.

National Oceanic and Atmospheric Administration, 2015, NOAA INL Weather Center—INL climate: U.S. Department of Commerce, accessed September 10, 2015, at http://niwc.noaa.inel.gov/climate.htm.

Nimmo, J.R., Perkins, K.S., Rose, P.A., Rousseau, J.P., Orr, B.R., Twining, B.V., and Anderson, S.R., 2002, Kilometer-scale rapid transport of naphthalene sulfonate tracer in the unsaturated zone at the Idaho National Engineering and Environmental Laboratory: Vadose Zone Journal, v. 1, issue 1, p. 89–101, http://vzj.geoscienceworld.org/content/1/1/89.full.pdf+html.

Olmsted, F.H., 1962, Chemical and physical characteristics of ground water in the National Reactor Testing Station, Idaho: U.S. Atomic Energy Commission, Idaho Operations Office Publication IDO-22043-USGS, 142 p.

Osmond, J.K., and Cowart, J.B., 2000, U-series nuclides as tracers in groundwater hydrology, *in* Cook, P.G., Herczeg, A.L., eds. Environmental tracers in subsurface hydrology: Boston, Massachusetts, Kluwer Academic Publishers, p. 145–173.

Ott, D.S., Cecil, L.D., and Knobel, L.L., 1994, Stable isotopes of hydrogen and oxygen in surface water and ground water at selected sites on or near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 95-55 (DOE/ID-22112), 14 p., http://pubs.er.usgs.gov/publication/ofr9455.

Parkhurst, D.L., and Appelo, C.A.J., 2013, Description of input and examples for PHREEQC Version 3—A computer program for speciation, batch reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Techniques and Methods, book 6, chap. A43, 497 p., available at http://pubs.usgs.gov/tm/06/a43/.

Parliman, D.J., 1983, Reconnaissance of ground-water quality, Eastern Snake River Basin, Idaho: U.S. Geological Survey Water-Resources Investigations Report 82-4004, 100 p., 4 pl.

Pearson, F.J., Jr., and White, D.E., 1967, Carbon 14 ages and flow rates of water in Carrizo Sand, Atascosa County, Texas: Water Resources Research, v. 3, p. 251–261.

Pittman, J.R., Jensen, R.G., and Fischer, P.R., 1988, Hydrologic conditions at the Idaho National Engineering Laboratory, 1982 to 1985: U.S. Geological Survey Water-Resources Investigations Report 89-4008 (DOE/ID-22078), 73 p.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, Eurybiades, 2004a, Hydrochemical tracers in the middle Rio Grande Basin, USA: Hydrogeology Journal, v. 12, p. 359–388.

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

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

Plummer, L.N., Michel, R.L., Thurman, E.M., and Glynn, P.D., 1993, Environmental tracers for age dating young groundwater, *in* Alley, W.M., ed., Regional Ground-Water Quality, Chap. 11, Van Nostrand Reinhold, New York, p. 255–294.

Plummer, L.N., Rupert, M.G., Busenberg, E., and Schlosser, P., 2000, Age of irrigation water in ground water from the eastern Snake River Plain aquifer, south-central Idaho: Ground Water, v. 38, no. 2, p. 264–283.

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

Prism Climate Group, 2015, 30-year normals: Northwest Alliance for Computational Science and Engineering, accessed September 10, 2015, at http://www.prism.oregonstate.edu/normals/.

Rattray, G.W., 2012, Evaluation of quality-control data collected by the U.S. Geological Survey for routine water-quality activities at the Idaho National Laboratory, southeastern Idaho, 1996–2001: U.S. Geological Survey Scientific Investigations Report 2012-5270 (DOE/ID-22222), 74 p., http://pubs.usgs.gov/sir/2012/5270/.

Rattray, G.W., 2014, Evaluation of quality-control data collected by the U.S. Geological Survey for routine water-quality activities at the Idaho National Laboratory, southeastern Idaho, 2002–2008: U.S. Geological Survey Scientific Investigations Report 2014-5027 (DOE/ID-22228), 65 p., http://pubs.usgs.gov/sir/2014/5027/.

Rattray, G.W., 2015, Geochemical evolution of groundwater in the Mud Lake area, eastern Idaho, USA: Environmental Earth Sciences, v. 73, no. 12, p. 8,251–8,269, http://link.springer.com/article/10.1007/s12665-014-3988-9/.

Rattray, G.W., and Ginsbach, M.L., 2014, Geochemistry of groundwater in the Beaver and Camas Creek drainage basins, eastern Idaho: U.S. Geological Survey Scientific Investigations Report 2013-5226 (DOE-ID-22227), 70 p., http://pubs.usgs.gov/sir/2013/5226/.

Reed, M.E., and Bartholomay, R.C., 1994, Mineralogy of selected sedimentary interbeds at or near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 94-374 (DOE/ID-22116), 19 p.

Reed, M.E., Bartholomay, R.C., and Hughes, S.S., 1997, Geochemistry and stratigraphic correlation of basalt lavas beneath the Idaho Chemical Processing Plant, Idaho National Engineering Laboratory: Environmental Geology, v. 30, p. 108–118.

Roback, R.C., Johnson, T.M., McLing, T.L., Murrell, M.T., Luo, Shangde, and Ku, The-Lung, 2001, Uranium isotopic evidence for groundwater chemical evolution and flow patterns in the eastern Snake River Plain aquifer, Idaho: Geological Society of America, GSA Bulletin, v. 113, no. 9, p. 1,133–1,141, http://gsabulletin.gsapubs.org/content/113/9/1133.full.pdf+html.

Roberson, C.E., and Schoen, Robert, 1973, Fluorite equilibria in thermal springs of the Snake River Basin, Idaho: Journal of Research of the U.S. Geological Survey, v. 1, no. 3, p. 367–370.

Robertson, J.B., Schoen, Robert, and Barraclough, J.T., 1974, The influence of liquid waste disposal on the geochemistry of water at the National Reactor Testing Station, Idaho—1952–1970: U.S. Geological Survey Open-File Report (IDO-22053), 231 p., http://pubs.er.usgs.gov/publication/ofr73238.

Rupert, M.G., 1996, Major sources of nitrogen input and loss in the upper Snake River Basin, Idaho and Western Wyoming, 1990: U.S. Geological Survey Water-Resources Investigations Report 96-4008, 15 p.

Sanford, W.E., Plummer, L.N., McAda, D.P., Bexfield, L.M., Anderholm, S.K., 2003, Hydrochemical tracers in the Middle Rio Grande Basin, USA—2. Calibration of a groundwater model: Hydrogeology Journal, v. 12, p. 389–407.

Sanford, W.E., Plummer, L.N., McAda, D.P., Bexfield, L.M., Anderholm, S.K., 2004, Use of environmental tracers to estimate parameters for a predevelopment ground-water-flow model of the Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Water Resources Investigations Report 03-4286, 102 p.

Schoen, Robert, 1972, Hydrochemical study of the National Reactor Testing Station, Idaho: 24th International Geological Congress conference, Montreal, Canada, p. 306–314.

Schramke, J.A., Murphy, E.M., and Wood, B.D., 1996, The use of geochemical mass-balance and mixing models to determine groundwater sources: Applied Geochemistry, v. 11, p. 523–539, http://www.sciencedirect.com/science/article/pii/0883292796000078.

Shakhashiri, B.Z., 2015, Chemical of the week—Agricultural fertilizers—Nitrogen, potassium, and phosphorous: accessed October 5, 2015, at http://scifun.chem.wisc.edu/chemweek/pdf/Agricultural_Fertilizers.pdf.

Sibson, Robin, 1981, A brief description of natural neighbor interpolation, *in* V. Barnett, ed., Interpolating Multivariate Data: New York, John Wiley and Sons, p. 21–36.

Skipp, Betty, Hoggan, R.D., Schleicher, D.L., and Douglass, R.C., 1979, Upper Paleozoic carbonate bank in east-central Idaho—Snaky Canyon, Bluebird Mountain, and Arco Hills Formations, and their paleotectonic significance: U.S. Geological Survey Bulletin 1486, 78 p.

Solomon, D.K., 2000, ^{4}He in groundwater, *in* Cook, P.G., and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Massachusetts, Kluwer Academic Publishers, p. 425–439.

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

Solomon, D.K., Hunt, A., and Poreda, R.J., 1996, Source of radiogenic helium 4 in shallow aquifers—Implications for dating young groundwater: Water Resources Research, v. 32, no. 6, p. 1,805–1,813.

Sorenson, K.S., Jr., Wylie, A.H., and Wood, T.R., 1996, Test Area North site conceptual model and proposed hydrogeologic studies—Operable Unit 1-07B: Prepared for Lockheed Idaho Technologies and U.S. Department of Energy by Parsons Engineering Science, Inc., INEL-96-0105, [variously paged], http://pbadupws.nrc.gov/docs/ML0609/ML060960436.pdf.

Spinazola, J.M., 1994, Geohydrology and simulation of flow and water levels in the aquifer system in the Mud Lake area of the eastern Snake River Plain, eastern Idaho: U.S. Geological Survey Water-Resource Investigations Report 93-4227, 78 p., http://pubs.er.usgs.gov/publication/ofr73238.

Stearns, H.T., Bryan, L.L., and Crandall, Lynn, 1939, Geology and water resources of the Mud Lake region, Idaho: U.S. Geological Survey Water-Supply Paper 818, 125 p.

Stute, M, Sonntag, C., Deák, J., and Schlosser, P., 1992, Helium in deep circulating groundwater in the Great Hungarian Plain—Flow dynamics and crustal and mantle helium fluxes: Geochimica et Cosmochimica Acta, v. 56, p. 2,051–2,067.

Swanson, S.A., Rosentreter, J.J., Bartholomay, R.C., and Knobel, L.L., 2002, Geochemistry of the Little Lost River drainage basin, Idaho: U.S. Geological Survey Water-Resources Investigations Report 02-4120 (DOE-ID22179), 29 p., http://pubs.er.usgs.gov/publication/wri024120.

Swanson, S.A., Rosentreter, J.J., Bartholomay, R.C., and Knobel, L.L., 2003, Geochemistry of the Birch Creek drainage basin, Idaho: U.S. Geological Survey Water-Resources Investigations Report 03-4272 (DOE-ID22188), 36 p., http://pubs.er.usgs.gov/publication/wri034272.

Thorstenson, D.C., Fisher, D.W., and Croft, M.G., 1979, The geochemistry of the Fox Hills-Basal Hell Creek aquifer in southwestern North Dakota and northwestern South Dakota: Water Resources Research, v. 15, no. 6, p. 1,479–1,497.

Troldborg, Lars, Refsgaard, J.C., Jensen, K.H., and Engesgaard, Peter, 2007, The importance of alternative conceptual models for simulation of concentrations in a multi-aquifer system: Hydrogeology Journal, v. 15, p. 843–860.

Uliana, M.M., and Sharp Jr., J.M., 2001, Tracing regional flow paths to major springs in Trans-Pecos Texas using geochemical data and geochemical models: Chemical Geology, v. 179, p. 53–72.

U.S. Department of Energy, 2011, Idaho National Laboratory groundwater monitoring and contingency plan update: U.S. Department of Energy, DOE/ID-11034, revision 2, [variously paged].

U.S. Department of Energy, 2016, Five-year review of CERCLA response actions at the Naval Reactors Facility: U.S. Department of Energy, NRLFO:IBO-16/401, [variously paged].

U.S. Geological Survey, 2014, National Water Information System: U.S. Geological Survey database, accessed July 31, 2014, at http://waterdata.usgs.gov/nwis.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, accessed September 1, 2015, at http://water.usgs.gov/owq/FieldManual/.

Welhan, J.A., Clemo, T.M., and Gego, E.L., 2002, Stochastic simulation of aquifer heterogeneity in a layered basalt aquifer system, eastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colo., Geological Society of America Special Paper 353, p. 225–247.

Welhan, J.A., Johannesen, C.M., Reeves, K.S., Clemo, T.M., Glover, J.A., and Bosworth, K.W., 2002, Morphology of inflated pahoehoe lavas and spatial architecture of their porous and permeable zones, eastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colo., Geological Society of America Special Paper 353, p. 135–150.

Weyhenmeyer, C.E., Burns, S.J., Waber, H.N., Macumber, P.G., and Matter, Albert, 2002, Isotope study of moisture sources, recharge areas, and groundwater flow paths within the eastern Batinah coastal plain, Sultanate of Oman: Water Resources Research, v. 38, no. 10, p. 2–1 to 2–22.

Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-B, 32 p., 6 pl., http://pubs.er.usgs.gov/publication/pp1408B.

Witkind, I.J., 1980, Preliminary geologic map of the Centennial Mountains Wilderness Study Area, including the Centennial Mountains Instant Study Area (BLM), Beaverhead County, Montana, and Clark and Fremont Counties, Idaho: U.S. Geological Survey Miscellaneous Investigations Map I-890, scale 1:62,500.

Wood, W.W., and Low, W.H., 1988, Solute geochemistry of the Snake River Plain regional aquifer system Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-D, 79 p.

Young, H.W., and Norvitch, R.F., 1984, Ground-water-level trends in Idaho, 1971–82: U.S. Geological Survey Water-Resources Investigations Report 83-4245, 28 p.

Figures 27–28

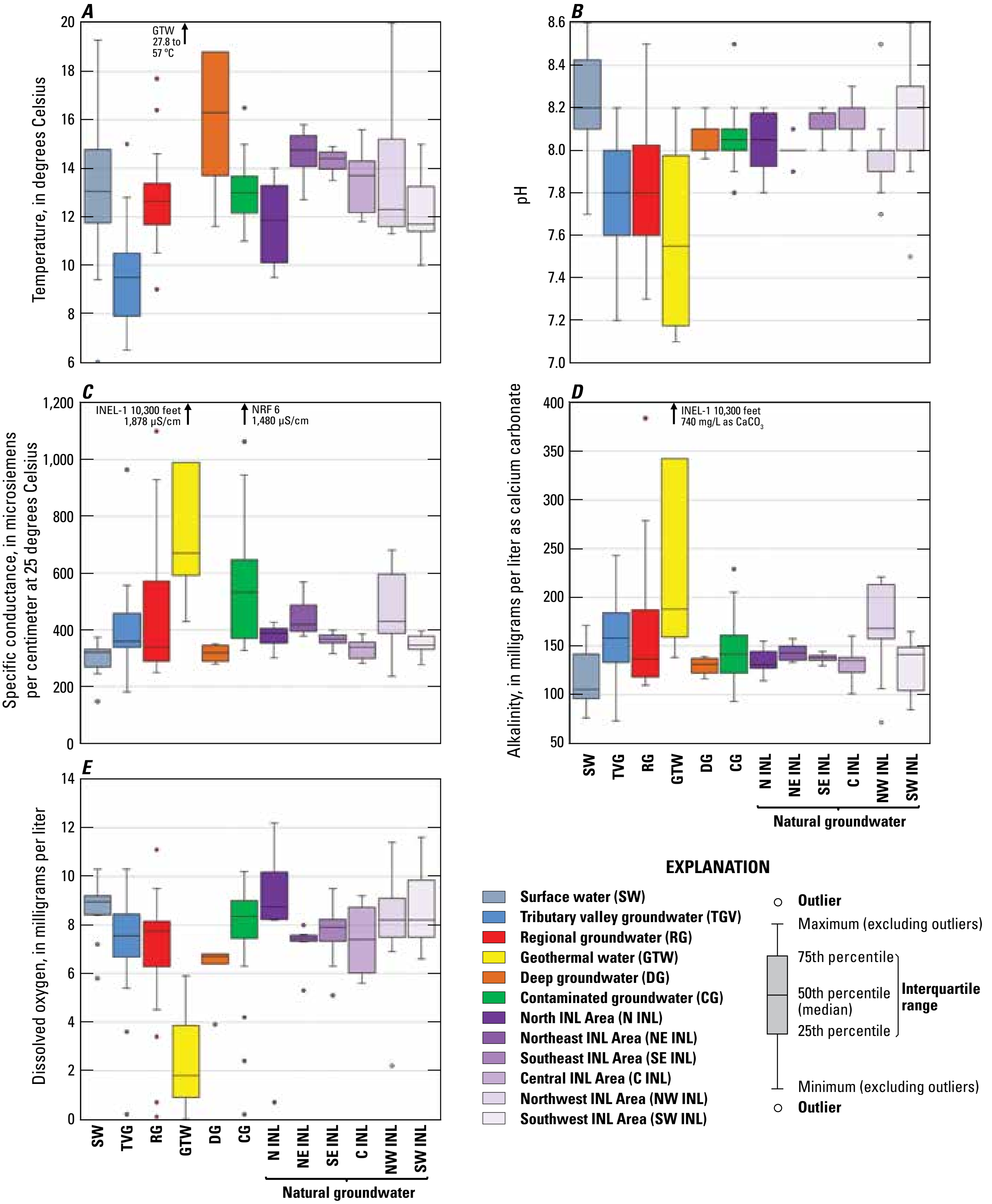


Figure 27. Statistical distribution of chemical and isotopic constituents in surface water and groundwater, Idaho National Laboratory and vicinity, eastern Idaho.

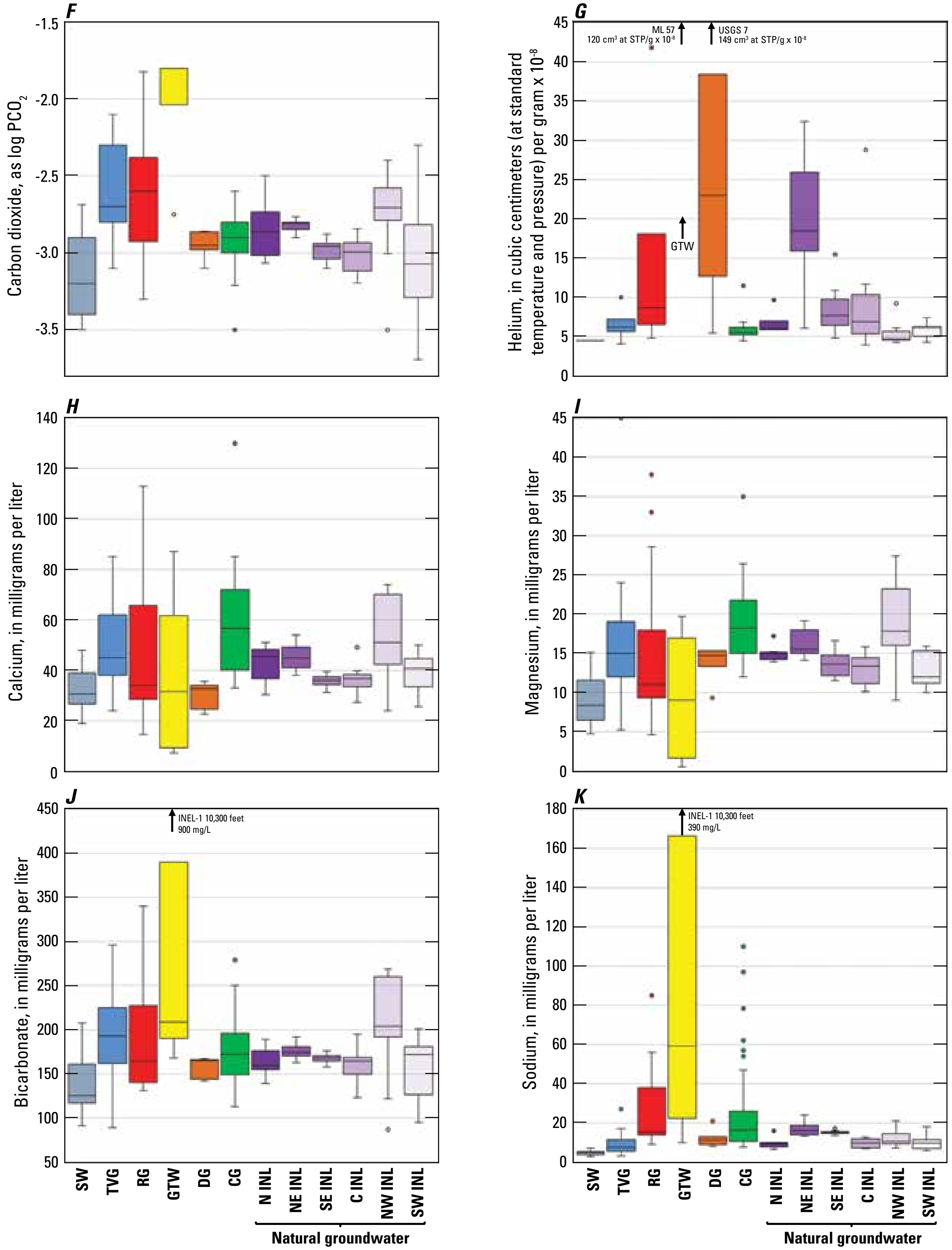


Figure 27.—Continued

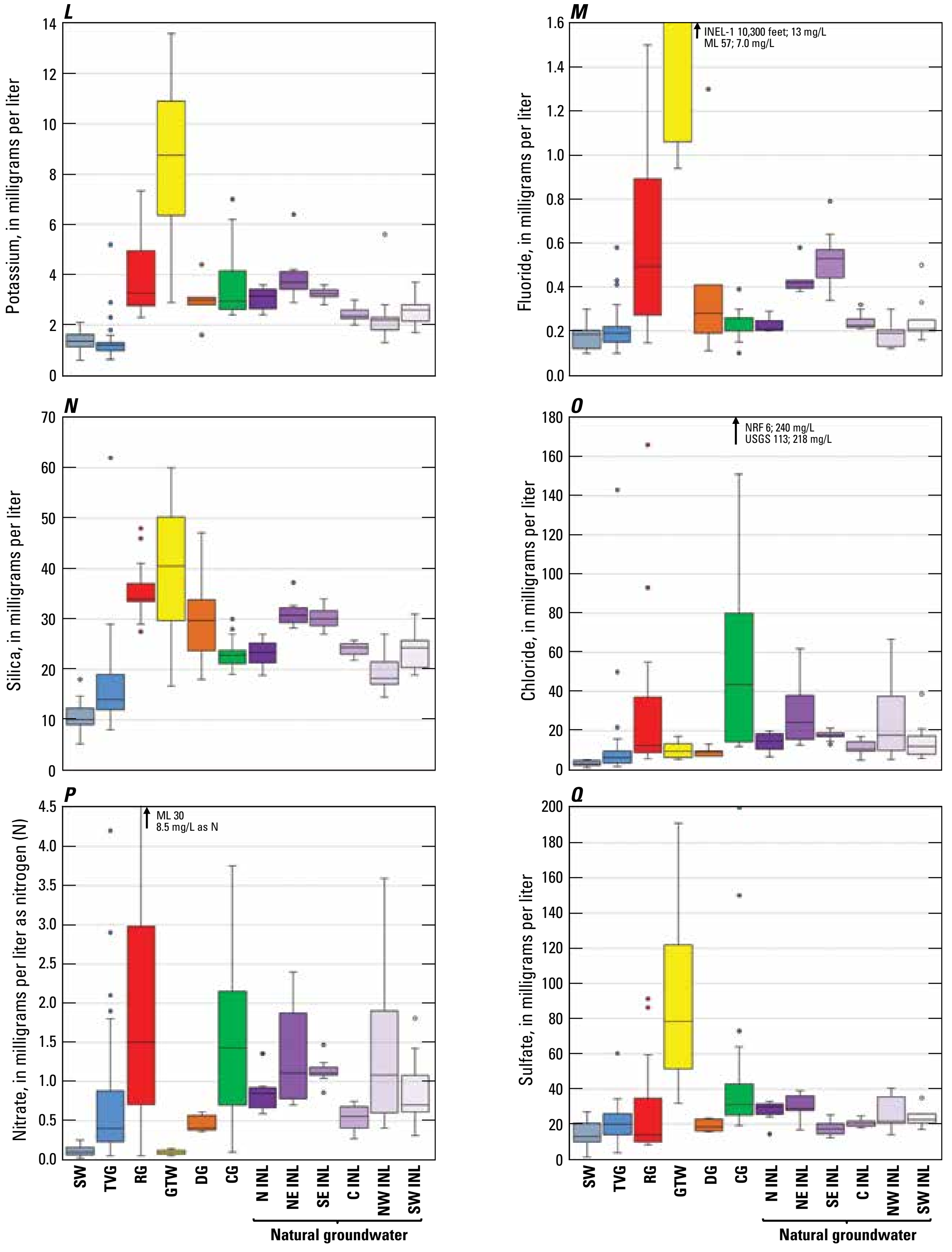


Figure 27.—Continued

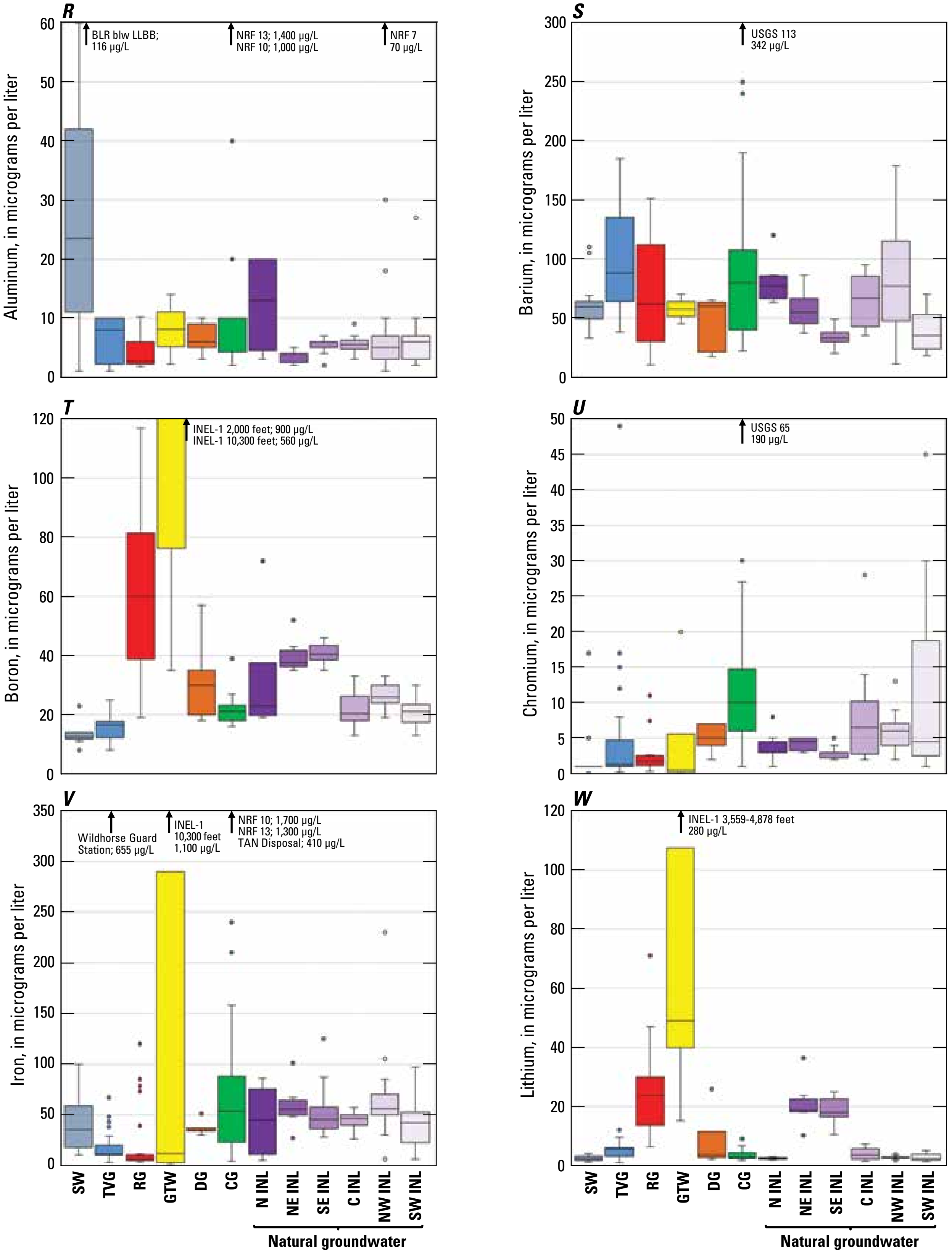


Figure 27.—Continued

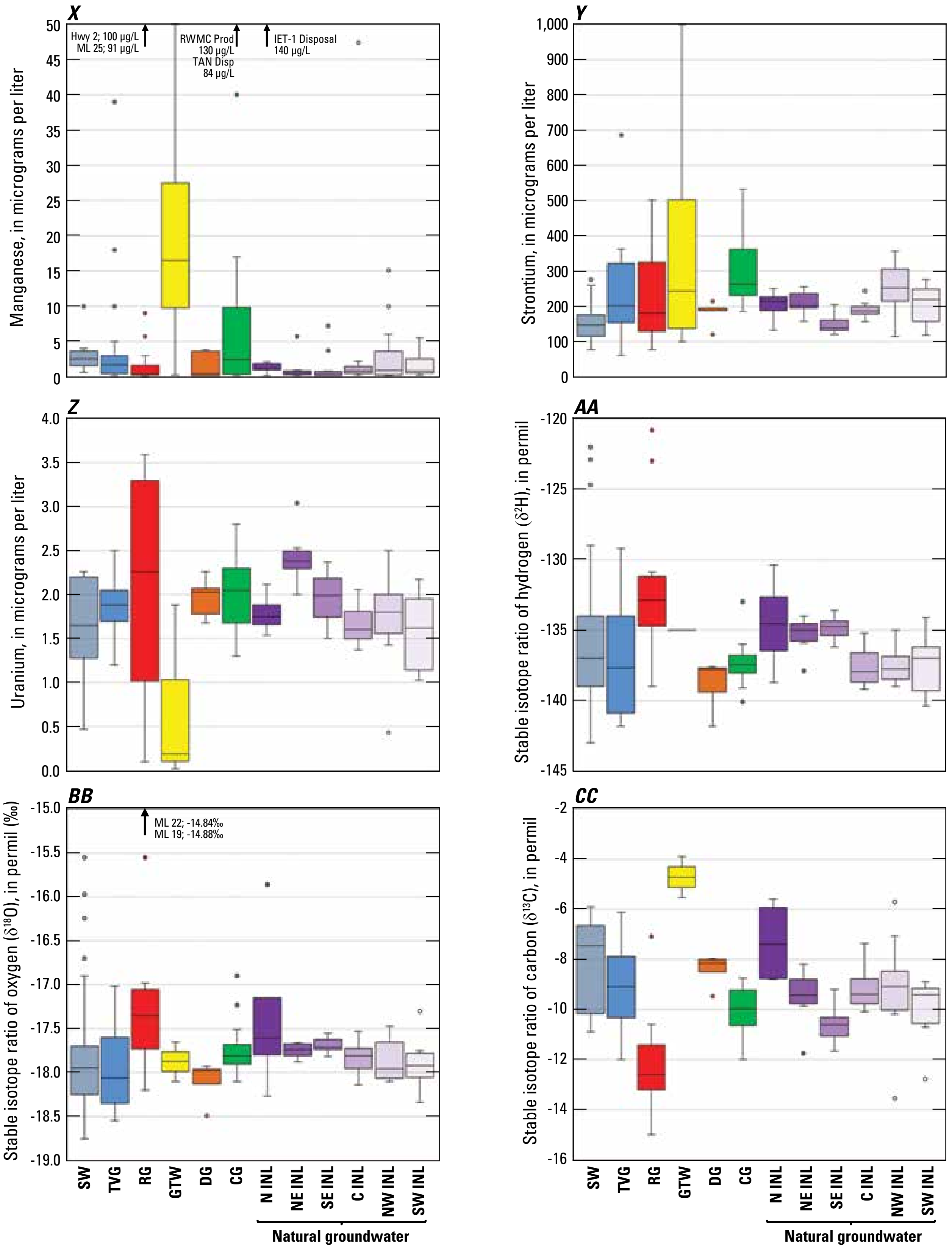


Figure 27.—Continued

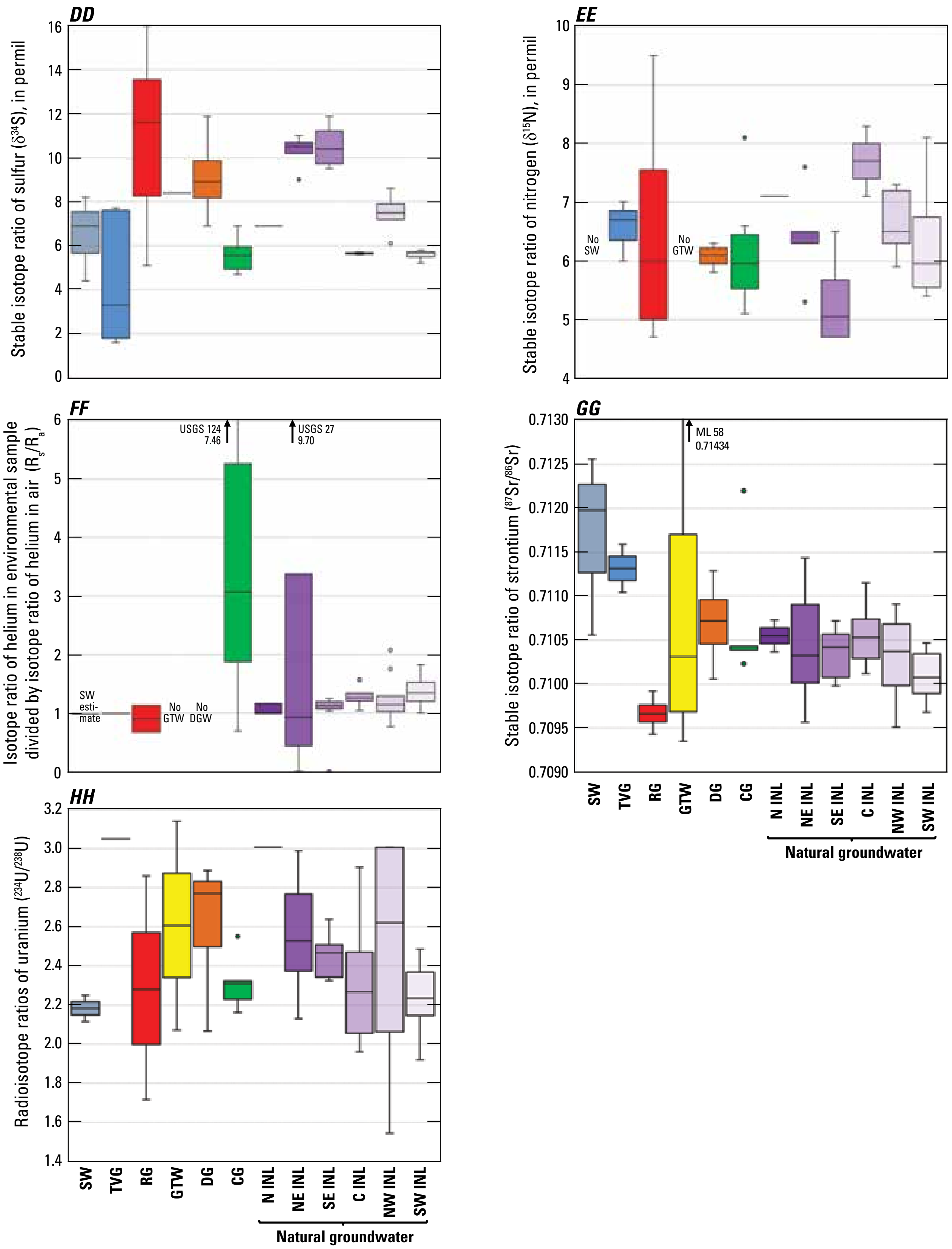


Figure 27.—Continued

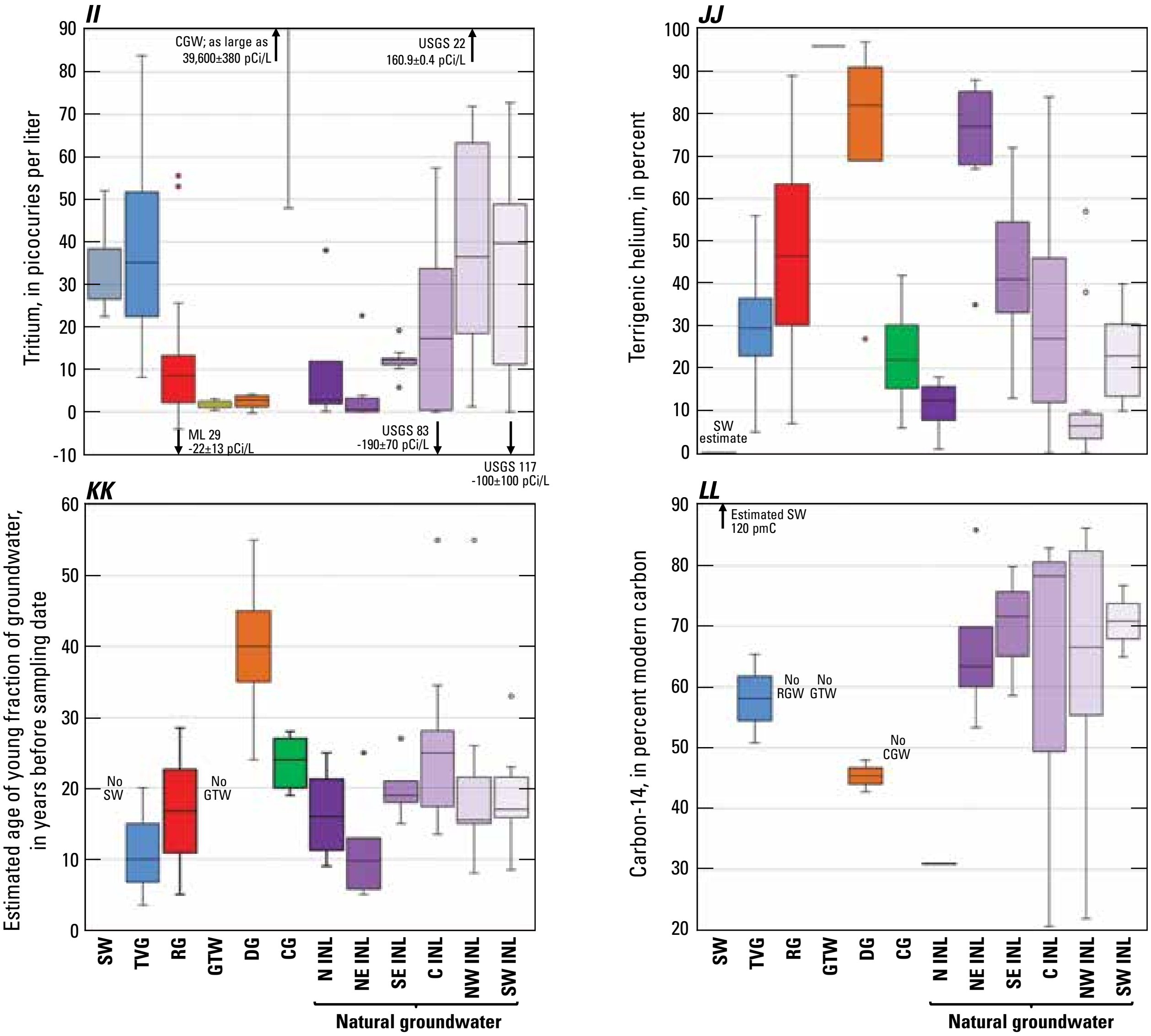
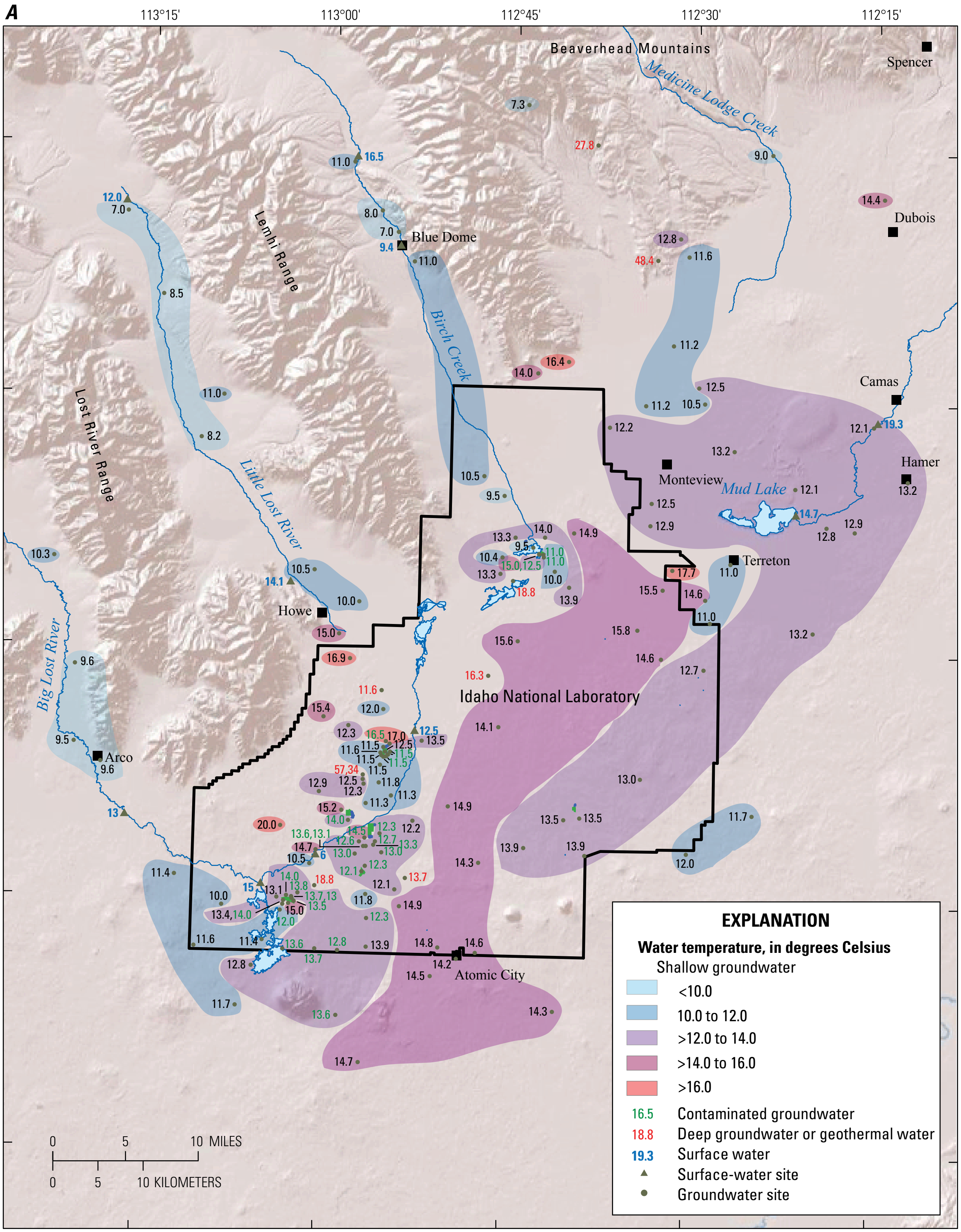
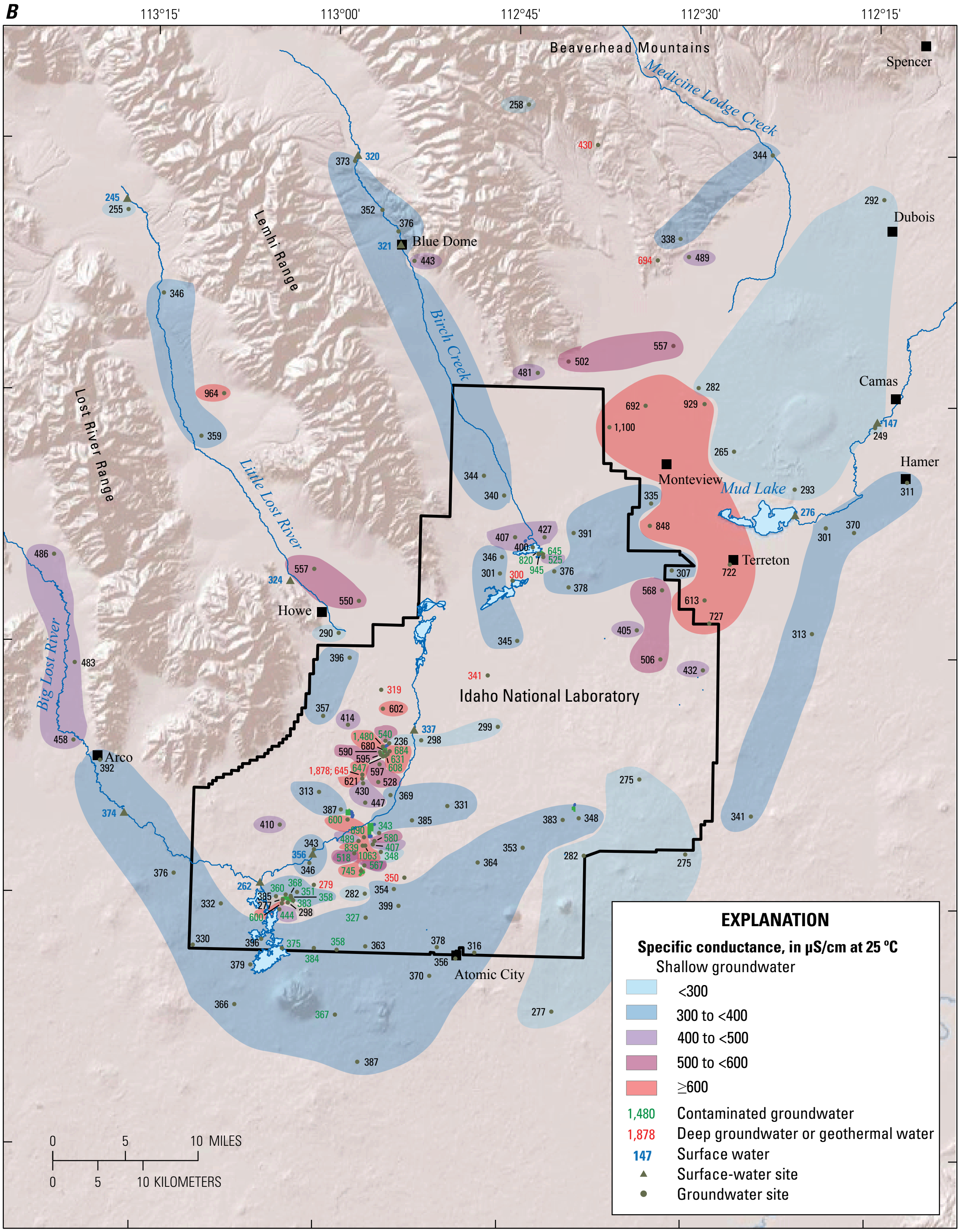


Figure 27.—Continued



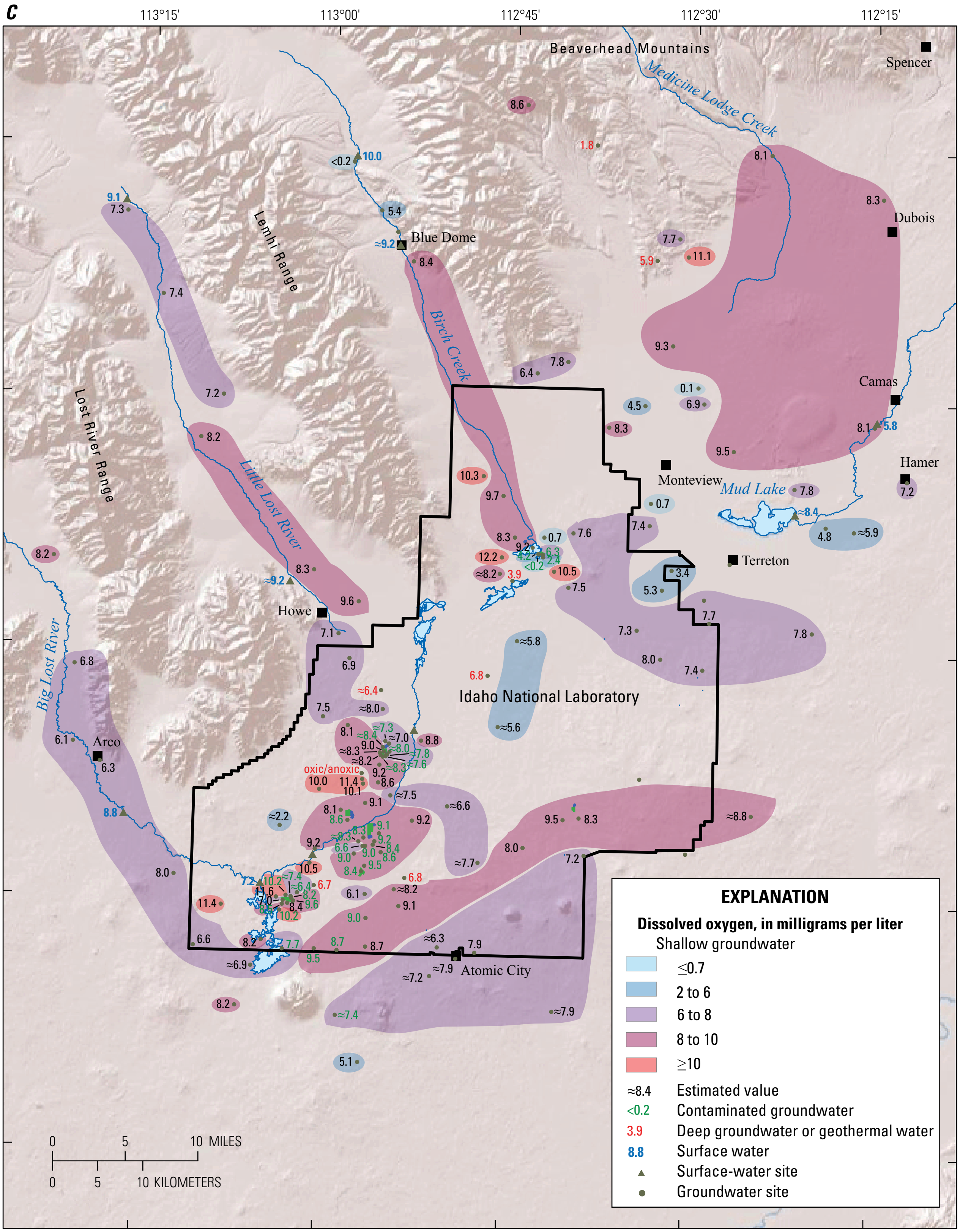
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28. Geographic distribution of selected chemical and isotopic constituents in surface water and groundwater, Idaho National Laboratory and vicinity eastern Idaho.



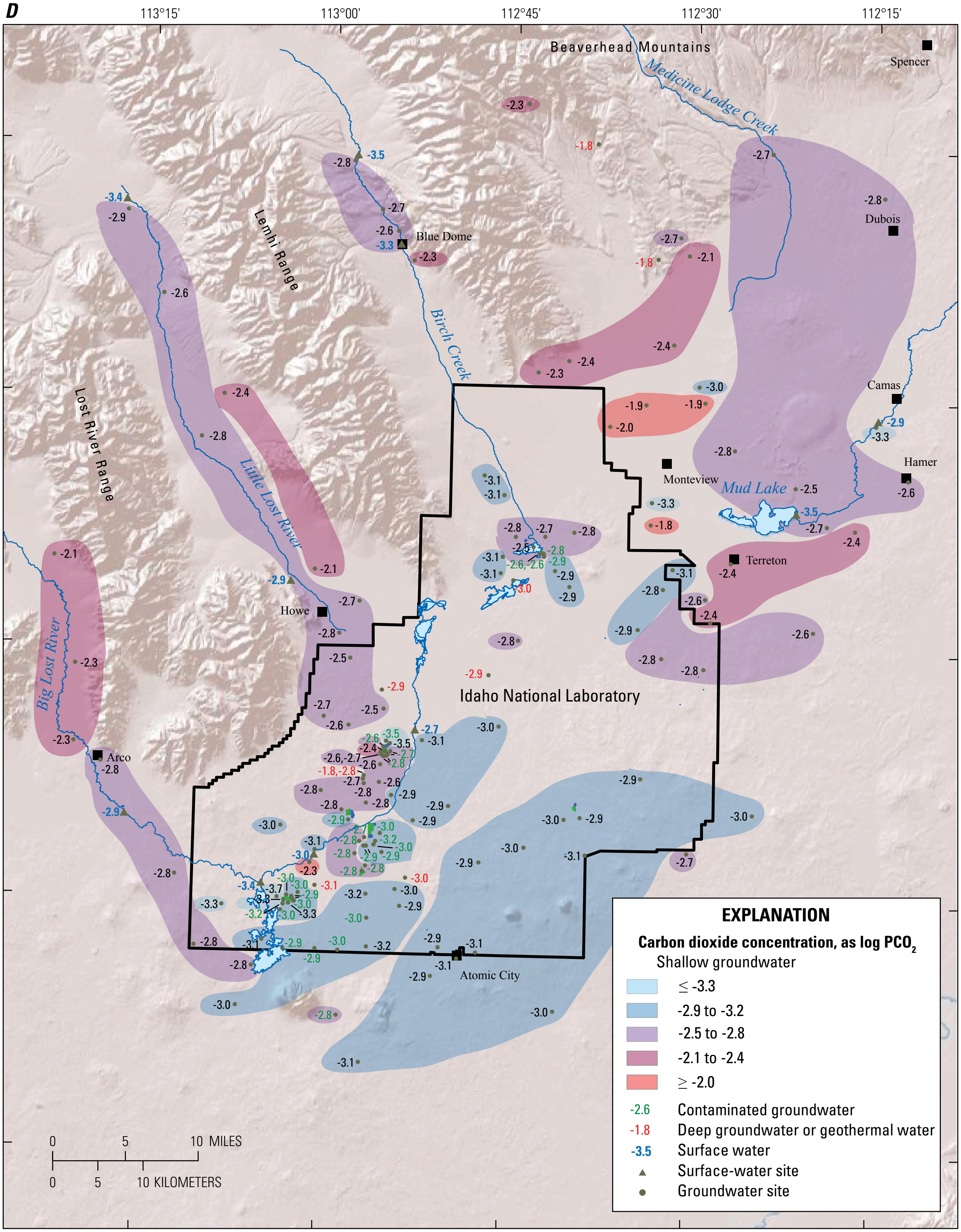
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



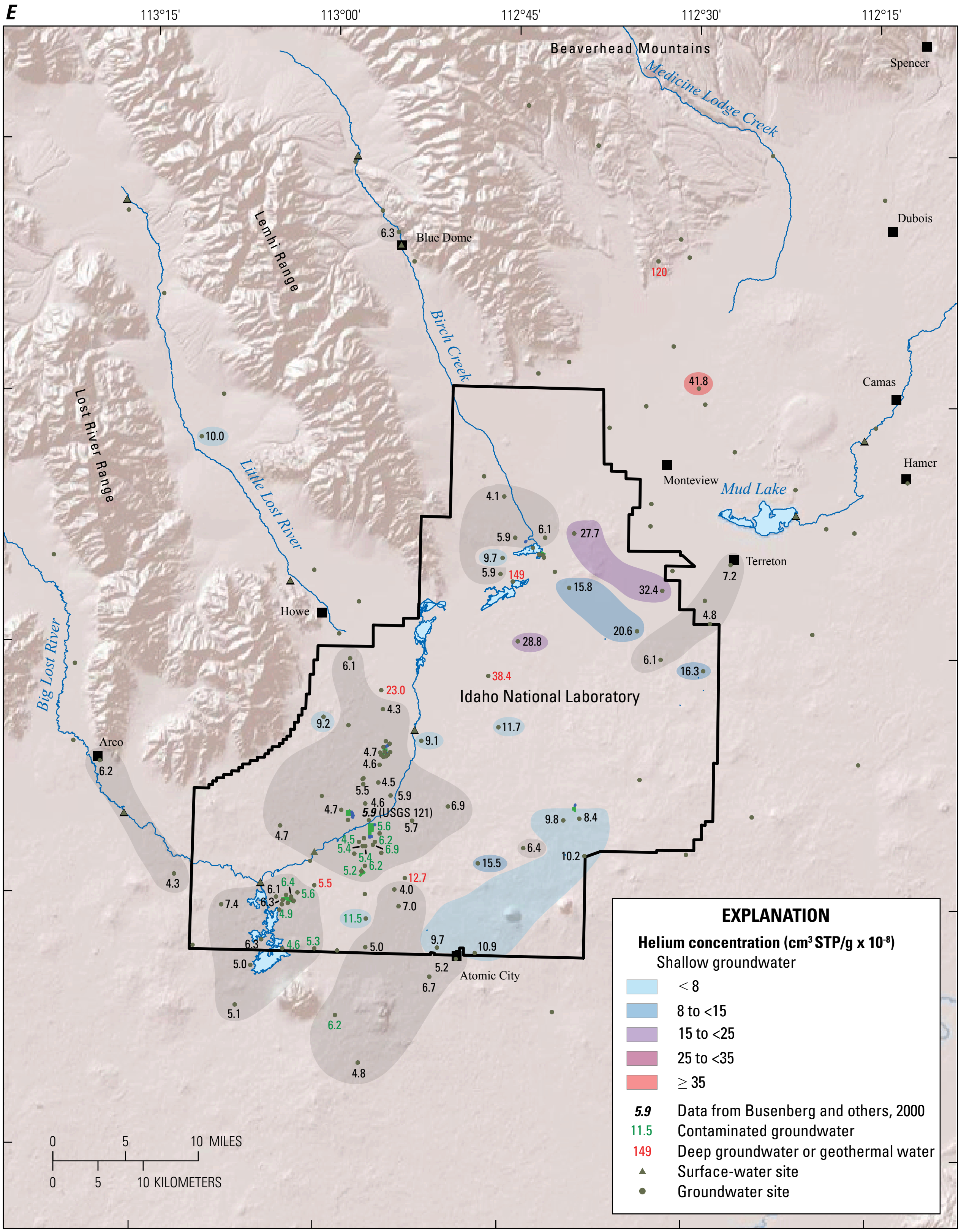
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



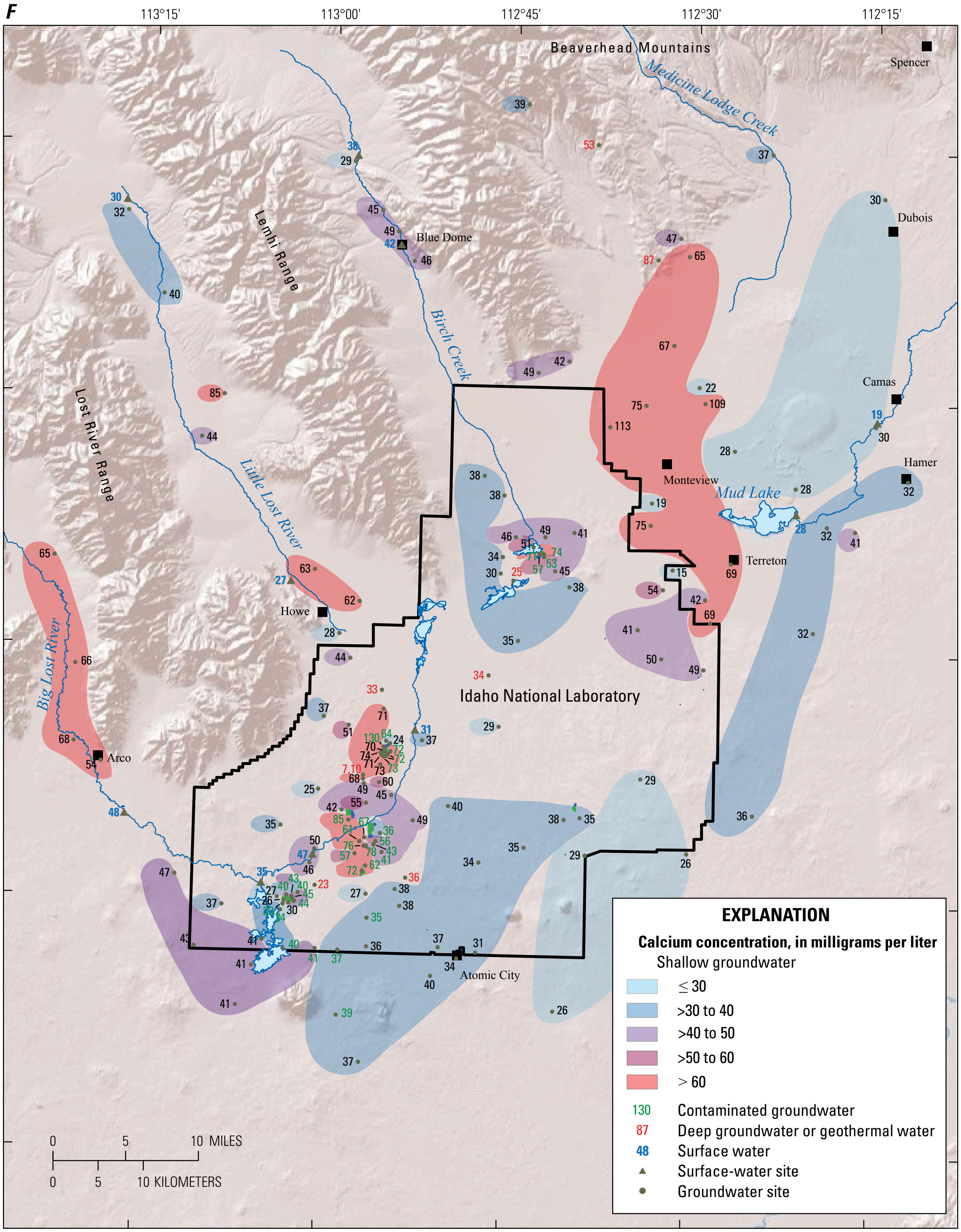
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



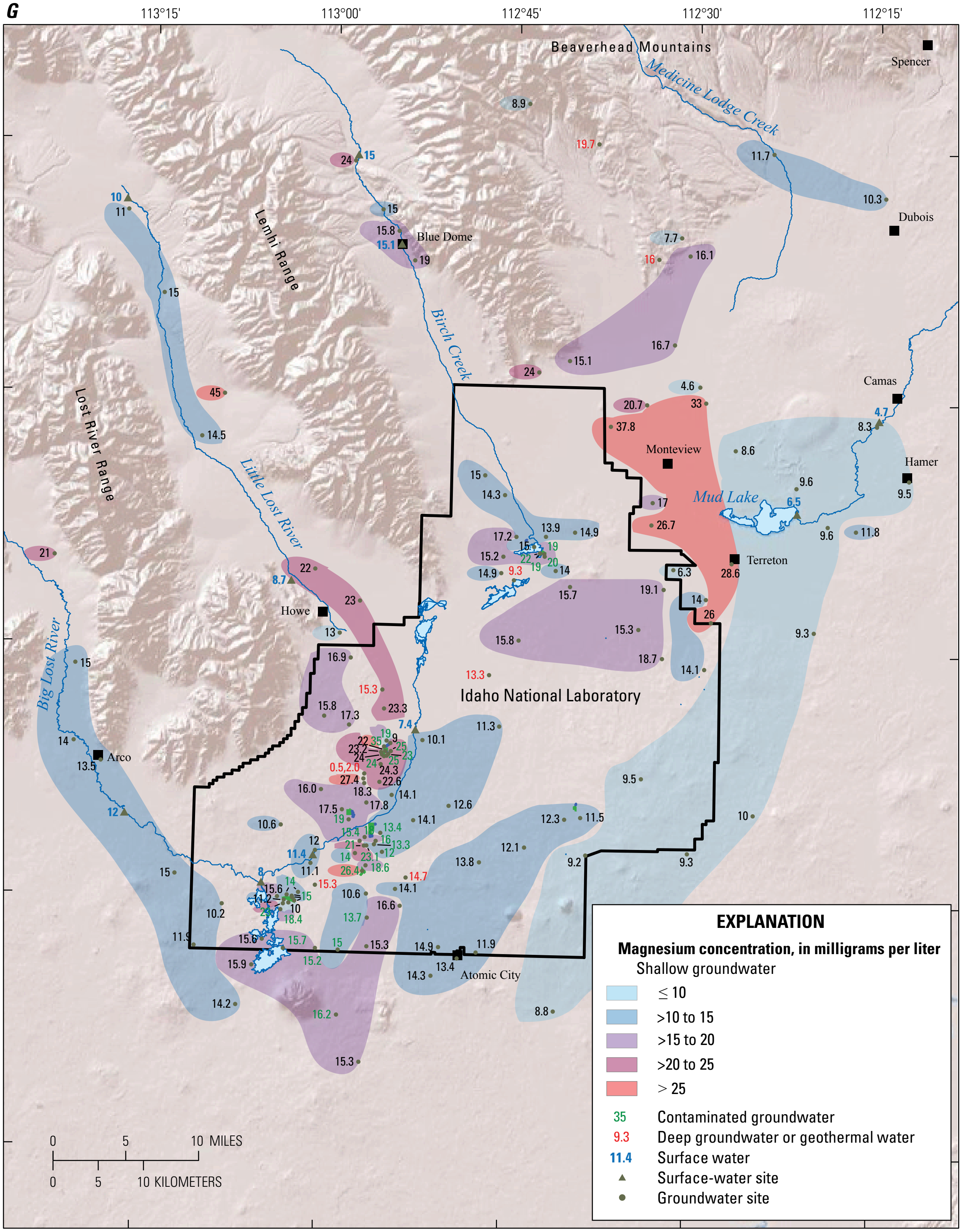
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



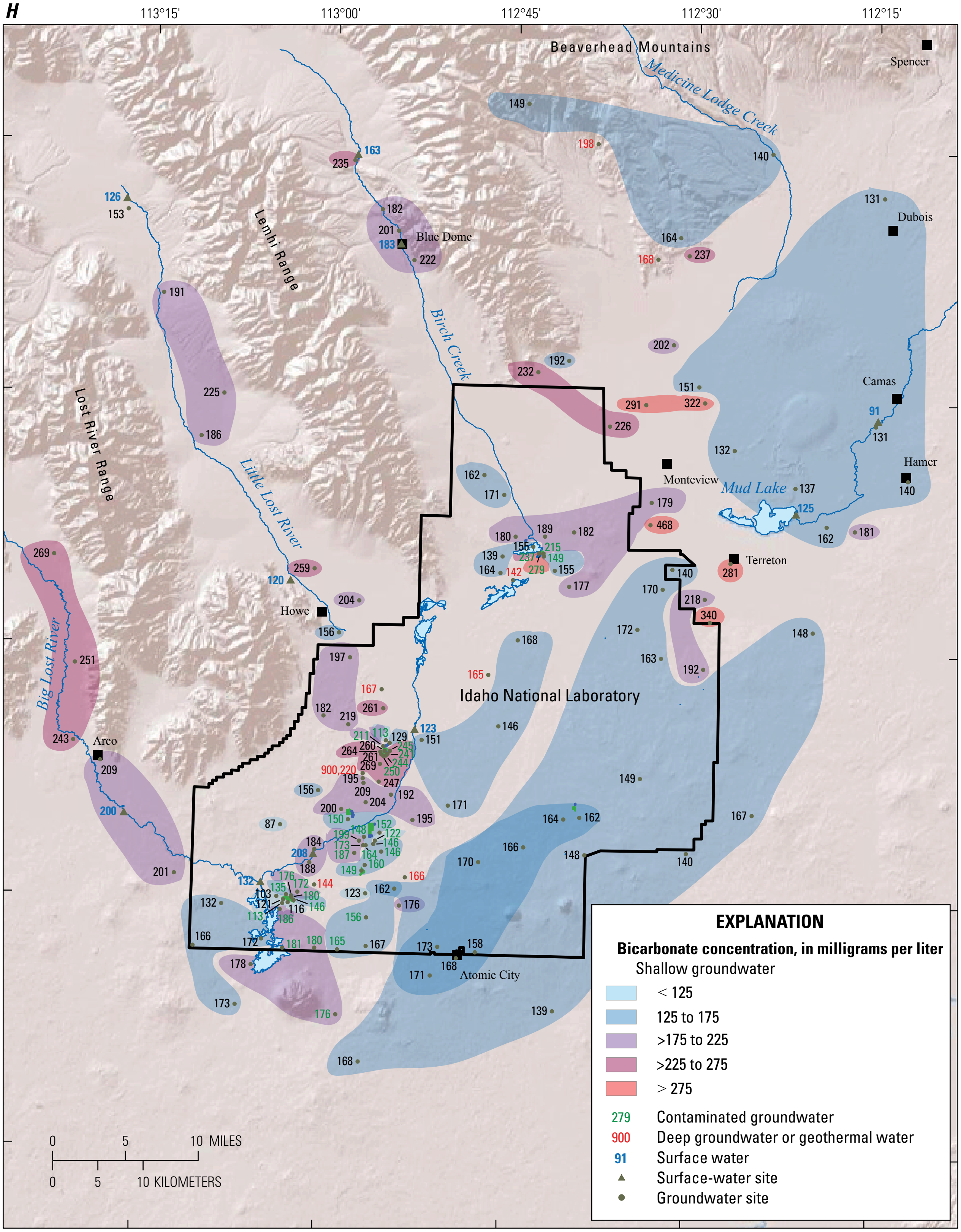
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



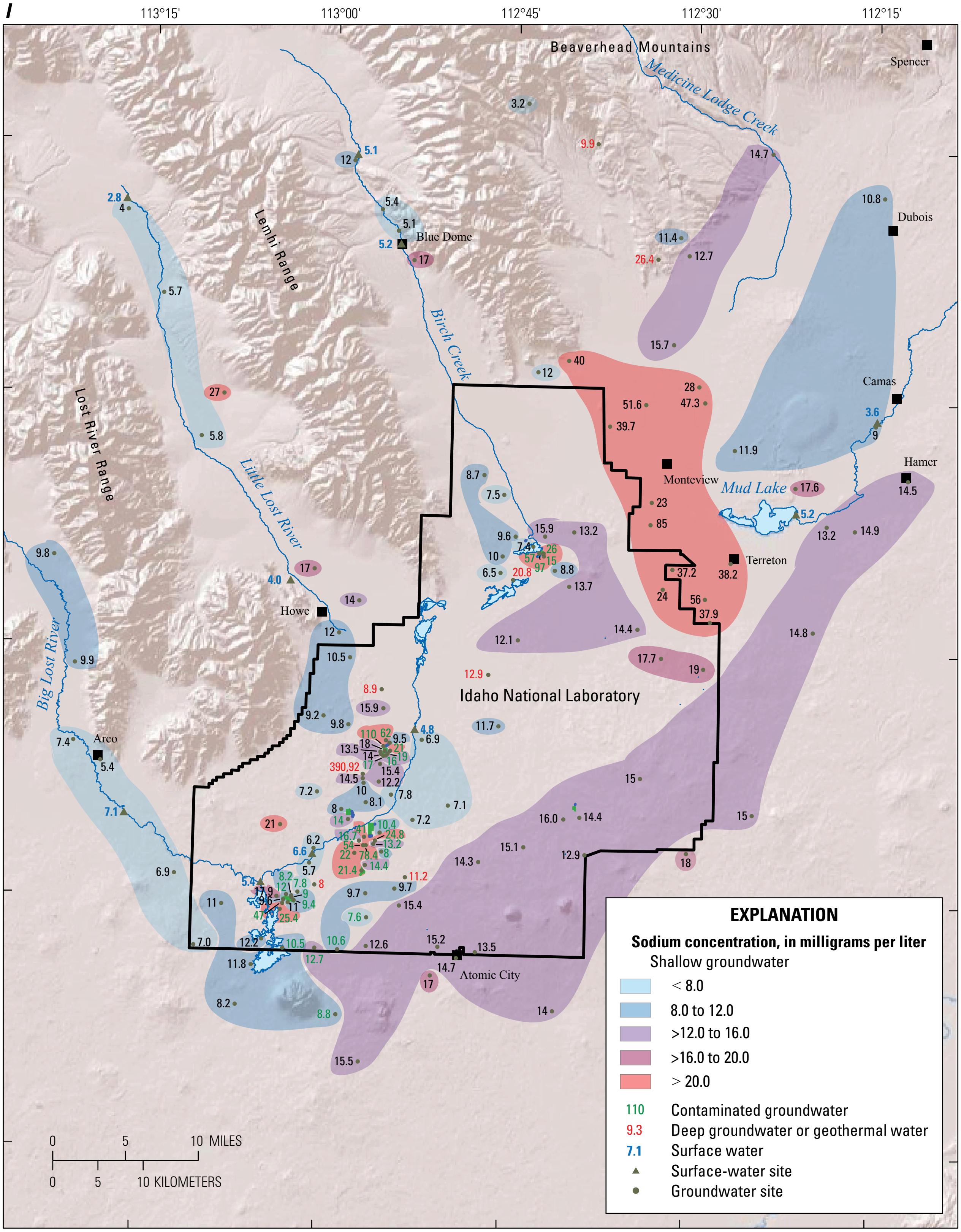
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



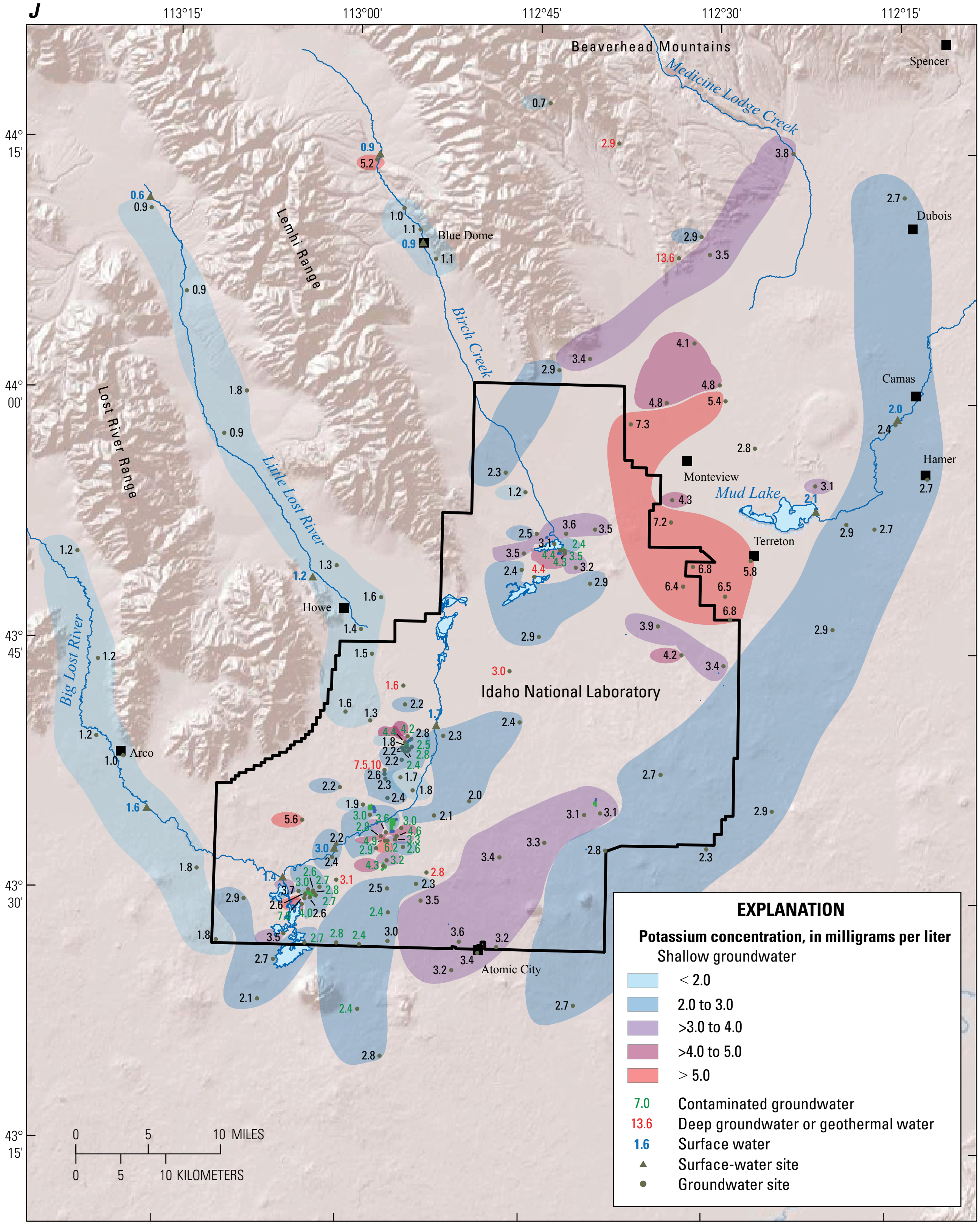
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



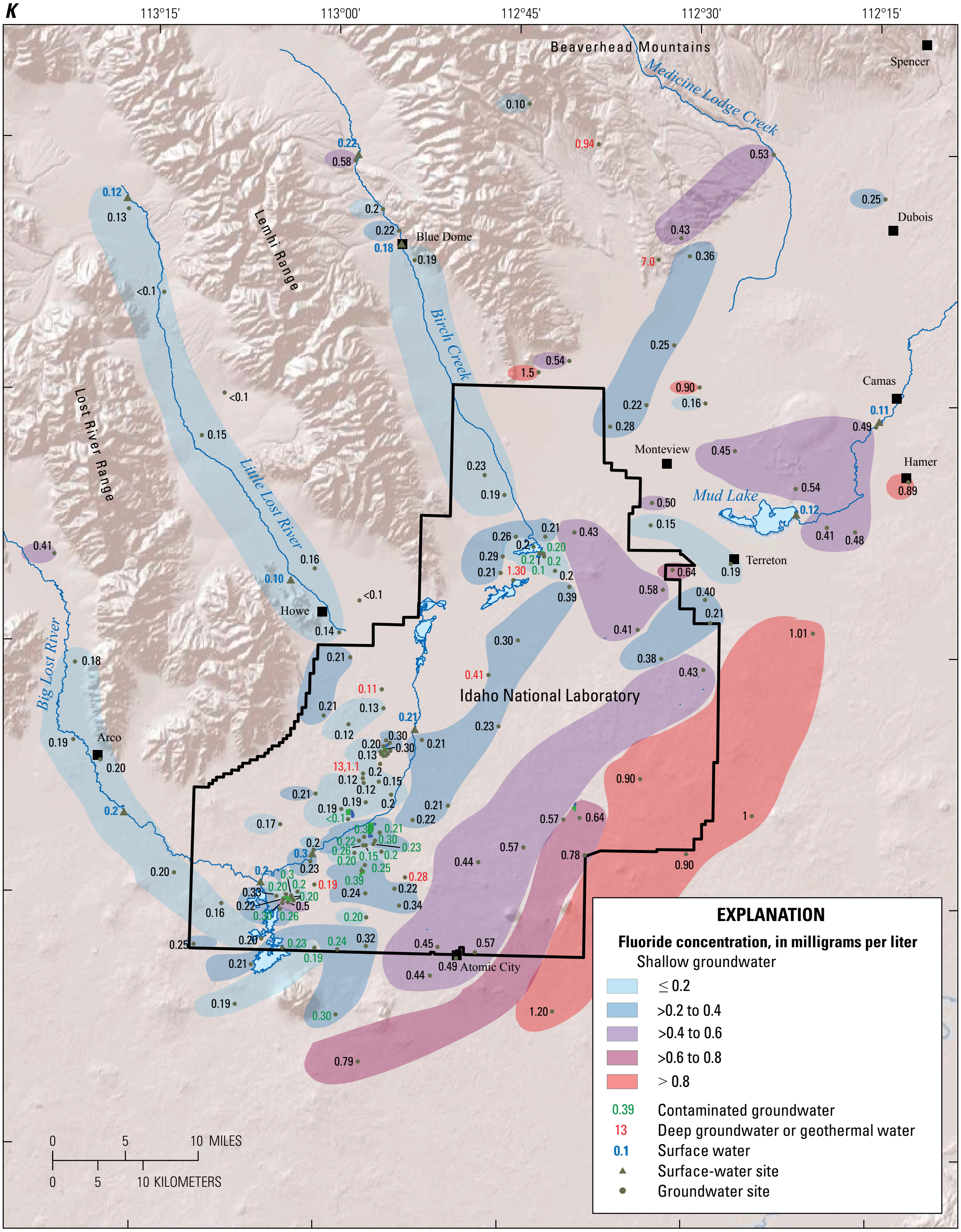
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



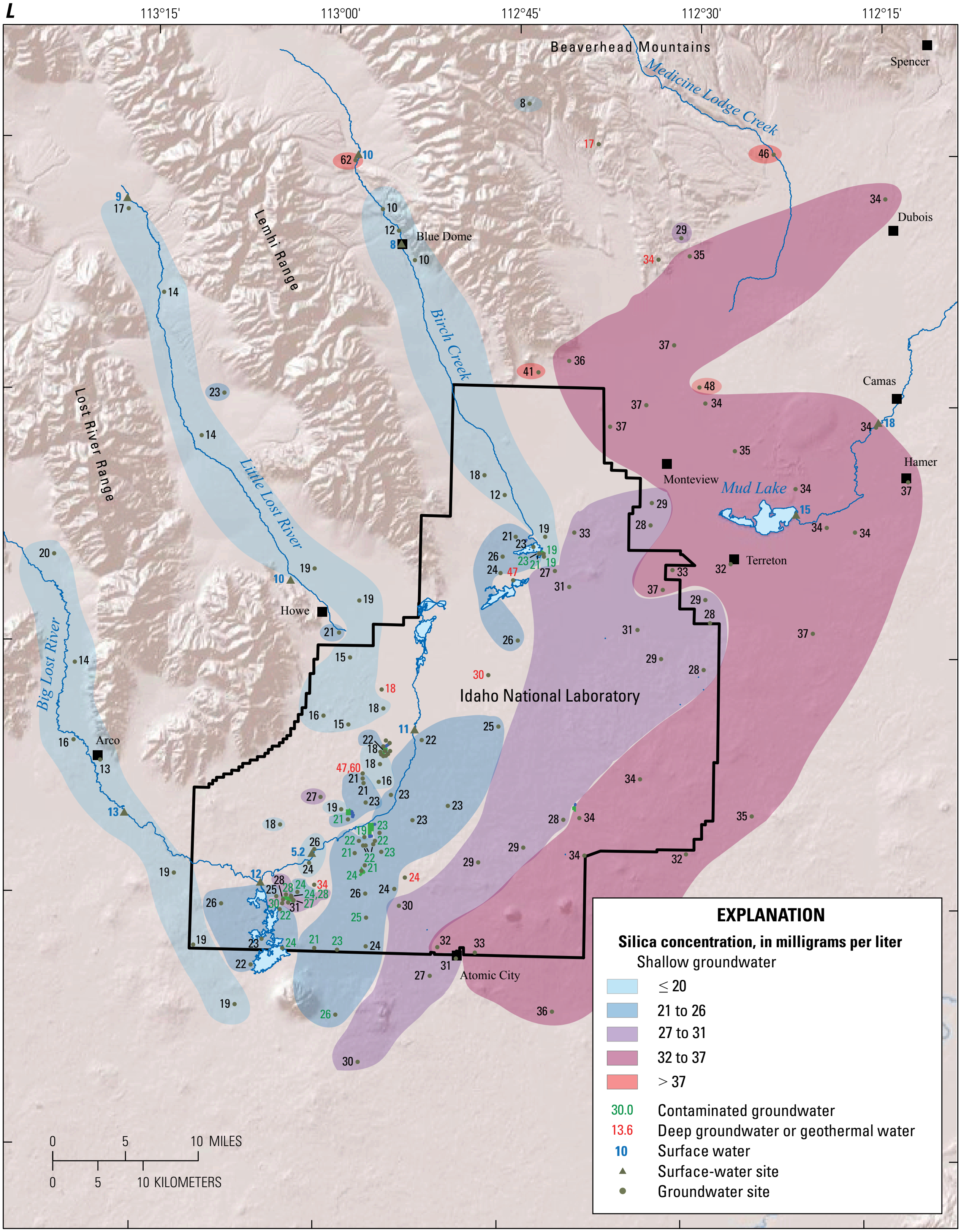
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



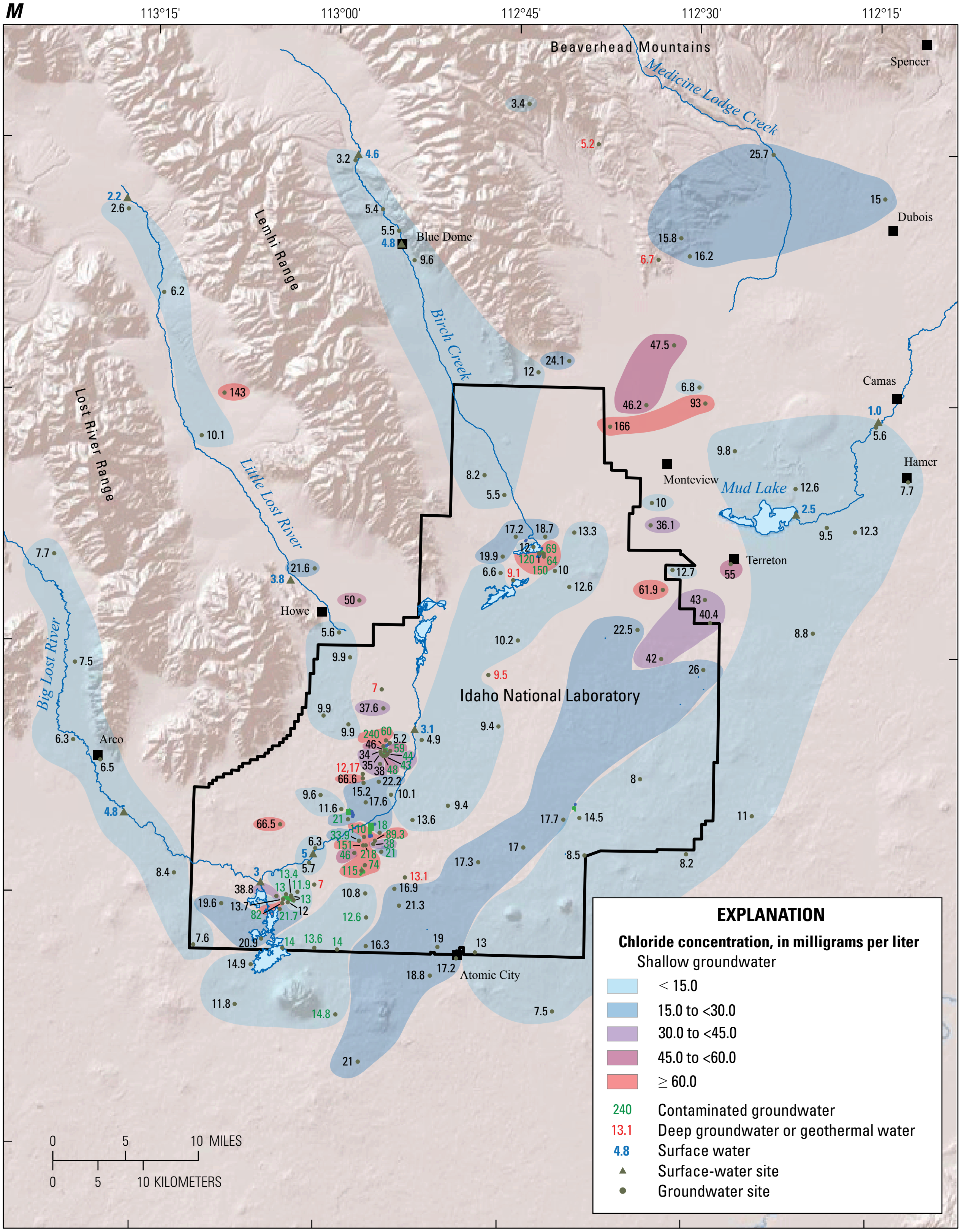
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



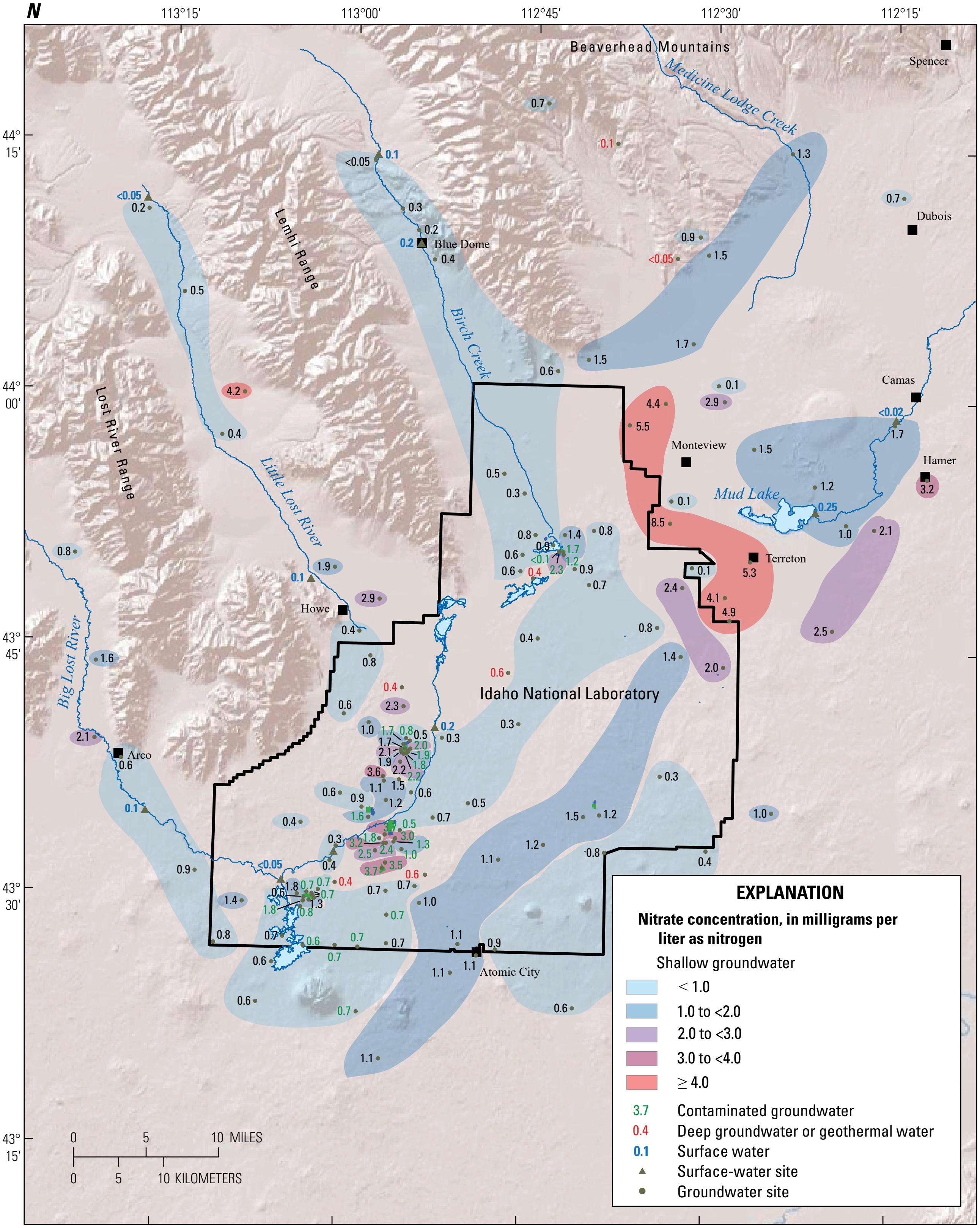
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



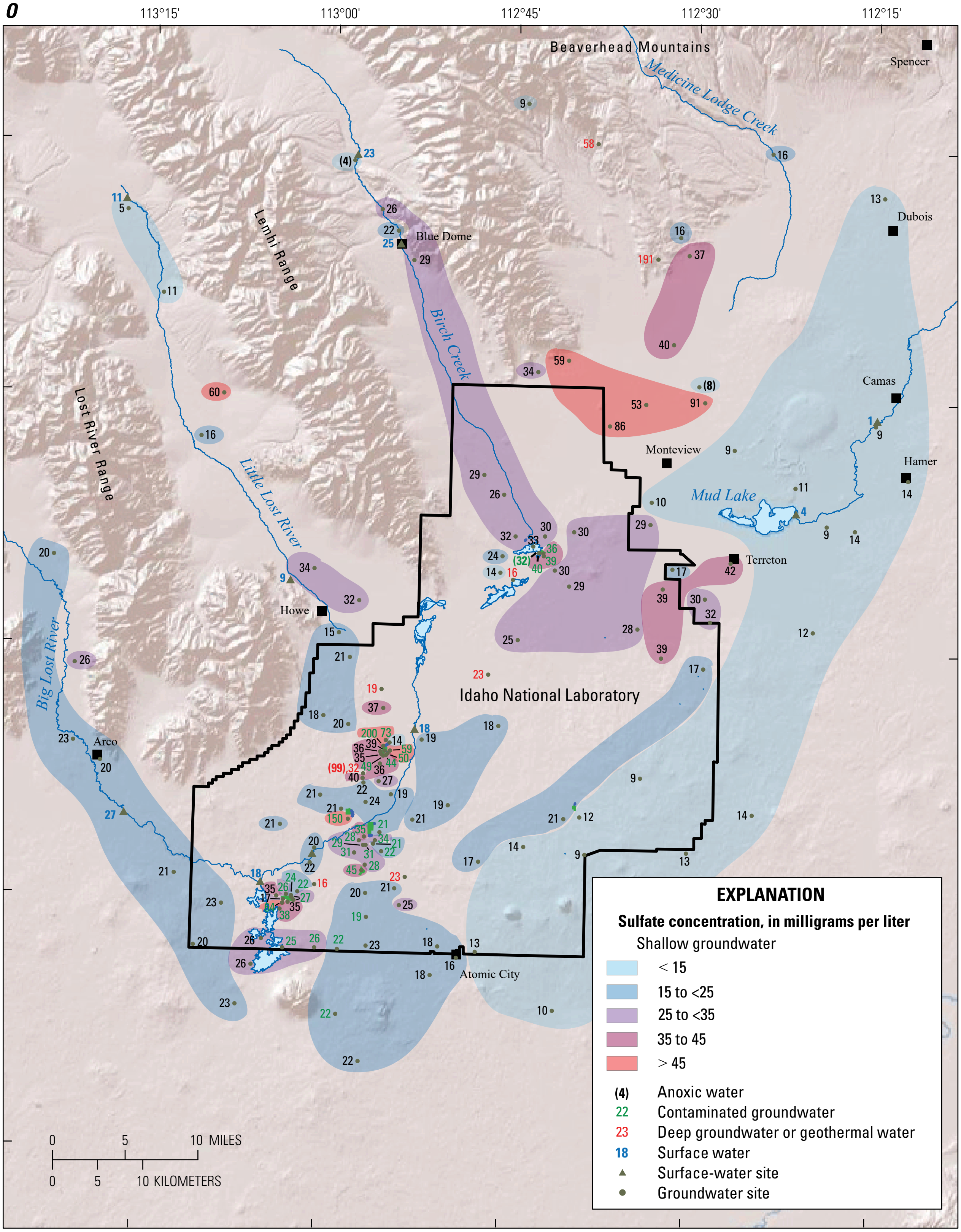
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



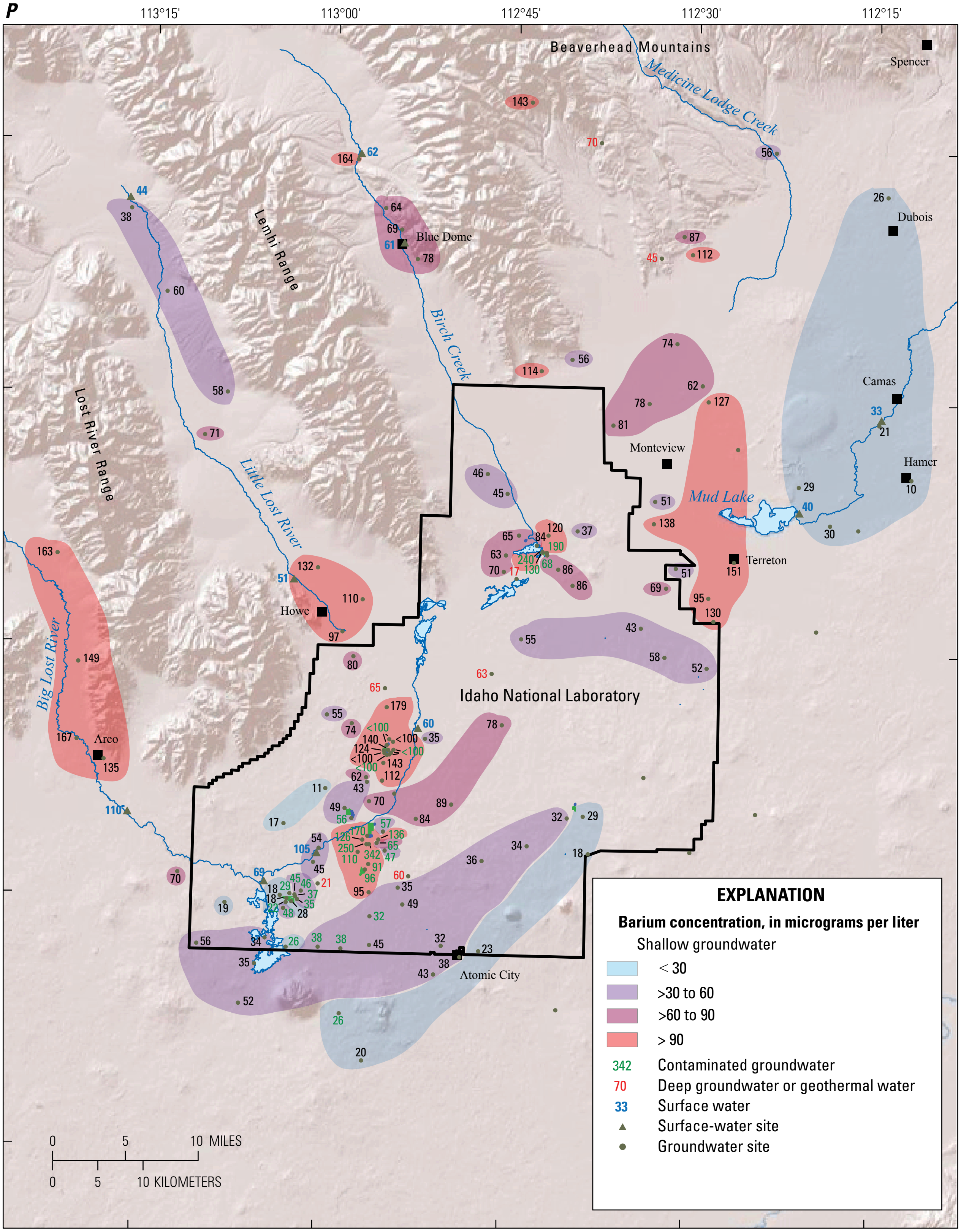
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



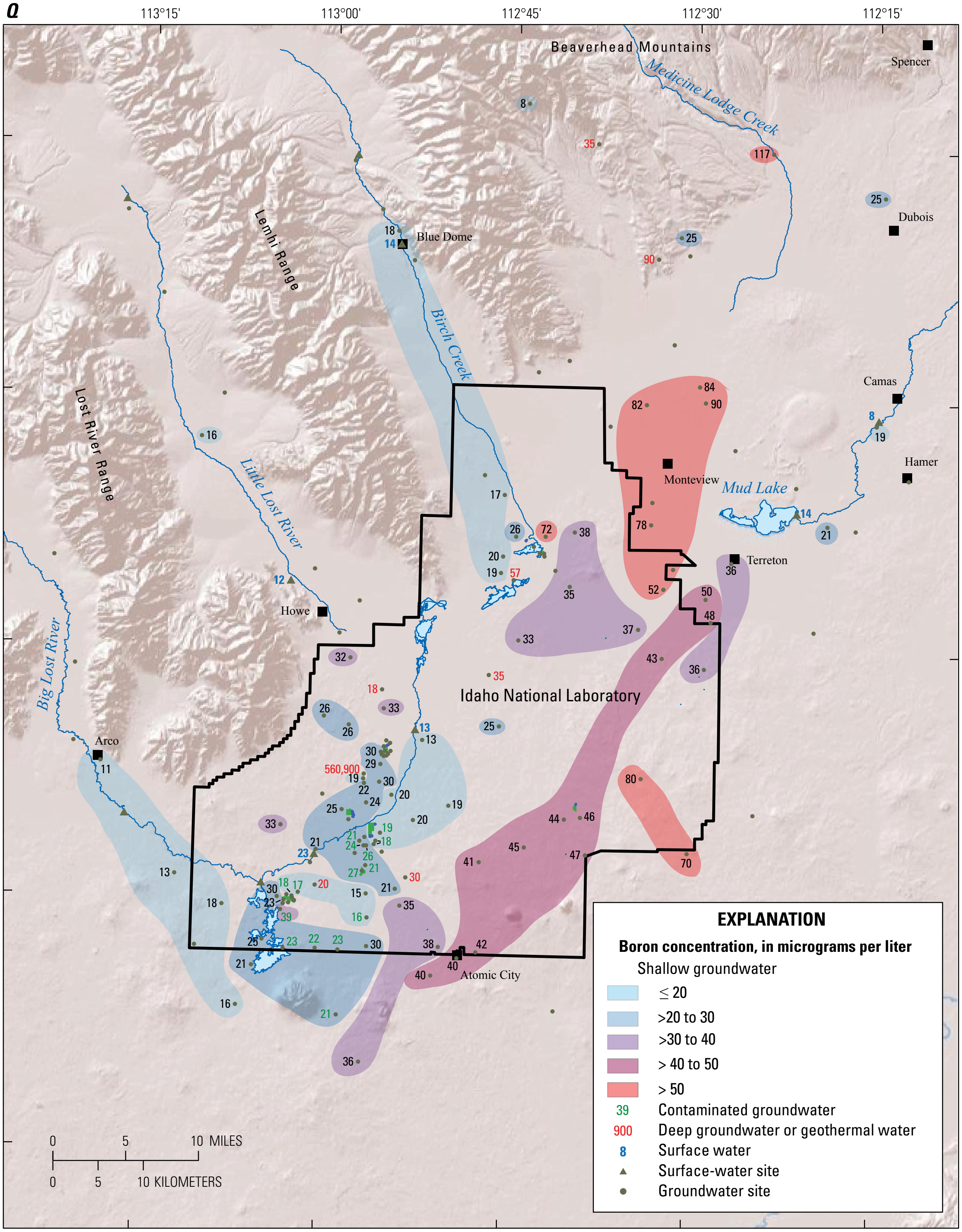
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



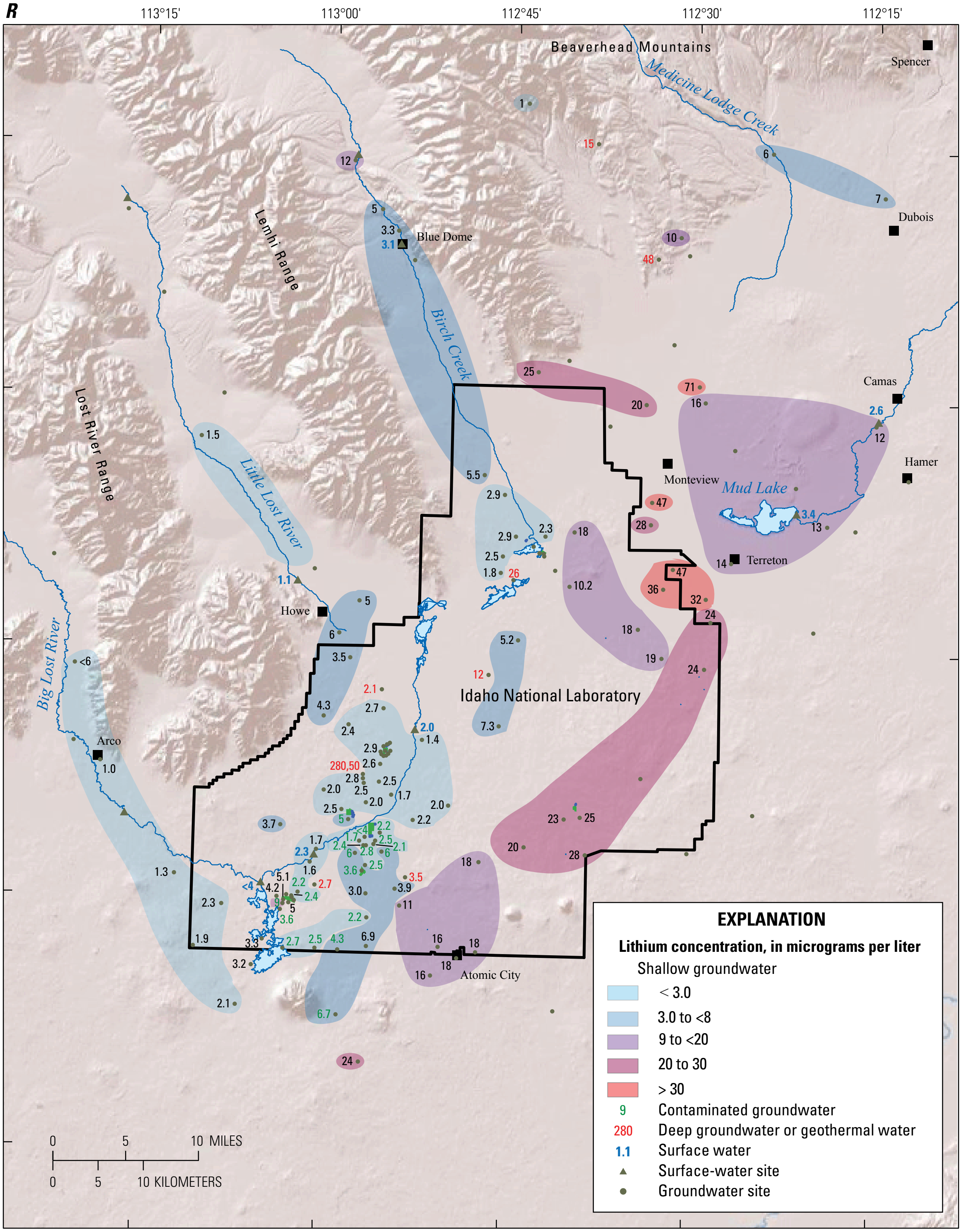
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



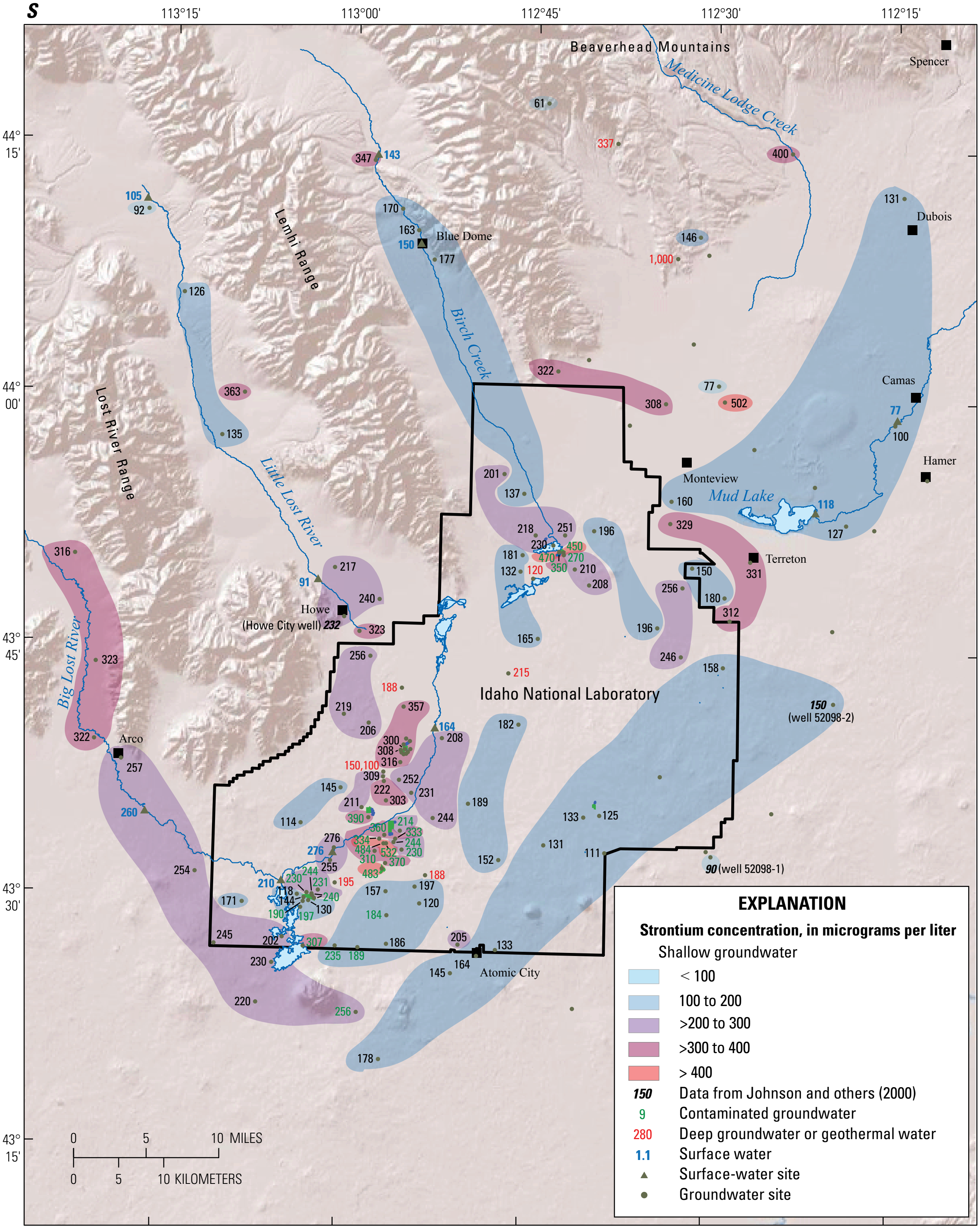
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



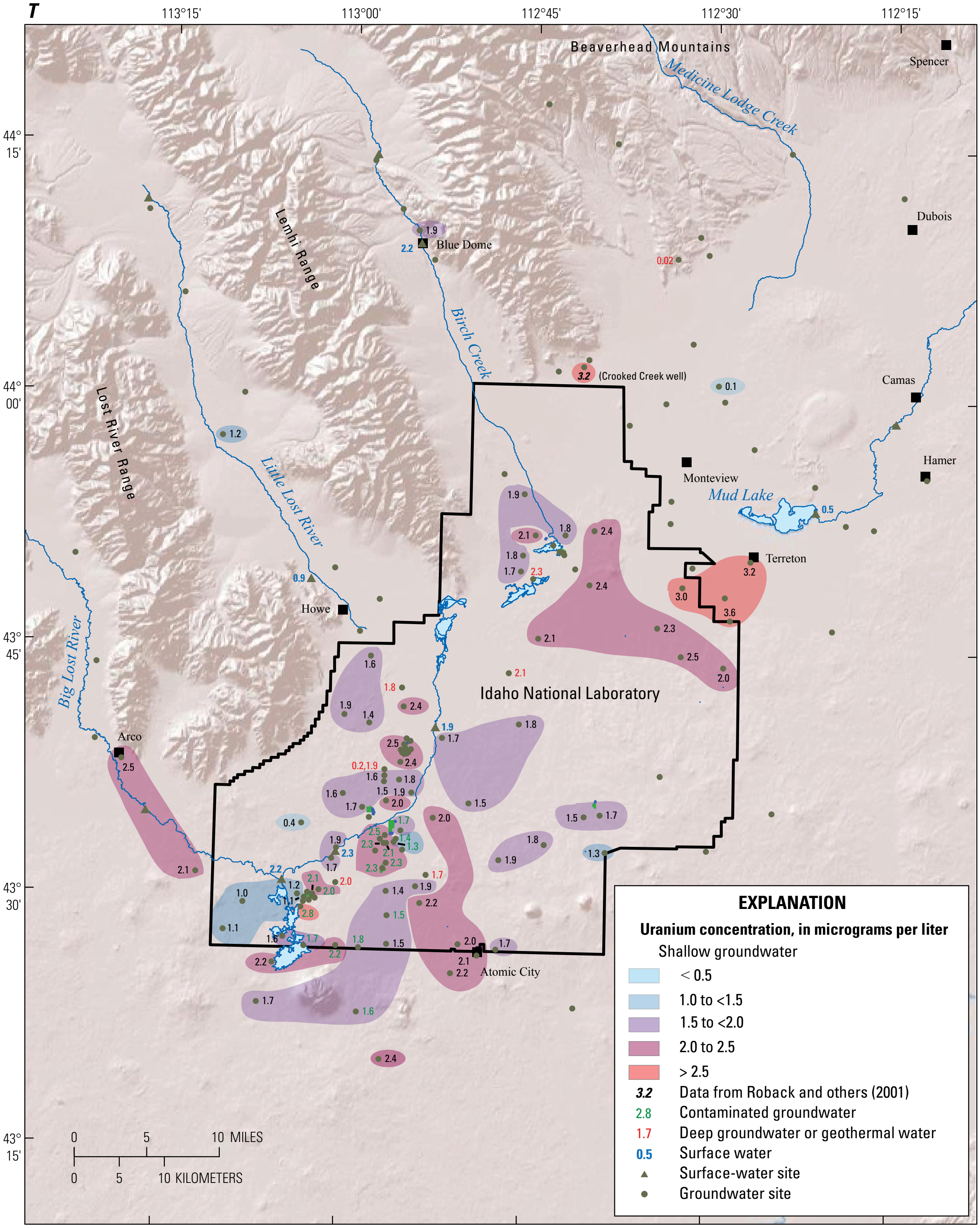
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



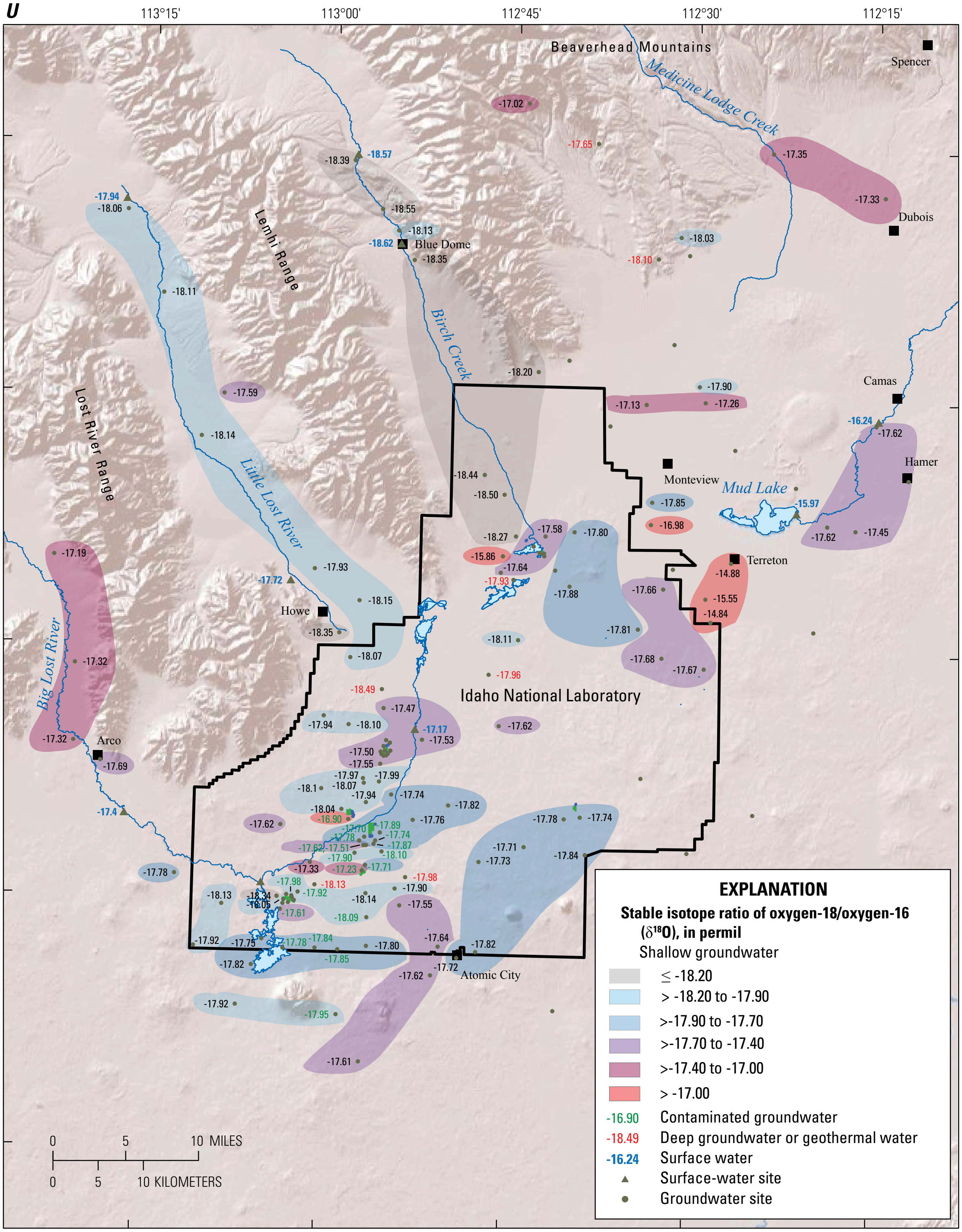
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



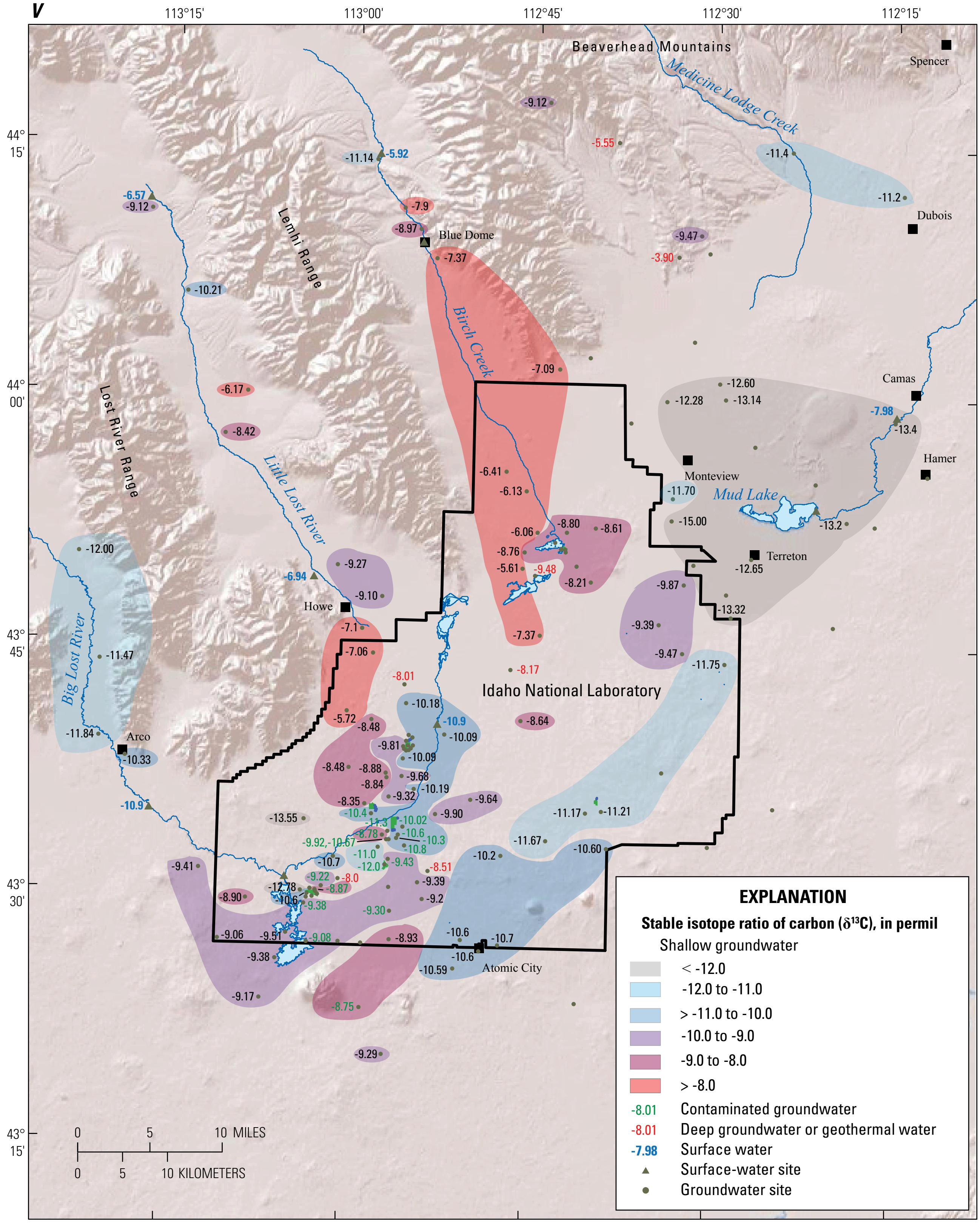
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



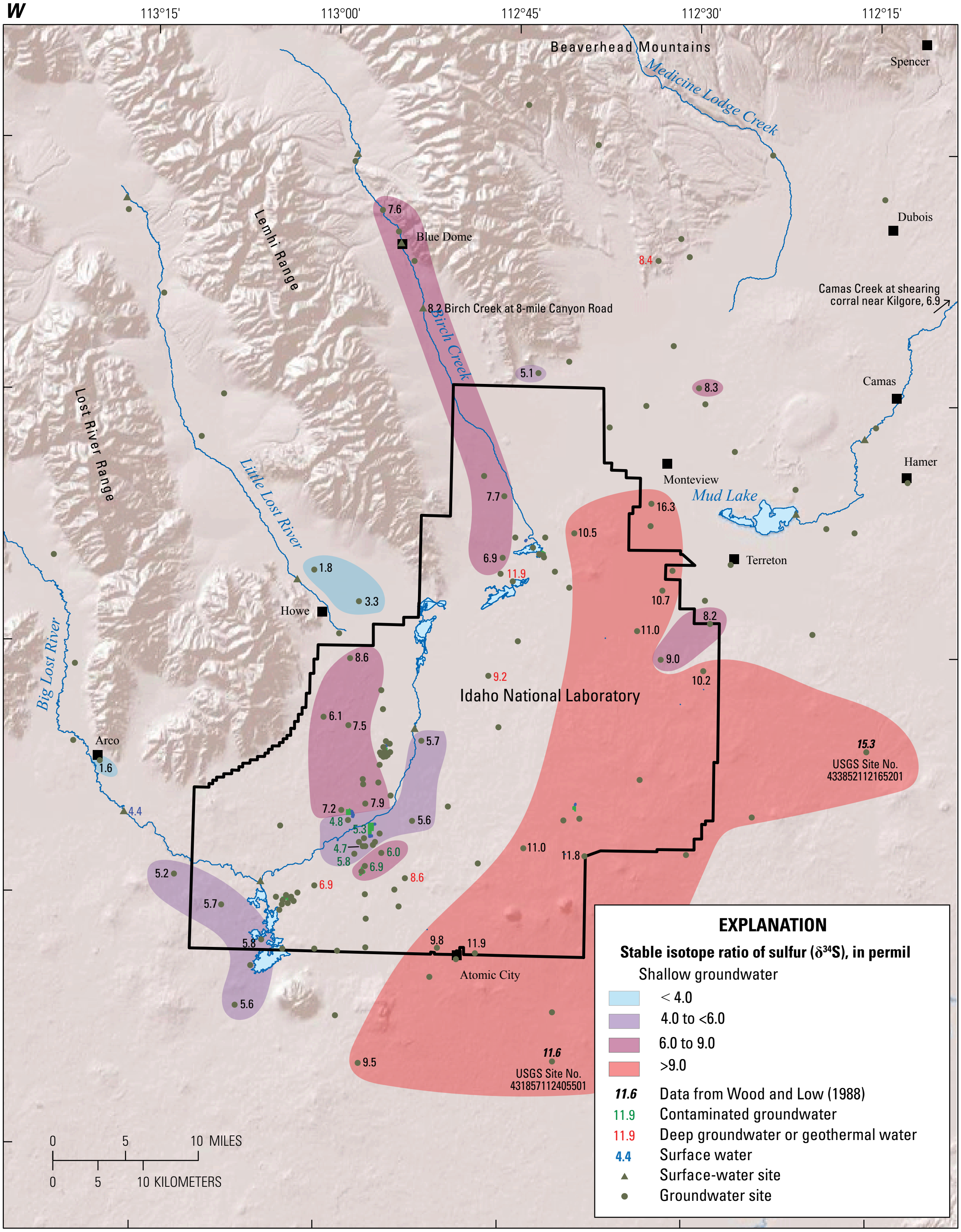
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



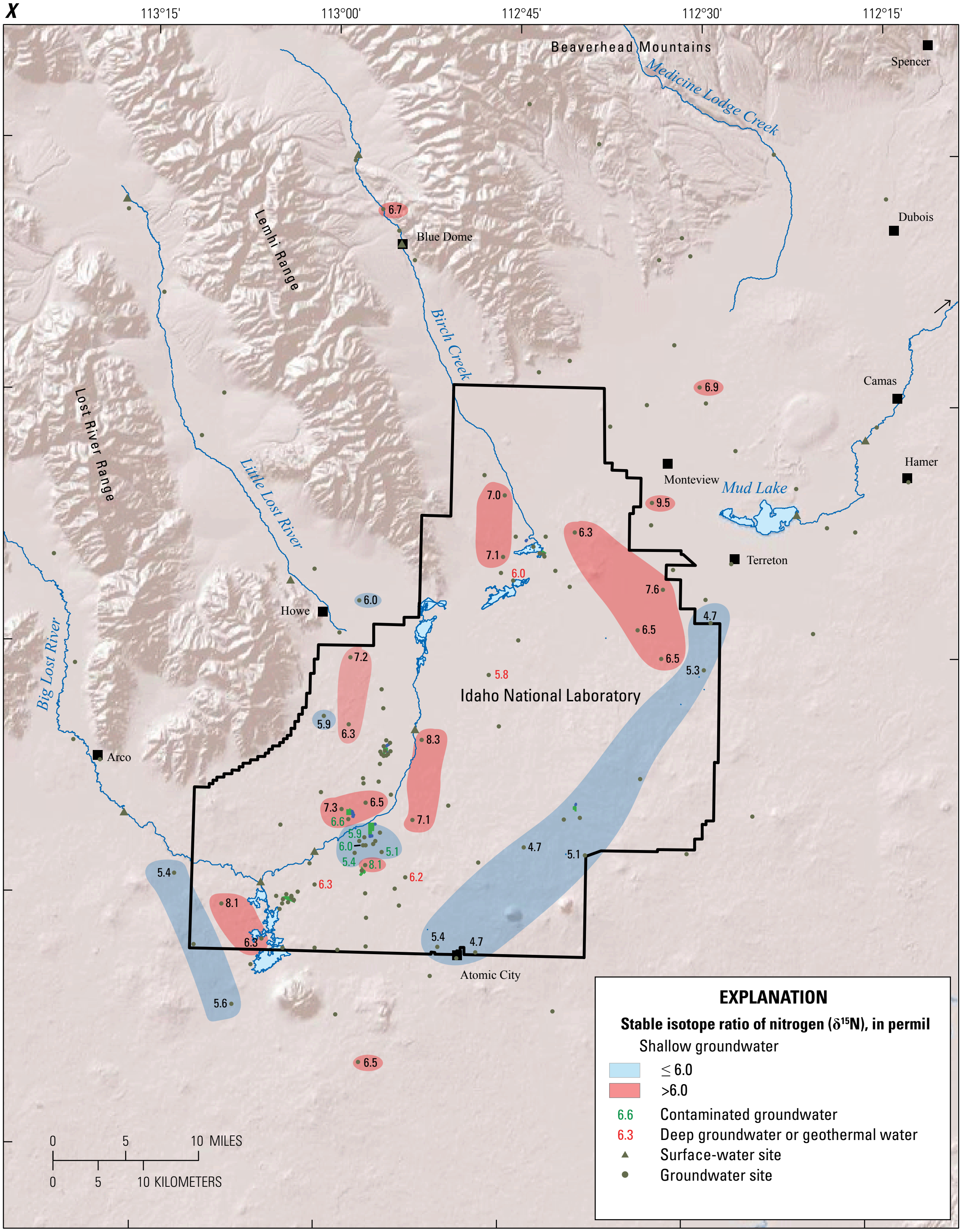
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



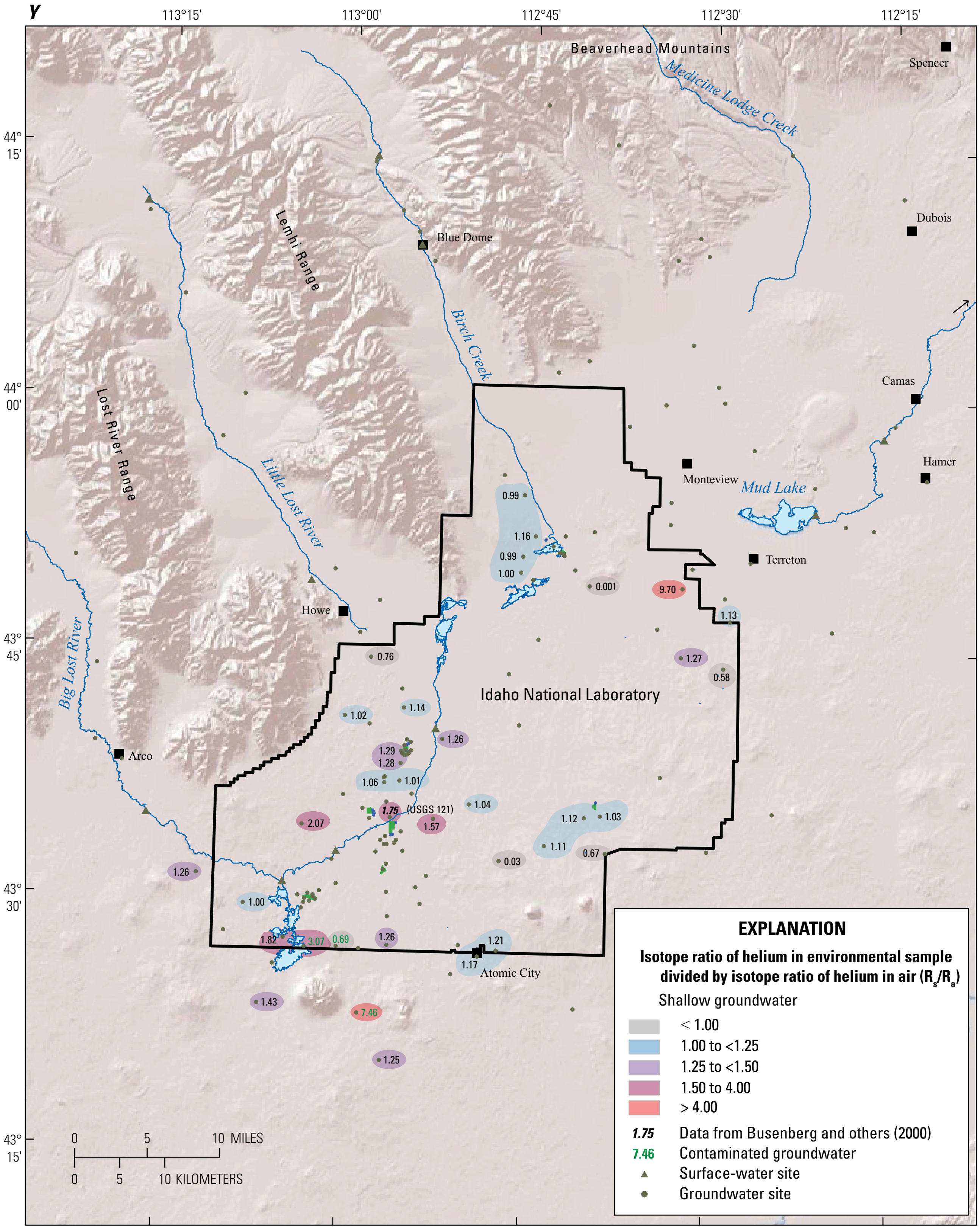
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



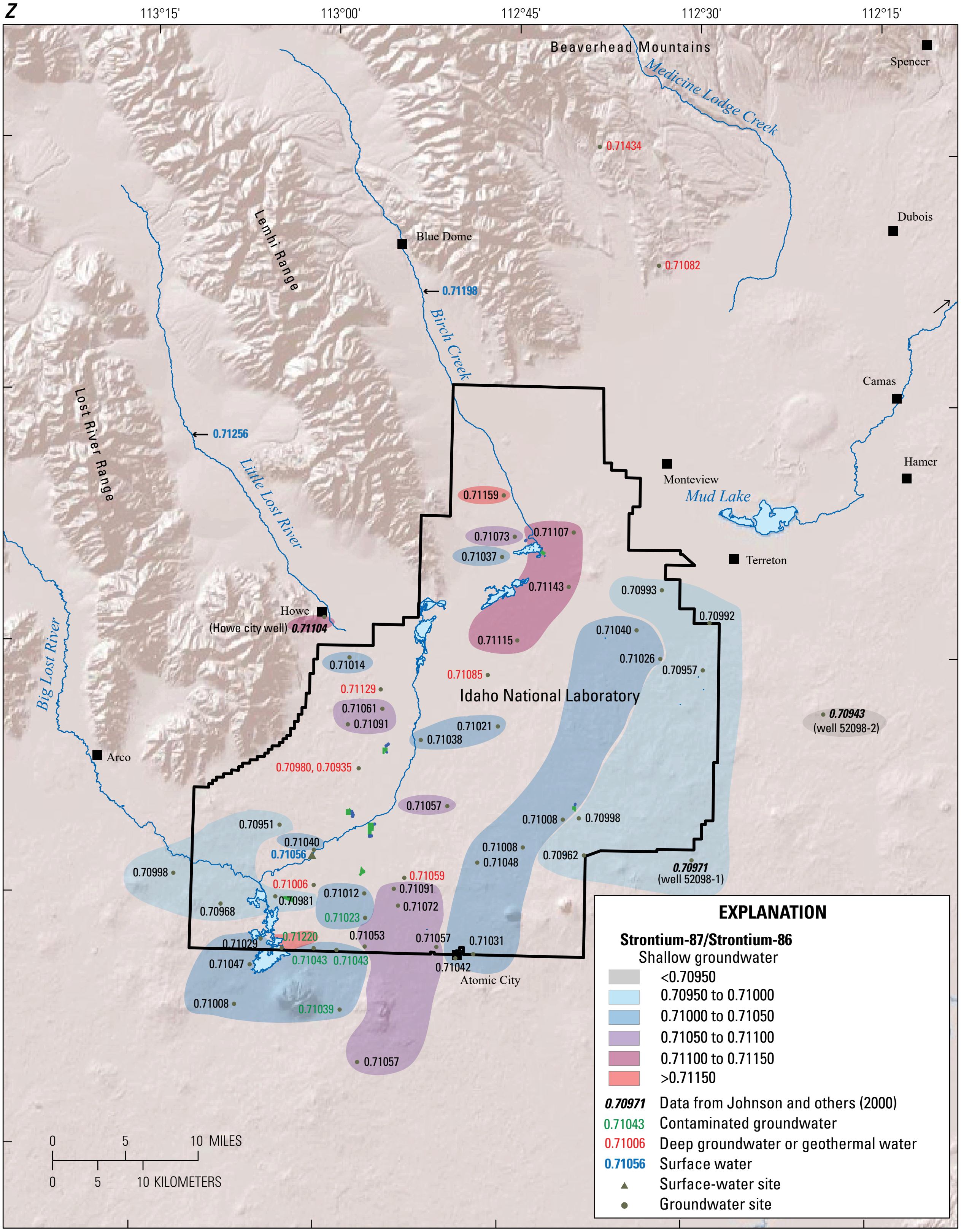
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



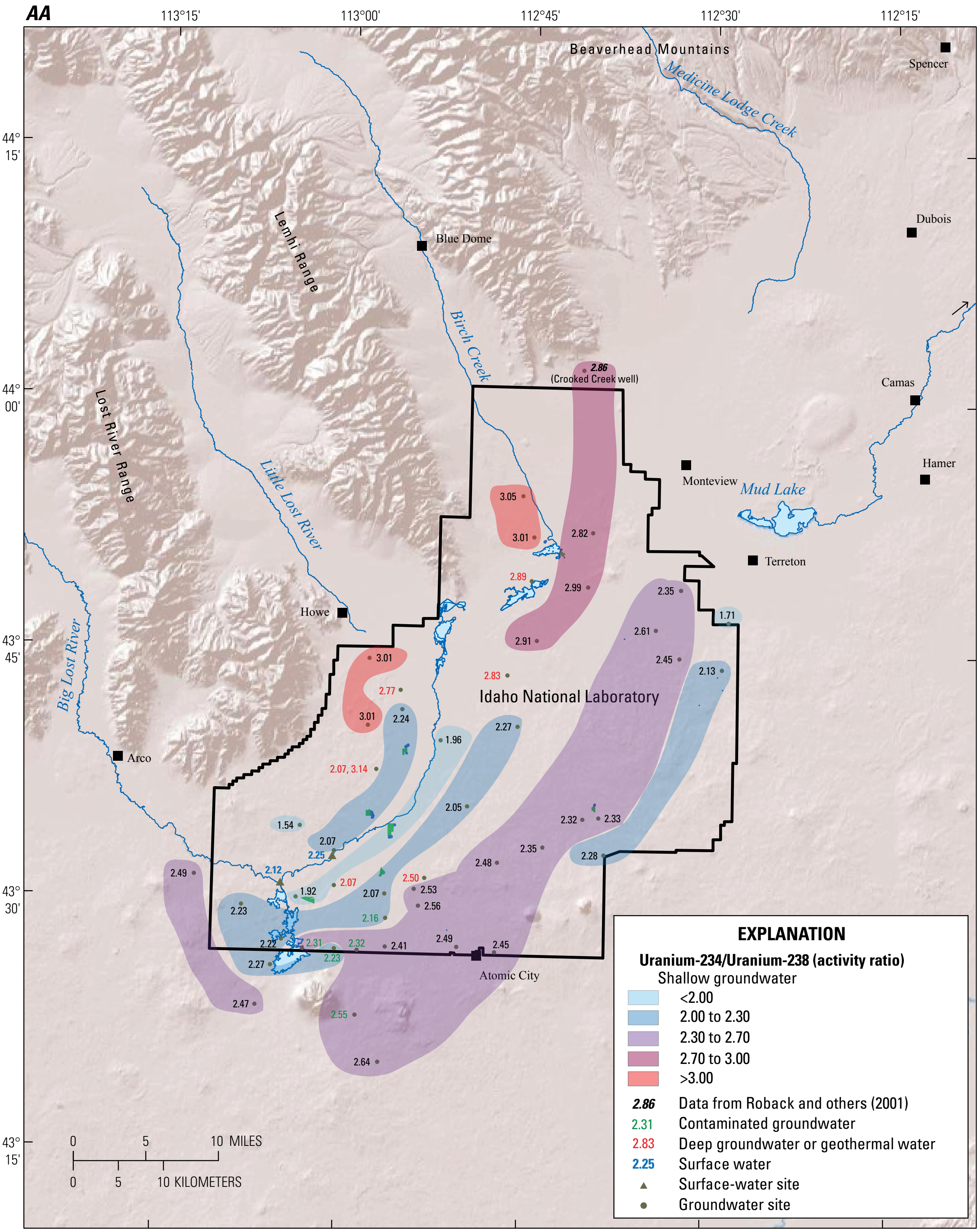
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



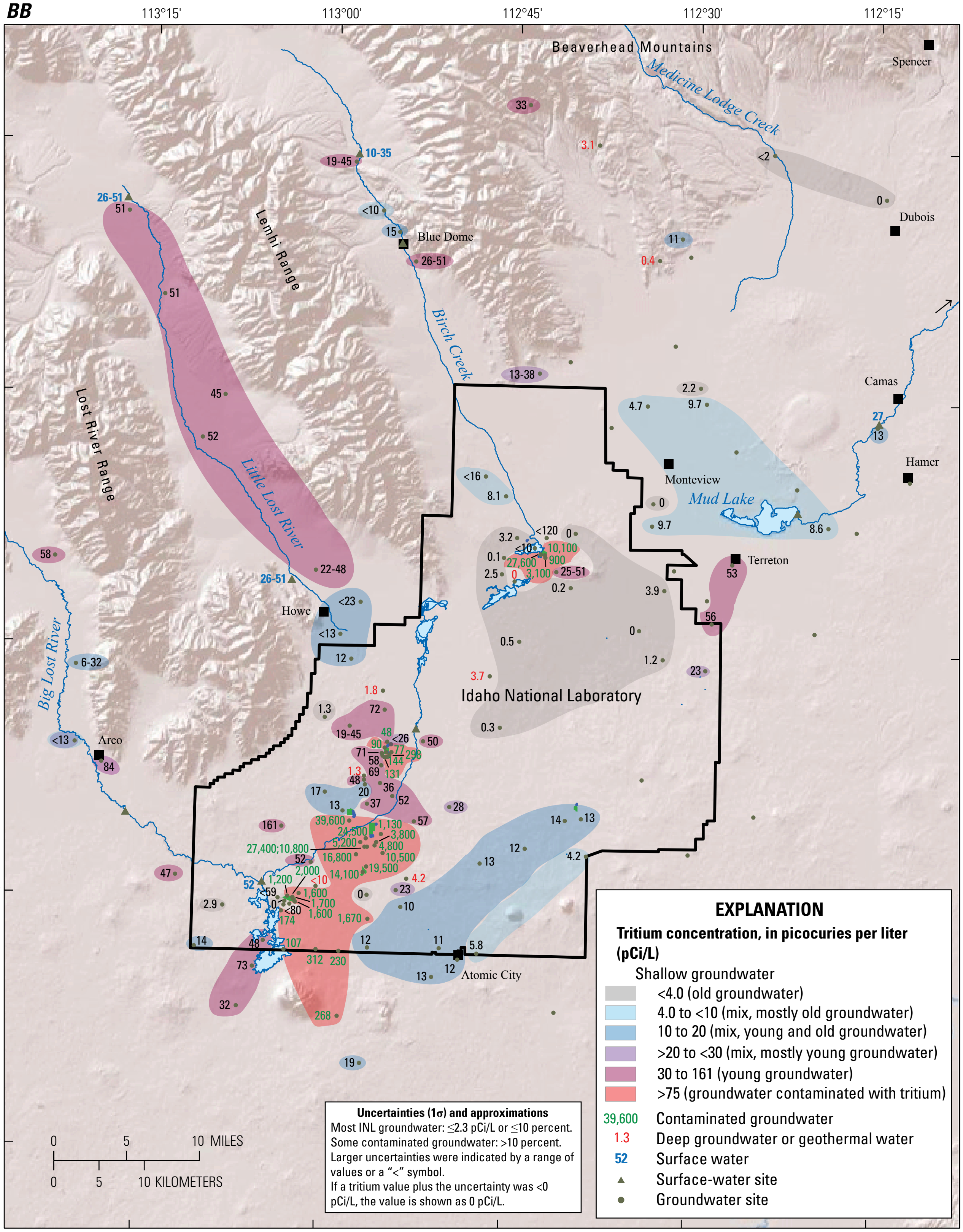
Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued



Uncertainties (1σ) and approximations

Most INL groundwater: ≤2.3 pCi/L or ≤10 percent.

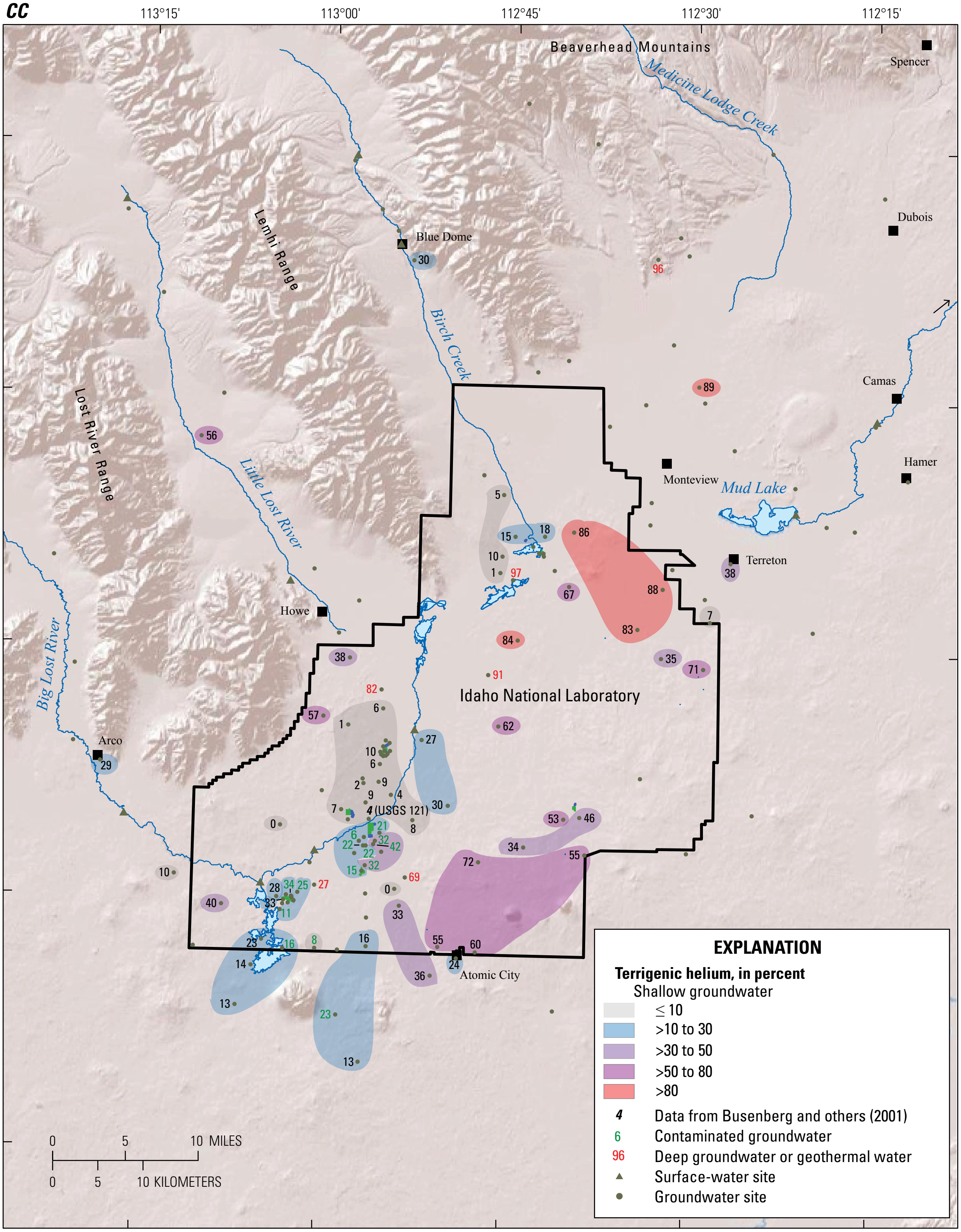
Some contaminated groundwater: >10 percent.

Larger uncertainties were indicated by a range of values or a "<" symbol.

If a tritium value plus the uncertainty was <0 pCi/L, the value is shown as 0 pCi/L.

Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

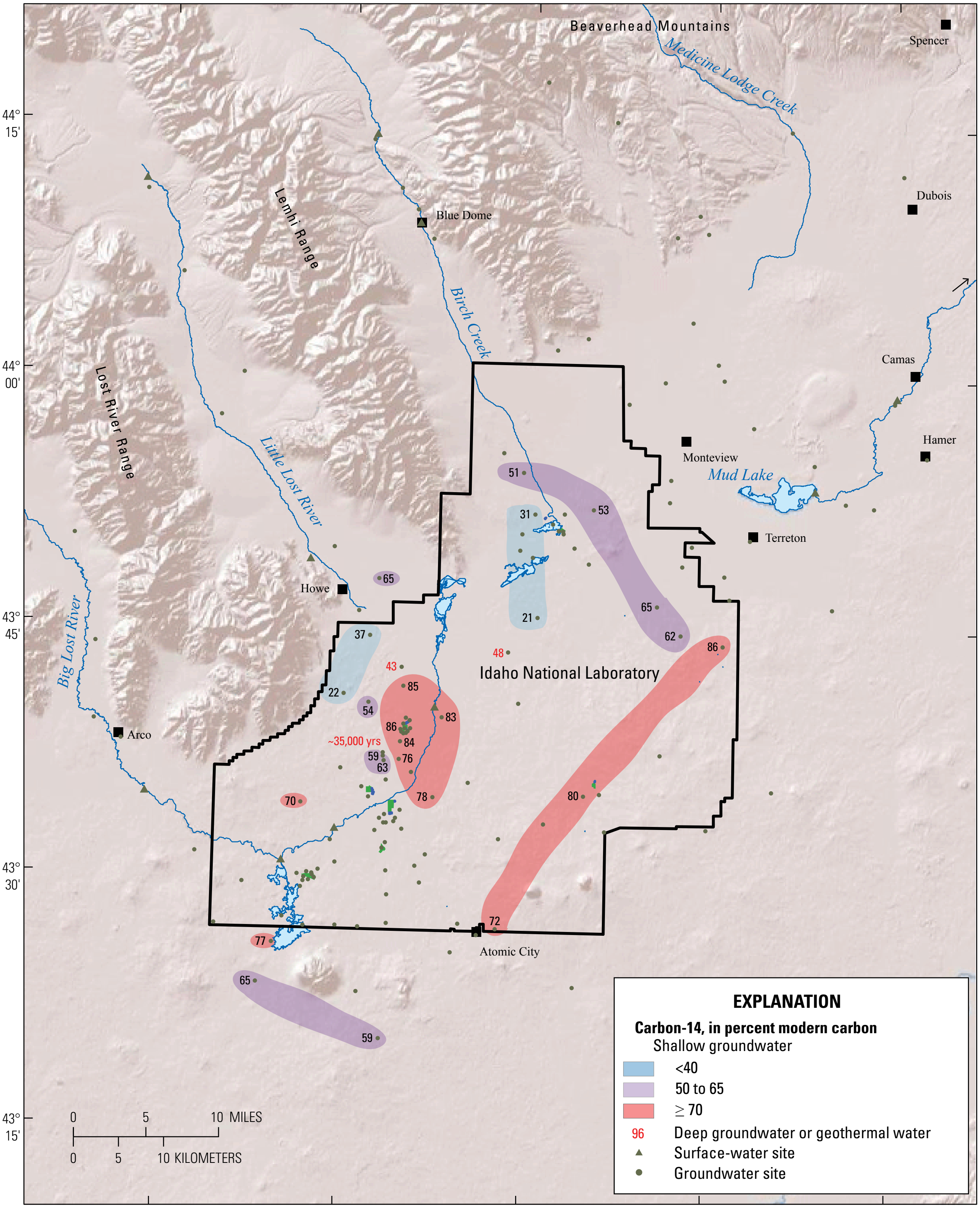
Figure 28.—Continued



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued

DD



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000.
Coordinate system and datum: NAD 1927 UTM Zone 12N

Figure 28.—Continued

Tables 10–17

Table 10. Site name, primary source of data, and alternate and abbreviated names for water-quality sites, Idaho National Laboratory and vicinity, eastern Idaho.

[Springs are shown in *italics*. Locations of sites shown in figures 8–9. **Alternate name:** CC ##, Sample number in Rattray and Ginsbach (2014); ML ##, Site number in Rattray (2015). **Abbreviations:** ft, foot; INL, Idaho National Laboratory; na, not applicable; RWMC, Radioactive Waste Management Complex; USGS, U.S. Geological Survey]

Site name	Primary source of data	Alternate name	Abbreviated name
Surface water			
Big Lost River at Mackay Dam	Busenberg and others, 2000	BLR at MD	BLR MD
Big Lost River below Mackay Reservoir	Ott and others, 1994	na	na
Big Lost River at Bridge near Mackay	Busenberg and others, 2000	BLR at Br nr Mackay	BLR M
Big Lost River near Arco	Bartholomay and others, 2015	BLR nr Arco	BLR A
Big Lost River below INL Diversion	Bartholomay and others, 2015	BLR blw INL Div	BLR INL
Big Lost River near Atomic City	U.S. Geological Survey, 2014	BLR nr AC	BLR AC
Big Lost River below lower Lincoln Boulevard Bridge near Howe	Busenberg and others, 2000	BLR, nr NRF, Lincoln Blvd	BLR LLBB
Birch Creek at Kaufman Guard Station	Swanson and others, 2003	BC at KGS	BC KGS
Birch Creek at Blue Dome	Busenberg and others, 2000	BC at BD	BC BD
Camas Creek below diversion near Camas National Wildlife Refuge	Rattray, 2015	CC 99, ML 78	CC
Little Lost River near Clyde	Swanson and others, 2002	LLR nr Clyde	LLR C
Little Lost River near Howe	Busenberg and others, 2000	Little Lost River north of Howe	LLR H
Mud Lake near Terreton	Busenberg and others, 2000	Camas Creek near Mud Lake	ML
Tributary Valley groundwater			
Big Lost River Valley			
Arco City Well 4	Busenberg and others, 2000	na	ACW4
Coates	Carkeet and others, 2001	na	na
Fulton	Carkeet and others, 2001	na	na
Hill	Carkeet and others, 2001	na	na
Lambert	Carkeet and others, 2001	na	na
MSR	Carkeet and others, 2001	na	na
Muffett	Carkeet and others, 2001	na	na
Owen	Carkeet and others, 2001	na	na
Wheeler	Carkeet and others, 2001	na	na
Wildhorse Guard Station	Carkeet and others, 2001	na	WGS
Little Lost River Valley			
Harrell	Swanson and others, 2002	na	na
Mays	Swanson and others, 2002	na	na
Nicholson	Swanson and others, 2002	na	na
Oar	Swanson and others, 2002	na	na
Pancheri	Busenberg and others, 2000	Pancheri 6	na
Ruby Farms	Swanson and others, 2002	na	RF
Sorenson	Swanson and others, 2002	na	na
Birch Creek Valley			
Kaufman Guard Station	Swanson and others, 2003	na	KGS
McKinney	Swanson and others, 2003	na	na
P&W 2	Busenberg and others, 2000	P and W 2	P&W2
USGS 126b	Swanson and others, 2003	na	126b
Wagoner	Busenberg and others, 2000	[2]Wagoner Ranch	W
Wagoner Ranch	Swanson and others, 2003	na	WR
Beaverhead Mountains			
ML 55	*Rattray, 2015*	*Blue Spring*	*na*
ML 59	*Rattray, 2015*	*Heart Spring*	*na*

Table 10. Site name, primary source of data, and alternate and abbreviated names for water-quality sites, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Primary source of data	Alternate name	Abbreviated name
Regional groundwater			
East Mud Lake area			
ML 2	Rattray, 2015	na	na
ML 5	Rattray, 2015	CC 15	na
ML 6	Rattray, 2015	CC 18	na
ML 9	Rattray, 2015	na	na
ML 12	Rattray, 2015	Davies, CC 20	na
ML 13	Rattray, 2015	na	na
ML 15	Rattray, 2015	na	na
ML 18	Rattray, 2015	na	na
North Mud Lake area			
ML 17	Rattray, 2015	Killian	na
ML 26	Rattray, 2015	na	na
ML 28	Rattray, 2015	na	na
ML 34	U.S. Geological Survey, 2014	na	na
Reno Ranch	Swanson and others, 2003	na	RR
West Mud Lake area			
ML 24	Rattray, 2015	Hawker	na
ML 30	Rattray, 2015	Holdaway	na
ML 31	Rattray, 2015	Maughan	na
ML 33	U.S. Geological Survey, 2014	na	na
Groundwater with geothermal input			
ML 25	Knobel and others, 1999a	Park Bell	na
ML 27	Rattray, 2015	na	na
ML 29	Knobel and others, 1999a	Stoddart	na
Southwest Mud Lake area			
ML 19	Busenberg and others, 2000	Engberson	na
ML 22	Busenberg and others, 2000	USGS 4	na
ML 23	Rattray, 2015	Martin	na
Southeast INL Boundary area			
Highway 2	U.S. Geological Survey, 2014	na	Hwy2
Kettle Butte Farms	U.S. Geological Survey, 2014	na	KBF
SE of Atomic City	U.S. Geological Survey, 2014	na	SE of AC
USGS 3A	Robertson and others, 1974	na	3A
USGS 101	Busenberg and others, 2000	na	101
Geothermal water			
INEL-1 2,000 feet[1]	Mann, 1986	INEL-1 2000’	INEL-1 2000 ft
INEL-1 10,300 feet[1]	Mann, 1986	INEL-1 10300’	INEL-1 10300 ft
ML 57	*Rattray, 2015*	*Lidy Hot Springs*	*na*
ML 58	*Rattray, 2015*	*Warm Spring*	*na*
Groundwater at the Idaho National Laboratory			
Deep groundwater			
EBR 1	Busenberg and others, 2000	na	EBR1
Site 9	Busenberg and others, 2000	na	Site9, S9
Site 14	Busenberg and others, 2000	na	Site14, S14
USGS 7	Busenberg and others, 2000	na	7
USGS 15	Busenberg and others, 2000	na	15

Table 10. Site name, primary source of data, and alternate and abbreviated names for water-quality sites, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Primary source of data	Alternate name	Abbreviated name
	Contaminated groundwater		
	Advanced Test Reactor Complex		
USGS 65	Knobel and others, 1999a	na	65
	Idaho Nuclear Technology and Engineering Center		
CFA 1	Busenberg and others, 2000	na	CFA1
CFA 2	Busenberg and others, 2000	na	CFA2
USGS 20	Knobel and others, 1999a	na	20
USGS 36	Busenberg and others, 2000	na	36
USGS 57	Knobel and others, 1999a	na	57
USGS 82	Busenberg and others, 2000	na	82
USGS 85	Knobel and others, 1999a	na	85
USGS 104	Busenberg and others, 2000	na	104
USGS 105	Busenberg and others, 2000	na	105
USGS 108	Busenberg and others, 2000	na	108
USGS 109	Busenberg and others, 2000	na	109
USGS 112	Busenberg and others, 2000	na	112
USGS 113	Busenberg and others, 2000	na	113
USGS 115	Busenberg and others, 2000	na	115
USGS 116	Busenberg and others, 2000	na	116
USGS 124	Busenberg and others, 2000	na	124
	Naval Reactors Facility		
NRF 6	Knobel and others, 1999b	na	N6
NRF 9	Knobel and others, 1999b	na	N9
NRF 10	Knobel and others, 1999b	na	N10
NRF 11	Knobel and others, 1999b	na	N11
NRF 12	Knobel and others, 1999b	na	N12
NRF 13	Knobel and others, 1999b	na	N13
	Radioactive Waste Management Complex		
RWMC M3S	Busenberg and others, 2000	na	M3S
RWMC M7S	Busenberg and others, 2000	na	M7S
RWMC Production	Knobel and others, 1992	RWMC Prod	RP
USGS 87	Knobel and others, 1992	na	87
USGS 88	Knobel and others, 1992	na	88
USGS 90	Knobel and others, 1992	na	90
USGS 120	Busenberg and others, 2000	na	120
	Test Area North		
TAN Disposal	Knobel and others, 1992	TAN Disp	TD
TDD 1	Knobel and others, 1992	na	T1
TDD 2	Knobel and others, 1992	na	T2
USGS 24	Busenberg and others, 2000	na	24
	Natural groundwater		
	North INL Area		
ANP 6	Busenberg and others, 2000	na	ANP6
ANP 8	Knobel and others, 1992	na	ANP8
IET 1 Disposal	Busenberg and others, 2000	ANP 4	IET1
No Name 1	Busenberg and others, 2000	TAN Exploration	NN1
PSTF Test	Busenberg and others, 2000	na	na
TDD 3	Knobel and others, 1992	na	T3

Table 10. Site name, primary source of data, and alternate and abbreviated names for water-quality sites, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Primary source of data	Alternate name	Abbreviated name
Natural groundwater—Continued			
Northeast INL Area			
ANP 9	Busenberg and others, 2000	na	ANP9
USGS 26	Busenberg and others, 2000	na	26
USGS 27	Busenberg and others, 2000	na	27
USGS 29	Busenberg and others, 2000	na	29
USGS 31	Busenberg and others, 2000	na	31
USGS 32	Busenberg and others, 2000	na	32
Southeast INL Area			
Arbor Test 1	Busenberg and others, 2000	Arbor Test	AT1
Area II	Busenberg and others, 2000	Area 2	na
Atomic City	Busenberg and others, 2000	na	AC
Leo Rogers 1	Busenberg and others, 2000	na	LR1
USGS 1	Busenberg and others, 2000	na	1
USGS 2	Busenberg and others, 2000	na	2
USGS 14	Busenberg and others, 2000	na	14
USGS 100	Busenberg and others, 2000	na	100
USGS 107	Busenberg and others, 2000	na	107
USGS 110A	Busenberg and others, 2000	na	110A
Central INL Area			
Badging Facility Well	Busenberg and others, 2000	na	BFW
NPR Test	Busenberg and others, 2000	NPR-W01	na
USGS 5	Busenberg and others, 2000	na	5
USGS 6	Busenberg and others, 2000	na	6
USGS 17	Busenberg and others, 2000	na	17
USGS 18	Busenberg and others, 2000	na	18
USGS 83	Busenberg and others, 2000	na	83
USGS 103	Busenberg and others, 2000	na	103
Northwest INL Area			
Fire Station 2	Busenberg and others, 2000	na	FS2
INEL-1 WS	Busenberg and others, 2000	WS INEL 1	INEL1
NRF 2	Knobel and others, 1992	na	N2
NRF 7	Knobel and others, 1999b	na	N7
NRF 8	Knobel and others, 1999b	na	N8
Site 4	Busenberg and others, 2000	na	Site4, S4
Site 17	Busenberg and others, 2000	na	Site17, S17
Site 19	Busenberg and others, 2000	na	Site19, S19
USGS 12	Busenberg and others, 2000	na	12
USGS 19	Busenberg and others, 2000	na	19
USGS 22	Busenberg and others, 2000	na	22
USGS 23	Busenberg and others, 2000	na	23
USGS 97	Busenberg and others, 2000	na	97
USGS 98	Busenberg and others, 2000	na	98
USGS 99	Busenberg and others, 2000	na	99
USGS 102	Busenberg and others, 2000	na	102
USGS 134	Bartholomay and Twining, 2010	USGS 134 Zone 5	134

Table 10. Site name, primary source of data, and alternate and abbreviated names for water-quality sites, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Primary source of data	Alternate name	Abbreviated name
Natural groundwater—Continued			
Southwest INL Area			
Highway 3	U.S. Geological Survey, 2014	na	Hwy3
Middle 2051	Bartholomay and Twining, 2010	Middle 2051 Zone 5	M2051
USGS 8	Busenberg and others, 2000	na	8
USGS 9	Busenberg and others, 2000	na	9
USGS 11	Busenberg and others, 2000	na	11
USGS 86	Busenberg and others, 2000	na	86
USGS 89	Busenberg and others, 2000	na	89
USGS 117	Busenberg and others, 2000	na	117
USGS 119	Knobel and others, 1992	na	119
USGS 125	Busenberg and others, 2000	na	125
USGS 135	Bartholomay and others, 2015	USGS 135 Zone 10	135

[1] INEL-1 2,000 feet and INEL-1 10,300 feet are both from borehole INEL-1. Samples identified as INEL-1 2,000 feet were collected from a depth interval of 1,511–2,206 feet below land surface, and samples identified as INEL-1 10,300 feet were collected from a depth interval of 4,210–10,365 feet below land surface.

[2] Referred to as Wagoner Ranch in Busenberg and others (2000).

Table 11. Site information, including site name, U.S. Geological Survey site number, location, altitude, well depth, open interval, approximate depth to water, depth of open intervals below water table, aquifer material, water use, and hydraulic conductivity, Idaho National Laboratory and vicinity, eastern Idaho.

[Well construction information from the U.S. Geological Survey (2014), Idaho Department of Water Resources (2014), Busenberg and others (1998), and Mann (1986). Hydraulic conductivity data from Anderson and others (1999) and Mann (1986). Springs are shown in *italics*. Locations of sites shown on figures 8–9. **Site name:** Alternate names used in other reports shown in table 10. **Depth of open intervals:** May include multiple open intervals. **Abbreviations:** ~, approximate; CNWR, Camas National Wildlife Refuge; ft, foot; ft bls, foot below land surface; ft bwt, foot below water table; INL, Idaho National Laboratory; na, not applicable; nd, not determined; USGS, U.S. Geological Survey; unk, unknown; <, less than; >, greater than]

Site name	USGS site No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude of land surface (ft)	Depth of well (ft bls)	Extent of open intervals (ft bls)	Depth to water table (ft bls)	Depth of open intervals below water table (ft bwt)	Aquifer material	Water use	Estimated hydraulic conductivity (ft/d as log K)
Surface water											
Big Lost River at Mackay Dam	13126000	43.951389	-113.675000	6,000	na	na	na	na	na	na	na
Big Lost River below Mackay Reservoir	13127000	43.939167	-113.648333	5,946	na	na	na	na	na	na	na
Big Lost River at Bridge near Mackay	13127700	43.886296	-113.616967	5,873	na	na	na	na	na	na	na
Big Lost River near Arco	13132500	43.581944	-113.270833	5,240	na	na	na	na	na	na	na
Big Lost River below INL Diversion	13132520	43.515833	-113.081944	5,000	na	na	na	na	na	na	na
Big Lost River near Atomic City	13132530	43.547129	-113.009165	4,950	na	na	na	na	na	na	na
Big Lost River below Lower Lincoln Blvd	13132553	43.670740	-112.875829	4,820	na	na	na	na	na	na	na
Birch Creek at Kaufman Guard Station	13116980	44.241298	-112.971673	6,470	na	na	na	na	na	na	na
Birch Creek at Blue Dome	13117020	44.153333	-112.909167	6,050	na	na	na	na	na	na	na
Camas Creek below diversion nr CNWR	13114150	43.980464	-112.248592	4,829	na	na	na	na	na	na	na
Little Lost River near Clyde	13117500	44.192222	-113.289444	6,030	na	na	na	na	na	na	na
Little Lost River near Howe	13119000	43.870278	-113.087778	5,020	na	na	na	na	na	na	na
Mud Lake near Terreton	13115000	43.891389	-112.358056	4,775	na	na	na	na	na	na	na
Tributary Valley groundwater											
Big Lost River Valley											
Arco City Well 4	433758113181701	43.632680	-113.305562	5,320	250	198–214	~132	~66–82	Alluvium	Production	nd
Coates	440323113533402	44.056305	-113.893648	6,353	88	60–80	38	22–42	Alluvium	Domestic	nd
Fulton	440803113541701	44.134085	-113.905592	6,340	30	unk	8	unk	Alluvium	Domestic	nd
Hill	435956113493401	43.998861	-113.825722	6,195	80	42–78	32	10–46	Alluvium	Domestic	nd
Lambert	435351113350301	43.897407	-113.585020	5,854	50	50	5	45	Alluvium	Domestic	nd
MSR	440454113554401	44.081584	-113.929761	6,380	unk	unk	75	unk	Alluvium	Irrigation	nd
Muffett	435011113223201	43.836292	-113.376400	5,628	63	40–59	36	4–23	Alluvium	Domestic	nd

Table 11. Site information, including site name, U.S. Geological Survey site number, location, altitude, well depth, open interval, approximate depth to water, depth of open intervals below water table, aquifer material, water use, and hydraulic conductivity, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	USGS site No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude of land surface (ft)	Depth of well (ft bls)	Extent of open intervals (ft bls)	Depth to water table (ft bls)	Depth of open intervals below water table (ft bwt)	Aquifer material	Water use	Estimated hydraulic conductivity (ft/d as log K)
Big Lost River Valley—Continued											
Owen	433908113203101	43.652124	-113.342787	5,391	114	113–114	42	71–72	Basalt	Domestic	nd
Wheeler	434345113203401	43.729068	-113.343620	5,455	80	62–78	48	14–30	Alluvium	Domestic	nd
Wildhorse Guard Station	435311114060101	43.886278	-114.101417	7,065	264	264	14	250	Alluvium	Domestic	nd
Little Lost River Valley											
Harrell	434940113005601	43.827944	-113.018139	4,880	118	117–118	71	46–47	Alluvium	Domestic	nd
Mays	434558112585301	43.765183	-112.982223	4,805	540	unk	273	unk	Basalt	Domestic	nd
Nicholson	440003113085101	44.000611	-113.148389	5,403	130	127–130	81	46–49	Alluvium	Domestic	nd
Oar	440558113140301	44.099351	-113.235010	5,790	80	unk	35	unk	Alluvium	Domestic	nd
Pancheri	435728113103701	43.957806	-113.177889	5,375	87	37–87	25	12–62	Alluvium	Irrigation	nd
Ruby Farms	434751112571801	43.797405	-112.955834	4,805	149	unk	125	unk	Basalt	Domestic	nd
Sorenson	441052113171001	44.181333	-113.287056	6,037	128	54–128	40	14–88	Alluvium	Irrigation	nd
Birch Creek Valley											
Kaufman Guard Station	441406112582601	44.234889	-112.975083	6,400	80	unk	2	unk	Alluvium	Domestic	nd
McKinney	441113112560601	44.186852	-112.935837	6,205	43	39–43	12	27–31	Alluvium	Domestic	nd
P&W 2	435419112453101	43.905184	-112.759384	4,891	378	313–383	317	0–66	Basalt	Production	3.30
USGS 126b	435529112471401	43.924559	-112.787746	4,989	472	407–472	412	0–60	Basalt	Monitoring	nd
Wagoner	440957112544301	44.165740	-112.912780	6,125	150	unk	10.7	unk	Alluvium	Domestic	nd
Wagoner Ranch	440813112532201	44.136851	-112.890280	6,010	295	294–295	250	44–45	Alluvium	Domestic	nd
Beaverhead Mountains											
ML 55	*440951112311701*	*44.164082*	*-112.522444*	*5,047*	*unk*	*unk*	*unk*	*unk*	*Rhyolite*	*Commercial*	*nd*
ML 59	*441741112440701*	*44.294667*	*-112.736355*	*7,458*	*unk*	*unk*	*unk*	*unk*	*Quartzite*	*na*	*nd*
Regional groundwater											
Highway 2	433307112300001	43.551854	-112.500817	5,217	783	741–786	725	16–61	Basalt	Production	nd
Kettle Butte Farms	433526112244201	43.590417	-112.411694	5,205	851	19–851	698	0–153	Basalt	Domestic	nd
ML 2	435028112202601	43.925333	-112.204694	4,784	275.5	120–160	10	110–150	Basalt	Domestic	nd
ML 5	441222112142701	44.206021	-112.241654	5,240	580	20–580	450	0–130	Basalt	Stock	nd
ML 6	435846112145601	43.979353	-112.249703	4,805	255	53–255	104	30–86	Basalt	Irrigation	nd
ML 9	435229112163202	43.874417	-112.276639	4,795	152	18–152	72	0–80	Basalt	Irrigation	nd
ML 12	435241112185201	43.878500	-112.315611	4,785	218	167–218	189	0–29	Basalt	Domestic	nd
ML 13	434624112194601	43.772972	-112.332389	4,900	350	16–350	264	0–86	Basalt	Irrigation	nd
ML 15	434407112285101	43.916806	-112.359028	4,877	425.5	unk	110	<316	Basalt	Irrigation	nd
ML 18	435712112263201	43.953583	-112.443417	4,805	88	30–88	37	0–51	Basalt	Irrigation	nd
ML 17	441456112234701	44.248945	-112.397388	5,414	405	365–405	270	95–135	Basalt	Domestic	nd
ML 19	435026112253101	43.841019	-112.446650	4,785	270	109–270	222	0–48	Basalt	Domestic	nd
ML 22	434657112282201	43.782111	-112.473489	4,791	553	285–553	263	22–290	Basalt	Monitoring	3.28
ML 23	434818112284801	43.804910	-112.480820	4,788	358	52–358	255	0–103	Basalt	Irrigation	nd

Table 11. Site information, including site name, U.S. Geological Survey site number, location, altitude, well depth, open interval, approximate depth to water, depth of open intervals below water table, aquifer material, water use, and hydraulic conductivity, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	USGS site No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude of land surface (ft)	Depth of well (ft bls)	Extent of open intervals (ft bls)	Depth to water table (ft bls)	Depth of open intervals below water table (ft bwt)	Aquifer material	Water use	Estimated hydraulic conductivity (ft/d as log K)
Regional groundwater—Continued											
ML 24	440001112290401	44.000279	-112.485361	4,810	125	110–125	62	48–63	Basalt	Domestic	nd
ML 25	440058112293605	44.016020	-112.494150	4,809	48	unk	32	<16	Basalt	Irrigation	nd
ML 26	440451112154601	44.146389	-112.510556	4,900	190	189–280	207	0–73	Basalt	Domestic	nd
ML 27	435003112313101	43.833972	-112.526333	4,785	660	366–396	213	153–183	Basalt	Irrigation	nd
ML 28	440328112314501	44.057685	-112.529989	4,817	214	156–214	85	71–129	Basalt	Irrigation	nd
ML 29	435402112332101	43.900460	-112.556650	4,784	207	unk	192	<15	Basalt	Domestic	nd
ML 30	435241112332401	43.878027	-112.557751	4,820	340	339–340	250	89–90	Basalt	Domestic	nd
ML 31	435951112335701	43.997418	-112.566667	4,831	247	115–247	99	16–148	Basalt	Irrigation	nd
ML 33	435831112365401	43.975333	-112.616167	4,801	298	255–298	211	44–87	Basalt	Irrigation	nd
ML 34	440226112402401	44.040000	-112.673889	4,950	480	unk	444	<36	Basalt	Domestic	nd
Reno Ranch	440142112425501	44.028240	-112.716106	5,110	540	unk	535	unk	Alluvium	Domestic	nd
SE of Atomic City	432335112404801	43.392750	-112.679694	4,795	360	20–360	290	0–70	Basalt	Domestic	nd
USGS 3A	433732112335401	43.625465	-112.565819	5,179	733	689–740	673	16–67	Basalt	Monitoring	nd
USGS 101	433255112381801	43.548729	-112.639685	5,251	842	750–865	773	0–92	Basalt	Monitoring	1.11
Geothermal water											
INEL–1 2,000 feet	433717112563501	43.621312	-112.944212	4,873	10,333	1,511–2,206	310	1,201–1,896	Basalt	Test hole	-2.7 to -1.5
INEL–1 10,300 feet	433717112563501	43.621312	-112.944212	4,873	10,333	4,210–10,333	310	3,900–10,023	Basalt	Test hole	-2.7 to -1.5
ML 57	*440832112331001*	*44.142129*	*-112.553602*	*5,260*	*unk*	*unk*	*unk*	*unk*	*Sandstone*	*na*	*nd*
ML 58	*441522112381901*	*44.256019*	*-112.639440*	*6,520*	*unk*	*unk*	*unk*	*unk*	*Limestone*	*na*	*nd*
Groundwater at the Idaho National Laboratory											
Deep groundwater											
EBR 1	433051113002601	43.513698	-113.008156	5,024	1,075	600–1,075	586	14–489	Basalt	Production	0.43
Site 9	433123112530101	43.522924	-112.884384	4,926	1,131	681–1,057	475	206–582	Basalt	Monitoring	>3.00
Site 14	434334112463101	43.726202	-112.776244	4,794	716	535–716	276	259–440	Basalt	Monitoring	2.57
USGS 7	434915112443901	43.820688	-112.745235	4,789	903	241–840	214	27–626	Basalt	Monitoring	1.38
USGS 15	434234112551701	43.709584	-112.922318	4,812	610	540–610	326	214–284	Basalt	Monitoring	3.08
Contaminated groundwater											
Advanced Test Reactor Complex											
USGS 65	433447112574501	43.579587	-112.963923	4,925	498	456–498	468	0–30	Basalt	Monitoring	2.45
Idaho Nuclear Technology and Engineering Center											
CFA 1	433204112562001	43.534304	-112.939588	4,928	639	440–685	479	0–206	Basalt	Production	1.08
CFA 2	433144112563501	43.528779	-112.943916	4,932	681	521–681	471	50–210	Basalt	Production	1.04
USGS 20	433253112545901	43.547905	-112.917332	4,915	658	471–481	464	7–17	Basalt	Monitoring	0.90
USGS 36	433330112565201	43.558271	-112.948461	4,929	567	430–567	475	0–92	Basalt	Monitoring	3.61
USGS 57	433344112562601	43.562140	-112.941386	4,922	582	477–582	469	8–113	Basalt	Monitoring	2.18

Table 11. Site information, including site name, U.S. Geological Survey site number, location, altitude, well depth, open interval, approximate depth to water, depth of open intervals below water table, aquifer material, water use, and hydraulic conductivity, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	USGS site No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude of land surface (ft)	Depth of well (ft bls)	Extent of open intervals (ft bls)	Depth to water table (ft bls)	Depth of open intervals below water table (ft bwt)	Aquifer material	Water use	Estimated hydraulic conductivity (ft/d as log K)
Contaminated groundwater—Continued											
Idaho Nuclear Technology and Engineering Center—Continued											
USGS 82	433401112551001	43.566832	-112.920368	4,907	693	470–700	452	18–248	Basalt	Monitoring	3.00
USGS 85	433246112571201	43.546082	-112.954133	4,939	614	522–614	486	36–128	Basalt	Monitoring	3.53
USGS 104	432856112560801	43.482149	-112.936423	4,988	700	550–700	558	0–142	Basalt	Monitoring	-1.03
USGS 105	432703113001801	43.450852	-113.005770	5,095	1,300	400–800	672	0–128	Basalt	Monitoring	2.80
USGS 108	432659112582601	43.449572	-112.974813	5,031	1,196	400–760	611	0–149	Basalt	Monitoring	2.98
USGS 109	432701113025601	43.450249	-113.049668	5,044	800	600–800	623	0–177	Basalt	Monitoring	2.78
USGS 112	433314112563001	43.553935	-112.942702	4,928	507	432–563	476	0–87	Basalt	Monitoring	2.83
USGS 113	433314112561801	43.553943	-112.939244	4,925	556	445–504	477	0–27	Basalt	Monitoring	3.30
USGS 115	433320112554101	43.555524	-112.928994	4,919	581	440–581	467	0–114	Basalt	Monitoring	-0.58
USGS 116	433331112553201	43.558671	-112.926571	4,916	572	438–580	461	0–119	Basalt	Monitoring	0.08
USGS 124	432307112583101	43.385145	-112.975335	5,102	800	750–800	686	64–114	Basalt	Monitoring	nd
Naval Reactors Facility											
NRF 6	433910112550101	43.652809	-112.917778	4,846	417	359–417	373	0–44	Basalt	Monitoring	nd
NRF 9	433840112550201	43.643270	-112.917722	4,853	422	372–422	380	0–42	Basalt	Monitoring	nd
NRF 10	433841112545201	43.643787	-112.914244	4,854	427	377–427	380	0–47	Basalt	Monitoring	nd
NRF 11	433847112544201	43.645298	-112.911733	4,852	417	362–417	377	0–40	Basalt	Monitoring	nd
NRF 12	433855112543201	43.648207	-112.908386	4,851	425	375–425	377	0–48	Basalt	Monitoring	nd
NRF 13	433928112545401	43.658968	-112.914522	4,842	425	371–421	368	3–53	Basalt	Monitoring	nd
Radioactive Waste Management Complex											
RWMC M3S	433008113021801	43.502209	-113.039251	5,016	633	603–633	590	13–43	Basalt	Monitoring	nd
RWMC M7S	433023113014801	43.506173	-113.030940	5,005	628	598–628	576	22–52	Basalt	Monitoring	nd
RWMC Production	433002113021701	43.500462	-113.038887	5,005	685	590–685	568	22–117	Basalt	Production	2.36
USGS 87	433013113024201	43.503445	-113.046126	5,018	673	585–640	587	0–53	Basalt	Monitoring	0.99
USGS 88	432940113030201	43.494407	-113.051377	5,021	663	587–635	590	0–45	Basalt	Monitoring	-0.77
USGS 90	432954113020501	43.497809	-113.035793	5,010	626	577–626	583	0–43	Basalt	Monitoring	1.20
USGS 120	432919113031501	43.488570	-113.054724	5,040	705	638–705	617	21–88	Basalt	Monitoring	3.36
Test Area North											
TAN Disposal	435053112423201	43.847963	-112.709715	4,781	310	180–305	195	0–110	Basalt	Disposal	nd
TDD 1	435042112420901	43.844907	-112.703326	4,800	315	75–315	206	0–109	Basalt	Disposal	nd
TDD 2	435054112423201	43.848240	-112.709715	4,784	252	117–252	197	0–55	Basalt	Disposal	nd
USGS 24	435053112420801	43.847343	-112.704254	4,795	326	255–325	220	35–105	Basalt	Monitoring	2.30

Table 11. Site information, including site name, U.S. Geological Survey site number, location, altitude, well depth, open interval, approximate depth to water, depth of open intervals below water table, aquifer material, water use, and hydraulic conductivity, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	USGS site No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude of land surface (ft)	Depth of well (ft bls)	Extent of open intervals (ft bls)	Depth to water table (ft bls)	Depth of open intervals below water table (ft bwt)	Aquifer material	Water use	Estimated hydraulic conductivity (ft/d as log K)
Natural groundwater											
North INL Area											
ANP 6	435152112443101	43.864232	-112.742880	4,794	295	211–296	220	9–76	Basalt	Production	3.83
ANP 8	434952112411301	43.831018	-112.687769	4,789	309	220–300	209	11–91	Basalt	Production	nd
IET 1 Disposal	435153112420501	43.864735	-112.702276	4,790	242	219–319	214	5–105	Basalt	Disposal	0.20
No Name 1	435038112453401	43.844015	-112.759928	4,784	500	267–550	212	55–338	Basalt	Monitoring	-0.49
PSTF Test	434941112454201	43.827890	-112.762344	4,786	319	190–316	214	0–102	Basalt	Production	1.76
TDD 3	435116112430301	43.854351	-112.718326	4,803	300	156–300	195	0–105	Basalt	Disposal	nd
Northeast INL Area											
ANP 9	434856112400001	43.815382	-112.667591	4,786	322	237–314	227	10–87	Basalt	Monitoring	2.54
USGS 26	435212112394001	43.869504	-112.662141	4,789	267	232–267	214	18–53	Basalt	Monitoring	4.38
USGS 27	434851112321801	43.814136	-112.539402	4,784	312	250–308	229	21–79	Basalt	Monitoring	1.20
USGS 29	434407112285101	43.735148	-112.481441	4,877	426	363–425	359	4–66	Basalt	Monitoring	3.15
USGS 31	434625112342101	43.773769	-112.573173	4,786	428	285–428	259	26–169	Basalt	Monitoring	2.08
USGS 32	434444112322101	43.745484	-112.540052	4,812	392	306–392	294	12–98	Basalt	Monitoring	3.81
Southeast INL Area											
Arbor Test 1	433509112384801	43.585720	-112.647491	5,164	790	680–787	682	0–105	Basalt	Production	3.75
Area II	433223112470201	43.539525	-112.784826	5,129	876	676–876	673	3–203	Basalt	Monitoring	2.88
Atomic City	432638112484101	43.443798	-112.812214	5,017	639	35–639	587	0–52	Basalt	Production	nd
Leo Rogers 1	432533112504901	43.425743	-112.847771	5,039	720	14–702	613	0–89	Basalt	Stock	nd
USGS 1	432700112470801	43.449932	-112.786530	5,022	630	600–630	590	10–40	Basalt	Monitoring	>4.04
USGS 2	433320112432301	43.555428	-112.723402	5,125	699	675–695	662	13–33	Basalt	Monitoring	3.26
USGS 14	432019112563201	43.338596	-112.943029	5,133	752	720–723	717	3–6	Basalt	Monitoring	2.78
USGS 100	433503112400701	43.583998	-112.669342	5,158	750	662–750	678	0–72	Basalt	Monitoring	2.26
USGS 107	432942112532801	43.494913	-112.891808	4,918	690	270–690	482	0–208	Basalt	Monitoring	2.52
USGS 110A	432717112501502	43.454667	-112.838248	4,999	644	240–657	566	0–91	Basalt	Monitoring	nd
Central INL Area											
Badging Facility well	433042112535101	43.511574	-112.898328	4,935	644	533–644	~491	~42–153	Basalt	Production	nd
NPR Test	433449112523101	43.580305	-112.876179	4,933	600	500–535	467	33–68	Basalt	Monitoring	2.38
USGS 5	433543112493801	43.595116	-112.827952	4,938	494	475–497	471	4–26	Basalt	Monitoring	-0.30
USGS 6	434031112453701	43.675219	-112.761009	4,899	620	532–620	417	115–203	Basalt	Monitoring	0.66
USGS 17	433937112515401	43.660024	-112.865904	4,833	498	438–498	359	79–139	Basalt	Monitoring	0.65
USGS 18	434540112440901	43.761213	-112.736740	4,804	329	298–322	275	23–47	Basalt	Monitoring	3.26
USGS 83	433023112561501	43.506305	-112.938407	4,941	752	516–752	501	15–251	Basalt	Monitoring	0.58
USGS 103	432714112560701	43.453678	-112.935976	5,007	1,297	575–760	586	0–174	Basalt	Monitoring	2.94

Table 11. Site information, including site name, U.S. Geological Survey site number, location, altitude, well depth, open interval, approximate depth to water, depth of open intervals below water table, aquifer material, water use, and hydraulic conductivity, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	USGS site No.	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude of land surface (ft)	Depth of well (ft bls)	Extent of open intervals (ft bls)	Depth to water table (ft bls)	Depth of open intervals below water table (ft bwt)	Aquifer material	Water use	Estimated hydraulic conductivity (ft/d as log K)
Natural groundwater—Continued											
Northwest INL Area											
Fire Station 2	433548112562301	43.596573	-112.940553	4,902	510	427–511	420	7–91	Basalt	Production	nd
INEL-1 WS	433716112563601	43.620612	-112.945248	4,872	490	340–595	401	0–194	Basalt	Production	0.25
NRF 2	433854112545401	43.648234	-112.915858	4,850	528	373–448	375	0–73	Basalt	Production	nd
NRF 7	433920112543601	43.656440	-112.909383	4,843	415	365–415	369	0–46	Basalt	Monitoring	nd
NRF 8	433843112550901	43.644776	-112.920625	4,853	420	373–423	378	0–45	Basalt	Monitoring	nd
Site 4	433617112542001	43.604907	-112.906385	4,795	495	422–497	401	21–96	Basalt	Monitoring	nd
Site 17	434027112575701	43.674000	-112.966527	4,880	600	15–600	403	0–197	Basalt	Monitoring	1.83
Site 19	433522112582101	43.589440	-112.973468	4,926	860	472–842	471	1–371	Basalt	Monitoring	2.23
USGS 12	434126112550701	43.690514	-112.919470	4,819	563	unk	335	<228	Basalt	Monitoring	2.00
USGS 19	434426112575701	43.740650	-112.966550	4,800	399	285–306	279	6–27	Basalt	Monitoring	3.53
USGS 22	433422113031701	43.572761	-113.056692	5,048	657	619–657	614	5–43	Basalt	Monitoring	<-0.77
USGS 23	434055112595901	43.681892	-113.000839	4,884	458	410–430	405	5–25	Basalt	Monitoring	3.64
USGS 97	433807112551501	43.635120	-112.922153	4,858	510	388–510	386	2–124	Basalt	Monitoring	2.76
USGS 98	433657112563601	43.615740	-112.944164	4,883	508	400–500	415	0–85	Basalt	Monitoring	2.92
USGS 99	433705112552101	43.617612	-112.923375	4,872	440	303–450	400	0–50	Basalt	Monitoring	3.23
USGS 102	433853112551601	43.647370	-112.922061	4,850	445	359–445	378	0–67	Basalt	Monitoring	2.40
USGS 134	433611112595819	43.603003	-113.000352	4,969	590	554–588	513	41–75	Basalt	Monitoring	nd
Southwest INL Area											
Highway 3	433256113002501	43.548795	-113.007776	4,981	750	680–750	538	142–212	Basalt	Domestic	>0.52
Middle 2051	433217113004905	43.537943	-113.014548	4,997	999	564–610	571	0–39	Basalt	Monitoring	nd
USGS 8	433121113115801	43.522269	-113.200122	5,195	812	782–812	770	12–42	Basalt	Monitoring	2.84
USGS 9	432740113044501	43.458901	-113.078549	5,030	654	618–654	610	8–44	Basalt	Monitoring	3.32
USGS 11	432336113064201	43.393290	-113.112645	5,067	704	673–704	655	18–49	Basalt	Monitoring	>3.36
USGS 86	432935113080001	43.492903	-113.134568	5,077	691	48–691	652	0–39	Basalt	Monitoring	0.81
USGS 89	433005113032801	43.501481	-113.059646	5,030	637	576–646	604	0–42	Basalt	Monitoring	-0.06
USGS 117	432955113025901	43.498379	-113.050463	5,012	655	550–655	588	0–67	Basalt	Monitoring	-0.72
USGS 119	432945113023401	43.495632	-113.043524	5,032	705	639–705	685	0–20	Basalt	Monitoring	-2.00
USGS 125	432602113052801	43.433076	-113.092603	5,051	774	620–774	630	0–144	Basalt	Monitoring	nd
USGS 135	432753113093613	43.464759	-113.160730	5,136	861	727–762	719	8–43	Basalt	Monitoring	nd

Table 12. Measurements of field parameters and helium and the calculated partial pressure of carbon dioxide, Idaho National Laboratory and vicinity, eastern Idaho.

[Data from Busenberg and others (2000), Rattray (2015), Knobel and others (1992, 1999a, 1999b), U.S. Geological Survey National Water Information System (2014), Swanson and others (2002, 2003), Carkeet and others (2001), Bartholomay and Twining (2010), Bartholomay and others (2015), and Mann (1986). Springs are shown in *italics*. Locations of sites shown in figures 8–9. **Site name:** Alternate names used in other reports shown in table 10. **Alkalinity:** Concentrations for data from Busenberg and others (2000) and Knobel and others (1992) were calculated from bicarbonate concentrations using the equation in Hem (1992). **Dissolved oxygen (DO):** Values preceded by a ≈ symbol indicate that no measurement of DO was made on the date shown and that the DO value was estimated as the mean value of all DO measurements for that site in NWIS through December 2015. **Carbon dioxide:** Calculated with PHREEQC (Parkhurst and Appelo, 2013). **Abbreviations:** cm^3 STP/g, cubic centimeters per gram at 0 °C and one atmosphere; INL, Idaho National Laboratory; mg/L, milligram per liter; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; nd, not determined; sz, shallowest zone. Units: pH, negative base-10 logarithm of the hydrogen ion activity; Log PCO_2, base-10 logarithm of carbon dioxide partial pressure. Symbols: °C, degrees Celsius; <, less than]

Site name	Date sampled	Temperature (°C)	pH	Specific conductance (µS/cm at 25 °C)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Carbon dioxide (Log PCO_2)	Helium ([cm^3 STP/g] × 10^{-8})
Surface water								
Big Lost River at Mackay Dam	06-28-1995	13.1	8.2	nd	89	≈10.3	-3.2	nd
Big Lost River at bridge near Mackay	06-17-1995	11.0	8.1	299	86	≈8.5	-3.2	nd
Big Lost River near Arco	06-05-1981	13	8.1	374	164	8.8	-2.9	nd
Big Lost River below INL Diversion	06-02-1995	15	8.4	262	108	7.2	-3.4	nd
Big Lost River near Atomic City	10-01-1965	6	8.2	356	171	nd	-3.0	nd
Big Lost River below lower Lincoln Blvd Br	06-19-1995	12.5	7.7	[1]337	101	nd	-2.7	nd
Birch Creek at Kaufman Guard Station	06-27-2000	16.5	8.6	320	134	10.0	-3.5	nd
Birch Creek at Blue Dome	06-28-1995	9.4	8.5	[2]326	165	≈9.2	-3.3	nd
Camas Creek below diversion near CNWR	08-08-2011	19.3	7.8	147	76	5.8	-2.9	nd
Little Lost River near Clyde	06-27-2000	12.0	8.4	245	107	9.1	-3.4	nd
Little Lost River near Howe	06-28-1995	14.1	8.1	[3]324	98	≈9.2	-3.1	nd
Mud Lake near Terreton	06-17-1995	14.7	8.5	276	103	≈8.4	-3.5	nd
Tributary valley groundwater								
Big Lost River Valley								
Arco City Well 4	05-13-1997	9.6	8.0	392	175	6.3	-2.8	6.2
Coates	06-01-1999	6.5	7.2	180	73	8.1	-2.3	nd
Fulton	06-02-1999	7.9	7.5	534	243	9.2	-2.1	nd
Hill	06-02-1999	8.9	8.0	238	101	9.6	-3.0	nd
Lambert	06-03-1999	8.7	7.6	389	175	3.6	-2.4	nd
MSR	06-01-1999	7.3	8.0	231	99	7.2	-3.0	nd
Muffett	06-03-1999	10.3	7.4	486	221	8.2	-2.1	nd
Owen	06-23-1999	9.5	7.6	458	199	6.1	-2.3	nd
Wheeler	06-02-1999	9.6	7.6	483	206	6.8	-2.3	nd
Wildhorse Guard Station	06-02-1999	7.1	8.0	342	158	<0.2	-2.8	nd
Little Lost River Valley								
Harrell	07-31-2000	10.5	7.4	557	213	8.3	-2.1	nd
Mays	06-26-2000	15.0	7.9	290	128	7.1	-2.8	nd
Nicholson	07-31-2000	11.0	7.6	964	184	7.2	-2.4	nd
Oar	06-28-2000	8.5	7.8	346	157	7.4	-2.6	nd
Pancheri	05-13-1997	8.2	8.0	359	153	8.2	-2.8	10.0
Ruby Farms	05-10-1991	10.0	7.9	550	167	9.6	-2.7	nd
Sorenson	07-31-2000	7.0	8.0	255	125	7.3	-2.9	nd

Table 12. Measurements of field parameters and helium and the calculated partial pressure of carbon dioxide, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Temperature (°C)	pH	Specific conductance (µS/cm at 25 °C)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Carbon dioxide (Log PCO_2)	Helium ([cm^3 STP/g] × 10^{-8})
				Birch Creek Valley				
Kaufman Guard Station	06-27-2000	11.0	8.1	373	193	<0.2	-2.8	nd
McKinney	06-13-1991	8.0	7.9	352	149	5.4	-2.7	nd
P&W2	04-19-1995	9.5	8.2	340	140	9.7	-3.1	4.1
USGS 126b	11-08-2000	10.5	8.2	344	133	10.3	-3.1	nd
Wagoner	05-22-1997	7.0	7.8	376	173	nd	-2.6	6.3
Wagoner Ranch	06-28-2000	11.0	7.6	443	182	8.4	-2.3	nd
				Beaverhead Mountains				
ML 55	*06-05-2012*	*12.8*	*7.8*	*338*	*138*	*7.7*	*-2.7*	*nd*
ML 59	*06-05-2012*	*7.3*	*7.4*	*258*	*124*	*8.6*	*-2.4*	*nd*
				Regional groundwater				
Highway 2	10-16-1952	12.0	7.8	275	120	nd	-2.7	nd
Kettle Butte Farms	06-29-1995	11.7	8.1	341	137	≈8.8	-3.0	nd
ML 2	07-30-2007	13.2	7.7	311	117	7.2	-2.6	nd
ML 5	08-09-2011	14.4	7.9	292	110	8.3	-2.8	nd
ML 6	08-08-2011	12.1	8.3	249	112	8.1	-3.3	nd
ML 9	08-23-2011	12.9	7.6	370	151	≈5.9	-2.4	nd
ML 12	08-09-2011	12.8	7.8	301	136	4.8	-2.7	nd
ML 13	07-30-2008	13.2	7.7	313	124	7.8	-2.6	nd
ML 15	06-19-2007	12.1	7.6	293	114	7.8	-2.5	nd
ML 18	09-23-2009	13.2	7.9	265	110	9.5	-2.8	nd
ML 17	06-04-2012	9.0	7.8	344	117	8.1	-2.7	nd
ML 19	05-14-1997	11.0	7.7	722	230	nd	-2.4	7.2
ML 22	10-15-1996	11.0	7.8	727	279	7.7	-2.4	4.8
ML 23	08-29-1989	14.6	7.9	613	184	nd	-2.6	nd
ML 24	06-06-2012	10.5	7.3	929	272	6.9	-1.9	nd
ML 25	06-11-1991	12.5	8.1	282	127	0.1	-3.0	41.8
ML 26	09-06-2006	11.6	7.4	489	198	11.1	-2.1	nd
ML 27	06-26-2008	17.7	8.2	307	119	3.4	-3.1	nd
ML 28	07-06-2006	11.2	7.6	557	166	9.3	-2.4	nd
ML 29	06-12-1991	12.5	8.5	335	156	0.7	-3.3	nd
ML 30	06-06-2012	12.9	7.4	848	384	7.4	-1.8	nd
ML 31	06-06-2012	11.2	7.3	692	244	4.5	-1.9	nd
ML 33	07-17-2002	12.2	7.3	1,100	186	8.3	-2.0	nd
ML 34	09-04-2001	16.4	7.6	502	157	7.8	-2.4	nd
Reno Ranch	06-28-2000	14.0	7.6	481	190	6.4	-2.3	nd
SE of Atomic City	06-27-1995	14.3	8.1	277	114	≈7.9	-3.0	nd
USGS 3A	10-22-1952	13.0	8.0	276	122	nd	-2.9	nd
USGS 101	10-10-1996	13.9	8.2	282	120	7.2	-3.1	10.2

Table 12. Measurements of field parameters and helium and the calculated partial pressure of carbon dioxide, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Temperature (°C)	pH	Specific conductance (µS/cm at 25 °C)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Carbon dioxide (Log PCO_2)	Helium ([cm^3 STP/g] × 10^{-8})
Geothermal water								
INEL-1 2,000 feet	03-24-1979	34	8.2	[4]645	210	[5]oxic	-2.8	nd
INEL-1 10,300 feet	07-20-1979	57	7.9	[4]1,878	740	[5]anoxic	-1.8	nd
ML 57	*11-27-2000*	*48.4*	*7.2*	*694*	*138*	*5.9*	*-1.8*	*120*
ML 58	*06-05-2012*	*27.8*	*7.1*	*430*	*166*	*1.8*	*-1.8*	*nd*
Groundwater at the Idaho National Laboratory								
Deep groundwater								
EBR 1	10-16-1996	18.8	8.2	279	116	6.7	-3.1	5.5
Site 9	07-22-1996	13.7	8.1	350	139	6.8	-3.0	12.7
Site 14	10-14-1996	16.3	8.0	341	131	6.8	-2.9	38.4
USGS 7	10-14-1996	18.8	8.1	300	122	3.9	-3.0	149
USGS 15	06-14-1995	11.6	8.0	319	137	≈6.4	-2.9	23.0
Contaminated groundwater								
Advanced Test Reactor Complex								
USGS 65	05-16-1991	14.0	8.0	600	123	8.6	-2.9	nd
Idaho Nuclear Technology and Engineering Center								
CFA 1	07-16-1996	12.3	7.9	567	131	9.5	-2.8	6.2
CFA 2	07-16-1996	12.1	7.9	745	122	8.4	-2.8	5.2
USGS 20	05-30-1991	13.0	8.0	348	120	8.6	-2.9	nd
USGS 36	07-16-1996	12.6	8.0	489	163	≈8.3	-2.8	4.5
USGS 57	05-13-1991	14.5	7.8	690	121	8.3	-2.7	nd
USGS 82	07-16-1996	12.3	8.1	343	125	9.1	-3.0	5.6
USGS 85	06-04-1991	13.0	8.0	518	153	9.0	-2.8	nd
USGS 104	07-15-1996	12.3	8.1	327	128	9.0	-3.0	11.5
USGS 105	04-18-1995	13.7	8.1	384	148	9.5	-2.9	5.3
USGS 108	04-19-1995	12.8	8.1	358	135	8.7	-3.0	nd
USGS 109	10-11-1996	13.6	8.1	375	148	7.7	-2.9	4.6
USGS 112	07-15-1996	13.6	8.0	839	142	6.6	-2.9	5.4
USGS 113	07-16-1996	13.1	8.0	1,063	135	9.0	-2.9	5.4
USGS 115	07-15-1996	13.3	8.1	407	120	8.4	-3.0	6.9
USGS 116	07-15-1996	12.7	8.2	580	100	9.2	-3.2	6.2
USGS 124	10-09-1996	13.6	8.0	367	144	≈7.4	-2.8	6.2
Naval Reactors Facility								
NRF 6	09-05-1996	11.5	7.8	1,480	173	≈8.4	-2.6	nd
NRF 9	09-04-1996	11.5	8.1	647	205	≈8.3	-2.8	nd
NRF 10	09-04-1996	11.5	8.1	608	200	≈7.6	-2.8	nd

Table 12. Measurements of field parameters and helium and the calculated partial pressure of carbon dioxide, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Temperature (°C)	pH	Specific conductance (µS/cm at 25 °C)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Carbon dioxide (Log PCO_2)	Helium ([cm^3 STP/g] × 10^{-8})
Naval Reactors Facility—Continued								
NRF 11	09-05-1996	11.5	8.0	631	198	≈7.8	-2.7	nd
NRF 12	09-05-1996	11.5	8.0	684	201	≈8.0	-2.7	nd
NRF 13	09-05-1996	16.5	8.5	540	93	≈7.3	-3.5	nd
Radioactive Waste Management Complex								
RWMC M3S	07-22-1996	13.7	8.1	368	144	≈7.4	-2.9	6.4
RWMC M7S	07-22-1996	13.8	8.2	351	141	≈6.4	-3.0	5.6
RWMC Production	03-23-1989	13.0	8.1	358	148	8.2	-2.9	nd
USGS 87	04-05-1989	14.0	8.1	360	111	10.2	-3.0	nd
USGS 88	04-04-1989	14.0	8.2	600	93	8.5	-3.2	nd
USGS 90	04-05-1989	13.5	8.1	383	120	9.6	-3.0	nd
USGS 120	07-17-1996	12.0	8.2	444	153	10.2	-3.0	4.9
Test Area North								
TAN Disposal	03-07-1989	15.0	8.0	945	229	<0.2	-2.6	nd
TDD 1	03-02-1989	11.0	8.0	525	122	2.4	-2.9	nd
TDD 2	03-06-1989	12.5	7.9	820	194	4.2	-2.6	nd
USGS 24	02-28-1989	11.0	8.0	645	176	6.3	-2.8	nd
Natural groundwater								
North INL Area								
ANP 6	07-19-1996	13.3	8.0	407	148	8.3	-2.8	5.9
ANP 8	12-13-1989	10.0	8.2	376	127	10.5	-2.9	nd
IET 1 Disposal	07-18-1996	14.0	7.9	427	155	0.7	-2.7	6.1
No Name 1	10-14-1996	10.4	8.1	346	114	12.2	-3.1	9.7
PSTF Test	10-14-1996	13.3	8.2	301	135	≈8.2	-3.1	5.9
TDD 3	12-13-1989	9.5	7.8	400	127	9.2	-2.5	nd
Northeast INL Area								
ANP 9	10-14-1996	13.9	8.1	378	145	7.5	-2.9	15.8
USGS 26	10-15-1996	14.9	8.0	391	151	7.6	-2.8	27.7
USGS 27	10-15-1996	15.5	8.0	568	140	5.3	-2.9	32.4
USGS 29	06-15-1995	12.7	8.0	432	157	7.4	-2.8	16.3
USGS 31	07-19-1996	15.8	8.0	405	133	7.3	-2.9	20.6
USGS 32	06-15-1995	14.6	7.9	506	134	8.0	-2.8	6.1
Southeast INL Area								
Arbor Test 1	10-10-1996	13.5	8.0	348	133	8.3	-2.9	8.4
Area II	07-18-1996	14.3	8.1	364	139	≈7.7	-2.9	15.5
Atomic City	10-09-1996	14.2	8.2	356	138	≈7.9	-3.1	5.2
Leo Rogers 1	07-17-1996	14.5	8.1	370	140	≈7.2	-2.9	6.7

Table 12. Measurements of field parameters and helium and the calculated partial pressure of carbon dioxide, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Temperature (°C)	pH	Specific conductance (µS/cm at 25 °C)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Carbon dioxide (Log PCO_2)	Helium ([cm^3 STP/g] × 10^{-8})
Natural groundwater—Continued								
Southeast INL Area—Continued								
USGS 1	10-09-1996	14.6	8.2	316	130	7.9	-3.1	10.9
USGS 2	07-17-1996	13.9	8.1	353	136	8.0	-3.0	6.4
USGS 14	10-09-1996	14.7	8.2	387	138	5.1	-3.1	4.8
USGS 100	04-21-1995	13.5	8.1	383	135	9.5	-3.0	9.8
USGS 107	10-09-1996	14.9	8.1	399	144	9.1	-2.9	7.0
USGS 110A	10-09-1996	14.8	8.1	378	142	≈6.3	-2.9	9.7
Central INL Area								
Badging Facility well	07-16-1996	12.1	8.1	354	133	≈8.2	-3.0	4.0
NPR Test	10-10-1996	12.2	8.1	385	160	9.2	-2.9	5.7
USGS 5	10-10-1996	14.9	8.1	331	139	≈6.6	-2.9	6.9
USGS 6	07-18-1996	14.1	8.1	299	120	≈5.6	-3.0	11.7
USGS 17	06-13-1995	13.5	8.2	298	124	8.8	-3.1	9.1
USGS 18	07-19-1996	15.6	8.0	345	138	≈5.8	-2.8	28.8
USGS 83	04-11-1995	11.8	8.2	282	101	6.1	-3.2	nd
USGS 103	07-15-1996	13.9	8.3	363	137	8.7	-3.2	5.0
Northwest INL Area								
Fire Station 2	10-16-1996	11.3	8.0	447	167	9.1	-2.8	4.6
INEL-1 WS	06-12-1995	12.5	7.9	621	160	11.4	-2.7	nd
NRF 2	05-23-1989	12.5	7.7	680	213	9.0	-2.4	nd
NRF 7	09-03-1996	17.0	8.5	236	106	≈7.0	-3.5	nd
NRF 8	09-04-1996	11.5	8.0	595	214	≈8.2	-2.7	nd
Site 4	10-16-1996	11.3	8.1	369	157	≈7.5	-2.9	5.9
Site 17	06-16-1995	12.3	7.9	414	180	8.1	-2.6	nd
Site 19	07-16-1996	15.2	8.0	387	164	8.1	-2.8	4.7
USGS 12	06-14-1995	12.0	7.8	602	214	≈8.0	-2.5	4.3
USGS 19	10-15-1996	16.9	7.8	396	168	6.9	-2.5	6.1
USGS 22	06-13-1995	[6]20.0	7.9	410	71	≈2.2	-3.0	4.7
USGS 23	04-19-1995	15.4	7.9	357	149	7.5	-2.7	9.2
USGS 97	06-13-1995	11.5	7.9	597	221	9.2	-2.6	4.6
USGS 98	06-12-1995	12.3	8.0	430	171	10.1	-2.8	5.5
USGS 99	06-12-1995	11.8	7.9	528	203	8.6	-2.6	4.5
USGS 102	06-13-1995	11.6	7.9	590	217	≈8.3	-2.6	4.7
USGS 134 (sz)	09-04-2008	12.9	7.9	313	128	10.0	-2.8	nd

Table 12. Measurements of field parameters and helium and the calculated partial pressure of carbon dioxide, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Temperature (°C)	pH	Specific conductance (µS/cm at 25 °C)	Alkalinity (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Carbon dioxide (Log PCO_2)	Helium ([cm^3 STP/g] × 10^{-8})
Natural groundwater—Continued								
Southwest INL Area								
Highway 3	10-12-1984	14.7	8.3	343	151	9.2	-3.1	nd
Middle 2051 (sz)	08-25-2008	10.5	7.5	346	154	10.5	-2.3	nd
USGS 8	10-08-1996	11.4	8.0	376	165	8.0	-2.8	4.3
USGS 9	10-11-1996	11.4	8.2	396	141	8.2	-3.1	6.3
USGS 11	04-20-1995	11.7	8.1	366	142	8.2	-3.0	5.1
USGS 86	10-11-1996	10.0	8.3	332	109	11.4	-3.3	7.4
USGS 89	07-17-1996	13.1	8.6	385	84	11.6	-3.7	6.1
USGS 117	07-17-1996	13.4	8.3	277	99	7.0	-3.3	6.3
USGS 119	04-03-1989	15.0	8.3	298	94	8.4	-3.3	nd
USGS 125	06-16-1995	12.8	8.0	379	146	≈6.9	-2.8	5.0
USGS 135 (sz)	09-14-2010	11.6	7.9	330	136	6.6	-2.8	nd

[1] Specific conductance measurement from 1996.

[2] Specific conductance measurement from 04-14-1995.

[3] Specific conductance measurements from 10-17-1995.

[4] Specific conductance was estimated by dividing the dissolved solids concentration by 0.543 (Olmsted, 1962).

[5] These geothermal waters were assumed to be oxic or anoxic based on their concentrations of uranium and iron.

[6] The temperature of 20.0 °C measured from well USGS 22 may not reflect the ambient groundwater temperature at this well. The estimated hydraulic conductivity for this well was small (log K of <-0.77 ft/d; table 11), the well pumps slowly (about 2.5 gal/min), and the groundwater temperature in the well increases with increased pumping time. These factors indicate that heat from the pump motor warms the water in this well during pumping. The initial water pumped from this well during each site visit has a temperature of about 15 °C, and this temperature probably represents the ambient groundwater temperature at this well.

Table 13. Concentrations of major ions, silica, and the charge balance for each water-quality analysis, Idaho National Laboratory and vicinity, eastern Idaho.

[Data from Busenberg and others (2000); Rattray (2015); Knobel and others (1992, 1999a, 1999b); Swanson and others (2002, 2003); Carkeet and others (2001); Bartholomay and Twining (2010); Bartholomay and others (2015); Mann (1986); Johnson and others (2000); and U.S. Geological Survey (2014). Springs are shown in *italics*; All concentrations except nitrate are in milligrams per liter, nitrate (nitrite plus nitrate) in milligrams per liter as nitrogen. Location of sites shown on figures 8–9. **Site name:** Alternate names used in other reports shown in table 10. **Bicarbonate:** Concentrations from Busenberg and others (2000) were calculated from alkalinity using the equation in Hem (1992). **Carbonate:** Concentrations calculated with PHREEQC (Parkhurst and Appelo, 2013). **Sulfate:** Values in parantheses indicate a sulfate concentration was reported for anoxic water. **Abbreviations:** INL, Idaho National Laboratory; nc, not calculated; nd, not determined; sz, shallowest zone; <, less than]

Site name	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Chloride	Sulfate	Fluoride	Nitrate	Silica	Charge balance (percent)
Surface water												
Big Lost River at Mackay Dam	26.1	6.3	3.8	1.3	108	0.69	2.3	13.1	0.19	nd	8.7	-2.9
Big Lost River at bridge near Mackay	25.9	6.3	3.8	1.4	105	0.50	2.3	12.6	0.18	0.1	9.1	-1.7
Big Lost River near Arco	48	12	7.1	1.6	200	1.06	4.8	27	0.2	0.1	13	-3.8
Big Lost River below INL Diversion	35	8	5.4	1.4	132	1.40	3	18	0.2	<0.05	12	1.7
Big Lost River near Atomic City[1]	46.7	11.4	6.6	1.3	208	1.12	5	nd	0.3	nd	5.2	nd
Big Lost River below lower Lincoln Blvd Br	31.2	7.4	4.8	1.7	123	0.25	3.1	17.5	0.21	0.2	10.7	-1.7
Birch Creek at Kaufman Guard Station	38	15	5.1	0.9	163	2.81	4.6	23	0.22	0.1	10	2.7
Birch Creek at Blue Dome	41.9	15.1	5.2	0.9	201	2.35	4.8	25.3	0.18	0.2	7.7	-4.2
Camas Creek below diversion near CNWR	19	4.7	3.6	2.0	91	0.27	1.0	1.4	0.11	<0.02	18	-0.7
Little Lost River near Clyde	30	10	2.8	0.6	130	1.28	2.2	11.4	0.12	<0.05	9.2	0.8
Little Lost River near Howe	26.8	8.7	4.0	1.2	120	0.63	3.8	8.5	0.10	0.1	10.1	-0.6
Mud Lake near Terreton	28.4	6.5	5.2	2.1	125	1.55	2.5	4.3	0.12	[3]0.25	14.7	-1.2
Tributary valley groundwater												
Big Lost River Valley												
Arco City Well 4	53.5	13.5	5.4	1.0	209	0.83	6.5	19.9	0.20	0.6	13.4	-0.8
Coates	24	5.2	3.1	0.6	89	0.05	1.6	12	0.18	0.1	8.7	0.2
Fulton	74	24	3.6	1.3	296	0.36	9.5	21	0.32	1.8	15	1.2
Hill	29	6.0	8.3	1.0	123	0.45	2.8	14	0.20	0.2	13	-2.1
Lambert	52	12	5.8	1.3	213	0.32	4.5	19	0.24	0.3	12	-2.4
MSR	33	7.6	3.9	0.9	121	0.42	2.7	13	0.15	0.2	14	2.1
Muffett	65	21	9.8	1.2	269	0.28	7.7	20	0.41	0.8	20	2.8
Owen	68	14	7.4	1.2	243	0.38	6.3	23	0.19	2.1	16	0.9
Wheeler	66	15	9.9	1.2	251	0.40	7.5	26	0.18	1.6	14	-0.1
Wildhorse Guard Station	42	15	7.7	1.2	193	0.68	2.6	[4](17)	0.21	<0.05	12	0.9
Little Lost River Valley												
Harrell	63	22	17	1.3	259	0.27	21.6	34.4	0.16	1.9	19	0.0
Mays	28	13	12	1.4	156	0.54	5.6	15.0	0.14	0.4	21	-0.9
Nicholson	85	45	27	1.8	225	0.39	143	60.3	<0.1	4.2	23	-0.7
Oar	40	15	5.7	0.9	191	0.45	6.2	10.5	<0.1	0.5	14	-1.1
Pancheri	43.6	14.5	5.8	0.9	186	0.69	10.1	15.5	0.15	0.4	14.0	-1.0
Ruby Farms	62	23	14	1.6	204	0.65	50	32	<0.1	2.9	19	-0.2
Sorenson	32	11	4	0.9	153	0.53	2.6	5.0	0.13	0.2	17	-0.5

Table 13. Concentrations of major ions, silica, and the charge balance for each water-quality analysis, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Chloride	Sulfate	Fluoride	Nitrate	Silica	Charge balance (percent)
Tributary Valley groundwater—Continued												
Birch Creek Valley												
Kaufman Guard Station	29	24	12	5.2	235	1.18	3.2	[4](3.9)	0.58	<0.05	62	-0.2
McKinney	45	15	5.4	1.0	182	0.53	5.4	26	0.2	0.3	10	0.2
P&W2	38.0	14.3	7.5	1.2	171	1.02	5.5	25.8	0.19	0.3	12.1	-1.9
USGS 126b	38	15	8.7	2.3	162	1.00	8.2	29	0.23	0.5	18	-0.1
Wagoner	48.6	15.8	5.1	1.1	201	0.48	5.5	21.9	0.22	0.2	11.9	0.4
Wagoner Ranch	46	19	17	1.1	222	0.36	9.6	29	0.19	0.4	10	0.7
Beaverhead Mountains												
ML 55	*46.9*	*7.7*	*11.4*	*2.9*	*164*	*0.45*	*15.8*	*15.9*	*0.43*	*0.9*	*29*	*-0.3*
ML 59	*39.0*	*8.9*	*3.2*	*0.7*	*149*	*0.13*	*3.4*	*9.3*	*0.10*	*0.7*	*8*	*0.8*
Regional groundwater												
Highway 2	26	9.3	18.0	2.3	140	0.37	8.2	13	0.9	0.4	32	0.3
Kettle Butte Farms	36	10	15	2.9	167	0.84	11	14	1	1.0	35	-2.1
ML 2	31.5	9.5	14.5	2.7	140	0.30	7.7	14.0	0.89	3.2	37	-0.6
ML 5	29.8	10.3	10.8	2.7	131	0.46	15.0	12.7	0.25	0.7	34	-0.7
ML 6	29.9	8.3	9.0	2.4	131	1.07	5.6	9.3	0.49	1.7	34	-1.1
ML 9	41.0	11.8	14.9	2.7	181	0.31	12.3	13.8	0.48	2.1	34	-0.7
ML 12	31.8	9.6	13.2	2.9	162	0.43	9.5	9.1	0.41	1.0	34	-3.1
ML 13	32.1	9.3	14.8	2.9	148	0.32	8.8	11.7	1.01	2.5	37	-1.2
ML 15	27.7	9.6	17.6	3.1	137	0.23	12.6	10.9	0.54	1.2	34	1.1
ML 17	37.2	11.7	14.7	3.8	140	0.34	25.7	16.1	0.53	1.3	46	0.9
ML 18	28.0	8.6	11.9	2.8	132	0.44	9.8	8.9	0.45	1.5	35	-1.5
ML 19	68.7	28.6	38.2	5.8	281	0.60	55.0	42.1	0.19	5.3	32	1.0
ML 22	68.9	26.0	37.9	6.8	340	0.92	40.4	31.9	0.21	4.9	28	-2.4
ML 23	42	14	56	6.5	218	0.81	43	30	0.40	4.1	29	0.8
ML 24	109	33.0	47.3	5.4	322	0.29	93.0	91.3	0.16	2.9	34	1.6
ML 25	22	4.6	28	4.8	151	0.79	6.8	7(8.3)	0.90	0.1	48	-1.7
ML 26	65.2	16.1	12.7	3.5	237	0.26	16.2	36.9	0.36	1.5	35	-0.2
ML 27	14.6	6.3	37.2	6.8	140	1.06	12.7	17.2	0.64	0.1	33	-0.8
ML 28	67.1	16.7	15.7	4.1	202	0.34	47.5	39.5	0.25	1.7	37	-0.9
ML 29	19	17	23	4.3	181	2.40	10	9.8	0.50	0.1	29	-1.5
ML 30	74.6	26.7	85.0	7.2	468	0.55	36.1	29.3	0.15	8.5	27.5	-0.7
ML 31	75.0	20.7	51.6	4.8	291	0.26	46.2	52.8	0.22	4.4	37	2.0
ML 33	113	37.8	39.7	7.3	226	0.21	166	86.3	0.28	5.5	37.3	0.3
ML 34	41.9	15.1	40.0	3.4	192	0.37	24.1	59.4	0.54	1.5	35.6	-0.5
Reno Ranch	49	24	12	2.9	232	0.41	12.0	34.0	1.5	0.6	41	0.3
SE of Atomic City	26.0	8.8	14	2.7	139	0.74	7.5	10	1.20	0.6	36	-2.3
USGS 3A	29.0	9.5	15	2.7	148	0.61	8.0	9.1	0.90	0.3	34	0.0
USGS 101	28.8	9.2	12.9	2.8	148	0.97	8.5	9.0	0.78	0.8	33.6	-2.7

Table 13. Concentrations of major ions, silica, and the charge balance for each water-quality analysis, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Chloride	Sulfate	Fluoride	Nitrate	Silica	Charge balance (percent)
Geothermal water												
INEL-1 2,000 feet	10	2.0	92	10	220	2.67	17	32	1.1	nd	60	0.2
INEL-1 10,300 feet	7.3	0.5	390	7.5	900	7.19	12	[4](99)	13	nd	47	-1.4
ML 57	*87.1*	*16.0*	*26.4*	*13.6*	*168*	*0.24*	*6.7*	*191*	*7.0*	*<0.05*	*34*	*-1.0*
ML 58	*53.3*	*19.7*	*9.9*	*2.9*	*198*	*0.16*	*5.2*	*58.0*	*0.94*	*0.1*	*16.7*	*1.3*
Groundwater at the Idaho National Laboratory												
Deep groundwater												
EBR 1	22.6	15.3	8.0	3.1	144	1.06	7	15.7	0.19	0.4	33.8	-2.4
Site 9	35.7	14.7	11.2	2.8	166	0.91	13.1	22.9	0.28	0.6	23.7	-1.5
Site 14	34.0	13.3	12.9	3.0	165	0.73	9.5	23.4	0.41	0.6	29.7	-1.7
USGS 7	24.6	9.3	20.8	4.4	142	0.89	9.1	16.1	1.30	0.4	47.1	-0.6
USGS 15	32.7	15.3	8.9	1.6	167	0.67	7.0	18.5	0.11	0.4	18.0	-0.9
Contaminated groundwater												
Advanced Test Reactor Complex												
USGS 65	85.0	19	14	3.0	150	0.68	21	150	<0.1	1.6	21.0	1.4
Idaho Nuclear Technology and Engineering Center												
CFA 1	61.6	18.6	14.4	3.2	160	0.54	74.0	27.7	0.25	3.5	20.9	-2.3
CFA 2	71.9	26.4	21.4	4.3	149	0.51	115	45.0	0.39	3.7	23.6	-0.9
USGS 20	41.0	12	8.0	2.6	146	0.61	21	22	0.20	1.0	23.0	-1.4
USGS 36	60.9	15.4	16.7	2.8	199	0.85	33.9	27.7	0.22	1.8	19.3	1.4
USGS 57	67.0	18	41	3.6	148	0.43	110	35	0.30	3.7	23.0	1.1
USGS 82	35.7	13.4	10.4	3.0	152	0.79	18	21	0.21	0.5	22.6	-1.4
USGS 85	57.0	14	22	2.9	187	0.81	46	31	0.20	2.5	21.0	-1.9
USGS 104	34.9	13.7	7.6	2.4	156	0.80	12.6	19.3	0.20	0.7	24.7	-2.1
USGS 105	40.8	15.2	12.7	2.8	180	0.98	13.6	26.0	0.19	0.7	21.2	-0.7
USGS 108	37.0	15.0	10.6	2.4	165	0.86	14.0	22.4	0.24	0.7	23.3	-0.7
USGS 109	39.8	15.7	10.5	2.7	181	0.97	14.0	25.0	0.23	0.6	24.4	-2.1
USGS 112	76.0	21.0	54.0	4.9	173	0.79	151	29.0	0.26	3.2	21.5	0.2
USGS 113	78.3	23.1	78.4	6.2	164	0.76	218	31.2	0.15	2.4	21.5	-1.6
USGS 115	42.9	13.3	13.2	3.3	146	0.78	38.0	21.2	0.23	1.3	21.5	-1.8
USGS 116	56.4	16.0	24.8	4.6	122	0.82	89.3	34.2	0.30	3.0	22.2	-1.5
USGS 124	38.6	16.2	8.8	2.4	176	0.75	14.8	21.5	0.30	0.7	25.7	-1.8
Naval Reactors Facility												
NRF 6	130	35	110	4.4	211	0.62	240	200	0.10	1.7	nd	-0.9
NRF 9	73	24	17	2.4	250	1.33	48	49	nd	2.2	nd	-1.9
NRF 10	72	25	16	2.4	244	1.30	43	44	nd	1.8	nd	0.8
NRF 11	72	23	19	2.8	241	1.02	44	50	nd	1.9	nd	-0.1
NRF 12	72	25	21	2.5	245	1.05	59	59	nd	2.0	nd	-3.3
NRF 13	64	19	62	4.2	113	1.65	60	73	nd	0.8	nd	18.8
Radioactive Waste Management Complex												
RWMC M3S	43.4	15	8.2	2.6	176	0.95	13.4	24.3	0.30	0.7	23.6	-0.6
RWMC M7S	39.6	14	7.8	2.7	172	1.16	11.9	22.2	0.20	0.7	23.5	-2.4
RWMC Production	45.0	15	9.0	2.8	180	0.96	13.0	27.0	0.20	0.7	28.0	-0.3

Table 13. Concentrations of major ions, silica, and the charge balance for each water-quality analysis, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Chloride	Sulfate	Fluoride	Nitrate	Silica	Charge balance (percent)
Contaminated groundwater—Continued												
Radioactive Waste Management Complex—Continued												
USGS 87	40.0	14	12	3.0	135	0.73	13	26	0.20	0.7	28.0	7.8
USGS 88	33.0	23	47	7.0	113	0.80	82	64	0.30	1.8	30.0	0.8
USGS 90	44.0	15	9.4	2.7	146	0.78	13	27.0	0.20	0.7	27.0	6.8
USGS 120	34.0	18.4	25.4	4.0	186	1.22	21.7	38.0	0.26	0.8	22.4	-1.6
Test Area North Area												
TAN Disposal	57	22	97	4.3	279	1.34	150	[4](32)	0.1	<0.1	23	-2.9
TDD 1	53	20	15	3.5	149	0.61	64	39	0.2	1.2	19	-1.4
TDD 2	71	19	57	4.4	237	0.84	120	40	0.2	2.3	19	-3.8
USGS 24	74.0	19	26	2.4	215	0.90	69	36	0.20	1.7	21.0	0.5
Natural groundwater												
North INL Area												
ANP 6	46.2	17.2	9.6	2.5	180	0.77	17.2	32.2	0.26	0.8	20.7	0.0
ANP 8	45.0	14	8.8	3.2	155	0.94	10	30	0.20	0.9	27.0	4.2
IET 1 Disposal	49	13.9	15.9	3.6	189	0.66	18.7	29.9	0.21	1.4	18.8	-0.1
No Name 1	34.0	15.2	10.0	3.5	139	0.68	19.9	24.2	0.29	0.6	25.7	0.7
PSTF Test	30.4	14.9	6.5	2.4	164	1.08	6.6	14.4	0.21	0.6	23.7	-2.8
TDD 3	51	15	7.4	3.1	155	0.38	12	33	0.2	0.9	23	6.7
Northeast INL Area												
ANP 9	38.1	15.7	13.7	2.9	177	0.96	12.6	29.1	0.39	0.7	30.6	-1.3
USGS 26	41.2	14.9	13.2	3.5	182	0.82	13.3	28.6	0.43	0.8	32.7	-1.4
USGS 27	54.0	19.1	24.0	6.4	170	0.79	61.9	38.5	0.58	2.4	37.2	-0.8
USGS 29	48.5	14.1	19.0	3.4	192	0.81	26.0	16.7	0.43	2.0	28.2	0.8
USGS 31	41.0	15.3	14.4	3.9	172	0.74	22.5	27.7	0.41	0.8	30.9	-1.3
USGS 32	49.5	18.7	17.7	4.2	163	0.59	42.0	39.1	0.38	1.4	28.9	0.8
Southeast INL Area												
Arbor Test 1	34.9	11.5	14.4	3.1	162	0.69	14.5	12.4	0.64	1.2	34.0	-1.0
Area II	34.2	13.8	14.3	3.4	170	0.92	17.3	16.8	0.44	1.1	28.7	-2.8
Atomic City	34.1	13.4	14.7	3.4	168	1.14	17.2	16.1	0.49	1.1	31.4	-2.5
Leo Rogers 1	39.6	14.3	17.0	3.2	171	0.94	18.8	18.1	0.44	1.1	27.0	1.7
USGS 1	31.2	11.9	13.5	3.2	158	1.08	13.0	13.0	0.57	0.9	32.5	-2.3
USGS 2	35.4	12.1	15.1	3.3	166	0.89	17.0	14.1	0.57	1.2	28.7	-1.9
USGS 14	36.9	15.3	15.5	2.8	168	1.16	21.0	21.5	0.79	1.1	30.4	-1.3
USGS 100	38.3	12.3	16.0	3.1	164	0.88	17.7	21.0	0.57	1.5	28.2	-1.2
USGS 107	37.6	16.6	15.4	3.5	176	0.98	21.3	25.3	0.34	1.0	29.7	-1.7
USGS 110A	36.7	14.9	15.2	3.6	173	0.96	19.0	18.0	0.45	1.1	31.7	-0.9
Central INL Area												
Badging Facility Well	37.9	14.1	9.7	2.3	162	0.83	16.9	21.4	0.22	0.7	24.4	-1.8
NPR Test	49.1	14.1	7.2	2.1	195	1.01	13.6	20.9	0.22	0.7	22.7	-1.6
USGS 5	39.8	12.6	7.1	2.0	171	0.93	9.4	18.7	0.21	0.5	23.1	-2.2
USGS 6	28.7	11.3	11.7	2.4	146	0.78	9.4	18.1	0.23	0.3	24.9	-2.7

Table 13. Concentrations of major ions, silica, and the charge balance for each water-quality analysis, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Chloride	Sulfate	Fluoride	Nitrate	Silica	Charge balance (percent)
Natural groundwater—Continued												
Central INL Area—Continued												
USGS 17	37.4	10.1	6.9	2.3	151	1.00	4.9	19.1	0.21	0.3	21.8	-0.4
USGS 18	35.1	15.8	12.1	2.9	168	0.76	10.2	24.7	0.30	0.4	25.8	0.3
USGS 83	27.3	10.6	9.7	2.5	123	0.77	10.8	20.1	0.24	0.7	25.5	-1.9
USGS 103	36.1	15.3	12.6	3.0	167	1.41	16.3	23.1	0.32	0.7	24.3	-1.5
Northwest INL Area												
Fire Station 2	54.8	17.8	8.1	2.4	204	0.83	17.6	23.5	0.19	1.2	22.7	1.8
INEL-1 WS	67.5	27.4	14.5	2.6	195	0.68	66.6	40.4	0.12	3.6	20.9	0.9
NRF 2	70	22	18	1.8	260	0.57	46	39	0.30	1.7	22.0	-3.1
NRF 7	24	9.0	10	2.8	129	1.78	5.2	14	nd	0.5	nd	-2.2
NRF 8	71	24	14	2.2	261	1.10	35	35	nd	1.9	nd	0.1
Site 4	45.3	14.1	7.8	1.8	192	0.97	10.1	19.4	0.20	0.6	22.5	-1.5
Site 17	51.0	17.3	9.8	1.3	219	0.73	9.9	20.4	0.12	1.0	14.5	0.4
Site 19	42.4	17.5	8.0	1.9	200	0.90	11.6	20.7	0.19	0.9	18.8	-2.3
USGS 12	71.1	23.3	15.9	2.2	261	0.71	37.6	37.0	0.13	2.3	18.2	-0.7
USGS 19	44.1	16.9	10.5	1.5	197	0.61	9.9	20.6	0.21	0.8	14.9	0.7
USGS 22	34.7	10.6	21.0	5.6	87	0.34	66.5	21.0	0.17	0.4	17.9	-1.7
USGS 23	37.4	15.8	9.2	1.6	182	0.65	9.9	17.6	0.21	0.6	16.1	-1.3
USGS 97	73.0	24.3	15.4	2.2	269	0.91	38.0	35.9	0.20	2.2	18.2	-0.4
USGS 98	48.9	18.3	10.0	2.3	209	0.87	15.2	21.7	0.12	1.1	20.9	0.2
USGS 99	59.8	22.6	12.2	1.7	247	0.83	22.2	27.0	0.15	1.5	16.2	0.3
USGS 102	73.9	23.2	13.5	2.2	264	0.90	34.0	35.5	0.13	2.1	18.2	0.3
USGS 134 (sz)	24.8	16	7.2	2.2	156	0.52	9.6	20.7	0.21	0.6	27	-6.5
Southwest INL Area												
Highway 3	50	12	6.2	2.2	184	1.58	6.3	20	0.2	0.3	26	1.5
Middle 2051 (sz)	46.3	11.1	5.7	2.4	188	0.24	5.7	22.0	0.25	0.4	24.3	-3.0
USGS 8	46.8	15.0	6.9	1.8	201	0.82	8.4	21.0	0.20	0.9	18.9	-1.9
USGS 9	40.7	15.6	12.2	3.5	172	1.09	20.9	26.0	0.20	0.7	23.1	-1.4
USGS 11	41.2	14.2	8.2	2.1	173	0.88	11.8	23.1	0.19	0.6	19.2	-1.3
USGS 86	37.0	10.2	11.0	2.9	132	1.00	19.6	22.7	0.16	1.4	25.5	-1.4
USGS 89	27.2	15.6	17.9	3.7	95	1.63	38.8	34.9	0.33	1.8	24.7	-0.9
USGS 117	25.7	11.2	9.6	2.6	121	0.98	13.7	17.1	0.22	0.6	27.7	-2.3
USGS 119[2]	30.0	10.0	11.0	2.6	116	0.98	12.0	35.0	0.50	1.3	31.0	-4.3
USGS 125	40.8	15.9	11.8	2.7	178	0.75	14.9	25.8	0.21	0.6	21.6	-0.4
USGS 135 (sz)	43.0	11.9	7.0	1.7	166	0.53	7.6	20.3	0.25	0.8	19.0	0.4

[1] Data from samples collected 04-10-1997 and 05-07-1985.

[2] Data from sample collected in September 1990.

[3] Data from sample collected 10-30-1984.

[4] The sulfur in these anoxic waters should originally have been in a reduced state as bisulfide (HS^-). The reported sulfate concentrations in these samples probably reflects oxidation of the sulfur after sampling that converted bisulfide to sulfate.

Table 14. Concentrations of selected dissolved metals, Idaho National Laboratory and vicinity, eastern Idaho.

[Concentrations are in micrograms per liter for dissolved metals, unless specified otherwise. Data from Busenberg and others (2000), Rattray (2015), Knobel and others (1992, 1999a, 1999b), U.S. Geological Survey (2014), Swanson and others (2002, 2003), Carkeet and others (2001), Liszewski and Mann, 1993; Bartholomay and Twining (2010), Bartholomay and others (2015), Mann (1986), Roback and others, (2001), and Johnson and others (2000). Springs are shown in *italics*. Locations of sites shown on figures 8–9. **Site name:** Alternate names used in other reports shown in table 10. **Abbreviations:** sz, shallowest zone; nd, not determined; INL, Idaho National Laboratory. Symbols: <, less than; E, estimated (Childress and others, 1999)]

Site name	Aluminum	Barium	Boron	Chromium	Iron	Lithium	Manganese	Strontium	Uranium
Surface water									
Big Lost River at Mackay Dam	60	59	12	<1	61	1.7	3.5	146	1.4
Big Lost River at bridge near Mackay	42	57	11	<1	43	1.7	3.1	148	1.4
Big Lost River near Arco	10	110	nd	0	<10	nd	10	260	nd
Big Lost River below INL Diversion	10	69	nd	<5	11	<4	2	210	2.20
Big Lost River near Atomic City[1]	17	105	23	nd	94	2.3	1.3	276	2.26
Big Lost River below lower Lincoln Blvd Br	116	60	13	<1	100	2.0	1.6	164	1.9
Birch Creek at Kaufman Guard Station	nd	62	nd	<17	<11	nd	<4	143	nd
Birch Creek at Blue Dome	1	61	14	<1	28	3.1	0.6	150	2.2
Camas Creek below diversion near CNWR	14	33	8	0.2	31	2.6	2.3	77	nd
Little Lost River near Clyde	nd	44	nd	nd	<20	nd	<10	105	nd
Little Lost River near Howe	30	51	12	<1	39	1.1	1.5	91	0.91
Mud Lake near Terreton	42	40	14	<1	58	3.4	2.7	118	0.47
Tributary Valley groundwater									
Big Lost River Valley									
Arco City Well 4	1	135	11	1	43	1.0	<0.1	257	2.5
Coates	<10	39	nd	<1	14	<6	<3	153	nd
Fulton	9.4	185	nd	E4.7	E4.4	nd	E1.1	357	nd
Hill	<10	88	nd	1.3	<10	<6	<3	171	nd
Lambert	<10	132	nd	<1	<10	<6	<3	254	nd
MSR	4	66	nd	E2.9	E6.3	nd	E0.4	202	nd
Muffett	9	163	nd	E2.1	E2.8	nd	E0.7	316	nd
Owen	8	167	nd	E12	E2.6	nd	E0.14	322	nd
Wheeler	8.6	149	nd	<1	12	<6	E0.7	323	nd
Wildhorse Guard Station	5	112	nd	E15	655	nd	18	686	nd
Little Lost River Valley									
Harrell	nd	132	nd	nd	<10	nd	5	217	nd
Mays	nd	97	nd	49	<10	6	<2.2	323	nd
Nicholson	nd	58	nd	nd	13.2	nd	E1.7	363	nd
Oar	nd	60	nd	nd	<20	nd	<10	126	nd
Pancheri	1	71	16	2	29	1.5	<0.1	135	1.2
Ruby Farms	<10	110	nd	8	14	5	<1	240	nd
Sorenson	nd	38	nd	nd	<10	nd	<2.2	92	nd
Birch Creek Valley									
Kaufman Guard Station	nd	164	nd	1	67	12	39	347	nd
McKinney	nd	64	nd	<1	7	5	<1	170	nd
P&W2	5	45	17	1	38	2.9	0.3	137	1.86
USGS 126b	E10	46	nd	2	<10	5.5	<3.2	201	nd
Wagoner	<1	69	18	<1	48	3.3	2.7	163	1.9
Wagoner Ranch	nd	78	nd	<17	<11	nd	<4	177	nd
Beaverhead Mountains									
ML 55	*<2.2*	*87*	*25*	*0.2*	*13.8*	*9.6*	*<0.1*	*146*	*nd*
ML 59	*<2.2*	*143*	*8*	*0.5*	*<3.2*	*0.9*	*<0.1*	*61*	*nd*

Table 14. Concentrations of selected dissolved metals, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Aluminum	Barium	Boron	Chromium	Iron	Lithium	Manganese	Strontium	Uranium
Regional groundwater									
Highway 2[2]	<10	nd	70	nd	80	nd	100	nd	nd
Kettle Butte Farms	nd	nd	nd	<1	5	nd	<1.0	nd	nd
ML 2	nd	10	nd	nd	<6	nd	E0.2	nd	nd
ML 5	3	26	25	2.5	<3.2	7.2	1.6	131	nd
ML 6	10	21	19	1.2	5.0	12.4	<0.1	100	nd
ML 9	nd	nd	nd	nd	<3.2	nd	<0.2	nd	nd
ML 12	<1.7	30	21	1.5	3.6	12.9	<0.1	127	nd
ML 13	nd	nd	nd	nd	E5.7	nd	<0.4	nd	nd
ML 15	nd	29	nd	nd	<6	nd	E0.1	nd	nd
ML 18	nd	nd	nd	nd	E3.4	nd	1.5	nd	nd
ML 17	<2.2	56	117	0.3	3.3	6.3	0.2	400	nd
ML 19	2	151	36	nd	73	14.4	nd	331	3.2
ML 22	3	130	48	11	78	23.7	<0.1	312	3.59
ML 23	nd	95	50	nd	5.0	32	nd	180	nd
ML 24	<2.2	127	90	2.6	5.2	16	0.2	502	nd
ML 25	3	62	84	nd	85	71	91	77	0.1
ML 26	nd	112	nd	nd	<6	nd	<0.6	nd	nd
ML 27	nd	51	nd	nd	E4.8	47	5.7	150	nd
ML 28	nd	74	nd	nd	<6	nd	<0.6	nd	nd
ML 29	10	51	nd	nd	11	47	nd	160	nd
ML 30	<2.2	138	78	7.4	5.4	27.8	0.3	329	nd
ML 31	<2.2	78	82	2.3	4.7	20	<0.1	308	nd
ML 33	nd	81	nd	nd	<10	nd	<2.0	nd	nd
ML 34	nd	56	nd	nd	<10	nd	<3.0	nd	nd
Reno Ranch	nd	114	nd	1	<10	25	9	322	nd
SE of Atomic City	nd	nd	nd	1.5	<3	nd	<1.0	nd	nd
USGS 3A	nd	nd	80	nd	120	nd	0	nd	nd
USGS 101	6	18	47	2	39	27.8	0.2	111	1.32
Geothermal water									
INEL-1 2,000 feet	nd	nd	900	20	0	50	20	100	1.88
INEL-1 10,300 feet[3]	nd	nd	560	0	1,100	280	50	150	0.19
ML 57	*E14*	*45*	*90*	*<0.8*	*20*	*48.1*	*13*	*1,000*	*0.02*
ML 58	*<2.2*	*70*	*35*	*0.2*	*<3.2*	*15.1*	*0.2*	*337*	*nd*
Groundwater at the Idaho National Laboratory									
Deep groundwater									
EBR 1	10	21	20	7	34	2.7	0.4	195	2.03
Site 9	9	60	30	4	51	3.5	3.8	188	1.68
Site 14	6	63	35	5	37	11.5	<0.1	215	2.07
USGS 7	5	17	57	2	35	25.9	3.6	120	2.26
USGS 15	3	65	18	7	30	2.1	<0.1	188	1.78
Contaminated groundwater									
Advanced Test Reactor Complex									
USGS 65	<10	56	nd	190	210	5	3	390	nd
Idaho Nuclear Technology and Engineering Center									
CFA1	4	91	21	10	68	2.5	0.2	370	2.3
CFA2	4	96	27	10	158	3.6	2.8	483	2.3
USGS 20	<10	47	nd	7	21	6	2	230	nd
USGS 36	3	126	21	13	57	1.7	<0.1	334	2.5
USGS 57	10	170	nd	<5	4	<4	<1	360	nd
USGS 82	3	57	19	6	62	2.2	1.3	214	1.7
USGS 85	<10	110	nd	10	28	6	3	310	nd
USGS 104	3	32	16	7	62	2.2	0.3	184	1.52

Table 14. Concentrations of selected dissolved metals, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Aluminum	Barium	Boron	Chromium	Iron	Lithium	Manganese	Strontium	Uranium
Contaminated groundwater—Continued									
Idaho Nuclear Technology and Engineering Center—Continued									
USGS 105	5	38	22	7	45	2.5	0.1	235	2.16
USGS 108	4	38	23	7	41	4.3	0.1	189	1.76
USGS 109	4	26	23	5	46	2.7	5.8	307	1.73
USGS 112	5	250	24	6	89	2.4	0.1	484	2.3
USGS 113	2	342	26	6	122	2.8	0.1	532	2.1
USGS 115	5	65	18	7	54	2.1	1.5	244	1.3
USGS 116	3	136	18	12	84	2.5	0.3	333	1.4
USGS 124	5	26	21	4	89	6.7	9.4	256	1.61
Naval Reactors Facility									
NRF 6[4]	<10	<100	nd	27	240	nd	<10	nd	nd
NRF 9[4]	<10	<100	nd	12	30	nd	<10	nd	nd
NRF 10[4,5]	1,000	<100	nd	14	1,700	nd	40	nd	nd
NRF 11[4]	40	<100	nd	23	60	nd	<10	nd	nd
NRF 12[4]	10	<100	nd	17	<10	nd	<10	nd	nd
NRF 13[4,5]	1,400	<100	nd	26	1,300	nd	<10	nd	nd
Radioactive Waste Management Complex									
RWMC M3S	7	45	18	15	51	2.4	0.1	244	2.1
RWMC M7S	6	46	17	11	53	2.2	0.1	231	2.0
RWMC Production	20	37	nd	20	7	nd	130	240	nd
USGS 87	<10	29	nd	10	6	nd	3	230	nd
USGS 88	<10	22	nd	30	7	9	6	190	nd
USGS 90	<10	35	nd	20	4	nd	2	240	nd
USGS 120	5	48	39	9	70	3.6	1	197	2.8
Test Area North									
TAN Disposal	<10	130	nd	<1	410	nd	84	350	nd
TDD 1	<10	68	nd	2	30	nd	3	270	nd
TDD 2	10	240	nd	<1	8	nd	17	470	nd
USGS 24	<10	190	nd	4	15	nd	2	450	nd
Natural groundwater									
North INL Area									
ANP 6	6	65	26	3	61	2.9	1.1	218	2.12
ANP 8	20	86	nd	5	5	nd	<1	210	nd
IET 1 Disposal	3	120	72	<1	86	2.3	140	251	1.8
No Name 1	20	63	20	8	80	2.5	2.1	181	1.5
PSTF Test	4	70	19	3	28	1.8	<0.1	132	1.7
TDD 3	20	84	nd	3	5	nd	1	230	nd
Northeast INL Area									
ANP 9	5	86	35	3	27	10.2	0.9	208	2.37
USGS 26	4	37	38	3	56	18.4	0.6	196	2.39
USGS 27	2	69	52	5	101	36.4	5.7	256	3.04
USGS 29	4	52	36	4	55	23.7	<0.1	158	2.00
USGS 31	4	43	37	5	48	18.1	0.2	196	2.27
USGS 32	2	58	43	5	67	19.1	0.4	246	2.53
Southeast INL Area									
Arbor Test 1	5	29	46	2	36	24.9	0.3	125	1.69
Area II	7	36	41	3	56	17.7	<0.1	152	1.94
Atomic City	7	38	40	3	28	18	0.1	164	2.1
Leo Rogers 1	6	43	40	3	58	16	<0.1	145	2.2
USGS 1	6	23	42	2	51	18	0.8	133	1.72
USGS 2	5	34	45	2	87	20.4	3.7	131	1.82

Table 14. Concentrations of selected dissolved metals, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Aluminum	Barium	Boron	Chromium	Iron	Lithium	Manganese	Strontium	Uranium
Natural groundwater—Continued									
Southeast INL Area—Continued									
USGS 14	6	20	36	4	37	24.3	0.6	178	2.37
USGS 100	2	32	44	3	39	23.4	0.5	133	1.50
USGS 107	4	49	35	5	34	10.5	<0.1	120	2.20
USGS 110A	6	32	38	3	125	15.9	7.2	205	2.03
Central INL Area									
Badging Facility Well	5	35	21	9	57	3.9	0.2	197	1.50
NPR Test	3	84	20	7	45	2.2	1.2	244	2.0
USGS 5	6	89	19	2	39	2	47.4	189	1.50
USGS 6	4	78	25	28	53	7.3	0.9	182	1.75
USGS 17	9	35	13	2	40	1.4	0.7	208	1.71
USGS 18	7	55	33	3	47	5.2	0.5	165	2.06
USGS 83	5	95	15	14	26	3	0.3	157	1.37
USGS 103	6	45	30	6	49	6.9	2.2	186	1.49
Northwest INL Area									
Fire Station 2	7	20	24	7	56	2	0.5	303	2.0
INEL-1 WS	1	62	19	8	105	2.8	3.6	309	1.69
NRF 2	30	140	nd	9	6	nd	<1	300	nd
NRF 7[4]	70	<100	nd	13	230	nd	<10	nd	nd
NRF 8[4]	<10	<100	nd	7	80	nd	<10	nd	nd
Site 4	7	nd	20	8	30	1.7	<0.1	231	1.9
Site 17	18	74	26	4	59	2.4	0.2	206	1.43
Site 19	5	49	25	3	55	2.5	<0.1	211	1.7
USGS 12	3	179	33	7	85	2.7	1.1	357	2.4
USGS 19	5	80	32	3	46	3.5	0.3	256	1.56
USGS 22	4	17	33	2	54	3.7	15.1	114	0.43
USGS 23	5	55	26	3	54	4.3	0.9	219	1.9
USGS 97	2	143	29	6	68	2.6	<0.1	316	2.4
USGS 98	2	43	22	6	50	2.5	6	222	1.5
USGS 99	3	112	30	5	58	2.5	0.9	252	1.8
USGS 102	4	124	30	7	70	2.9	<0.1	308	2.5
USGS 134 (sz)	3	11	nd	6	<8	2.0	0.6	145	nd
Southwest INL Area									
Highway 3[6]	27	54	21	nd	97	1.7	0.9	276	1.90
Middle 2051 (sz)	2	45	nd	1	<8	1.6	E0.2	255	1.69
USGS 8	6	70	13	2	45	1.3	1.1	254	2.10
USGS 9	4	34	25	4	40	3.3	3.9	202	1.57
USGS 11	6	52	16	4	42	2.1	0.6	220	1.67
USGS 86	2	19	18	12	37	2.3	0.8	171	1.03
USGS 89	3	18	30	45	63	4.2	0.4	118	1.16
USGS 117	3	18	23	21	49	5.1	0.8	144	1.1
USGS 119	<10	28	nd	30	6	5	4	130	nd
USGS 125	6	35	21	5	56	3.2	5.5	230	2.17
USGS 135 (sz)	8	56	nd	2	6	1.9	0.4	245	nd

[1] Data are from samples collected on 04-10-1997 and 05-07-1985.

[2] Aluminum value from sample collected in 1984.

[3] Lithium measurement from sample collected at 3,559–4,878 feet below land surface.

[4] Total recoverable metals.

[5] Extremely large total recoverable aluminum and iron concentrations may be due to suspended sediment (U.S. Department of Energy, 2016).

[6] Data from sample collected 04-29-1997 (Johnson and others, 2000; Roback and others, 2001).

Table 15. Stable isotope ratios of hydrogen, oxygen, carbon, sulfur, and nitrogen, and the isotope ratio of helium, Idaho National Laboratory and vicinity, eastern Idaho.

[Locations of sites shown in figures 8–9. Alternate names used in other reports are shown in table 10. Data from Busenberg and others (2000); Rattray (2015); Knobel and others (1992, 1999a, 1999b); U.S. Geological Survey (2014); Swanson and others (2002, 2003); Carkeet and others (2001); Bartholomay and Twining (2010); Bartholomay and others (1994, 1995, 2015); and Wood and Low (1988). **Date sampled:** Date that hydrogen, oxygen, and most carbon isotope samples were collected. Helium isotopes were collected in 1994–95, and most sulfur and nitrogen stable isotope samples were collected in 1991. **$\delta^{2}H$ and $\delta^{18}O$:** Measured from water. **$\delta^{13}C$:** Measured from dissolved inorganic carbon. **$\delta^{34}S$:** Measured from sulfate. **$\delta^{15}N$:** Measured from nitrate. Springs are shown in *italics*. **Abbreviations:** INL, Idaho National Laboratory; sz, shallowest zone. **Symbols:** $\delta^{2}H$, $\delta^{18}O$, $\delta^{13}C$, $\delta^{34}S$, $\delta^{15}N$, and $\delta^{3}He$, delta notation for the stable isotope ratios of hydrogen, oxygen, carbon, sulfur, nitrogen and isotope ratio of helium, respectively; R_s, $(^{3}He/^{4}He)_{sample}$; R_a, $(^{3}He/^{4}He)_{atmosphere}$; ≈, approximately; ±, plus or minus the indicated uncertainty (uncertainties are 1 sigma); nd, not determined]

Site name	Date sampled	$\delta^{2}H$ (±1.0 permil)	$\delta^{18}O$ (±0.10 permil)	$\delta^{13}C$ (±0.1 permil)	$\delta^{34}S$ (±0.1 permil)	$\delta^{15}N$ (±0.1 permil)	$\delta^{3}He$ (±≈0.2 percent)	R_s/R_a
Surface water								
Big Lost River at Mackay Dam	06-28-1995	-134.4	-17.57	nd	nd	nd	nd	nd
Big Lost River at Bridge near Mackay	06-17-1995	-134.9	-17.60	nd	nd	nd	nd	nd
Big Lost River near Arco	06-05-1981	-135.0	-17.4	-10.9	4.4	nd	nd	nd
Big Lost River below lower Lincoln Blvd Br	05-21-1997	-132.2	-17.17	-10.9	nd	nd	nd	nd
Birch Creek at Kaufman Guard Station	06-27-2000	-141.2	-18.57	-5.92	nd	nd	nd	nd
Birch Creek at Blue Dome	06-28-1995	-140.1	-18.62	nd	[1]8.2	nd	nd	nd
Camas Creek below diversion near CNWR	08-08-2011	-124.7	-16.24	-7.98	[2]6.9	nd	nd	nd
Little Lost River near Clyde	06-27-2000	-137.4	-17.94	-6.57	nd	nd	nd	nd
Little Lost River near Howe	06-28-1995	-134.1	-17.72	-6.9	nd	nd	nd	nd
Mud Lake near Terreton	06-17-1995	-122.9	-15.97	nd	nd	nd	nd	nd
Tributary valley groundwater								
Big Lost River Valley								
Arco City Well 4	05-13-1997	-134.7	-17.69	-10.33	1.6	nd	nd	nd
Coates	06-01-1999	-134.7	-17.60	-7.9	nd	nd	nd	nd
Fulton	06-02-1999	-130.7	-17.28	-10.79	nd	nd	nd	nd
Hill	06-02-1999	-134.0	-17.72	-9.03	nd	nd	nd	nd
Lambert	06-23-1999	-135.1	-17.60	-10.88	nd	nd	nd	nd
MSR	06-01-1999	-136.7	-18.12	-9.01	nd	nd	nd	nd
Muffett	06-03-1999	-131.9	-17.19	-12	nd	nd	nd	nd
Owen	06-23-1999	-132.0	-17.32	-11.84	nd	nd	nd	nd
Wheeler	06-02-1999	-132.6	-17.32	-11.47	nd	nd	nd	nd
Wildhorse Guard Station	06-02-1999	-141.7	-18.37	-7.88	nd	nd	nd	nd
Little Lost River Valley								
Harrell	07-31-2000	-135.2	-17.93	-9.27	1.8	nd	nd	nd
Mays	06-26-2000	-141.2	-18.35	-7.1	nd	nd	nd	nd
Nicholson	07-31-2000	-133.7	-17.59	-6.17	nd	nd	nd	nd
Oar	06-28-2000	-138.7	-18.11	-10.21	nd	nd	nd	nd
Pancheri	05-13-1997	-141.8	-18.14	-8.42	nd	nd	nd	nd
Ruby Farms	05-10-1991	-138.0	-18.15	-9.1	3.3	6.0	nd	nd
Sorenson	07-31-2000	-137.9	-18.06	-9.12	nd	nd	nd	nd
Birch Creek Valley								
Kaufman Guard Station	06-27-2000	-139.7	-18.39	-11.14	nd	nd	nd	nd
McKinney	06-13-1991	-141.0	-18.55	-7.9	7.6	6.7	nd	nd
P&W2	10-15-1996	-141.3	-18.50	-6.13	7.7	7.0	-0.84	0.99
USGS 126b	11-08-2000	-140.9	-18.44	-6.41	nd	nd	nd	nd
Wagoner	05-22-1997	-141.7	-18.13	-8.97	nd	nd	nd	nd
Wagoner Ranch	06-28-2000	-139.2	-18.35	-7.37	nd	nd	nd	nd

Table 15. Stable isotope ratios of hydrogen, oxygen, carbon, sulfur, and nitrogen, and the isotope ratio of helium, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	δ^{2}H (±1.0 permil)	δ^{18}O (±0.10 permil)	δ^{13}C (±0.1 permil)	δ^{34}S (±0.1 permil)	δ^{15}N (±0.1 permil)	δ^{3}He (±≈0.2 percent)	R_s/R_a
Beaverhead Mountains								
ML 55	*06-5-2012*	*-137.7*	*-18.03*	*-9.47*	*nd*	*nd*	*nd*	*nd*
ML 59	*06-5-2012*	*-129.2*	*-17.02*	*-9.12*	*nd*	*nd*	*nd*	*nd*
Regional groundwater								
ML 5	08-09-2011	-131.5	-17.33	-11.2	nd	nd	nd	nd
ML 6	08-08-2011	-132.9	-17.62	-13.4	nd	nd	nd	nd
ML 9	08-29-1989	-133.0	-17.45	nd	nd	nd	nd	nd
ML 12	08-09-2011	-134.4	-17.62	-13.2	nd	nd	nd	nd
ML 17	06-04-2012	-134.1	-17.35	-11.4	nd	nd	nd	nd
ML 19	05-14-1997	-120.8	-14.88	-12.7	nd	nd	nd	nd
ML 22	10-15-1996	-120.6	-14.84	-13.32±0.04	8.2	4.7	13.47	1.13
ML 23	08-29-1989	-123.0	-15.55	nd	nd	nd	nd	nd
ML 24	06-06-2012	-132.3	-17.26	-13.10	nd	nd	nd	nd
ML 25	06-11-1991	-135.0	-17.9	-12.6	8.3	6.9	nd	nd
ML 29	06-12-1991	-135.0	-17.85	-11.7	16.0	9.5	nd	nd
ML 30	06-06-2012	-130.9	-16.98	-15.0	nd	nd	nd	nd
ML 31	06-06-2012	-132.4	-17.13	-12.30	nd	nd	nd	nd
Reno Ranch	06-28-2000	-139	-18.2	-7.09	5.1	nd	nd	nd
USGS 101	10-10-1996	-135.3	-17.84	-10.60	11.8	5.1	-33.16	0.67
Geothermal water								
ML 57	*11-05-1990*	*-135.0*	*-18.10*	*-3.9*	*8.4*	*nd*	*nd*	*nd*
ML 58	*06-05-2012*	*-135.0*	*-17.65*	*-5.55*	*nd*	*nd*	*nd*	*nd*
Groundwater at the Idaho National Laboratory								
Deep groundwater								
EBR 1	10-16-1996	-139.4	-18.13	-8.0	6.9	6.3	nd	nd
Site 9	07-22-1996	-137.7	-17.98	-8.51±0.02	8.6	6.2	nd	nd
Site 14	10-14-1996	-137.8	-17.96	-8.17	9.2	5.8	nd	nd
USGS 7	10-14-1996	-137.6	-17.93	-9.48	11.9	6.0	nd	nd
USGS 15	06-14-1995	-141.8	-18.49	-8.01	nd	nd	nd	nd
Contaminated groundwater								
Advanced Test Reactor Complex								
USGS 65	05-16-1991	-133.0	-16.90	-10.4	4.8	6.6	nd	nd
Idaho Nuclear Technology and Engineering Center								
CFA 1	07-16-1996	-137.4	-17.71	-9.43	6.9	8.1	nd	nd
CFA 2	07-16-1996	-136.6	-17.23	-11.99±0.05	nd	nd	nd	nd
USGS 20	05-30-1991	-139.0	-18.10	-10.8	6.0	5.1	nd	nd
USGS 36	07-16-1996	-137.6	-17.78	-8.78	nd	nd	nd	nd
USGS 57	05-13-1991	-136.0	-17.70	-11.3	5.3	5.9	nd	nd
USGS 82	07-16-1996	-137.5	-17.89	-10.02	nd	nd	nd	nd
USGS 85	06-04-1991	-136.0	-17.90	-11.0	5.8	5.4	nd	nd
USGS 104	07-15-1996	-139.1	-18.09	-9.30±0.03	nd	nd	nd	nd
USGS 105	04-18-1995	-136.7	-17.84	nd	nd	nd	-31.11	0.69
USGS 108	04-18-1995	-137.2	-17.85	nd	nd	nd	nd	nd
USGS 109	10-11-1996	-137.0	-17.78	-9.08	nd	nd	207.28	3.07
USGS 112	07-15-1996	-137.8	-17.62	-9.92	4.7	6.0	nd	nd
USGS 113	07-16-1996	-137.1	-17.51	-10.67	nd	nd	nd	nd
USGS 115	07-15-1996	-140.1	-17.87	-10.27±0.02	nd	nd	nd	nd
USGS 116	07-15-1996	-138.9	-17.74	-10.56±0.00	nd	nd	nd	nd
USGS 124	10-09-1996	-138.8	-17.95	-8.75	nd	nd	646.05	7.46

Table 15. Stable isotope ratios of hydrogen, oxygen, carbon, sulfur, and nitrogen, and the isotope ratio of helium, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	δ^{2}H (±1.0 permil)	δ^{18}O (±0.10 permil)	δ^{13}C (±0.1 permil)	δ^{34}S (±0.1 permil)	δ^{15}N (±0.1 permil)	δ^{3}He (±≈0.2 percent)	R_s/R_a
Radioactive Waste Management Complex								
RWMC M3S	07-22-1996	-137.5	-17.98	-8.87	nd	nd	nd	nd
RWMC M7S	07-22-1996	-137.7	-17.92	-9.22	nd	nd	nd	nd
USGS 120	07-17-1996	-136.8	-17.61	-9.38	nd	nd	nd	nd
Natural groundwater								
North INL Area								
ANP 6	07-19-1996	-138.7	-18.27	-6.06	nd	nd	15.75	1.16
IET 1 Disposal	07-18-1996	-135.7	-17.58	-8.80±0.01	nd	nd	nd	nd
No Name 1	10-14-1996	-130.4	-15.86	-8.76	6.9	7.1	-1.13	0.99
PSTF Test	10-14-1996	-133.4	-17.64	-5.61	nd	nd	-0.28	1.00
Northeast INL Area								
ANP 9	10-14-1996	-137.9	-17.88	-8.21±0.07	nd	nd	-99.95	0.001
USGS 26	10-15-1996	-134.6	-17.80	-8.61	10.5	6.3	nd	nd
USGS 27	10-15-1996	-134.0	-17.66	-9.87	10.7	7.6	869.50	9.70
USGS 29	07-19-1996	-134.5	-17.67	-11.75	10.2	5.3	-41.64	0.58
USGS 31	07-19-1996	-135.9	-17.81	-9.39	11.0	6.5	nd	nd
USGS 32	07-19-1996	-135.4	-17.68	-9.47	9.0	6.5	27.18	1.27
Southeast INL Area								
Arbor Test 1	10-10-1996	-133.6	-17.74	-11.21±0.01	nd	nd	3.36	1.03
Area II	07-18-1996	-134.8	-17.73	-10.23±0.01	nd	nd	-99.75	0.003
Atomic City	10-09-1996	-135.8	-17.72	-10.57±0.01	nd	nd	17.07	1.17
Leo Rogers 1	07-17-1996	-134.7	-17.62	-10.59±0.02	nd	nd	nd	nd
USGS 1	10-09-1996	-136.2	-17.82	-10.71±0.00	11.9	4.7	21.21	1.21
USGS 2	07-17-1996	-135.0	-17.71	-11.67±0.02	11.0	4.7	11.12	1.11
USGS 14	10-09-1996	-135.5	-17.61	-9.29±0.00	9.5	6.5	25.39	1.25
USGS 100	04-21-1995	-133.8	-17.78	-11.17	nd	nd	12.27	1.12
USGS 107	10-09-1996	-134.3	-17.55	-9.21±0.05	nd	nd	nd	nd
USGS 110A	10-09-1996	-134.4	-17.64	-10.64±0.01	9.8	5.4	nd	nd
Central INL Area								
Badging Facility Well	07-16-1996	-139.2	-17.90	-9.39	nd	nd	nd	nd
NPR Test	10-10-1996	-137.6	-17.76	-9.90	5.6	7.1	56.96	1.57
USGS 5	10-10-1996	-138.3	-17.82	-9.64	nd	nd	4.17	1.04
USGS 6	07-18-1996	-135.2	-17.62	-8.64	nd	nd	nd	nd
USGS 17	06-13-1995	-135.7	-17.53	-10.09	5.7	8.3	25.75	1.26
USGS 18	07-19-1996	-138.6	-18.11	-7.37	nd	nd	nd	nd
USGS 83	04-17-1995	-138.9	-18.14	nd	nd	nd	nd	nd
USGS 103	07-15-1996	-136.9	-17.80	-8.93	nd	nd	26.48	1.26
Northwest INL Area								
Fire Station 2	10-16-1996	-138.7	-17.94	-9.32	7.9	6.5	nd	nd
INEL-1 WS	06-12-1995	-138.6	-17.97	-8.88	nd	nd	nd	nd
Site 4	10-16-1996	-137.9	-17.74	-10.19	nd	nd	nd	nd
Site 17	06-16-1995	-138.9	-18.10	-8.48	7.5	6.3	nd	nd
Site 19	07-16-1996	-139.0	-18.04	-8.35	7.2	7.3	nd	nd
USGS 12	06-14-1995	-135.0	-17.47	-10.18	nd	nd	13.57	1.14
USGS 19	10-15-1996	-138.1	-18.07	-7.06±0.03	8.6	7.2	-23.99	0.76
USGS 22	07-18-1996	-136.8	-17.62	-13.55	nd	nd	106.80	2.07
USGS 23	10-15-1996	-138.1	-17.94	-5.72	6.1	5.9	1.62	1.02
USGS 97	06-13-1995	-137.1	-17.55	-10.09	nd	nd	28.20	1.28
USGS 98	06-12-1995	-137.6	-18.07	-8.84	nd	nd	6.33	1.06

Table 15. Stable isotope ratios of hydrogen, oxygen, carbon, sulfur, and nitrogen, and the isotope ratio of helium, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	δ^2H (±1.0 permil)	δ^{18}O (±0.10 permil)	δ^{13}C (±0.1 permil)	δ^{34}S (±0.1 permil)	δ^{15}N (±0.1 permil)	δ^3He (±≈0.2 percent)	R_s/R_a
Natural groundwater—Continued								
Northwest INL Area—Continued								
USGS 99	06-12-1995	-136.8	-17.99	-9.68	nd	nd	0.75	1.01
USGS 102	06-13-1995	-135.3	-17.50	-9.81	nd	nd	28.96	1.29
USGS 134 (sz)	09-04-2008	-137.0	-18.08	-8.48	nd	nd	nd	nd
Southwest INL Area								
Middle 2051 (sz)	08-25-2008	-134.1	-17.3	-10.7	nd	nd	nd	nd
USGS 8	10-08-1996	-135.7	-17.78	-9.41±0.00	5.2	5.4	25.65	1.26
USGS 9	10-11-1996	-136.2	-17.75	-9.51	5.8	6.3	81.74	1.82
USGS 11	10-09-1996	-138.6	-17.92	-9.17±0.03	5.6	5.6	43.10	1.43
USGS 86	10-11-1996	-139.4	-18.13	-8.90±0.01	5.7	8.1	0.14	1.00
USGS 89	07-17-1996	-140.4	-18.34	-12.78	nd	nd	nd	nd
USGS 117	07-17-1996	-139.3	-18.05	-10.56	nd	nd	nd	nd
USGS 125	10-11-1996	-136.3	-17.82	-9.38	nd	nd	nd	nd
USGS 135 (sz)	09-14-2010	-137.0	-17.92	-9.06	nd	nd	nd	nd

[1] Sulfur isotope data for Birch Creek at 8-mi Canyon Rd near Reno (Wood and Low, 1988).

[2] Sulfur isotope data for Camas Creek at shearing corral near Kilgore (Wood and Low, 1988).

Table 16. Stable isotope ratios of strontium and radioisotope ratios of uranium, Idaho National Laboratory and vicinity, eastern Idaho.

[Data from Johnson and others (2000); Roback and others (2001); and McLing and others (2002). **$^{234}U/^{238}U$ (activity ratio):** Multiple samples (small and large volume) were collected at some sites. Results reported are from a small volume sample where more than one sample result was available. Analytical results from sites with two or more results varied by less than or equal to 0.02 (activity ratio, rounded two decimal places). **Site name:** Alternate names used in other reports shown in table 10. Springs are shown in *italics*. Location of sites shown in figures 8–9. **Abbreviations:** INL, Idaho National Laboratory. ≈, approximately; nd, not determined; ≤, less than or equal to; ±, plus or minus the analytical precision; 1997?, uncertain sample collection date]

Site name	Date sampled	$^{87}Sr/^{86}Sr$ (±0.002 percent)	$^{234}U/^{238}U$ activity ratio (≈ ±0.25 percent)
Surface water			
Big Lost River below INL diversion	07-14-99	nd	2.12
Big Lost River near Atomic City	04-10-97	0.71056	2.25
Little Lost River	1997?	0.71256	nd
Birch Creek	1997?	0.71198	nd
Tributary Valley groundwater			
Birch Creek Valley			
P&W2	10-15-96	0.71159	3.05
Regional groundwater			
ML 22	04-28-97	0.70992	1.71
USGS 101	10-10-96	0.70962	2.28
Geothermal water			
INEL-1 2,000 feet	03-24-79	0.70935	3.14
INEL-1 10,300 feet	07-20-79	0.70980	2.07
ML 57	*1997?*	*0.71082*	*nd*
ML 58	*1997?*	*0.71434*	*nd*
Groundwater at the Idaho National Laboratory			
Deep groundwater			
EBR 1	10-16-96	0.71006	2.07
Site 9	07-22-96	0.71059	2.50
Site 14	08-20-96	0.71085	2.83
USGS 7	04-21-97	nd	2.89
USGS 15	07-25-96	0.71129	2.77
Contaminated groundwater			
Idaho Nuclear Technology and Engineering Center			
USGS 104	07-15-96	0.71023	2.16
USGS 105	05-05-97	0.71043	2.23
USGS 108	09-09-97	0.71043	2.32
USGS 109	09-01-98	0.71220	2.31
USGS 124	04-10-97	0.71039	2.55
Natural groundwater			
North INL Area			
ANP 6	07-19-96	0.71073	3.01
No Name 1	10-14-96	0.71037	nd
Northeast INL Area			
ANP 9	04-28-97	0.71143	2.99
USGS 26	10-15-96	0.71107	2.82
USGS 27	10-15-96	0.70993	2.35
USGS 29	07-19-96	0.70957	2.13
USGS 31	09-02-98	0.71040	2.61
USGS 32	07-19-96	0.71026	2.45

Table 16. Stable isotope ratios of strontium and radioisotope ratios of uranium, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	$^{87}Sr/^{86}Sr$ (±0.002 percent)	$^{234}U/^{238}U$ activity ratio (≈ ±0.25 percent)
	Natural groundwater—Continued		
	Southeast INL Area		
Arbor Test 1	10-10-96	0.70998	2.33
Area II	07-18-96	0.71048	2.48
Atomic City	10-09-96	0.71042	nd
USGS 1	04-21-97	0.71031	2.45
USGS 2	08-26-98	0.71008	2.35
USGS 14	04-10-97	0.71057	2.64
USGS 100	04-28-97	0.71008	2.32
USGS 107	08-27-98	0.71072	2.56
USGS 110A	08-25-98	0.71057	2.49
	Central INL Area		
Badging Facility well	07-17-96	0.71091	2.53
USGS 5	10-10-96	0.71057	2.05
USGS 6	07-16-96	0.71021	2.27
USGS 17	10-16-96	0.71038	1.96
USGS 18	07-19-96	0.71115	2.91
USGS 83	08-28-98	0.71012	2.07
USGS 103	07-15-96	0.71053	2.41
	Northwest INL Area		
Site 17	07-25-96	0.71091	3.01
USGS 12	09-10-97	0.71061	2.24
USGS 19	10-15-96	0.71014	3.01
USGS 22	07-18-96	0.70951	1.54
	Southwest INL Area		
Highway 3	04-29-97	0.71040	2.07
USGS 8	10-08-96	0.70998	2.49
USGS 9	09-01-98	0.71029	2.22
USGS 11	10-09-96	0.71008	2.47
USGS 86	10-11-96	0.70968	2.23
USGS 89	07-17-96	0.70981	1.92
USGS 125	10-11-96	0.71047	2.27

Table 17. Activity of tritium and approximate age of water samples, calculated percentage of terrigenic helium, apparent age of young fraction of groundwater estimated from environmental tracer data, and activity of carbon-14, Idaho National Laboratory and vicinity, eastern Idaho.

[Data from Busenberg and others (2000, 2001); Rattray (2015); Knobel and others (1992, 1999a, 1999b); U.S. Geological Survey (2014); Swanson and others (2002, 2003); Carkeet and others (2001); Schramke and others (1996); Bartholomay and Twining (2010); and Bartholomay and others (2015). Locations of sites shown in figures 8–9. **Site name:** Alternate names used in other reports shown in table 10. **Date sampled:** Date that the tritium samples were collected. Springs are shown in *italics*. **Abbreviations:** INL, Idaho National Laboratory; sz, shallowest zone. **Units:** pCi/L, picocuries per liter; pmC, percent modern carbon. **Symbols:** ±, plus or minus the indicated standard deviation (standard deviations are 1 sigma); >, greater than; >>, much greater than; nd, not determined; ?, uncertain; O, old water; Y, young water; M, mixture of old and young water; C, contaminated water]

Site name	Date sampled	Tritium (pCi/L)	Approximate age of water sample based on tritium activity	Terrigenic helium (percent)	Apparent age of young groundwater estimated from atmospheric tracer data (years before sampling date)	Carbon-14 (pmC)
Surface water						
Big Lost River below INL Diversion	06-02-1995	52±1.6	Y	nd	nd	[1]120
Birch Creek at Kaufman Guard Station	06-27-2000	22.4±12.8	Y or M	nd	nd	nd
Camas Creek below diversion near CNWR	08-08-2011	26.6±2.1	Y	nd	nd	nd
Little Lost River near Clyde	06-27-2000	38.4±12.8	Y	nd	nd	nd
Little Lost River near Howe	11-08-2000	38.4±12.8	Y	nd	nd	nd
Tributary Valley groundwater						
Big Lost River Valley						
Arco City Well 4	05-13-1997	83.8±2.9	Y	29	nd	nd
Coates	06-01-1999	19.2±12.8	M	nd	nd	nd
Fulton	06-02-1999	54.4±13.4	Y	nd	nd	nd
Hill	06-02-1999	25.6±12.8	Y or M	nd	nd	nd
Lambert	06-23-1999	3.2±12.8	O or M	nd	nd	nd
MSR	06-01-1999	83.2±12.8	Y	nd	nd	nd
Muffett	06-03-1999	57.6±12.8	Y	nd	nd	nd
Owen	06-23-1999	0±12.8	O or M	nd	nd	nd
Wheeler	06-02-1999	19.2±12.8	M	nd	nd	nd
Wildhorse Guard Station	06-02-1999	32±12.8	Y or M	nd	nd	nd
Little Lost River Valley						
Harrell	07-31-2000	35.2±12.8	Y or M	nd	nd	nd
Mays	06-26-2000	0±12.8	O or M	nd	nd	nd
Nicholson	07-31-2000	44.8±12.8	Y	nd	nd	nd
Oar	06-28-2000	51.2±12.8	Y	nd	nd	nd
Pancheri	05-13-1997	52.2±1.9	Y	56	nd	nd
Ruby Farms	05-10-1991	9.6±13	M or O	nd	20	65.4
Sorenson	07-31-2000	51.2±12.8	Y	nd	nd	nd
Birch Creek Valley						
Kaufman Guard Station	06-27-2000	32±12.8	Y or M	nd	nd	nd
McKinney	06-13-1991	-3.2±13	O or M	nd	2–5	nd
P&W2	10-25-1994	8.1±0.2	M	5	4–16	50.84±0.41
USGS 126b	11-08-2000	6.4±9.6	O or M	nd	nd	nd
Wagoner	05-22-1997	14.7±1.0	M	nd	nd	nd
Wagoner Ranch	06-28-2000	38.4±12.8	Y or M	30	nd	nd
Beaverhead Mountains						
ML 55	*06-05-2012*	*10.5±2.2*	*M*	*nd*	*nd*	*nd*
ML 59	*06-05-2012*	*33.1±2.5*	*Y*	*nd*	*nd*	*nd*

Table 17. Activity of tritium and approximate age of water samples, calculated percentage of terrigenic helium, apparent age of young fraction of groundwater estimated from environmental tracer data, and activity of carbon-14, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Tritium (pCi/L)	Approximate age of water sample based on tritium activity	Terrigenic helium (percent)	Apparent age of young groundwater estimated from atmospheric tracer data (years before sampling date)	Carbon-14 (pmC)
Regional groundwater						
ML 5	08-09-2011	-4±2.3	O	nd	nd	nd
ML 6	08-08-2011	13.3±2.1	M	nd	nd	nd
ML 12	08-09-2011	8.6±1.9	M	nd	nd	nd
ML 17	06-04-2012	-0.1±2.1	O	nd	nd	nd
ML 19	05-14-1997	53.1±1.9	Y	38	nd	nd
ML 22	04-19-1995	55.6±0.2	Y	7	5	nd
ML 24	06-06-2012	9.7±2.2	M	nd	nd	nd
ML 25	05-21-1997	2.2±1.0	O	89	nd	nd
ML 29	06-12-1991	-22±13	O	nd	nd	nd
ML 30	06-06-2012	9.7±2.2	M	nd	nd	nd
ML 31	06-06-2012	4.7±2.1	M	nd	nd	nd
Reno Ranch	06-28-2000	25.6±12.8	Y or M	nd	nd	nd
USGS 101	04-21-1995	4.2±0.1	M	55	27–30	nd
Geothermal water						
INEL-1 10,300 ft	04-19-1989	nd	nd	nd	nd	[2]35,000
ML 57	*11-05-1990*	*0.4±0.3*	*O*	*96*	*nd*	*nd*
ML 58	*06-05-2012*	*3.1±2.1*	*M or O*	*nd*	*nd*	*nd*
Groundwater at the Idaho National Laboratory						
Deep groundwater						
EBR 1	06-19-1991	-3.2±13	O or M	27	>45	nd
Site 9	07-22-1996	4.2±1.0	M or O	69	>35	nd
Site 14	10-13-1994	3.7±0.3	O	91	>40	48.0
USGS 7	10-14-1996	-0.2±0.1	O	97	>>55	nd
USGS 15	06-14-1995	1.76±0.03	O	82	22–26	42.76±0.31
Contaminated groundwater						
Advanced Test Reactor Complex						
USGS 65	05-16-1991	39,600±380	C	nd	nd	nd
Idaho Nuclear Technology and Engineering Center						
CFA 1	07-16-1996	19,500±160	C	32	C	nd
CFA2	07-16-1996	14,100±1,400	C	15	C	nd
USGS 20	05-30-1991	10,500±90	C	nd	nd	nd
USGS 36	07-19-1996	5,200±800	C	6	C	nd
USGS 57	05-13-1991	24,500±260	C	nd	nd	nd
USGS 82	07-19-1996	1,130±160	C	21	27	nd
USGS 85	06-04-1991	16,800±130	C	nd	nd	nd
USGS 104	07-15-1996	1,670±240	C	nd	>28	nd
USGS 105	04-18-1995	312.0±2.0	C	8	?	nd
USGS 108	04-18-1995	230±13	C	nd	>20	nd
USGS 109	10-04-1994	107.3±0.6	C	16	18–20	nd
USGS 112	07-15-1996	27,400±260	C	22	C	nd
USGS 113	07-16-1996	10,800±1,200	C	22	C	nd
USGS 115	07-15-1996	4,800±400	C	42	C	nd
USGS 116	07-15-1996	3,800±300	C	32	C	nd
USGS 124	07-20-1994	268.4±2.1	C	23	>24	nd

Table 17. Activity of tritium and approximate age of water samples, calculated percentage of terrigenic helium, apparent age of young fraction of groundwater estimated from environmental tracer data, and activity of carbon-14, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Tritium (pCi/L)	Approximate age of water sample based on tritium activity	Terrigenic helium (percent)	Apparent age of young groundwater estimated from atmospheric tracer data (years before sampling date)	Carbon-14 (pmC)
Contaminated groundwater—Continued						
Naval Reactors Facility						
NRF 6	09-05-1996	89.6±12.8	C	nd	nd	nd
NRF 9	09-04-1996	131.2±12.8	C	nd	nd	nd
NRF 10	09-04-1996	144.0±12.8	C	nd	nd	nd
NRF 11	09-05-1996	297.6±12.8	C	nd	nd	nd
NRF 12	09-05-1996	76.8±12.8	C	nd	nd	nd
NRF 13	09-05-1996	48.0±12.8	Y	nd	nd	nd
Radioactive Waste Management Complex						
RWMC M3S	07-22-1996	2,000±600	C	34	C	nd
RWMC M7S	07-22-1996	1,600±400	C	25	C	nd
RWMC Production	03-23-1989	1,700±200	C	nd	nd	nd
USGS 87	04-05-1989	1,200±200	C	nd	?	nd
USGS 88	04-04-1989	90±160	?	nd	?	nd
USGS 90	04-05-1989	1,600±200	C	nd	nd	nd
USGS 120	07-17-1996	174.1±5.4	C	11	C	nd
Test Area North						
TAN Disposal	03-07-1989	27,600±220	C	nd	nd	nd
TDD 1	03-02-1989	900±200	C	nd	nd	nd
TDD 2	03-06-1989	3,100±200	C	nd	nd	nd
USGS 24	02-28-1989	10,100±400	C	nd	nd	nd
Natural groundwater						
North INL Area						
ANP 6	10-14-1994	3.2±0.1	O	15	20–30	30.91±0.28
ANP 8	12-13-1989	38±13	Y	nd	nd	nd
IET 1 Disposal	07-21-1997	10±110	?	18	>12	nd
No Name 1	10-13-1994	0.13±0.03	O	10	19–21	nd
PSTF Test	10-13-1994	2.5±0.1	O	1	<9	nd
TDD 3	12-13-1989	-3.2±13	O or M	nd	nd	nd
Northeast INL Area						
ANP 9	10-14-1994	0.2±0.2	O	67	6–7	nd
USGS 26	10-14-1994	0.0±0.1	O	86	5–6	53.3
USGS 27	10-11-1994	3.9±0.1	O	88	13	nd
USGS 29	06-15-1995	22.7±0.4	M	71	25	85.85±0.51
USGS 31	07-19-1996	-1.6±0.8	O	83	13	64.56±0.44
USGS 32	10-11-1994	1.2±0.1	O	35	5	62.28±0.43
Southeast INL Area						
Arbor Test 1	04-21-1995	12.5±0.1	M	46	13–25	nd
Area II	07-18-1996	12.5±1.0	M	72	20–21	nd
Atomic City	10-03-1994	11.9±0.3	M	24	14–19	nd
Leo Rogers 1	07-17-1996	12.5±1.3	M	36	nd	nd
USGS 1	10-09-1996	5.8±1.0	M	60	18–24	71.6
USGS 2	07-17-1996	12.2±1.3	M	34	18–24	nd
USGS 14	10-26-1994	19.2±0.1	M	13	>27	58.6
USGS 100	04-21-1995	14.0±0.3	M	53	17–21	79.83±0.50
USGS 107	10-09-1996	10.2±1.0	M	33	>15	nd
USGS 110A	10-09-1996	10.9±1.0	M	55	16–20	nd

Table 17. Activity of tritium and approximate age of water samples, calculated percentage of terrigenic helium, apparent age of young fraction of groundwater estimated from environmental tracer data, and activity of carbon-14, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

Site name	Date sampled	Tritium (pCi/L)	Approximate age of water sample based on tritium activity	Terrigenic helium (percent)	Apparent age of young groundwater estimated from atmospheric tracer data (years before sampling date)	Carbon-14 (pmC)
Natural groundwater—Continued						
Central INL Area						
Badging Facility Well	07-16-1996	22.7±1.3	M	0	20–30?	nd
NPR Test	10-10-1996	57.4±0.2	Y	8	25?	78.25
USGS 5	10-12-1994	28.4±0.4	M	30	17–18	nd
USGS 6	07-18-1996	0.3±0.8	O	62	>>55	nd
USGS 17	06-13-1995	50.0±0.5	Y	27	11–16	82.90±0.47
USGS 18	07-18-1994	0.5±0.5	O	84	17	20.58
USGS 83	04-17-1995	-190±70	O	nd	34-35	nd
USGS 103	04-18-1995	11.8±0.1	M	16	>26	nd
Northwest INL Area						
Fire Station 2	10-16-1996	36.5±1.6	Y	9	11-20	nd
INEL-1 WS	06-12-1995	48.3±1.9	Y	nd	20-21	59.48±0.55
NRF 7	09-03-1996	12.8±12.8	O or M	nd	nd	nd
NRF 8	09-04-1996	57.6±12.8	Y	nd	nd	nd
Site 4	10-16-1996	51.5±1.9	Y	4	25	nd
Site 17	06-18-1991	32±13	Y or M	1	21-22	53.99±0.39
Site 19	07-16-1996	13.4±1.0	M	7	15	nd
USGS 12	06-14-1995	71.9±0.7	Y	6	3–17	85.21±0.47
USGS 19	04-19-1995	11.8±0.3	M	38	15–16	36.99
USGS 22	06-13-1995	160.9±0.4	Y	0	8	69.91±0.52
USGS 23	04-19-1995	1.3±0.1	O	57	>>55	21.88±0.24
USGS 97	06-13-1995	69.0±1.0	Y	6	10–20	84.42±0.53
USGS 98	10-04-1994	20.0±0.4	M	2	10–20	63.17±0.44
USGS 99	06-12-1995	36.2±0.5	Y	9	10–20	76.30±0.51
USGS 102	06-13-1995	70.8±0.6	Y	10	26?	86.17±0.52
USGS 134 (sz)	09-04-2008	17±1.9	M	nd	nd	nd
Southwest INL Area						
Middle 2051 (sz)	08-25-2008	51.7±2.9	Y	nd	nd	nd
USGS 8	10-04-1994	47.4±0.5	Y	10	8–9	nd
USGS 9	10-04-1994	47.9±0.2	Y	23	>23	nd
USGS 11	04-20-1995	31.8±0.2	Y	13	>17	65.0
USGS 86	10-11-1996	2.9±1.0	O	40	12–19	nd
USGS 89	10-14-1998	10±49	M or Y	28	?	nd
USGS 117	07-17-1996	-100±100	O	33	>33	nd
USGS 119	04-03-1989	-70±150	?	nd	?	nd
USGS 125	06-16-1995	72.8±0.6	Y	14	>17	76.65±0.46
USGS 135 (sz)	09-14-2010	14±1.9	M	nd	nd	nd

[1] Estimated pmC, based on typical carbon-14 activity of atmospheric carbon dioxide during the 1980s and 1990s (Plummer, Sanford, and others, 2004, fig. 98).

[2] Estimated age in years (Mann, 1986).

Glossary

Contaminated groundwater Groundwater at the Idaho National Laboratory probably influenced by wastewater disposal. Contaminated groundwater was identified from various chemical signatures. These included groundwater samples with (1) large tritium activities (>75 pCi/L); (2) large sodium and sulfate concentrations (>25 and >40 mg/L, respectively); (3) large specific conductance values (>600 µS/cm at 25 °C); and (4) in the area near the Naval Reactors Facility, large chloride/nitrate ratios (>75).

Deep groundwater Groundwater at the Idaho National Laboratory that is more than the 250 ft below the water table (does not include geothermal water).

Environmental tracers Refers to tritium (^3H), carbon-14 (^{14}C), chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and the ratio tritium/helium-3 ($^3H/^3He$). Radioactive isotopes ^3H and ^{14}C are used to date groundwater (Clark and Fritz, 1997); the age of the young fraction of groundwater was determined from CFCs, SF_6, and $^3H/^3He$ (Busenberg and others, 2001).

Geothermal water Groundwater in the study area with temperatures exceeding 25 °C.

Groundwater at the Idaho National Laboratory (INL) Deep groundwater, contaminated groundwater, and natural groundwater.

Modern activity of carbon-14 (^{14}C) Percent modern carbon (pmC) values greater than 100 and indicates a post-1950 age of groundwater.

Natural groundwater Groundwater at and south of the Idaho National Laboratory, excluding contaminated groundwater, that is less than the 250 ft below the water table.

Old groundwater Groundwater that is older than the onset of atmospheric bomb testing (pre-1952). In this report, this qualitative age was assigned to groundwater with tritium activities less than 4 pCi/L.

Recent recharge Generally refers to groundwater that has recharged since CFCs were introduced into the atmosphere (about 1940). When in reference to groundwater with a He_{terr} less than 10 percent, refers to groundwater that has been in contact with air or the unsaturated-zone atmosphere within the past several hundred years (Busenberg and others, 2001).

Regional groundwater Groundwater in the eastern Snake River Plain aquifer east and southeast of the Idaho National Laboratory. Includes ML 22, USGS 3A, and USGS 101 in the southeastern part of the INL.

Sources of recharge Sources of recharge include surface water, tributary valley groundwater, regional groundwater, geothermal water, precipitation, industrial wastewater discharge, and agricultural return flows.

Tributary valley groundwater Groundwater from the Big Lost River, Little Lost River, and Birch Creek valleys. Includes two groundwater samples (ML 55 and ML 59) from the Beaverhead Mountains.

Young fraction of groundwater Water that has recharged since the 1940s.

Young groundwater Groundwater that is younger than the onset of atmospheric bomb testing (post-1952). This qualitative groundwater age was determined from tritium activities.

Appendix 1. Water-Level Measurements

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.

[Water-level measurements are from U.S. Geological Survey (2014). Water-table contours are shown in figure 6. **Site name:** –, no name. **Altitudes:** In feet (ft) above National Geodetic Vertical Datum of 1929 (NGVD 29). **Abbreviations:** ft bls, feet below land surface; NAD 27, North American Datum of 1927]

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
431517112190101	02S 35E 11DDD1	–	431517.00	1121901.00	4,518.38	03-29-1989	49.98	4,468.40
431517112190102	02S 35E 11DDD2	–	431517.00	1121901.00	4,518.38	03-29-1989	70.23	4,448.15
431520112360901	02S 33E 16ABB1	–	431520.00	1123608.50	4,556.00	03-29-1989	133.95	4,422.05
431902112284301	01S 34E 21DAC1	–	431859.80	1122842.60	4,547.00	03-29-1989	111.32	4,435.68
431929112421701	01S 32E 22BDB1	–	431928.40	1124220.20	4,740.00	03-29-1989	318.29	4,421.71
431946113161401	01S 27E 14DCC1	SITE 2	431946.00	1131614.00	5,158.86	04-11-1989	995.74	4,163.12
432019112563201	01S 30E 15BCA1	USGS 14	432019.27	1125631.92	5,132.88	05-01-1989	714.66	4,418.22
432042112193201	01S 35E 11CAD1	–	432042.00	1121931.00	4,662.00	03-29-1989	172.93	4,489.07
432336113064201	01N 29E 30BBD1	USGS 11	432336.18	1130642.52	5,067.12	05-01-1989	651.03	4,416.09
432618112555501	01N 30E 10BBA1	Cerro Grande	432618.00	1125553.86	4,979.30	05-01-1989	552.43	4,426.87
432659112582601	02N 29E 35CCC1	USGS 108	432658.79	1125826.34	5,031.36	04-19-1989	604.86	4,426.50
432700112470801	02N 31E 35DCC1	USGS 1	432700.08	1124708.54	5,022.34	04-27-1989	586.24	4,436.10
432701113025601	02N 29E 31CDC1	USGS 109	432701.23	1130255.81	5,043.64	04-21-1989	619.08	4,424.56
432703113001801	02N 29E 33DCC1	USGS 105	432703.40	1130017.78	5,095.12	04-21-1989	668.36	4,426.76
432714112560701	02N 30E 31CBC1	USGS 103	432713.57	1125606.53	5,007.42	04-14-1989	580.22	4,427.20
432717112501501	02N 30E 35DAD1	USGS 110	432716.97	1125015.05	4,999.91	04-12-1989	567.75	4,432.16
432731113143902	02N 27E 33ACC2	USGS 13	432730.57	1131438.51	5,374.58	05-01-1989	984.61	4,389.97
432740113044501	02N 28E 35AAC1	USGS 9	432732.38	1130439.78	5,030.32	04-21-1989	605.84	4,424.48
432854113201001	02N 26E 22DDA1	–	432854.00	1132010.00	5,361.81	04-11-1989	660.07	4,701.74
432854113201002	02N 26E 22DDA2	–	432854.00	1132010.00	5,361.81	04-11-1989	981.21	4,380.60
432856112560801	02N 29E 24DAD1	USGS 104	432856.07	1125608.14	4,987.64	04-14-1989	553.95	4,433.69
432919113031501	02N 29E 19BCB1	USGS 120	432919.19	1130314.01	5,040.43	04-04-1989	613.12	4,427.31
432935113080001	02N 28E 21BBB1	USGS 86	432934.79	1130801.44	5,076.92	04-21-1989	649.12	4,427.80
432940113030201	02N 29E 18CCD1	USGS 88	432940.20	1130301.96	5,020.81	04-04-1989	582.83	4,437.98
432942112532801	02N 30E 16CCA1	USGS 107	432942.02	1125327.53	4,917.50	04-11-1989	477.66	4,439.84
432945113023401	02N 29E 18DCB1	USGS 119	432944.61	1130233.69	5,031.84	04-03-1989	602.22	4,429.62
432954113020501	02N 29E 17CBC1	USGS 90	432952.45	1130205.86	5,010.01	01-18-1989	580.67	4,429.34
432955113025901	02N 29E 18CBD1	USGS 117	432954.50	1130258.67	5,012.50	04-03-1989	582.89	4,429.61
432959112593101	02N 29E 15CBA1	USGS 106	432958.60	1125931.38	5,015.30	04-14-1989	586.19	4,429.11
433005113032801	02N 28E 13ADD1	USGS 89	433005.67	1130331.73	5,030.24	04-04-1989	598.29	4,431.95
433013113024201	02N 29E 18BDA1	USGS 87	433012.74	1130243.06	5,017.85	04-05-1989	586.77	4,431.08
433023112561501	02N 29E 13AAA1	USGS 83	433023.03	1125615.28	4,941.11	04-13-1989	495.53	4,445.58
433121113115801	02N 27E 02DDC1	USGS 8	433120.51	1131157.43	5,194.94	05-01-1989	764.43	4,430.51
433123112530101	02N 30E 04DCC1	Site 9	433122.86	1125300.80	4,925.65	04-05-1989	469.80	4,455.85
433144112563501	02N 29E 01DBB1	CFA 2	433143.94	1125635.11	4,931.70	01-25-1989	474.55	4,457.15
433216112563201	03N 29E 36DCD1	CFA LF 2-8	433216.00	1125632.00	4,932.88	01-19-1989	471.93	4,460.95
433216112563301	03N 29E 36DCC2	CFA LF 2-10	433215.87	1125632.97	4,932.03	01-26-1989	475.50	4,456.53
433217112563401	03N 29E 36DCC1	CFA LF 2-9	433217.00	1125634.00	4,933.37	01-26-1989	469.88	4,463.49
433218112191601	02N 35E 02BBC1	Highway 1C	433218.00	1121916.00	5,089.83	04-08-1989	578.31	4,511.52
433218112571001	03N 29E 36CCB1	CFA LF 3-8	433218.00	1125710.00	4,941.43	01-19-1989	480.32	4,461.11
433223112470201	03N 31E 35DCA1	Area II	433222.62	1124702.40	5,128.60	03-29-1989	667.05	4,461.55
433230112561701	03N 29E 36DAC1	CFA LF 2-11	433230.40	1125617.01	4,928.37	12-06-1989	470.20	4,458.17
433246112571201	03N 29E 36BCB1	USGS 85	433246.23	1125711.89	4,938.99	04-01-1989	479.37	4,459.62
433253112545901	03N 30E 31AAD1	USGS 20	433252.79	1125459.41	4,915.11	04-01-1989	457.89	4,457.22
433303112184201	03N 35E 35BAD1	–	433302.50	1121842.40	5,160.00	04-11-1989	645.20	4,514.80
433307112300001	03N 34E 32BBC1	Highway 2	433307.00	1123000.00	5,216.55	04-08-1989	720.39	4,496.16
433314112561801	03N 29E 25DDB1	USGS 113	433314.53	1125618.29	4,925.32	03-31-1989	464.27	4,461.05
433314112563001	03N 29E 25DCA1	USGS 112	433314.50	1125630.74	4,927.82	03-30-1989	467.98	4,459.84
433315112560301	03N 30E 30CCB1	USGS 77	433315.25	1125603.57	4,921.43	03-31-1989	461.68	4,459.75
433318112555001	03N 30E 30CBD1	USGS 114	433318.87	1125550.75	4,920.04	03-31-1989	460.10	4,459.94
433320112432301	03N 32E 29DDC1	USGS 2	433319.87	1124321.28	5,125.22	04-27-1989	655.49	4,469.73

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
433320112554101	03N 30E 30CAD1	USGS 115	433320.22	1125541.39	4,918.86	04-06-1989	459.25	4,459.61
433322112564301	03N 29E 25CAD1	USGS 38	433322.35	1125643.25	4,929.04	03-31-1989	469.06	4,459.98
433326112564801	03N 29E 25CAA1	USGS 37	433325.80	1125648.13	4,928.54	03-31-1989	468.60	4,459.94
433330112565201	03N 29E 25BDD1	USGS 36	433330.11	1125651.47	4,928.83	03-31-1989	468.90	4,459.93
433331112553201	03N 30E 30ACC1	USGS 116	433331.55	1125532.67	4,916.05	04-06-1989	455.88	4,460.17
433331112560501	03N 30E 30BCC1	USGS 111	433331.16	1125605.18	4,920.48	04-06-1989	461.51	4,458.97
433334112565501	03N 29E 25BDC1	USGS 34	433334.44	1125654.76	4,928.54	03-31-1989	468.71	4,459.83
433339112565801	03N 29E 25BDB1	USGS 35	433338.37	1125658.14	4,928.97	03-31-1989	469.47	4,459.50
433343112570001	03N 29E 25BBD1	USGS 39	433343.19	1125701.42	4,930.55	03-31-1989	470.85	4,459.70
433344112554101	03N 30E 30BAD1	USGS 67	433344.09	1125540.72	4,913.34	04-10-1989	453.59	4,459.75
433344112562601	03N 29E 25ABD1	USGS 57	433344.04	1125626.00	4,922.23	04-07-1989	462.53	4,459.70
433350112560601	03N 30E 30BBB1	USGS 51	433350.01	1125606.06	4,916.91	04-17-1989	455.19	4,461.72
433354112554701	03N 30E 30BAB1	USGS 59	433354.32	1125548.02	4,912.88	04-10-1989	452.28	4,460.60
433356112574201	03N 29E 23DCD1	USGS 84	433356.51	1125741.84	4,937.63	04-01-1989	477.68	4,459.95
433401112551001	03N 30E 19DDC2	USGS 82	433400.93	1125510.34	4,906.83	04-13-1989	446.15	4,460.68
433401112560301	03N 30E 19CCC1	USGS 48	433400.62	1125602.52	4,916.84	04-06-1989	456.06	4,460.78
433402112561801	03N 29E 24DDC1	USGS 45	433402.35	1125617.76	4,917.69	04-07-1989	457.78	4,459.91
433403112555401	03N 30E 19CCA1	USGS 49	433402.91	1125554.13	4,913.67	04-07-1989	452.97	4,460.70
433404112561301	03N 29E 24DDA2	USGS 42	433402.76	1125611.73	4,916.87	04-07-1989	456.11	4,460.76
433407112203101	03N 35E 28AAA1	–	433407.00	1122031.00	5,195.00	04-10-1989	681.35	4,513.65
433407112560301	03N 30E 19CCB1	USGS 47	433407.51	1125603.13	4,915.63	04-20-1989	453.77	4,461.86
433407112561501	03N 29E 24DDA3	USGS 46	433406.55	1125614.68	4,916.42	04-07-1989	455.87	4,460.55
433409112561301	03N 29E 24DDA1	USGS 41	433407.70	1125611.78	4,916.26	04-07-1989	455.49	4,460.77
433409112562101	03N 29E 24DDB1	USGS 44	433408.61	1125621.15	4,917.73	04-07-1989	456.90	4,460.83
433411112561101	03N 29E 24DAD1	USGS 40	433411.68	1125611.83	4,915.65	03-27-1989	455.44	4,460.21
433414112554201	03N 30E 19CAC1	USGS 52	433414.74	1125544.26	4,909.44	04-07-1989	448.57	4,460.87
433415112561501	03N 29E 24DAD2	USGS 43	433414.79	1125614.82	4,915.48	04-20-1989	454.78	4,460.70
433422113031701	03N 29E 19CBB1	USGS 22	433422.28	1130321.09	5,048.27	04-05-1989	608.09	4,440.18
433425112573201	03N 29E 23ADC1	USGS 76	433425.31	1125732.31	4,929.74	04-07-1989	469.84	4,459.90
433447112574501	03N 29E 23ABB1	USGS 65	433446.85	1125747.13	4,924.75	04-10-1989	463.56	4,461.19
433449112523101	03N 30E 16DDD1	NPR Test	433449.43	1125231.26	4,933.13	04-28-1989	458.60	4,474.53
433500112182201	03N 35E 14DDC1	–	433500.00	1121822.00	5,057.00	04-11-1989	532.45	4,524.55
433500112572502	03N 29E 14DDA2	USGS 58	433500.19	1125725.07	4,918.11	04-13-1989	457.16	4,460.95
433503112400701	03N 32E 14CDD1	USGS 100	433502.72	1124006.67	5,157.94	04-19-1989	672.67	4,485.27
433505112581901	03N 29E 14CBD1	USGS 79	433505.49	1125819.11	4,930.50	04-01-1989	469.80	4,460.70
433509112384801	03N 32E 13DCA1	Arbor Test I	433508.92	1123848.01	5,163.95	04-27-1989	675.57	4,488.38
433520112572601	03N 29E 14ADD1	MTR Test	433520.08	1125729.20	4,916.47	03-27-1989	455.15	4,461.32
433522112582101	03N 29E 14BCB1	Site19	433522.32	1125821.49	4,925.95	04-10-1989	464.97	4,460.98
433543112493801	03N 30E 12CDD1	USGS 5	433542.75	1124937.65	4,937.57	03-28-1989	462.86	4,474.71
433545112391501	03N 32E 13BBD1	Site 16	433544.69	1123915.42	5,121.23	03-20-1989	632.69	4,488.54
433643112210401	03N 35E 09BAA1	–	433643.00	1122104.00	5,119.00	04-12-1989	596.42	4,522.58
433657112563601	03N 29E 01DBB1	USGS 98	433657.00	1125636.00	4,882.64	04-19-1989	399.75	4,482.89
433658112173201	03N 35E 01CAD1	–	433657.00	1121736.00	4,948.00	04-12-1989	425.68	4,522.32
433705112552101	03N 30E 06ACD1	USGS 99	433703.74	1125521.16	4,871.55	04-19-1989	388.42	4,483.13
433716112563601	03N 29E 01ABC1	INEL 1 WS	433714.54	1125639.90	4,872.23	04-19-1989	389.12	4,483.11
433718112190801	03N 35E 02BCB1	–	433723.00	1121910.00	5,035.00	04-12-1989	502.95	4,532.05
433745112172701	04N 35E 36DCB1	–	433748.00	1121729.00	4,930.00	04-14-1989	402.11	4,527.89
433748112151201	04N 36E 32CDA1	–	433748.00	1121512.00	4,860.00	04-19-1989	340.00	4,520.00
433759112202701	04N 35E 34CBB1	–	433759.00	1122027.00	5,040.00	04-12-1989	514.90	4,525.10
433802112192401	04N 35E 34ADD1	–	433801.00	1121929.00	5,010.00	04-13-1989	483.78	4,526.22
433807112551501	04N 30E 31ABD1	USGS 97	433806.77	1125516.76	4,858.49	04-19-1989	373.95	4,484.54
433819113191601	04N 26E 26DCD1	–	433818.99	1131919.46	5,332.25	03-31-1989	48.87	5,283.38

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
433853112551601	04N 30E 30ACA1	USGS 102	433850.87	1125516.43	4,850.28	12-20-1989	367.72	4,482.56
433900112145901	04N 36E 29ACD1	–	433900.00	1121459.00	4,895.00	04-12-1989	370.35	4,524.65
433906112165601	04N 35E 25ADA1	–	433906.00	1121656.00	4,958.00	04-15-1989	425.19	4,532.81
433937112515401	04N 30E 22BDD1	USGS 17	433936.42	1125154.27	4,833.44	04-08-1989	349.12	4,484.32
433945112221701	04N 35E 20CAA1	–	433946.00	1122217.00	5,030.00	04-13-1989	503.61	4,526.39
434027112575701	04N 29E 14CAA1	Site 17	434026.74	1125756.50	4,880.47	03-28-1989	390.17	4,490.30
434031112453701	04N 31E 16ADC1	USGS 6	434031.12	1124536.66	4,898.55	05-22-1989	410.51	4,488.04
434037112193501	04N 35E 15DBA1	–	434037.00	1121935.00	4,981.00	04-15-1989	450.78	4,530.22
434040112163501	04N 36E 18BDC1	–	434040.00	1121635.00	4,898.00	04-19-1989	364.64	4,533.36
434055112595901	04N 29E 09DCD1	USGS 23	434055.15	1130000.02	4,884.20	03-29-1989	393.10	4,491.10
434117112191801	04N 35E 10DAD1	–	434117.00	1121918.00	4,995.00	04-17-1989	458.45	4,536.55
434126112550701	04N 30E 07ADB1	USGS 12	434126.19	1125507.10	4,819.00	04-15-1989	322.06	4,496.94
434234112551701	04N 30E 06ABA1	USGS 15	434234.84	1125517.35	4,811.99	03-28-1989	312.73	4,499.26
434307112382601	05N 32E 36ADD1	USGS 21	434307.49	1123825.90	4,838.70	04-15-1989	327.91	4,510.79
434327112161101	05N 36E 31ACB1	–	434327.00	1121611.00	4,880.00	04-18-1989	316.71	4,563.29
434334112463101	05N 31E 28CCC1	Site 14	434334.66	1124631.50	4,793.52	04-18-1989	263.42	4,530.10
434407112285101	05N 34E 29DAA1	USGS 29	434406.86	1122850.25	4,877.48	04-26-1989	349.60	4,527.88
434426112575701	05N 29E 23CDD1	USGS 19	434426.68	1125756.58	4,800.06	04-15-1989	272.43	4,527.63
434444112322101	05N 33E 23DDA1	USGS 32	434444.07	1123221.24	4,812.02	04-17-1989	284.82	4,527.20
434540112440901	05N 31E 14BCC1	USGS 18	434540.70	1124409.29	4,804.23	03-29-1989	264.67	4,539.56
434600112360101	05N 33E 17ADD1	USGS 28	434559.97	1123600.53	4,771.48	04-17-1989	226.94	4,544.54
434601112315401	05N 33E 13BDC1	USGS 30C	434600.72	1123154.36	4,793.87	04-26-1989	264.67	4,529.20
434611112504301	05N 30E 11CDD1	DH 1B	434611.02	1125043.22	4,792.12	05-19-1989	264.26	4,527.86
434624112194601	05N 35E 10DCC1	–	434622.70	1121956.60	4,900.00	04-13-1989	258.84	4,641.16
434657112282201	05N 34E 09BDA1	USGS 4	434655.93	1122821.62	4,790.73	04-16-1989	256.40	4,534.33
434701112214301	05N 35E 08AAD1	–	434701.00	1122143.00	4,790.00	04-11-1989	250.13	4,539.87
434713112222301	05N 35E 08BAA1	–	434713.00	1122223.00	4,790.00	04-11-1989	246.09	4,543.91
434714112175801	05N 35E 01CCC1	–	434714.00	1121758.00	4,793.00	04-13-1989	236.09	4,556.91
434714112231101	05N 35E 06DDC1	–	434713.50	1122314.40	4,789.00	04-11-1989	248.29	4,540.71
434718112290501	05N 34E 05DDC1	–	434718.00	1122910.70	4,790.00	08-28-1989	249.45	4,540.55
434726112200801	05N 35E 03CDB1	–	434726.00	1122008.00	4,792.00	04-13-1989	247.92	4,544.08
434726112244101	05N 34E 01DBC1	–	434729.00	1122435.00	4,786.00	04-12-1989	246.78	4,539.22
434731112282901	05N 34E 04CAC1	–	434731.00	1122829.00	4,788.00	08-28-1989	260.08	4,527.92
434734112241401	05N 34E 01DAB1	–	434734.00	1122414.00	4,787.00	04-12-1989	248.21	4,538.79
434736112253001	05N 34E 02DAB1	–	434733.00	1122535.00	4,790.00	04-12-1989	251.95	4,538.05
434738112273901	05N 34E 04DAA1	–	434738.00	1122739.00	4,790.00	08-28-1989	258.68	4,531.32
434741112291101	05N 34E 05DAB1	–	434733.00	1122907.00	4,789.00	04-16-1989	253.25	4,535.75
434744112193701	05N 35E 03ACD1	–	434744.00	1121937.00	4,801.00	04-12-1989	251.97	4,549.03
434744112212203	05N 35E 04BDB3	–	434744.00	1122122.00	4,789.00	04-11-1989	244.39	4,544.61
434751112571801	05N 29E 01BBB1	–	434751.00	1125718.00	4,805.00	03-29-1989	122.83	4,682.17
434756112212101	06N 35E 32DDD1	–	434756.00	1122121.00	4,789.00	04-17-1989	243.83	4,545.17
434805112204501	06N 35E 33CDA1	–	434805.00	1122045.00	4,792.28	04-10-1989	245.07	4,547.21
434805112303501	06N 34E 31CDB1	–	434805.00	1123035.00	4,785.00	04-15-1989	257.68	4,527.32
434810112230401	06N 35E 31DBC1	–	434810.00	1122304.00	4,785.00	04-11-1989	239.53	4,545.47
434817112292101	06N 34E 32CAB1	–	434817.00	1122921.00	4,786.00	04-16-1989	250.67	4,535.33
434818112240401	06N 34E 36DBA1	–	434818.00	1122404.00	4,785.00	04-12-1989	248.53	4,536.47
434818112284801	06N 34E 32ACD1	–	434818.00	1122848.00	4,788.00	04-16-1989	251.10	4,536.90
434819112380501	06N 32E 36ADD1	2nd Owsley	434819.82	1123806.05	4,784.80	04-26-1989	218.07	4,566.73
434824112214901	06N 35E 32ACC1	–	434824.00	1122149.00	4,788.00	04-11-1989	238.00	4,550.00
434828112185001	06N 35E 35BCB1	–	434828.00	1121850.00	4,802.95	04-12-1989	239.66	4,563.29
434831112273601	06N 34E 33ADB1	–	434831.00	1122736.00	4,790.00	08-31-1989	257.24	4,532.76
434831112303501	06N 34E 31BDB1	–	434831.00	1123035.00	4,785.00	08-24-1989	248.66	4,536.34

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
434842112210601	06N 35E 33BBA1	–	434842.00	1122106.00	4,788.00	04-10-1989	240.07	4,547.93
434843112271601	06N 34E 34BBB1	–	434844.00	1122720.00	4,790.00	04-16-1989	251.07	4,538.93
434851112321801	06N 33E 26DDB1	USGS 27	434851.22	1123218.90	4,783.90	04-15-1989	219.89	4,564.01
434856112400001	06N 32E 26CDB1	ANP 9	434855.71	1124000.36	4,786.14	03-01-1989	216.48	4,569.66
434857112185801	06N 35E 27DDA1	–	434857.00	1121858.00	4,798.23	04-12-1989	234.60	4,563.63
434858112295901	06N 34E 30DAC1	–	434858.00	1122959.00	4,786.00	04-16-1989	217.65	4,568.35
434905112213801	06N 35E 29DBA1	–	434905.00	1122138.00	4,786.00	04-10-1989	238.86	4,547.14
434915112443901	06N 31E 27BDD1	USGS 7	434914.81	1124439.87	4,789.24	03-30-1989	206.05	4,583.19
434924112183701	06N 35E 26BAC1	–	434924.00	1121837.00	4,790.59	04-13-1989	218.05	4,572.54
434924112193101	06N 35E 27ABC1	–	434924.00	1121931.00	4,796.00	04-13-1989	237.29	4,558.71
434935112210701	06N 35E 28BBA1	–	434934.00	1122106.00	4,785.00	04-10-1989	233.20	4,551.80
434938112200701	06N 35E 22CCC1	–	434938.00	1122007.00	4,788.00	04-11-1989	234.07	4,553.93
434939112174501	06N 35E 23DDD1	–	434939.00	1121745.00	4,833.00	04-13-1989	178.68	4,654.32
434941112454201	06N 31E 21DCC1	PSTF Test	434940.74	1124541.46	4,786.35	05-19-1989	201.95	4,584.40
434949112413401	06N 32E 22CCB1	GIN 2	434948.89	1124133.96	4,786.23	04-27-1989	202.74	4,583.49
434950112311201	06N 33E 24DDB1	–	434950.00	1123112.00	4,785.00	04-18-1989	197.70	4,587.30
435003112313101	06N 33E 24BDD1	–	435002.30	1123134.80	4,785.00	04-18-1989	213.45	4,571.55
435016112182701	06N 35E 23BAD1	–	435016.00	1121830.00	4,790.14	04-13-1989	176.66	4,613.48
435016112311201	06N 33E 24AAC1	–	435016.00	1123112.00	4,785.00	04-18-1989	148.85	4,636.15
435028112194801	06N 35E 22BAB1	–	435028.00	1121948.00	4,786.00	04-11-1989	101.64	4,684.36
435028112202601	06N 35E 21AAB1	–	435028.00	1122026.00	4,784.50	04-10-1989	99.45	4,685.05
435028112245601	06N 34E 23AAA1	–	435028.00	1122456.00	4,787.00	04-18-1989	220.88	4,566.12
435038112453401	06N 31E 16DCA1	No Name 1	435038.79	1124532.76	4,784.30	05-19-1989	200.35	4,583.95
435042112182001	06N 35E 14CAD1	–	435041.00	1121824.00	4,789.00	04-13-1989	100.62	4,688.38
435045112180901	06N 35E 14DBD1	–	435045.00	1121809.00	4,789.00	04-19-1989	97.95	4,691.05
435050112423202	06N 31E 13CAB6	TAN 11	435050.00	1124232.00	4,781.84	12-14-1989	196.88	4,584.96
435053112420801	06N 31E 13DBB1	USGS 24	435050.77	1124212.34	4,795.10	04-15-1989	209.23	4,585.87
435053112423202	06N 31E 13CAB3	TAN 9	435053.00	1124232.00	4,781.91	12-11-1989	197.06	4,584.85
435100112271601	06N 34E 15BCC1	–	435100.00	1122716.00	4,784.75	04-18-1989	199.60	4,585.15
435107112180001	06N 35E 14ACA1	–	435108.00	1121804.00	4,790.00	04-19-1989	96.64	4,693.36
435108112172601	06N 35E 13BCA1	–	435108.00	1121726.00	4,810.00	04-19-1989	113.68	4,696.32
435108112185601	06N 35E 15AAD1	–	435108.00	1121856.00	4,787.85	04-14-1989	93.16	4,694.69
435120112182001	06N 35E 14BAA1	–	435120.00	1121820.00	4,789.00	04-14-1989	94.04	4,694.96
435123112163201	06N 35E 12DDD1	–	435123.00	1121632.00	4,850.00	04-14-1989	148.96	4,701.04
435124112433701	06N 31E 11CDC1	FET Disposal 3	435124.31	1124337.20	4,782.39	05-19-1989	196.10	4,586.29
435132112234001	06N 35E 07CCB1	–	435132.00	1122340.00	4,783.71	04-10-1989	198.27	4,585.44
435134112335501	06N 33E 10DBC1	ML 15	435134.00	1123357.50	4,783.00	04-18-1989	96.55	4,686.45
435140112155401	06N 36E 07DBC1	–	435140.00	1121554.00	4,851.00	04-14-1989	146.28	4,704.72
435152112443101	06N 31E 10ACC1	ANP 6	435151.57	1124431.39	4,794.43	05-19-1989	208.24	4,586.19
435153112320801	06N 33E 11ADD1	–	435153.00	1123208.00	4,783.00	04-18-1989	119.06	4,663.94
435153112420501	06N 31E 12ACD1	IET 1 Disposal	435153.38	1124205.22	4,790.02	03-01-1989	204.15	4,585.87
435200112164801	06N 35E 12ADB1	–	435200.00	1121648.00	4,795.00	04-14-1989	89.52	4,705.48
435201112194901	06N 35E 10BDD1	–	435200.00	1121954.00	4,785.00	04-11-1989	101.94	4,683.06
435212112311301	06N 33E 01DCD1	–	435214.00	1123113.00	4,784.00	04-18-1989	118.55	4,665.45
435212112394001	06N 32E 11ABA1	USGS 26	435210.55	1123940.74	4,788.69	04-27-1989	202.48	4,586.21
435213112302001	06N 34E 07BAA1	–	435213.00	1123020.00	4,784.00	04-18-1989	106.24	4,677.76
435226112150101	06N 36E 05CDB1	–	435226.00	1121501.00	4,850.00	04-20-1989	131.86	4,718.14
435226112172301	06N 35E 01CDB1	–	435226.00	1121723.00	4,790.00	04-14-1989	89.40	4,700.60
435229112163202	06N 35E 01DAD2	–	435227.90	1121635.90	4,795.00	04-14-1989	82.90	4,712.10
435230112161301	06N 36E 06CAC1	–	435230.00	1121613.00	4,815.00	04-19-1989	111.00	4,704.00
435252112150301	06N 36E 05BCA1	–	435252.00	1121503.00	4,819.00	04-20-1989	99.15	4,719.85
435253112161201	06N 36E 06BDB1	–	435253.00	1121612.00	4,792.00	04-20-1989	75.36	4,716.64

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
435253112172701	06N 35E 01BBD1	–	435253.00	1121727.00	4,790.00	04-19-1989	70.10	4,719.90
435304112280801	06N 34E 04BAB1	–	435302.90	1122810.60	4,783.00	08-21-1989	161.27	4,621.73
435308112454101	07N 31E 33DCD1	ANP 5	435308.18	1124541.41	4,872.18	05-19-1989	285.96	4,586.22
435310112320901	07N 33E 35DDD1	–	435306.00	1123216.00	4,782.00	03-16-1989	99.86	4,682.14
435313112274101	07N 34E 33DCD1	–	435307.00	1122744.00	4,782.21	04-10-1989	43.58	4,738.63
435320112165301	07N 35E 36DAC1	–	435320.00	1121653.00	4,790.00	04-11-1989	65.10	4,724.90
435339112444601	07N 31E 34BDD1	USGS 25	435338.49	1124446.01	4,848.47	04-15-1989	262.09	4,586.38
435347112165301	07N 35E 36AAC1	–	435347.00	1121653.00	4,790.00	04-11-1989	37.04	4,752.96
435347112173301	07N 35E 36BBD1	–	435347.00	1121733.00	4,790.00	04-13-1989	9.61	4,780.39
435352112161701	07N 36E 31BBA1	–	435352.00	1121617.00	4,790.00	04-20-1989	37.59	4,752.41
435352112171601	07N 35E 36BAA1	–	435352.00	1121716.00	4,790.00	04-13-1989	9.30	4,780.70
435357112150201	07N 36E 32BAB1	–	435357.00	1121502.00	4,791.00	04-20-1989	14.33	4,776.67
435358112161102	07N 36E 31BAB2	–	435358.00	1121611.00	4,793.00	04-20-1989	28.28	4,764.72
435359112182501	07N 35E 26CDD1	–	435359.00	1121825.00	4,790.00	04-13-1989	7.13	4,782.87
435400112174101	07N 35E 25CCC1	–	435400.00	1121741.00	4,790.00	04-12-1989	10.67	4,779.33
435403112170501	07N 35E 25DCC1	–	435403.00	1121705.00	4,790.00	04-11-1989	8.82	4,781.18
435405112174304	07N 35E 25CCB4	–	435405.00	1121743.00	4,795.00	04-13-1989	9.66	4,785.34
435407112170904	07N 35E 25DCB4	–	435407.00	1121709.00	4,790.00	04-11-1989	6.92	4,783.08
435408112170805	07N 35E 25DCB5	–	435408.00	1121708.00	4,790.00	04-11-1989	6.60	4,783.40
435408112171202	07N 35E 25DCB2	–	435408.00	1121712.00	4,790.00	04-11-1989	6.77	4,783.23
435408112184201	07N 35E 26CDB1	–	435408.00	1121842.00	4,785.00	04-14-1989	4.89	4,780.11
435409112174303	07N 35E 25CCB3	–	435409.00	1121743.00	4,795.00	04-13-1989	10.55	4,784.45
435410112170903	07N 35E 25DCB3	–	435410.00	1121709.00	4,790.00	04-11-1989	6.74	4,783.26
435410112171403	07N 35E 25CDA3	–	435410.00	1121714.00	4,790.00	04-11-1989	7.47	4,782.53
435410112174801	07N 35E 25CCB1	–	435410.00	1121748.00	4,795.00	04-12-1989	9.47	4,785.53
435411112171001	07N 35E 25DCB1	–	435411.00	1121710.00	4,790.00	04-13-1989	6.55	4,783.45
435411112175101	07N 35E 26DDA1	–	435411.00	1121751.00	4,790.00	04-12-1989	9.93	4,780.07
435411112175801	07N 35E 26DDB1	–	435411.00	1121758.00	4,792.00	04-12-1989	12.39	4,779.61
435411112180101	07N 35E 26DAC1	–	435411.00	1121801.00	4,790.00	04-12-1989	9.30	4,780.70
435412112174701	07N 35E 25CBC1	–	435412.00	1121747.00	4,800.00	04-12-1989	18.31	4,781.69
435416112460401	07N 31E 28CAC1	P&W 1	435415.86	1124603.56	4,895.62	05-19-1989	309.14	4,586.48
435418112175601	07N 35E 26DAA1	–	435418.00	1121756.00	4,795.00	04-13-1989	11.80	4,783.20
435419112453101	07N 31E 28DAB1	P&W 2	435419.00	1124530.80	4,890.86	04-18-1989	304.65	4,586.21
435420112184801	07N 35E 26CBA1	–	435420.00	1121848.00	4,790.00	04-14-1989	5.92	4,784.08
435422112190401	07N 35E 27DAA1	–	435422.00	1121904.00	4,790.00	04-14-1989	6.41	4,783.59
435425112180301	07N 35E 26ADC1	–	435425.00	1121803.00	4,795.00	04-13-1989	9.68	4,785.32
435431112190201	07N 35E 27ADD1	–	435431.00	1121902.00	4,790.00	04-15-1989	6.99	4,783.01
435433112191001	07N 35E 27ADB1	–	435433.00	1121910.00	4,786.00	04-15-1989	4.57	4,781.43
435440112175701	07N 35E 26AAC1	–	435440.00	1121757.00	4,791.00	04-13-1989	8.01	4,782.99
435440112192002	07N 35E 27ABD2	–	435440.00	1121920.00	4,790.00	04-15-1989	7.79	4,782.21
435441112191901	07N 35E 27ABD1	–	435441.00	1121919.00	4,790.00	04-15-1989	7.49	4,782.51
435443112435801	07N 31E 26BBC1	P&W 3	435443.18	1124358.17	4,885.49	05-19-1989	298.70	4,586.79
435444112171001	07N 35E 25ABB1	–	435444.00	1121710.00	4,788.00	04-12-1989	6.88	4,781.12
435445112174501	07N 35E 25BBB1	–	435445.00	1121745.00	4,790.00	04-13-1989	6.47	4,783.53
435446112173501	07N 35E 25BBA1	–	435446.00	1121735.00	4,795.00	04-13-1989	7.31	4,787.69
435450112193601	07N 35E 27ABB1	–	435450.00	1121936.00	4,792.00	04-15-1989	7.56	4,784.44
435454112185501	07N 35E 23CCC1	–	435454.00	1121855.00	4,790.00	04-14-1989	10.32	4,779.68
435458112151301	07N 36E 20CCA1	–	435458.00	1121513.00	4,785.00	04-19-1989	0.64	4,784.36
435459112212901	07N 35E 20DDA1	–	435500.00	1122132.00	4,798.77	04-14-1989	19.84	4,778.93
435500112212502	07N 35E 20DDA2	–	435500.50	1122132.50	4,790.00	04-14-1989	10.49	4,779.51
435504112222301	07N 35E 20CBD1	–	435505.00	1122222.00	4,818.15	04-15-1989	35.71	4,782.44
435505112190201	07N 35E 22DAD1	–	435505.00	1121902.00	4,792.49	04-15-1989	8.16	4,784.33

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
435505112200001	07N 35E 22CBD1	–	435505.00	1122000.00	4,790.00	04-17-1989	8.40	4,781.60
435505112200002	07N 35E 22CBD2	–	435505.00	1122000.00	4,790.00	04-17-1989	8.76	4,781.24
435506112185301	07N 35E 23CBC1	–	435506.00	1121853.00	4,790.00	04-14-1989	9.03	4,780.97
435506112191701	07N 35E 22DAC1	–	435506.00	1121903.00	4,790.00	04-15-1989	9.67	4,780.33
435522112444201	07N 31E 22BDD1	ANP 7	435519.50	1124443.67	4,934.64	05-19-1989	346.86	4,587.78
435529112232501	07N 35E 19BDB1	–	435529.00	1122325.00	4,791.00	04-11-1989	8.21	4,782.79
435529112233601	07N 35E 19BCA1	–	435529.00	1122336.00	4,793.00	04-11-1989	8.39	4,784.61
435533112244801	07N 34E 24BBC1	–	435533.00	1122448.00	4,795.00	04-12-1989	12.08	4,782.92
435535112235801	07N 34E 24AAC1	–	435535.00	1122358.00	4,792.61	04-11-1989	8.73	4,783.88
435537112231901	07N 35E 19BAA1	–	435537.00	1122319.00	4,810.00	04-11-1989	13.00	4,797.00
435539112244101	07N 34E 24BBA2	–	435539.00	1122441.00	4,790.00	04-15-1989	10.40	4,779.60
435541112240301	07N 34E 24ABA1	–	435541.00	1122403.00	4,792.00	04-11-1989	7.26	4,784.74
435541112254303	07N 34E 23BAB3	–	435541.00	1122547.00	4,791.83	04-12-1989	9.20	4,782.63
435543112174401	07N 35E 13CCC2	–	435543.00	1121744.00	4,793.72	04-18-1989	11.94	4,781.78
435543112320401	07N 33E 14DDC1	–	435543.00	1123225.00	4,783.00	04-16-1989	70.32	4,712.68
435544112173001	07N 35E 13CDC1	–	435544.00	1121730.00	4,800.00	04-17-1989	13.42	4,786.58
435544112174303	07N 35E 13CCC3	–	435544.00	1121743.00	4,795.00	04-18-1989	11.25	4,783.75
435544112234001	07N 35E 18CCD1	–	435544.00	1122340.00	4,798.00	04-12-1989	11.13	4,786.87
435547112173701	07N 35E 13CCD1	–	435547.00	1121737.00	4,792.29	04-18-1989	12.25	4,780.04
435548112173503	07N 35E 13CCD3	–	435548.00	1121735.00	4,800.00	04-17-1989	14.86	4,785.14
435548112233901	07N 35E 18CDC1	–	435548.00	1122339.00	4,809.00	04-12-1989	24.71	4,784.29
435551112313301	07N 33E 13CDA1	–	435550.00	1123135.70	4,783.00	04-19-1989	25.94	4,757.06
435553112240201	07N 34E 13DCA1	–	435553.00	1122402.00	4,795.00	04-11-1989	8.91	4,786.09
435604112240501	07N 34E 13DBA1	–	435604.00	1122405.00	4,799.00	04-11-1989	9.75	4,789.25
435610112241501	07N 34E 13ACC1	–	435610.00	1122418.00	4,799.61	04-11-1989	16.92	4,782.69
435626112164301	07N 35E 13AAD1	–	435626.00	1121643.00	4,789.50	04-19-1989	5.24	4,784.26
435626112365401	07N 33E 17BBC1	ML 2	435626.00	1123654.00	4,791.00	04-17-1989	207.26	4,583.74
435634112263201	07N 34E 15ABA1	–	435634.00	1122632.00	4,815.00	04-10-1989	32.56	4,782.44
435640112265601	07N 34E 10CDC1	–	435640.00	1122656.00	4,795.00	04-11-1989	13.69	4,781.31
435644112315901	07N 33E 12CCB1	–	435644.00	1123159.00	4,790.02	04-16-1989	38.42	4,751.60
435645112311301	07N 33E 12DDB1	–	435645.00	1123113.00	4,784.00	04-16-1989	34.64	4,749.36
435647112263401	07N 34E 10DCB1	–	435647.00	1122634.00	4,829.00	04-10-1989	44.42	4,784.58
435652112362701	07N 33E 08CAD1	–	435652.00	1123627.00	4,792.00	04-17-1989	202.07	4,589.93
435707112270701	07N 34E 10BCA1	–	435707.00	1122707.00	4,795.00	04-12-1989	6.91	4,788.09
435712112263201	07N 34E 10ACA1	–	435712.90	1122636.30	4,805.00	04-10-1989	17.43	4,787.57
435716112273601	07N 34E 09ABD1	–	435716.00	1122736.00	4,792.00	04-12-1989	7.22	4,784.78
435716112365701	07N 33E 07AAD1	–	435716.00	1123657.00	4,791.00	04-17-1989	202.46	4,588.54
435720112255101	07N 34E 11BBD1	–	435720.00	1122556.00	4,856.00	04-10-1989	71.35	4,784.65
435726112274401	07N 34E 04DCD1	–	435726.00	1122744.00	4,794.00	04-14-1989	10.02	4,783.98
435727112354501	07N 33E 05DDD1	–	435727.00	1123545.00	4,792.00	04-18-1989	116.95	4,675.05
435728112281101	07N 34E 04CDC1	–	435728.00	1122809.00	4,791.76	04-14-1989	7.98	4,783.78
435728112303601	07N 34E 06CDC1	–	435728.00	1123036.00	4,791.00	04-18-1989	14.16	4,776.84
435731112272801	07N 34E 04DDD1	–	435731.00	1122728.00	4,794.00	04-14-1989	7.63	4,786.37
435735112264701	07N 34E 03CDA1	–	435736.00	1122651.00	4,798.00	04-13-1989	13.78	4,784.22
435744112152801	07N 36E 06DAD1	–	435744.00	1121528.00	4,800.00	04-19-1989	11.13	4,788.87
435744112324201	07N 33E 02DBC1	–	435744.00	1123245.00	4,789.00	04-18-1989	52.18	4,736.82
435745112273901	07N 34E 04DAD1	–	435745.00	1122739.00	4,794.00	04-13-1989	8.24	4,785.76
435745112284601	07N 34E 05DAC1	–	435745.00	1122846.00	4,790.00	04-14-1989	6.30	4,783.70
435747112155001	07N 36E 06DBA1	–	435747.00	1121550.00	4,800.00	04-19-1989	8.15	4,791.85
435749112164001	07N 35E 01DAA1	–	435749.00	1121640.00	4,794.90	04-18-1989	10.09	4,784.81
435751112332401	07N 33E 03DAA1	–	435751.00	1123324.00	4,789.00	04-18-1989	24.10	4,764.90
435752112371501	07N 33E 06DBA1	–	435752.00	1123715.00	4,800.00	04-17-1989	209.46	4,590.54

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
435754112363601	07N 33E 05BDC1	–	435754.00	1123636.00	4,794.00	04-17-1989	203.15	4,590.85
435755112231001	07N 35E 06ACC1	–	435755.00	1122310.00	4,857.00	04-15-1989	73.36	4,783.64
435756112263301	07N 34E 03ACD1	–	435756.00	1122633.00	4,811.00	04-13-1989	25.02	4,785.98
435756112264601	07N 34E 03BDD1	–	435757.00	1122651.00	4,798.00	04-13-1989	12.26	4,785.74
435759112164801	07N 35E 01ADC1	–	435759.00	1121648.00	4,798.00	04-19-1989	7.28	4,790.72
435803112162101	07N 36E 06BCA1	–	435803.00	1121623.00	4,798.22	04-20-1989	8.57	4,789.65
435805112270501	07N 34E 03BCA1	–	435805.00	1122705.00	4,800.00	04-13-1989	16.74	4,783.26
435806112265501	07N 34E 03BAC1	–	435806.00	1122655.00	4,800.00	04-13-1989	14.05	4,785.95
435809112320901	07N 33E 02AAD1	–	435809.00	1123209.00	4,789.00	04-19-1989	39.21	4,749.79
435810112264901	07N 34E 03BAD1	–	435810.00	1122649.00	4,800.00	04-13-1989	14.88	4,785.12
435810112365401	07N 33E 05BBC1	ML 3	435810.00	1123654.00	4,795.00	04-17-1989	204.42	4,590.58
435812112264301	07N 34E 03BAA1	–	435812.00	1122643.00	4,798.00	04-13-1989	17.00	4,781.00
435814112241301	07N 34E 01ABB1	–	435814.00	1122413.00	4,870.00	04-15-1989	85.18	4,784.82
435817112365401	07N 33E 05BBB1	–	435817.00	1123657.00	4,796.00	06-23-1989	207.92	4,588.08
435820112343501	08N 33E 33DDD1	–	435820.00	1123438.00	4,790.00	06-23-1989	81.85	4,708.15
435825112161801	08N 36E 31CDB1	–	435825.00	1121618.00	4,800.00	04-18-1989	13.86	4,786.14
435828112153101	08N 36E 31DDA1	–	435828.00	1121531.00	4,800.00	04-20-1989	11.10	4,788.90
435831112365401	08N 33E 32CCB1	–	435831.20	1123658.20	4,801.00	04-17-1989	210.76	4,590.24
435842112303601	08N 34E 31CAB1	–	435842.00	1123036.00	4,793.00	04-19-1989	11.13	4,781.87
435844112354301	08N 33E 33CBB1	–	435844.00	1123543.00	4,791.00	04-18-1989	195.50	4,595.50
435857112365501	08N 33E 32BCB1	–	435857.00	1123655.00	4,804.00	04-17-1989	214.47	4,589.53
435900112302801	08N 34E 31BAD1	–	435900.00	1123028.00	4,794.00	04-19-1989	10.42	4,783.58
435903112280001	08N 34E 33BAD1	–	435903.00	1122800.00	4,803.75	04-18-1989	17.53	4,786.22
435910112261801	08N 34E 34AAB1	–	435910.00	1122618.00	4,820.00	04-15-1989	24.85	4,795.15
435910112361901	08N 33E 32ABB1	–	435910.00	1123619.00	4,794.00	04-17-1989	203.97	4,590.03
435912112264801	08N 34E 27CDD1	–	435912.00	1122648.00	4,805.00	04-16-1989	29.99	4,775.01
435913112271601	08N 34E 27CCC1	–	435913.00	1122716.00	4,810.00	08-23-1989	40.13	4,769.87
435913112281501	08N 34E 28CCD1	–	435913.00	1122815.00	4,810.00	08-23-1989	40.95	4,769.05
435914112261301	08N 34E 27DDD1	–	435914.00	1122613.00	4,800.00	04-15-1989	24.41	4,775.59
435917112255801	08N 34E 26CCC1	–	435917.00	1122558.00	4,820.00	08-23-1989	46.75	4,773.25
435919112260201	08N 34E 26CCB1	–	435919.00	1122606.00	4,813.94	04-15-1989	27.50	4,786.44
435922112272401	08N 34E 28DDA1	–	435922.00	1122724.00	4,805.00	04-18-1989	25.19	4,779.81
435925112281401	08N 34E 28CBD1	–	435925.00	1122814.00	4,805.00	04-18-1989	18.57	4,786.43
435925112333601	08N 33E 27DAC1	–	435924.00	1123340.00	4,793.00	06-23-1989	14.79	4,778.21
435927112324401	08N 33E 26CAD1	–	435927.00	1123244.00	4,793.00	04-19-1989	8.98	4,784.02
435931112262701	08N 34E 27DBA1	–	435931.00	1122627.00	4,811.00	08-23-1989	42.67	4,768.33
435935112255401	08N 34E 26CBA1	–	435935.00	1122554.00	4,822.00	08-23-1989	50.23	4,771.77
435935112325401	08N 33E 26CAB2	–	435935.00	1123254.00	4,800.00	04-19-1989	9.83	4,790.17
435950112332304	08N 33E 27AAD4	–	435950.00	1123323.00	4,794.00	04-19-1989	15.51	4,778.49
435951112275101	08N 34E 28ABC1	–	435951.00	1122751.00	4,806.00	04-18-1989	18.54	4,787.46
435952112332102	08N 33E 27AAD2	–	435952.00	1123321.00	4,794.00	04-19-1989	47.65	4,746.35
435958112290602	08N 34E 29ABB2	–	435958.00	1122906.00	4,815.00	04-18-1989	29.72	4,785.28
440012112291401	08N 34E 20CDA2	–	440012.00	1122914.00	4,818.94	04-16-1989	37.93	4,781.01
440014112343001	08N 33E 22CCB1	–	440014.00	1123430.00	4,800.00	04-19-1989	174.59	4,625.41
440019112320301	08N 33E 24CBC1	–	440019.00	1123203.00	4,794.00	04-17-1989	7.50	4,786.50
440022112284601	08N 34E 20DAC1	–	440022.00	1122846.00	4,808.00	04-17-1989	27.72	4,780.28
440024112252501	08N 34E 23DBB1	–	440024.00	1122525.00	4,837.00	04-18-1989	40.61	4,796.39
440025112272701	08N 34E 21DAA1	–	440025.00	1122727.00	4,820.00	04-18-1989	19.65	4,800.35
440029112352601	08N 33E 21CAB1	–	440029.00	1123526.00	4,800.00	04-18-1989	174.09	4,625.91
440030112261801	08N 34E 22ADC1	–	440030.00	1122618.00	4,830.00	04-18-1989	40.37	4,789.63
440043112275001	08N 34E 21ABC1	–	440043.00	1122750.00	4,825.00	04-17-1989	38.75	4,786.25
440045112283501	08N 34E 20AAD1	–	440044.10	1122837.70	4,810.00	04-17-1989	25.13	4,784.87

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
440052112314901	08N 33E 24BAB1	–	440052.00	1123149.00	4,797.00	04-17-1989	7.71	4,789.29
440054112260801	08N 34E 22AAA1	–	440054.00	1122608.00	4,824.74	04-18-1989	39.55	4,785.19
440106112263101	08N 34E 15DCA1	–	440106.00	1122634.00	4,822.45	04-18-1989	35.52	4,786.93
440108112335701	08N 33E 15CAD1	–	440108.00	1123357.00	4,804.90	04-18-1989	59.37	4,745.53
440108112350901	08N 33E 16CAD1	–	440108.00	1123509.00	4,806.00	04-18-1989	131.98	4,674.02
440109112391301	08N 32E 13CBC1	–	440109.00	1123913.00	4,880.00	04-17-1989	292.51	4,587.49
440118112262001	08N 34E 15DAB1	–	440118.00	1122620.00	4,828.00	04-18-1989	39.23	4,788.77
440123112280101	08N 34E 16BDD1	–	440123.00	1122801.00	4,810.00	04-17-1989	23.89	4,786.11
440134112350901	08N 33E 16ACB1	–	440134.00	1123509.00	4,811.00	04-18-1989	132.30	4,678.70
440142112302001	08N 34E 18BAA1	–	440142.00	1123020.00	4,803.00	04-17-1989	14.45	4,788.55
440143112330501	08N 33E 14BBA1	–	440143.00	1123305.00	4,807.00	04-17-1989	57.09	4,749.91
440150112351001	08N 33E 09CDD1	–	440150.00	1123510.00	4,816.00	04-18-1989	123.16	4,692.84
440151112252301	08N 34E 11DCC1	–	440151.00	1122523.00	4,870.00	04-18-1989	82.60	4,787.40
440155112272901	08N 34E 09DDB1	–	440155.00	1122729.00	4,830.00	04-17-1989	39.78	4,790.22
440159112335701	08N 33E 10CDA1	–	440159.00	1123357.00	4,816.00	04-18-1989	69.81	4,746.19
440220112381201	08N 32E 12ADB1	–	440220.00	1123812.00	4,848.00	04-17-1989	257.33	4,590.67
440225112332101	08N 33E 10ADA1	–	440225.00	1123321.00	4,815.00	04-19-1989	64.06	4,750.94
440226112402401	08N 32E 11BCB1	–	440224.00	1124026.00	4,950.00	04-17-1989	444.00	4,506.00
440237112295201	08N 34E 07AAA1	–	440237.00	1122952.00	4,810.00	04-19-1989	21.44	4,788.56
440240112330201	08N 33E 02CDC1	–	440240.00	1123302.00	4,812.00	04-19-1989	63.65	4,748.35
440252112352401	08N 33E 04CDB1	–	440252.00	1123524.00	4,827.00	04-15-1989	227.78	4,599.22
440303112322001	08N 33E 02DAB1	–	440303.00	1123220.00	4,813.00	04-19-1989	77.24	4,735.76
440321112353401	08N 33E 04BBC1	–	440321.00	1123534.00	4,849.00	04-15-1989	248.64	4,600.36
440322112320301	08N 33E 01BBC1	–	440322.00	1123203.00	4,821.00	04-19-1989	38.52	4,782.48
440328112314501	08N 33E 01BAB1	–	440328.00	1123145.00	4,817.00	04-10-1989	64.44	4,752.56
440328112335101	08N 33E 03ABB1	–	440328.00	1123351.00	4,835.00	04-10-1989	188.77	4,646.23
440329112293001	08N 34E 05BBA1	–	440329.00	1122930.00	4,816.00	04-19-1989	33.76	4,782.24
440329112353801	08N 33E 04BBB1	–	440329.00	1123538.00	4,850.00	04-11-1989	255.50	4,594.50
440333112301201	09N 34E 31DCC1	–	440333.00	1123012.00	4,816.00	04-15-1989	47.44	4,768.56
440343112332101	09N 33E 34DAD1	–	440343.00	1123323.00	4,840.00	04-10-1989	147.72	4,692.28
440347112313001	09N 33E 36CAD1	–	440347.00	1123130.00	4,817.00	04-10-1989	44.31	4,772.69
440348112354601	09N 33E 32DAD1	–	440348.00	1123546.00	4,880.00	04-10-1989	259.60	4,620.40
440351112372701	09N 33E 31DBB1	–	440351.00	1123727.00	4,902.00	04-11-1989	301.56	4,600.44
440355112291901	09N 34E 32BDC1	–	440355.00	1122919.00	4,826.00	04-19-1989	47.40	4,778.60
440355112343101	09N 33E 33DAA1	–	440355.00	1123431.00	4,866.00	04-10-1989	220.80	4,645.20
440357112385901	09N 32E 36CCB1	–	440343.00	1123921.00	4,940.00	04-17-1989	347.93	4,592.07
440405112151101	09N 36E 32BCB1	–	440405.00	1121511.00	4,879.00	04-13-1989	87.39	4,791.61
440408112361601	09N 33E 32ACB1	–	440408.00	1123616.00	4,915.00	04-11-1989	303.00	4,612.00
440409112155801	09N 36E 31BAD1	–	440409.00	1121558.00	4,919.00	09-01-1989	129.97	4,789.03
440409112313001	09N 33E 36ACB1	–	440409.00	1123130.00	4,823.00	04-19-1989	62.26	4,760.74
440409112343501	09N 33E 33AAD1	–	440409.00	1123435.00	4,880.00	04-10-1989	263.25	4,616.75
440416112294002	09N 34E 32BBB2	–	440416.00	1122940.00	4,827.00	04-19-1989	50.66	4,776.34
440420112303801	09N 34E 31BBA1	–	440420.00	1123038.00	4,823.00	04-10-1989	60.18	4,762.82
440420112314601	09N 33E 36BAB1	–	440420.00	1123146.00	4,834.00	04-11-1989	77.71	4,756.29
440421112305501	09N 33E 36AAA1	–	440421.00	1123055.00	4,824.00	04-10-1989	58.68	4,765.32
440428112282801	09N 34E 28CCB1	–	440428.00	1122828.00	4,835.00	04-19-1989	52.25	4,782.75
440434112305401	09N 33E 25DDA1	–	440434.00	1123054.00	4,827.00	04-11-1989	64.90	4,762.10
440434112312701	09N 33E 25DCB1	–	440434.00	1123127.00	4,831.00	04-11-1989	75.53	4,755.47
440438112151001	09N 36E 29CBC1	–	440438.00	1121510.00	4,887.00	04-13-1989	86.90	4,800.10
440447112280301	09N 34E 28CAB1	–	440447.00	1122803.00	4,839.00	04-19-1989	57.33	4,781.67
440447112284401	09N 34E 29DAB1	–	440447.00	1122845.00	4,838.00	04-19-1989	56.96	4,781.04
440447112292201	09N 34E 29CAB1	–	440447.00	1122922.00	4,837.00	04-19-1989	58.15	4,778.85

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
440447112303701	09N 34E 30CBA1	–	440447.00	1123037.00	4,829.00	04-11-1989	67.63	4,761.37
440448112283801	09N 34E 29DAA1	–	440448.00	1122838.00	4,839.00	03-29-1989	57.82	4,781.18
440451112154601	09N 36E 30ACC1	–	440447.10	1121548.90	4,900.00	04-13-1989	106.10	4,793.90
440457112265201	09N 34E 27BDB1	–	440458.00	1122654.00	4,853.00	04-19-1989	65.26	4,787.74
440458112325701	09N 33E 26BDB1	–	440458.00	1123257.00	4,885.00	04-12-1989	206.20	4,678.80
440500112313001	09N 33E 25ACB1	–	440500.00	1123130.00	4,845.00	04-11-1989	89.93	4,755.07
440514112300001	09N 34E 30ABA1	–	440514.00	1123000.00	4,839.00	04-19-1989	65.14	4,773.86
440514112303501	09N 34E 30BBA1	–	440514.00	1123038.00	4,837.00	04-11-1989	70.34	4,766.66
440515112284701	09N 34E 20DCD1	–	440515.00	1122847.00	4,845.00	04-19-1989	65.19	4,779.81
440523112154501	09N 36E 19DCB1	–	440523.00	1121545.00	4,907.00	04-13-1989	114.15	4,792.85
440525112314601	09N 33E 24CDB1	–	440525.00	1123146.00	4,868.00	04-12-1989	123.39	4,744.61
440537112295401	09N 34E 19DAB1	–	440537.00	1122954.00	4,845.00	04-19-1989	72.13	4,772.87
440539112281201	09N 34E 21BCD1	–	440539.00	1122812.00	4,857.00	04-19-1989	72.38	4,784.62
440541112303501	09N 34E 19CAB1	–	440541.00	1123035.00	4,846.00	04-11-1989	86.28	4,759.72
440553112162401	09N 36E 19BBC1	–	440553.00	1121624.00	4,921.00	04-13-1989	128.28	4,792.72
440553112170001	09N 35E 24ABC1	–	440551.50	1121703.90	4,921.00	04-13-1989	129.09	4,791.91
440554112154501	09N 36E 19ABC1	–	440554.00	1121545.00	4,924.00	04-13-1989	131.84	4,792.16
440557112361401	09N 33E 20ACC1	–	440545.00	1123612.00	5,091.00	04-13-1989	433.62	4,657.38
440600112261601	09N 34E 15DDC1	–	440606.00	1122606.00	4,870.00	08-23-1989	90.02	4,779.98
440605112313201	09N 33E 24BAA1	–	440605.00	1123133.00	4,878.00	04-12-1989	175.40	4,702.60
440606112303601	09N 34E 18CCD1	–	440606.00	1123036.00	4,852.00	04-11-1989	90.45	4,761.55
440619112172301	09N 35E 13CBD1	–	440619.00	1121723.00	4,926.00	04-14-1989	133.37	4,792.63
440619112330001	09N 33E 14CCA1	–	440619.00	1123300.00	4,990.00	08-24-1989	287.89	4,702.11
440620112164101	09N 35E 13DAC1	–	440620.00	1121641.00	4,929.00	04-14-1989	136.90	4,792.10
440626112154501	09N 36E 18DBB1	–	440626.00	1121545.00	4,942.00	04-13-1989	147.14	4,794.86
440631112301901	09N 34E 18CAA1	–	440631.00	1123019.00	4,855.00	04-12-1989	98.77	4,756.23
440633112261801	09N 34E 15ADC1	–	440633.00	1122618.00	4,885.00	08-23-1989	84.37	4,800.63
440633112280901	09N 34E 16BCD1	–	440633.00	1122809.00	4,873.00	04-20-1989	89.25	4,783.75
440633112284801	09N 34E 17ACD1	–	440633.00	1122848.00	4,867.00	04-20-1989	85.37	4,781.63
440633112292101	09N 34E 17BDC1	–	440633.00	1122921.00	4,862.00	04-20-1989	93.85	4,768.15
440634112265801	09N 34E 15BCD1	–	440634.00	1122658.00	4,885.00	04-20-1989	95.10	4,789.90
440634112273301	09N 34E 16ADC1	–	440634.00	1122733.00	4,880.00	04-20-1989	93.00	4,787.00
440637112183401	09N 35E 14BCD1	–	440637.00	1121834.00	4,928.00	04-15-1989	148.27	4,779.73
440640112150901	09N 36E 17BCB1	–	440640.00	1121509.00	4,960.00	04-12-1989	166.02	4,793.98
440645112303501	09N 34E 18BDB1	–	440645.00	1123035.00	4,855.00	04-11-1989	97.53	4,757.47
440645112333701	09N 33E 15ACA1	–	440645.00	1123337.00	5,040.00	04-14-1989	337.16	4,702.84
440655112313301	09N 33E 13BAA1	–	440656.00	1123135.00	4,893.00	04-12-1989	173.63	4,719.37
440657112154501	09N 36E 18ABA1	–	440657.00	1121545.00	4,955.00	04-13-1989	161.02	4,793.98
440659112190601	09N 35E 10DDC1	–	440659.00	1121906.00	4,945.00	04-11-1989	153.38	4,791.62
440710112150901	09N 36E 08CCB1	–	440710.00	1121509.00	4,970.00	04-12-1989	179.40	4,790.60
440710112300101	09N 34E 07DCA1	–	440710.00	1123001.00	4,868.00	04-12-1989	94.50	4,773.50
440714112303401	09N 34E 07CCA1	–	440711.00	1123035.00	4,864.00	04-12-1989	92.80	4,771.20
440720112262001	09N 34E 10DAB1	–	440720.00	1122620.00	4,903.00	04-14-1989	149.32	4,753.68
440721112272901	09N 34E 09DAB1	–	440721.00	1122729.00	4,893.00	04-14-1989	123.41	4,769.59
440722112260301	09N 34E 10DAA1	–	440722.00	1122603.00	4,914.00	04-14-1989	136.09	4,777.91
440725112245301	09N 34E 11ADD1	–	440725.00	1122453.00	4,945.00	04-20-1989	156.23	4,788.77
440734112205401	09N 35E 09BDB1	–	440736.50	1122059.20	4,973.00	04-10-1989	183.34	4,789.66
440737112301701	09N 34E O7ABC1	–	440737.00	1123017.00	4,875.00	04-11-1989	111.38	4,763.62
440737112314501	09N 33E 12BAC1	–	440732.00	1123148.00	4,898.00	04-13-1989	180.53	4,717.47
440805112250801	09N 34E 02DAC1	–	440805.00	1122508.00	4,945.00	04-14-1989	154.20	4,790.80
440813112270101	09N 34E 03CBA1	–	440813.00	1122701.00	4,920.00	04-13-1989	144.00	4,776.00
440814112292401	09N 34E 05CBA1	–	440814.00	1122924.00	4,892.00	04-13-1989	129.03	4,762.97

Table 1-1. Water-level measurements used to construct water-table contours, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

USGS site No.	USGS station No.	Site name	Latitude (NAD 27)	Longitude (NAD 27)	Altitude (ft)	Water-level measurement date	Water level (ft bls)	Water-level altitude (ft)
440815112254601	09N 34E 02CBA1	–	440815.00	1122546.00	4,938.00	04-13-1989	155.50	4,782.50
440815112261901	09N 34E 03DAB1	–	440815.00	1122619.00	4,931.00	04-13-1989	148.28	4,782.72
440815112284501	09N 34E 05DAB1	–	440815.00	1122845.00	4,901.00	04-13-1989	131.25	4,769.75
440815112295801	09N 34E 06ADC1	–	440815.00	1122958.00	4,890.00	04-13-1989	130.18	4,759.82
440816112280901	09N 34E 04BDC1	–	440816.00	1122809.00	4,910.00	04-13-1989	134.00	4,776.00
440816112303201	09N 34E 06CAB1	–	440816.00	1123032.00	4,885.00	04-13-1989	150.77	4,734.23
440817112201601	09N 35E 04ADC1	–	440817.00	1122016.00	4,988.00	04-10-1989	195.25	4,792.75
440817112213501	09N 35E 05ACD1	–	440817.00	1122135.00	4,992.00	04-10-1989	202.71	4,789.29
440817112273501	09N 34E 04ACD1	–	440816.00	1122737.00	4,915.00	04-13-1989	143.20	4,771.80
440847112303501	10N 34E 31CCD1	–	440847.00	1123035.00	4,917.00	04-14-1989	178.80	4,738.20
440908112213501	10N 35E 32DBA1	–	440907.60	1122135.00	5,030.00	04-10-1989	240.16	4,789.84
441003112290801	10N 34E 29BDD1	–	440957.00	1122907.00	5,030.00	03-29-1989	258.68	4,771.32
441014112284501	10N 34E 29AAC1	–	441014.00	1122845.00	4,990.00	04-14-1989	225.68	4,764.32
441132112173301	10N 35E 13CBC1	–	441133.00	1121737.00	5,150.96	04-10-1989	356.89	4,794.07

Appendix 2. Equations

Alkalinity

For alkalinity titrations to the methyl-orange end point, alkalinity expressed as milligrams per liter as calcium carbonate ($CaCO_3$) can be converted to an equivalent concentration of bicarbonate in milligrams per liter with the following equation (Hem, 1992):

$$\text{Alkalinity} / 0.8202 = \text{Bicarbonate}. \qquad (2\text{–}1)$$

Delta Notation

The isotope ratios of helium ($^{3}He/^{4}He$), hydrogen ($^{2}H/^{1}H$), oxygen ($^{18}O/^{16}O$), carbon ($^{13}C/^{12}C$), sulfur ($^{34}S/^{32}S$), and nitrogen ($^{15}N/^{14}N$) were reported as a percentage or permil using delta notation (δ), which is the ratio of the abundance of the minor isotope to the predominant isotope for an element in a sample relative to the same isotopes in a reference material. For example, for the oxygen stable isotope ratio the delta notation is:

$$\delta^{18}\mathrm{O}_{\mathrm{sample}} = \frac{\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{sample}} - \left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{reference}}}{\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{reference}}} \times M, \qquad (2\text{–}2)$$

where

$\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{sample}}$	is the isotope ratio of oxygen-18 and oxygen-16 of the sample,
$\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{reference}}$	is the isotope ratio of oxygen-18 and oxygen-16 of the reference material, and
M	is a multiplication factor of 100 or 1,000 to express reported δ-values as parts per hundred (percent) or parts per thousand (permil), respectively.

Delta notations are $\delta^{3}He$ for helium, $\delta^{2}H$ for hydrogen, $\delta^{13}C$ for carbon, $\delta^{34}S$ for sulfur and $\delta^{15}N$ for nitrogen.

Normalized Absolute Difference

Normalized absolute difference (NAD) is calculated as:

$$NAD = \frac{\left|x = y\right|}{\sqrt{CSU_x^2 + CSU_y^2}}, \qquad (2\text{–}3)$$

where

x	is the concentration of a radiochemical in the environmental sample,
y	is the concentration of the same radiochemical in the replicate sample,
CSU_x	is the combined standard uncertainty of x at the 1σ confidence level, and
CSU_y	is the combined standard uncertainty of y at the 1σ confidence level.

Relative Standard Deviation

Relative standard deviation (RSD) is the percent coefficient of variation (CV), and CV "is a dimensionless quantity that measures the amount of variability relative to the value of the mean" (Devore, 1995, p. 39). RSD was calculated as (Taylor, 1987, p. 20):

$$RSD = CV \times 100 \, . \qquad (2\text{–}4)$$

The CV was calculated as:

$$CV = \frac{s}{\bar{x}}, \qquad (2\text{–}5)$$

where

s	is the standard deviation for a constituent from a replicate, and
$\bar{x}$	is the mean concentration for the same constituent from a replicate.

The standard deviations and mean concentrations for constituents from replicates were calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}, \qquad (2\text{–}6)$$

and

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}, \qquad (2\text{–}7)$$

where

x_i	is a constituent concentration from the replicate, and
n	is the number of measured concentrations for a constituent from the replicate.

The degrees of freedom is an important piece of information for estimates of standard deviation (Taylor, 1987, p. 21), and is included in the equation for standard deviation as $n-1$, or the number of independent values. The degrees of freedom (or number of independent values) is 1 for duplicates because *n* is 2, 2 for triplicates because *n* is 3, and so forth.

Relative Percent Difference

If the uncertainty of a chemical constituent is not readily available, which is often the case for measurements of inorganic and organic constituents, the relative percent difference (RPD) can be used to compare equivalency of replicate pairs (Bartholomay and others, 2015). The RPD is calculated as:

$$RPD = \left(\left(ABS\left(X1 - X2\right)\right) / \left(X1 + X2\right)\right) \times 100\,, \qquad (2\text{–}8)$$

where

RPD is the relative percent difference,

ABS is the absolute value,

$X1$ is the result from the environmental sample, and

$X2$ is the result from the replicate.

Binomial Probability Distribution

A non-parametric statistical method was used to estimate the potential contamination bias of environmental samples because the distribution of constituent concentrations from blank samples was highly skewed. The statistical method consisted of order statistics (ranking concentrations for each constituent from small to large) and the binomial probability distribution (Rattray, 2014). This statistical method provided an upper confidence limit, or confidence level (*cl*), that represented “the probability that *m* observed values from a total of *n* observations are equal to or less than the 100*p*th percentile of the sample population” (Mueller, 1998, p. 5). The confidence level is calculated as:

$$cl = \mathrm{Prob}\left(n, m, p\right). \qquad (2\text{–}9)$$

Charge Balance

Charge balance (CB) was calculated as:

$$CB = \frac{\sum_1^i C_i - \sum_1^j C_j}{\sum_1^i C_i + \sum_1^j C_j} \times 100\,, \qquad (2\text{–}10)$$

where

CB is the charge balance for a water sample,

C_i is the concentration of a cation in the water sample,

C_j is the concentration of an anion in the water sample, and

i and j are the number of measured cation and anion species, respectively, in the water sample.

R_s/R_a

The R_s/R_a ratio is a convenient method for evaluating the $^3He/^4He$ ratios of environmental samples. The R_s/R_a ratio was calculated from δ^3He values as (Plummer and others, 2000):

$$\delta^3\mathrm{He} = \left[\left(\mathrm{R_s} / \mathrm{R_a}\right) - 1\right] \times 100\,, \qquad (2\text{–}11)$$

where

R_s is the $^3He/^4He$ ratio of the environmental sample, and

R_a is the $^3He/^4He$ ratio of air = 1.384×10^{-6}.

Radioactive Decay of Tritium

The equation for radioactive decay is (Faure, 1986):

$$^3\mathrm{H_t} = {}^3\mathrm{H_0} e^{-\lambda t}\,, \qquad (2\text{–}12)$$

where

^3H_t is the activity of ^3H in groundwater at time (t),

$^3H_0$ is the initial (t_0) activity of ^3H in groundwater[1],

λ is the decay constant ($\lambda = 0.05575$/year for ^3H), and

t is the time elapsed between recharge and sample collection.

---

[1] Initial, or t_0, refers to the time of recharge, and the activity of ^3H in groundwater at t_0 is assumed to be the same as the activity of ^3H in precipitation at t_0 for rapid recharge (rapid recharge is a far more prevalent recharge process on the ESRP at the INL than slow recharge [fig. 14]).

Regression of Tritium Data

The monthly activity of ^{3}H in precipitation at the INL for 2002 through 2012 was estimated from a regression ($R^2 = 0.91$) of calculated monthly ^{3}H activities from data provided by R.L. Michel (U.S. Geological Survey, written commun., 2012) with monthly ^{3}H activities in precipitation measured at Vienna (International Atomic Energy Agency/World Meteorological Organization, 2015) for 1990 through 2001. The regression was performed on monthly ^{3}H activities for 1990 through 2001 because these ^{3}H activities were the closest representation of the expected ^{3}H activities in precipitation at the INL for 2002 through 2012. The equation resulting from the regression was:

$$y = mx + b\,, \tag{2–13}$$

where

y is the activity of ^{3}H in precipitation at the INL,
m is 0.9564,
x is the activity of ^{3}H in precipitation at Vienna, and
b is 9.1317.

Ingrowth of Helium-3 Produced by Decay of Tritium

The equation for ingrowth of ^{3}He produced by radioactive decay of ^{3}H (that is, tritiogenic ^{3}He) is (Faure, 1986):

$$^{3}\mathrm{He}_{t} = {}^{3}\mathrm{H}_{0}\left(\mathrm{e}^{-\lambda t} - 1\right), \tag{2–14}$$

where

$^{3}\mathrm{He}_{t}$ is the activity of ^{3}He in groundwater at time (t) produced by decay of ^{3}H,
$^{3}\mathrm{H}_{0}$ is the activity of ^{3}H in precipitation at the time of recharge,
λ is the decay constant ($\lambda = 0.05575$/year for ^{3}H), and
t is the time elapsed between recharge and sample collection.

Radioisotope Mixing Equation

The radioisotope mixing equation is for a mixture of two waters, where the chemical element of interest has different concentrations and isotope ratios in each water. The mixing equation is (Faure, 1986, eq. 9.21):

$$R_m^x = \frac{R_a^x C_a^x f + R_b^x C_b^x \left(1 - f\right)}{C_a^x f + C_b^x \left(1 - f\right)}\,, \tag{2–15}$$

where

x is the chemical element,
a is one of the waters being mixed,
b is the other water being mixed,
m is a mixture of waters a and b,
R is the isotope ratio of the chemical element,
C is the concentration of the chemical element, and
f is the weight fraction of water a in the mixture $[(a)/(a+b)]$.

References Cited

Bartholomay, R.C., Hopkins, C.B., and Maimer, N.V., 2015, Chemical constituents in groundwater from multiple zones in the Eastern Snake River Plain aquifer at the Idaho National Laboratory, Idaho, 2009–13: U.S. Geological Survey Scientific Investigations Report 2015-5002 (DOE/ID-22232), 109 p., http://pubs.er.usgs.gov/publication/sir20155002.

Devore, J.L., 1995, Probability and statistics for engineering and the sciences (4th ed.): Belmont, Calif., Wadsworth Publishing Co., 743 p.

Faure, Gunter, 1986, Principles of Isotope Geology (2nd ed.): New York, John Wiley & Sons, 589 p.

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p., http://pubs.er.usgs.gov/publication/wsp2254.

International Atomic Energy Agency/World Meteorological Organization, 2015, Global network of isotopes in precipitation database: International Atomic Energy Agency, accessed December 24, 2015, at http://www.iaea.org/water.

Mueller, D.K., 1998, Quality of nutrient data from streams and ground water sampled during 1993–95—National Water-Quality assessment Program: U.S. Geological Survey Open-File Report 98-276, 25 p., http://pubs.er.usgs.gov/publication/ofr98276.

Plummer, L.N., Rupert, M.G., Busenberg, E., and Schlosser, P., 2000, Age of irrigation water in ground water from the eastern Snake River Plain aquifer, south-central Idaho: Ground Water, v. 38, no. 2, p. 264–283.

Rattray, G.W., 2014, Evaluation of quality-control data collected by the U.S. Geological Survey for routine water-quality activities at the Idaho National Laboratory, southeastern Idaho, 2002–2008: U.S. Geological Survey Scientific Investigations Report 2014-5027 (DOE/ID-22228), 65 p., http://pubs.usgs.gov/sir/2014/5027/.

Taylor, J.K., 1987, Quality assurance of chemical measurements: Chelsea, Mich., Lewis Publishers, Inc., 328 p.

Appendix 3. Description of Water Groups

Surface Water

Surface water in the study area includes the Big Lost River (BLR), Little Lost River (LLR), Birch Creek (BC), Camas Creek, and Mud Lake. Only the BLR and BC actually flow onto the INL and contribute recharge directly to groundwater at the INL.

Tributary Valley Groundwater

Tributary valley groundwater includes groundwater from the BLR, LLR, and BC valleys. Tributary valley groundwater flows south or southeast into the ESRP aquifer, so groundwater from the BLR valley may provide recharge to the southwestern corner of the INL and groundwater from the LLR and BC valleys provides recharge to the northern parts of the INL.

Regional Groundwater

Regional groundwater refers to groundwater flowing into the INL from hydrologically upgradient areas of the ESRP aquifer (Busenberg and others, 2001; Fisher and others, 2012). Owing to the influence of agricultural practices and upwelling of geothermal water, the chemistry of some regional groundwater has been significantly altered from the typically dilute character of regional groundwater (Rattray, 2015). Consequently, regional groundwater includes

1. Dilute groundwater north and east of Mud Lake (East Mud Lake Area; table 10) representative of groundwater from the Camas Creek drainage basin that was slightly influenced by infiltration of groundwater or surface water used for irrigation;
2. Groundwater north of Mud Lake and near the Beaverhead Mountains (North Mud Lake Area; table 10) representative of groundwater from the Beaverhead Mountains and extensive infiltration of groundwater or surface water used for irrigation;
3. Groundwater north and west of Mud Lake (West Mud Lake Area; table 10) representative of groundwater from the Beaver and Camas Creek drainage basins, the Beaverhead Mountains, and extensive infiltration of groundwater and (or) surface water used for irrigation;
4. Groundwater north and west of Mud Lake influenced by upwelling geothermal water (groundwater with geothermal input; table 10) (Rattray, 2015);
5. Groundwater southwest of Mud Lake (Southwest Mud Lake Area; table 10) representative of extensive infiltration of groundwater or surface water used for irrigation; and
6. Dilute groundwater adjacent to the southeast boundary of the INL (Southeast INL Boundary Area; table 10) representative of regional groundwater in the ESRP aquifer east, southeast, and in the southeastern corner, of the INL that was slightly influenced by infiltration of groundwater used for irrigation.

Geothermal Water

Recharge of geothermal water to the ESRP aquifer within the study area occurs as upwelling of water from thousands of feet below the land surface of the ESRP (Mann, 1986) and perhaps from upwelling of deep water along faults and caldera boundaries along the transition zone between the ESRP and the mountains (McLing and others, 2002; Ginsbach, 2013). Geothermal water in the study area (table 12 and figs. 8*A* and 9) included groundwater from hot springs (Lidy Hot Springs and Warm Springs, sites ML 57 and ML 58, respectively) in the Beaverhead Mountains and groundwater pumped from borehole INEL-1 (at depths of 1,511–2,206 [site INEL-1 2,000 feet] and 4,210–10,333 [site INEL-1 10,300 feet] feet below the land surface).

Deep Groundwater

Deep groundwater samples were collected from sites EBR-1, Site 9, Site 14, USGS 7, and USGS 15 (table 12 and fig. 9). These samples were representative of groundwater in the ESRP aquifer at the INL from depths greater than 250 ft below the water table, and these wells have maximum open-interval depths of 284–626 ft below the water table (table 11). All of these deep wells are in the western part of the INL where, based on the chemistry of shallow groundwater, the primary source of water should be streams and (or) groundwater from the tributary valleys (Olmsted, 1962).

Contaminated Groundwater

Contaminated groundwater at the INL was initially identified using two criteria. First, only sample sites that were within or near a site facility discharging wastewater to the subsurface (table 8) or a contaminant plume extending downgradient from the site facilities (figs. 3*B* and 28*BB*;

Bartholomay, Tucker, and others, 2000) could be influenced by discharge of wastewater. Second, contaminated groundwater was identified from tritium activities, where groundwater from sites that probably did not include significant recharge from the 1960s–70s and that had tritium activities exceeding the activity in precipitation at the INL for the year of sample collection were considered likely to contain tritium from wastewater discharge (fig. 13*A*). Using these criteria, groundwater at or downgradient of site facilities with tritium activities that exceeded 75 pCi/L was considered likely to be contaminated with tritium (fig. 28*BB*).

Additional criteria to identify contaminated groundwater were needed because (1) tritium was not analyzed from all samples and (2) non-radioactive and radioactive wastes were frequently discharged in wastewater to the subsurface using different disposal methods and (or) locations (Bartholomay, Tucker, and others, 2000), so some groundwater samples that probably were influenced by wastewater discharge of non-radioactive wastes may not have been influenced by wastewater discharge of tritium. Consequently, an additional criterion was that groundwater samples with sodium and sulfate concentrations exceeding 25 and 40 mg/L, respectively, were considered likely to be influenced by wastewater discharge. These concentrations exceeded the maximum concentrations for these constituents in samples that seem to be natural groundwater at the INL (table 13, figs. 28*I* and *O*).

Another criterion used to identify contaminated groundwater was that samples from shallow groundwater at the INL with specific conductance values equal to or exceeding 600 µS/cm at 25 °C were considered likely to be influenced by wastewater discharge. This criterion was based on the distribution of specific conductance in figure 28*B*, which shows that values exceeding 600 µS/cm at 25 °C was detected only at or downgradient of site facilities and irrigated areas.

The specific conductance criterion may not be reliable in groundwater south of the LLR valley and near Naval Reactors Facility (NRF) because some specific conductance values equaling or exceeding 600 µS/cm at 25 °C in this area may be due to irrigation in the LLR valley and not from waste discharge from the NRF. A statistical analysis (minimum, maximum, and mean values and standard deviation) of the ratio of chloride and nitrate concentrations (table 3-1) in groundwater from the NRF area was done to distinguish groundwater that was influenced by waste discharge from the NRF industrial waste ditch from groundwater that was influenced by irrigation in the LLR valley. These chemical constituents were selected for the statistical analysis because (1) large amounts of chloride discharged from the NRF industrial waste ditch (Bartholomay, Tucker, and others, 2000) generated large chloride concentrations in groundwater at NRF 6 (240 mg/L), which is adjacent to the ditch, compared to chloride concentrations in groundwater from the Ruby Farms well (50 mg/L), which was influenced by irrigation in the lower LLR valley and (2) nitrate concentrations in groundwater from the Ruby Farms well (2.9 mg/L as N) seem to be larger than nitrate concentrations in groundwater at NRF (nitrate concentrations at NRF were ≤2.2 mg/L as N) that may be influenced by industrial sewage at NRF (fig. 28*N*). Recharge from the BLR with small concentrations of chloride (≤5 mg/L) and nitrate (≤0.2 mg/L as N) will dilute concentrations of these constituents in groundwater at the NRF but will not appreciably change the ratio of chloride to nitrate.

The statistical analysis performed for data from 19 wells included only pairs of chloride and nitrate data from water samples that were collected on the same day, included all data from 1975 through 2014, and consisted of 785 calculated ratios. Thirteen outlier data points[2] (1.7 percent of the data), mostly nitrate concentrations, were excluded from the analysis. The statistical analysis showed that mean ratios of chloride and nitrate concentrations at individual wells were 15–17 in water in the lower LLR valley (Harrell, Mays, Ruby Farms) or upgradient of the NRF industrial waste ditch (USGS 12), 77–181 in water from wells NRF 6 and NRF 13 that are adjacent to the NRF industrial waste ditch, and 11–25 in all wells downgradient of the waste ditch. This statistical analysis shows that wells NRF 6 and NRF 13 were influenced by discharge from the industrial waste ditch and that a large influence of discharge from the waste ditch was not apparent at the other wells (this analysis did not evaluate other, less intensive, waste discharge methods at NRF [U.S. Department of Energy, 2014]).

Based on all of these criteria, 34 groundwater samples were identified as probably influenced by wastewater discharge (contaminated groundwater in table 12), and all of these samples were collected at or downgradient of Advanced Test Reactor Complex (ATRC), Idaho Nuclear Technology and Engineering Center (INTEC), NRF, Radioactive Waste Management Complex (RWMC), and Test Area North (TAN). Contaminated groundwater at Central Facilities Area (CFA) included discharge of waste at CFA, but was predominantly from discharge of waste at INTEC and was considered part of the waste plume extending downgradient from INTEC.

---

[2] Outliers probably were due to errors in sample collection, processing, analysis, or data reporting (Rattray, 2012).

Table 3-1. Statistical analysis of ratios of chloride and nitrate concentrations in groundwater in the vicinity of the Naval Reactors Facility, Idaho National Laboratory and vicinity, eastern Idaho.

[Locations of sites shown in figures 8–9. **Abbreviations:** NRF, Naval Reactors Facility]

Site name	Years of data collection	Number of samples	Chloride-nitrate ratio			Standard deviation	Number of outliers
			Minimum	Maximum	Mean		
			Wells in the lower Little Lost River valley				
Harrell	1978, 1981, 1992, 1996, 2000, 2005, 2010	7	8	28	15	6.3	0
Mays	1978, 2000	2	14	19	17	3.6	0
Ruby Farms	1991	1	17	17	17	na	0
			Wells upgradient of the NRF Industrial Waste Ditch				
USGS 12	1984, 1990–2014	80	10	22	17	2.2	1
			Wells adjacent to the NRF Industrial Waste Ditch				
NRF 6	1991–96, 2000–14	53	93	316	181	65	1
NRF 13	1996, 2000–10	28	35	98	77	14	0
			Wells near or downgradient of the NRF Industrial Waste Ditch				
Fire Station 2	1982–96	17	10	22	14	2.9	0
INEL 1 WS	1984–85, 1989–95	27	16	26	20	1.7	1
NRF 2	1987, 1989–95	27	20	29	25	2.1	[1]1
NRF 7	1991–96, 2000–14	52	7.4	18	11	1.8	2
NRF 8	1996, 2000–14	34	13	20	17	1.8	1
NRF 9	1996, 2000–14	35	17	24	20	1.9	1
NRF 10	1996, 2000–14	35	20	27	23	1.8	0
NRF 11	1996, 2000–14	37	19	28	23	2.2	1
NRF 12	1996, 2000–14	35	16	32	23	3.6	0
USGS 97	1975, 1982–2014	91	13	28	17	2.1	1
USGS 98	1975, 1984–85, 1989–2014	82	10	25	13	1.9	1
USGS 99	1975, 1984, 1989–96, 2000–14	64	11	17	13	1.2	1
USGS 102	1990–2014	78	11	20	16	1.9	1

[1] Outlier data point was from 1984.

Natural Groundwater

Natural groundwater refers to shallow groundwater (groundwater <250 ft below the water table) within or downgradient of the INL that probably was not influenced by wastewater. Thus, natural groundwater samples for this study include samples collected at or downgradient of the INL that were not included in discussions of sources of recharge, deep groundwater, or contaminated groundwater.

The chemistry of natural groundwater at the INL differs across the site in response to various sources of recharge, such as underflow of groundwater from the tributary valleys north of the INL, underflow of regional groundwater east of the INL, infiltration of irrigation water north and east of the INL, infiltration recharge from the BLR in the western part of the INL, and possibly local recharge from precipitation (Olmsted, 1962; Robertson and others, 1974, Busenberg and others, 2001). The 58 natural groundwater samples were grouped into 6 spatially defined areas (fig. 9) based on their similarity of potential source waters and chemical and isotopic compositions (figs. 28*A*–*DD*). The spatially defined areas at the INL are

1. Groundwater near TAN (North INL Area) that may be representative of surface water from BC and groundwater from the BC valley;
2. Groundwater east and southeast of TAN (Northeast INL Area) that may be representative of regional groundwater, upwelling of geothermal water or deep groundwater, and irrigation return flows;
3. Groundwater in the southeast part of the INL and south of Atomic City (Southeast INL Area) that may be representative of regional groundwater and irrigation return flows;

4. Groundwater between TAN and the southern boundary of the INL (Central INL Area) that may be representative of surface water from the BLR, tributary groundwater from the BC and (or) LLR valleys, upwelling of geothermal water or deep groundwater, and regional groundwater;
5. Groundwater north and west of the BLR (Northwest INL Area) that may be representative of surface water from the BLR, tributary groundwater from the LLR valley, irrigation return flows, groundwater underflow from the Lost River Range, and precipitation; and
6. Groundwater southwest of the ATRC, INTEC, and CFA (Southwest INL Area) that may be representative of surface water from the BLR, tributary groundwater from the LLR and (or) BLR valleys, and precipitation.

References Cited

Bartholomay, R.C., Tucker, B.J., Davis, L.C., and Greene, M.R., 2000, Hydrologic conditions and distribution of selected constituents in water, Snake River Plain aquifer, Idaho National Engineering and Environmental Laboratory, Idaho, 1996 through 1998: U.S. Geological Survey Water-Resources Investigations Report 00-4192 (DOE/ID-22167), 52 p.

Busenberg, Eurybiades, Plummer, L.N., and Bartholomay, R.C., 2001, Estimated age and source of the young fraction of ground water at the Idaho National Engineering and Environmental Laboratory: U.S. Geological Survey Water-Resources Investigations Report 01-4265 (DOE/ID-22177), 144 p., http://pubs.er.usgs.gov/publication/wri014265.

Fisher, J.C., Rousseau, J.R., Bartholomay, R.C., and Rattray, G.W., 2012, A comparison of U.S. Geological Survey three-dimensional model estimates of groundwater source areas and velocities to independently derived estimates, Idaho National Laboratory and vicinity, Idaho: U.S. Geological Survey Scientific Investigations Report 2012-5152 (DOE/ID-22218), 130 p.

Ginsbach, M.L., 2013, Geochemical evolution of groundwater in the Medicine Lodge Creek drainage basin, eastern Idaho: Pocatello, Idaho State University, M.S. Thesis, 241 p., http://geology.isu.edu/thesis/Ginsbach.Michael.2013.pdf.

Mann, L.J., 1986, Hydraulic properties of rock units and chemical quality of water for INEL-1—A 10,365-foot deep test hole drilled at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 86-4020 (DOE/ID-22070), 23 p., http://pubs.er.usgs.gov/publication/wri864020.

McLing, T.L., Smith, R.W., and Johnson, T.M., 2002, Chemical characteristics of thermal water beneath the eastern Snake River Plain: *in* Link, P.K., and Mink, L.L. eds., Geology, Hydrogeology, and Environmental Restoration—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353, p. 205–211.

Olmsted, F.H., 1962, Chemical and physical characteristics of ground water in the National Reactor Testing Station, Idaho: U.S. Atomic Energy Commission, Idaho Operations Office Publication IDO-22043-USGS, 142 p.

Rattray, G.W., 2012, Evaluation of quality-control data collected by the U.S. Geological Survey for routine water-quality activities at the Idaho National Laboratory, southeastern Idaho, 1996–2001: U.S. Geological Survey Scientific Investigations Report 2012-5270 (DOE/ID-22222), 74 p., http://pubs.usgs.gov/sir/2012/5270/.

Rattray, G.W., 2015, Geochemical evolution of groundwater in the Mud Lake area, eastern Idaho, USA: Environmental Earth Sciences, v. 73, no. 12, p. 8,251–8,269, http://link.springer.com/article/10.1007/s12665-014-3988-9/.

Robertson, J.B., Schoen, Robert, and Barraclough, J.T., 1974, The influence of liquid waste disposal on the geochemistry of water at the National Reactor Testing Station, Idaho—1952–1970: U.S. Geological Survey Open-File Report (IDO-22053), 231 p., http://pubs.er.usgs.gov/publication/ofr73238.

U.S. Department of Energy, 2014, Naval Reactors Facility Environmental Summary Report: U.S. Department of Energy, NRFOSQ-ESH-EE-14-003, 44 p.

Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma Publishing Service Center

For more information concerning the research in this report, contact the
Director, Idaho Water Science Center
U.S. Geological Survey
230 Collins Road
Boise, Idaho 83702
http://id.water.usgs.gov

Rattray—**Geochemistry of Groundwater in the Eastern Snake River Plain Aquifer, Idaho National Laboratory and Vicinity, Eastern Idaho**—Professional Paper 1837–A

ISSN 2330-7102 (online)
https://doi.org/10.3133/pp1837A