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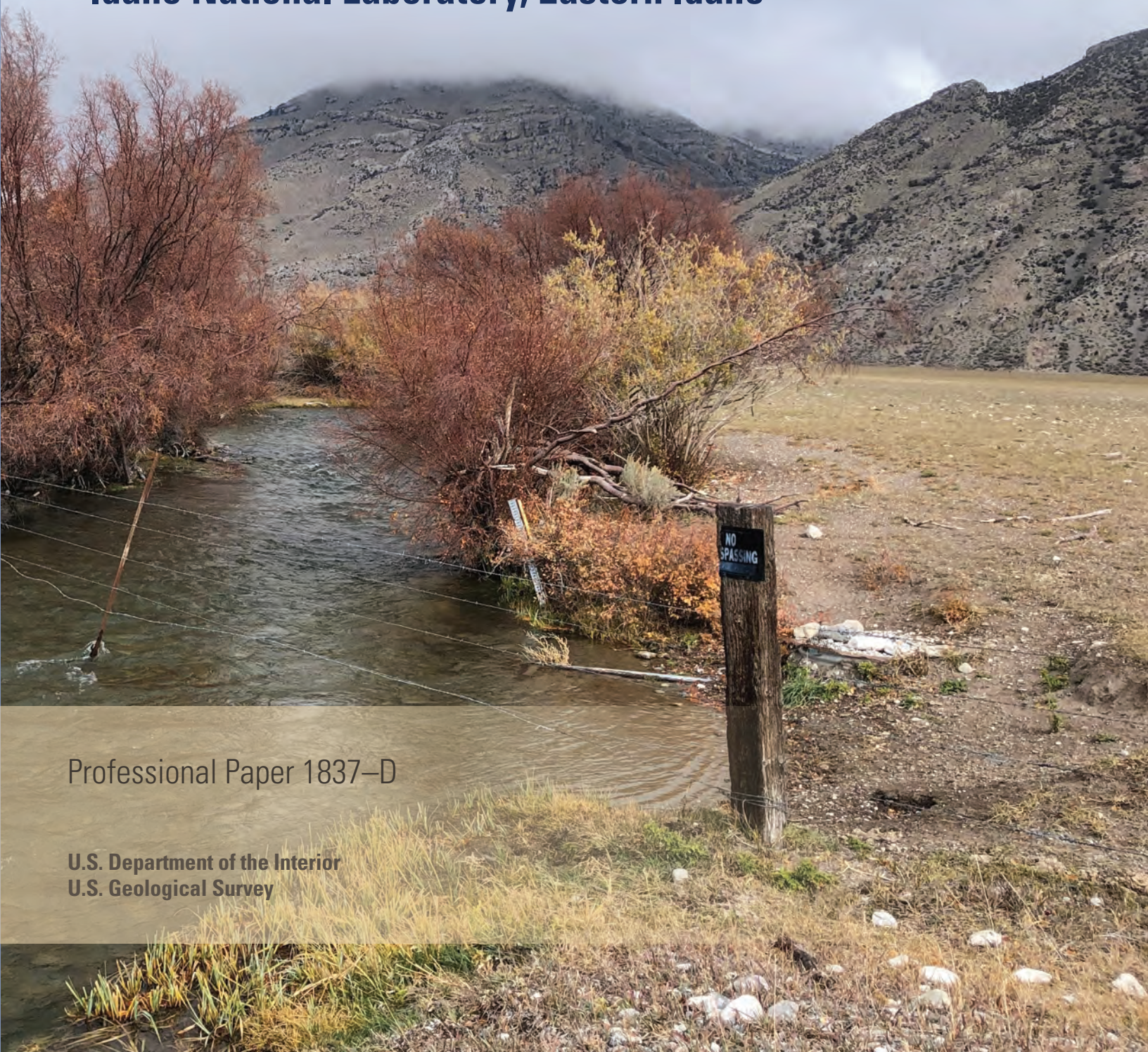
Evaluation of Hydrologic Processes in the Eastern Snake River Plain Aquifer Using Uranium and Strontium Isotopes, Idaho National Laboratory, Eastern Idaho



Professional Paper 1837–D

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

Cover. Birch Creek looking northeast from Idaho State Route 28 near Blue Dome, Idaho. Photograph by Kerri C. Treinen, U.S. Geological Survey, October 2021.

Evaluation of Hydrologic Processes in the Eastern Snake River Plain Aquifer Using Uranium and Strontium Isotopes, Idaho National Laboratory, Eastern Idaho

By Gordon W. Rattray and James B. Paces

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Rattray, G.W., 2023, Determining three-dimensional hydrologic processes in the eastern Snake River Plain aquifer using geochemical mass-balance modeling, Idaho National Laboratory, eastern Idaho, with contributions by Treinen, K.C.: U.S. Geological Survey Professional Paper 1837–C (DOE/ID-22258), 133 p., https://doi.org/10.3133/pp1837C.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	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, 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 in milligrams per liter (mg/L) or parts per million (ppm), micrograms per liter (µg/L), or parts per billion (ppb).

Activities for radioactive constituents in water are given in picocuries per liter (pCi/L).

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (iE) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

ATRC	Advanced Test Reactor Complex
AVH	axial volcanic highland
BC	Birch Creek
BCV	Birch Creek Valley
BLR	Big Lost River
BLRV	Big Lost River Valley
BLT	Big Lost Trough
CFA	Central Facilities Area
DOE	U.S. Department of Energy
ESRP	eastern Snake River Plain
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
K	hydraulic conductivity
LLR	Little Lost River
LLRV	Little Lost River Valley
MFC	Materials and Fuels Complex
NRF	Naval Reactors Facility
NWIS	U.S. Geological Survey National Water Information System
NWQL	U.S. Geological Survey National Water Quality Laboratory
ppb	parts per billion
ppm	parts per million
RWMC	Radioactive Waste Management Complex
USGS	U.S. Geological Survey

Evaluation of Hydrologic Processes in the Eastern Snake River Plain Aquifer Using Uranium and Strontium Isotopes, Idaho National Laboratory, Eastern Idaho

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Abstract

Waste constituents discharged to the eastern Snake River Plain aquifer at the U.S. Department of Energy (DOE) Idaho National Laboratory (INL) pose risks to the water quality of the aquifer. To understand these risks, the U.S. Geological Survey, in cooperation with the DOE, is conducting geochemical studies to better understand the hydrologic processes at the INL that affect the movement of groundwater and waste constituents. In this study, we used natural uranium ($^{234}U/^{238}U$) and strontium ($^{87}Sr/^{86}Sr$) isotope ratios of surface water and groundwater to identify the sources of water, the mixing of different source waters, and the flow directions in the shallow part (upper 250 feet) of the aquifer at the INL.

Samples were collected from 17 sites at and near the INL that represent the source-water contributions to the aquifer. These source-water sites included surface water, regional groundwater, and springs. Groundwater samples from 63 sites were collected at and near the INL. For all sites, sample collection dates ranged from 1979 to 2019, but groundwater samples collected at the INL are representative of wet climate cycles when the Big Lost River (BLR) was flowing onto the INL.

The $^{234}U/^{238}U$ activity ratios and $^{87}Sr/^{86}Sr$ from groundwater at the INL were plotted on graphs within ternary mixing webs in which the three end members of the mixing web represented specific sources of recharge. The large number of sources of recharge required numerous mixing webs, representing various geographic locations at the INL, so that each mixing web represented an area with just three sources of recharge. Considerations for determining the sources of recharge to groundwater sites included chemical signatures in addition to $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$, hydrologic context, and geographic location. The mixing webs were used to estimate the percentage of recharge from specific sources to groundwater at wells.

The results of this study identified groundwater from the Lemhi Range as a source of recharge to the INL, which was a previously unsuspected source of recharge. The estimated spatial distribution of recharge from the BLR and groundwater from the Lost River Range also decreased and increased, respectively, relative to the spatial distribution estimated from an earlier study. Upwelling geothermal water was identified at only one well, which indicates that the upward movement of deep groundwater to the shallow part of the aquifer is largely nonexistent. Mixing between surface water and groundwater, different groundwater recharge sources, or both is ubiquitous at the INL. Mixing of water fully explains the distribution of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in groundwater at the INL and thus renders unnecessary the hypothesis that fast and slow flow zones at the INL are required to explain the distribution of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$.

Introduction

Water from the eastern Snake River Plain (ESRP) aquifer supplies water for industry, irrigates approximately 900,000 acres of farmland, and provides the sole source of drinking water for approximately 200,000 people in eastern Idaho (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 chemical and radiochemical wastes that were disposed to the subsurface at various INL facilities (fig. 1, table 1). The disposal of these wastes resulted in detectable concentrations of some waste constituents in the ESRP aquifer (Davis and others, 2013).

The presence of chemical and radiochemical 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, the U.S. Geological Survey (USGS), in cooperation with the DOE, collects water-quality data and conducts investigative studies of the aquifer (Knobel and others, 2005). The water-quality data, in addition to providing information about risks to groundwater quality from waste constituents, are used in geochemistry studies (Olmsted, 1962; Robertson and others, 1974; Busenberg and others, 2001; Rattray, 2018, 2019, 2023) to understand hydrologic and chemical processes in the ESRP aquifer and to determine how these processes influence the concentrations and movement of groundwater and waste constituents in the aquifer. Results from geochemistry studies also provide information that may be used to improve, constrain, and (or) calibrate groundwater-flow models of the ESRP aquifer at the INL (Fisher and others, 2012).

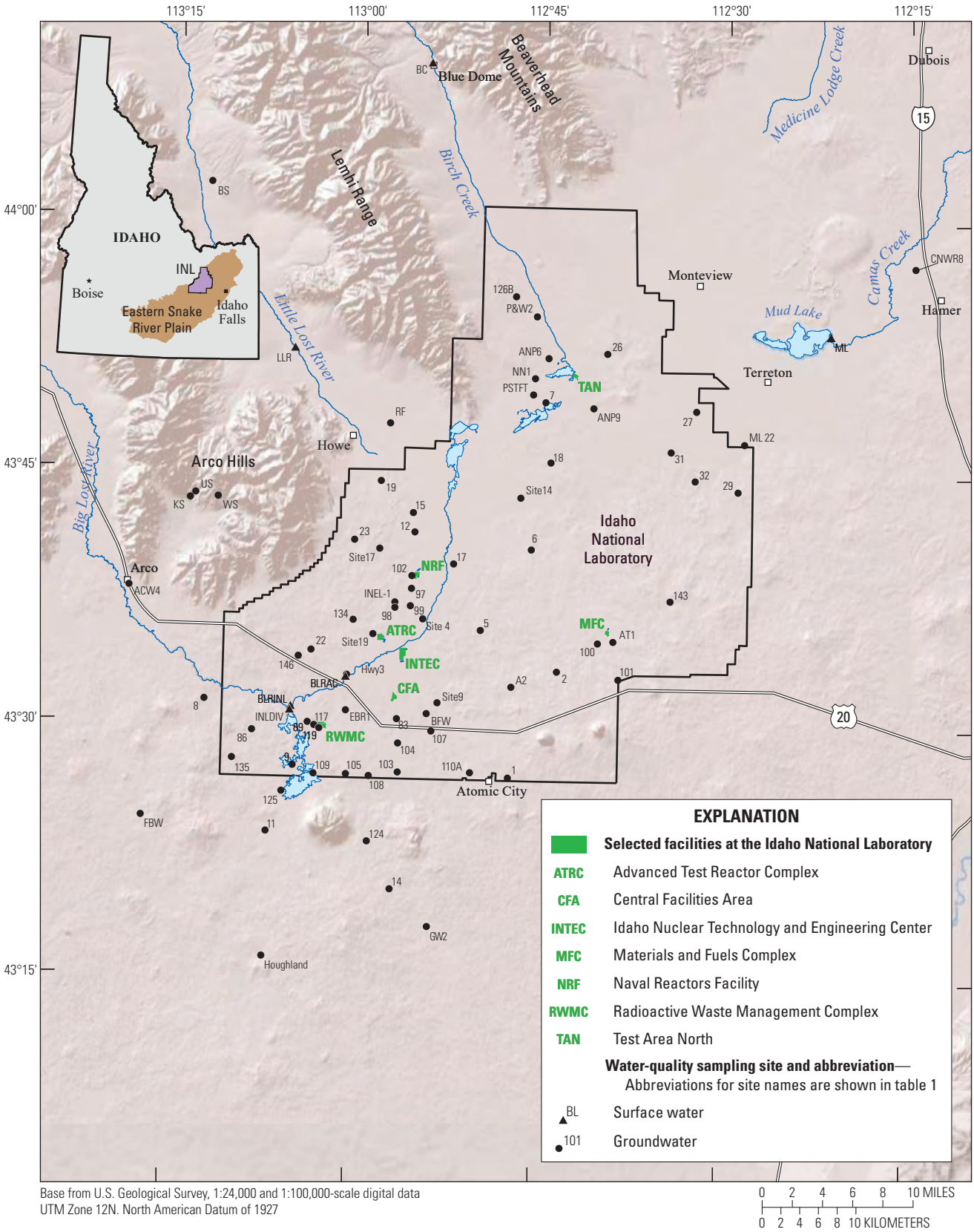

Figure 1. Geographic features and water-quality sampling sites at and near the Idaho National Laboratory (INL) and vicinity, eastern Idaho.

Table 1. Site names and abbreviated names for water-quality sampling sites, Idaho National Laboratory (INL) and vicinity, eastern Idaho.

[The first five sets of data (surface water, tributary valley groundwater, Arco Hills Springs in the Lost River Range, regional groundwater, and geothermal water) are considered sources of recharge to groundwater at the INL. Locations of sites are shown in figure 1. Site information is available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021)]

Site name	Abbreviated name
Surface water	
Big Lost River near Atomic City	BLRAC
Big Lost River below INL diversion	BLRINL
Birch Creek at Blue Dome Inn	BC
INL diversion at head, near Arco	INLDIV
Little Lost River near Howe	LLR
Mud Lake near Terreton	ML
Tributary valley groundwater	
Arco City Well #4	ACW4
Big Springs near Clyde	BS
Ruby Farms	RF
USGS 126B	126B
Arco Hills Springs in the Lost River Range	
King Spring near Arco	KS
Unnamed Spring near Arco	US
Walker Spring near Arco	WS
Regional groundwater	
CNWR Well #8	CNWR8
ML 22	ML22
Geothermal water	
INEL-1 2,000 feet	INEL-1 or INEL1 2,000 feet
INEL-1 10,300 feet	INEL-1 or INEL1 10,300 feet
Deep groundwater at the INL	
EBR-1	EBR1
Site 9	Site9
Site 14	Site14
USGS 7	7
USGS 15	15
Shallow groundwater in the North INL Area	
ANP 6	ANP6
No Name 1	NN1
P&W 2	P&W2
PSTF TEST	PSTF
USGS 18	18
Shallow groundwater in the Northeast INL Area	
ANP 9	ANP9
USGS 26	26
USGS 27	27
USGS 29	29
USGS 31	31
USGS 32	32
Shallow groundwater in the Southeast INL Area	
Arbor Test 1	AT1
Area II	A2
Grazing Well #2	GW2
USGS 1	1
USGS 2	2
USGS 100	100
USGS 101	101
USGS 107	107
USGS 110A	110A
USGS 143	143
Shallow groundwater in the Northwest INL Area	
Site 4	Site4
Site 17	Site17
Site 19	Site19
USGS 12	12
USGS 19	19
USGS 22	22
USGS 23	23
USGS 97	97
USGS 98	98
USGS 99	99
USGS 102	102
USGS 134 zone 15	134
USGS 146	146
Shallow groundwater in the Central INL Area	
Badging Facility Well	BFW
USGS 5	5
USGS 6	6
USGS 17	17

Table 1. Site names and abbreviated names for water-quality sampling sites, Idaho National Laboratory (INL) and vicinity, eastern Idaho.—Continued

[The first five sets of data (surface water, tributary valley groundwater, Arco Hills Springs in the Lost River Range, regional groundwater, and geothermal water) are considered sources of recharge to groundwater at the INL. Locations of sites are shown in figure 1. Site information is available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021)]

Site name	Abbreviated name
Shallow groundwater in the South INL Area	
Houghland	Houghland
USGS 14	14
USGS 124	124
Shallow groundwater in the Southwest INL Area	
Highway 3	Hwy3
USGS 8	8
USGS 9	9
USGS 11	11
USGS 83	83
USGS 86	86
USGS 89	89
USGS 103	103
USGS 104	104
USGS 105	105
USGS 108	108
USGS 109	109
USGS 117	117
USGS 119	119
USGS 125	125
USGS 135 zone 10	135

This study used naturally occurring uranium (U) and strontium (Sr) isotope ratios of surface water and groundwater to investigate hydrologic processes in the ESRP aquifer at the INL. Several characteristics of these isotope systems make them excellent tracers of water, well-suited for investigating hydrologic processes. Uranium and Sr are abundant trace elements in most natural waters, they have isotopic compositions that can vary widely in different hydrologic systems, and their isotopic compositions remain unfractionated by near-surface chemical and physical processes (Paces and Wurster, 2014).

Chapter A of Professional Paper 1837 (Rattray, 2018) documented the use of natural U and Sr isotopic compositions and a two-component mixing model to identify sources of recharge to groundwater at the INL. Information derived from that study indicated that U and Sr isotope ratios were not available for all sources of recharge to groundwater at the INL or from enough well-distributed groundwater samples from the INL to completely and confidently identify the sources of recharge throughout the INL. In addition, due to the many sources of recharge to groundwater at the INL, it was determined that a three-component mixing model would better represent the multiple sources of recharge than a two-component mixing model. Consequently, during 2018–19, water samples were collected from sources of recharge to, and groundwater from, the INL and were analyzed for U and Sr concentrations and isotope ratios. This report (Professional Paper 1837, Chapter D) incorporates these recently collected data and uses three-component mixing to evaluate sources of recharge to groundwater at the INL.

Purpose and Scope

The objective of this report is to identify the sources of water, mixing of different source waters, and the flow directions of groundwater in the ESRP aquifer at the INL from U ($^{234}U/^{238}U$), expressed as an activity ratio (AR), and Sr ($^{87}Sr/^{86}Sr$) isotope ratios. Ninety-five groundwater samples were collected at and near the INL from 58 shallow wells (those that penetrate only the upper 250 feet [ft]) of aquifer) and 5 deep wells (those that penetrate deeper than 250 ft into the aquifer). Surface-water, spring, and groundwater samples were collected from 17 sites that are potential sources of water (recharge) to the INL (BLR; fig. 1). Data from the 95 groundwater samples used in this study include two water samples collected in 1979 (Mann, 1986; McLing and others, 2002), one water sample collected in 1991, 64 water samples collected during 1996–99 (Johnson and others, 2000; Roback and others, 2001), and 28 water samples collected during 2018–19 (this study, available at U.S. Geological Survey, 2021).

Because the number of shallow groundwater sites with available U and Sr isotopic compositions was greater than the number of deep groundwater sites, the hydrologic processes presented in this report are representative of the shallow aquifer. However, these hydrologic processes also may be representative of some parts of the deeper aquifer.

Description of Study Area

The study area encompasses approximately 5,000 square miles (mi^2) of eastern Idaho and includes the (1) southern extents of the Pioneer, Lost River, Lemhi, and Beaverhead Mountains; (2) Big Lost River, Little Lost River, and Birch Creek tributary valleys that bisect the mountains; and (3) the ESRP at and adjacent to the INL (fig. 1). The ESRP is a relatively flat topographic depression with altitudes at the INL ranging from about 4,800 to 5,300 feet (ft), and altitudes in the mountains as high as 12,655 ft in the Lost River Range. The climate is semi-arid on the ESRP and continental in the mountains with mean annual temperatures and precipitation of 5.7 degrees Celsius (°C) and 8.4 inches (in.) at the INL (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 1981–2000; PRISM Climate Group, 2015).

Geology

The study area consists of two geologic provinces, the northern Basin and Range province and the Snake River Plain-Yellowstone Plateau volcanic province, that are represented by the mountains and the ESRP, respectively (Link and Janecke, 1999; Morgan and McIntosh, 2005). The mountains are a heterogeneous mixture of late Cenozoic to Paleozoic sedimentary and Neogene silicic volcanic rocks (fig. 2). Limestone and dolostone are the primary sedimentary rock type, but sandstone and other silicic sedimentary rocks are also present. Silicic volcanic rocks in the mountains include rhyolite, dacite, and andesite (Lewis and others, 2012).

The ESRP is a structural depression that formed as the Yellowstone hot spot moved progressively northeastward across Idaho; as the ESRP subsided, it was filled with numerous, massive volcanic eruptions. Consequently, the ESRP consists of a thick sequence of Neogene rhyolite that is overlain by a thick sequence of Quaternary and Neogene basalt.

The ESRP contains several structural features (fig. 2) at and near the INL. These include (1) volcanic rift zones, which are linear to curvilinear belts of numerous volcanic structures and landforms that generally trend northwestward and are perpendicular to the direction of regional groundwater flow (Kuntz and others, 1992), (2) volcanic vent corridors, which are narrow zones in and near (and parallel to) volcanic rift zones that contain known or inferred volcanic vents, fissures, and dikes (Anderson and others, 1999), and (3) the Big Lost Trough (BLT) and Mud Lake subbasins, long-lived sedimentary basins that were part of Pleistocene Lake Terreton (Gianniny and others, 2002).

Hydrology

The amount of precipitation occurring at the INL makes precipitation a minor contributor to groundwater at the INL. Infiltration of wastewater from ponds at INL facilities also is a minor contributor to groundwater. However, wastewater discharged at the INL is actually recycled groundwater, so this source of recharge is not really a new source of water. Other surface water in the study area includes the Big Lost River (BLR), Little Lost River (LLR), Birch Creek (BC),[1] Mud Lake, and irrigation water. Except for the BLR, infiltration from these sources of surface water occurs beyond the physical boundaries of the INL. Consequently, the BLR is the only actual surface-water source that infiltrates through the shallow, unsaturated zone to the ESRP aquifer at the INL (Bennett, 1990).

[1]Since 1969, when most water from BC was diverted north of the INL, the amount of water flowing onto the INL from BC is small and periodic (Swanson and others, 2003).

The BLR is an ephemeral stream on the ESRP, with mean annual discharge onto the INL fluctuating between 0 and greater than 100 cubic feet per second (ft^3/s; fig. 3) (U.S. Geological Survey, 2021) in response to seasonal flow cycles and short-term (3–8 year) wet-dry climate cycles. The BLR is a losing river that infiltrates to the subsurface and terminates on the ESRP, and the distance that the BLR flows downstream is dependent on the amount of discharge in the stream. Localized, episodic infiltration from the BLR, including at the BLR sinks, playas, and INL spreading areas (natural depressions into which water from the BLR was diverted for flood control purposes beginning in 1965; Bennett, 1990) (fig. 1) occurs when there is sufficient discharge, which usually occurs during wet climate cycles (Bennett, 1990). The nonuniform nature of recharge from the BLR causes the ESRP aquifer beneath the western half of the INL to behave as a transient hydrologic system. Due to the ephemeral nature of the BLR, the geochemical signature of this source water will change over time (Rattray, 2019).

Regional groundwater is the only source of recharge to the ESRP aquifer in the eastern half of the INL. Consequently, the aquifer in the eastern half of the INL behaves as a steady-state hydrologic system.

The ESRP aquifer underlies the INL. The aquifer is composed of hundreds of interfingered layers of discontinuous basalt flows and sediment, with the thickness of individual basalt flows estimated to range from 2 to 100 ft (Anderson and Liszewski, 1997). The fractured-basalt aquifer is heterogeneous, largely unconfined, and ranges from several hundred to several thousand-feet-in thickness (Ackerman and others, 2006). The aquifer is overlain by an unsaturated zone that ranges from about 200 to 2,000 ft (Whitehead, 1992).

The porosity of the basalt ranges from 0.05 to 0.27 (Ackerman and others, 2006), with porosity and permeability generally lower in the massive interiors of basalt flows and higher in the interflow zones between basalt flows (Welhan, Clemo, and others, 2002; Welhan, Johannesen, and others, 2002; Ackerman and others, 2006). Hydraulic conductivities (K) were estimated to range over more than six orders of magnitude (log K of -2.00 to 4.38 feet per day [ft/d]; Anderson and others, 1999), and average linear flow velocities were estimated to range from 2 to 20 ft/d (Barraclough and others, 1981; Pittman and others, 1988; Mann and Beasley, 1994; Cecil and others, 2000; Busenberg and others, 2001).

Most groundwater moves horizontally through the rubble- and sediment-filled interflow zones between basalt flows (Whitehead, 1992), although structural features in the aquifer may impede and (or) enhance horizontal and (or) vertical flow. For example, volcanic vents and noneruptive fissures are highly porous and may cut across highly permeable zones in and between basalt layers (Anderson and others, 1999), so they may provide conduits for the rapid vertical movement of groundwater. In contrast, dikes have low permeability, and they may impede the horizontal movement of groundwater if they have a large lateral and vertical extent (Anderson and others, 1999).

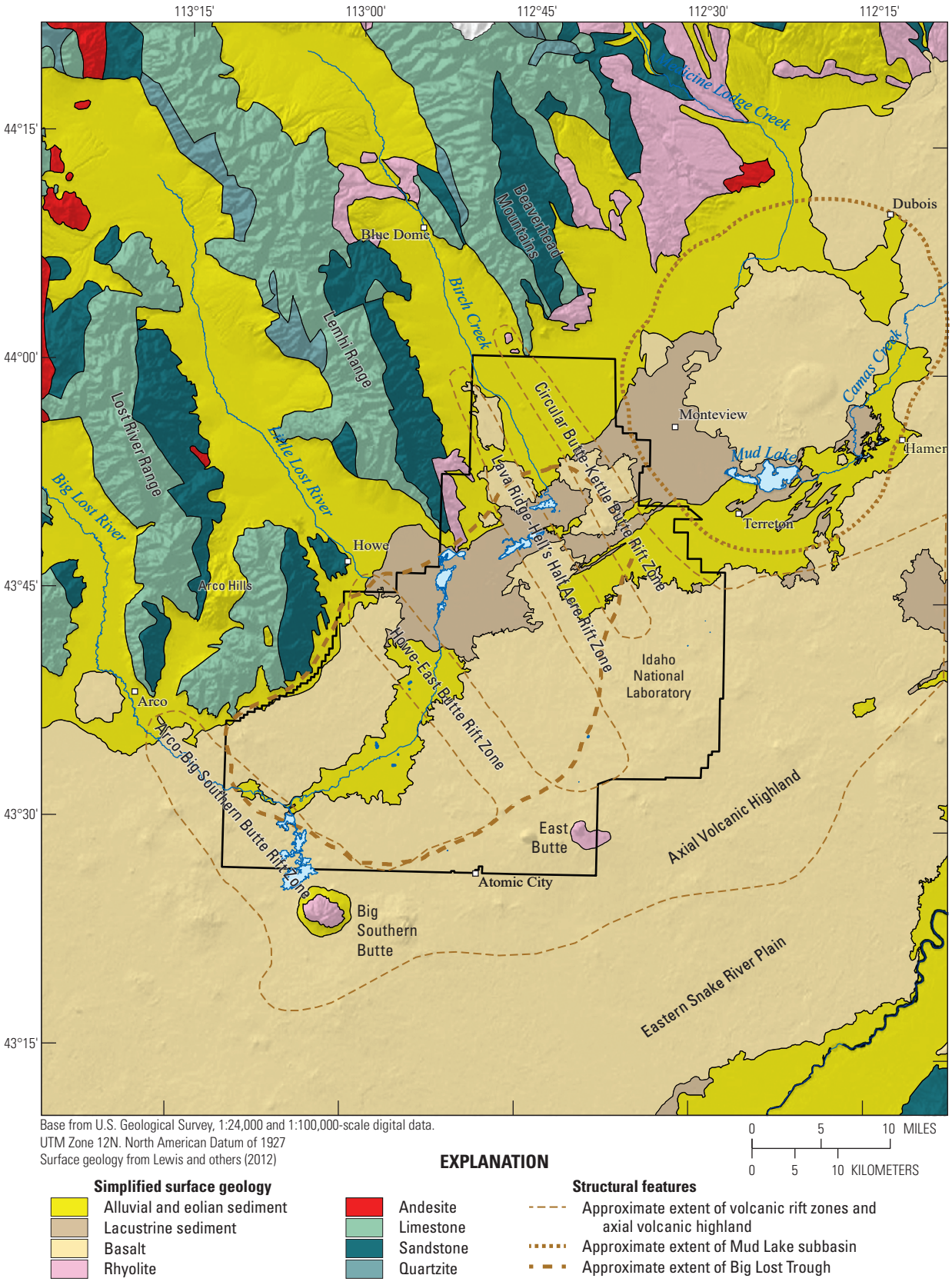

Figure 2. Surface geology and structural features, Idaho National Laboratory and vicinity, eastern Idaho. Surface geology modified from Lewis and others (2012).

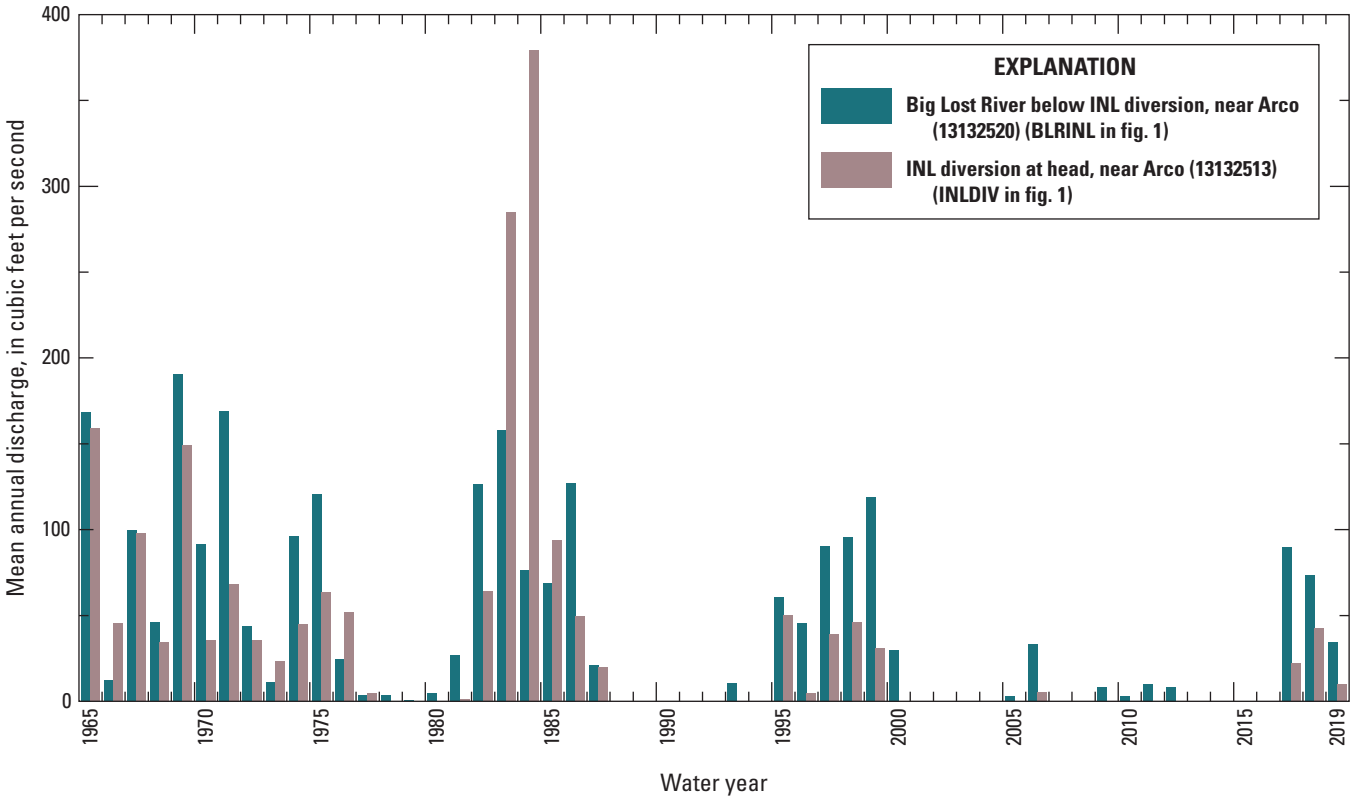

Figure 3. Mean annual discharge at U.S. Geological Survey (USGS) streamgages Big Lost River below INL diversion, near Arco (13132520), and INL diversion at head near Arco (13132513), Idaho National Laboratory (INL), eastern Idaho. A water year is the 12-month period from October 1, for any given year, through September 30 of the following year. A water year is designated by the calendar year in which it ends. More information is available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

Water-table contours for April 1989 for the ESRP aquifer were interpolated from 481 water-level measurements (water-level data presented in Rattray, 2018, table 1-1) using the natural neighbor technique (Sibson, 1981). Water-table contours (fig. 4) indicate that groundwater at the INL generally flows south or southwest with a hydraulic gradient of about 1–8 feet per mile (ft/mi).

Numerous sources of water to the ESRP aquifer are present at the INL. These sources include:

- streamflow infiltration from the BLR in the BLR channel, sinks, playas, and the INL spreading areas (fig. 1) (Bennett, 1990; Busenberg and others, 2001; Nimmo and others, 2002);
- inflow of tributary valley groundwater from the BLRV, LLRV, and BCV, which includes infiltration of surface water from the LLR, BC, and irrigation (fig. 2) (Rattray, 2019);
- inflow of mountain front groundwater from the Lost River Range (fig. 1) (Rattray, 2019, 2023);
- inflow of regional groundwater northeast of the INL, which includes infiltration of surface water from irrigation and Mud Lake (Rattray, 2018, fig. 3*B*; Rattray, 2019);
- infiltration of precipitation (Ackerman and others, 2006; Rattray, 2019); and
- upwelling geothermal water (Mann, 1986; Rattray, 2018).

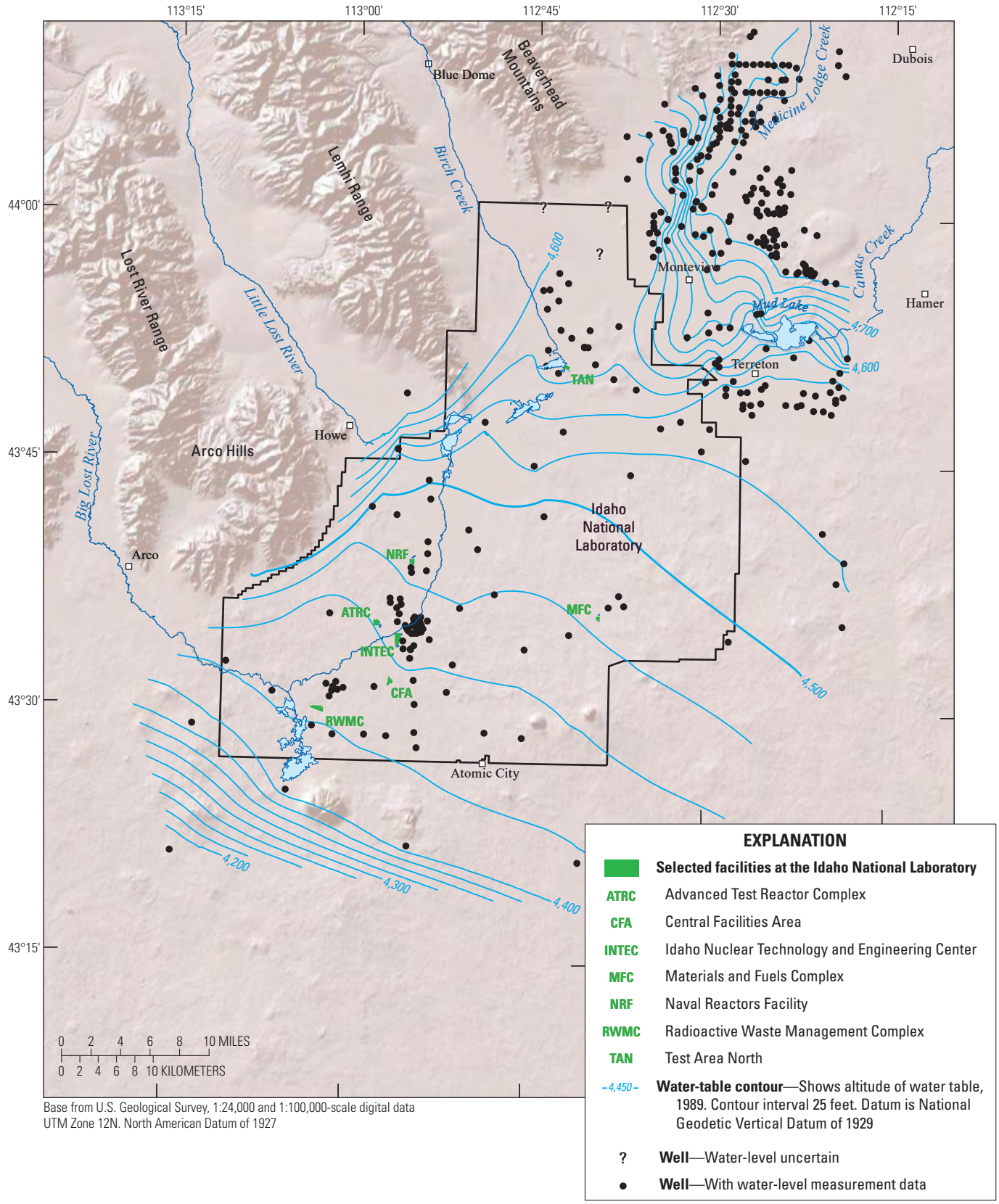

Figure 4. Locations of wells with water-level measurements and 1989 water-table contours, Idaho National Laboratory and vicinity, eastern Idaho. More information is available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

Previous Investigations

Luo and others (2000), Johnson and others (2000), Roback and others (2001), McLing and Roback (2007), and Rattray (2018) conducted studies that used U and (or) Sr isotopes to understand hydrologic processes in the ESRP aquifer at the INL. Luo and others (2000) used U- and thorium (Th)-decay series disequilibria to understand chemical and groundwater processes in the ESRP aquifer at the INL. The disequilibria were interpreted to be largely a function of adsorption-desorption processes and, for long-lived isotopes such as ^{238}U and ^{234}U, dissolution and precipitation. Mass balance modeling of the disequilibria enabled them to estimate groundwater residences times. From plots of contours of residence time, Luo and others (2000) suggested that there were two preferential (fast) groundwater-flow paths originating at the mouths of the LLRV and BCV and oriented in a north-south direction. These fast flow paths were estimated to transport water 2–5 times faster than surrounding slow flow areas, resulting in slow flow zones having longer residence times than the fast flow zones.

Johnson and others (2000) used $^{87}Sr/^{86}Sr$ to investigate groundwater flow in the ESRP aquifer at the INL. They suggested that water-rock interaction between groundwater and the host basalt (which have a lower $^{87}Sr/^{86}Sr$ isotope ratio relative to higher ratios inherited from Paleozoic sediments to the north of the INL) was an important control on the Sr isotope ratios in the groundwater. After plotting contours of $^{87}Sr/^{86}Sr$, Johnson and others (2000) identified a zone of high isotope ratios (high isotope-ratio zone $^{87}Sr/^{86}Sr > 0.71100$) trending southward from the LLRV that was flanked by zones of lower isotope ratios to the east and west (low isotope-ratio zones). They hypothesized that mixing between different sources of water could not entirely explain these contours. Instead, the high and low isotope ratio zones represented fast (preferential) and slow groundwater flow zones, respectively, with the greater time available for water-basalt interaction in the slow-flow zones responsible for the relatively low Sr isotope ratios in these zones.

Roback and others (2001) used the natural variations of U and Sr concentrations and isotope ratios, which reflect the varying geologic strata of different source waters, to identify chemically distinct water masses, to assess mixing and water-rock interaction, and to delineate groundwater flow paths. They indicated that mixing and water-rock interaction were both required to account for the observed trends in isotopic data in the groundwater, with incongruent dissolution of the host basalt required to explain the lower $^{234}U/^{238}U$ (relative to regional groundwater) and $^{87}Sr/^{86}Sr$ (Johnson and others, 2000) in parts of the aquifer. Two high $^{234}U/^{238}U$ isotope ratio zones and two lower $^{234}U/^{238}U$ isotope ratio zones were identified in this study. The two high isotope ratio zones were interpreted to represent preferential (fast) flow paths and extend southeast from the mouths of the LLRV and BCV, and the two low-isotope ratio zones reside in the western and central parts of the INL (west and east of the high isotope ratio zone extending south from the mouth of the LLRV). The two low-isotope ratio zones were interpreted to represent stagnant (slow) flow zones, largely consisting of recharge from the BLR, that are relatively isolated from flow in the regional aquifer due to their lower permeability.

McLing and Roback (2007) suggested that the various sources of recharge to the aquifer system at the INL have distinct thermal and chemical signatures. Consequently, they used temperature, chemical, and isotopic (Th, U, and Sr) data to understand the groundwater-flow system at the INL. Their interpretations of chemical and isotopic data are identical to those of Luo and others (2000) and Roback and others (2001) and consist of the same long-range preferential (fast) flow paths and stagnant (slow) flow zones. They also suggest that zones of colder and warmer water temperature correlate with preferential and stagnant flow zones, respectively, and provide additional evidence for the presence of fast- and slow-flow zones.

Rattray (2018) compiled and evaluated a comprehensive suite of chemical and isotopic data collected from groundwater at the INL, including U data from Roback and others (2001) and Sr data from Johnson and others (2000), to improve the understanding of hydrologic processes in the ESRP aquifer at the INL. Interpretation based on understanding of the hydrologic system and chemical and isotopic data, including the spatial distribution of U and Sr isotope ratios (Rattray, 2018, fig. 28*Z*–28*AA*), indicated that mixing between recent recharge from the BLR with older groundwater sources, not fast- and slow-flow zones, is the predominant hydrologic process affecting the geochemical evolution of groundwater in the western and central parts of the INL. Geochemical modeling also indicated that mixing between recent recharge and old groundwater[2] explains the geochemical evolution of groundwater in the western and central parts of the INL (Rattray, 2019, table 11, fig. 15).

Data, Methods, and Quality Assurance

Concentrations and isotopic ratios of U and Sr were analyzed for 95 water samples (table 2) collected from 79 sites (figs. 1 and 5; table 2). Mann (1986), Johnson and others (2000), Roback and others (2001), and McLing and others (2002) reported the results from two water samples that were collected in 1979 and analyzed in 1979 for U and Sr concentrations and in 1996–99 for U and Sr isotope ratios (from an archived water sample) and from 64 water samples that were collected and analyzed in 1996–99. The USGS reported results from one water sample that was collected in 1991 and was analyzed from an archived water sample in 2019 and 28 water samples that were collected and analyzed in 2018–19. The USGS-collected results are stored in the USGS National Water Information System database (U.S. Geological Survey, 2021).

[2]The term "old groundwater" in this report refers to groundwater that is older than the onset of atmospheric bomb testing (pre-1952). Sites at the INL containing old groundwater are identified in Rattray (2018, fig. 13).

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[Site locations are shown in figure 1. Springs samples are shown in *italics*. Samples collected in 1991 and 2018–19 were analyzed by the U.S. Geological Survey Radiogenic Isotope Laboratory in Denver, Colorado (data are available from the U.S. Geological Survey National Water Information System [NWIS] at https://dx.doi.org/10.5066/F7P55KJN, U.S. Geological Survey, 2021). Uranium concentration and isotope analyses of samples collected in 1979 and 1996–98 are from Roback and others (2001), and strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and 1996–98 are from Johnson and others (2000), and McLing and others (2002). **Abbreviations and symbol:** LVS, large volume sample; NAD 27, North American Datum of 1927; mm-dd-yyyy, month, day, year; nd, not determined; yyyy-yy, year range; ±2s, plus or minus two standard deviations; ppb, parts per billion]

Site name	Sample date (mm-dd-yyyy; yyyy-yy)	Site No.	Latitude (NAD 27)	Longitude (NAD 27)	Uranium (ppb)	±2s	$^{234}U/^{238}U$ (activity ratio)	±2s	Strontium (ppb)	±2s	$^{87}Sr/^{86}Sr$	±2s
Surface water												
Big Lost River near Atomic City	04-10-1997	13132530	43.547129	–113.009165	2.26	0.005	2.251	0.003	276	nd	0.71056	0.00001
Big Lost River below INL diversion	07-14-1999	13132520	43.515833	–113.081944	2.20	0.22	2.116	0.004	nd	nd	nd	nd
Birch Creek	1996–99	Unknown	Unknown	Unknown	nd	nd	nd	nd	nd	nd	0.71198	0.000011
Birch Creek at Blue Dome Inn	04-30-2018	13117020	44.153333	–112.909167	2.11	0.02	3.363	0.007	149	2	0.711981	0.000010
INL diversion at head, near Arco	05-30-2018	13132513	43.513611	–113.083889	1.73	0.02	2.128	0.005	197	2	0.710496	0.000010
Little Lost River	1996–99	Unknown	Unknown	Unknown	nd	nd	nd	nd	nd	nd	0.71256	0.000011
Little Lost River near Howe	05-01-2018	13119000	43.870278	–113.088056	1.06	0.01	2.609	0.006	106	1	0.711576	0.000009
Mud Lake near Terreton	04-30-2018	13115000	43.889722	–112.358056	0.28	0.00	1.775	0.005	80	1	0.709381	0.000010
Tributary valley groundwater												
Arco City Well #4	04-25-2018	433758113181701	43.632778	–113.305556	2.19	0.02	2.252	0.005	257	3	0.710027	0.000010
Big Springs near Clyde	05-01-2018	13118900	44.031847	–113.206397	0.93	0.01	2.875	0.006	122	1	0.712312	0.000009
Ruby Farms[1]	05-10-1991	434751112571801	43.797406	–112.955836	0.21	0.00	2.660	0.012	240	1	0.710670	0.000009
USGS 126B	05-01-2018	435529112471401	43.924492	–112.787961	1.83	0.02	3.116	0.007	254	3	0.711910	0.000010
Arco Hills Springs in the Lost River Range												
King Spring near Arco	07-02-2019	434311113132801	43.720361	–113.225569	6.94	0.07	3.622	0.008	177	2	0.709502	0.000009
Unnamed Spring near Arco	04-25-2018	434332113130501	43.725753	–113.218281	7.21	0.07	1.714	0.004	301	3	0.708217	0.000010
Walker Spring near Arco	07-02-2019	434314113111501	43.722064	–113.188064	2.63	0.03	2.383	0.005	231	2	0.708156	0.000009

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Site name	Sample date (mm-dd-yyyy; yyyy-yy)	Site No.	Latitude (NAD 27)	Longitude (NAD 27)	Uranium (ppb)	±2s	$^{234}U/^{238}U$ (activity ratio)	±2s	Strontium (ppb)	±2s	$^{87}Sr/^{86}Sr$	±2s
Regional groundwater												
CNWR Well #8	04-30-2018	435752112145301	43.964464	–112.248158	1.28	0.01	2.405	0.006	106	1	0.709445	0.000010
ML 22	04-28-1997	434657112282201	43.782111	–112.473489	3.59	0.010	1.715	0.006	333	nd	0.70992	0.00001
Geothermal water												
INEL–1 2,000 feet[2]	03-24-1979	433717112563501	43.621311	–112.944211	1.88	0.004	3.140	0.006	100	nd	0.70935	0.00001
INEL–1 10,300 feet[2]	07-20-1979	433717112563501	43.621311	–112.944211	0.19	0.000	2.073	0.010	150	nd	0.70980	0.00001
Deep groundwater at the INL												
EBR–1	10-16-1996	433051113002601	43.513697	–113.008156	2.03	0.004	2.067	0.004	194	nd	0.71006	0.00001
Site 9	07-22-1996	433123112530101	43.522925	–112.884383	1.68	0.003	2.498	0.004	204	nd	0.71059	0.00001
Site 14	08-20-1996	434334112463101	43.726203	–112.776244	2.07	0.004	2.833	0.003	173	nd	0.71085	0.00001
Site 14 LVS	09-11-1997	434334112463101	43.726203	–112.776244	2.07	0.005	2.833	0.004	nd	nd	nd	nd
USGS 7	04-21-1997	434915112443901	43.820689	–112.745236	2.26	0.005	2.889	0.003	nd	nd	nd	nd
	04-11-2018	434915112443901	43.820689	–112.745236	2.07	0.02	2.888	0.007	111	1	0.709821	0.000009
USGS 15	07-25-1996	434234112551701	43.709583	–112.922317	1.78	0.004	2.771	0.005	254	nd	0.71129	0.00001
Shallow groundwater in the North INL Area												
ANP 6	07-19-1996	435152112443101	43.864400	–112.741900	2.12	0.003	3.007	0.005	223	nd	0.71073	0.00001
ANP 6 LVS	09-11-1997	435152112443101	43.864400	–112.741900	2.25	0.009	3.002	0.007	nd	nd	nd	nd
No Name 1	04-09-2019	435038112453401	43.844014	–112.759928	1.61	0.02	1.733	0.004	171	2	0.710338	0.000009
P&W 2	10-15-1996	435419112453101	43.905183	–112.759383	1.86	0.004	3.051	0.004	157	nd	0.71159	0.00001
PSTF TEST	04-09-2019	434941112454201	43.827889	–112.762344	1.48	0.01	2.641	0.006	134	1	0.710695	0.000009
USGS 18	07-19-1996	434540112440901	43.761214	–112.736739	2.06	0.006	2.905	0.003	178	nd	0.71115	0.00001
USGS 18 LVS	09-12-1997	434540112440901	43.761214	–112.736739	2.07	0.004	2.911	0.004	nd	nd	nd	nd
Shallow groundwater in the Northeast INL Area												
ANP 9	04-28-1997	434856112400001	43.385383	–112.667592	2.37	0.005	2.989	0.004	198	nd	0.71143	0.00001
USGS 26	10-15-1996	435212112394001	43.869506	–112.662142	2.39	0.009	2.820	0.011	189	nd	0.71107	0.00001
USGS 26 LVS	09-03-1998	435212112394001	43.869506	–112.662142	2.41	0.007	2.800	0.005	nd	nd	nd	nd
USGS 27	10-15-1996	434851112321801	43.814136	–112.539403	3.04	0.006	2.349	0.002	248	nd	0.70993	0.00001

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Site name	Sample date (mm-dd-yyyy; yyyy-yy)	Site No.	Latitude (NAD 27)	Longitude (NAD 27)	Uranium (ppb)	±2s	$^{234}U/^{238}U$ (activity ratio)	±2s	Strontium (ppb)	±2s	$^{87}Sr/^{86}Sr$	±2s
Shallow groundwater in the Northeast INL Area—Continued												
USGS 27 LVS	09-02-1998	434851112321801	43.814136	–112.539403	3.10	0.007	2.353	0.003	nd	nd	nd	nd
USGS 29	07-19-1996	434407112285101	43.735147	–112.481442	2.00	0.004	2.131	0.005	161	nd	0.70957	0.00001
USGS 31 LVS	09-02-1998	434625112342101	43.773769	–112.573172	2.27	0.005	2.607	0.004	199	nd	0.71040	0.00001
USGS 32	07-19-1996	434444112322101	43.745483	–112.540053	2.53	0.004	2.449	0.005	271	nd	0.71026	0.00001
Shallow groundwater in the Southeast INL Area												
Arbor Test 1	10-10-1996	433509112384801	43.585997	–112.647492	1.69	0.00	2.331	0.003	123	nd	0.70998	0.00001
Area II	07-18-1996	433223112470201	43.539525	–112.784825	1.94	0.003	2.484	0.004	162	nd	0.71048	0.00001
Grazing Well #2	06-06-1997	431553112492001	43.264636	–112.823053	1.69	0.012	2.405	0.014	135	nd	0.71032	0.00001
USGS 1	04-21-1997	432700112470801	43.449931	–112.786531	1.70	0.005	2.447	0.010	130	nd	0.71031	0.00001
USGS 1 LVS	08-31-1998	432700112470801	43.449931	–112.786531	1.72	0.004	2.436	0.003	nd	nd	nd	nd
USGS 1 LVS replicate	08-31-1998	432700112470801	43.449931	–112.786531	1.72	0.004	2.433	0.005	nd	nd	nd	nd
USGS 2 LVS	08-26-1998	433320112432301	43.555428	–112.723403	1.82	0.004	2.345	0.003	141	nd	0.71008	0.00001
USGS 100	04-28-1997	433503112400701	43.584200	–112.668300	1.50	0.004	2.324	0.003	135	nd	0.71008	0.00001
USGS 101	10-10-1996	433255112381801	43.548728	–112.639686	1.32	0.003	2.280	0.004	89	nd	0.70962	0.00001
USGS 101 LVS	09-08-1997	433255112381801	43.548728	–112.639686	1.36	0.003	2.285	0.004	nd	nd	nd	nd
USGS 107 LVS	08-27-1998	432942112532801	43.494914	–112.891808	2.20	0.005	2.562	0.004	189	nd	0.71072	0.00001
USGS 110A LVS	08-25-1998	432717112501502	43.454667	–112.838247	2.03	0.004	2.491	0.003	152	nd	0.71057	0.00001
USGS 143	04-15-2019	433736112341301	43.626497	–112.571036	1.58	0.02	2.148	0.006	103	1	0.709485	0.000010
Shallow groundwater in the Northwest INL Area												
Site 4	05-01-2019	433617112542001	43.605000	–112.906389	1.53	0.02	2.064	0.005	178	2	0.710686	0.000009
Site 17	07-25-1996	434027112575701	43.674000	–112.966528	1.43	0.001	3.005	0.004	218	nd	0.710912	0.000014
Site 17	04-11-2019	434027112575701	43.674000	–112.966528	1.33	0.01	3.081	0.023	192	2	0.710880	0.000009
Site 19	04-17-2019	433522112582101	43.589439	–112.973467	1.21	0.01	3.220	0.007	210	2	0.710264	0.000009
USGS 12 LVS	09-10-1997	434126112550701	43.690514	–112.919475	2.36	0.006	2.236	0.005	342	nd	0.71061	0.00001
USGS 19	10-15-1996	434426112575701	43.740650	–112.966550	1.56	0.003	3.007	0.004	265	nd	0.71014	0.00001
USGS 19 LVS	09-10-1997	434426112575701	43.740650	–112.966550	1.59	0.003	3.020	0.004	nd	nd	nd	nd

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Shallow groundwater in the Northwest INL Area—Continued												
[3]USGS 22	07-18-1996	433422113031701	43.572761	–113.056692	0.33	0.001	1.544	0.013	120	nd	0.70951	0.00001
USGS 22 LVS	08-31-1998	433422113031701	43.572761	–113.056692	0.43	0.001	1.562	0.003	nd	nd	nd	nd
USGS 23	05-30-2018	434055112595901	43.681892	–113.000839	2.08	0.02	3.627	0.009	222	2	0.709587	0.000010
USGS 97	04-10-2019	433807112551501	43.635119	–112.922153	2.13	0.02	2.346	0.005	265	3	0.710766	0.000009
USGS 98	04-17-2019	433657112563601	43.615739	–112.944164	1.95	0.02	2.245	0.005	200	2	0.710448	0.000009
USGS 99	04-08-2019	433705112552101	43.617611	–112.923375	1.64	0.02	2.698	0.006	219	2	0.711019	0.000010
USGS 102	04-10-2019	433853112551601	43.647369	–112.922061	2.19	0.02	2.293	0.005	279	3	0.710693	0.000009
USGS 134 zone 15	06-25-2019	433611112595819	43.603003	–113.000353	1.15	0.01	2.870	0.006	159	2	0.710179	0.000009
USGS 146	04-22-2019	433359113042501	43.566447	–113.073664	1.25	0.01	2.857	0.006	220	2	0.712860	0.000009
Shallow groundwater in the Central INL Area												
Badging Facility Well	07-17-1996	433042112535101	43.511944	–112.898333	1.50	0.004	2.531	0.008	215	nd	0.71091	0.00001
USGS 5	10-10-1996	433543112493801	43.595117	–112.827953	1.50	0.003	2.045	0.003	190	nd	0.71057	0.00001
USGS 6	07-16-1996	434031112453701	43.675219	–112.761008	1.75	0.002	2.267	0.004	195	nd	0.71021	0.00001
USGS 6 LVS	09-12-1997	434031112453701	43.675219	–112.761008	1.75	0.004	2.275	0.004	nd	nd	nd	nd
USGS 17	10-16-1996	433937112515401	43.660022	–112.865906	1.71	0.006	1.960	0.009	217	nd	0.71038	0.00001
USGS 17 LVS	09-11-1997	433937112515401	43.660022	–112.865906	1.75	0.004	1.964	0.003	nd	nd	nd	nd
Shallow groundwater in the South INL Area												
Houghland	06-03-1997	431439113071401	43.244139	–113.121611	1.81	0.004	2.542	0.003	162	nd	0.71044	0.00001
USGS 14	04-10-1997	432019112563201	43.338594	–112.943028	2.37	0.005	2.638	0.004	188	nd	0.71057	0.00001
USGS 124	04-10-1997	432307112583101	43.385144	–112.975336	1.61	0.003	2.551	0.003	212	nd	0.71039	0.00001

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Shallow groundwater in the Southwest INL Area												
Fingers Butte Well	06-03-1997	432424113165301	43.406575	–113.282233	1.78	0.004	2.631	0.003	211	nd	0.70986	0.00001
Highway 3	04-29-1997	433256113002501	43.548794	–113.007775	1.89	0.005	2.075	0.006	276	nd	0.71040	0.00001
USGS 8	10-08-1996	433121113115801	43.522269	–113.200122	2.10	0.004	2.485	0.003	251	nd	0.70998	0.00001
USGS 9 LVS	09-01-1998	432740113044501	43.458900	–113.078550	1.57	0.003	2.218	0.003	178	nd	0.71029	0.00001
USGS 11	10-09-1996	432336113064201	43.393292	–113.112644	1.67	0.004	2.469	0.003	235	nd	0.71008	0.00001
USGS 83 LVS	08-28-1998	433023112561501	43.506306	–112.938408	1.37	0.003	2.065	0.004	140	nd	0.71012	0.00001
USGS 86	10-11-1996	432935113080001	43.492903	–113.134567	1.03	0.002	2.235	0.003	152	nd	0.70968	0.00001
USGS 86 LVS	09-08-1997	432935113080001	43.492903	–113.134567	0.99	0.009	2.224	0.015	nd	nd	nd	nd
USGS 89	07-17-1996	433005113032801	43.501481	–113.059647	1.16	0.003	1.918	0.006	149	nd	0.70981	0.00001
USGS 103	07-15-1996	432714112560701	43.453678	–112.935975	1.49	0.002	2.409	0.004	198	nd	0.71053	0.00001
USGS 103 LVS	09-09-1997	432714112560701	43.453678	–112.935975	1.46	0.007	2.420	0.006	nd	nd	nd	nd
USGS 104	07-15-1996	432856112560801	43.482150	–112.936422	1.52	0.002	2.162	0.004	212	nd	0.71023	0.00001
USGS 105	05-05-1997	432703113001801	43.450853	–113.005769	2.16	0.005	2.229	0.004	253	nd	0.71043	0.00001
USGS 108 LVS	09-09-1997	432659112582601	43.449572	–112.974814	1.76	0.004	2.322	0.004	209	nd	0.71043	0.00001
USGS 109 LVS	09-01-1998	432701113025601	43.450761	–113.049619	1.73	0.004	2.309	0.003	214	nd	0.71220	0.00001
USGS 117	04-11-2019	432955113025901	43.498378	–113.050464	1.08	0.01	2.108	0.005	133	1	0.709833	0.000009
USGS 119	04-08-2019	432945113023401	43.495631	–113.043522	0.61	0.01	2.122	0.005	135	1	0.709859	0.000009
USGS 125	10-11-1996	432602113052801	43.433075	–113.092603	2.17	0.004	2.267	0.003	236	nd	0.71047	0.00001
USGS 135 zone 10	06-19-2019	432753113093613	43.464758	–113.160731	1.83	0.02	2.895	0.017	246	2	0.709999	0.000010

[1]Sample was collected in 1991 and archived until 2019 when it was analyzed for U and Sr concentrations and isotope ratios. Sr concentration was 240 ppb in original 1991 analysis and 74 ppb in 2019 analysis of archived water sample (Rattray, 2018, table 14). Small U concentration of 0.21 ppb in 2019 analysis probably reflects reducing conditions in archived water sample caused by decay of organic material.

[2]Analyzed during 1996–99.

[3]Because there are no U or Sr isotope ratios measured from precipitation at the INL, the isotope ratios of groundwater from USGS 22, seem to consist entirely of precipitation (Busenberg and others, 2001, p. 90; Rattray, 2019, table 11).

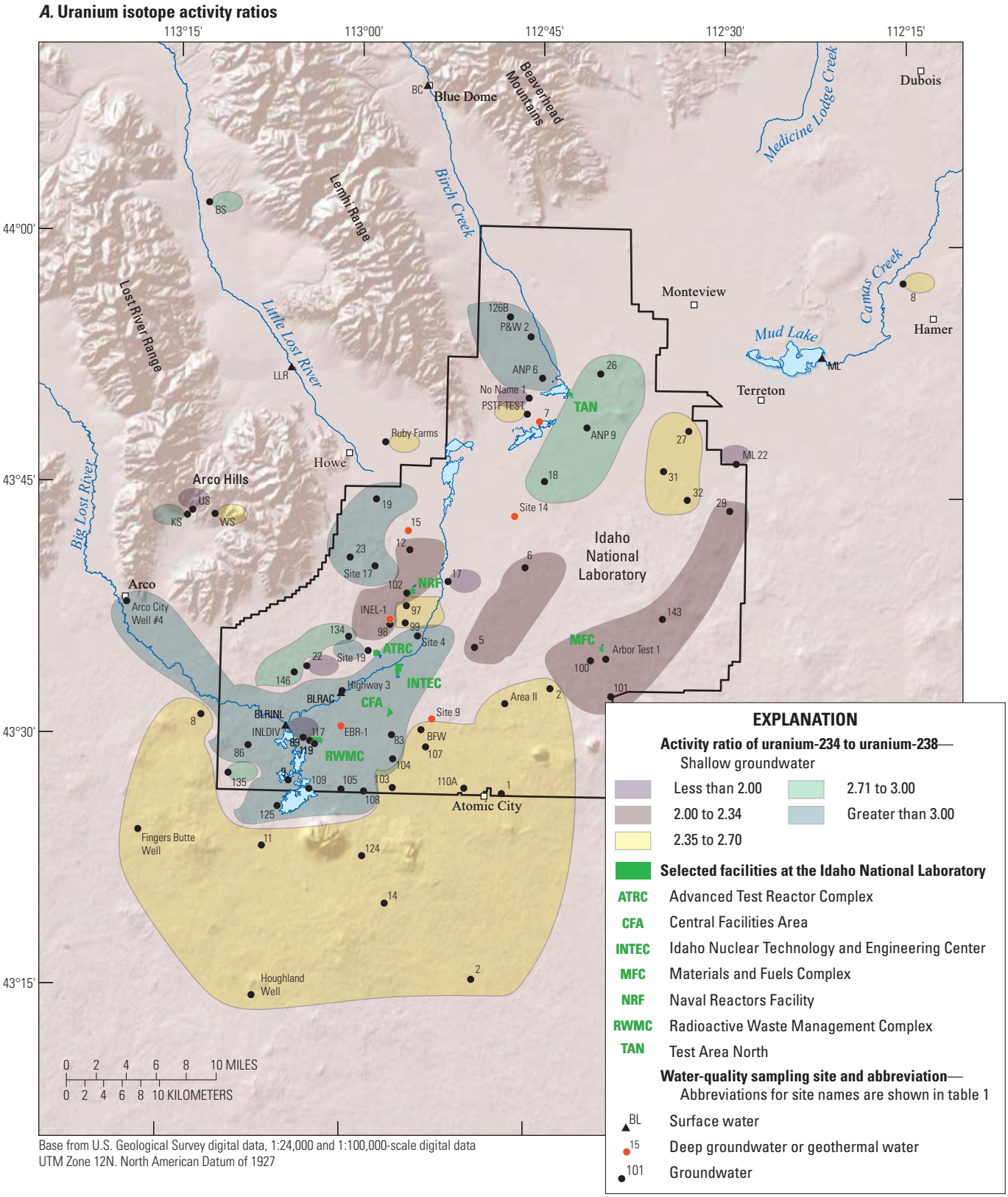


Figure 5. Spatial distribution and groupings of (*A*) uranium isotope activity ratios and (*B*) strontium isotope ratios, Idaho National Laboratory and vicinity, eastern Idaho. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

***B.* Strontium isotope ratios**

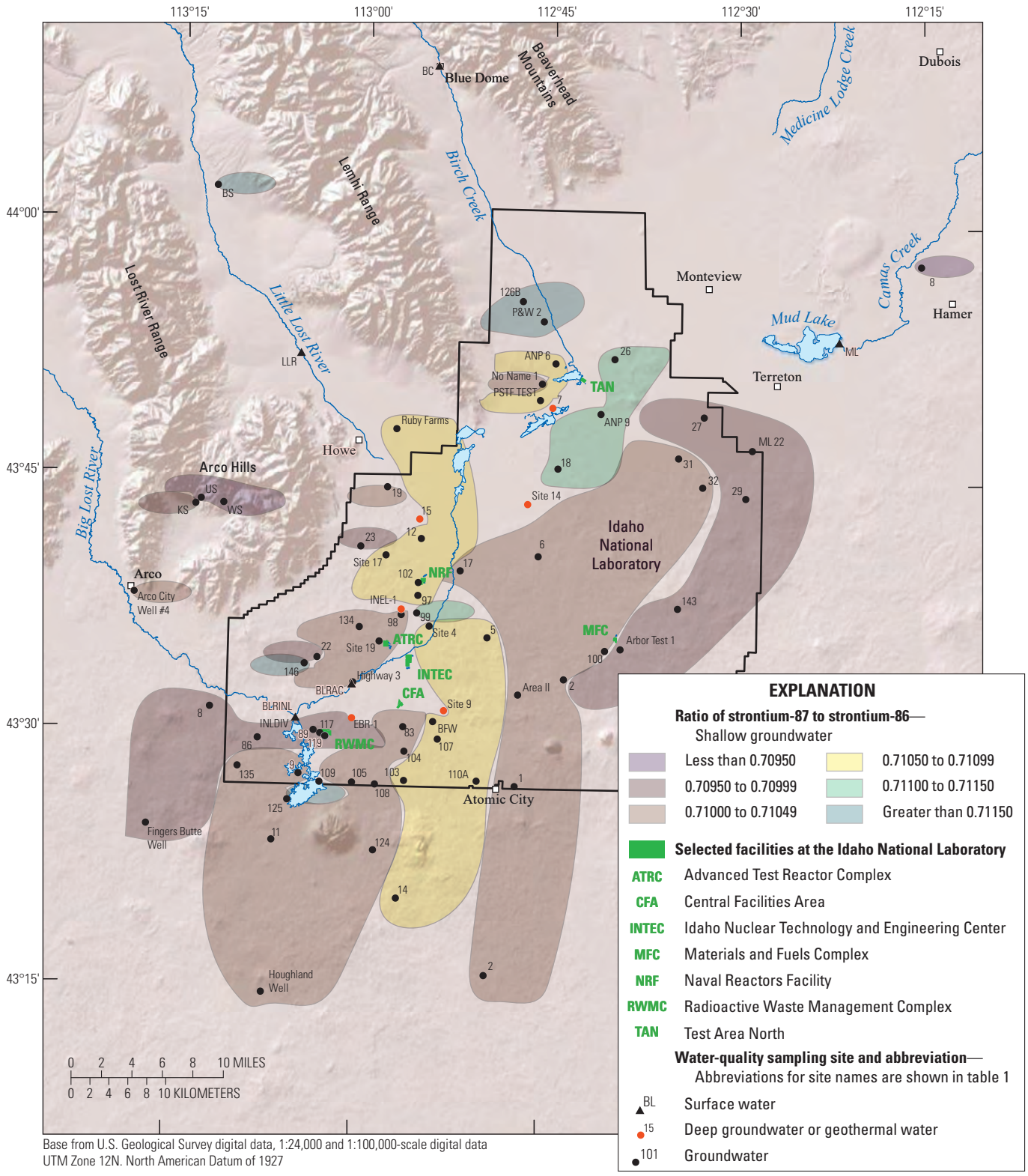


Figure 5.—Continued

Methods of sample collection and laboratory analysis for water samples collected during 1979 and 1996–99 were described by L.J. Mann (U.S. Geological Survey, written commun., 1989), and in Johnson and others (2000), Roback and others (2001), and McLing and others (2002). Water samples collected during 1991 and 2018–19 by the USGS were collected by pumping water through 0.45-µm filters into 250-mL acid-rinsed polyethylene bottles following the 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 sample collection (L.J. Mann, written commun., 1989; Bartholomay and others, 2014). Water samples collected during 1991 and 2018–19 were analyzed for U and Sr concentrations and isotope ratios with thermal ionization mass spectrometry (TIMS) at the USGS Denver Radiogenic Isotope Laboratory in Denver, Colo. The U results ($^{234}U/^{238}U$) are reported hereinafter as activity ratios (AR), which are calculated using the decay constants for ^{234}U and ^{238}U and the isotopic composition determined by TIMS. The laboratory analytical methods, references, and calculations are described in Paces and Wurster (2014).

Few field quality-assurance (QA) samples (replicates and blanks) were collected with environmental samples, so there is limited QA information associated with U and Sr concentrations and isotope ratios. Field QA information was not reported for Sr samples collected during 1996–99 (Johnson and others, 2000), and field QA samples were not collected during 2018–19. Roback and others (2001) collected one field replicate and an unknown number of blank samples; they reported that the maximum field blank correction for U concentration was less than 0.3 percent.

Although only one replicate sample was collected, water samples were collected during different years from 18 sites (table 3). These data provide information for evaluating the stability of U and Sr concentrations and isotope ratios over time. The replicate sample and stability of U and Sr concentrations and isotope ratios over time were evaluated using relative percent difference (RPD) and (or) normalized absolute difference (NAD) (table 3), respectively. Acceptable criteria for the replicate sample is an RPD less than or equal to 20 percent (Bartholomay and others, 2015) and an NAD less than 1.96 (Rattray, 2012, 2014). An NAD of less than 1.96 indicates that, at the 95-percent confidence level, the environmental and replicate measurements did not differ significantly. These same criteria were used to evaluate the stability of U and Sr concentrations and isotope ratios over time.

The replicate sample was analyzed for U concentration and $^{234}U/^{238}U$ (table 2). The RPD for U concentration was 0.00, and the NAD for $^{234}U/^{238}U$ was 1.03. Both results indicate that sample variability due to collection of water samples and analysis of U and $^{234}U/^{238}U$ was within acceptable limits.

The stability of U and Sr chemistry in surface water and groundwater over time was evaluated with data from 18 sites, with each site sampled a second time one or more years after the first sample collection event. Thirteen sites had both samples collected during 1996–99 and five sites had samples collected during 1996–99 and 2018–19 (table 2). Four of the sites were streams, 2 were deep groundwater, and 12 were shallow groundwater.

The BLR has a large range of RPD (2.70–33.40; table 3) and NAD (8.48–54.00), and the LLR has a large NAD for $^{87}Sr/^{86}Sr$ (145.69). This wide range of RPD and NAD shows that U and Sr concentrations and (or) isotope ratios are quite variable in these streams. In contrast, an NAD of 0.00 for $^{87}Sr/^{86}Sr$ in BC indicates that the Sr isotope ratio in this stream may be nearly constant. However, additional Sr data from BC source water would be necessary to confirm whether this source water shows Sr isotope ratio variability over time.

The large variability in U and Sr chemistry in the BLR and LLR is due to variable relative amounts of the sources of water, precipitation runoff, and groundwater,[3] to these streams (Rattray, 2018) and the lower U and Sr concentrations and isotope ratios in precipitation relative to groundwater. The chemical composition of water from USGS 22 is consistent with a large percentage of water that has been impacted by evapotranspiration and therefore likely represents precipitation recharge in the western part of the INL (Busenberg and others, 2001). Consequently, annual precipitation amounts in the BLRV and LLRV affect the U and Sr concentrations and (or) isotope ratios in these two streams.

The NAD for U isotope ratios were small in deep groundwater, as was the RPD for the concentration of U at Site 14, indicating that the U concentrations and isotopic compositions in deep groundwater may be nearly constant. However, the RPD for the concentration of U at USGS 7 showed large variability. Approximately 69 percent of geothermal water, containing anoxic conditions where U is insoluble (Rattray, 2018), provides recharge to USGS 7 (Rattray, 2019). Consequently, variable amounts of recharge from geothermal water may be responsible for the variability in U concentrations at USGS 7.

The RPD for shallow groundwater for U (12 replicates) and Sr (1 replicate) concentrations are all less than 13 percent except for an RPD of 26.30 for U concentrations in water from USGS 22 (table 3). These results show that changes in U and Sr concentrations over time were relatively minor. Even the large RPD for USGS 22 only represented a change in U concentration of 0.1 ppb, from 0.33 to 0.43 ppb (table 2), which is just 3.6 percent of the range of U concentrations measured from groundwater at the INL (0.33–3.10 ppb; table 2).

[3]Precipitation is represented with water from USGS 22 (Busenberg and others, 2001; Rattray, 2018, 2019) and groundwater from the BLR and LLR valleys is represented with water from the Arco City Well #4, Big Springs near Clyde, and the Ruby Farms well (table 2, fig. 1).

Table 3. Relative percent difference and normalized absolute difference for uranium and strontium concentrations and isotopic ratios analyzed from multiple samples collected from the same site, Idaho National Laboratory and vicinity, eastern Idaho.

[Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).**Site name:** LVS, large volume sample. Uranium expressed as activity ratios. **Normalized absolute difference:** $^{234}U/^{238}U$ and ^{87}Sr and ^{86}Sr, isotope ratios of uranium and strontium, respectively. **Abbreviations and symbol:** mm-dd-yyyy, month, day, year; yyyy-yy, year range; –, analytical data not available]

Site name	Sample dates (mm-dd-yyyy; yyyy-yy)	Years between sample dates	Relative percent difference		Normalized absolute difference	
			Uranium	Strontium	$^{234}U/^{238}U$	$^{87}Sr/^{86}Sr$
Surface water						
Big Lost River near Atomic City	04-10-1997	2	2.70	–	54.00	–
Big Lost River below INL diversion	07-14-1999					
Big Lost River near Atomic City	04-10-1997	21	26.60	33.40	42.19	8.48
INL diversion at head, near Arco	05-30-2018					
Birch Creek	1996–99	About 20	–	–	–	0.00
Birch Creek at Blue Dome Inn	04-30-2018					
Little Lost River	1996–99	About 20	–	–	–	145.69
Little Lost River near Howe	05-01-2018					
Deep groundwater at the INL						
Site 14	08-20-1996	1	0.00	–	0.00	–
Site 14 LVS	09-11-1997					
USGS 7	04-21-1997	21	8.80	–	0.26	–
USGS 7	04-11-2018					
Shallow groundwater in the North INL Area						
USGS 18	07-19-1996	1	0.50	–	2.40	–
USGS 18 LVS	09-12-1997					
Shallow groundwater in the Northeast INL Area						
USGS 26	10-15-1996	2	0.83	–	3.33	–
USGS 26 LVS	09-03-1998					
USGS 27	10-15-1996	2	1.92	–	2.22	–
USGS 27 LVS	09-02-1998					
Shallow groundwater in the Southeast INL Area						
USGS 1	04-21-1997	1	1.20	–	2.11	–
USGS 1 LVS	08-31-1998					
USGS 1 LVS	08-31-1998	0	0.00	–	1.03	–
USGS 1 LVS replicate	08-31-1998					
USGS 101	10-10-1996	1	3.00	–	1.77	–
USGS 101 LVS	09-08-1997					
Shallow groundwater in the Northwest INL Area						
Site 17	07-25-1996	23	6.80	12.70	6.51	3.85
Site 17	04-11-2019					
USGS 19	10-15-1996	1	1.90	–	4.60	–
USGS 19 LVS	09-10-1997					
USGS 22	07-18-1996	2	26.30	–	2.70	–
USGS 22 LVS	08-31-1998					

Table 3. Relative percent difference and normalized absolute difference for uranium and strontium concentrations and isotopic ratios analyzed from multiple samples collected from the same site, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

[Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).**Site name:** LVS, large volume sample. Uranium expressed as activity ratios. **Normalized absolute difference:** $^{234}U/^{238}U$ and ^{87}Sr and ^{86}Sr, isotope ratios of uranium and strontium, respectively. **Abbreviations and symbol:** mm-dd-yyyy, month, day, year; yyyy-yy, year range; –, analytical data not available]

Site name	Sample dates (mm-dd-yyyy; yyyy-yy)	Years between sample dates	Relative percent difference		Normalized absolute difference	
			Uranium	Strontium	$^{234}U/^{238}U$	$^{87}Sr/^{86}Sr$
Shallow groundwater in the Central INL Area						
USGS 6	07-16-1996	1	0.00	–	2.83	–
USGS 6 LVS	09-12-1997					
USGS 17	10-16-1996	1	2.30	–	0.84	–
USGS 17 LVS	09-11-1997					
Shallow groundwater in the Southwest INL Area						
USGS 86	10-11-1996	1	4.00	–	1.44	–
USGS 86 LVS	09-08-1997					
USGS 103	07-15-1996	1	2.00	–	3.05	–
USGS 103 LVS	09-09-1997					

The NAD for shallow groundwater for U (12 replicates) and Sr (1 replicate) isotope ratios included three NAD that were less than 1.96, eight NAD ranging from 2.11 to 3.33, and two higher NAD of 4.60 and 6.51. The NAD of 6.51 was for $^{234}U/^{238}U$ from Site 17 and represented a change in $^{234}U/^{238}U$ of 0.076, from 3.005 to 3.081 (table 2), which is just 3.6 percent of the range of $^{234}U/^{238}U$ measured from groundwater at the INL (1.544–3.627; table 2). These results show that while U and Sr isotope ratios sampled during different years were statistically significantly different, the differences were relatively small. Thus, even though shallow groundwater samples were collected for this study over a 29-year time period, the relatively stable U and Sr isotope ratios of these groundwater samples means that the results of this study are not biased by the time elapsed between discrete sample collection campaigns.

Geochemistry

The solubility of U depends on redox conditions; but, in oxidized water, U "readily forms uranyl ions (UO_2^{2+}) that complex with other ligands (that is, uranyl carbonate)" (Paces and Wurster, 2014, p. 216). Natural U consists of three, long-lived radioactive isotopes—^{238}U, ^{235}U, and ^{234}U with half-lives on the order of 10^9, 10^8, and 10^5 years, respectively (anthropogenic and non-natural U isotopes have been discharged to the subsurface at the INL, but they were not detected in any environmental water samples [Roback and others, 2001]). Uranium-234 is a daughter product in the ^{238}U decay chain and, in rocks older than about 1.5 million years, ^{234}U reaches a state of secular equilibrium "such that the ratio of $^{234}U/^{238}U$ activities is equal to 1.0" (Paces and Wurster, 2014, p. 216, and references within). However, the $^{234}U/^{238}U$ activity ratio in water is usually larger than 1.0 due to physical processes associated with α-decay recoil that cause ^{234}U (or the parent isotope ^{234}Th) to preferentially etch, leach, or dissolve from the rock relative to ^{238}U (Osmond and Cowart, 2000; Rattray, 2018). These physical processes cause the $^{234}U/^{238}U$ 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).

Sr is a divalent alkali-earth element, is highly soluble in most aqueous solutions, and is a relatively abundant trace metal with a strong chemical affinity to Ca^{2+} (Paces and Wurster, 2014). Natural Sr has three stable isotopes (^{84}Sr, ^{86}Sr, and ^{88}Sr) and a radiogenic isotope (^{87}Sr) derived from β-decay of rubidium-87 (^{87}Rb, half-life on the order of 10^{10} years) (Paces and Wurster, 2014). Non-natural ^{90}Sr has been discharged to the subsurface at the INL, but because this Sr isotope decays to zircon-90 and yttrium-90, it does not affect $^{87}Sr/^{86}Sr$ (Rattray, 2018). Because Sr and Rb may substitute for Ca and K, respectively, in minerals, the $^{87}Sr/^{86}Sr$ in water reflect the isotopic compositions of soluble minerals in geologic strata in which the water resides or has resided.

Three-Component Mixing

Two-component mixing ratios were used by Roback and others (2001) and Rattray (2018) to identify sources of water at wells throughout the INL. However, the numerous sources of water to the ESRP aquifer at the INL present complexities for using two-component mixing with U and Sr isotope ratios to identify source waters. These complexities were resolved with two methods.

The first method was to use a three-component mixing model (Paces and Wurster, 2014) instead of a two-component model. The additional source water end member available with the three-component mixing model was necessary because geochemical modeling indicated that groundwater at many sites had more than two sources of water (Rattray, 2019, table 11). However, three-component mixing was sufficient for modeling the sources of water to most groundwater sites because, based on geochemical modeling, three or fewer sources of water accounted for 94 percent[4] or more of the sources of water at 97 percent of the deep and shallow groundwater sites at the INL.

The second method was to group shallow groundwater sites at the INL (table 2) into seven geographic areas referred to hereinafter as the North, Northeast, Southeast, Central, Northwest, South, and Southwest INL Areas (fig. 6). Sites in these INL Areas were largely the same as presented in Rattray (2019, fig. 7), although some differences reflect the additional information available from $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ analyses from water samples collected during 2018–19. Additional chemical data were used to identify probable sources of recharge when the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ of groundwater from sites did not constrain the groundwater to three or fewer sources of recharge. For example, groundwater with lithium concentrations less than 5 µg/L indicates that the groundwater contains recharge that is entirely from tributary valley water (surface water and groundwater) (Rattray, 2018, fig. 20). Consequently, lithium concentrations greater than 5 µg/L indicates that the groundwater probably contains some recharge from regional groundwater. In addition, tritium activities may be used to identify young or old groundwater (Rattray, 2018, fig. 13), with young groundwater containing recharge from streams, Mud Lake, and surface-water irrigation return flows.

These two methods, taken together, attempt to resolve complexities with determining source water end members for the three-component mixing models. By grouping the groundwater sites into geographical areas, the end members were determined by the local geochemistry and hydrologic constraints. Although the intention is for the three-component mixing models to use one set of source water end members for each geographical site, for some sites the geochemistry, amount of recharge for some source waters, and mixing of surface and groundwaters requires additional end members. The complicated recharge and mixing conditions for some areas at the INL can be addressed by allowing for multiple ternary diagrams to describe the scope of source-water contributions in each INL Area, as applicable.

The three-component mixing used in this report was described by Paces and Wurster (2014) and is based on a two-component mixing theory presented in Faure (1986) and Faure and Mensing (2005). This theory states that for a system with two end members, X and Y, elemental concentrations in the two-component mixture depend on the element concentrations, C_X and C_Y, and the fraction of mixing, f (from 0 to 1):

$$C_M = f(C_X - C_Y) + C_Y \text{ (Faure, 1986).} \quad (1)$$

Similarly, the isotopic composition of the mixture, R_M, depends on the elemental and isotope ratios of the end members, R_X and R_Y:

$$R_M = (R_X C_X f/C_M) + (R_Y C_Y (1-f)/C_M) \text{ (Faure, 1986).} \quad (2)$$

Values of R_M define a family of hyperbolic curves with the degree of curvature dependent on the difference in element concentrations. Mixing fractions are distributed unevenly along the curve and are compressed towards the end member with the largest concentration. Using two sets of the above equations, binary mixtures of U and Sr from sources with different isotope ratios will plot along a curve in $^{234}U/^{238}U$–$^{87}Sr/^{86}Sr$ space (Paces and Wurster, 2014; Rattray, 2018).

In this report, three-component mixing of U and Sr isotope ratios is treated as a series of separate two-component mixtures using concentrations and isotope ratios from three distinct source water end members, X, Y, and Z (Paces and Wurster, 2014). Three-component mixtures plot within a polygonal space defined by the three two-component mixing curves, X–Y, X–Z, and Y–Z (hypothetical two-component mixing curves for end members are represented by dark lines in fig. 7) (Paces and Wurster, 2014). Mixing webs were constructed to quantify the proportions of each source water end member "by calculating individual two-component mixing curves between intermediate end members consisting of values for C_M and R_M determined at 0.1 intervals of f for mixtures along all three two-end member curves" (hypothetical two-component mixing curves for intermediate end members are represented by the light lines in figure 7 and create a mixing web) (Paces and Wurster, 2014, p. 220).

[4]Because "Groundwater containing recharge from wastewater" is just recycled groundwater, it was not included as a source of water in this report. Consequently, the percentages of "Sources of Recharge" in Rattray (2019, table 11) were recalculated and normalized to 100 percent without including recharge from wastewater.

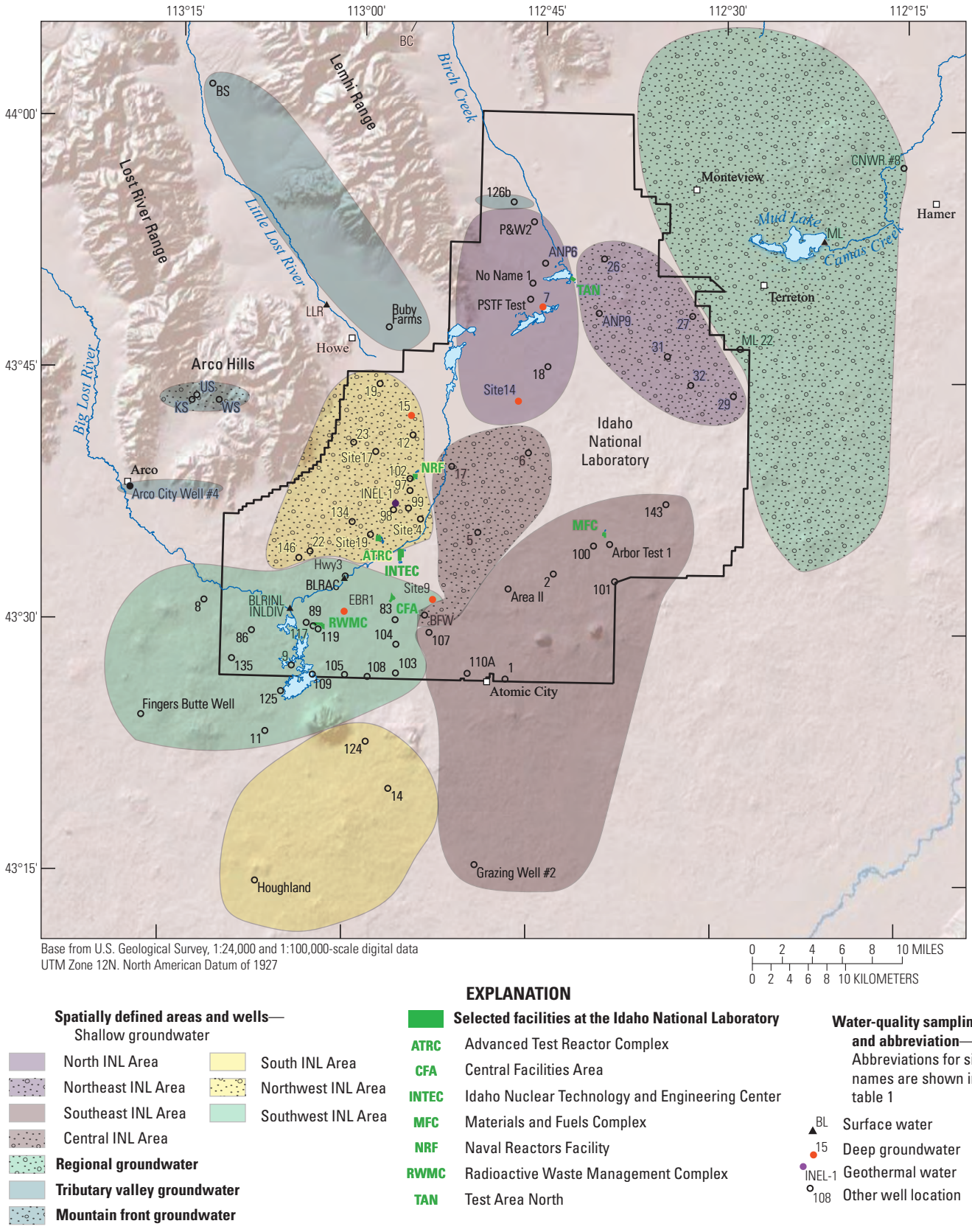


Figure 6. Locations of water-quality sample collection sites, Idaho National Laboratory (INL) and vicinity, eastern Idaho. More information is available from the National Water Information System (NWIS) at https://doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

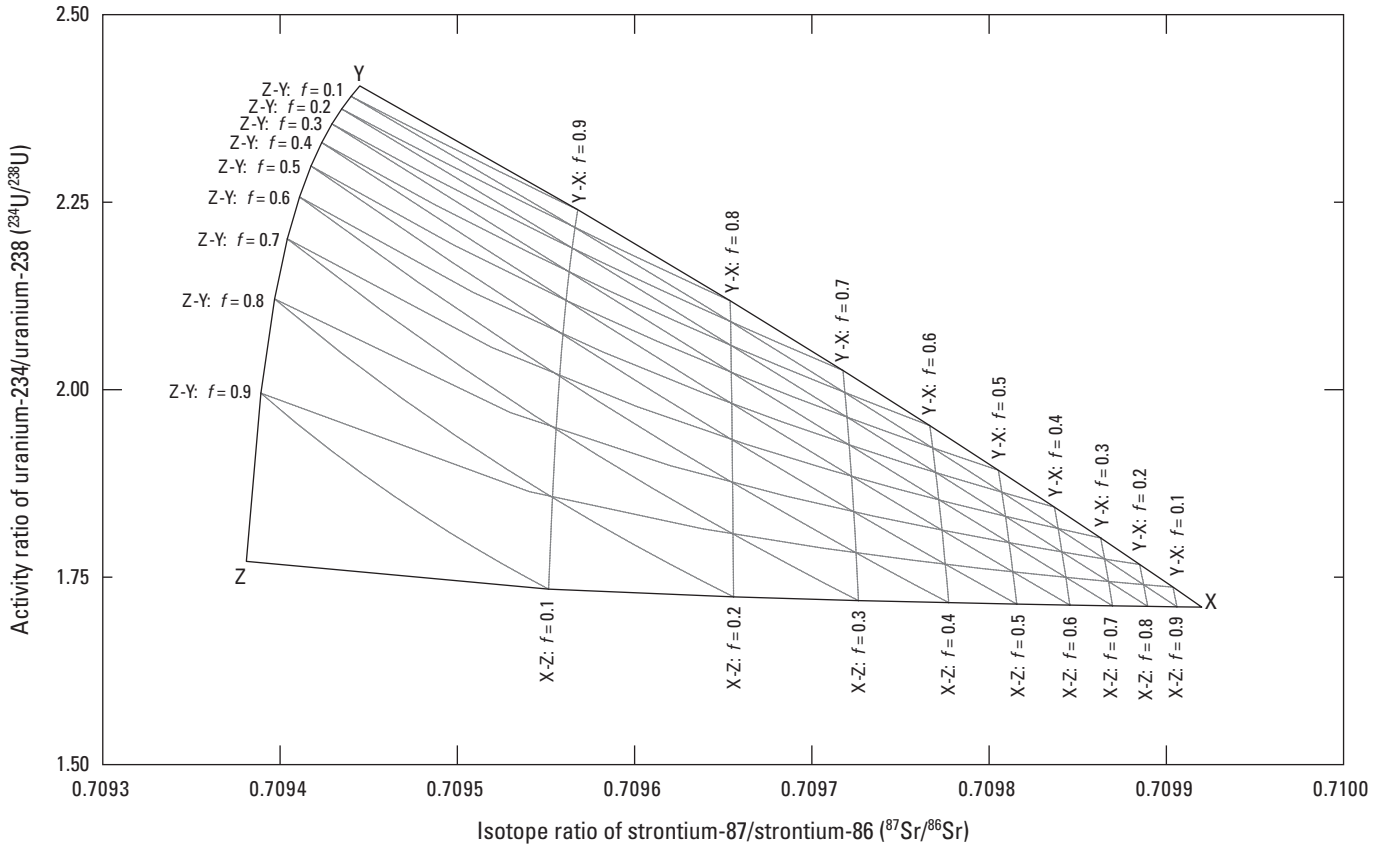


Figure 7. Three-component (X, Y, and Z) mixing web with two-component mixing curves at 0.1 mixing fraction intervals. Graphical representation created using descriptions from Paces and Wurster (2014).

Interpretation of Isotope Ratios

Groundwater at the INL contains $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ that reflect a combined isotope ratio of the sources of recharge that mixed to form the groundwater. Because these sources of recharge have distinctive U and Sr isotope ratios, these isotope ratios may be used to identify different sources of recharge, and to estimate the relative amounts of each source of recharge, to groundwater at the INL. The distinct isotope ratios for different sources of recharge provide confidence in accurately identifying individual sources of recharge. However, to assess the accuracy of the estimated relative amounts of individual sources of recharge in a groundwater sample the uncertainties associated with these estimates must be evaluated.

Characterization of Sources of Recharge

Known or suspected sources of recharge to groundwater at the INL include precipitation, streams (BLR, LLR, and BC), groundwater from tributary valleys (BLRV, LLRV, and BCV), groundwater from the Lost River Range, regional groundwater, geothermal water, and wastewater (Ackerman and others, 2006; Rattray, 2018, 2019). However, because wastewater is actually recycled groundwater, the U and Sr isotope ratios of wastewater merely reflect the isotope ratios of the original groundwater. Consequently, for the purposes of this study, wastewater was disregarded as a source of recharge.

The distinct U and Sr isotope ratios of sources of recharge are derived from the residence time of this water in the geologic strata hosting the sources of recharge and the dissolution rates, U and Sr concentrations, and isotope ratios of the rocks comprising the geologic strata. At the INL, geologic strata of recharge water are the carbonate rocks of the mountains and tributary valleys north and northwest of the INL and the ESRP basalt east of the INL (fig. 2). Groundwater may travel long distances through these geologic strata and have relatively long residence times. However, the mean residence time of sources of recharge to the INL in these terranes may be relatively short, and therefore young, due to abundant recharge from precipitation, streams, and lakes that occurs near the INL. The carbonate rocks contain minerals that dissolve rapidly while the ESRP basalt contains silicate minerals that dissolve slowly. Carbonate rocks have typical U and Sr concentrations of about 1.9 and 610 parts per million (ppm), respectively, which are about 2 to 3 times higher than concentrations of these elements in the basalt rock units (Faure, 1986; Rattray, 2018, p. 39–40). Although the geologic host unit U isotope ratio does not change relative

to groundwater residence time, the groundwater hosted in carbonate rocks or ESRP basalt have U isotope ratios that vary depending on groundwater residence times. Strontium isotope ratios in carbonate rocks, which typically range from about 0.7068 to 0.7092, are slightly higher than Sr isotope ratios of about 0.7056–0.7080 measured from ESRP basalt (Rattray, 2018, p. 39).

Uranium concentrations in potential sources of recharge range from 0.19 parts per billion (ppb) in geothermal water from INEL-1 to 7.21 ppb in spring water from the Lost River Range, and Sr concentrations range from 74 ppb in groundwater from the Little Lost River valley to 333 ppb in regional groundwater southwest of Mud Lake (fig. 1 and table 1; potential sources of recharge in table 2 are surface water, tributary valley groundwater, Arco Hills Springs in the Lost River Range, regional groundwater, and geothermal water). Uranium activity ratios in potential sources of recharge range from 1.714 to 3.622 in spring water from the Lost River Range and Sr isotope ratios range from 0.708156 in spring water from the Lost River Range to 0.71256 in the Little Lost River (table 2; figs. 5 and 8).

Precipitation is a minor source of recharge that may occur anywhere at the INL. Because there are no U or Sr isotope ratios measured from precipitation at the INL, an assumption was made for this source. Using other geochemical lines of evidence, the isotope ratios of groundwater from USGS 22 in the Northwest INL Area, which appear to consist entirely of precipitation (Busenberg and others, 2001, p. 90; Rattray, 2019, table 11), were used to characterize this source. These authors based this conclusion on a combination of isotopic and chemical signatures including carbon, oxygen, and deuterium isotopes, as well as nitrate and chloride concentrations (Rattray, 2018, 2019). Groundwater from USGS 22 is distinctive from other sources of recharge because it has the lowest $^{234}U/^{238}U$, 1.544, in the study area (table 2). This comparatively low activity ratio is consistent with the lower value that is expected for recent recharge from precipitation relative to older groundwater. The $^{87}Sr/^{86}Sr$, 0.70951, is relatively low but not unique when compared to other sources of recharge in the study area (fig. 8).

Streams are an important source of recharge at the INL. However, because the BLR is an ephemeral stream and the LLR and BC terminate or are largely diverted north of the INL, large amounts of direct recharge from streams is limited to periodic recharge from the BLR in the central and southwestern parts of the INL (Rattray, 2019, fig. 15). Although the U and Sr isotope ratios from two water samples collected from BLR are not unique, the low $^{234}U/^{238}U$ and intermediate $^{87}Sr/^{86}Sr$ are distinctive from the isotope ratios of other sources of recharge in the central or southwestern part of the INL (fig. 8). Because groundwater from USGS 17 (located in the Central INL Area; fig. 6) consists entirely of recharge from the BLR, and plots in figure 8 in a similar location as water from the BLR, the isotope ratios measured from USGS 17 represent a third isotope ratio signature of water from the BLR. Groundwater from No Name 1, located in the North INL Area (fig. 6), consists almost entirely of recharge from surface water. Earlier studies indicated that water at this well was a mixture of water from the BLR and BC (Rattray, 2018, 2019). However, the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ of this water plot near, and along a trend line for, the three representative water samples of the BLR and far from the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ of water from BC (fig. 8). Consequently, water from No Name 1 is entirely from the BLR and provides a fourth water sample with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ of water from the BLR. The trend line in figure 8 of these four representative BLR end-member water samples probably reflects increasing ratios of spring season runoff to groundwater in the BLR as isotope ratios decrease.

Recharge of groundwater from tributary valleys occurs across the northern and southwestern INL boundaries and groundwater from the BLRV, LLRV, and BCV is a significant source of water to the southwestern corner, western part, and northern and central parts of the INL, respectively (Rattray, 2019, fig. 17). Groundwater from the BLRV (Arco City Well #4) has distinctive $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ because it has a lower $^{87}Sr/^{86}Sr$ than the BLR and there are no other sources of recharge to the southwestern corner of the INL with similar ratios (fig. 8). Groundwater from the LLRV (Ruby Farms and Big Springs) is distinctive from other sources of recharge in the western part of the INL because it has $^{234}U/^{238}U$ that are higher than the ratio for the BLR and lower than ratios for groundwater from the BCV (USGS 126b) and Lost River Range. The $^{87}Sr/^{86}Sr$ in groundwater from the LLRV, however, varies widely (fig. 8), perhaps because these sites have different source waters. They may have different source waters because the Ruby Farms well[5] is located near the mouth of the LLRV whereas Big Springs is located about 20 mi up the valley (fig. 1). Groundwater from the BCV is distinctive from other sources of recharge because groundwater from this valley has relatively higher $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ than other tributary valleys (fig. 8).

[5]The water sample for Ruby Farms was collected in 1991 and archived until 2019 when it was analyzed for U and Sr concentrations. The U concentration measured for this water sample (0.21 ppb; table 2) is much lower than the U concentrations of other water collected from the LLR valley (0.93 for Big Springs and 1.06 ppb for the LLR; table 2) and may be due to organic material creating reducing conditions in the archived water sample. Consequently, the U concentration for Ruby Farms was adjusted to 1.0 ppb in three-component mixing models.

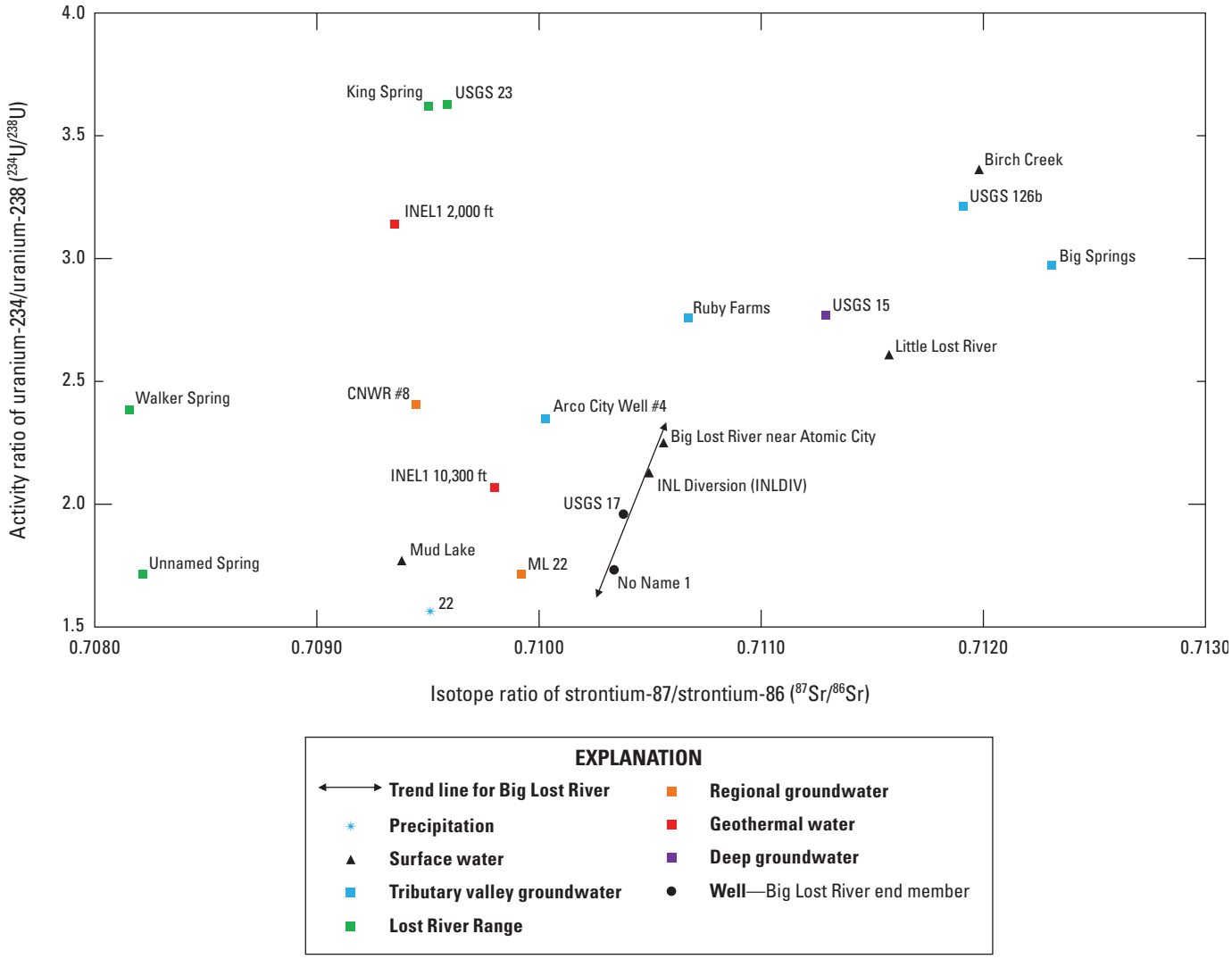


Figure 8. Uranium activity ($^{234}U/^{238}U$) and strontium ($^{87}Sr/^{86}Sr$) isotope ratios in sources of recharge to groundwater at the Idaho National Laboratory (INL) and vicinity, eastern Idaho. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

Recharge of groundwater from the mountain front of the Lost River Range occurs across the western INL boundary and is a source of water to the western part of the INL. $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ were analyzed from three spring water samples from the Arco Hills area of the Lost River Range (fig. 1). Unnamed Spring had a small flow and appeared to consist of shallow groundwater. Both Walker and King Springs had a large, steady flow of water with the outflow from Walker Spring about 500 ft higher in elevation than the outflow from King Spring. $^{234}U/^{238}U$ varied widely between these three springs and indicate that these springs tap different sources of water. Previous studies have indicated that the source of water to USGS 23, near the Lost River Range in the western part of the INL (fig. 1), was groundwater from the Lost River Range (Busenberg and others, 2001, p. 90; Rattray, 2019, fig. 15). The close similarity between $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ from USGS 23 and King Spring (fig. 8) shows that the deeper groundwater flowing from King Spring is representative of some groundwater providing recharge from the Lost River Range to the ESRP aquifer in the western part of the INL. King Spring is a distinctive source of recharge because it has high $^{234}U/^{238}U$ and low $^{87}Sr/^{86}Sr$ (fig. 8). However, when King Spring is used as an end member for three-component mixing, the large U concentration of King Spring (table 2) creates distortion in the ternary mixing web. Consequently, the isotope ratios from USGS 23, which has a lower U concentration than King Spring, will be used in ternary mixing webs to represent recharge of groundwater from the Lost River Range.

Regional groundwater is the largest source of recharge to the ESRP aquifer at the INL (Rattray, 2018, table 1), provides recharge across the eastern INL boundary, and is the dominant source of water in the eastern part of the INL (Rattray, 2019, fig. 15). Types of regional groundwater potentially providing recharge to the INL include groundwater in the ESRP aquifer (1) largely uninfluenced by infiltration of surface water (lakes, streams, or irrigation return flows), (2) strongly influenced by infiltration of surface water, and (3) that represents infiltration recharge from Mud Lake. These types of regional groundwater are represented with isotope ratios in water from CNWR #8, ML 22, and Mud Lake (fig. 8), respectively. The $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ of regional groundwater are low, although the $^{234}U/^{238}U$ of ML 22 and Mud Lake are much lower than the $^{234}U/^{238}U$ of CNWR #8. The $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ of regional groundwater are distinctive because they are much lower than the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in groundwater from the BCV, the other principal source of recharge to the eastern part of the INL.

Geothermal water is a minor source of recharge that occurs across the base of the ESRP aquifer (Ackerman and others, 2006). Geothermal water is present in groundwater from some deep boreholes, such as INEL-1 (Mann, 1986) and USGS 7 (Rattray, 2019, table 11), but upward flowing geothermal water does not appear to reach shallow groundwater at the INL. However, a small amount of upward flowing geothermal water does reach shallow groundwater in the Mud Lake area east of the INL (Rattray, 2015), and this shallow groundwater flows onto the INL across the eastern INL boundary. Consequently, geothermal water is present in small amounts in some regional groundwater flowing onto the INL (Rattray, 2019, p. 40). Although $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ data are available for geothermal water (INEL 1, fig. 8), geothermal water will not be included in three-component mixing models because it does not appear to be a source of recharge to shallow groundwater at the INL.

Uncertainty

Uncertainty in the estimated relative amounts of individual sources of recharge in a groundwater sample includes (1) whether or not all sources of recharge are accounted for, (2) whether the available isotope ratios accurately and completely represent a particular source of recharge, (3) whether the number of these sources are three or less (that is, can three-component mixing account for all sources of recharge), (4) whether it is possible to uniquely identify three or fewer sources of recharge to a groundwater site, (5) the error in estimating the percentage of a source of recharge from a ternary mixing web with grids at intervals of 10 percent, and (6) measurement error.

Gaps in U and Sr isotope ratios were found by Rattray (2018), wherein not all sources of recharge to groundwater at INL were represented. During 2018–19, additional samples that addressed these gaps were collected and analyzed. Consequently, all known and suspected sources of recharge to groundwater at the INL are now represented with U and Sr isotope ratios.

Although $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ are available for all known or suspected sources of recharge, some of these sources of recharge have variable $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$. For example, there are four water samples from the BLR with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$, and the $^{234}U/^{238}U$ in these samples range from 1.733 to 2.251 (fig. 8; table 2). This large range of $^{234}U/^{238}U$ in the BLR creates uncertainty as to which pair of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in the BLR should be used in three-component mixing models. A similar large range of $^{234}U/^{238}U$ is present in regional groundwater (CNWR #8 and ML 22) and a large range of $^{87}Sr/^{86}Sr$ is present in groundwater from the LLRV (Ruby Farms and Big Springs).

Resolving the uncertainties derived from nonuniform $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ for a source of recharge may be straightforward in some instances. For example, the four different pairs of U and Sr isotope ratios in the BLR probably reflect differing amounts of spring season runoff contributing to total discharge, with greater discharge traveling greater distances along the BLR channel. The four water samples from the BLR were collected at different locations along the river channel, so the water sample with the closest proximity to the most likely location of recharge from the BLR can be selected for different areas at the INL. Proximity to sources of recharge also may be used to choose the most likely source of recharge in three-component mixing models that have more than three potential sources of recharge. The large range of $^{234}U/^{238}U$ in regional groundwater represents differences in this isotope ratio in regional groundwater with and without recharge from surface water. These are two distinct types of regional groundwater and both may be included in a single three-component mixing model. In situations like the LLRV, where the difference in $^{87}Sr/^{86}Sr$ (or $^{234}U/^{238}U$ in other situations) in groundwater is large, the isotope ratios in groundwater at the INL may provide an indication of which isotope ratio in the source of recharge best represents that source.

The sources of recharge to groundwater sites at the INL were estimated by Rattray (2019, table 11; Rattray, 2023, table 11) with geochemical modeling. Groundwater from 57 sites with $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ were modeled, 12 (21 percent) of which were estimated to have more than three sources of recharge. Five of these sites are from the western part of the INL and seven are from the eastern part. Of the five sites in the western part of the INL, three sources of recharge were estimated to account for 99 percent of the recharge to three sites, 93 percent at USGS 103, and 90 percent at USGS 135. Of the seven sites in the eastern part of the INL, four have geothermal water as a source of recharge. However, this geothermal water flowed onto the INL as part of regional groundwater (Rattray, 2019) and, therefore, is not actually a separate source of recharge. For the three other sites, three sources of recharge were estimated to account for 98 percent of the recharge to USGS 107, 95 percent at USGS 14, and 92 percent at the Houghland well. These results indicate that ternary mixing webs that account for three sources of recharge will adequately represent all sources of recharge to most groundwater sites at the INL.

Related to number of sources of recharge is whether it is possible to uniquely identify three or fewer sources of recharge to each groundwater site to include in the ternary mixing web. Because there is a wide distribution of $^{234}U/^{238}U$–$^{87}Sr/^{86}Sr$ for sources of recharge (fig. 8), this will not be a problem for most groundwater sites. Consequently, this problem will be addressed on a case-by-case basis in section, "Groundwater at the Idaho National Laboratory" when questions do arise about which sources of recharge should be included in the ternary mixing web.

The percentage of sources of recharge to groundwater sites at the INL will be estimated from ternary mixing webs. These webs have coarse grids, with grid intervals of 10 percent (fig. 7), so estimates from these grids will have some uncertainty. However, decreasing the grid size will allow estimation of uncertainty to about ±1 percent for the combined sources of recharge.

The absolute measurement uncertainty for $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ can be calculated from activity and isotopic ratios and uncertainties presented in table 2. Typical values for $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ are about 2.000±0.006 and 0.710000±0.000010 (table 2 and the data sources referenced therein), respectively. These lead to absolute measurement uncertainties, at the 95-percent confidence level of about 0.3 percent for $^{234}U/^{238}U$ and 0.001 percent for $^{87}Sr/^{86}Sr$.

For any groundwater at the INL that is from a single source of recharge, the absolute measurement uncertainty is the total measurement uncertainty. If there are two sources of recharge (where the problem reduces to a binary mixing line), the total measurement uncertainty for each source of recharge is a relative measurement uncertainty calculated using the difference between $^{234}U/^{238}U$ or $^{87}Sr/^{86}Sr$ from the two sources of recharge. Because either $^{234}U/^{238}U$ or $^{87}Sr/^{86}Sr$ may provide the largest relative separation, or uniqueness, in isotope ratios between different sources of recharge, the relative measurement uncertainty used for calculating uncertainty is the U or Sr isotope ratio pair that provides the smallest relative measurement error between the two sources of recharge. The relative measurement uncertainty for two sources of recharge is calculated as follows:

$$z = (x_{(U,Sr)} \pm u_x) - (y_{(U,Sr)} \pm u_y), \quad (3)$$

where

z is the difference between two isotope ratios, $x_{(U,Sr)}$ and $y_{(U,Sr)}$, for either $^{234}U/^{238}U$ or $^{87}Sr/^{86}Sr$; and

u_x and u_y are the absolute measurement uncertainties associated with isotope ratios $x_{(U,Sr)}$ and $y_{(U,Sr)}$.

The sum of the absolute measurement uncertainty is equal to u_x plus u_y, and the relative measurement error, δ^z, is

$$(\delta_z) = \frac{(u_x + u_y)}{|x_{(U,Sr)} - y_{(U,Sr)}|}. \quad (4)$$

If there are three sources of recharge, then the measurement uncertainty is the sum of the relative measurement uncertainties calculated for the three binary mixing lines that make up the ternary mixing web (Paces and Wurster, 2014).

Using the isotope ratios and uncertainties in table 2, relative measurement uncertainties can be calculated at the 95-percent confidence level. For example, the southeastern part of the INL potentially receives recharge entirely from regional groundwater (represented with water from Mud Lake and groundwater from CNWR Well #8 and ML 22). Using equation 2, the smallest relative measurement uncertainties were produced using $^{87}Sr/^{86}Sr$ for the Mud Lake–ML 22 binary mixing line and $^{234}U/^{238}U$ for the Mud Lake–CNWR Well #8 and CNWR Well #8–ML 22 binary mixing lines, and the respective relative measurement uncertainties were 3.7, 1.7, and 1.7 percent. The total relative measurement uncertainty for this ternary mixing web is 7.1 percent, the sum of these three relative measurement uncertainties.

Groundwater at the Idaho National Laboratory

The U and Sr isotope ratios for sources of recharge to, and groundwater at, the INL are plotted in figure 9. Due to the large number of sources of recharge, and the limitations to the number of sources of recharge that can make up end members in the three-component mixing models, it is necessary to construct three-component mixing models that represent smaller areas at the INL with fewer sources of recharge. Smaller areas were created by identifying areas at the INL with about three sources of recharge and grouping together the groundwater sites within these INL Areas (fig. 6). The groundwater sites within these INL Areas represent shallow groundwater (upper 250 ft of the aquifer) at the INL. There are five sites that represent deep groundwater (fig. 9) from wells that extend more than 250 feet below water table (ft bwt), and this deep groundwater may have different sources of recharge than nearby shallow groundwater. However, to provide some insight into the sources of recharge to deep groundwater at the INL, the U and Sr isotope ratios for deep groundwater will be evaluated along with the isotope ratios of nearby shallow groundwater.

North INL Area

There are five shallow and two deep groundwater sites in the North INL Area (fig. 6). Shallow groundwater from site No Name 1 consists entirely of recharge from the BLR (see discussion in section, "Characterization of Sources of Recharge"), and the lower $^{234}U/^{238}U$ in groundwater from site No Name 1 not only distinguishes this site from other sites from the North INL Area (fig. 10*A*), but also indicates that the BLR probably is not a significant source of recharge to the other sites.

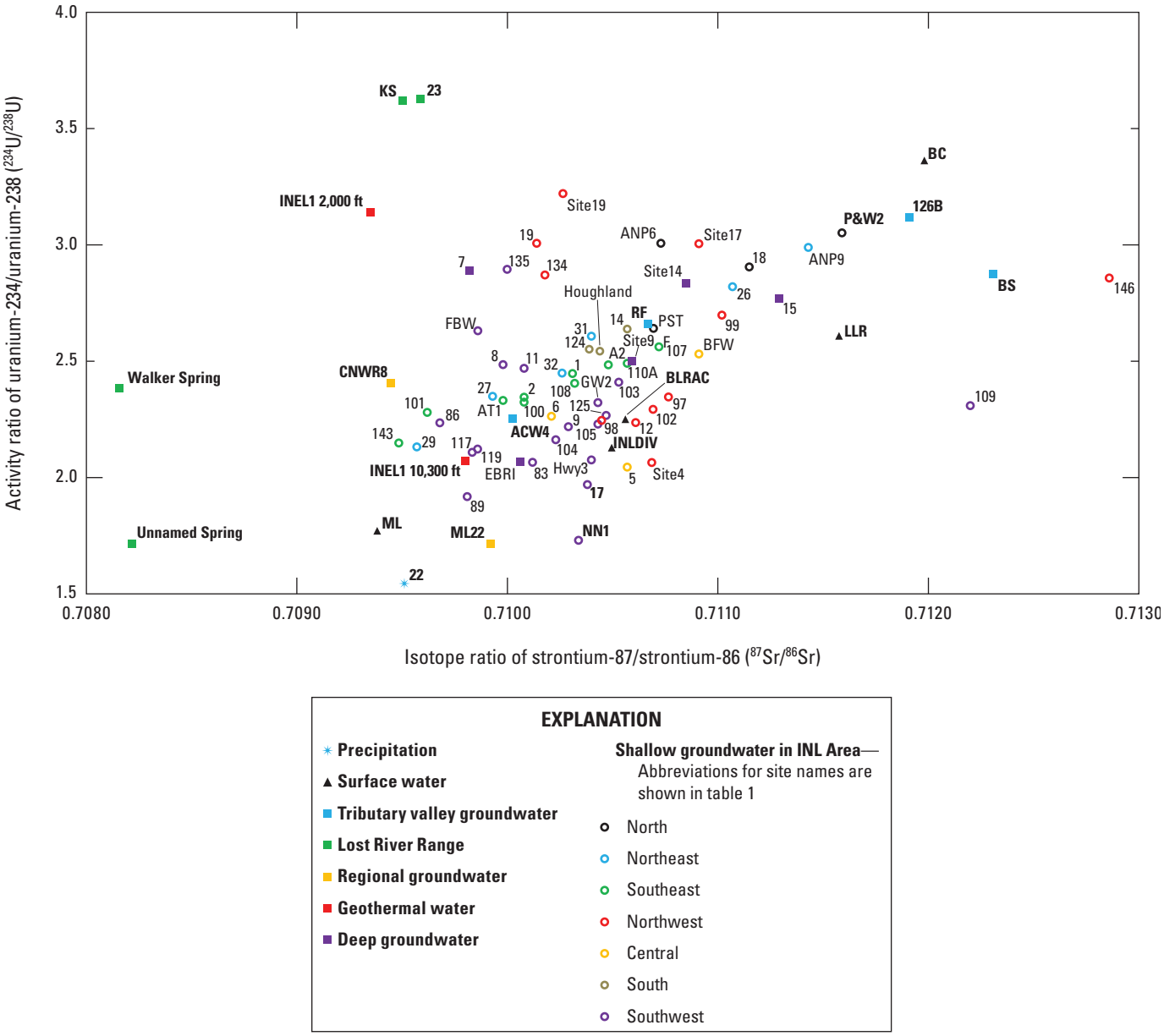


Figure 9. Uranium ($^{234}U/^{238}U$) activity ratios and strontium ($^{87}Sr/^{86}Sr$) isotope ratios in surface water and groundwater, Idaho National Laboratory (INL) and vicinity, eastern Idaho. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

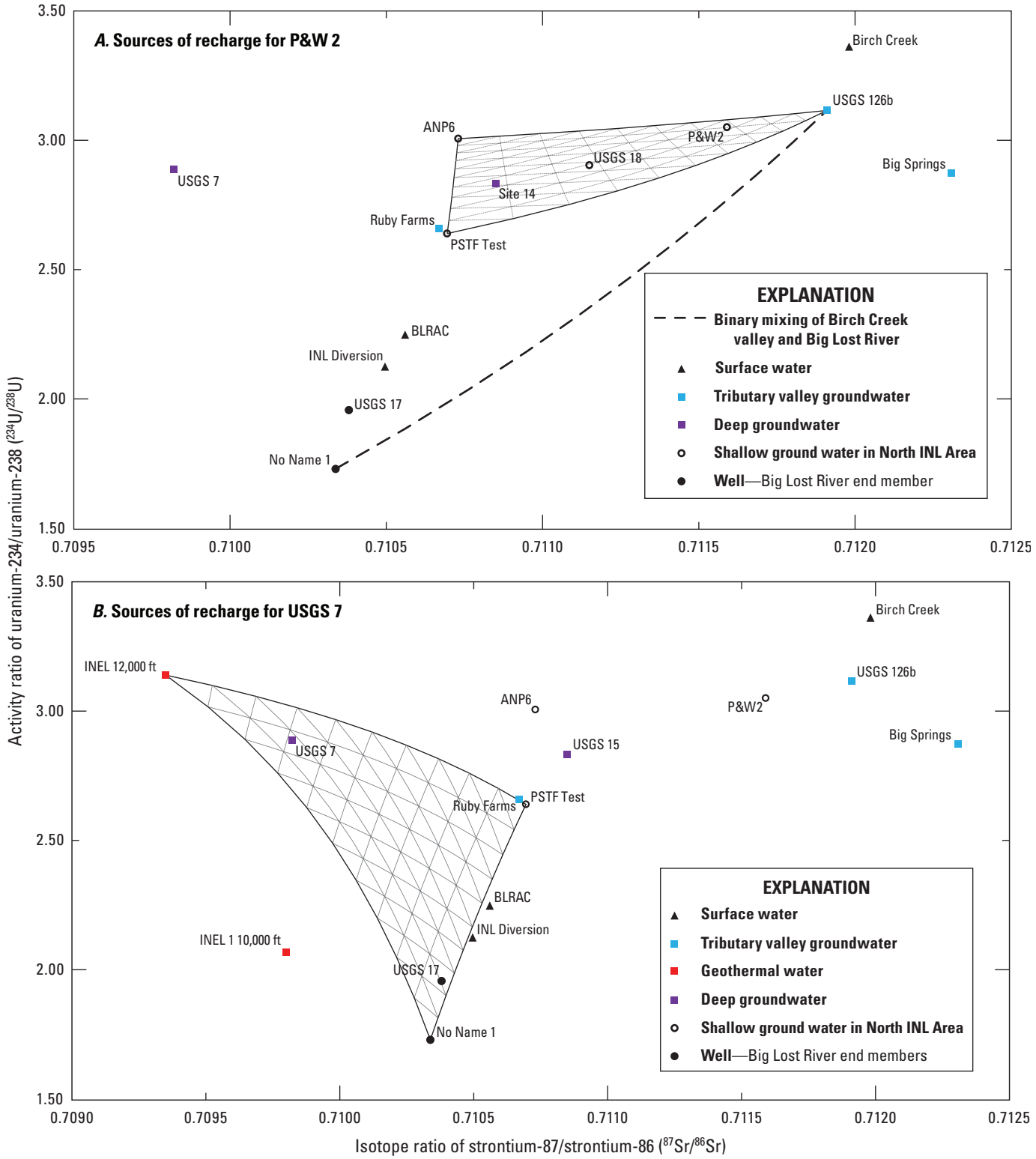


Figure 10. Ternary mixing webs for the North INL Area, Idaho National Laboratory (INL) and vicinity, eastern Idaho. *A.* Sources of recharge for P&W 2. *B.* Sources of recharge for USGS 7. *C.* Sources of recharge for Site 14 and USGS 18. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

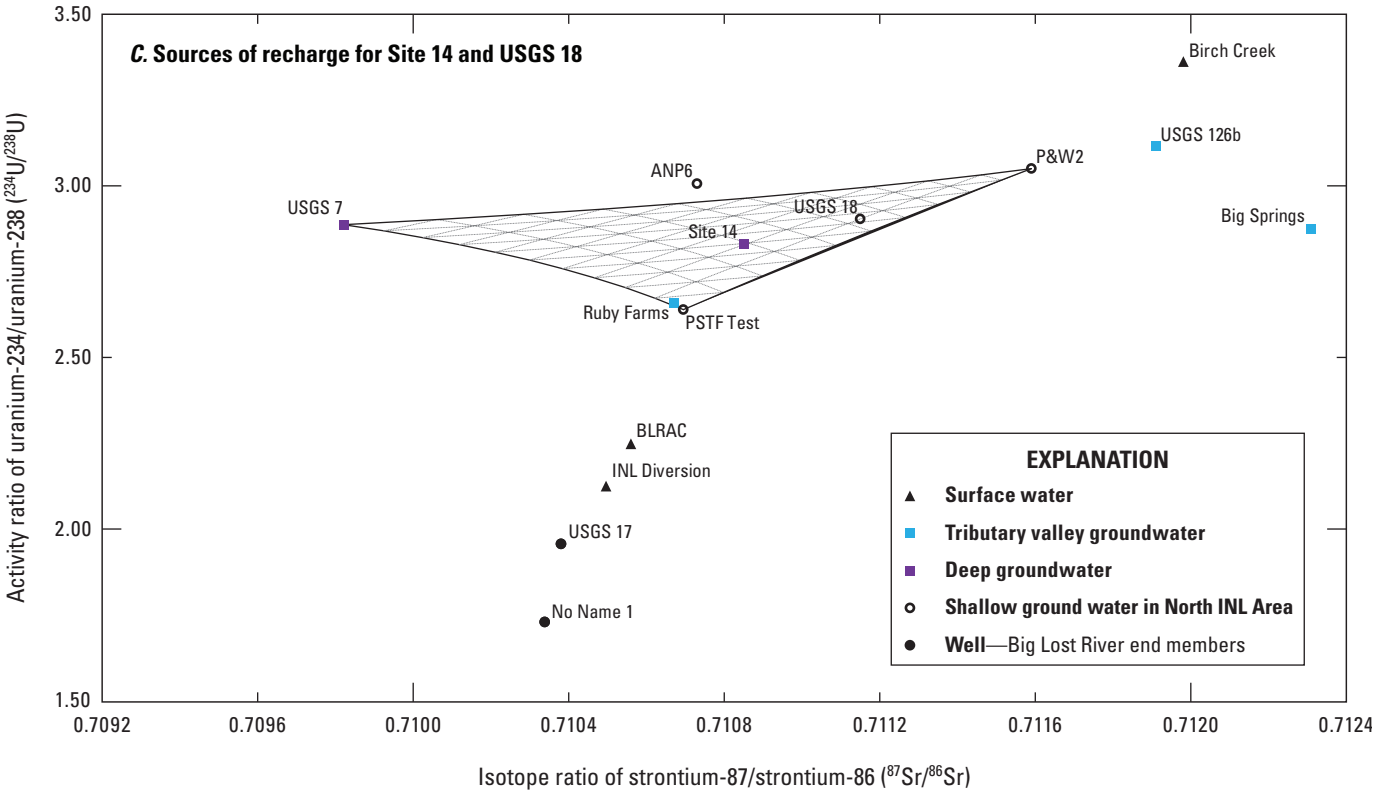


Figure 10.—Continued

Geochemical modeling indicated that sources of recharge to the other six groundwater sites in the North INL area (fig. 6) were predominantly groundwater from the BCV (which includes recharge from BC) or recharge from the BLR, plus a small amount of upwelling geothermal water at USGS 7 (Rattray, 2019, table 11). However, the interpretation that the BLR and groundwater from the BCV are significant sources of recharge to these sites appears to be incorrect because groundwater from these sites has much higher $^{234}U/^{238}U$ than the BLR (represented with No Name 1 for the North INL Area) and, except for P&W 2, much lower $^{87}Sr/^{86}Sr$ than were measured in water from BC or groundwater from the BCV (represented with USGS 126b). The $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ from these sites plot significantly above and to the left of a binary mixing line between the BLR and groundwater from the BCV (fig. 10*A*).

PSTF Test plots adjacent to Ruby Farms on $^{234}U/^{238}U$–$^{87}Sr/^{86}Sr$ mixing webs for the North INL Area (fig. 10*A*), and the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ for Ruby Farms do not plot near any known or suspected sources of recharge to the North INL Area (fig. 9). Ruby Farms is in the LLRV and is located on the opposite side of the southern extent of the Lemhi Range from PSTF Test (fig. 1). Based on their nearly identical $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ and proximity to the southern extent of the Lemhi Range, groundwater from this part of the Lemhi Range may be the source of recharge to Ruby Farms and PSTF Test. The relatively low tritium activity in groundwater from PSTF Test (2.5±0.1 pCi/L; Rattray, 2019, table 8) shows that this water consists of old groundwater (Rattray, 2018, fig. 13*A*) and probably has not received any recent recharge from BC, the BLR, or surface-water-influenced groundwater from the BCV. The most likely source of old groundwater at PSTF Test is groundwater from beneath the Lemhi Range, and the presence of old groundwater at PSTF Test supports this hypothesis.

ANP 6 is located about 2.6 mi north of PSTF Test (fig. 6). ANP 6 and PSTF Test have similar $^{87}Sr/^{86}Sr$ but ANP 6 has a higher $^{234}U/^{238}U$ than PSTF Test (fig. 10*A*). ANP 6, like PSTF Test, has a low tritium activity (3.2±0.1 pCi/L; Rattray, 2019, table 8) that shows that ANP 6 consists of old groundwater (Rattray, 2018, fig. 13*A*). The old groundwater at ANP 6 indicates that the source of recharge to this well is most likely groundwater from the Lemhi Range, and their different $^{234}U/^{238}U$ probably means that recharge to these two wells consists of groundwater from different locations in the Lemhi Range.

Three ternary mixing webs were created for the North INL Area. The first mixing web has groundwater from the BCV (represented with USGS 126b) and the Lemhi Range (represented with PSTF Test and ANP 6) as end members (fig. 10*A*). Any recharge from BC was assumed to be represented as part of the groundwater from the BCV (Rattray, 2019, table 11). Three sites plot within this mixing web—Site 14, P&W 2, and USGS 18. However, Site 14 and USGS 18 appear to contain some geothermal water (Rattray, 2018, fig. 14) and their sources of recharge will be represented with a different mixing web. Groundwater from the BCV and the Lemhi Range, respectively, comprise 67 and 33 percent of the recharge to P&W 2 (table 4; fig. 10*A*).

Table 4. Sources of recharge (where the source of recharge represents the origin of the water) to groundwater sites, percentage of total recharge for each source, and measurement and estimation uncertainties associated with the ternary mixing webs, Idaho National Laboratory (INL) and vicinity, eastern Idaho.

[Results from geochemical modeling are presented in Rattray (2019, table 11). **Sources of recharge:** BCV, groundwater from the Birch Creek valley; BLR, Big Lost River; BLRV, groundwater form the Big Lost River valley; DGW, deep groundwater; GTW, geothermal water; LLR, Little Lost River; LLRV, groundwater from the Little Lost River valley; LR, groundwater from the Lemhi Range; LRR, groundwater from the Lost River Range; Pre, precipitation; RGW, regional groundwater. **Abbreviations and symbols:** na, not applicable; 2s, 2 standard deviations; +, plus; ±, plus or minus; ?, uncertain or unknown]

Site name	Sources of recharge	Percentage of recharge	Measurement (2s) + estimate uncertainty from mixing web (± percent)
Deep groundwater at the INL			
EBR-1	BLR, Pre, LRR	62, 26, 12	5.1
Site 9	BLR, LR, LRR, LLRV, LLR	53, 23, 15, 8, 1	4.9
Site 14	LR, DGW, BCV	60, 21, 19	6.2
USGS 7	GTW, LR, BLR	69, 17, 14	4.2
USGS 15	LR, LLRV, LLR	71, 25, 4	6.5
Shallow groundwater in the North INL Area			
ANP 6	LR	100	na
No Name 1	BLR	100	na
P&W 2	BCV, LR	67, 33	7.3
PSTF TEST	LR	100	na
USGS 18	LR, BCV, DGW	54, 36, 10	6.2
Shallow groundwater in the Northeast INL Area			
ANP 9	BCV, LR, RGW	62, 30, 8	4.9
USGS 26	BCV, LR, RGW	51, 25, 24	4.9
USGS 27	RGW, BCV, LR	84, 11, 5	4.9
USGS 29	RGW	100	8.1
USGS 31	RGW, BCV, LR	61, 26, 13	4.9
USGS 32	RGW, BCV, LR	67, 22, 11	4.9
Shallow groundwater in the Southeast INL Area			
Arbor Test 1	RGW, BCV, LR	82, 12, 6	4.9
Area II	RGW, BCV, LR	54, 31, 15	4.9
Grazing Well #2	RGW, BCV, LR	63, 25, 12	4.9
USGS 1	RGW, BCV, LR	64, 24, 12	4.9
USGS 2	RGW, BCV, LR	77, 15, 8	4.9
USGS 100	RGW, BCV, LR	77, 15, 8	4.9
USGS 101	RGW, BCV, LR	97, 2, 1	4.9
USGS 107	RGW, BCV, LR	42, 38, 20	4.9
USGS 110A	RGW, BCV, LR	47, 36, 17	4.9
USGS 143	RGW	100	8.1
Shallow groundwater in the Northwest INL Area			
Site 4	BLR, LR, LLRV, LLR, LRR	71, 20, 7, 1, 1	3.6

Table 4. Sources of recharge (where the source of recharge represents the origin of the water) to groundwater sites, percentage of total recharge for each source, and measurement and estimation uncertainties associated with the ternary mixing webs, Idaho National Laboratory (INL) and vicinity, eastern Idaho.—Continued

[Results from geochemical modeling are presented in Rattray (2019, table 11). **Sources of recharge:** BCV, groundwater from the Birch Creek valley; BLR, Big Lost River; BLRV, groundwater form the Big Lost River valley; DGW, deep groundwater; GTW, geothermal water; LLR, Little Lost River; LLRV, groundwater from the Little Lost River valley; LR, groundwater from the Lemhi Range; LRR, groundwater from the Lost River Range; Pre, precipitation; RGW, regional groundwater. **Abbreviations and symbols:** na, not applicable; 2s, 2 standard deviations; +, plus; ±, plus or minus; ?, uncertain or unknown]

Site name	Sources of recharge	Percentage of recharge	Measurement (2s) + estimate uncertainty from mixing web (± percent)
Shallow groundwater in the Northwest INL Area—Continued			
Site 17	LR, LRR, LLRV, LLR	53, 25, 19, 3	3.9
Site 19	LRR, LR, BLR, LLRV, LLR	58, 24, 9, 8, 1	3.6
USGS 12	BLR, LR, LRR, LLRV, LLR	64, 20, 8, 7, 1	3.6
USGS 19	LRR, LR, LLRV, LLR	56, 31, 11, 2	3.7
USGS 22	Pre	100	na
USGS 23	LRR	100	na
USGS 97	BLR, LR, LLRV, LRR, LLR	51, 30, 10, 7, 2	3.6
USGS 98	BLR, LRR, LR, LLRV, LLR	68, 14, 13, 4, 1	3.6
USGS 99	LR, BLR, LLRV, LRR, LLR	52, 18, 18, 9, 3	3.6
USGS 102	BLR, LR, LLRV, LRR, LLR	57, 25, 9, 8, 1	3.6
USGS 134 zone15	LRR, BLR, LR, LLRV, LLR	46, 37, 12, 4, 1	3.6
USGS 146	?	?	na
Shallow groundwater in the Central INL Area			
Badging Facility Well	LR, BLR, LLRV, LLR	50, 36, 12, 2	9.3
USGS 5	BLR, LR, LLRV, LLR	69, 26, 4, 1	6.7
USGS 6	BLR, DGW, LR	58, 37, 5	5.2
USGS 17	BLR	100	na
Shallow groundwater in the South INL Area			
Houghland	?	?	na
USGS 14	?	?	na
USGS 124	?	?	na
Shallow groundwater in the Southwest INL Area			
Fingers Butte Well	BLRV, LRR, Pre	55, 26, 19	5.6
Highway 3	BLR, LRR, LR, LRRV	92, 4, 3, 1	4.9
USGS 8	BLRV, LRR, BLR	76, 18, 6	7.2
USGS 9	BLR, LRR, LR, LLRV	85, 13, 1, 1	4.9
USGS 11	BLR, LRR, LLRV	66, 33, 1	3.8

Table 4. Sources of recharge (where the source of recharge represents the origin of the water) to groundwater sites, percentage of total recharge for each source, and measurement and estimation uncertainties associated with the ternary mixing webs, Idaho National Laboratory (INL) and vicinity, eastern Idaho.—Continued

[Results from geochemical modeling are presented in Rattray (2019, table 11). **Sources of recharge:** BCV, groundwater from the Birch Creek valley; BLR, Big Lost River; BLRV, groundwater form the Big Lost River valley; DGW, deep groundwater; GTW, geothermal water; LLR, Little Lost River; LLRV, groundwater from the Little Lost River valley; LR, groundwater from the Lemhi Range; LRR, groundwater from the Lost River Range; Pre, precipitation; RGW, regional groundwater. **Abbreviations and symbols:** na, not applicable; 2s, 2 standard deviations; +, plus; ±, plus or minus; ?, uncertain or unknown]

Site name	Sources of recharge	Percentage of recharge	Measurement (2s) + estimate uncertainty from mixing web (± percent)
Shallow groundwater in the Southwest INL Area—Continued			
USGS 83	Pre, BLR, LR, LLRV, LLR	71, 13, 11, 4, 1	5.3
USGS 86	Pre, BLR, LRR	75, 15, 10	5.1
USGS 89	Pre, BLR, LRR	66, 29, 5	5.1
USGS 103	BLR, LR, LRR, LLRV, LLR	63, 17, 13, 6, 1	4.9
USGS 104	Pre, LR, BLR, LLRV, LLR	67, 15, 12, 5, 1	5.3
USGS 105	BLR, LR, LRR, LLRV	79, 9, 9, 3	4.9
USGS 108	BLR, LRR, LR, LLRV, LLR	73, 13, 10, 3, 1	4.9
USGS 109	?	?	na
USGS 117	Pre, BLR, LRR	58, 32, 10	5.1
USGS 119	Pre, BLR, LRR	54, 35, 11	5.1
USGS 125	BLR, LRR, LR, LLRV	90, 7, 2, 1	4.6
USGS 135 zone 10	LRR, BLR, BLRV	46, 43, 11	7.2

The second mixing web for the North INL Area represents sources of recharge to the deep groundwater at USGS 7 (fig. 10*B*). USGS 7 has a much lower $^{87}Sr/^{86}Sr$ than other groundwater in the North INL Area (fig. 10*A*), probably because deep groundwater at USGS 7 has a geothermal influence (Rattray, 2018, fig. 14; Rattray, 2019, table 11). Figure 10*B* indicates that recharge to USGS 7 consists primarily of geothermally influenced groundwater (represented with INEL-1 2,000 ft; Mann, 1986) plus smaller amounts of groundwater from the Lemhi Range (represented with PSTF Test) and water from the BLR (represented with No Name 1) (table 4).

The third mixing web for the North INL Area (fig. 10*C*) represents sources of recharge to Site 14 and USGS 18, which are downgradient of USGS 7 (figs. 4 and 6). Groundwater at these wells have slightly higher water temperatures, lithium concentrations, and percentage of terrigenic helium than are measured in other groundwater (except for USGS 7) in the North INL Area (Rattray, 2018, fig. 28*A*, 28*R*, and 28*CC*), all of which indicate that groundwater at these wells contains some geothermal water (Mann, 1986, table 2; Rattray, 2018, fig. 14). End member sources of recharge for figure 10*C* are groundwater from P&W 2 (representing groundwater from the BCV) PSTF Test (representing groundwater from the Lemhi Range), and USGS 7 (geothermally influenced groundwater). These sources of recharge, respectively, represent 60, 21, and 19 percent of the groundwater at Site 14 and 54, 36, and 10 percent of the groundwater at USGS 18 (table 4). The BCV source water is represented by USGS 126b (100 percent) in figure 10*A*. Previous geochemical modeling determined that P&W 2 source water is comprised of 75 percent BC and 25 percent USGS 126b (Rattray, 2019, table 11). The Sr and U isotope ratios used for the ternary mixing calculations show that P&W 2 also has some input from the Lemhi Range (33 percent). The decision to use P&W 2 as the BCV end member allows that small component of Lemhi Range source water to be an additional water source to the wells in figure 10*C*.

In summary, the North INL Area $^{87}Sr/^{86}Sr$ and $^{234}U/^{238}U$ compositions can be described using multiple sources of groundwater, geothermal, and surface-water recharge, including from the BLR. Multiple end members, even for the same source waters, were necessary to explain the sources of water to both shallow and deep groundwater sites. Given that the aquifer system is transient, the ternary mixing webs, and thus water sources, may be variable over time given spring season water runoff, geothermal, and old groundwater influence.

Northeast INL Area

There are seven shallow groundwater sites in the Northeast INL Area (fig. 6). Geochemical modeling (Rattray, 2019, table 11) indicated that sources of recharge to these sites were regional groundwater (some of which contains some geothermal water; Rattray, 2019, table 11), groundwater from the BCV (which includes recharge from BC), and the BLR. However, the presence of the BLR as a source of recharge to the Northeast INL Area is questionable because (1) the BLR does not appear to be a source of recharge to groundwater at sites in the North INL Area, with the exception of site No Name 1, and (2) water from the BLR is unlikely to travel so far east from what now appears to be concentrated, but not widespread, recharge from the BLR in the North INL Area. Consequently, ternary mixing webs were created for the Northeast INL Area with (1) groundwater from the BCV and the Lemhi Range (represented with site P&W 2) and regional groundwater (represented with CNWR #8 and ML 22) as end members for five shallow groundwater sites and (2) regional groundwater (represented with CNWR8, ML 22, and ML) as end members for USGS 29 (fig. 11).

The sites closest to the mouth of the BCV (fig. 1) contain larger percentages of water from the BCV and the Lemhi Range (table 4; fig. 11), whereas the sites farthest south and east contain larger percentages of regional groundwater. Thus, recharge to ANP 9, near the mouth of the BCV, consists of 62, 30, and 8 percent groundwater from the BCV, the Lemhi Range, and regional groundwater, respectively, whereas recharge to USGS 29, the site farthest east, is comprised entirely of regional groundwater (table 4).

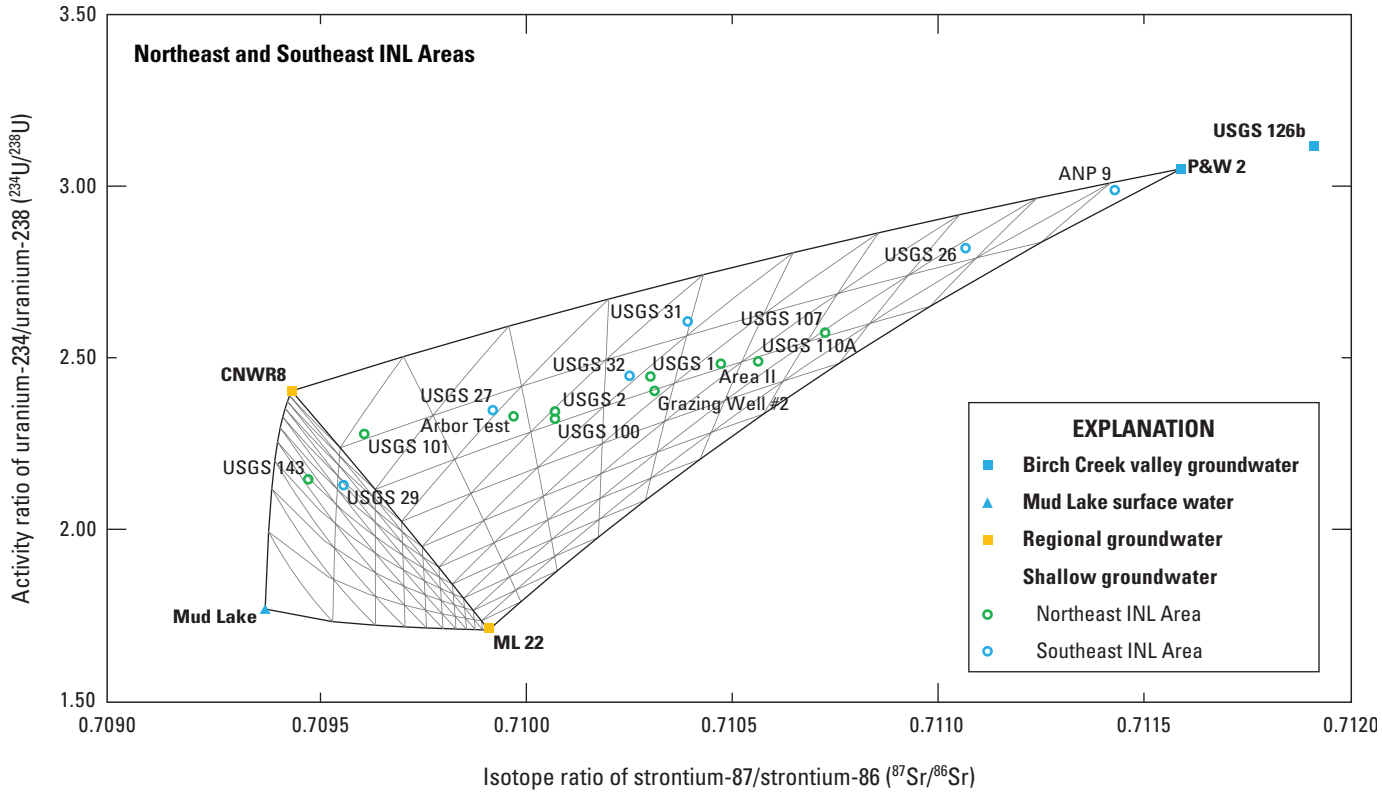


Figure 11. Ternary mixing webs for the Northeast INL Area (ANP 9, USGS 26, USGS 27, USGS 29, USGS 31, and USGS 32) and Southeast INL Area (Arbor Test, Area II, Grazing well #2, USGS 1, USGS 2, USGS 100, USGS 101, USGS 107, USGS 110A, and USGS 143), Idaho National Laboratory (INL) and vicinity, eastern Idaho. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

Southeast INL Area

There are 10 shallow groundwater sites in the Southeast INL Area (fig. 6). Geochemical modeling (Rattray, 2019, table 11) indicated that sources of recharge to these sites were regional groundwater, groundwater from the BCV (which includes recharge from BC), and the BLR. However, the presence of the BLR as a source of recharge to the Southeast INL Area is questionable for the same reasons as for the Northeast INL Area. The sites from the Southeast INL Area are plotted on the same ternary mixing webs that were used to represent sites from the Northeast INL Area (fig. 11) because they share the same sources of recharge.

The sites plot on the mixing webs with decreasing and increasing percentages of regional groundwater and groundwater from the Lemhi Range and BCV (fig. 11), respectively, with increasing distance west from the Mud Lake area (fig. 1). Thus, recharge to USGS 143, the site closest to the Mud Lake area, is comprised entirely of regional groundwater and recharge to USGS 107, the site farthest west from the Mud Lake area, consists of 42, 38, and 20 percent regional groundwater and groundwater from the BCV and Lemhi Range, respectively (table 4).

Northwest INL Area

There are 13 shallow and 1 deep groundwater sites in the Northwest INL Area (fig. 6). Shallow groundwater from USGS 22 and USGS 23 consist entirely of recharge from precipitation and the Lost River Range (see discussion in section, "Characterization of Sources of Recharge"), respectively. Geochemical modeling (Rattray, 2019, table 11) indicated that sources of recharge to the Northwest INL Area were primarily water from the BLR and groundwater from the LLRV, with precipitation and groundwater from the Lost River Range providing recharge to some sites in the western part of the Northwest INL Area.

Two sources of recharge in the Northwest INL Area are No Name 1 (representing water from the BLR) and USGS 23 (representing groundwater from the Lost River Range). Representing groundwater from the LLRV is problematic because three sources of water together represent the recharge from LLR, each of which has a distinct Sr isotope ratio. These three sources are the LLR, groundwater from Big Springs, and groundwater from Ruby Farms (that represents water from the Lost River Range). Deep groundwater from USGS 15 plots within a ternary mixing web of these three sources of recharge (fig. 12*A*), with recharge amounts of about 71 percent groundwater from the Lost River Range (represented with Ruby Farms), 25 percent groundwater from upgradient parts of the LLRV (represented with Big Springs), and 4 percent surface water from the LLR. It is possible that the surface water from the LLR could actually be an even smaller percentage of surface water from the BLR. USGS 15 is about 5 mi downgradient from the LLRV and may be a good representation of groundwater exiting the LLRV. Therefore, groundwater from USGS 15 will be used in ternary mixing webs as an end member source of recharge representing groundwater exiting the LLRV.

Ten of the remaining 11 shallow groundwater sites in the Northwest INL Area plot within a ternary mixing web with USGS 23 (representing groundwater from the Lost River Range), USGS 15, and No Name 1 (representing the BLR) as end members (fig. 12*B*). One site, USGS 146, plots outside of the mixing web and, for reasons that are not understood, has the highest $^{87}Sr/^{86}Sr$ in the study area. USGS 19 also is just downgradient of the LLRV (fig. 1) and, based on its location relative to the BLR (fig. 6), probably does not receive any recharge from the BLR. The most reasonable ternary mixing web for USGS 19 includes Walker Spring as source of recharge, which represents a second groundwater source of recharge from the Lost River Range (fig. 12*C*).

The ternary mixing web illustrated in figure 12*B* for five groundwater sites (Site 4, USGS 12, USGS 97, USGS 98, and USGS 102) in the western part of the Northwest INL Area (fig. 6), and south of the BLR sinks (fig. 1), shows the BLR is the primary source of recharge (table 4). These results show that the sinks and channel of the BLR in the eastern part of the Northwest INL Area are significant sources of recharge to the ESRP aquifer (Bennett, 1990).

Groundwater from the Lost River and Lemhi Ranges are the primary sources of recharge to Site 17, Site 19, USGS 19, USGS 99, and USGS 134 z15 (table 4). The large amount of recharge of groundwater from the Lemhi and Lost River Ranges may indicate that groundwater in the lower part of the LLRV is comprised primarily of groundwater from the southern extent of these mountain ranges. Down-valley flow of groundwater in the LLRV and recharge of water from the LLR apparently are lesser sources of recharge to the lower part of the LLRV.

Central INL Area

There are four shallow groundwater sites in the central INL area (fig. 6). These four sites were grouped together because these sites have a similar geographic location (fig. 6). However, the U and Sr isotope ratios and other chemistry data indicate that groundwater at these sites are not chemically homogeneous. For example, tritium activities indicate that groundwater at USGS 6 is old water, groundwater at the Badging Facility Well and USGS 5 are a mixture of young and old water, and USGS 17 is young water (Rattray, 2018, fig. 13).

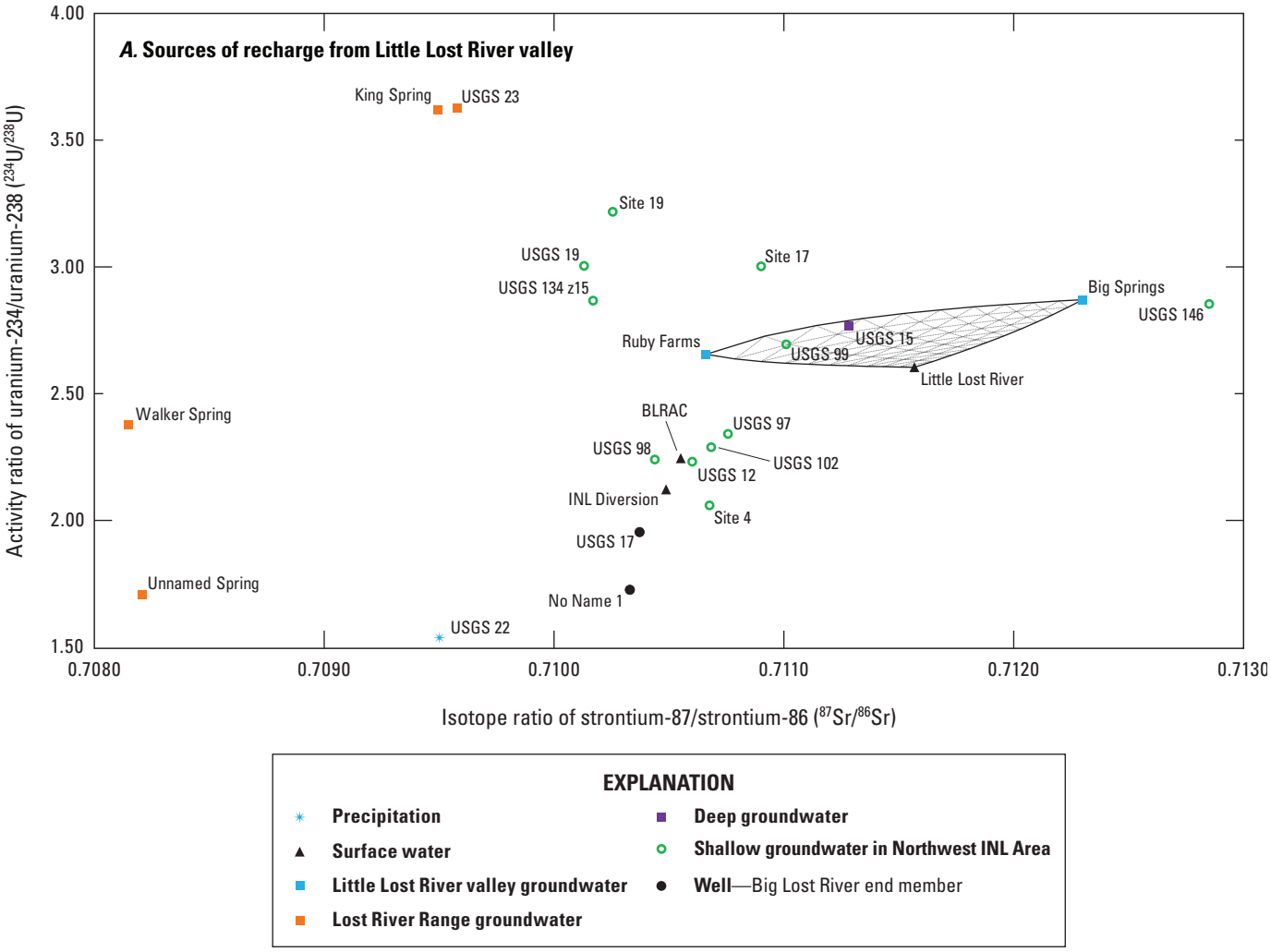
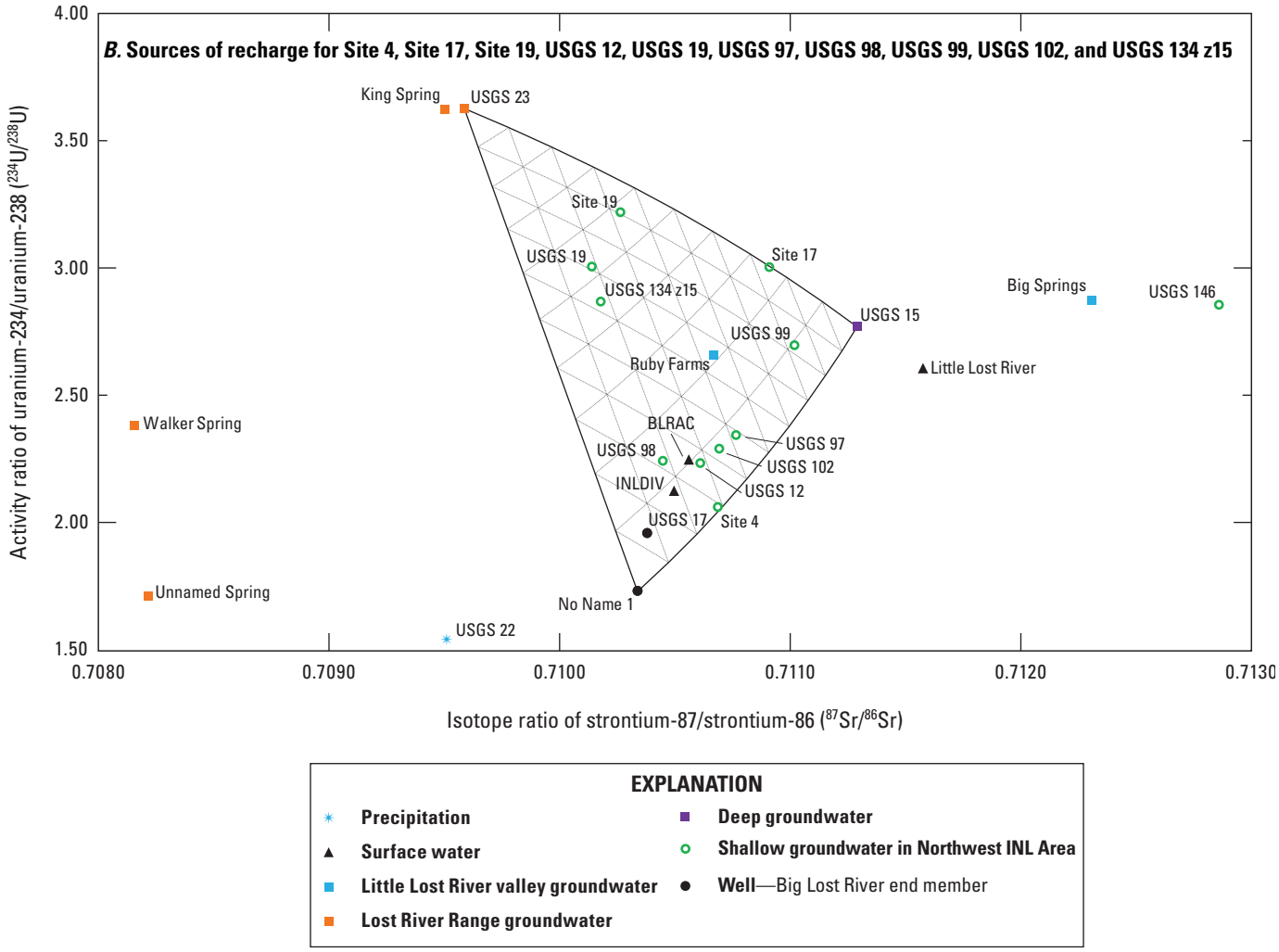


Figure 12. Ternary mixing webs for the Northwest INL Area, Idaho National Laboratory (INL) and vicinity, eastern Idaho. *A.* Sources of recharge from the Little Lost River valley. *B.* Sources of recharge for Site 4, Site 17, Site 19, USGS 12, USGS 19, USGS 97, USGS 98, USGS 99, USGS 102, USGS 134 z15. *C.* Sources of recharge for USGS 19. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).



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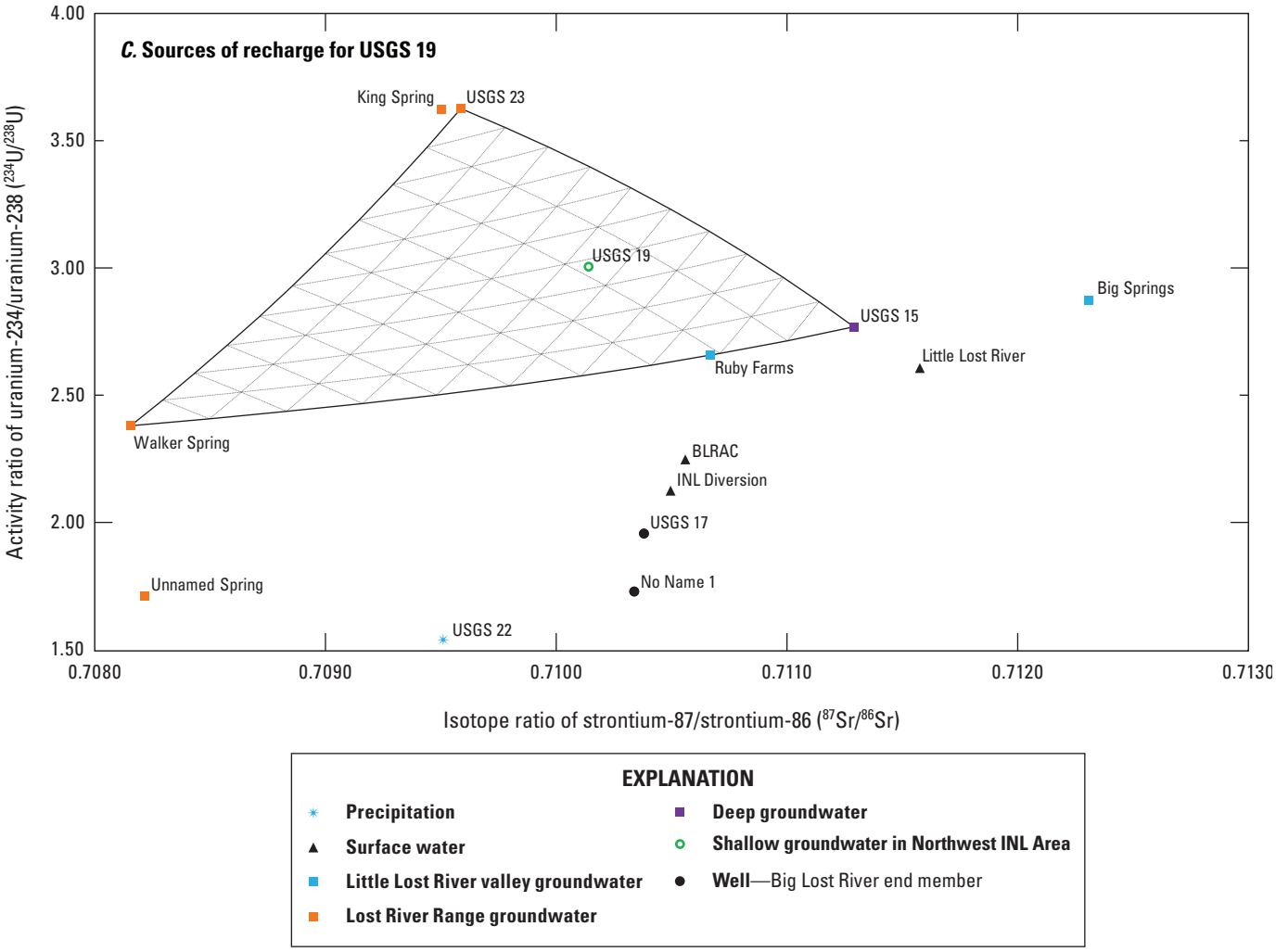


Figure 12.—Continued

Sources of recharge to the Central INL Area may include a mixture of the sources of recharge to the North, Northeast, and Norththwest INL Areas such as regional groundwater, the BLR, groundwater from the BCV and LLRV, and groundwater from the Lemhi and Lost River Ranges. In addition, the slightly elevated concentration of lithium and percentage of terrigenic helium in groundwater at USGS 6 (Rattray, 2018, figs. 14 and 20) indicates that this water probably contains a small amount of geothermal water. Groundwater at USGS 17 consists entirely of recharge from the Big Lost River and was discussed in section "Characterization of Sources of Recharge." Sources of recharge used as end members in ternary mixing webs for the other three groundwater sites in the Central INL Area were restricted (1) by the chemical data described earlier, (2) to being hydrologically upgradient of the groundwater sites (fig. 4), and (3) to generate $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ ternary mixing webs that include one or more of the groundwater sites.

Three separate ternary mixing webs were generated for the sites in the Central INL Area (fig. 13*A*–13*C*). End member sources of recharge for the mixing webs included deep groundwater (represented with USGS 7, which contains geothermal water), the BLR (represented with No Name 1 and the BLR near Atomic City), and groundwater from the Lemhi Range (represented with Ruby Farms and PSTF Test) and the LLRV (represented with USGS 15). The resulting percentages for sources of recharge at each site were (table 4):

- USGS 6: 58, 37, and 5 percent water from the BLR, deep groundwater, and groundwater from the Lemhi Range, respectively.
- Badging Facility Well: 50, 36, 12, and 12 percent groundwater from the Lemhi Range, and water from the BLR, LLRV, and LLR, respectively.
- USGS 5: 69, 26, 4, and 1 percent water from the BLR, groundwater from the Lemhi Range, and water from the LLRV, and LLR, respectively.

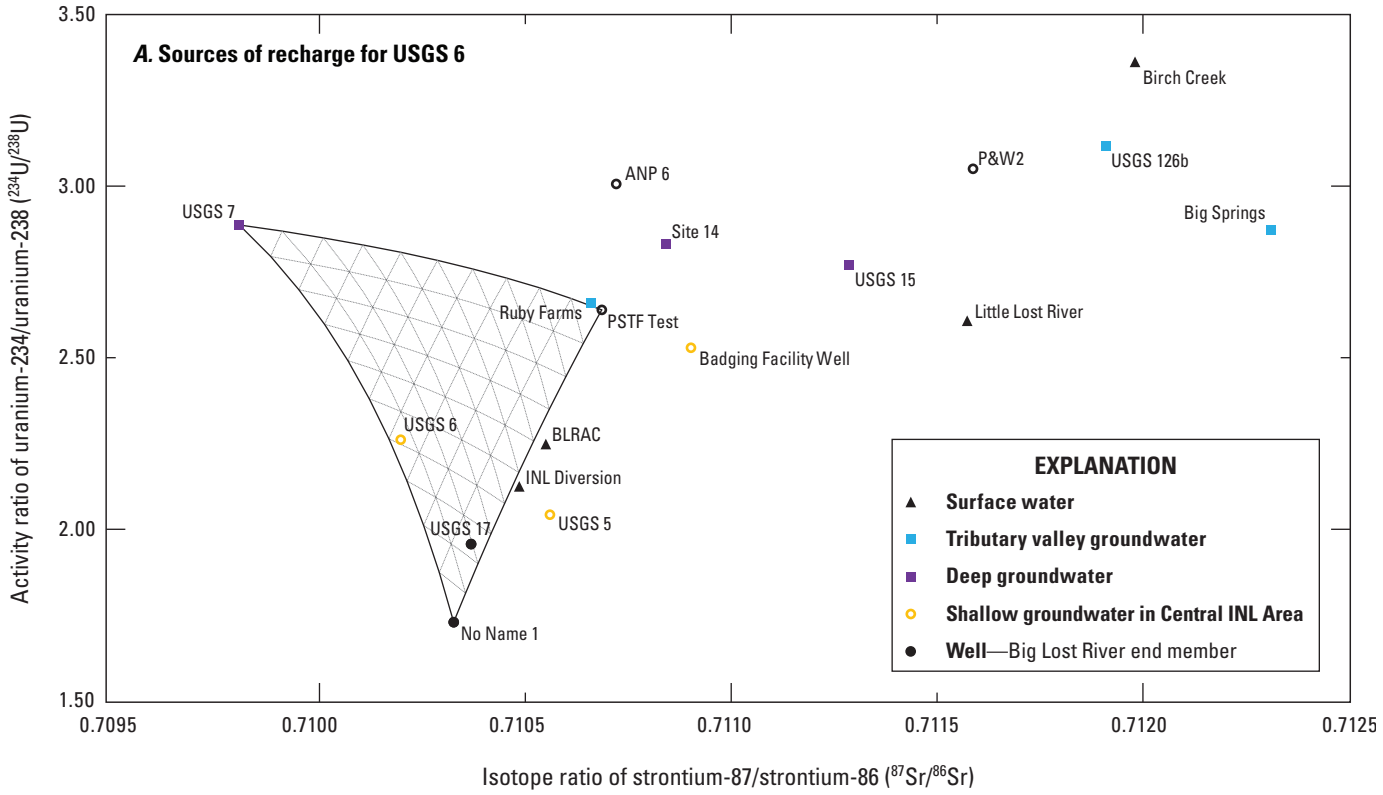
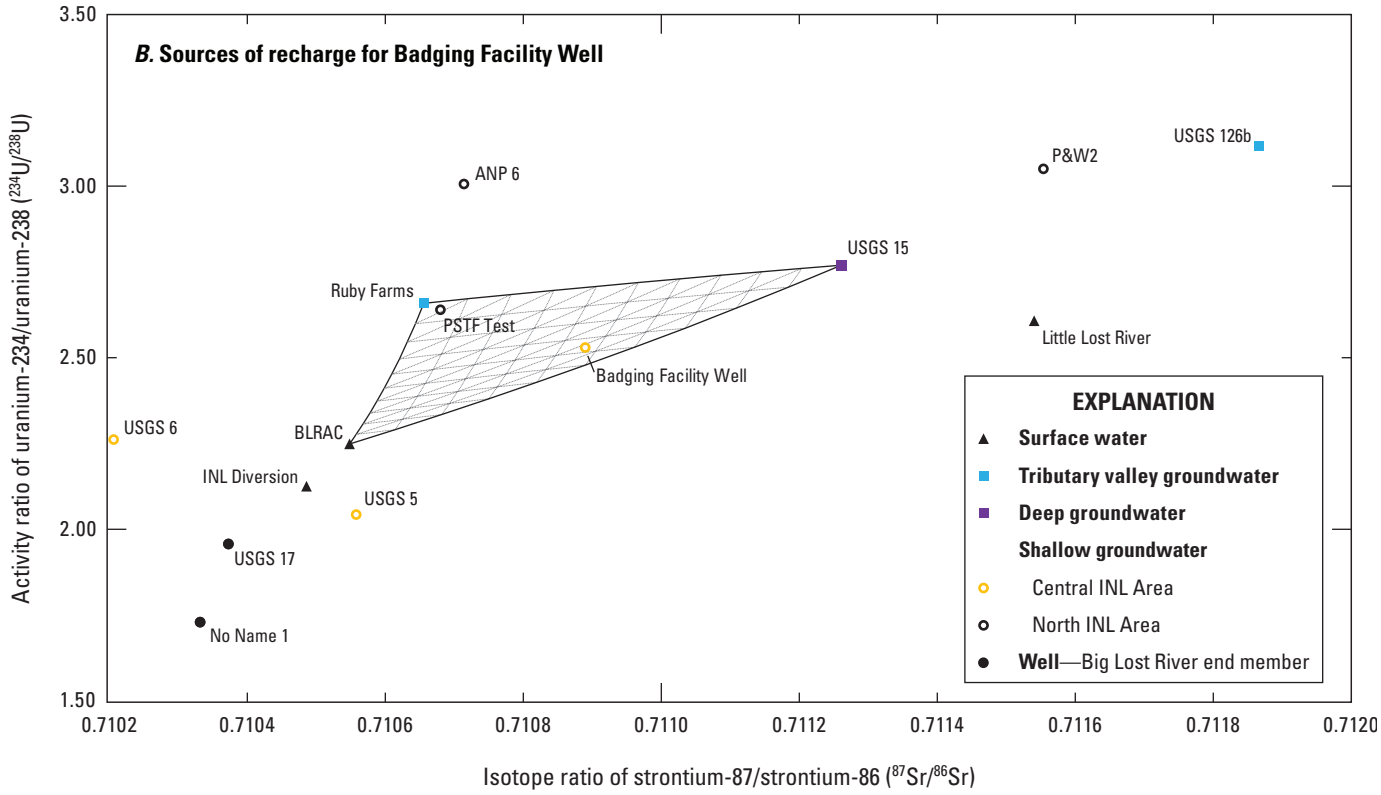


Figure 13. Ternary mixing webs for the Central INL Area, Idaho National Laboratory (INL) and vicinity, eastern Idaho. *A*. Sources of recharge for USGS 6. *B*. Sources of recharge for the Badging Facility Well. *C*. Sources of recharge for USGS 5. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).



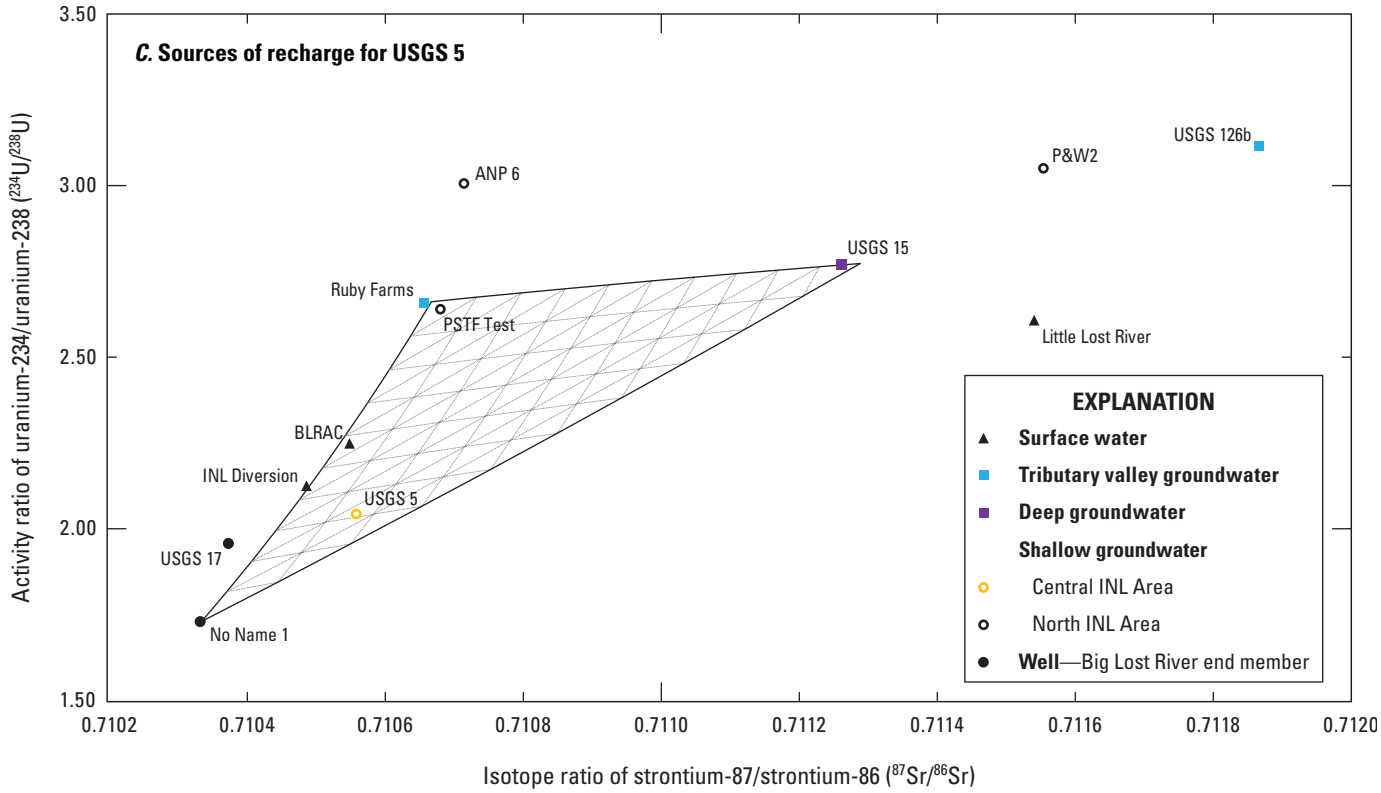


Figure 13.—Continued

South INL Area

There are three shallow groundwater sites, the Houghland Well, USGS 14, and USGS 124 in the South INL Area (fig. 6). These three sites were grouped together in the South INL Area because (1) they are located south of the INL (fig. 6), (2) lithium and silica concentrations indicate that this water contains some regional groundwater (Rattray, 2018, fig. 20; Rattray, 2019, table 7; U.S. Geological Survey, 2021), and (3) geochemical modeling indicates that the BLR, regional groundwater, and groundwater from the LLRV and BCV contribute water to these sites (Rattray, 2019, table 11).

Possible sources of recharge to the South INL Area include the BLR, regional groundwater, water from the BCV and LLRV, and groundwater from the Lemhi and Lost River Ranges. Groundwater from the BLRV also is a possible source of recharge to the Houghland Well, which is about 11 mi southwest of USGS 14 (fig. 6). Lithium concentrations at the Houghland Well, USGS 14, and USGS 124 were 12, 24.3, and 6.7 µg/L (U.S. Geological Survey, 2021) and indicate that regional groundwater is a source of recharge to these sites, albeit a small source to USGS 124. The BLR also is probably a source of recharge to these sites because they are located downgradient of the BLR and within an area that appears to receive recharge from the BLR (Rattray, 2019, figs. 15 and 18). There are too many potential sources of recharge to the South INL Area to positively identify the sources of recharge to these wells using Sr and U isotope ternary mixing webs exclusively.

Southwest INL Area

There are 17 shallow and 2 deep groundwater sites in the Southwest INL Area (fig. 6). The potential sources of recharge to this area include precipitation, the BLR and LLR, and groundwater from the BLRV and LLRV and the Lemhi and Lost River Ranges. Sources of recharge to these sites were evaluated with six ternary mixing webs (fig. 14*A*–14*F*) because of the large number of sources of recharge and the need to use three different representations of water from the BLR to define the source waters in the Southwest INL Area. The sites were grouped into different ternary mixing webs based on (1) sources of recharge that are hydrologically upgradient of groundwater sites (figs. 4 and 6), (2) sources of recharge at sites indicated from geochemical modeling (Rattray, 2019, table 11), (3) a site or group of sites plotting within a ternary mixing web that has plausible end member sources of recharge, and (4) the spatial consistency of sources of recharge at a site with sources of recharge at upgradient sites. Groundwater from one site, USGS 109, plots outside any plausible mixing web and, like groundwater from USGS 146 (fig. 10), has a relatively high $^{87}Sr/^{86}Sr$ for reasons that are not understood.

The different U and Sr isotope ratios used to represent recharge from the BLR in the Southwest INL Area were from (1) the INL diversion at head, near Arco for three shallow groundwater sites in the western part of the Southwest INL Area, (2) USGS 17 for five shallow and one deep groundwater sites along the BLR or in the southeastern part of the area, and (3) No Name 1 for seven shallow and one deep groundwater sites near, west, east, and south of the Radioactive Waste Management Complex (RWMC). The sites for which the INL diversion at head, near Arco and USGS 17 are sources of recharge are hydrologically downgradient of these actual and hypothetical BLR sites. Site No Name 1 is in the North INL Area and located far from the RWMC. No Name 1 was used to represent the BLR for sites where water appears to be (1) mostly recharge from surface water (Rattray, 2019, table 11) yet the low tritium activities in the groundwater[6] (Rattray, 2019, table 5) indicate that the water is old (Rattray, 2018, fig. 13; U.S. Geological Survey, 2021) and probably stagnant or (2) recharge through the spreading areas and therefore represents years where discharge in the BLR was large. Arguments based on other chemical characteristics of the apparently old, stagnant water were used to suggest that this water may represent large paleorecharge events, and that the water in the BLR during these events may be more dilute than represented with the current water samples from the BLR. Consequently, No Name 1, which has the U and Sr isotope ratios from BLR water that is most like dilute precipitation (fig. 9), was believed to be a reasonable representation for recharge of water from the BLR to these sites. Low U and Sr isotope ratios in groundwater from some sites in the Southwest INL Area suggest that significant amounts of precipitation are a source of recharge. However, in general, precipitation is a minor source of recharge to groundwater at the INL (Ackerman and others, 2006) so, although some recharge from precipitation likely does occur, most of the indicated recharge from precipitation probably represents dilute recharge from the BLR. Although there are three representations of water from the BLR for this area, each of these sites used to characterize source water to the Southwest INL Area lie on a trend line in $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ space and likely represent expected variation in the source of BLR water because of the ephemeral nature of this sinking river, and the extent of recharge at the INL (see section, "Characterization of Sources of Recharge").

Precipitation and the BLR were the major sources of recharge in the eastern and central parts of the Southwest INL Area (fig. 6; table 4). Precipitation (represented with USGS 22) was the primary source of recharge to groundwater at USGS 83 and USGS 104 in the northeast (fig. 14*A*) and to USGS 86, USGS 89, USGS 117, and USGS 119 near the RWMC (fig. 14*B*), and the BLR (represented with USGS 17 or INL diversion at head) was the primary source of recharge to groundwater at nine shallow and two deep groundwater sites in the southeastern part of the Southwest INL Area (fig. 14*C*). In the western part of the Southwest INL Area groundwater from the BLRV (represented with Arco City Well #4) was the primary source of recharge to USGS 8 and the Fingers Butte Well and groundwater from the Lost River Range (represented with USGS 23) was the primary source of recharge to USGS 135 z10 (fig. 14*D*–14*F*).

[6]Except for groundwater from USGS 104, which contains tritium from waste disposal (Rattray, 2018, fig. 13).

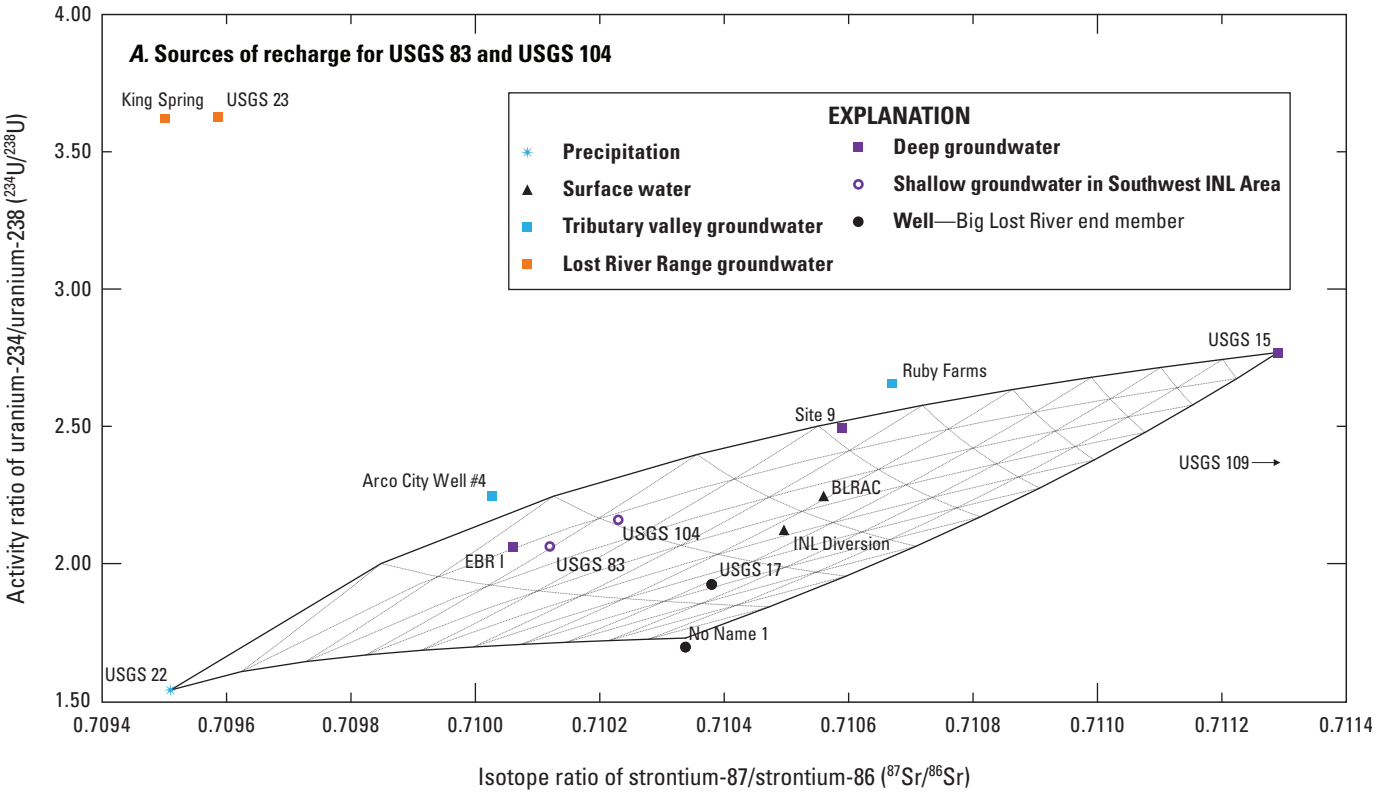
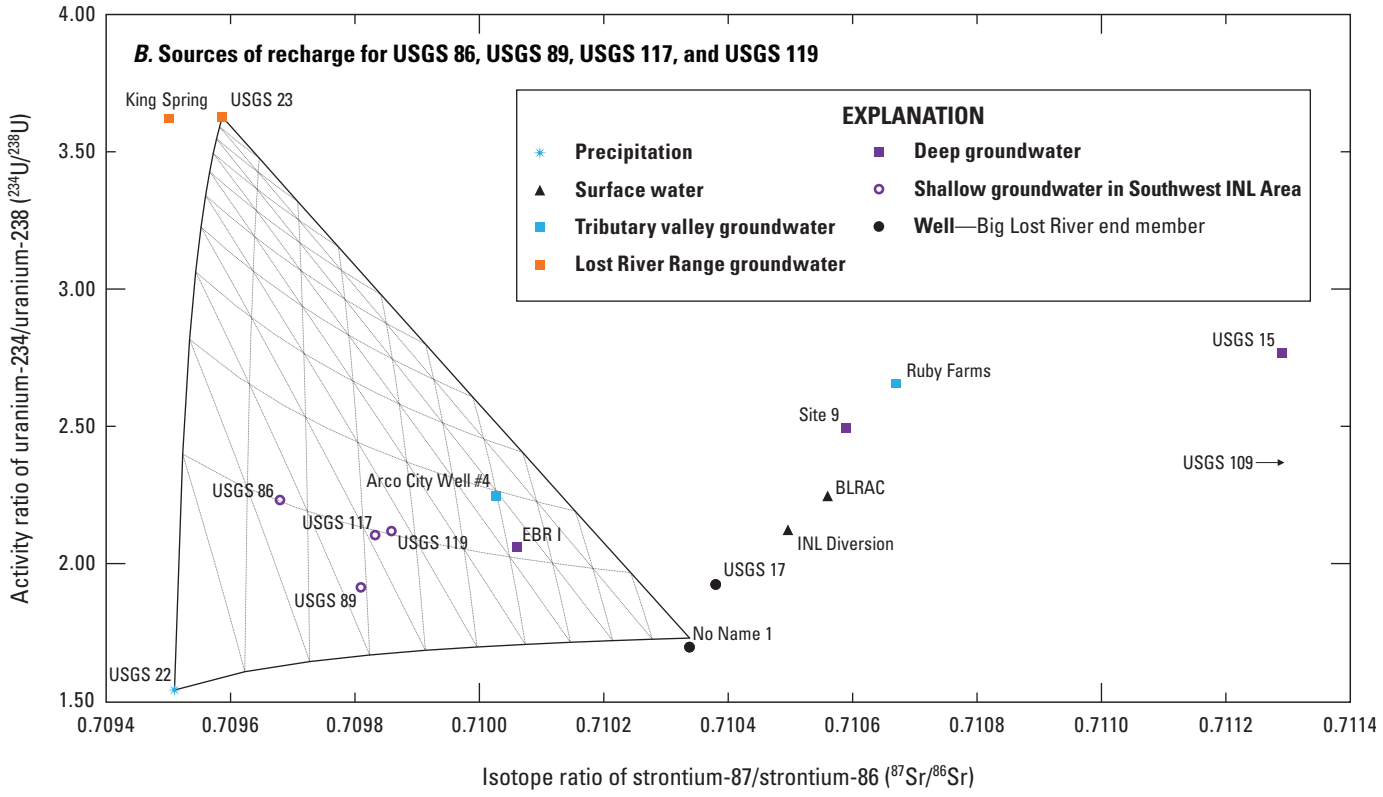


Figure 14. Ternary mixing webs for the Southwest INL Area, Idaho National Laboratory (INL) and vicinity, eastern Idaho. *A*. Sources of recharge for USGS 83 and USGS 104. *B*. Sources of recharge for USGS 86, USGS 89, USGS 117, and USGS 119. *C*. Sources of recharge for USGS 9, USGS 103, USGS 105, USGS 108, and Highway 3. *D*. Sources of recharge for USGS 125. *E*. Sources of recharge for USGS 8, USGS 11, and USGS 135 z10. *F*. Sources of recharge for Fingers Butte well. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).



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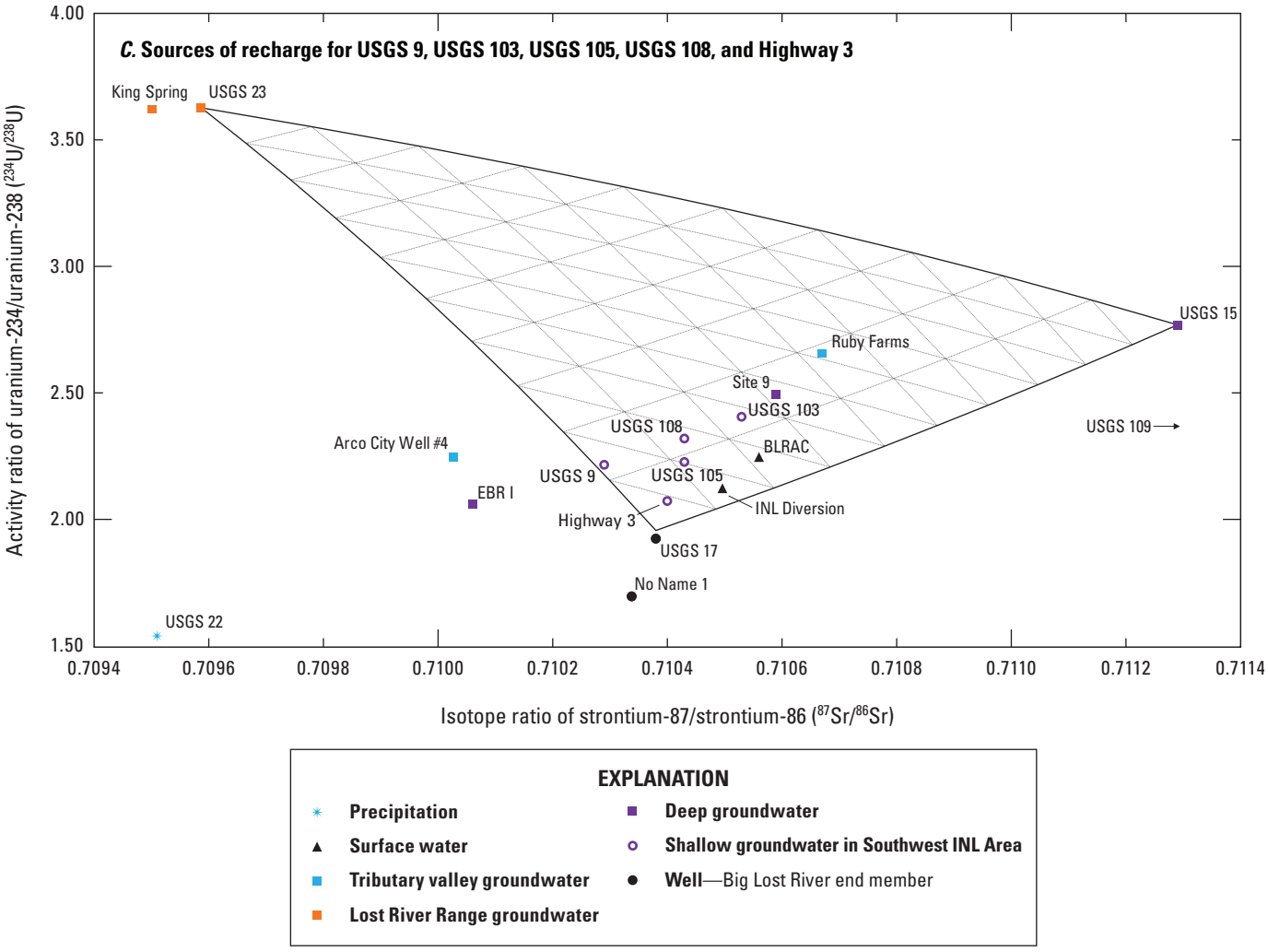

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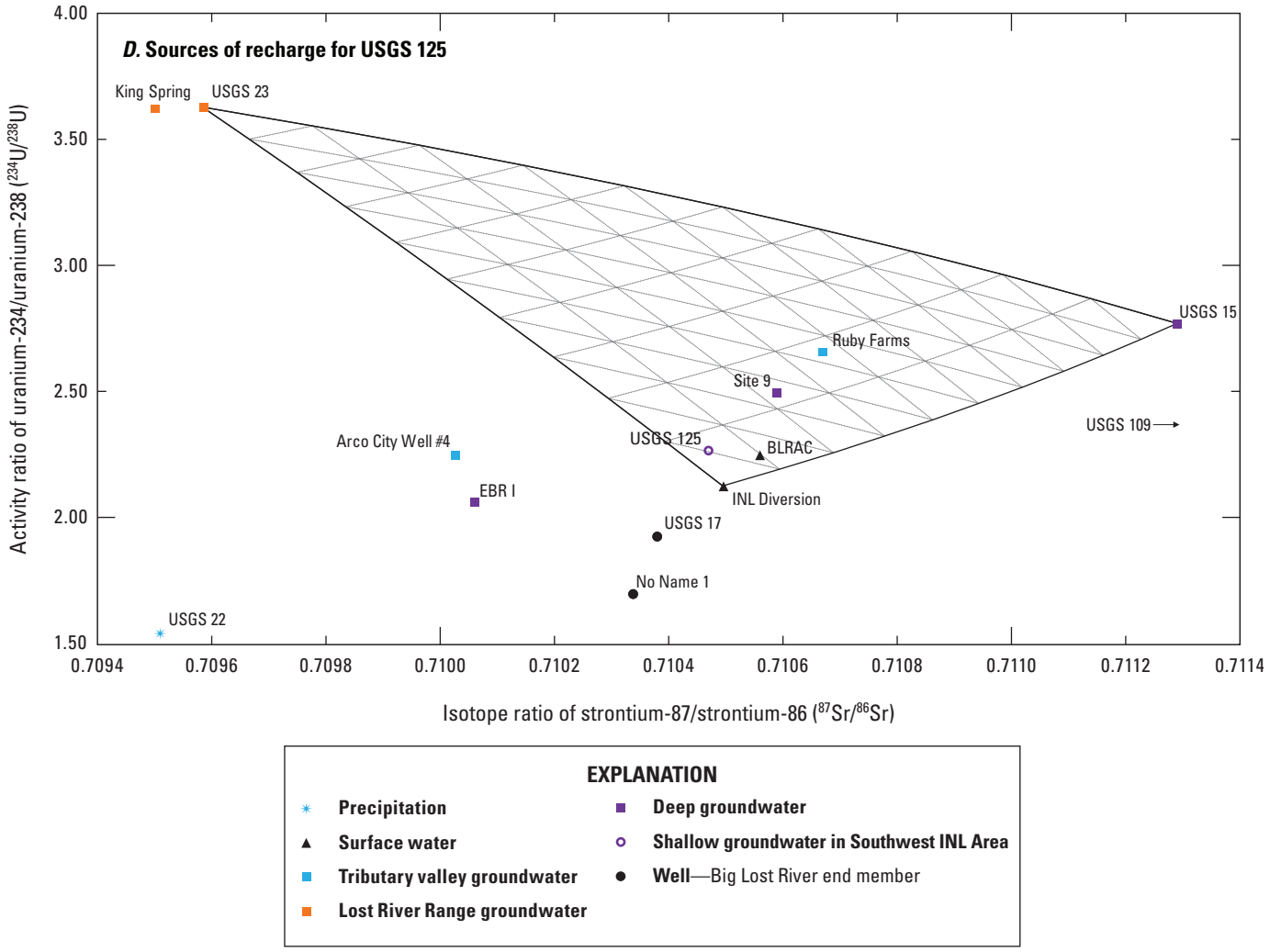

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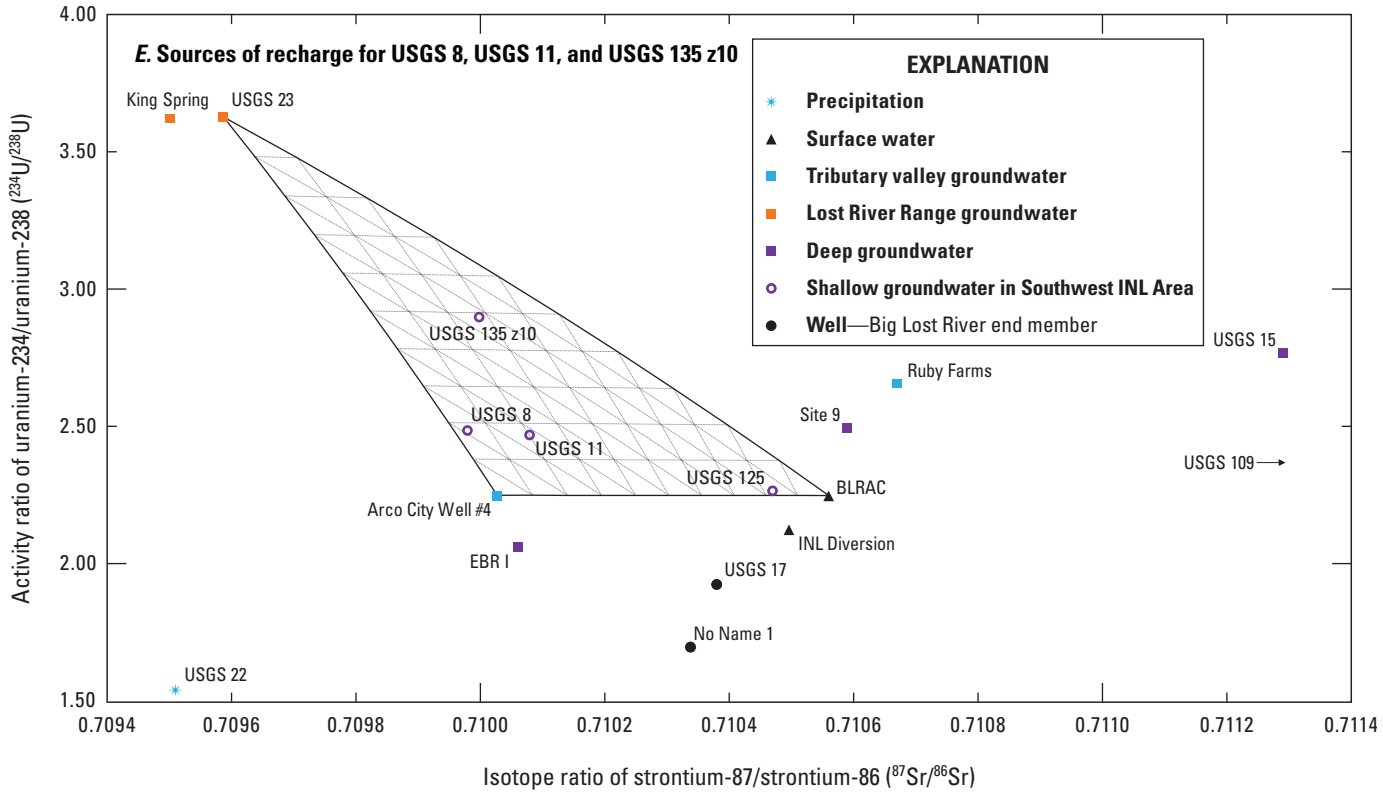

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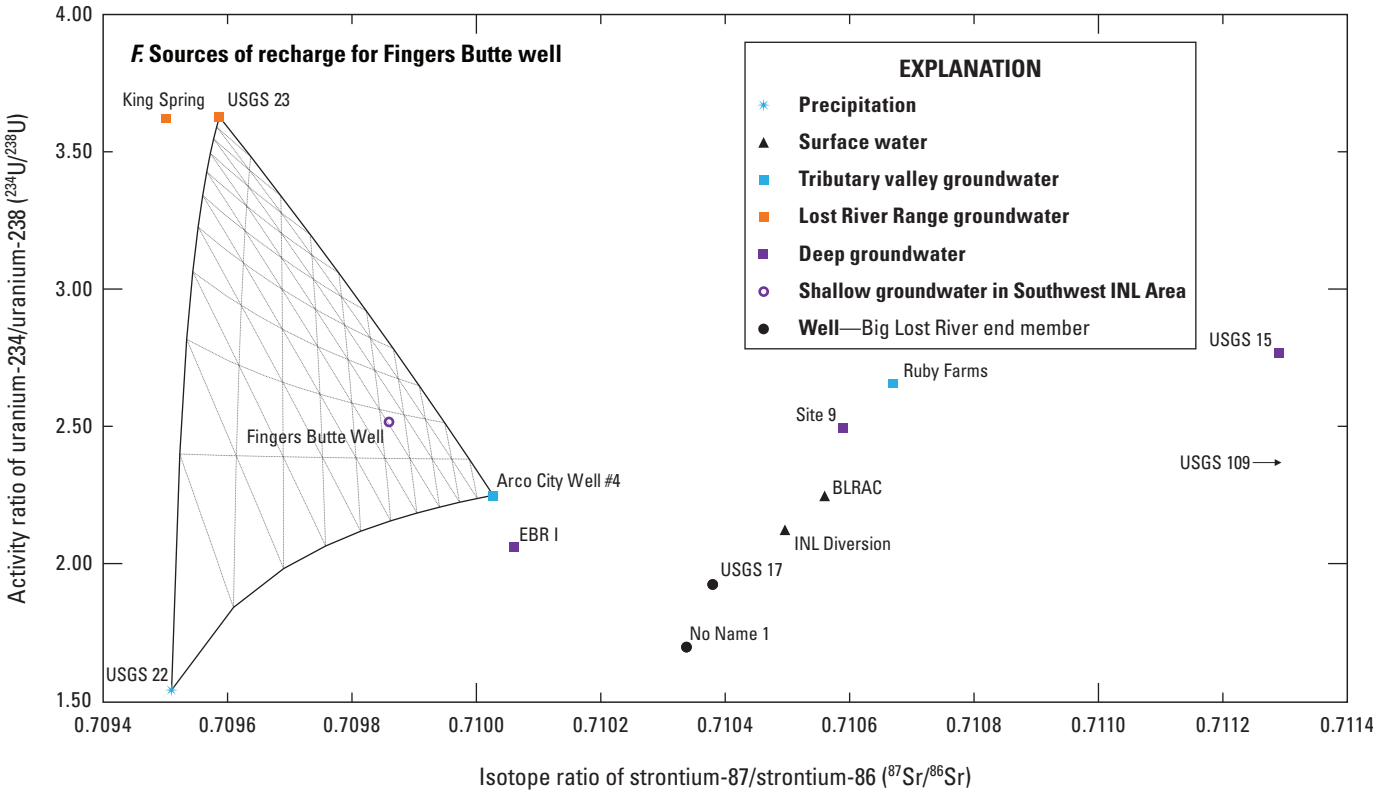

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Confidence in Results

Confidence in the precision and accuracy of sources, and their percentage, of recharge to groundwater sites determined with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ ternary mixing webs was assessed with two methods. The first method assessed the precision of estimates of recharge from ternary mixing webs and the second method assessed precision and accuracy by comparing the difference in results between the ternary mixing webs and geochemical modeling (Rattray, 2019, table 11). Precision errors in the ternary mixing webs result from measurement and estimation errors (described in section, "Uncertainty"). The sum of these two errors was calculated for each ternary mixing web and is shown in table 4 for 52 groundwater sites. This precision error ranged from 3.6 to 9.3 percent with a mean and standard deviation of 5.1±1.3 percent.

Assessing precision and accuracy of sources of recharge by comparing differences in sources of recharge between the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ ternary mixing webs (table 4) and geochemical modeling (Rattray, 2019, table 11) requires reporting comparable sources of recharge with both methods. However, the geochemical model identifies sources of recharge entering the ESRP aquifer across the boundaries of the INL whereas the sources of recharge identified from the mixing webs reflects the origin of water at groundwater sites. This difference is because the major ion chemistry of water used in modeling takes on the chemical signature of all hydrochemical systems it travels through while $^{234}U/^{238}U$ or $^{87}Sr/^{86}Sr$ used in the mixing webs retains the isotope signature of the original, unmixed water.

The principal difference in sources of recharge between these two methods occurs where water enters the ESRP aquifer from the BCV and LLRV. For example, sources of recharge identified from $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ ternary mixing webs show that groundwater exiting the BCV is a mixture of groundwater from the BCV and the Lemhi Range whereas geochemical modeling identifies this water as groundwater from the BCV. Similarly, $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ mixing webs identify groundwater exiting the LLRV as a mixture of groundwater from the Lost River and Lemhi Ranges, the LLRV, and water from the LLR whereas geochemical modeling identifies this water as groundwater from the LLRV. Another difference is that wastewater is identified as a source of recharge with geochemical modeling (Rattray, 2019, table 1; Rattray, 2023, table 11) but not with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ mixing webs (table 4). However, wastewater represents a minor source of recharge to all sites in this study area, except USGS 89 (table 4; Rattray, 2019, table 11), and therefore will cause only slight differences in sources of recharge identified from $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ mixing webs and geochemical modeling.

The difference in sources of recharge identified with the mixing webs and geochemical modeling was resolved by assuming that the sources of recharge to P&W 2 and USGS 15 (table 4) are representative of groundwater exiting the BCV and LLRV (fig. 1), respectively. Based on this assumption, the sources of recharge to groundwater sites shown in table 4 were recalculated, and table 5 shows the sources of recharge that are approximately representative of water entering the ESRP aquifer across the INL boundaries.

Uncertainty when comparing results from $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ ternary mixing webs (table 4) and geochemical modeling (Rattray, 2019, table 11) was estimated by identifying the largest discrepancy for a single source of recharge, even if that source of recharge was only represented in one of the two methods used for identifying the sources of recharge. This discrepancy, or estimated uncertainty, is shown in table 5 for 53 groundwater sites and ranged from 0 to 100 percent with a mean and standard deviation of 33±25 percent.

Many of these discrepancies are large, and many of these large discrepancies can be attributed to erroneous sources of recharge identified with geochemical modeling or improved resolution of sources of recharge with the $^{234}U/^{238}U$–$^{87}Sr/^{86}Sr$ ternary mixing webs. For example, the large discrepancies in the North INL Area are due to geochemical models erroneously identifying the BLR as a significant and widespread source of recharge to this area and the $^{234}U/^{238}U$–$^{87}Sr/^{86}Sr$ ternary mixing webs, but not the geochemical models, identifying geothermal water, deep groundwater, and groundwater from the Lemhi Range as sources of recharge (table 5; Rattray, 2019, table 11). These apparent errors in sources of recharge in the North INL Area also affect many hydrologically downgradient sites in the Northeast, Southeast, and Central INL Areas.

Several sites in the Northwest INL Area have large discrepancies for a source of recharge (table 5). These discrepancies are mostly due to the better resolution of recharge of groundwater from the Lost River Range with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ than with the major ion chemistry used for geochemical modeling. However, at USGS 98, the discrepancy is due to the large percentage of recharge attributed to the BLR with the mixing web. The large discrepancy for USGS 98 can be attributed to the transient nature of recharge from the BLR (fig. 4) and chemistry data that were collected during the first and third years of short-term wet climate cycles for geochemical modeling and the $^{234}U/^{238}U$–$^{87}Sr/^{86}Sr$ ternary mixing web, respectively (Roback and others, 2001). Consequently, the percentage of recharge from the BLR to USGS 98 estimated with the model and mixing web probably are both correct and reflect the transient nature of recharge in this part of the aquifer.

There are several sites in the Southwest INL Area that have a large discrepancy for a source of recharge (table 5). Although the hydrologic system in this part of the INL is transient, this does not appear to influence the discrepancies at most of these sites. At many sites, the large discrepancy is due to larger amounts of recharge of surface water (precipitation plus the BLR) in the mixing webs than the geochemical models. It is not clear why there is a difference in surface water between these two methods, although the isotope ratios may be more affected than major ion chemistry by the greater surface water to groundwater ratio in the BLR during periods with large discharge amounts. The relatively low U isotope ratios in groundwater from many sites in the Southwest INL Area (fig. 5*A*) are, however, consistent with large amounts of recharge from surface water in this area (fig. 9).

The other cause for large discrepancies for a source of recharge in the Southwest INL Area is the amount of recharge attributed to groundwater from the Lost River Range. Both major ions and U and Sr isotopes were analyzed in water collected from USGS 23. However, the major ion chemistry of groundwater from the Lost River Range is affected by agricultural practices in the BLRV and LLRV, whereas the U and Sr isotope ratios probably are not affected, and this is the most likely cause for large discrepancies in recharge amounts of groundwater from the Lost River Range.

Hydrologic Processes

Hydrologic processes were evaluated by creating illustrations from the data in table 5 that show the areal distribution of sources of recharge, mixing of water, and groundwater-flow directions. Figure 15*A* shows a hand-drawn areal distribution of groundwater sources of recharge across the INL, where the indicated source of recharge represents the primary source of groundwater at each site. This figure indicates that:

- the eastern part of the INL consists of regional groundwater;
- groundwater from the BCV and LLRV flow south and southwest from the mouth of their respective valleys to slightly beyond the southern boundary of the INL;
- groundwater from the BLRV largely resides west of the boundary of the INL; and
- groundwater from the Lemhi and Lost River Ranges flows south from the mountain fronts and comprise relatively small and large areas of the INL, respectively.

These areas of primary groundwater sources of recharge are similar to those indicated from geochemical modeling (Rattray, 2019, fig. 15*A*). However, some differences between these two interpretations of primary groundwater sources of recharge are that $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ indicate that:

- groundwater at USGS 107 and USGS 110A in the south-central part of the INL is primarily from the BCV and not regional groundwater;
- the Lemhi Range is a source of recharge, and this groundwater extends to the central part of the INL and separates groundwater from the BCV and LLRV; and
- groundwater from the Lost River Range is the primary groundwater source of recharge in the western part of the INL and extends south of the INL.

Table 5. Sources of recharge (where the source of recharge represents water entering the eastern Snake River Plain at the Idaho National Laboratory) to groundwater sites, the percentage of total recharge for each source, and the difference with results from geochemical modeling, Idaho National Laboratory and vicinity, eastern Idaho.

[**Uncertainty represented as difference with results from geochemical modeling:** The largest discrepancy for a single source of recharge between results from geochemical modeling and uranium and strontium isotope ratios (Rattray, 2019, table 11; Rattray, 2023, table 11). **Abbreviation and Symbols:** na, not applicable; –, none; ±, plus or minus]

Site name	Sources of recharge											Uncertainty represented as difference with results from geochemical modeling (± percent)
	Surface water			Groundwater								
	Precipitation	Little Lost River	Big Lost River	Geothermal	Deep	Regional	Birch Creek valley	Little Lost River valley	Big Lost River valley	Lemhi Range	Lost River Range	
Deep groundwater at the INL												
EBR-1	26	–	62	–	–	–	–	–	–	–	12	12
Site 9	–	–	53	–	–	–	–	32	–	–	15	na
Site 14	–	–	–	–	21	–	29	–	–	50	–	na
USGS 7	–	–	14	69	–	–	–	–	–	17	–	72
USGS 15	–	–	–	–	–	–	–	100	–	–	–	na
Shallow groundwater in the North INL Area												
ANP 6	–	–	–	–	–	–	–	–	–	100	–	100
No Name 1	–	–	100	–	–	–	–	–	–	–	–	61
P&W 2	–	–	–	–	–	–	100	–	–	–	–	0
PSTF TEST	–	–	–	–	–	–	–	–	–	100	–	100
USGS 18	–	–	–	–	10	–	53	–	–	37	–	47
Shallow groundwater in the Northeast INL Area												
ANP 9	–	–	–	–	–	8	92	–	–	–	–	43
USGS 26	–	–	–	–	–	24	76	–	–	–	–	17
USGS 27	–	–	–	–	–	84	16	–	–	–	–	20
USGS 29	–	–	–	–	–	100	–	–	–	–	–	7
USGS 31	–	–	–	–	–	61	39	–	–	–	–	34
USGS 32	–	–	–	–	–	67	33	–	–	–	–	8
Shallow groundwater in the Southeast INL Area												
Arbor Test 1	–	–	–	–	–	82	18	–	–	–	–	16
Area II	–	–	–	–	–	54	46	–	–	–	–	27
Grazing Well #2	–	–	–	–	–	63	37	–	–	–	–	24
USGS 1	–	–	–	–	–	64	36	–	–	–	–	23
USGS 2	–	–	–	–	–	77	23	–	–	–	–	10
USGS 100	–	–	–	–	–	77	23	–	–	–	–	15

Table 5. Sources of recharge (where the source of recharge represents water entering the eastern Snake River Plain at the Idaho National Laboratory) to groundwater sites, the percentage of total recharge for each source, and the difference with results from geochemical modeling, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

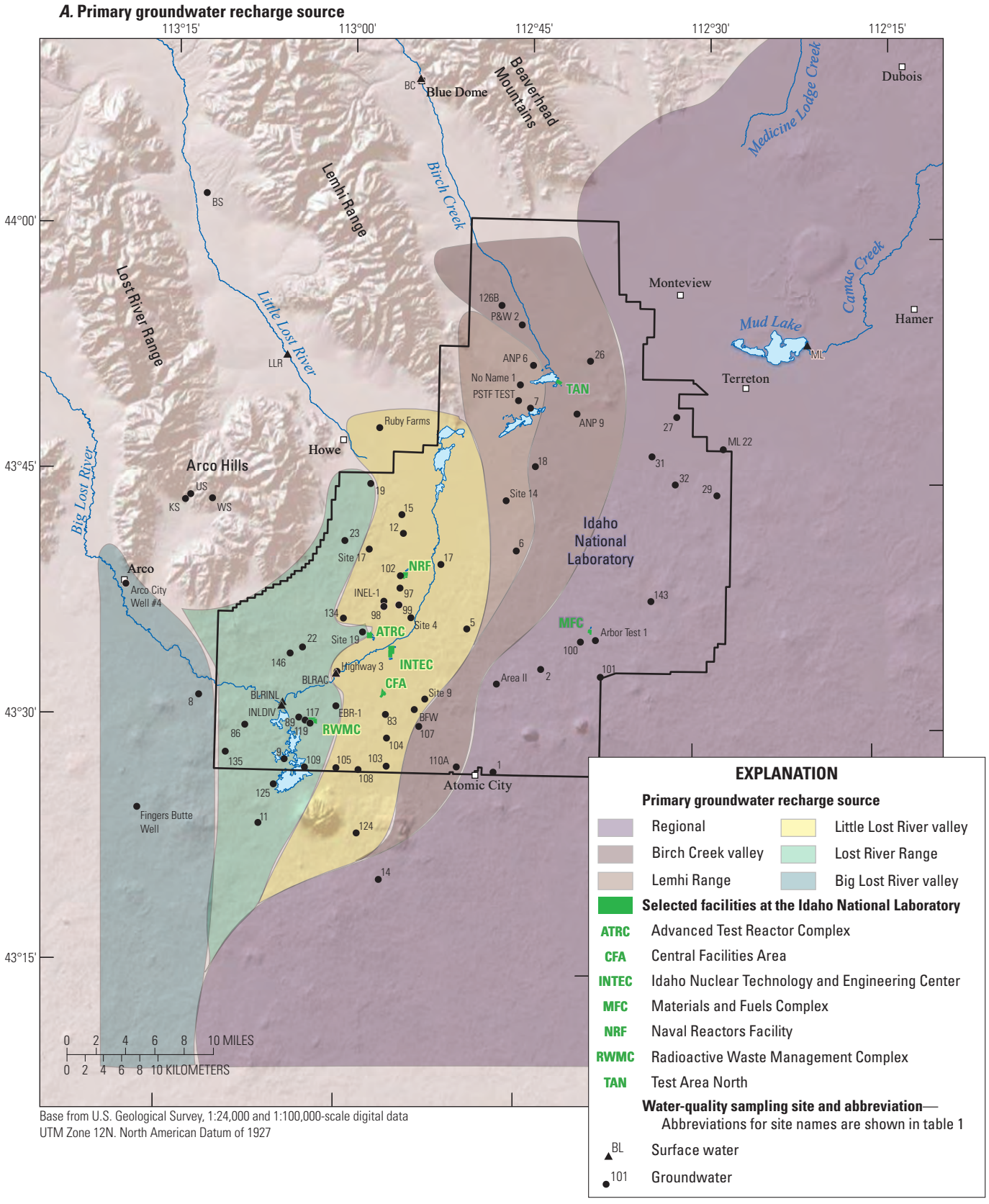
[**Uncertainty represented as difference with results from geochemical modeling:** The largest discrepancy for a single source of recharge between results from geochemical modeling and uranium and strontium isotope ratios (Rattray, 2019, table 11; Rattray, 2023, table 11). **Abbreviation and Symbols:** na, not applicable; –, none; ±, plus or minus]

Site name	Sources of recharge											Uncertainty represented as difference with results from geochemical modeling (± percent)
	Surface water			Groundwater								
	Precipitation	Little Lost River	Big Lost River	Geothermal	Deep	Regional	Birch Creek valley	Little Lost River valley	Big Lost River valley	Lemhi Range	Lost River Range	
Shallow groundwater in the Southeast INL Area—Continued												
USGS 101	–	–	–	–	–	97	3	–	–	–	–	na
USGS 107	–	–	–	–	–	38	62	–	–	–	–	56
USGS 110A	–	–	–	–	–	47	53	–	–	–	–	27
USGS 143	–	–	–	–	–	100	–	–	–	–	–	2
Shallow groundwater in the Northwest INL Area												
Site 4	–	–	71	–	–	–	–	28	–	–	1	11
Site 17	–	–	–	–	–	–	–	75	–	–	25	25
Site 19	–	–	9	–	–	–	–	33	–	–	58	58
USGS 12	–	–	64	–	–	–	–	28	–	–	8	22
USGS 19	–	–	–	–	–	–	–	44	–	–	56	55
USGS 22	100	–	–	–	–	–	–	–	–	–	–	0
USGS 23	–	–	–	–	–	–	–	–	–	–	100	na
USGS 97	–	–	51	–	–	–	–	42	–	–	7	12
USGS 98	–	–	68	–	–	–	–	18	–	–	14	61
USGS 99	–	–	18	–	–	–	–	73	–	–	9	9
USGS 102	–	–	57	–	–	–	–	35	–	–	8	19
USGS 134 zone 15	–	–	37	–	–	–	–	17	–	–	46	71
Shallow groundwater in the Central INL Area												
Badging Facility Well	–	–	36	–	–	–	–	48	–	16	–	49
USGS 5	–	–	69	–	–	–	–	16	–	15	–	22
USGS 6	–	–	58	–	37	–	–	–	–	5	–	37
USGS 17	–	–	100	–	–	–	–	–	–	–	–	0

Table 5. Sources of recharge (where the source of recharge represents water entering the eastern Snake River Plain at the Idaho National Laboratory) to groundwater sites, the percentage of total recharge for each source, and the difference with results from geochemical modeling, Idaho National Laboratory and vicinity, eastern Idaho.—Continued

[**Uncertainty represented as difference with results from geochemical modeling:** The largest discrepancy for a single source of recharge between results from geochemical modeling and uranium and strontium isotope ratios (Rattray, 2019, table 11; Rattray, 2023, table 11). **Abbreviation and Symbols:** na, not applicable; –, none; ±, plus or minus]

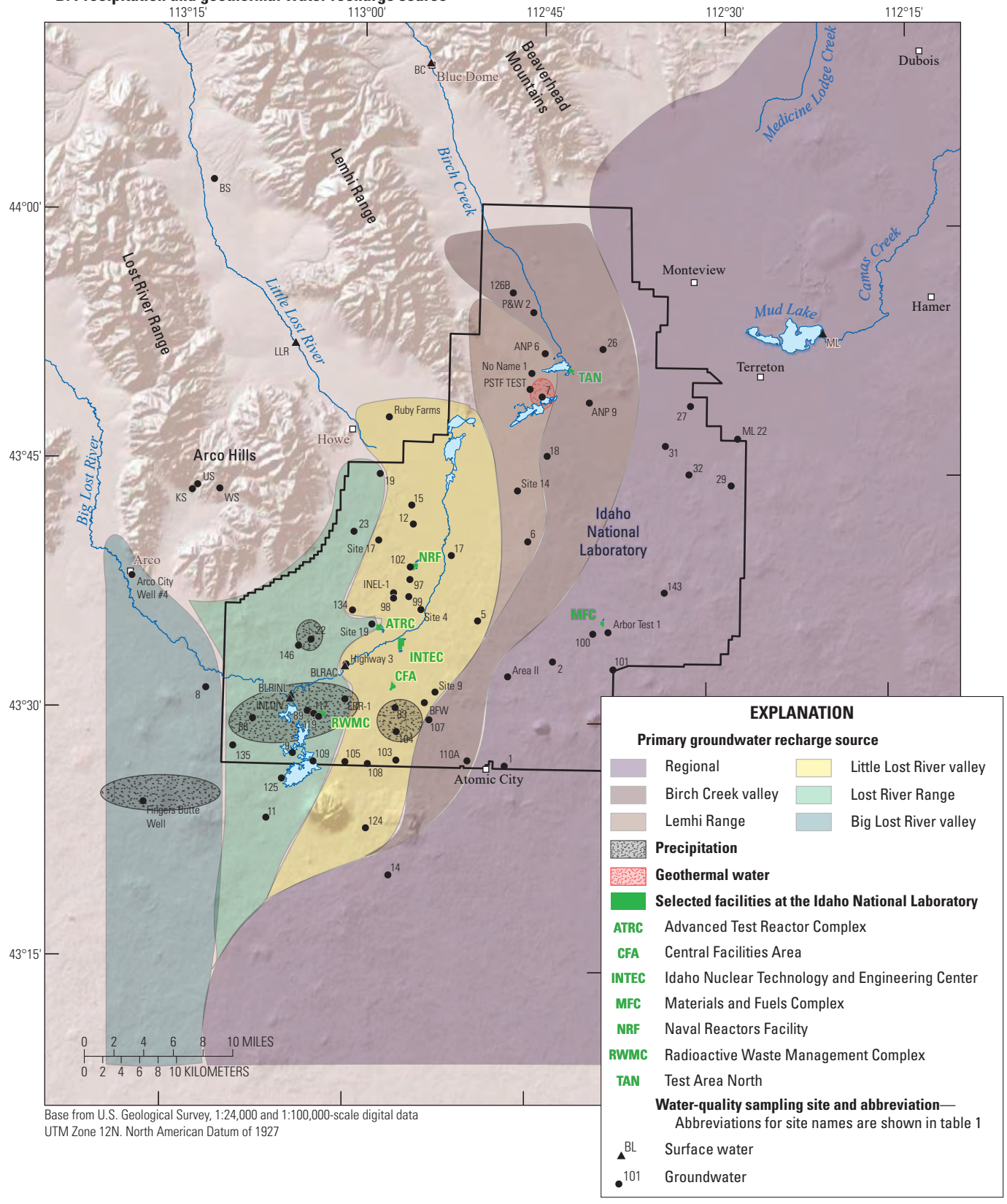
Site name	Sources of recharge											Uncertainty represented as difference with results from geochemical modeling (± percent)
	Surface water			Groundwater								
	Precipitation	Little Lost River	Big Lost River	Geothermal	Deep	Regional	Birch Creek valley	Little Lost River valley	Big Lost River valley	Lemhi Range	Lost River Range	
Shallow groundwater in the Southwest INL Area												
Fingers Butte Well	19	–	–	–	–	–	–	–	55	–	26	30
Highway 3	–	–	92	–	–	–	–	4	–	–	4	25
USGS 8	–	–	6	–	–	–	–	–	76	–	18	20
USGS 9	–	–	85	–	–	–	–	2	–	–	13	13
USGS 11	–	–	66	–	–	–	–	2	–	–	32	24
USGS 83	71	–	13	–	–	–	–	16	–	–	–	79
USGS 86	75	–	15	–	–	–	–	–	–	–	10	32
USGS 89	66	–	29	–	–	–	–	–	–	–	5	25
USGS 103	–	–	63	–	–	–	–	24	–	–	13	17
USGS 104	67	–	12	–	–	–	–	21	–	–	–	81
USGS 105	–	–	79	–	–	–	–	12	–	–	9	10
USGS 108	–	–	73	–	–	–	–	14	–	–	13	13
USGS 117	58	–	32	–	–	–	–	–	–	–	10	59
USGS 119	54	–	35	–	–	–	–	–	–	–	11	54
USGS 125	–	–	90	–	–	–	–	3	–	–	7	45
USGS 135 zone 10	–	–	43	–	–	–	–	–	11	–	46	36



Base from U.S. Geological Survey, 1:24,000 and 1:100,000-scale digital data
UTM Zone 12N. North American Datum of 1927

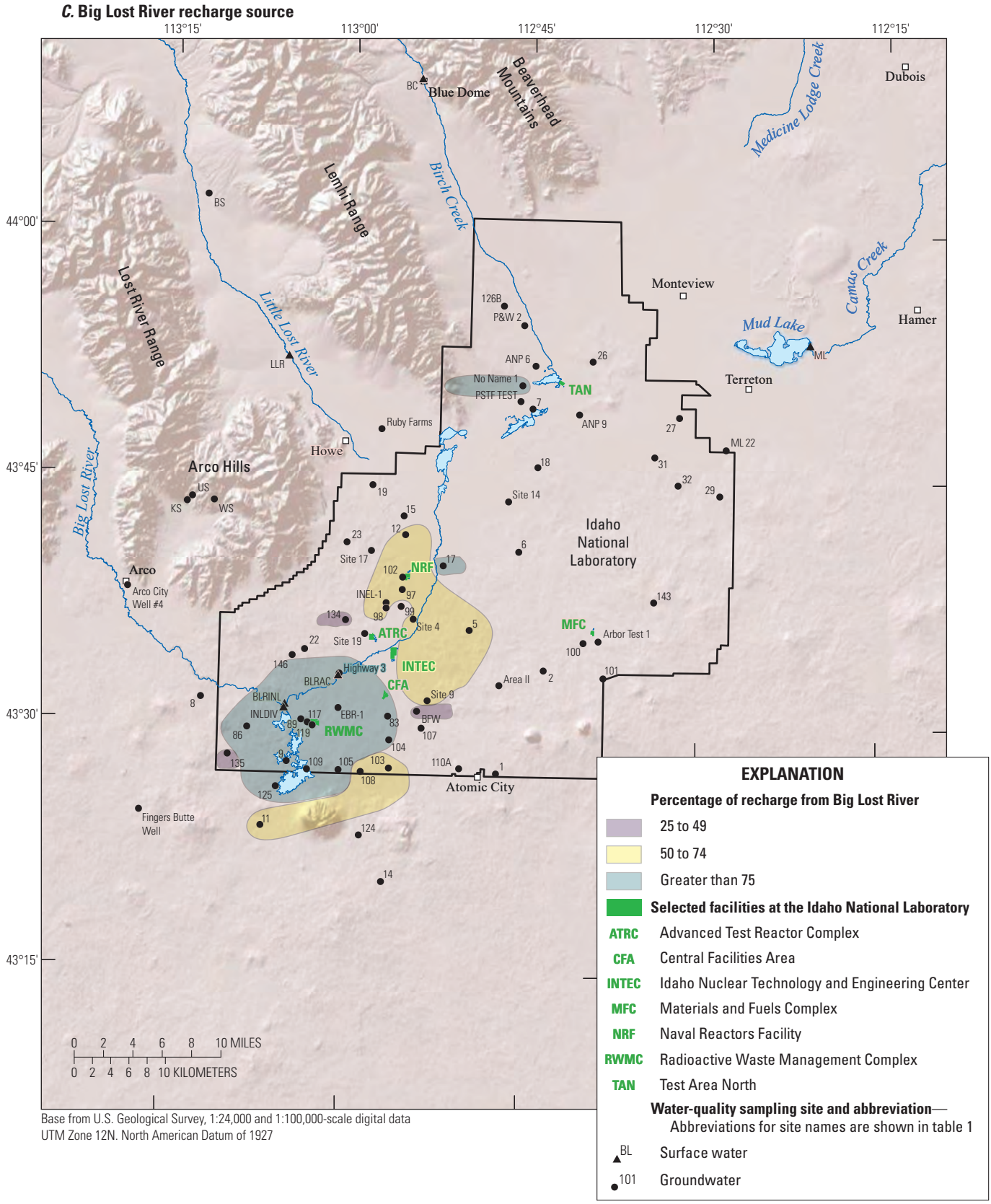
Figure 15. Sources of recharge, Idaho National Laboratory and vicinity, eastern Idaho. *A*. Primary groundwater recharge source. *B*. Precipitation and geothermal water recharge source. *C*. Big Lost River recharge source. Boundaries of primary groundwater sources are hand-drawn and approximate.

***B.* Precipitation and geothermal water recharge source**



Base from U.S. Geological Survey, 1:24,000 and 1:100,000-scale digital data
UTM Zone 12N. North American Datum of 1927

Figure 15.—Continued



Base from U.S. Geological Survey, 1:24,000 and 1:100,000-scale digital data
UTM Zone 12N. North American Datum of 1927

Figure 15.—Continued

$^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ indicate that precipitation is a source of recharge in the southwestern part of the INL (fig. 15*B*), a result similar to interpretations from geochemical modeling (Rattray, 2019, fig. 15*C,* table 11; Rattray, 2023, table 11). Although precipitation is indicated in these figures, the precipitation indicated in the Southwest INL Area (fig. 6) in these figures and tables is assumed to represent paleorecharge from the BLR (Rattray, 2018). Consequently, the only site at the INL where precipitation is assumed to be a significant source of recharge is at USGS 22. Although the general area where precipitation/paleorecharge is indicated as a source of recharge is consistent between interpretations from geochemical modeling and $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$, the specific sites do vary. Both methods, however, indicate that precipitation/paleorecharge occurs at many sites near the RWMC and the INL spreading areas.

Figure 15*B* also indicates that geothermal water moves upward to, and resides in, groundwater at USGS 7. USGS 7 is located within the Lava Ridge-Hells Half Acre volcanic rift zone (Kuntz and others, 1992; Rattray, 2018), and geologic features within the rift zone may facilitate the upward movement of deep geothermal water. Geochemical modeling (Rattray, 2019, fig. 15*C*) indicates that geothermal water is present in groundwater at several sites in the North and Northeast INL Areas and at USGS 146 in the Northwest INL Area (fig. 6). Helium concentrations and isotopic composition recently analyzed from water collected from the Northeast INL Area (USGS 26 and USGS 31) and the North INL Area (Site 14, USGS 18) support the interpretation that groundwater at these sites contains some geothermal water, but the helium data analyzed from water collected at USGS 146 indicate that this groundwater does not contain geothermal water (U.S. Geological Survey, 2021).

Geothermal water present in groundwater in the Northeast INL Area moved upward east of the INL (Rattray, 2015) and was incorporated into shallower groundwater that subsequently flowed onto the INL (Rattray, 2019). Similarly, interpretation of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ indicates that geothermal water in the North INL Area, in groundwater at USGS 18 and Site 14 (and USGS 6 in the Central INL Area), represents shallow groundwater that flowed downgradient from the vicinity of USGS 7 (table 5). This interpretation differs from the interpretation by Anderson and others (1999), who suggested that the relatively warm water at USGS 18 (Rattray, 2019, table 6) may be influenced by nearby dikes and fissures associated with an underlying vent corridor. Although upwelling geothermal water probably is a source of recharge to deeper parts of the aquifer (Mann, 1986; Ackerman and others, 2006), interpretations from $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ and geochemical modeling indicate that upwelling geothermal water provides minimal recharge to the shallow aquifer. Consequently, the shallow aquifer probably is dominated by horizontal or downward flow of groundwater (Ackerman and others, 2006, fig. 24; Rattray, 2023).

Recharge from the BLR is shown in figure 15*C*, with recharge amounts in the figure consisting of the sum of recharge from the BLR and precipitation (except at USGS 22, precipitation is assumed to represent paleorecharge from the BLR) in table 5. Hand-drawn areas in this figure represent recharge from the BLR that ranges from 25 to 49 percent, 50 to 74 percent, and exceeds 75 percent of the total recharge at a site. Recharge from the BLR exceeds 75 percent at most sites adjacent to or south of the BLR and the INL spreading areas, in the southwestern corner of the INL, and at USGS 17 and No Name 1, which are either adjacent to the river channel or the terminal playas for the BLR. Relative to the 75 percent recharge area, recharge from the BLR ranges from 50 to 74 percent to the south and northeast. The sites to the northeast may receive recharge from the BLR from either the river channel or the BLR sinks. Sites where recharge from the BLR ranges from 25 to 49 percent are few. The limited extent of recharge from the BLR that is less than 50 percent may be due to changes in vertical to horizontal conductivity ratios. Horizontal transport in the unsaturated zone of surface water infiltrating from the INL spreading areas is rapid, at the scale of kilometers (Nimmo and others, 2002). However, water moving horizontally may eventually reach areas where fracture zones, fissures, or smaller sediment thickness increase vertical hydraulic conductivity, which will increase the downward, and reduce the horizontal, movement of water.

The estimated area of the ESRP aquifer affected by recharge from the BLR is smaller in figure 15*C* than the area indicated with geochemical modeling (Rattray, 2019, fig. 15*B*), even though data from both datasets represents recharge during the first few years of wet cycles. An error in the estimates of recharge from the BLR with geochemical modeling was described in section, "Confidence in Results," and this error probably accounts for much of the discrepancy in the estimated areas of recharge from the BLR between geochemical modeling and mixing estimations made using $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$. Consequently, the recharge areas indicated for the BLR with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ (fig. 15*C*) probably are a better representation of recharge from the BLR, and the transient part of the hydrologic system, than the areas indicated with geochemical modeling.

Table 5 shows that mixing, between surface water and groundwater, two different sources of groundwater, or both types of mixing, occurs throughout the INL. The areas of BLR recharge shown in figure 15*C* also are indicative of the areas at the INL where surface water and groundwater mix. Mixing between surface water and the underlying groundwater will occur when there is flow in the BLR on the INL, which usually occurs during wet climate cycles, and in some years only during spring season runoff, but not during dry climate cycles. Mixing of regional groundwater with groundwater from the mountains and valleys is particularly important to understand and identify because groundwater entering the INL from the mountains and valleys north of the INL travels southeast and regional groundwater entering the INL is traveling southwest. Consequently, the convergence of these two water bodies directly influences groundwater flow directions in the central and eastern parts of the INL.

Mixing lines are shown in figure 16 with hand-drawn contours that identify where regional groundwater contributes 0, 50, and 90 percent of the total recharge. In the northern part of the INL mixing lines trend approximately north-south. This directional trend probably reflects the influence of groundwater from the BCV, which is moving southeasterly when entering the INL on the generally southwesterly flow of regional groundwater. In the central and eastern parts of the INL, the mixing lines trend northeast-southwest, which suggests a diminishing influence of groundwater from the BCV on the direction of flow of regional groundwater. In the south-central part of the INL, the mixing lines begin to trend north-south again, which probably reflects the influence of southerly flowing groundwater from the BCV on regional groundwater-flow directions. These mixing lines also show that groundwater residing in the eastern part of the INL is mostly regional groundwater, whereas groundwater residing in the western half of the INL is entirely from the mountains and valleys north of the INL.

Figure 17 shows areas that indicate the primary groundwater sources of recharge, mixing lines that show where regional groundwater makes up 50 and 90 percent of the underlying groundwater, 1989 water-table contours (from fig. 4), and hand-drawn arrows that indicate approximate groundwater-flow directions at the INL. The arrows were drawn approximately through the center of the groundwater areas, through the center of area between the 50 and 90 percent mixing lines, and parallel to the 90 percent mixing line for the arrow in the southeastern part of the INL. The arrows indicate that flow directions are southwest in the southeastern and south-central parts, southeast in the northern part, and south in the central and western parts of the INL. With one exception, these arrows cross water-table contours in a roughly perpendicular direction, consistent with expected flow directions relative to water-table contours. This consistency provides confidence that the orientation of the areas and lines depicting the primary groundwater resources of recharge and the percentage of regional groundwater are reasonably accurate.

The one exception to this apparent accuracy is near the 4,475-foot-altitude water-table contour in the south-central part of the INL. In this area, the flow direction perpendicular to the water-table contour would be south, but the areas representing groundwater from the BCV and LLRV indicate a southwesterly flow for groundwater in this area. Terminating the southern extension of the area representing groundwater from the BCV near USGS 5 (fig. 15*A*) and extending farther south the areas representing groundwater from the Lemhi Range and LLRV, resolves the discrepancy in flow directions inferred from the 4,475-foot-altitude water-table contour (fig. 17) and areas representing the primary groundwater source of recharge.

End member sources of recharge for ternary mixing webs for USGS 107 and USGS 110A included regional groundwater and groundwater from the BCV (fig. 11). However, if groundwater from the BCV does not extend south to these wells then they require a revised ternary mixing web that does not include groundwater from the BCV. Changing the end member sources of recharge to the BLR, regional groundwater, and groundwater from the LLRV (fig. 18) indicates that these sources of recharge provide, respectively, 8, 46, and 46 percent of recharge to USGS 107 and 14, 50, and 36 percent of recharge to USGS 110A. This revised interpretation probably is a better representation of the groundwater at these wells because it is consistent with lithium and silica concentrations that indicate the groundwater at these wells is primarily regional groundwater (Rattray, 2018, fig. 20). Figure 19 shows the (1) revised areas representing the primary groundwater sources of recharge, (2) 50 and 90 percent mixing lines, and (3) groundwater-flow directions.

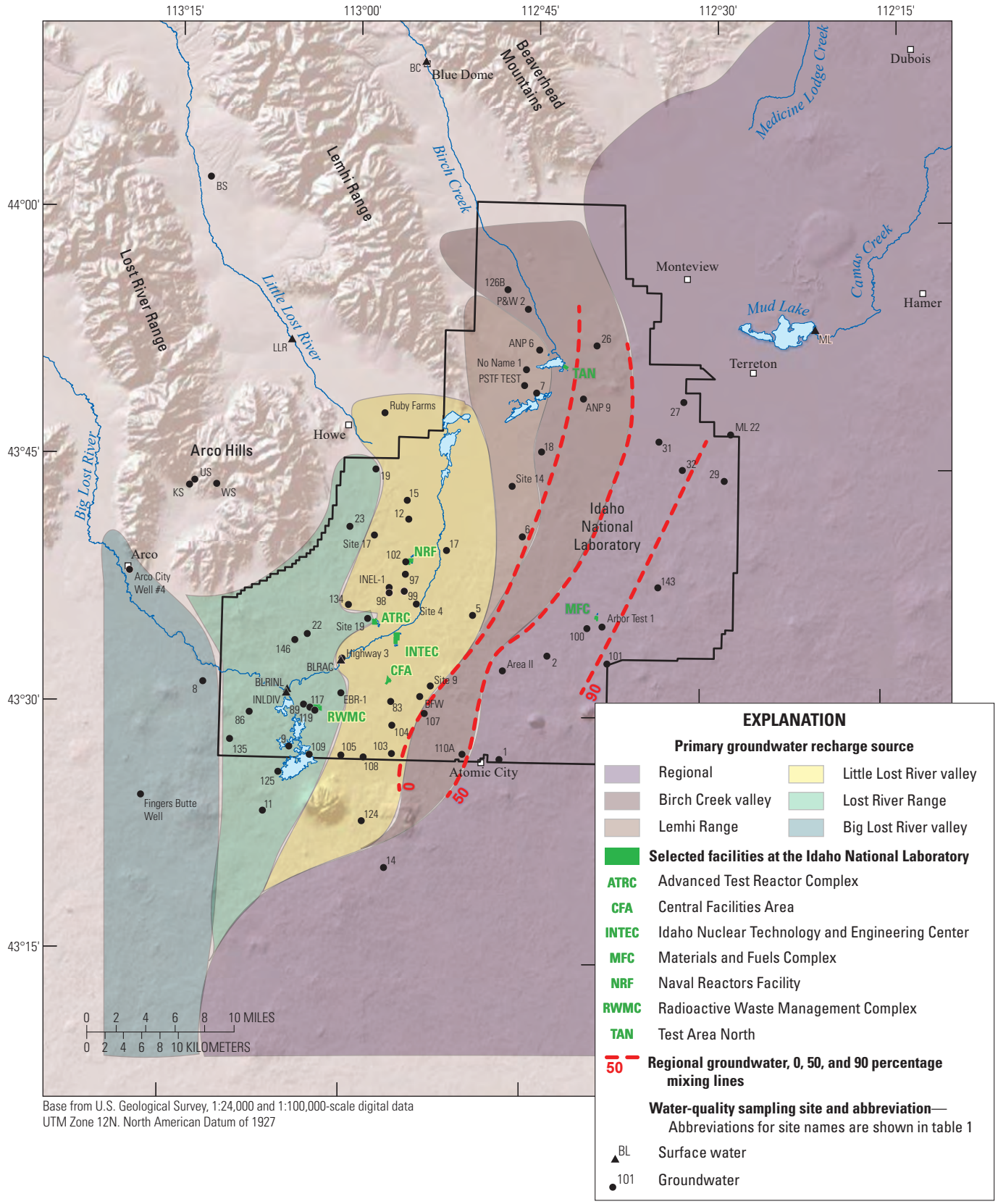


Figure 16. Primary groundwater sources of recharge and mixing lines representing 0, 50, and 90 percent regional groundwater relative to groundwater from the mountains and valleys, Idaho National Laboratory and vicinity, eastern Idaho. Boundaries of primary groundwater sources are hand-drawn and approximate.

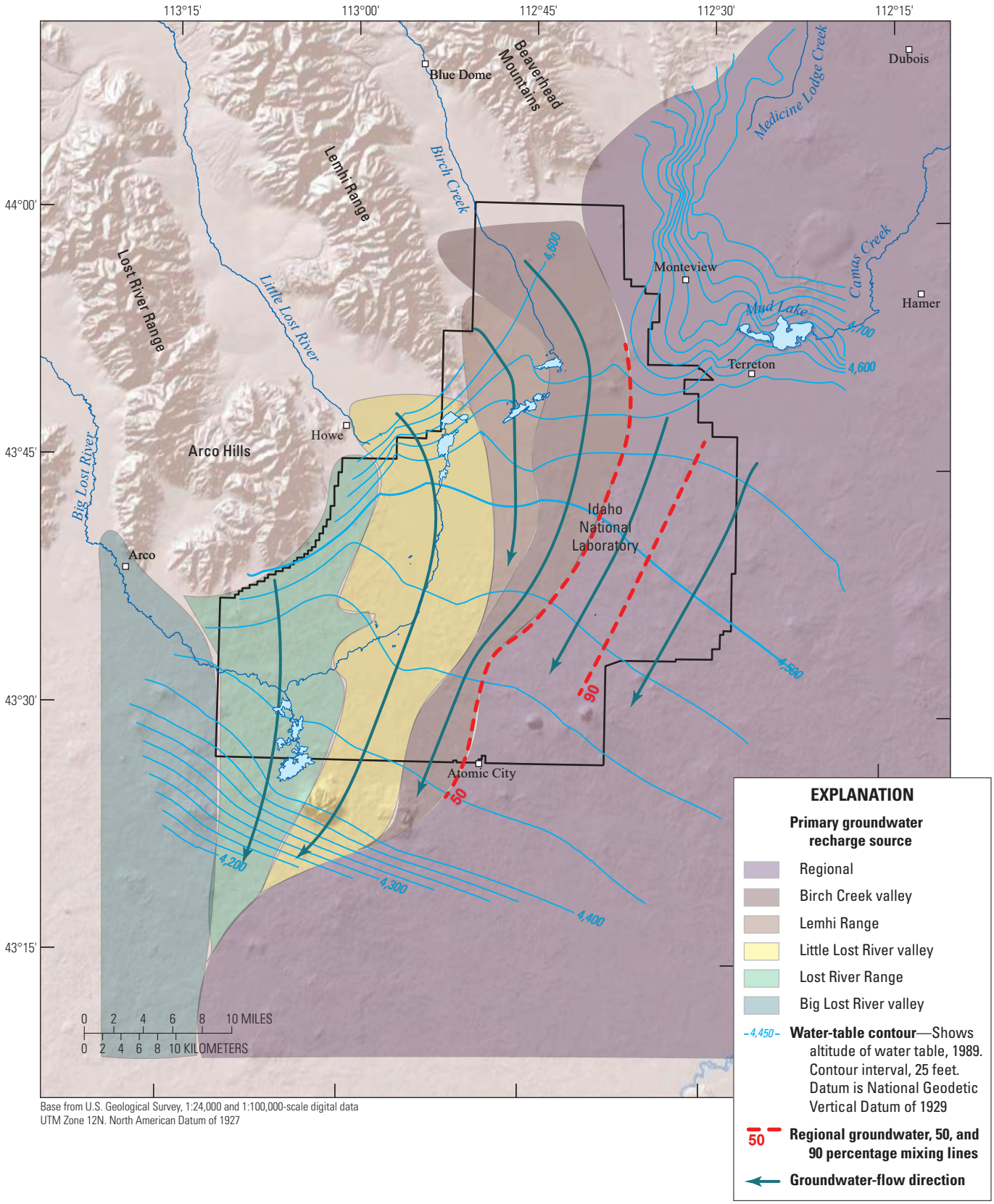


Figure 17. Primary groundwater sources of recharge, percentage of regional groundwater, 1989 water-table contours, and groundwater-flow directions, Idaho National Laboratory and vicinity, eastern Idaho. Boundaries of primary groundwater sources are hand-drawn and approximate.

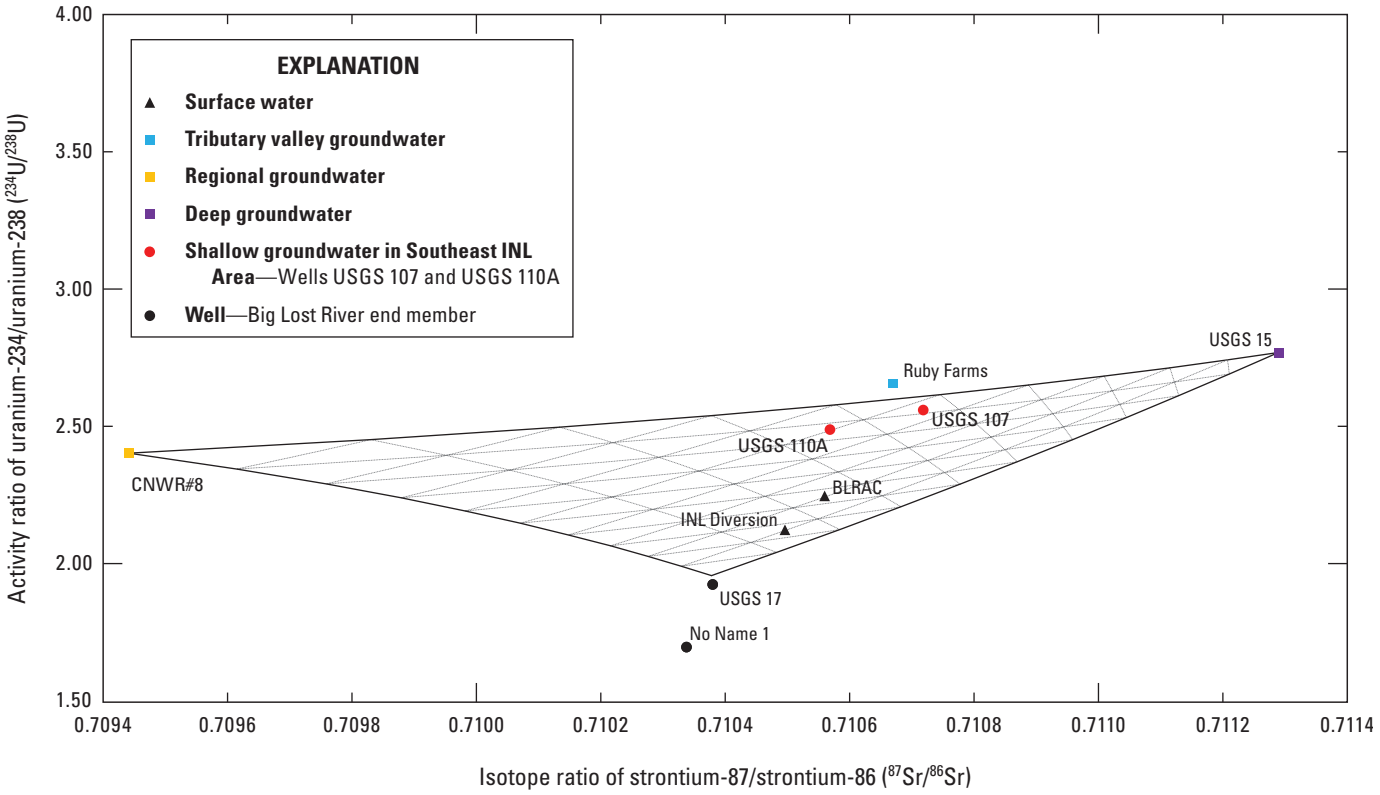


Figure 18. Revised ternary mixing web and sources of recharge for USGS 107 and USGS 110A, Idaho National Laboratory (INL) and vicinity, eastern Idaho. Uranium activities are calculated from isotope analyses of samples collected in 1979 and during 1996–98 (Roback and others, 2001). Strontium concentration and isotope analyses of samples collected in 1979 (Mann, 1986) and during 1996–98 are from Johnson and others (2000), and McLing and others (2002). Samples collected for this study in 1991 and during 2018–19 are available from the U.S. Geological Survey National Water Information System (NWIS) at https://dx.doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2021).

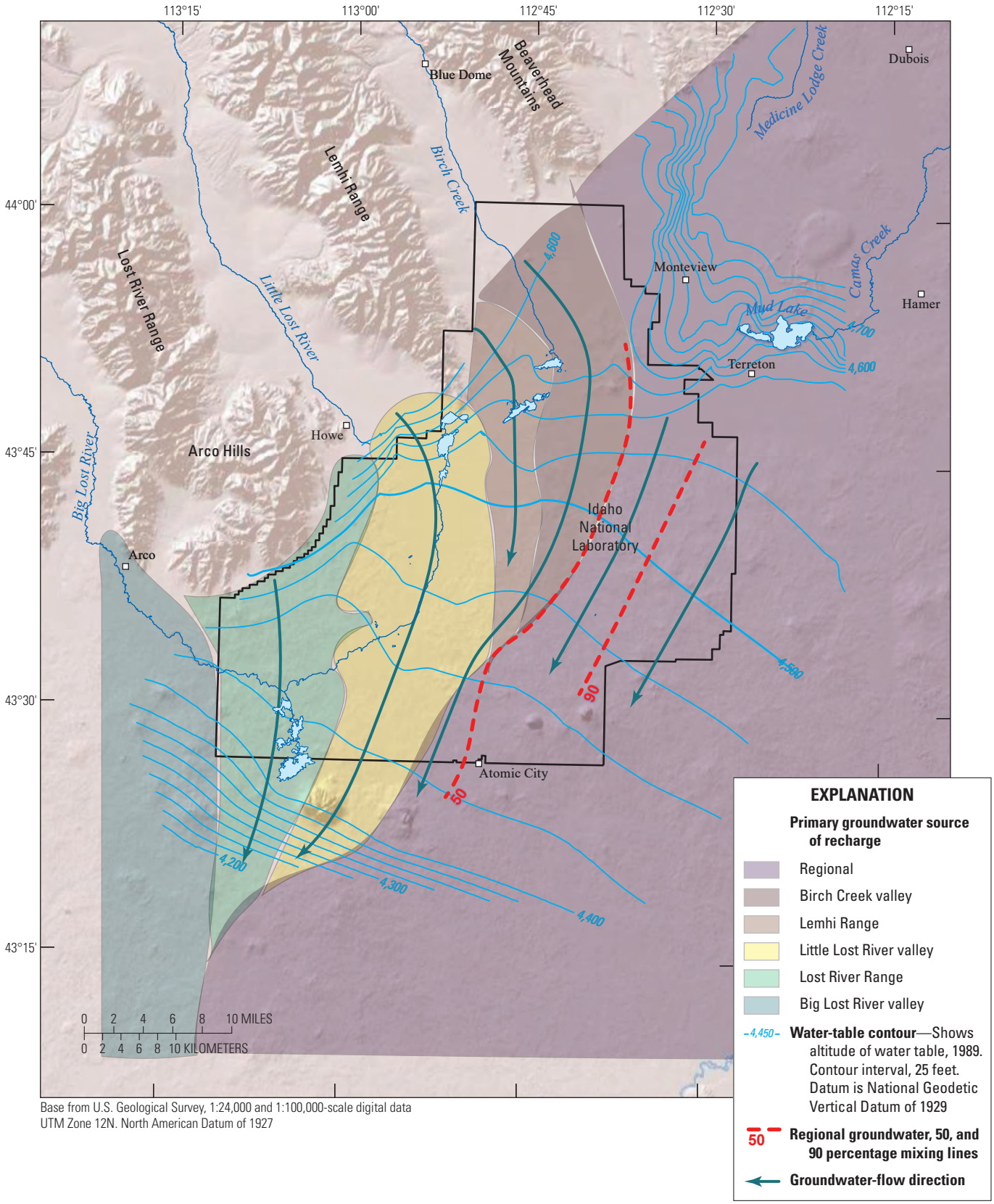


Figure 19. Revised primary groundwater sources of recharge, 50 and 90 percent mixing lines, and groundwater-flow directions, Idaho National Laboratory and vicinity, eastern Idaho. Boundaries of primary groundwater sources are hand-drawn and approximate.

Comparison of Results with Previous Investigations

This study, and geochemical modeling (Rattray, 2019), show that mixing fully explains the distribution of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in groundwater at the INL. Consequently, the hypothesis that fast and slow flow zones are required to explain the distribution of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in groundwater at the INL (Johnson and others, 2000; Luo and others, 2000; Roback and others, 2001; McLing and Roback, 2007) is unnecessary. The differing hydrologic interpretations between this study and these previous investigations are explained by different interpretations about the (1) necessity of water-rock interaction to produce low isotope ratios (that is, a slow flow zone) in groundwater, (2) source and age of water in the slow flow zones, and (3) reliability and accuracy of the contours for the high isotope ratio zone (that is, a fast flow zone) that extends south from the mouth of the LLRV and separates the western and central low isotope ratio zones.

Luo and others (2000), Johnson and others (2000), Roback and others (2001), and McLing and Roback (2007) suggest that water-rock interaction between groundwater and the host basalt, which has low U and Sr isotope ratios (Rattray, 2018, fig. 22), is responsible for the low U and Sr isotope ratios in groundwater in the low isotope ratio zones. They discount mixing between the BLR and groundwater as responsible for these low isotope ratios because some of the isotope ratios in groundwater in the low isotope ratio zones are lower than the isotope ratios in the BLR. However, this interpretation assumes that the U and Sr isotope ratios in the BLR have constant values. This is unlikely because, while groundwater inflow to the BLR probably is relatively constant with time, precipitation in the BLR drainage, and the contribution of surface water runoff to the BLR, varies dramatically on annual and short-term climate cycle time scales. Consequently, the ratio of surface-water runoff to groundwater in the BLR increases as precipitation amounts increase. Because precipitation has lower U and Sr isotope ratios than the BLR (Rattray, 2018, p. 54, fig. 22*B*), U and Sr isotope ratios in the BLR decrease when a larger proportion of precipitation contribute water to the BLR. Therefore, U and Sr isotope ratios in the BLR are not constant with time and infiltration recharge from the BLR is a viable source for the low U and Sr isotope ratios in groundwater in the low isotope ratio zones. Due to the limited sample size to study this effect directly, additional discrete sampling of precipitation inputs to the BLR drainage basin and associated recharge locations during high-water years may further refine this isotope distribution observation for future studies.

Uranium and Sr isotope ratios in the western and central low isotope ratio zones are lowest in groundwater from wells USGS 22 and USGS 17, respectively. Johnson and others (2000), Luo and others (2000), Roback and others (2001), and McLing and Roback (2007) suggest that the low isotope ratios in this water means that it is old, slow-moving groundwater relative to groundwater in the fast-flow zones. In addition, Luo and others (2000, fig. 9) assign residence times of 67 and 77 years to groundwater at USGS 22 and USGS 17, respectively, which indicates that recharge of the source water for these wells predates atmospheric bomb testing. However, other hydrochemical studies indicate that groundwater at USGS 22 and USGS 17 consists entirely or mostly of young recharge from precipitation and the BLR (Busenberg and others, 2001, p. 86 and 90; Rattray, 2019, table 11), respectively. Groundwater at these wells have large tritium activities (160.9±0.4 pCi/L at USGS 22 and 50.0±0.5 pCi/L at USGS 17), which shows that the groundwater contains atmospheric tritium that postdates atmospheric bomb testing (Rattray, 2018, table 17, fig. 13). Consequently, the available chemical evidence supports an interpretation that groundwater at these two wells is young water, not old groundwater.

The reliability and validity of the isotope ratio contours used to define high isotope ratio zones from previous studies were questionable because no U or Sr isotope ratios were available from the area between USGS 22 and USGS17 in the LLRV (fig. 1; Johnson and others, 2000, fig. 2; Luo and others, 2000, fig. 9; Roback and others, 2001, fig. 2; McLing and Roback, 2007, fig. 1). The large isotope ratio zone without isotope data extends from Site 17 in the northern part of the INL to the Badging Facility Well in the southern part of the INL (Johnson and others, 2000, fig. 2; Roback and others, 2001, fig. 2). $^{234}U/^{238}U$ decreased in the downgradient direction from 3.01 at Site 17 to 2.53 at the Badging Facility Well (Roback and others, 2001, table 1, values divided by 55 ppm to convert to activity ratios) whereas $^{87}Sr/^{86}Sr$ at these two wells, 0.71091, were identical (Johnson and others, 2000, GSA Data Repository Table). Consequently, these isotope ratio contours indicate that isotope ratios in the large isotope ratio zone between Site 17 and the Badging Facility Well should be a uniform 0.71091 for $^{87}Sr/^{86}Sr$ and decrease from 3.01 to 2.53 in a north-to-south direction for $^{234}U/^{238}U$.

The validity of the large isotope ratio contours was tested by collecting and analyzing water samples for $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in 2019 from five wells (Site 4, USGS 97, USGS 98, USGS 99, and USGS 102; fig. 1) located between Site 17 and the Badging Facility Well (fig. 1). One well, USGS 99, had a $^{234}U/^{238}U$, 2.70, that was within the isotope ratio range for the large isotope ratio zone, but the $^{87}Sr/^{86}Sr$, 0.71102, was larger than isotope ratio indicated from the isotope ratio contours. The isotope ratios for the other four wells were all lower than suggested from the isotope ratio contours and ranged from 2.06 to 2.35 for $^{234}U/^{238}U$ and 0.71045 to 0.71077 for $^{87}Sr/^{86}Sr$ (table 2; fig. 5). Consequently, the U activity ratios refute the interpretation that there is a large isotope ratio zone located between Site 17 and the Badging Facility Well, the key interpretation presented in support of preferential fast flow paths. The isotope ratios are consistent, however, with mixing between recent recharge from the BLR and old groundwater containing low and high isotope ratios, respectively. Thus, while the $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ from groundwater at the INL do reflect the various and distinct sources of recharge to the aquifer, they do not indicate the presence of slow and fast flow zones of groundwater transport.

Summary and Conclusions

Uranium (U) activity ratios and strontium (Sr) isotope ratios were used to trace sources of recharge from source areas to groundwater at 62 wells distributed throughout the Idaho National Laboratory (INL) by plotting $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in groundwater from the INL on ternary mixing webs with sources of recharge as end members for the mixing webs. The many sources of recharge to groundwater at the INL preclude identifying sources of recharge with only one or a few mixing webs. Consequently, numerous mixing webs were created that represent various geographic areas throughout the INL, such that each area could be limited to just three likely sources of recharge. This strategy was generally successful, although limiting to three sources of recharge in the Central, South, and Southwest INL Areas required interpretation of additional hydrologic and chemical constraints.

The mixing webs were used to estimate the percent recharge from individual sources of recharge to groundwater at well locations. A previously unrecognized source of recharge, groundwater from the Lemhi Range, was identified. Also, the estimated spatial distribution of recharge from the Big Lost River (BLR) and groundwater from the Lost River Range decreased and increased, respectively, relative to the spatial distribution estimated with geochemical modeling. These changes were due to over estimating recharge from the BLR in the North INL Area with geochemical modeling and better resolution of recharge of groundwater from the Lost River Range using $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ signatures.

Uncertainty in estimates of percent recharge were evaluated. Precision, representing measurement error plus error in estimates of recharge from the mixing web, were generally 5 percent or less. Accuracy was evaluated by comparing the percent sources of recharge determined with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ and geochemical modeling. However, due to the additional sources of recharge and improved resolution of recharge with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$, this comparison resulted in large differences in percent recharge between the two methods. Based on the additional recharge information identified with $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$, though, the mixing webs probably provide better estimates of the sources of recharge. These estimates are less accurate in areas at the INL where the ESRP aquifer acts as a transient hydrologic system as compared to the steady-state parts of the aquifer because flow, and $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$, in the BLR vary significantly in response to precipitation amounts in the BLR drainage basin.

Groundwater in the eastern Snake River Plain aquifer generally flows from northeast to southwest. This general direction of flow is altered at the INL by the southeasterly flow of groundwater from the Birch Creek and Little Lost River valleys into the ESRP aquifer. As this valley groundwater converges with regional groundwater, the flow direction turns south and eventually southwest in the central and south-central parts of the INL, respectively.

Upwelling geothermal water is presumed to flow across the base of the aquifer. However, upwelling geothermal water was identified at just one well (USGS 7) at the INL, indicating that the upward movement of deep groundwater to the shallow (upper 250 ft) part of the aquifer is largely nonexistent. Consequently, shallow groundwater must flow in horizontal or downward directions.

Mixing between surface water and groundwater, different groundwaters, or both is ubiquitous at the INL. Mixing of water fully explains the distribution of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$ in groundwater at the INL and thus renders unnecessary the hypothesis that fast and slow flow zones at the INL are required to explain the distribution of $^{234}U/^{238}U$ and $^{87}Sr/^{86}Sr$.

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Glossary

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

groundwater from multilevel wells Groundwater from wells with multiple, discrete sampling zones of various depths below the land surface. Provides a vertical profile of groundwater chemistry in the ESRP aquifer. Groundwater from multilevel wells may be either contaminated or natural groundwater.

natural groundwater Groundwater at and south of the Idaho National Laboratory, excluding contaminated groundwater, that is less than 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.

paleorecharge Groundwater that was recharged during the last glacial epoch.

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.

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

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 83702-4520
https://www.usgs.gov/centers/idaho-water-science-center

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