

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

Nitrate ($\text{NO}_2 + \text{NO}_3 - \text{N}$) in Ground Water of the Upper Snake River Basin, Idaho and Western Wyoming, 1991–95

Water-Resources Investigations Report 97–4174

NATIONAL WATER - QUALITY ASSESSMENT PROGRAM

Nitrate ($\text{NO}_2+\text{NO}_3-\text{N}$) in Ground Water of the Upper Snake River Basin, Idaho and Western Wyoming, 1991–95

By Michael G. Rupert

U.S. Geological Survey

Water-Resources Investigations Report 97–4174

Boise, Idaho
1997

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Mark Schaefer, Acting Director

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

For additional information write to:

District Chief
U.S. Geological Survey
230 Collins Road
Boise, ID 83702-4520

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Federal Center
Denver, CO 80225

Information regarding the National Water-Quality Assessment (NAWQA) Program is available on the Internet via the World Wide Web. You may connect to the NAWQA home pages using the universal resource locator (URL) at:

http://wwwrvares.er.usgs.gov/nawqa/nawqa_home.html

or

http://wwwidaho.wr.usgs.gov/nawqa/usnk_home.html

FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for a specific contamination problem; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequence of new policies.

To address these needs, the Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 60 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 60 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

CONTENTS

Foreword.....	iii
Abstract.....	1
Introduction	2
Purpose and scope	3
Acknowledgments	3
Study unit description	3
Geohydrology	3
Eastern Snake River Plain aquifer	8
Local alluvial aquifers	8
Tributary valley aquifers	8
Sources of nitrogen	10
Methods	10
Regional network	10
Idaho Statewide Ground-Water Monitoring Program	10
NAWQA Program	13
Local network	13
Sampling	13
Quality assurance	14
Regional evaluation of nitrite plus nitrate as nitrogen in ground water	14
Relations between concentrations of nitrite plus nitrate as nitrogen and depth to water, land use, precipitation, and soils	18
Depth to water	18
Land use	18
Precipitation	19
Soils	19
Ground-water vulnerability and probability mapping	19
Ground-water vulnerability mapping	21
Ground-water probability mapping	22
Local evaluation of nitrite plus nitrate as nitrogen in ground water	26
Dissolved organic carbon and oxygen	27
Methylene blue active substances	30
Dissolved nutrients	30
Major ions	31
Isotopes	31
Hydrogen and oxygen	33
Nitrogen	35
Tritium	38
Hypothesis for observed ground-water quality in local study areas	38
Long-term trends of nitrite plus nitrate as nitrogen in ground water	40
Summary	43
References cited	45

FIGURES

1–6. Maps showing:	
1. Location of the upper Snake River Basin and local alluvial aquifer near Burley	4
2. Major land-use classifications in the upper Snake River Basin	5

3.	Water table in part of the eastern Snake River Plain aquifer and in the local alluvial aquifer near Burley, 1993–95	6
4.	Depth to first-encountered ground water, eastern Snake River Plain, 1980–88	9
5.	Locations of wells sampled as part of the Idaho Statewide Ground-Water Monitoring Program, 1991–94, and wells sampled as part of the U.S. Geological Survey National Water-Quality Assessment Program, 1995, upper Snake River Basin	11
6.	Land use and sources of irrigation water in local study areas, eastern Snake River Plain	12
7.	Boxplots showing relations between concentrations of dissolved nitrite plus nitrate as nitrogen and water use, number of wells, well depth, depth to water, and saturated interval of wells, upper Snake River Basin, 1991–95	16
8.	Maps showing concentrations of dissolved orthophosphorus as phosphorus and dissolved nitrite plus nitrate as nitrogen in ground water, upper Snake River Basin, 1991–95	17
9.	Boxplots showing correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and depth to first-encountered ground water, eastern Snake River Plain, 1991–94	18
10.	Boxplot showing correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and land use, upper Snake River Basin, 1991–94	19
11.	Map showing STATSGO soil-drainage categories, upper Snake River Basin	20
12.	Boxplots showing correlations between concentrations of dissolved nitrite plus nitrate as nitrogen in ground water and STATSGO soil-drainage categories, upper Snake River Basin, 1991–94	21
13.	Boxplots showing correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and relative ground-water vulnerability ratings of Rupert and others (1991), eastern Snake River Plain, 1991–94	22
14.	Map showing probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, eastern Snake River Plain	23
15.	Boxplots showing correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and contamination probability, eastern Snake River Plain, 1991–94	24
16.	Boxplots showing correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and nitrogen input, upper Snake River Basin, 1991–94	24
17.	Map showing probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, nitrogen input included, eastern Snake River Plain	25
18–20.	Boxplots showing:	
18.	Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and contamination probability, nitrogen input included, eastern Snake River Plain, 1991–94	26
19.	Relations among water use, well depth, depth to water, and saturated interval of wells, local study areas, eastern Snake River Plain, 1993–95	27
20.	Concentrations of dissolved nitrite plus nitrate as nitrogen in surface and ground water, eastern Snake River Plain, 1993–95	31
21.	Map showing concentrations of dissolved nitrite plus nitrate as nitrogen in ground water, local study areas, eastern Snake River Plain, 1993–95	32
22.	Boxplots showing concentrations of bicarbonate in surface and ground water, local study areas, eastern Snake River Plain, 1993–95	33
23.	Graphs showing relations between concentrations of dissolved nitrite plus nitrate as nitrogen and bicarbonate in ground water, local study areas, eastern Snake River Plain, 1993–95	33
24.	Graph showing relations between relative hydrogen isotope ratios and relative oxygen isotope ratios in ground water, local study areas, eastern Snake River Plain, 1993–95	34
25.	Map showing relative hydrogen isotope compositions in ground water, local study areas, eastern Snake River Plain, 1993–95	36
26.	Graph showing relations between concentrations of dissolved nitrite plus nitrate as nitrogen and relative hydrogen isotope ratios in ground water, local study areas, eastern Snake River Plain, 1993–95	37
27.	Boxplots showing nitrogen isotope ratios in ground and surface water, local study areas, eastern Snake River Plain, 1993–95	37
28.	Map showing concentrations of tritium in ground water, local study areas, eastern Snake River Plain, 1993–95	39

29. Map and graphs showing long-term concentrations of dissolved nitrite plus nitrate as nitrogen in water from Box Canyon, Briggs, and Blue Lakes Springs, upper Snake River Basin, 1980–96	41
30. Map showing long-term concentrations of nitrite plus nitrate as nitrogen in ground water, A&B study area, eastern Snake River Plain, 1980–95	42

TABLES

1. Hydrogeologic and land-use conditions, local study areas, eastern Snake River Plain	13
2. Fecal coliform bacteria and nutrients in ground water, upper Snake River Basin, 1991–95	14
3. Rating scheme for probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, eastern Snake River Plain	22
4. Summary statistics for selected constituents in ground water, local study areas, eastern Snake River Plain, 1993–95	28
5. Summary statistics for selected constituents in water from the Snake River downstream from Lake Walcott, the North Side and Main Canals near Milner Dam, the Snake River near Kimberly, the Snake River near Twin Falls, and the Snake River near Buhl, eastern Snake River Plain, 1993–95	35
6. Summary of selected characteristics of ground water in local study areas, eastern Snake River Plain	40

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
¹ foot squared per day (ft ² /d)	0.0929	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
picocurie per liter (pCi/L)	0.037	becquerel per liter
square mile (mi ²)	2.590	square kilometer

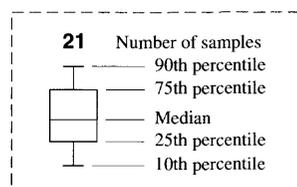
Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units:

- µm micrometers
- mg/L milligrams per liter
- mL milliliters

EXPLANATION FOR BOXPLOTS

(Figures 7, 9, 10, 12, 13, 15, 16, 18, 19, 20, 22, 27)



¹The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft³/d)/ft²ft]. In this report the mathematically reduced form, foot squared per day (ft²/d), is used for convenience.

NITRATE ($\text{NO}_2+\text{NO}_3\text{-N}$) IN GROUND WATER OF THE UPPER SNAKE RIVER BASIN, IDAHO AND WESTERN WYOMING, 1991–95

By Michael G. Rupert

Abstract

Factors related to contamination of ground water by dissolved nitrite plus nitrate as nitrogen ($\text{NO}_2+\text{NO}_3\text{-N}$) in parts of the upper Snake River Basin were evaluated at regional and local scales. Regional-scale relations between $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations and depth to first-encountered ground water, land use, precipitation, and soils were evaluated using a geographic information system. Local-scale relations between $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations and other nutrients, major ions, nitrogen isotopes, stable isotopes, and tritium in five areas with different hydrogeologic settings, land use, and sources of irrigation water were evaluated to determine the factors causing differences in $\text{NO}_2+\text{NO}_3\text{-N}$. Data were collected and analyzed as part of the U.S. Geological Survey's National Water-Quality Assessment Program, which began in 1991.

Regionally, where depth to first-encountered ground water was between 0 and 300 feet, $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water were significantly higher than where depth to water was between 301 and 900 feet. Ground water in urban areas contained the highest $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations; ground water in irrigated agriculture areas contained the next-highest concentrations. Ground water in rangeland, dryland agriculture, and forest areas contained similar low $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations. There was no correlation between pre-

cipitation and $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water. Ground water in areas with excessively drained soils contained the highest $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations; ground water in areas with poorly drained soils contained the lowest $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations. Ground water in counties where residual nitrogen input was greater than 3,000,000 kilograms contained significantly higher nitrogen concentrations than in counties where residual total nitrogen input was less than 3,000,000 kilograms.

Two maps showing the probability of ground-water contamination by $\text{NO}_2+\text{NO}_3\text{-N}$ were developed; one used data on depth to first-encountered ground water, land use, and soils, and the other incorporated additional data on nitrogen input. Probability categories were based on correlations between $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations and those four hydrogeologic and land-use factors. Correlations between $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water and probability categories demonstrated significant differences at a greater-than-99-percent confidence level. Because the probability maps are calibrated to actual ground-water quality data, they are a significant improvement over ground-water vulnerability maps generated using the DRASTIC technique.

Local-scale evaluation determined that high $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water were correlated with high major ion concentrations, heavy hydrogen and oxygen isotopes, and

ground-water ages that postdate atmospheric nuclear testing (1952). The heavy hydrogen and oxygen isotope values indicated that high $\text{NO}_2 + \text{NO}_3 - \text{N}$ was associated with water that had undergone evaporation; high major ion concentrations indicated that concentrated ions and $\text{NO}_2 + \text{NO}_3 - \text{N}$ may be leaching from the soil by excess irrigation water. $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water in parts of the A&B study area were high because of continual recycling of ground water as it is pumped from the ground, applied to fields, and then leached back to the water table. $\text{NO}_2 + \text{NO}_3 - \text{N}$ and major ion concentrations decrease as ground water travels from the A&B area to the Eden area because of dilution by Snake River irrigation water. $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations and stable isotope ratios increase from background concentrations as ground water travels through the Jerome/Gooding area, similar to conditions observed in the A&B area, but at a lesser rate, possibly due to less infiltration of contaminated recharge water.

Long-term $\text{NO}_2 + \text{NO}_3 - \text{N}$ data are available for three springs that discharge water from the eastern Snake River Plain aquifer and for several wells in the A&B study area. Long-term overall $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations from all three springs do not appear to have changed significantly since 1980. However, $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in samples collected from Briggs and Box Canyon Springs during the fall months have increased since the mid-1980's. It is unknown whether concentrations will change as the result of a large increase in the number of dairy cattle from 1990 through 1995 in areas upgradient from these springs. $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water in several parts of the A&B study area increased dramatically during 1980–95. Concentrations in parts of the A&B study area could exceed the drinking water maximum contaminant level of 10 mg/L in the next 10 to 15 years if the current rate of increase continues.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) began full-scale implementation of the National Water-Quality Assessment (NAWQA) Program. The long-term goals of the program are to (1) provide a nationally consistent description of current water-quality conditions for a large part of the Nation's water resources; (2) define long-term trends in water quality; and (3) identify, to the extent possible, the major factors that affect observed water-quality conditions and trends (Leahy and others, 1990, p. 1).

The design of the program enables integration of the information into a nationally consistent data base for comparisons of water-quality data over a large range of geographic and hydrologic conditions. The general concepts for full-scale implementation of the NAWQA Program are outlined in reports by Hirsch and others (1988) and Gilliom and others (1995). Sixty study units across the United States were selected to incorporate between 60 and 70 percent of the Nation's usable water supply. Investigations will occur in three phases. Work on the first 20 study units began in 1991; work on the second and third sets of study units began in 1994 and 1997, respectively. The upper Snake River Basin was selected as part of the first phase of 20 study units, and assessment of the basin began in 1991. Intensive monitoring and analysis proceeded through fiscal year 1995 and will be followed by a 5-year, less intensive, data-collection phase.

Nitrite plus nitrate as nitrogen ($\text{NO}_2 + \text{NO}_3 - \text{N}$) concentrations in ground water in parts of the upper Snake River Basin (USNK) exceed the U.S. Environmental Protection Agency (USEPA) maximum contaminant level of 10 mg/L (Young, Parlman, and Jones, 1987; Young, Parlman, and O'Dell, 1987; Parlman and Young, 1987, 1988, 1989; Rupert, 1994; Rupert and others, 1996). The primary health hazard of high $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in drinking water is methemoglobinemia, or blue baby syndrome, which is characterized by the reduced ability of blood to carry oxygen. Methemoglobinemia can affect livestock as well as humans. High concentrations of $\text{NO}_2 + \text{NO}_3 - \text{N}$ in drinking water also may be implicated with a high incidence of non-Hodgkin's lymphoma (Weisenburger, 1991, p. 309).

Concern about $\text{NO}_2 + \text{NO}_3 - \text{N}$ in ground water of the USNK has generated interest in determining the factors related to $\text{NO}_2 + \text{NO}_3 - \text{N}$ contamination. Factors

that cause elevated $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water of the basin are not well understood.

Purpose and Scope

This report describes the evaluation of factors related to $\text{NO}_2+\text{NO}_3\text{-N}$ contamination of ground water in the USNK. Data were examined at two scales: regional and local. Regional-scale relations between $\text{NO}_2+\text{NO}_3\text{-N}$ and depth to first-encountered ground water, land use, precipitation, and soils across the entire basin were examined using a geographic information system (GIS). Local-scale relations among ground-water quality constituents in five areas on the eastern Snake River Plain, where hydrogeologic setting, land-use practices, and sources of irrigation water vary, were compared to help determine factors related to differences in $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations.

Acknowledgments

The author acknowledges the assistance and information provided by personnel from the following agencies: Idaho Agricultural Statistics Service; Idaho Department of Agriculture; Idaho Division of Environmental Quality (formerly Idaho Department of Health and Welfare, Division of Environmental Quality); Idaho Department of Water Resources; University of Idaho, Cooperative Extension Service and Agricultural Research Service; and the U.S. Natural Resource Conservation Service. John Mitchell, Idaho Department of Water Resources, is particularly noted for his assistance in examining the long-term $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water of the A&B study area. The assistance of Karen Burow, Mark Hardy, LeRoy Knobel, Gerald Lindholm, and Niel Plummer, USGS, for their comments during the colleague review process also is acknowledged.

STUDY UNIT DESCRIPTION

The 35,800-mi² USNK extends from Yellowstone National Park in Wyoming to King Hill in south-central Idaho (fig. 1). The 10,800-mi² eastern Snake River Plain is about 60 mi wide and 200 mi long. About 50 percent of the USNK is rangeland, about 21 percent is agricultural land, and about 23 percent is forest land (Maupin, 1995, p. 22). Most of the 4.7 million acres of

agricultural land is near the Snake River and near the mouths of tributary basins (fig. 2). Most cities and industrial centers are near the Snake River. Predominant native vegetation includes cedar, fir, and pine forests in the mountains, and sagebrush and bunchgrass in valleys and on the plain. Large parts of the plain contain surface exposures of sparsely vegetated Quaternary basalt.

The climate of most of the basin is semiarid. Mean annual precipitation ranges from less than 10 in. on much of the plain to as much as 70 in. on the southern part of the Teton Range. The basin is characterized by moderately to severely cold winters and hot, dry summers. The average length of the growing season is about 120 to 160 days.

Land-surface altitude ranges from about 2,500 ft above sea level at the western edge of the basin to 13,770 ft in the mountainous eastern part in Wyoming. The northern and northwestern parts of the basin are characterized by mountains that, in places, exceed 12,000 ft in altitude, and by deep intermontane valleys. The relatively flat eastern Snake River Plain is 2,500 to 6,000 ft above sea level.

Idaho ranks third in the Nation, behind California and Texas, for total water use (Rupert, 1994, p. 5). In 1990, 2.5 million acres on the eastern Snake River Plain were irrigated with 6.6 million acre-ft of ground water and 7.6 million acre-ft of surface water (Maupin, 1995, p. 33). The USNK contained 71 percent of all irrigated acreage in Idaho in 1990; potatoes, wheat, sugar beets, hay, and barley were the predominant crops.

Geohydrology

Three major types of aquifers are present in the USNK: a regional basalt aquifer, local alluvial aquifers, and tributary valley aquifers. The regional aquifer underlying the eastern Snake River Plain is composed primarily of fractured basalt, although some isolated deposits of alluvium and silicic volcanic rocks also are present, particularly along the margins of the plain. Locally overlying the eastern Snake River Plain aquifer are alluvial aquifers, some of which are perched. A series of tributary valley aquifers adjoin the plain and are a major source of recharge to the eastern Snake River Plain aquifer because of underflow and seepage from streams that flow onto the plain. Tributary valley aquifers are composed primarily of alluvium. Greater emphasis is placed on the eastern Snake River Plain aquifer throughout this report because most water-

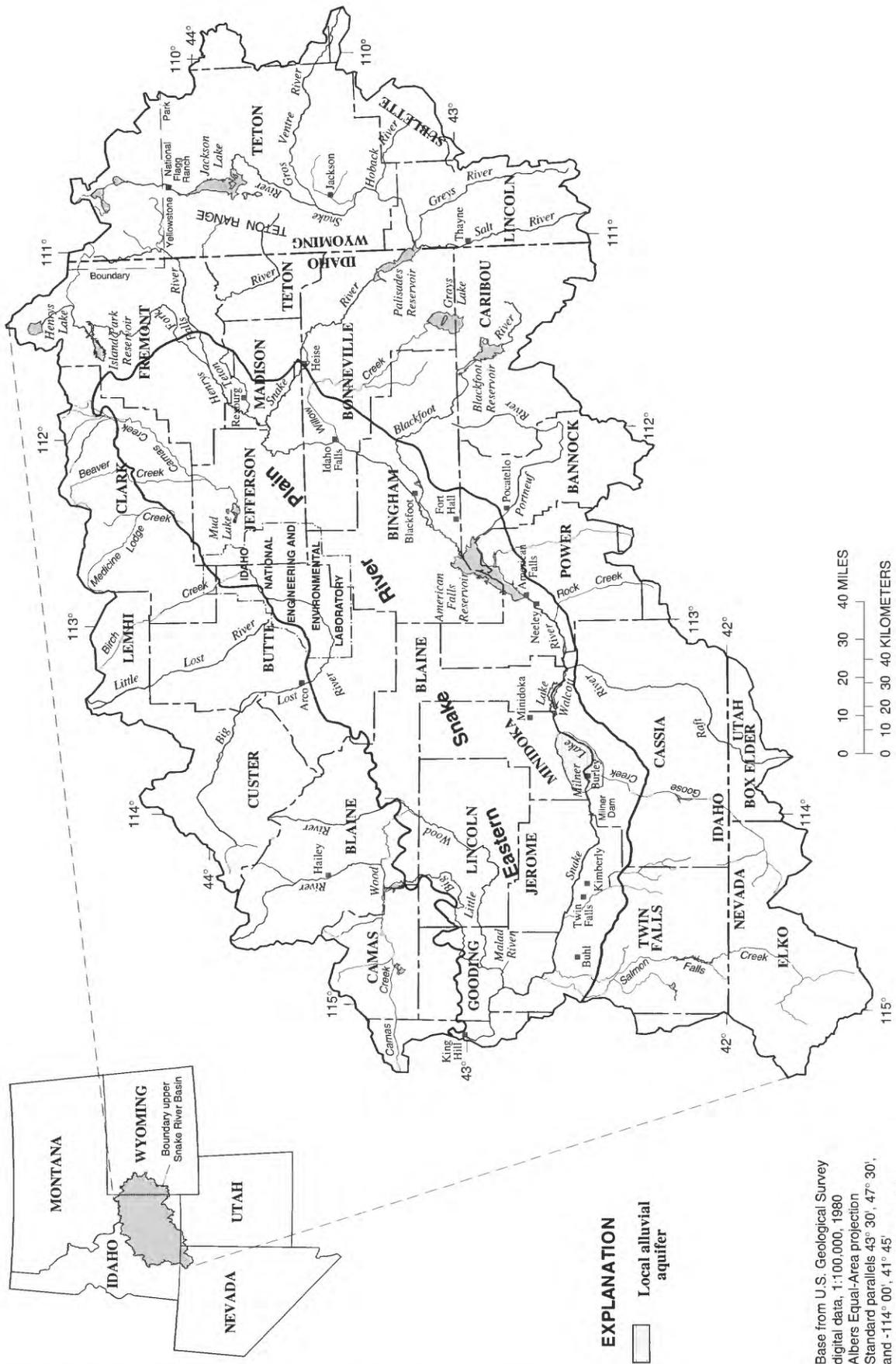
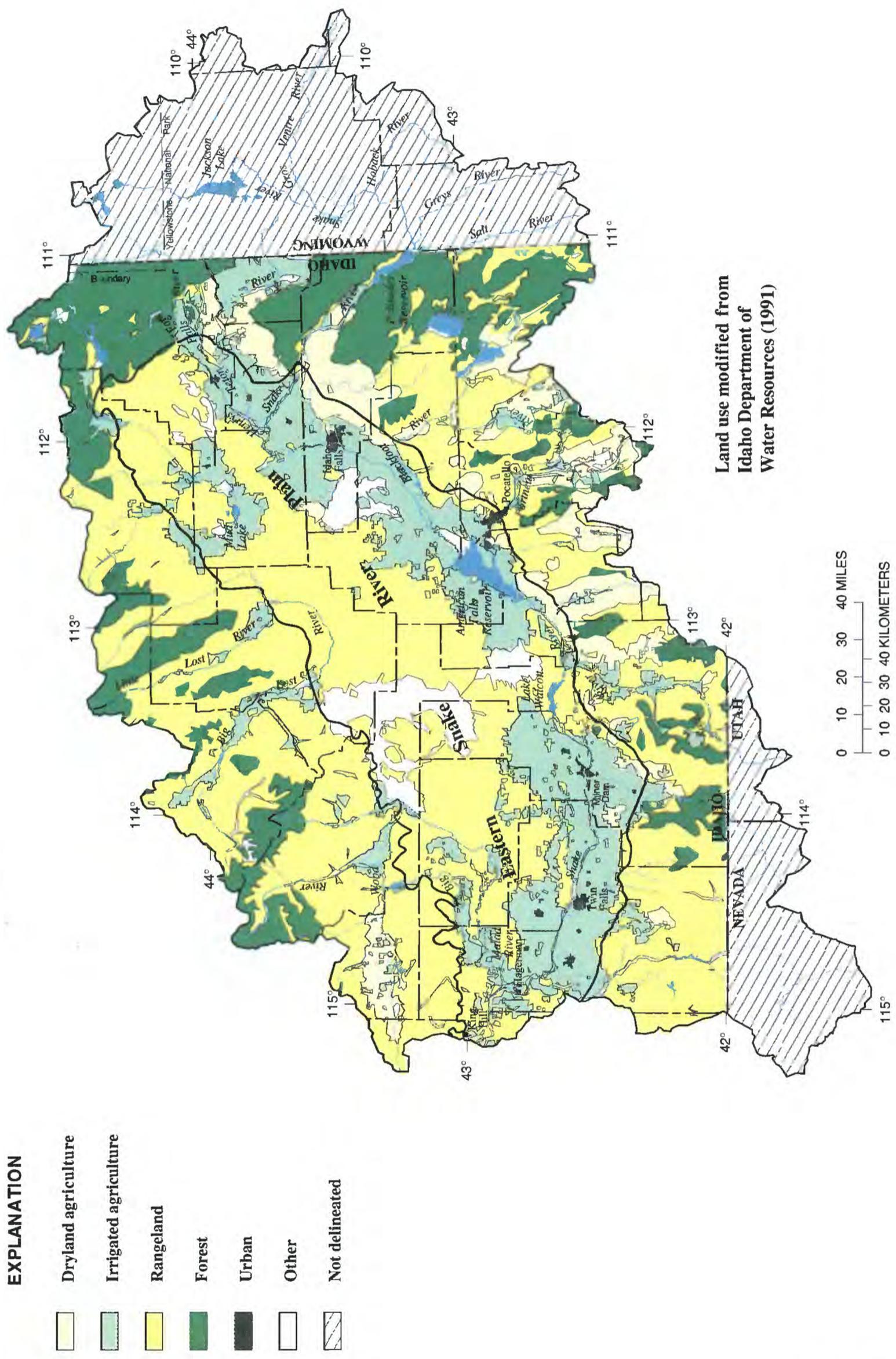
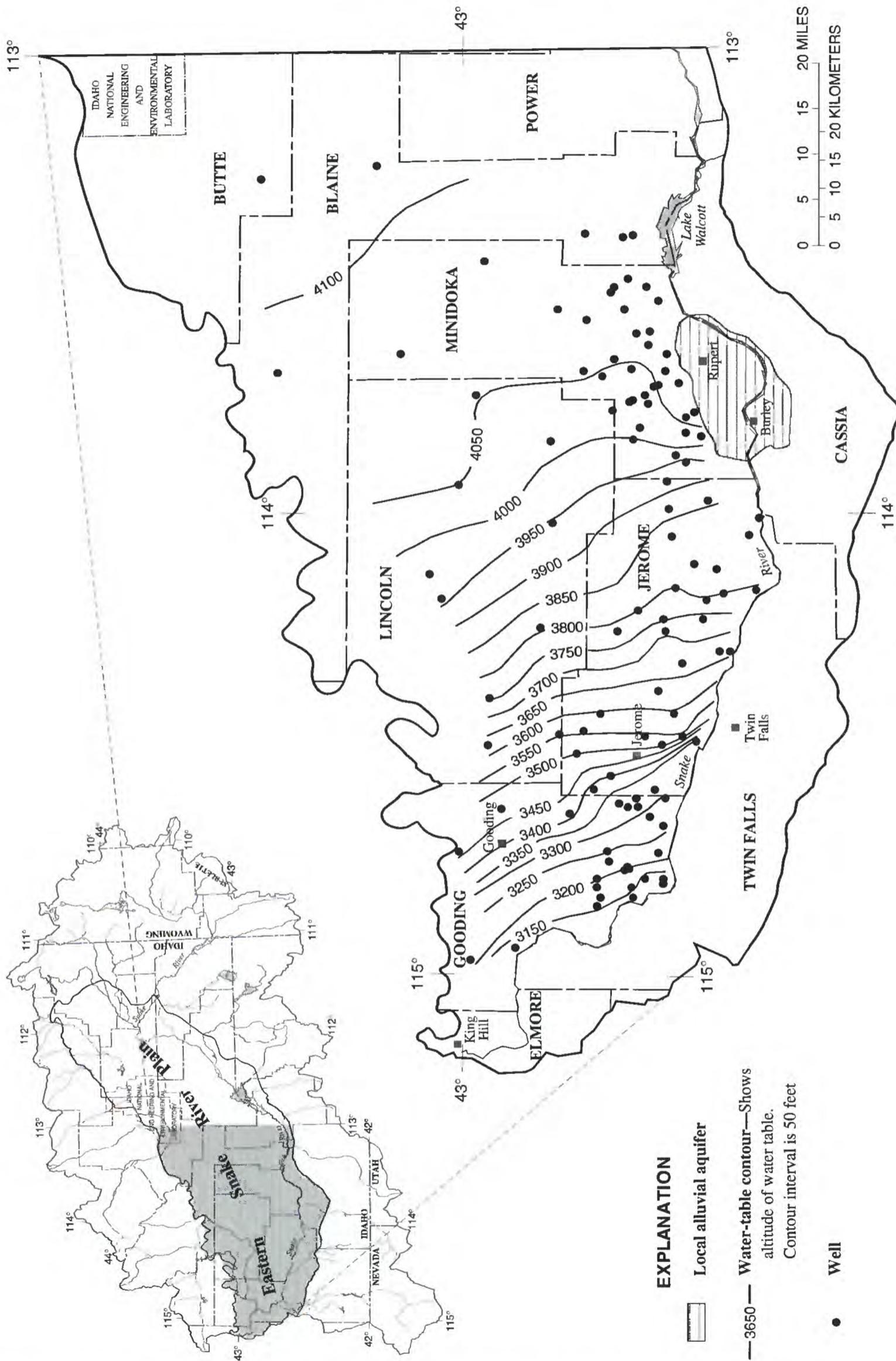


Figure 1. Location of the upper Snake River Basin and local alluvial aquifer near Burley.



Land use modified from
Idaho Department of
Water Resources (1991)

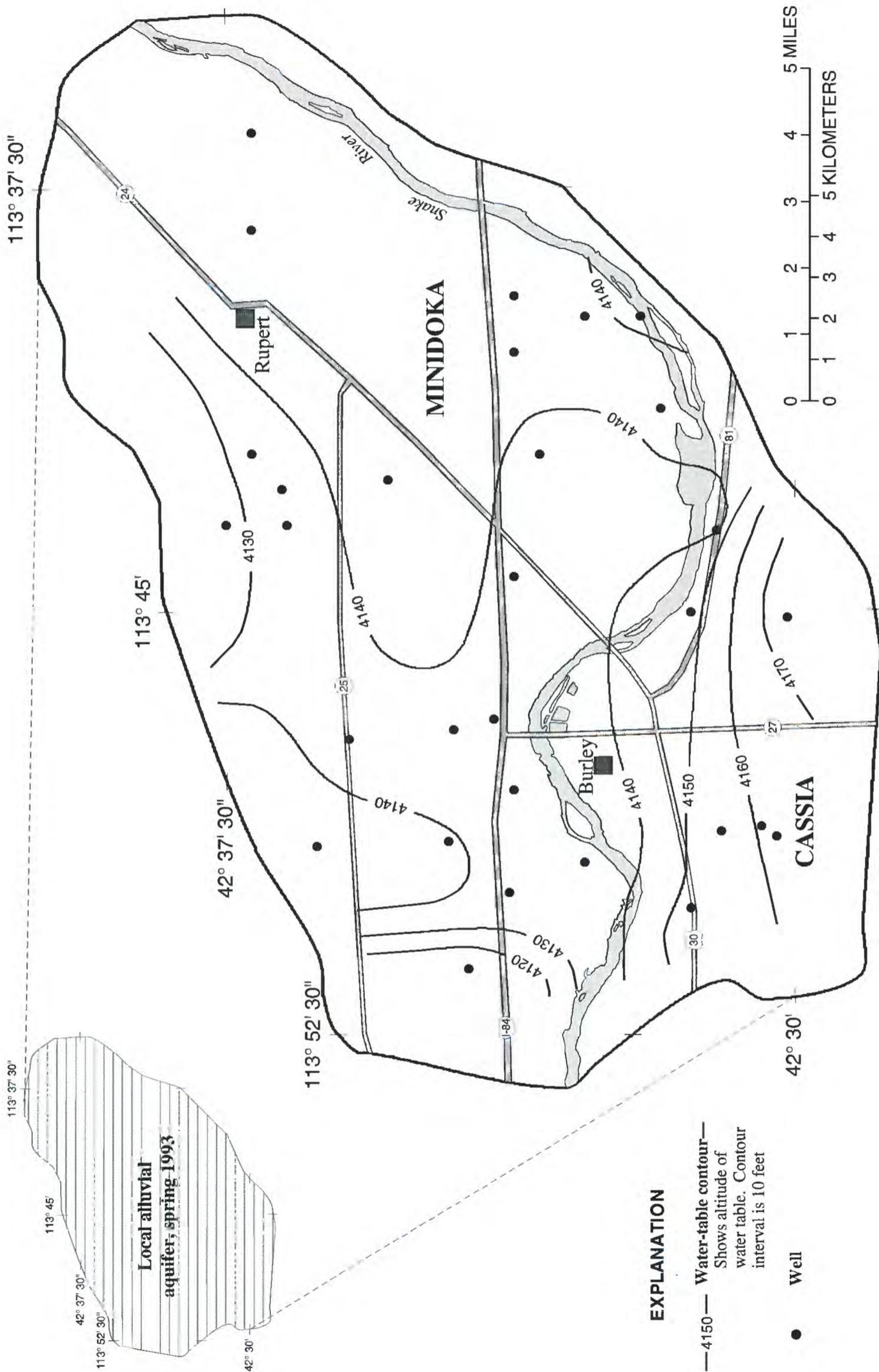
Figure 2. Major land-use classifications in the upper Snake River Basin.



EXPLANATION

-  Local alluvial aquifer
-  —3650— Water-table contour—Shows altitude of water table. Contour interval is 50 feet
-  • Well

Figure 3. Water table in part of the eastern Snake River Plain aquifer and in the local alluvial aquifer near Burley, 1993-95.



EXPLANATION

- 4150— Water-table contour— Shows altitude of water table. Contour interval is 10 feet
- Well

Figure 3. Water table in part of the eastern Snake River Plain aquifer and in the local alluvial aquifer near Burley, 1993-95—Continued.

quality data are for the plain and most water use is on the plain.

EASTERN SNAKE RIVER PLAIN AQUIFER

The eastern Snake River Plain is underlain predominantly by a series of vesicular and broken Quaternary olivine basalt flows of the Snake River Group. Individual flows average 20 to 25 ft in thickness; geophysical data and drillers' logs indicate that total thickness is as much as 5,000 ft (Whitehead, 1992, p. B1). Basalt is generally less than 10 ft below land surface in the central part of the plain and is generally less than 100 ft below land surface elsewhere.

Layered basalt flows underlying the eastern Snake River Plain contain and yield exceptionally large volumes of water to wells and springs. Wells open to less than 100 ft of the aquifer yield as much as 7,000 gal/min; yields of 2,000 to 3,000 gal/min with only a few feet of drawdown are common (Whitehead, 1992, p. 22–25; Lindholm, 1996, p. 18–22). Individual well yields from the eastern Snake River Plain aquifer are some of the largest in the Nation. Transmissivity commonly exceeds 100,000 ft²/d and locally is as much as 1,000,000 ft²/d.

Water levels measured in April and early May during 1993–95 were used to generate a regional water-table map (M. Donato, U.S. Geological Survey, written commun., 1996) for the southeastern half of the eastern Snake River Plain aquifer (fig. 3). Configuration of the water table is similar to that shown by Lindholm and others (1988), except for slightly lower water levels resulting from a regional lowering of the water table. Regionally, water in the eastern Snake River Plain aquifer moves from northeast to southwest. The potentiometric surface descends 2,000 ft along a 200-mi-long flowpath at an average gradient of 10 ft/mi (Lindholm and others, 1988). Flow velocities average about 10 ft/d (Robertson and others, 1974, p. 13). Ground-water travel times are as much as 350 years (Ackerman, 1995, p. 1). Depth to first-encountered water ranges from less than 3 ft in alluvium along the Snake River (Maupin, 1992) to about 1,000 ft in the north-central part of the eastern plain (fig. 4).

Ground water is discharged from the eastern Snake River Plain aquifer as spring flow and seepage to the Snake River between Milner Dam and King Hill (fig. 1). Discharge to this reach was about 6,000 ft³/s in 1980 (Kjelstrom, 1992, fig. 2). Ground-water discharge increased considerably from about 1910 through the early 1950's (Kjelstrom, 1992, fig. 2). The increase is attrib-

uted to recharge from surface-water irrigation north and east of the springs. Since the early 1950's, ground-water discharge has decreased as a result of (1) increased ground-water withdrawals for irrigation (Moreland, 1976, p. 9), (2) more efficient irrigation practices such as conversion from gravity-fed to sprinkler irrigation, and (3) local droughts (Kjelstrom, 1992, p. 2). Elevations of water levels in wells reflect the same long-term downward trend (Kjelstrom, 1992).

LOCAL ALLUVIAL AQUIFERS

Local alluvial aquifers overlie the eastern Snake River Plain aquifer in some areas (Young, 1984; Lindholm and others, 1988) and typically are composed of alluvium deposited by tributary streams or the Snake River.

The local alluvial aquifer north and south of the Snake River near Burley (fig. 1) was investigated as part of this study. In the Burley area, a clay layer about 60 to 120 ft below land surface acts as a perching layer for the alluvial aquifer above. The top of the blue-clay layer was mapped by Ken Skinner (U.S. Geological Survey, written commun., 1996), who reviewed several hundred well driller records. Recharge to the local alluvial aquifer is predominantly from infiltration of irrigation water. According to local accounts, the local alluvial aquifer was dry prior to 1907, when a canal network was constructed to transport irrigation water from Lake Walcott. Reportedly, several wells completed in the local alluvial aquifer go dry after irrigation ceases; these wells become operational again less than 2 weeks after the start of the next irrigation season.

The water table for the local alluvial aquifer near Burley is fairly flat over much of its extent, compared with that of the regional aquifer (fig. 3). Ground-water flow in the local alluvial aquifer is generally northward on the southern edge and westward on the western edge. Water levels are about 100 ft higher than water levels in the regional aquifer.

TRIBUTARY VALLEY AQUIFERS

Seepage and underflow from streams that flow onto the eastern Snake River Plain from tributary valleys on the north, east, and south recharge the regional aquifer. Aquifers in tributary valleys are predominantly alluvial. Near the mouths of several valleys, basaltic lava flows of the Snake River Group interfinger with and overlie the alluvium. Prominent northwest-trending

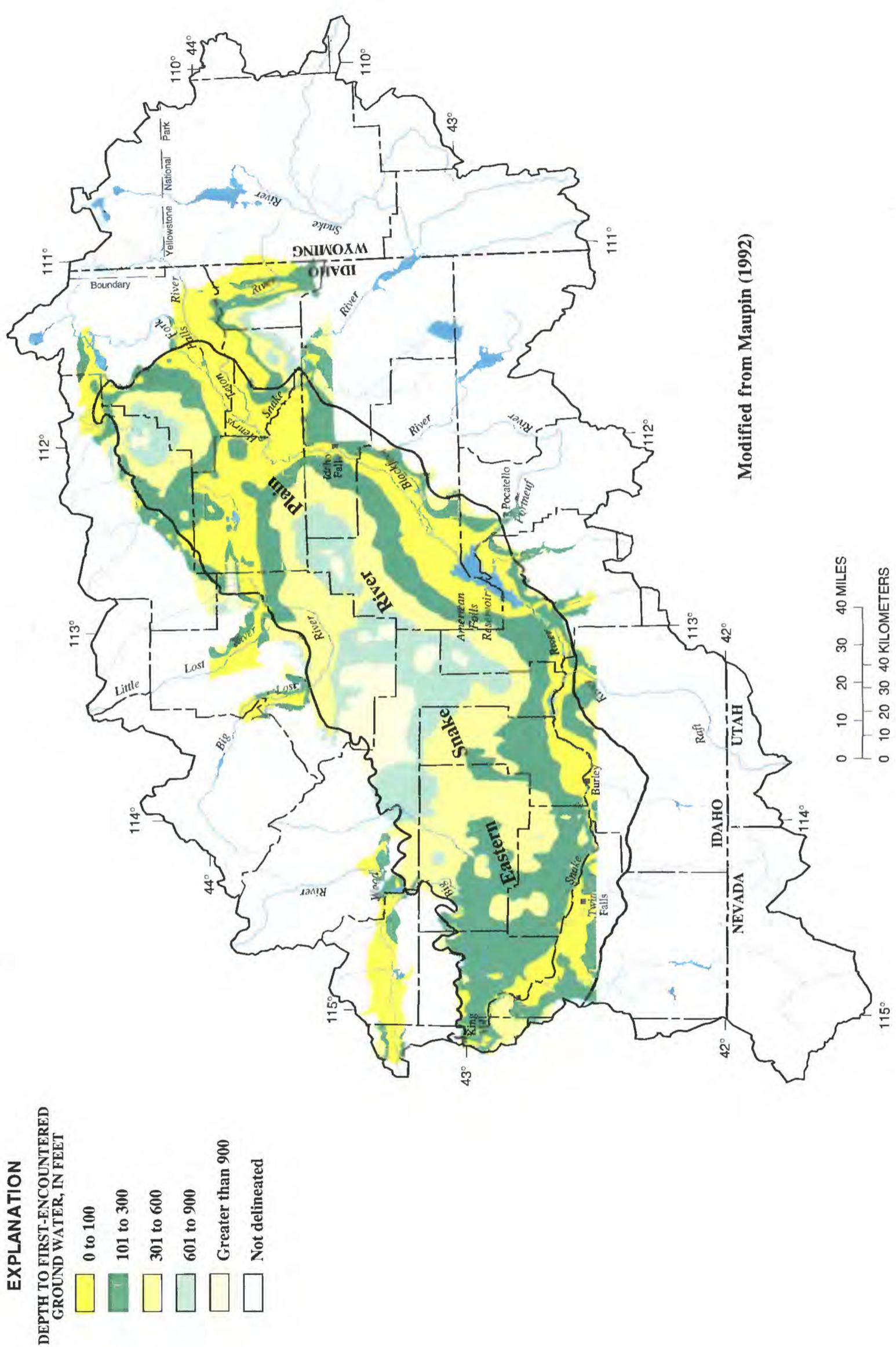


Figure 4. Depth to first-encountered ground water, eastern Snake River Plain, 1980–88.

mountain ranges north and south of the plain separate the tributary valleys. A more complete description of these tributary valleys is provided in a report by Muñdorff and others (1964).

Sources of Nitrogen

$\text{NO}_2 + \text{NO}_3 - \text{N}$ in ground water is a result of nitrogen input from many different sources. The proportions of nitrogen supplied by the various sources depend on land-use practices. For instance, most nitrogen in the A&B study area is from inorganic fertilizer and legume crops. In the Jerome/Gooding study area, a greater percentage of nitrogen is from cattle manure because of the large number of dairies, particularly in Gooding County.

Rupert (1996) calculated the amount of nitrogen supplied by cattle manure, domestic septic systems, inorganic fertilizer, legume crops (alfalfa and beans), and precipitation for each county in the USNK. He concluded that domestic septic systems provided minimal amounts of nitrogen input (less than 1 percent) and that precipitation provided only 6 percent of the nitrogen input to the basin as a whole. The remaining 93 percent was provided by cattle manure (29 percent), fertilizer (45 percent), and legume crops (19 percent). Rupert (1996) also calculated the amount of residual total nitrogen available for leaching to ground water or runoff to surface water after losses of the nitrogen input from crop uptake, storage and application of cattle manure to fields, and crop residue decomposition. The greatest amount of mean residual total nitrogen input of all 24 counties in the basin occurs in Cassia, Gooding, and Twin Falls Counties. A geologic source of nitrogen has been identified in only one small area in Blaine County (Mansfield, 1915, p. 28) and is considered insignificant.

METHODS

In this study, $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water were evaluated at regional and local scales. Regional data characterize ambient water-quality conditions in the entire basin. Local data characterize ground-water quality in specific parts of the basin and were used to help quantify the factors that relate to present (1995) water-quality conditions.

Regional Network

Regional $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water were based on samples collected for the Idaho Statewide Ground-Water Monitoring Program (ISGWMP) and the USGS NAWQA Program. Most of the regional-scale data were collected for the ISGWMP. Locations of wells sampled as part of each program are shown in figure 5.

IDAHO STATEWIDE GROUND-WATER MONITORING PROGRAM

The ISGWMP is a cooperative program between the USGS and the Idaho Department of Water Resources (IDWR). Primary objectives of the program are to (1) characterize the quality of water in Idaho's aquifers, (2) identify trends of water quality in individual aquifers, and (3) identify aquifers or geographic areas where water-quality problems may exist or be emerging (Idaho Department of Water Resources, 1991; Neely and Crockett, 1992; Neely, 1994; Crockett, 1995). Water-quality data generated by the program are stored in the USGS National Water Information System data base and the IDWR Environmental Data Management System data base. The first ground-water samples were collected from 97 wells statewide in the summer of 1990. Since then, the program has been expanded to include about 400 wells annually. Data collected from 1991 through 1994 were evaluated for this report. Data collected in 1990 were not used because the random well-selection methodology was not yet fully established; data collected in 1995 were not used because they were mostly from wells sampled in 1991 and resampled in 1995 as part of the trend-monitoring phase of the program.

Wells were selected using a statistically based stratified-random approach. The State was subdivided into 22 hydrogeologic subareas on the basis of aquifer type, water chemistry, and ground-water flow characteristics (Neely and Crockett, 1992). Ten of these subareas are in the USNK.

The number of wells in each hydrogeologic subarea was determined using the Neyman Optimal Allocation method (Snedecor and Cochran, 1967). This method takes into account the population within each subarea (census data), the size of the subarea, and the variability of water quality based on specific conductance. Subareas with the most wells sampled were those

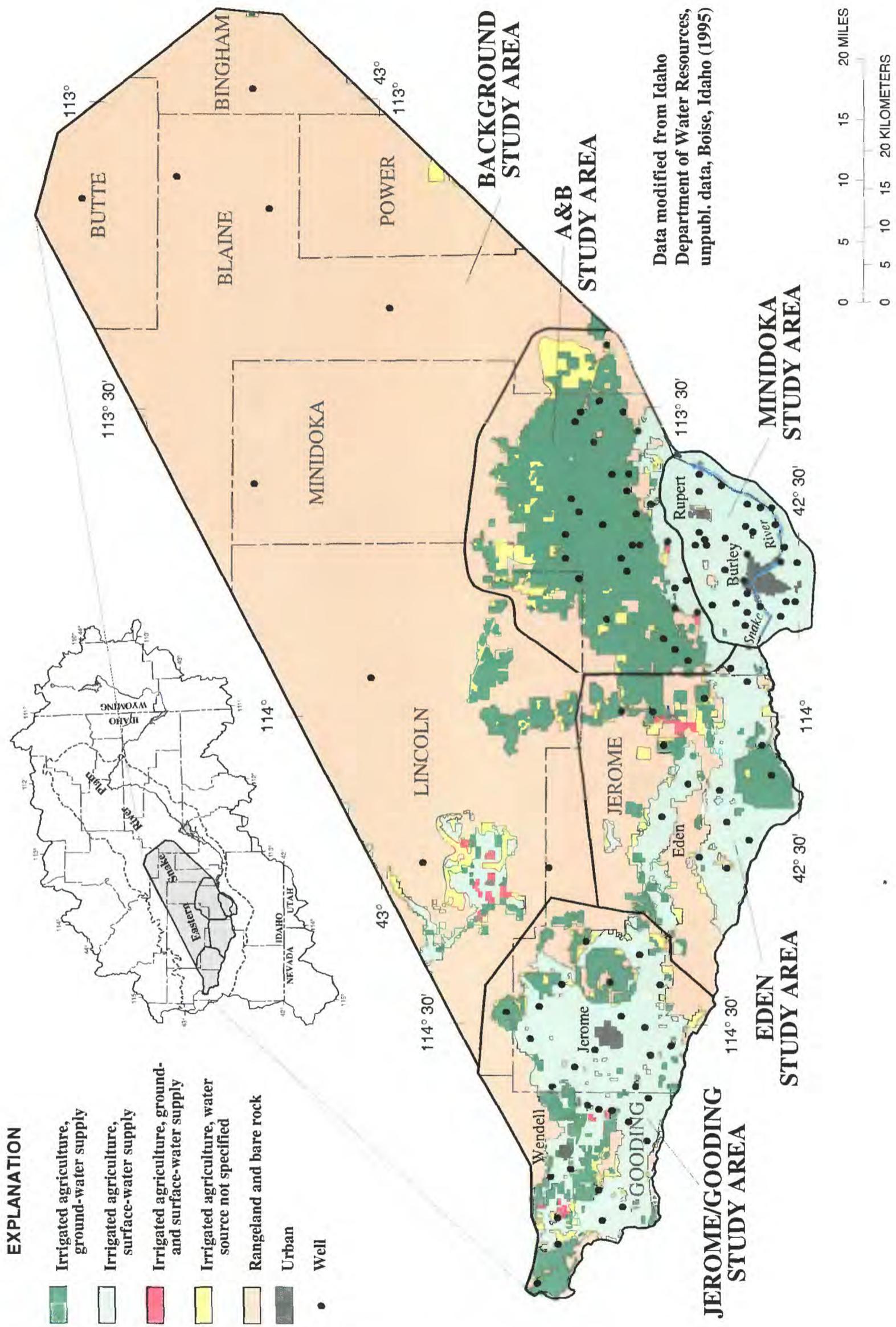


Figure 6. Land use and sources of irrigation water in local study areas, eastern Snake River Plain.

with the greatest population, largest area, and most variation in water quality.

Sections of the township-range-section coordinate system within each subarea were selected randomly. Only wells that met the following criteria were selected for sampling: (1) known well depth, (2) driller's record, (3) operational pump, and (4) completed in only one aquifer. Water from selected wells was used for irrigation, domestic, industrial, or municipal supply.

NAWQA PROGRAM

As part of the regional network, ground-water samples were collected near Jackson, Wyoming, by the USGS NAWQA Program in the summer of 1995. A systematic method was used to select wells; sections of the township-range-section coordinate system were selected randomly using a computer program developed by Scott (1990). All wells in each selected section were evaluated for their suitability for sampling. Well selection criteria included (1) existence of a driller's record, (2) a good surface seal, (3) a short plumbing line, (4) a sampling port upflow from any pressure tank or treatment equipment, (5) permission to sample from the well owner, and (6) access for water-level measurement.

Local Network

Water-quality data from five local areas were collected by the USGS NAWQA Program—A&B, Background, Eden, Jerome/Gooding, and Minidoka (fig. 6). The purpose of the local-scale studies was to examine the hydrogeologic and land-use factors that are related to elevated concentrations of $\text{NO}_2 + \text{NO}_3 - \text{N}$ in ground water. The A&B and Minidoka study areas include the irrigation districts with corresponding names and surrounding areas. Study areas were selected because each has a history of elevated $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water and because each has unique hydrogeologic and land-use conditions (table 1). The Background study area was selected because it is upgradient from the other areas and is far removed from major anthropogenic sources of nitrogen. The boundary of the Minidoka area delineates the areal extent of the underlying blue-clay perching layer. Differences in water quality between the areas, as well as changes in water quality downgradient through these areas, were investigated. Wells sampled for the local-scale studies were selected specifically for this NAWQA Program study.

Well-selection methods used for the A&B, Eden, Jerome/Gooding, and Minidoka study areas were the same as those used by NAWQA for the regional network. Random well selection was not performed in the Background study area because of the small number of existing wells. Most operational wells in the Background study area were sampled.

Sampling

Samples for the ISGWMP were collected by USGS staff, and most data evaluated in this report were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver. Each sample was analyzed for specific conductance, pH, water temperature, fecal coliform, alkalinity, major ions, nutrients, trace elements, radioactivity, selected radionuclides, and selected organic compounds. Wells were purged prior to sampling until field parameters of specific conductance, pH, and temperature stabilized (at least 15 minutes). Nutrient and major ion samples were filtered through a 0.45- μm filter prior to analysis.

The same sampling techniques were utilized by the NAWQA Program for both the regional and local networks. Samples were collected by using vehicles dedicated for water-quality sampling. In addition to the well plumbing system, samples contacted only teflon hoses and stainless-steel connectors. Enclosed sampling and preservation chambers were used to isolate samples from potential atmospheric contamination. Wells were purged for at least 25 minutes prior to sampling. Field

Table 1. Hydrogeologic and land-use conditions, local study areas, eastern Snake River Plain

[GW, ground water; SW, surface water; irrig. ag., irrigated agriculture. ESRP, Eastern Snake River Plain]

Study area	Aquifer	Primary source of irrigation water	Comments
A&B	ESRP (basalt)	Mostly GW	Irrig. ag.
Eden	ESRP (basalt)	Mostly SW	Irrig. ag., transition from GW to SW source.
Jerome/Gooding	ESRP (basalt)	Mostly SW	Dairies and irrig. ag.
Minidoka	Local alluvial	Mostly SW	Irrig. ag.
Background	ESRP (basalt)	None	Rangeland and sparsely vegetated basalt flows.

measurements of specific conductance, pH, temperature, turbidity, and dissolved oxygen were observed during purging; samples were collected after three consecutive readings 5 minutes apart showed no change. Nutrients, major ions, dissolved organic carbon, and methylene blue active substances (MBAS); hydrogen, oxygen, and nitrogen isotopes; and tritium data were analyzed by the USGS NWQL. Nutrient and major ion samples were filtered through a 0.45- μ m filter prior to analysis.

Quality Assurance

Quality-assurance and quality-control (QA/QC) practices for NAWQA sample collection for the regional and local networks included equipment blanks and replicate samples at 10 percent of the sites to assure that the sampling techniques and laboratory analyses were producing accurate data. Equipment blanks help evaluate whether samples are contaminated by sampling equipment. Replicate samples help define the precision (or variability) of the sampling methods and laboratory analyses. The QA/QC practices of the ISGWMP included equipment blanks and replicate samples at 5 percent of the sites; a smaller percentage of QA/QC sites were chosen for the ISGWMP because of the large number of wells sampled for this program.

The NWQL maintains its own internal program of blank, replicate, and spike samples to assure that it is accurately analyzing water-quality samples (Pritt and Raese, 1995). The Quality Assurance Unit of the NWQL routinely submits blind reference and blank

samples to the NWQL. The USGS Branch of Technical Development and Quality Systems, which is independent of the NWQL, also submits blind samples to the NWQL.

Analysis of QA/QC data from this project suggests that all sampling and analytical techniques provided acceptable data (D.S. Ott, U.S. Geological Survey, written commun., 1997). All replicate and spike samples were within 2 standard deviations of the expected mean. The only anomaly was ammonia, which was detected in many equipment blanks near the reporting level of 0.01 mg/L. The source of the ammonia was contaminated blank water (Michael Koterba, U.S. Geological Survey, oral commun., 1995), not the sampling equipment or laboratory error. Detections of ammonia in ground water were rare, so the contaminated blank water was of little concern.

Instruments used to measure field parameters for the regional and local networks were calibrated to standard solutions at least daily; many times they were calibrated before sampling at each site. Water levels were measured until two consecutive measurements agreed within 0.1 in.

REGIONAL EVALUATION OF NITRITE PLUS NITRATE AS NITROGEN IN GROUND WATER

Ground-water quality data collected for the ISGWMP and the NAWQA Program (Harenberg and others, 1992, 1993, 1994; Brennan and others, 1995, 1996; D.S. Ott, U.S. Geological Survey, written com-

Table 2. Fecal coliform bacteria and nutrients in ground water, upper Snake River Basin, 1991–95

[Data for Wyoming were collected as part of the U.S. Geological Survey National Water-Quality Assessment Program in July 1995; data for Idaho were collected as part of the Idaho Statewide Ground-Water Quality Monitoring Program, summer 1991–94; col/mL, colonies per 100 milliliters of filtered water; mg/L, milligrams per liter; <, less than]

Constituent	No. of wells sampled	Reporting level	Minimum concentration measured	Percentile					Maximum concentration measured
				10	25	50	75	90	
Fecal coliform (col/mL)	690	<1	<1	<1	<1	<1	<1	<1	176
Nitrite, dissolved, as nitrogen (mg/L)	726	<.01	<.01	<.01	<.01	<.01	<.01	<.01	.40
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N) (mg/L)	726	<.05	<.05	.17	.50	1.4	2.9	5.4	35
Nitrogen ammonia, dissolved, as nitrogen (mg/L)	726	<.01	<.02	<.02	<.02	<.02	<.02	.04	2.3
Orthophosphorus, dissolved, as phosphorus (mg/L)	726	<.01	<.01	<.01	<.01	.02	.03	.05	.70
Phosphorus, total, as phosphorus (mg/L) ..	136	<.01	<.01	<.01	<.01	.02	.05	.07	.40

mun., 1997) provided a good representation of nutrient and bacteria concentrations in the basin (table 2). Wells sampled were in most types of land-use areas and in all major hydrogeologic units. Of the wells sampled, 59 percent were for domestic use, 29 percent for irrigation, 5 percent for public supply, 5 percent for stock, and 2 percent for other uses (fig. 7). Wells were 20 to 1,340 ft deep; median well depth was 187 ft. Commercial wells had the shallowest median depth, 111 ft; stock wells had the greatest median depth, 300 ft. Depth to water was 0 to 732 ft; median depth was about 75 ft. Saturated interval in wells, or interval between the water table and the bottom of the well, was 5 to 904 ft; median saturated interval was 74 ft.

Nitrogen in ground water of the USNK was typically present as dissolved $\text{NO}_2+\text{NO}_3\text{-N}$ (table 2). Rarely were ammonia or nitrite detected in substantial concentrations. The median $\text{NO}_2+\text{NO}_3\text{-N}$ concentration was 1.4 mg/L. Rupert (1996, p. 4) suggested that background $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water of the basin are typically less than 1 mg/L. Concentrations of $\text{NO}_2+\text{NO}_3\text{-N}$ measured during this study were elevated (fig. 8) in the same areas where several investigators had previously identified elevated concentrations (Parlman and Young, 1987, 1988, 1989; Young, Parlman, and Jones, 1987; Young, Parlman, and O'Dell, 1987; and Rupert, 1994). Concentrations in ground water from 3 percent of the wells sampled were above the maximum contaminant level of 10 mg/L. Although 35 mg/L is the maximum $\text{NO}_2+\text{NO}_3\text{-N}$ concentration reported in table 2, much higher concentrations have been reported in other studies of the USNK. For instance, the maximum concentration in the Minidoka study area, sampled as part of the local network, was 58 mg/L. Concentrations of $\text{NO}_2+\text{NO}_3\text{-N}$ decreased with increasing well depth and depth to water, but with a weaker correlation than that previously reported by Rupert (1994, p. 26). Median $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations were highest in domestic wells (fig. 7), consistent with Rupert's findings (1994, p. 24). Relations of total phosphorus and orthophosphorus to well depth, depth to water, and use of well were not significant, consistent with Rupert's findings (1994, p. 26).

Fecal coliform bacteria were detected in only 3 percent of the wells sampled; the highest concentration was 176 colonies per 100 mL (table 2). The presence of these bacteria in water indicates fecal contamination by warmblooded animals and, therefore, the potential presence of pathogenic organisms (American Public Health Association and others, 1985, p. 827–

828; Bouwer, 1978, p. 361). Raw sewage, for example, typically contains millions of colonies of fecal coliform per 100 mL of water. To protect public health, the USEPA set the maximum contamination level goal for fecal coliform in drinking water at 0 colonies per 100 mL (U.S. Environmental Protection Agency, 1995). Wells in which fecal coliform were detected were widely scattered throughout the USNK, a pattern that suggests that fecal coliform contamination occurs in isolated locations and not on a regional scale like $\text{NO}_2+\text{NO}_3\text{-N}$ does.

Excessive aquatic plant growth in USNK surface water is a major concern, particularly in the Snake River between Milner Dam and King Hill. Ground-water discharge can contribute significant amounts of phosphorus and nitrogen to the receiving surface water (Clark and Ott, 1996). A concentration of 0.3 mg/L of inorganic nitrogen is considered the critical limit for stimulation of aquatic plant growth in surface water in the presence of adequate phosphorus (Mackenthun, 1969, p. 156). Water from more than 78 percent of the regional wells contained $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations higher than 0.3 mg/L, which suggests that nitrogen is not a limiting factor for aquatic plant growth in most streams that receive significant amounts of recharge from ground water. A total phosphorus concentration of 0.1 mg/L is considered the limit at or below which nuisance growths of algae and plants in moving surface water are prevented; 0.05 mg/L of phosphorus in the presence of adequate nitrogen is the limit for nuisance growth in lakes, reservoirs, or other standing water bodies (Mackenthun, 1969, p. 41). Water from less than 2 percent of the wells sampled contained total phosphorus (as P) concentrations higher than 0.1 mg/L; less than 12 percent of the concentrations were higher than 0.05 mg/L. Dissolved orthophosphorus was detected in a similarly low percentage of wells; water from less than 2 percent of the wells sampled contained orthophosphorus concentrations higher than 0.1 mg/L; less than 8 percent of the wells contained concentrations higher than 0.05 mg/L. Even though Mackenthun (1969, p. 41) specified a critical limit for total phosphorus, orthophosphorus is a good substitute because it is a major soluble component of total phosphorus and is readily available for use by aquatic plants. Orthophosphorus concentrations were higher than 0.05 mg/L near Twin Falls, southeast of Pocatello, and in the Rexburg/Idaho Falls area. Additional localized studies would be needed to determine whether ground-water contributions of nutrients are

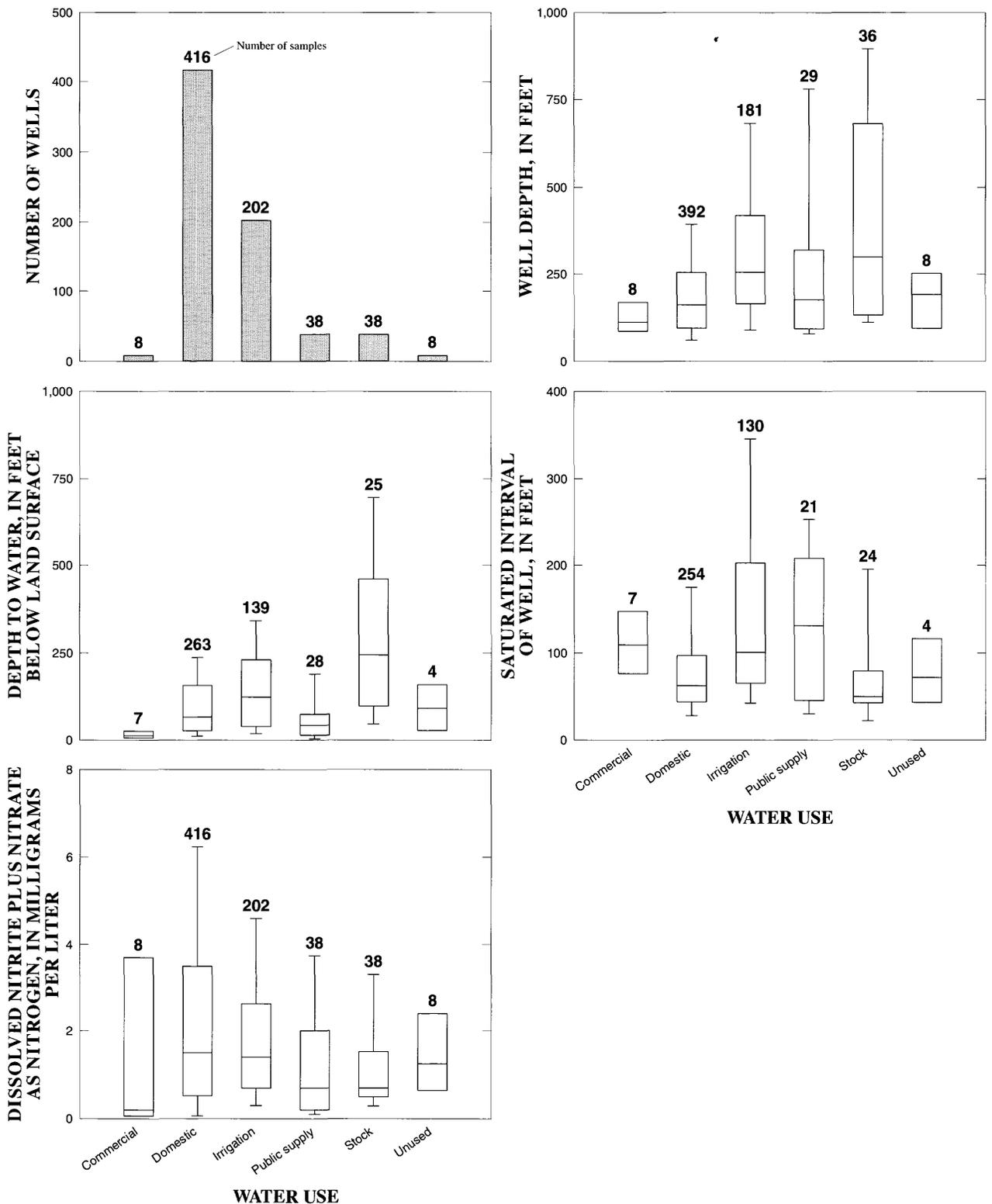


Figure 7. Relations between concentrations of dissolved nitrite plus nitrate as nitrogen and water use, number of wells, well depth, depth to water, and saturated interval of wells, upper Snake River Basin, 1991–95. (Data are from the Idaho Statewide Ground-Water Monitoring Program and the U.S. Geological Survey National Water-Quality Assessment Program. The 10th and 90th percentiles are not shown on boxplots if fewer than 10 wells were sampled)

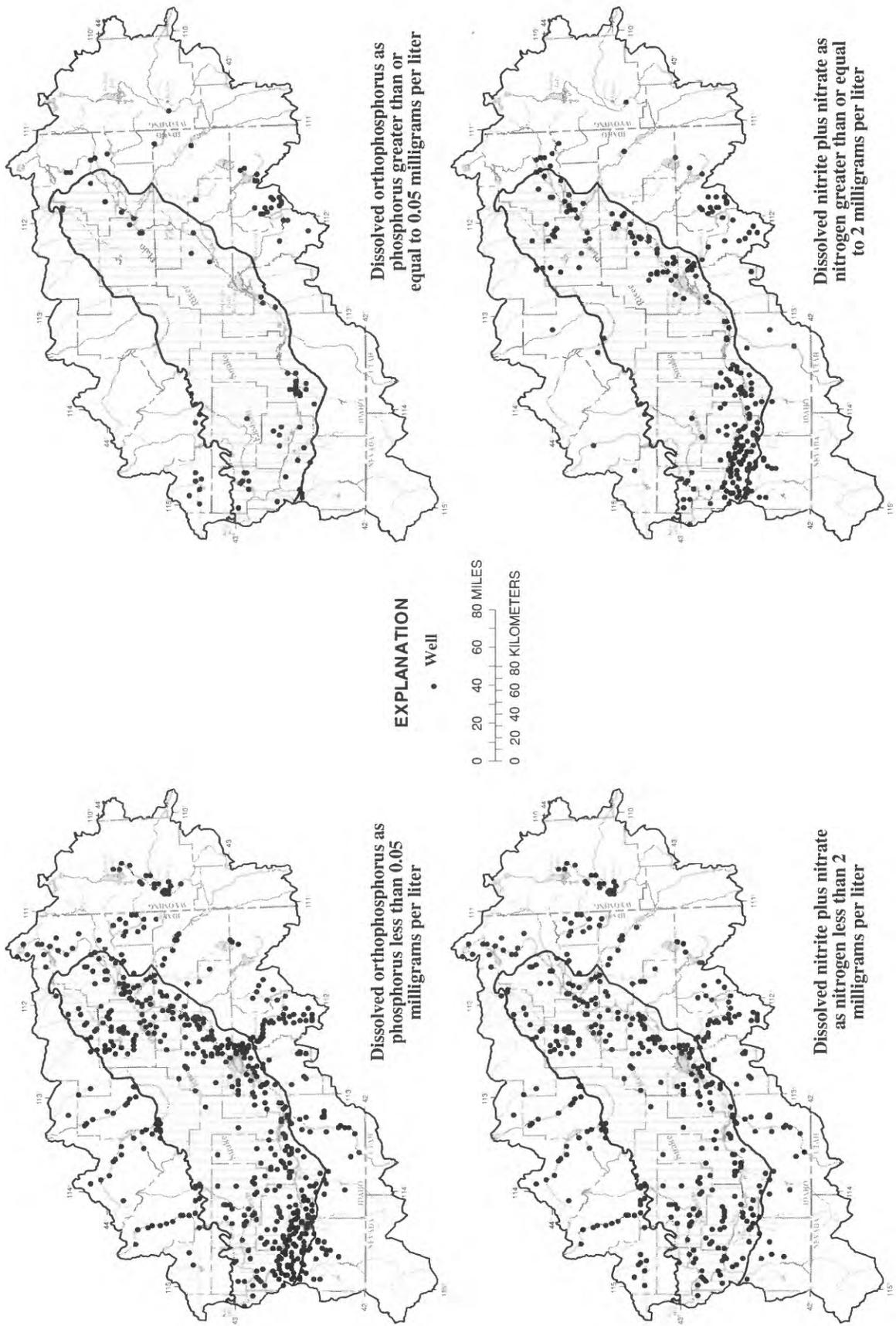


Figure 8. Concentrations of dissolved orthophosphorus as phosphorus and dissolved nitrite plus nitrate as nitrogen in ground water, upper Snake River Basin, 1991–95.

affecting aquatic plant growth in areas of ground-water discharge.

Relations Between Concentrations of Nitrite Plus Nitrate as Nitrogen and Depth to Water, Land Use, Precipitation, and Soils

Data collected from 1991 to 1994 for the ISGWMP were used to relate $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations to depth to water, land use, precipitation, and soils. These data were ideal for correlations because the wells were selected in a random manner, all wells were sampled using the same techniques, all samples were analyzed by the same laboratory, and all data were stored consistently in a single data base. Correlations were made using a GIS.

The Kruskal-Wallis and Wilcoxon rank-sum non-parametric statistical tests (Ott, 1993, p. 279, 793) were used to determine whether statistically significant differences in $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations existed among the various data groups; for example, whether $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in ground water in irrigated agriculture areas were statistically different from concentrations in rangeland areas. Both tests calculate a p-value; if the resulting p-value is less than 0.05, the data sets are significantly different at the 95-percent confidence level. If the p-value is less than 0.01, the data sets are significantly different at the 99-percent confidence level. In this study, the 95-percent confidence level was the cutoff value for determining whether the data sets were significantly different.

DEPTH TO WATER

Depth to first-encountered ground water in the eastern Snake River Plain was mapped by Maupin (1992), who divided depth to water into five categories (fig. 4); 0 to 100 ft, 101 to 300 ft, 301 to 600 ft, 601 to 900 ft, and greater than 900 ft.

No significant difference in $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations was detected in ground-water samples from depths of 0 to 100 ft and 101 to 300 ft ($p > 0.05$) (fig. 9). There also was no significant difference in $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in water from depths of 301 to 600 ft and 601 to 900 ft (fig. 9). However, $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in water from 0 to 100 ft were significantly higher than in water from 301 to 600 ft and 601 to 900 ft ($p < 0.05$). Concentrations in water from 101 to

300 ft were significantly higher than in water from 301 to 600 ft and 601 to 900 ft. These results are similar to those of Rupert (1994, p. 26), who reported that $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations decreased with increasing well depth.

LAND USE

Land-use data for Idaho were obtained from the IDWR (fig. 2), who combined the data from three sources: a map denoting vegetation types; a map differentiating between sprinkler- and gravity-fed irrigation methods; and a map differentiating dryland agriculture from irrigated agriculture (Rupert and others, 1991, p. 12). Land-use data were not available for Wyoming, Utah, or Nevada.

$\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in ground water in irrigated agriculture and urban areas were significantly higher than in rangeland, dryland agriculture, and forest areas (fig. 10). In addition, $\text{NO}_2 + \text{NO}_3\text{-N}$ concentra-

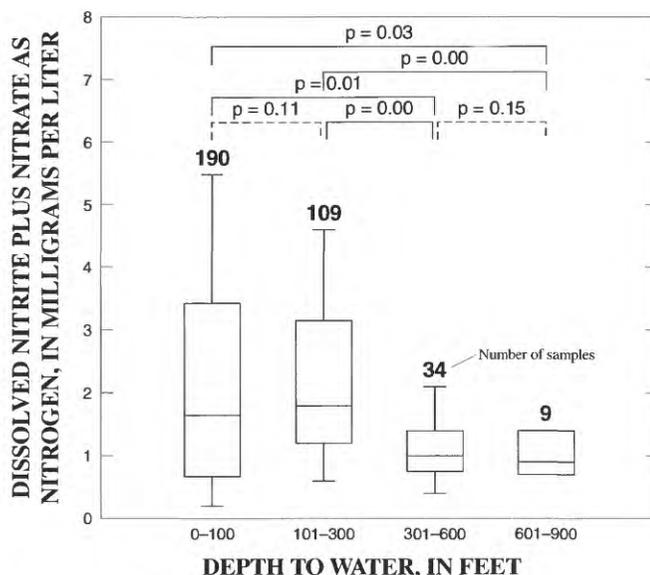


Figure 9. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and depth to first-encountered ground water, eastern Snake River Plain, 1991-94. [Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each depth-to-water category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines. Resulting p-values greater than 0.05 (concentrations are not different at a 95-percent confidence level) are labeled on dashed lines. The 10th and 90th percentiles are not shown on boxplots if fewer than 10 wells were sampled]

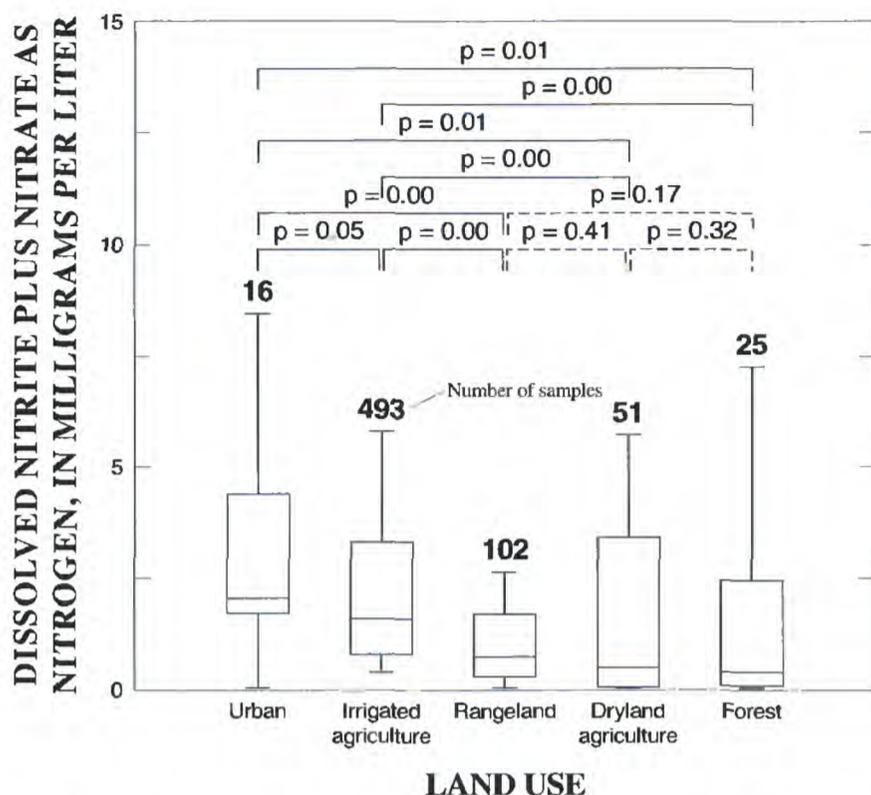


Figure 10. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and land use, upper Snake River Basin, 1991–94. [Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each land-use category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines. Resulting p-values greater than 0.05 (concentrations are not different at a 95-percent confidence level) are labeled on dashed lines]

tions in urban areas were significantly higher than in irrigated agriculture areas, but the small number of wells sampled in urban areas might have biased this result. These results are similar to those reported by Rupert (1994, p. 29).

High $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in irrigated agriculture areas are likely the result of nitrogen application in excess of plant needs. Excess irrigation water flushes the soluble nitrate to ground water. Sources of nitrogen are primarily inorganic fertilizer, cattle waste, and legume crops (Rupert, 1996, p. 1). Domestic septic systems and precipitation provide negligible amounts of nitrogen. $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations are low in dryland agriculture areas because recharge is insufficient to carry excess nitrogen to ground water. Because most urban areas in the USNK are surrounded by irrigated agriculture, it is not clear whether the high $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in urban areas are the result of urban land use alone or of a combination of urban and upgradient agricultural land uses.

PRECIPITATION

$\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water were correlated with precipitation data obtained from an isohyetal map (Molnau, 1995). $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water were expected to be lower in areas of greater rainfall because $\text{NO}_2+\text{NO}_3\text{-N}$ would be diluted in the recharge water, and that concentrations in areas of less rainfall would be high because irrigation water would carry excess nitrogen from agricultural activities to the water table. However, results showed no direct correlation between $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations and precipitation. Depth to water, land use, and soils play a much greater role than precipitation in affecting $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water.

SOILS

Soil data (fig. 11) were obtained from the State Soil Geographic Data Base (STATSGO), developed by the U.S. Natural Resource Conservation Service (U.S. Department of Agriculture, 1991). Soil criteria considered in this study were clay content, drainage, hydrologic group, percentage of organic matter, permeability, and Unified Soil Classification ratings. STATSGO soil data were aggregated from many large-scale soil surveys (1:12,000 to 1:62,500) into one large data base at an approximate scale of 1:250,000 (U.S. Department of Agriculture, 1991, p. 1, 2).

$\text{NO}_2+\text{NO}_3\text{-N}$ concentrations and soil drainage were the most strongly correlated of the soil criteria examined in this study (fig. 12). Although the relations are not illustrated, $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations also increased significantly with decreasing amounts of clay and decreasing amounts of organic matter. Concentrations increased with increasing amounts of sand and gravel, as represented by the Unified Soil Classification ratings. Surprisingly, soil permeability and hydrologic group were not correlated with $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations.

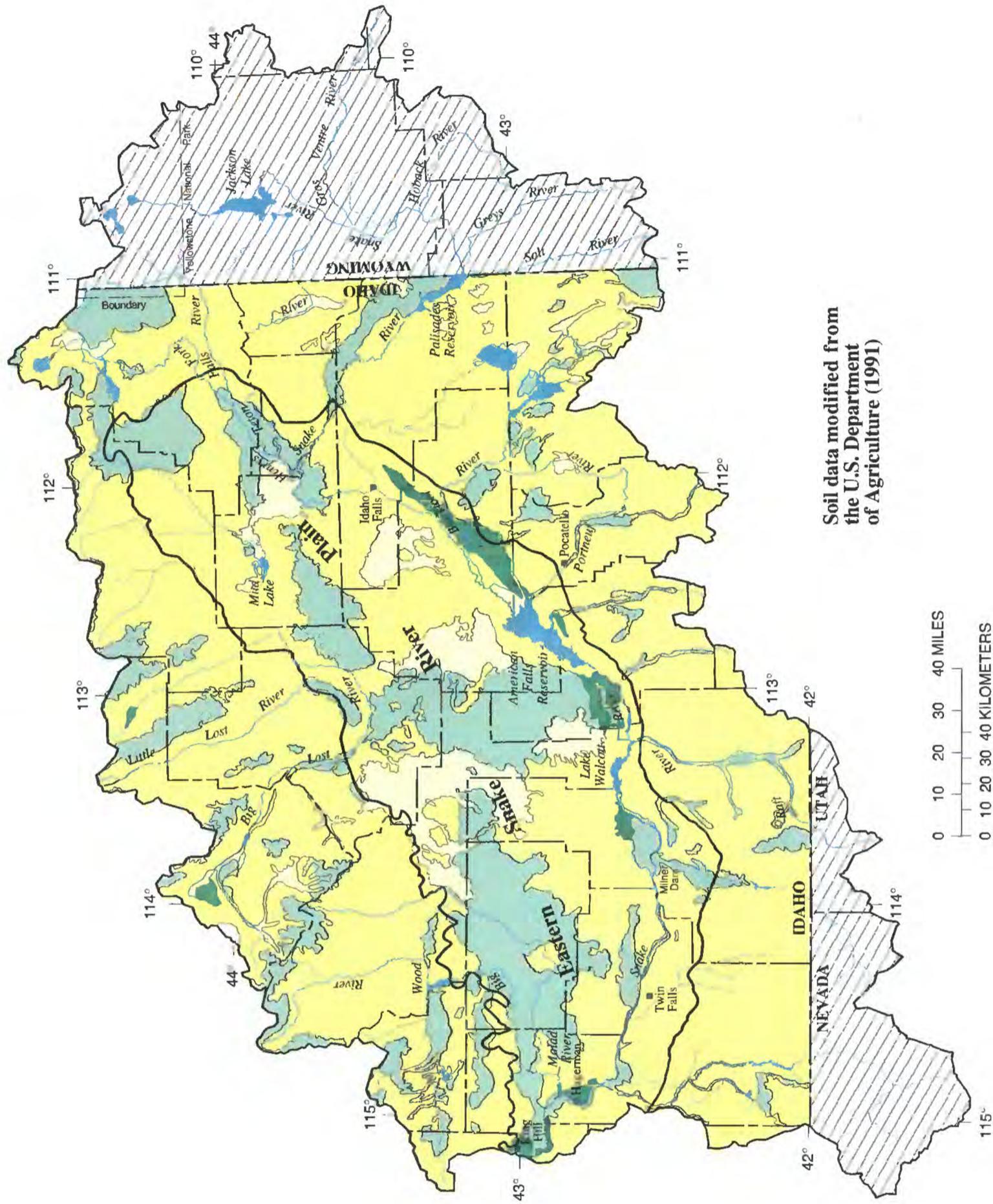
Ground-Water Vulnerability and Probability Mapping

Ground-water vulnerability and probability maps are designed to show areas of greatest potential for ground-water contamination by $\text{NO}_2+\text{NO}_3\text{-N}$ on the basis of hydrogeologic and anthropogenic factors.

EXPLANATION

SOIL DRAINAGE

-  Excessive
-  Well
-  Moderate
-  Poor
-  Not delineated



Soil data modified from the U.S. Department of Agriculture (1991)

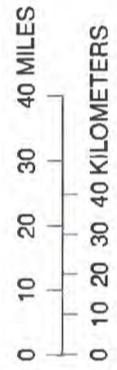


Figure 11. STATSGO soil-drainage categories, upper Snake River Basin. (STATSGO, State Soil Geographic Data Base)

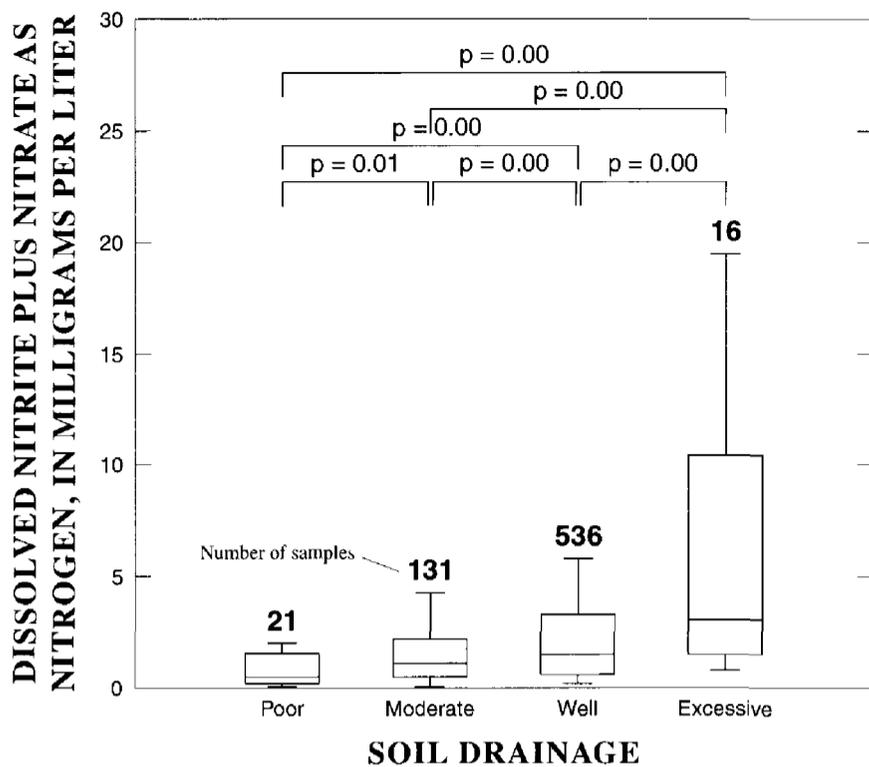


Figure 12. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen in ground water and STATSGO soil-drainage categories, upper Snake River Basin, 1991–94. [STATSGO, State Soil Geographic Data Base. Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each soil-drainage category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines]

Rupert and others (1991) developed a ground-water vulnerability map for the Snake River Plain and tributary valleys. As part of this study, ground-water probability maps were developed for the same area and using the same GIS data layers as were used for the vulnerability maps produced in 1991. The ground-water probability maps differ from the ground-water vulnerability maps in that the probability maps were calibrated to measured $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water. Ground-water probability maps can be used by resource protection agencies to focus pollution prevention programs on areas of greatest concern and to focus ground-water sampling programs on areas of greatest potential for contamination. A brief summary of ground-water vulnerability and probability mapping follows.

GROUND-WATER VULNERABILITY MAPPING

Ground-water vulnerability maps were produced for the Snake River Plain as part of the Idaho Ground-

Water Vulnerability Project (IGWVP), which was a cooperative effort by the USGS, the Idaho Division of Environmental Quality, the IDWR, and the U.S. Natural Resource Conservation Service (formerly the U.S. Soil Conservation Service) (Rupert and others, 1991). The IGWVP used a modified form of the DRASTIC model (Aller and others, 1985), which was designed to evaluate the potential for ground-water contamination in a given area on the basis of hydrogeologic factors. The DRASTIC acronym was named after the seven factors considered in the model: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone media, and hydraulic conductivity of the aquifer (Aller and others, 1985, p. iv).

The IGWVP used three of the seven DRASTIC factors—depth to water, recharge (land use), and soil media. Depth to water was developed by Maupin (1992), who mapped depth to first-encountered ground water in the eastern Snake River Plain and tributary valleys. Land-use data were used as a surrogate to determine recharge; the vulnerability ratings were based on the concept that areas of high recharge have a high predisposition to contamination because contaminants can be carried in recharge water (Rupert and others, 1991). For instance, gravity-fed irrigated agriculture areas received high recharge ratings because of the high chance for infiltration of excess irrigation water; rangeland areas received low ratings because of the low chance for infiltration of rain-water. Soil data were obtained from STATSGO (U.S. Department of Agriculture, 1991). Rupert and others (1991) entitled their vulnerability map “relative ground-water vulnerability” because the vulnerability ratings (low, medium, high, and very high) were determined relative to each other and were not based on comparison with actual ground-water quality data. Rupert and others (1991, p. 23) stated that the point rating schemes may need to be adjusted to conform with ground-water monitoring data.

Relative ground-water vulnerability map ratings (Rupert and others, 1991) and $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water correlated fairly well (fig. 13). For instance, median $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations with a medium relative vulnerability rating were significantly higher than those with a low rating. Median $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations with a high relative vulnerability rating were slightly higher than those with a medium rating. However, the median, quartiles, and ranges of $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations with a very high relative vulnerability rating were lower than those with a high rating. Of the three DRASTIC factors, depth

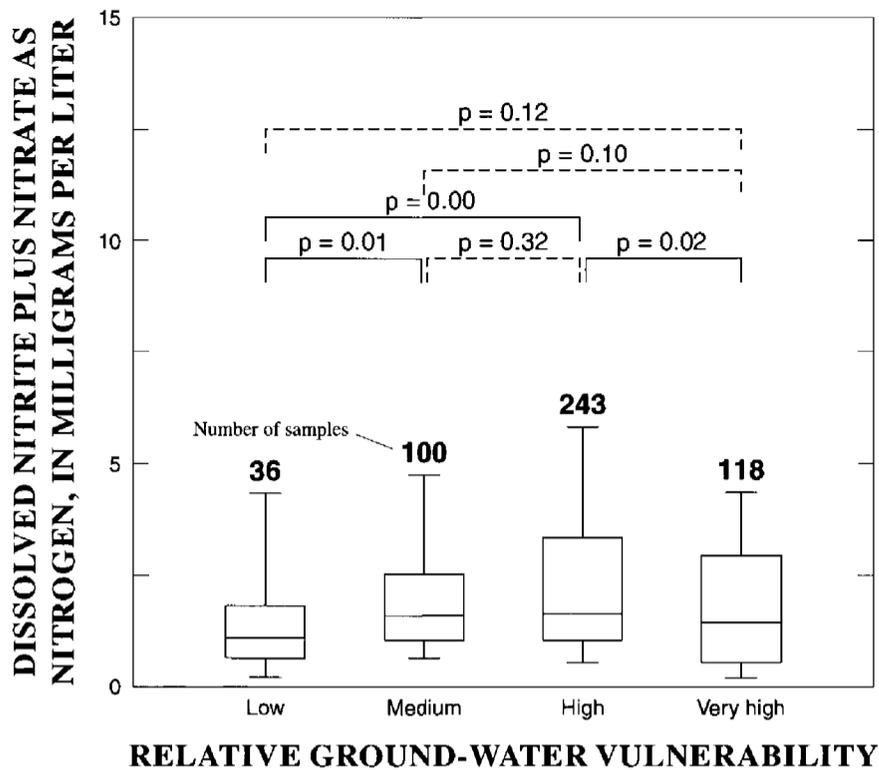


Figure 13. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and relative ground-water vulnerability ratings of Rupert and others (1991), eastern Snake River Plain, 1991–94. [Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each relative vulnerability category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines. Resulting p-values greater than 0.05 (concentrations are not different at a 95-percent confidence level) are labeled on dashed lines]

to water (fig. 9) and land use (fig. 10) correlated strongly with measured $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations. However, there was no correlation between the soil ratings used by Rupert and others (1991) and $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations because their soils ratings included lab permeability as one of the primary soil criteria. As shown earlier in this report, correlation would have been stronger if soil drainage had been used. Lack of correlation between $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations and soils in turn adversely affected the correlation between $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations and relative ground-water vulnerability, because the soil factor was weighted three times greater than the depth to water and recharge factors.

GROUND-WATER PROBABILITY MAPPING

A map showing the probability of ground-water contamination by $\text{NO}_2 + \text{NO}_3 - \text{N}$ was developed (fig. 14) using the same GIS data layers as for the IGWVP, but with a different rating scheme (table 3). Probability rat-

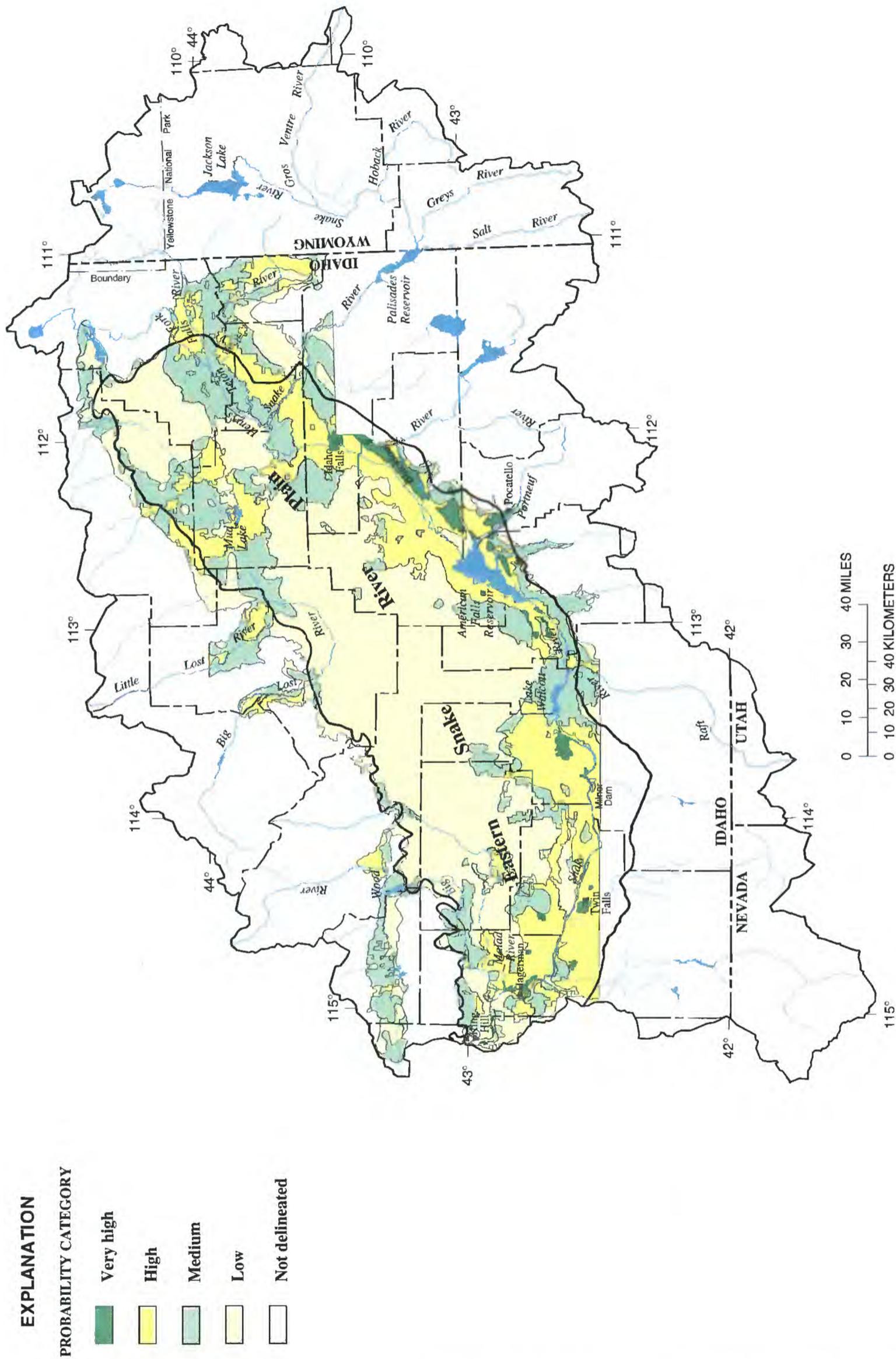
ings, in points, were based on the correlations between $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations and depth to water, land use, and soil drainage, as shown in figures 9, 10, and 12, respectively. For example, urban areas were assigned a probability rating of 3 because $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water in urban areas were higher than in all other land-use areas. Irrigated agriculture areas were assigned a probability rating of 2 because $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in irrigated areas were significantly higher than in other land-use areas except urban. Rangeland, dryland agriculture, and forest were combined and assigned a probability rating of 1 because $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations were lowest in those areas and differences in concentrations were not significant.

The maps are termed probability maps instead of vulnerability maps because (1) the probability catego-

Table 3. Rating scheme for probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, eastern Snake River Plain

[<, less than; >, greater than; kg, kilograms; divide kg by 907.2 to obtain tons]

Depth to water	Rating (points)
0 to 300 feet	2
Greater than 300 feet.....	1
Land use	Rating (points)
Urban.....	3
Irrigated agriculture	2
Rangeland	1
Dryland agriculture	1
Forest.....	1
Soil drainage	Rating (points)
Excessive.....	4
Well.....	3
Moderate	2
Poor.....	1
Contamination probability	Resultant probability rating (points)
Very high.....	8
High.....	7
Medium.....	6
Low	4 to 5
Nitrogen input	Rating (points)
High (> 3,000,000 kg/county).....	2
Low (< 3,000,000 kg/county)	1
Contamination probability, nitrogen input included	Resultant probability rating (points)
Very high.....	10
High.....	9
Medium.....	7 to 8
Low	5 to 6



EXPLANATION

PROBABILITY CATEGORY	
	Very high
	High
	Medium
	Low
	Not delineated

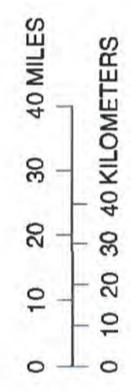


Figure 14. Probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, eastern Snake River Plain.

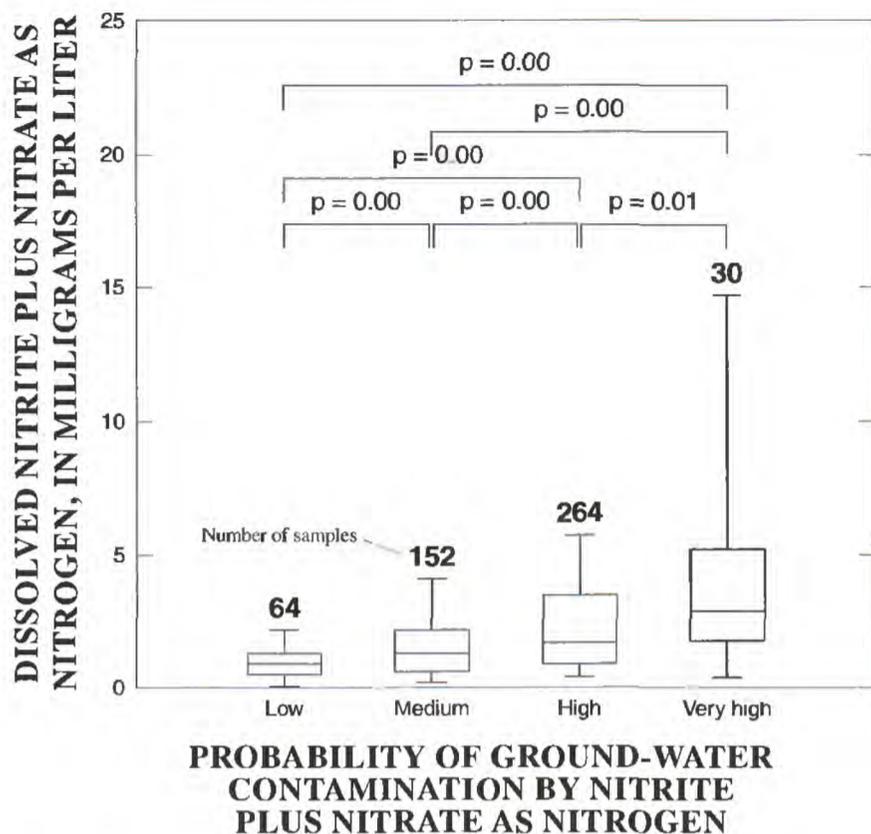


Figure 15. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and contamination probability, eastern Snake River Plain, 1991–94. [Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each probability category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines]

ries are based on the results of statistical comparisons of $\text{NO}_2+\text{NO}_3\text{-N}$ in ground water, and (2) the term probability more clearly states what the maps portray: whether an area has a high or low probability for $\text{NO}_2+\text{NO}_3\text{-N}$ contamination of ground water. Calibration of the probability maps with measured water-quality data makes them a superior predictive tool compared with the relative ground-water vulnerability maps developed by Rupert and others (1991).

Results of ground-water probability mapping were compared with measured $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water (fig. 15). Correlations were extremely good; the largest p-value of 0.01 and five of the p-values of less than 0.01 suggest statistically significant differences (greater-than-99-percent confidence level) of $\text{NO}_2+\text{NO}_3\text{-N}$ between the probability categories.

Different point rating schemes for depth to first-encountered ground water, land use, and soil drainage were evaluated. For example, a rating of 4 points instead of 2 points was tried for depth to first-encountered ground water of 0 to 300 ft. The point rating scheme shown in table 3 produced the lowest p-values in the

final correlation between $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations and probability categories.

Determination of the probability of ground-water contamination by $\text{NO}_2+\text{NO}_3\text{-N}$ was taken one step further by including nitrogen input with depth to water, land use, and soil drainage. Nitrogen input for each county was estimated by Rupert (1996), who calculated the amount of nitrogen supplied by cattle manure, domestic septic systems, inorganic fertilizer, legume crops, and precipitation. The amount of residual nitrogen available for leaching to ground water or runoff to surface water was estimated by subtracting crop uptake, manure losses, and decomposition of the previous year's crop residue from total input. After the relation between nitrogen input and $\text{NO}_2+\text{NO}_3\text{-N}$ concentrations in ground water was examined, a point rating scheme was developed for nitrogen input (table 3) on the basis of the lowest p-value, as shown in figure 16. The probability of $\text{NO}_2+\text{NO}_3\text{-N}$ contamination in relation to nitrogen input is best represented as low or high. The cutoff was 3,000,000 kilograms (3,306 tons)

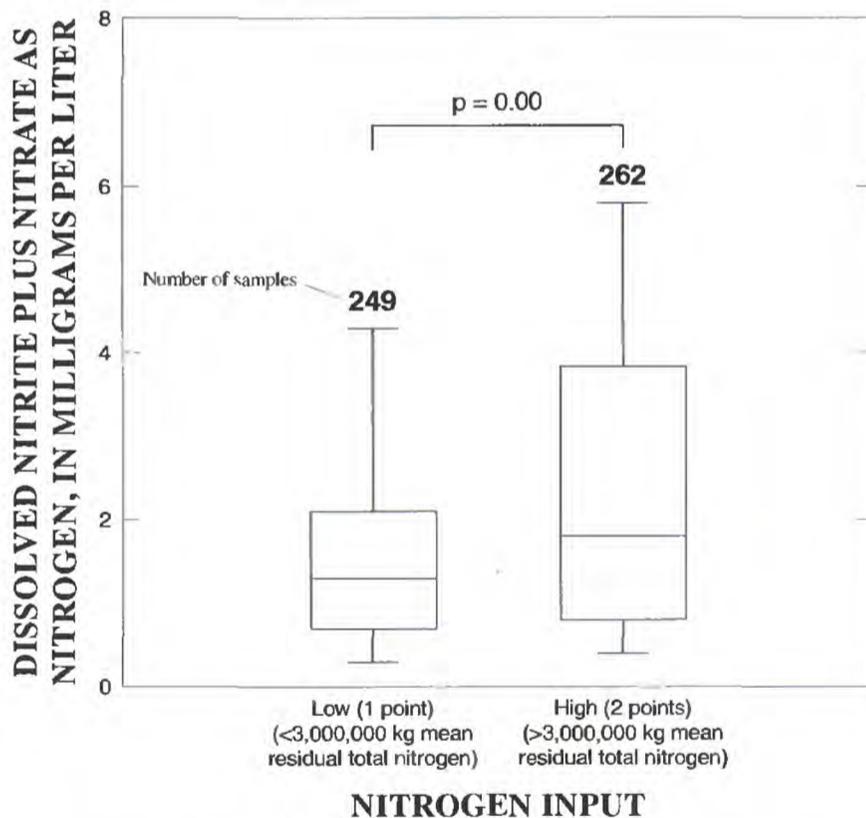


Figure 16. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and nitrogen input, upper Snake River Basin, 1991–94. [Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each nitrogen input category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines. <, less than; >, greater than; kg, kilograms; divide kilograms by 907.2 to obtain tons]

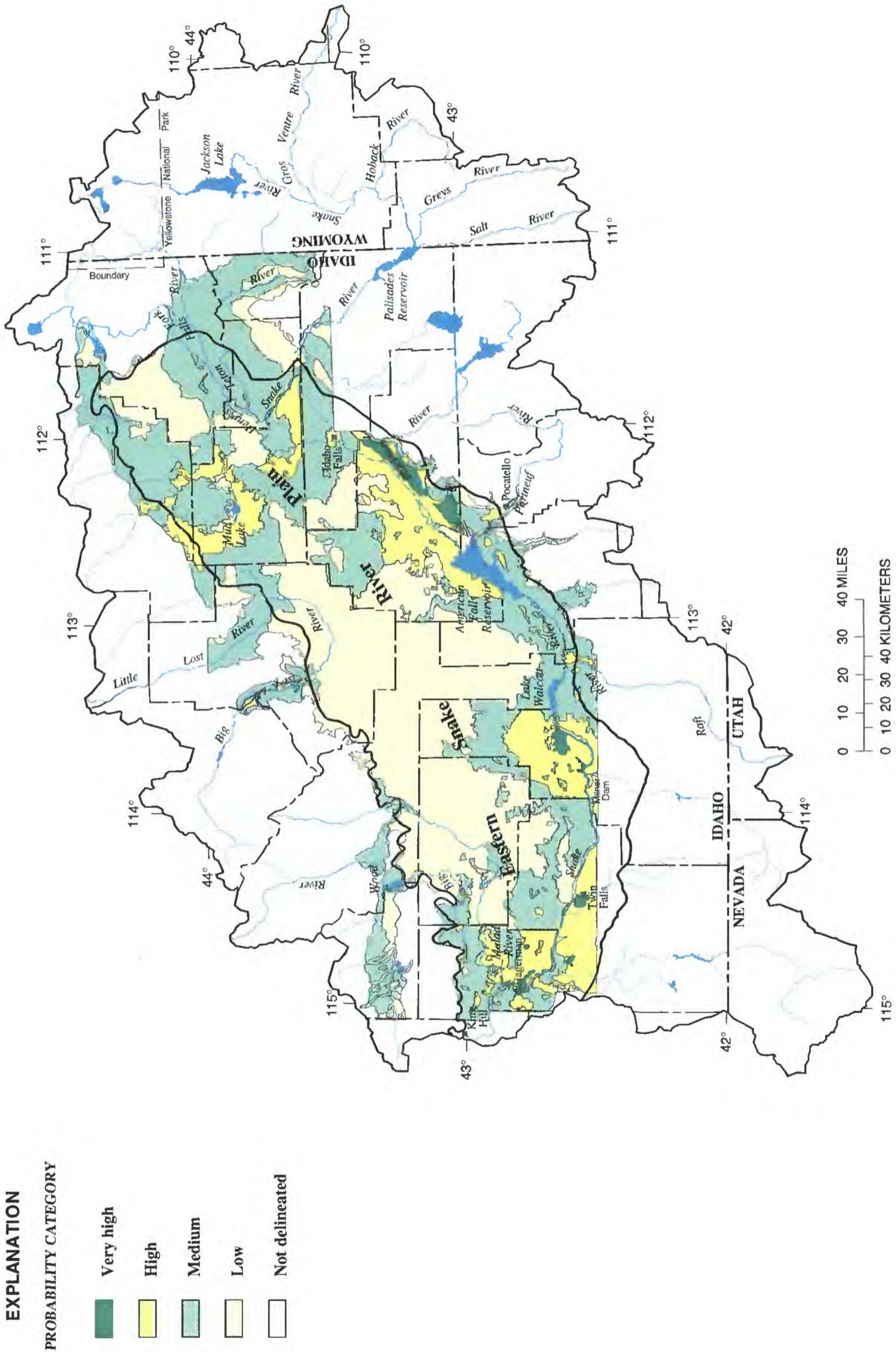


Figure 17. Probability of ground-water contamination by dissolved nitrite plus nitrate as nitrogen, nitrogen input included, eastern Snake River Plain.

of mean residual nitrogen input from each county. A disadvantage of the nitrogen input data is that the data were available only at a county level, which does not always relate well to physical boundaries in the watershed; depth to water, land use, and soil drainage are mapped at a much finer scale.

A second map was produced to show the probability of ground-water contamination by $\text{NO}_2 + \text{NO}_3\text{-N}$ with nitrogen input estimates included (fig. 17). Correlations between probability categories and measured $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in ground water were extremely good (fig. 18); there was a statistically significant difference (greater-than-99-percent confidence level) of $\text{NO}_2 + \text{NO}_3\text{-N}$ between the probability categories.

Inclusion of nitrogen input allows more accurate identification of areas subject to $\text{NO}_2 + \text{NO}_3\text{-N}$ contamination, but nitrogen input can change rapidly from year

to year and thus quickly outdate the probability maps. For instance, the probability categories for the western part of Jerome County changed from high to medium when nitrogen input was included (figs. 14 and 17). However, the number of dairy cattle in Jerome County has increased dramatically since 1990. Nitrogen input values used in this report were calculated for 1990; probability categories for the western part of Jerome County probably would be higher if nitrogen input could be calculated for 1997. The accuracy of probability categories shown in figure 17 could be improved if nitrogen input data were available at a finer scale than county level.

The probability maps were calibrated only for $\text{NO}_2 + \text{NO}_3\text{-N}$. They may not be effective for determining the probability of contamination by other constituents such as pesticides and volatile organic compounds, which can behave differently in the environment. If adequate water-quality data were available, additional probability maps, calibrated to specific compounds, could be produced using the same methods as used in this study. The probability maps do not allow estimation of a particular $\text{NO}_2 + \text{NO}_3\text{-N}$ concentration at a particular well; they only show areas where $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations differ significantly.

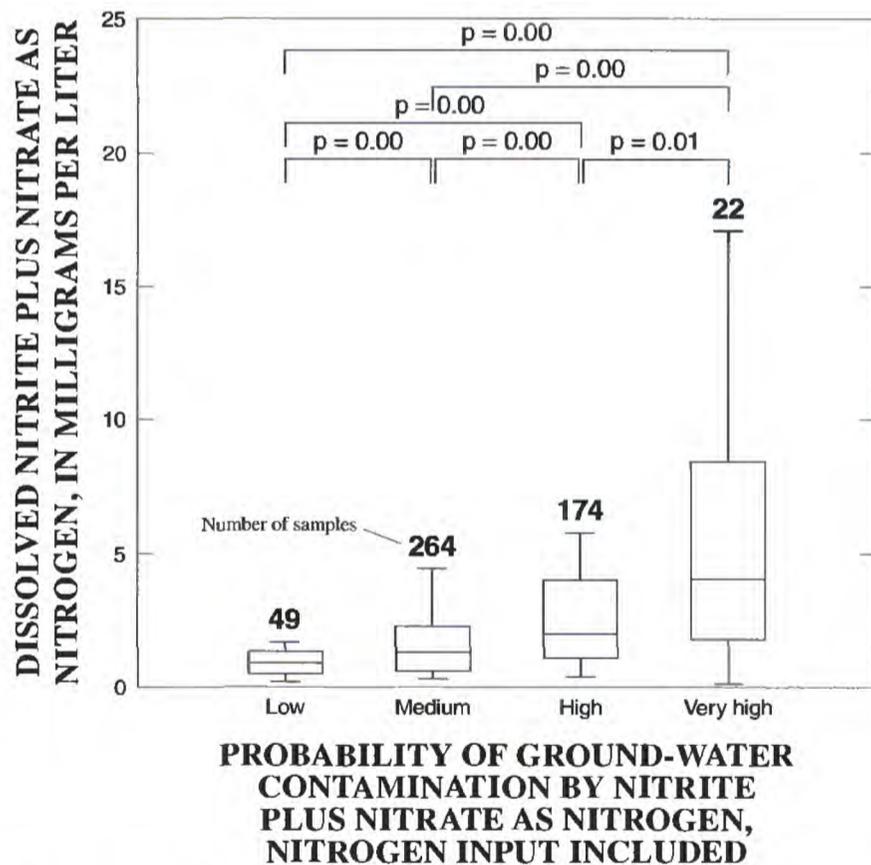


Figure 18. Correlations between concentrations of dissolved nitrite plus nitrate as nitrogen and contamination probability, nitrogen input included, eastern Snake River Plain, 1991–94. [Lines above boxplots indicate results of individual Wilcoxon rank-sum tests between each probability category. Resulting p-values less than or equal to 0.05 (concentrations are different at a 95-percent or greater confidence level) are labeled on solid lines]

LOCAL EVALUATION OF NITRITE PLUS NITRATE AS NITROGEN IN GROUND WATER

Most water use in local study areas is for irrigation. Irrigation water is from ground water and the Snake River (fig. 6). Most ground water is pumped from wells greater than 300 ft deep completed in the eastern Snake River Plain aquifer. Water is applied to fields by using gravity-fed or sprinkler irrigation methods. Snake River water is diverted in several places and distributed by means of an extensive canal network.

The most significant difference in land use among the local study areas is the source (ground water or surface water) of irrigation water and the number of dairies. The Minidoka study area is irrigated almost entirely with surface water; the Eden and Jerome/Gooding areas are irrigated mostly with surface water, except in areas that are topographically too high for irrigation canals. The A&B study area is irrigated almost entirely with ground water. The A&B and Eden areas contain no dairies and the Minidoka area contains a few dairies, but the Jerome/Gooding area contains a large dairy industry,

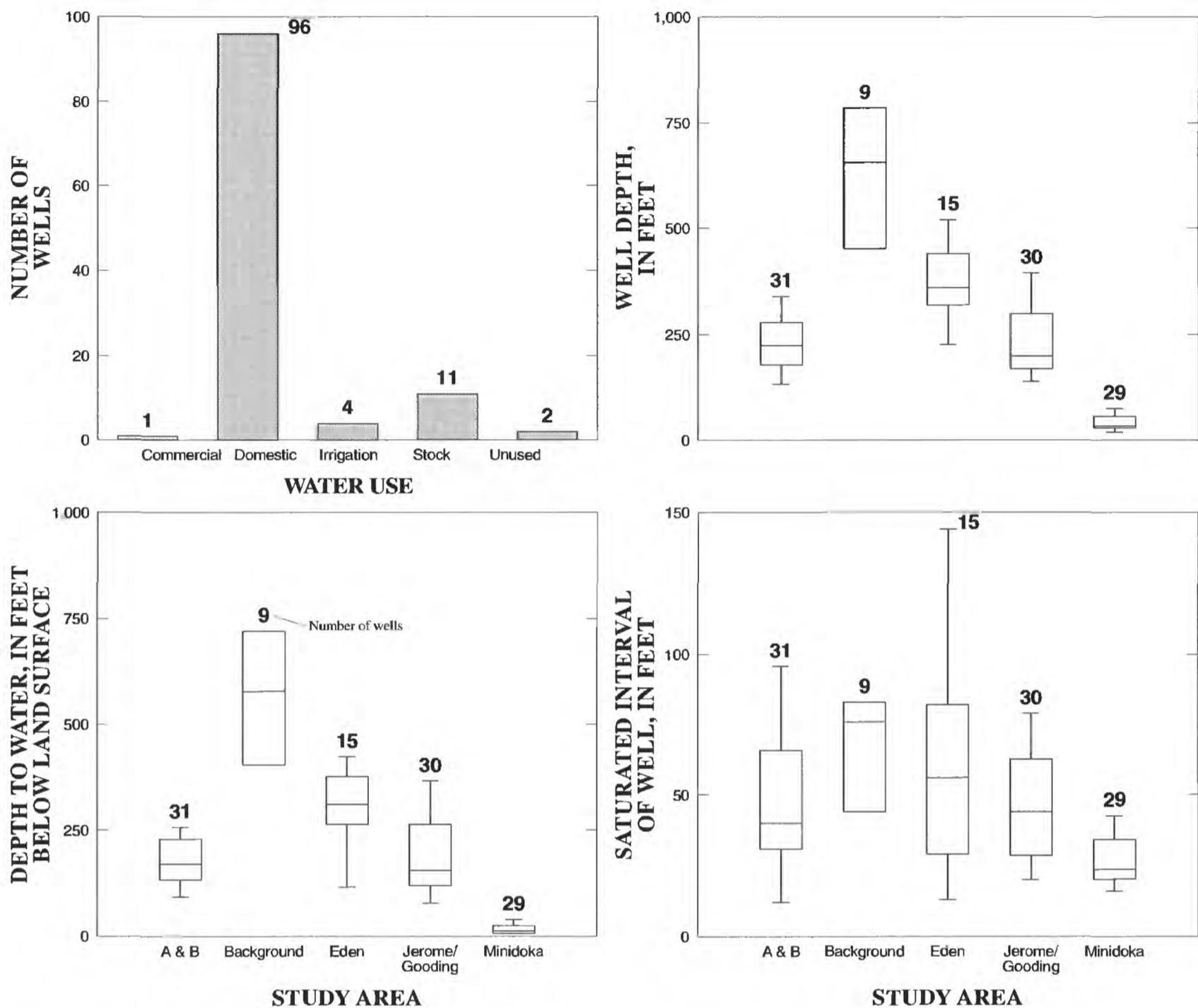


Figure 19. Relations among water use, well depth, depth to water, and saturated interval of wells, local study areas, eastern Snake River Plain, 1993–95. (The 10th and 90th percentiles are not shown on boxplots if fewer than 10 wells were sampled)

particularly in the western half. The Background area is predominantly rangeland and sparsely vegetated basalt; anthropogenic sources of nitrogen are negligible.

Most wells selected for sampling are domestic wells (fig. 19). Well depths in the Minidoka study area are typically less than 50 ft; in all other study areas, well depths are typically greater than 200 ft. Water is about 15 ft below land surface in the Minidoka study area and typically greater than 150 ft in all other areas. In the Background area, depth to water averages about 600 ft. Median distance between the water table and the base of the well (saturated interval) at all wells is about 40 ft.

Dissolved Organic Carbon and Oxygen

Dissolved organic carbon concentrations in the eastern Snake River Plain aquifer were relatively low (table 4) and were in the range expected for most aquifers (Thurman, 1985, p. 14). Ground water in the A&B, Background, Eden, and Jerome/Gooding study areas (eastern Snake River Plain aquifer) contained high concentrations of dissolved oxygen; the median concentration was 7.8 mg/L and median saturation was 90 percent. The relatively low dissolved organic carbon and high dissolved oxygen concentrations suggest unfavorable conditions for denitrification in the eastern Snake

Table 4. Summary statistics for selected constituents in ground water, local study areas, eastern Snake River Plain, 1993–95

[mg/L, milligrams per liter; pCi/L, picocuries per liter; <, less than; —, insufficient data; NA, not applicable]

Constituent	No. of wells sampled	Reporting level	Minimum concentration measured	Percentile					Maximum concentration measured
				10	25	50	75	90	
A&B study area									
Dissolved organic carbon (mg/L).....	30	<0.10	0.20	0.50	0.60	0.90	1.4	1.8	4.9
Dissolved oxygen (mg/L).....	31	NA	3.0	5.0	6.2	7.3	8.3	8.6	9.3
Dissolved oxygen (percent saturation) ..	31	NA	33	58	70	85	93	97	100
Methylene blue active substances (mg/L).....	31	<.02	<.02	<.02	<.02	<.02	<.02	<.02	.02
Kjeldahl nitrogen (ammonia plus organic), dissolved, as nitrogen (mg/L).....	31	<.20	<.20	<.20	<.20	<.20	<.20	<.20	.20
Nitrite, dissolved, as nitrogen (mg/L)....	31	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N) (mg/L).....	31	<.05	.06	1.1	1.8	3.9	5.8	8.5	11
Nitrogen ammonia, dissolved, as nitrogen (mg/L)	31	<.01	<.01	<.01	.01	.02	.02	.03	.03
Phosphorus, dissolved, as phosphorus (mg/L).....	31	<.01	<.01	<.01	.01	.02	.03	.05	.10
Orthophosphorus, dissolved, as phosphorus (mg/L)	31	<.01	<.01	<.01	.01	.02	.03	.04	.06
Hydrogen isotope (δ ² H) (±2 permil)	27	NA	-138	-136	-135	-127	-126	-125	-125
Oxygen isotope (δ ¹⁸ O) (±0.2 permil) ...	27	NA	-18.23	-18.19	-17.96	-16.66	-16.46	-16.25	-15.93
Nitrogen isotope (δ ¹⁵ N) (±0.2 permil) ..	9	NA	2.6	2.6	3.3	3.6	4.2	4.8	4.8
Tritium (pCi/L).....	14	<1±1	2±1	5±1	4±5	74±5	96±7	105±7	110±7
Background study area									
Dissolved organic carbon (mg/L).....	0	<0.10	—	—	—	—	—	—	—
Dissolved oxygen (mg/L).....	8	NA	7.1	—	7.4	7.7	8.1	—	9.0
Dissolved oxygen (percent saturation) ..	8	NA	85	—	91	92	93	—	100
Methylene blue active substances (mg/L).....	0	<.02	—	—	—	—	—	—	—
Kjeldahl nitrogen (ammonia plus organic), dissolved, as nitrogen (mg/L).....	9	<.20	<.20	0.20	<.20	<.20	<.20	<.20	<.20
Nitrite, dissolved, as nitrogen (mg/L).....	9	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N) (mg/L).....	9	<.05	.40	.40	.45	.60	.70	1.5	1.5
Nitrogen ammonia, dissolved, as nitrogen (mg/L)	9	<.01	<.01	<.01	<.01	<.01	.02	.02	.02
Phosphorus, dissolved, as phosphorus (mg/L).....	9	<.01	<.01	<.01	<.01	<.01	<.01	<.01	.01
Orthophosphorus, dissolved, as phosphorus (mg/L)	9	<.01	<.01	<.01	<.01	<.01	<.01	.01	.01
Hydrogen isotope (δ ² H) (±2 permil).....	9	NA	-139	-139	-138	-137	-136	-136	-136
Oxygen isotope (δ ¹⁸ O) (±0.2 permil) ...	9	NA	-18.09	-18.08	-17.99	-17.91	-17.83	-17.67	-17.64
Nitrogen isotope (δ ¹⁵ N) (±0.2 permil) ..	9	NA	3.1	3.1	3.5	4.1	4.9	5.6	5.62
Tritium (pCi/L).....	8	<1±1	<1±1	—	<1±1	<1±1	7±1	—	21±2

Table 4. Summary statistics for selected constituents in ground water, local study areas, eastern Snake River Plain, 1993–95—Continued

Constituent	No. of wells sampled	Reporting level	Minimum concentration measured	Percentile					Maximum concentration measured
				10	25	50	75	90	
Eden study area									
Dissolved organic carbon (mg/L).....	15	<0.10	0.40	0.50	0.60	0.80	1.0	1.3	1.4
Dissolved oxygen (mg/L).....	14	NA	4.8	5.6	7.0	7.4	7.7	8.7	9.0
Dissolved oxygen (percent saturation) ..	14	NA	55	68	82	88	92	100	100
Methylene blue active substances (mg/L).....	14	<.02	<.02	<.02	<.02	<.02	<.02	<.02	.02
Kjeldahl nitrogen (ammonia plus organic), dissolved, as nitrogen (mg/L).....	15	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20
Nitrite, dissolved, as nitrogen (mg/L)....	15	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N) (mg/L).....	15	<.05	.70	.80	1.5	2.0	2.8	4.3	4.6
Nitrogen ammonia, dissolved, as nitrogen (mg/L)	15	<.01	<.01	<.01	<.01	<.01	.02	.02	.02
Phosphorus, dissolved, as phosphorus (mg/L).....	15	<.01	<.01	<.01	<.01	.02	.03	.06	.10
Orthophosphorus, dissolved, as phosphorus (mg/L)	15	<.01	<.01	<.01	.01	.02	.02	.06	.10
Hydrogen isotope (δ ² H) (±2 permil).....	11	NA	-136	-136	-132	-130	-128	-125	-125
Oxygen isotope (δ ¹⁸ O) (±0.2 permil) ...	11	NA	-17.75	-17.65	-17.11	-16.69	-16.58	-16.26	-16.25
Nitrogen isotope (δ ¹⁵ N) (±0.2 permil)..	11	NA	4.5	4.6	4.9	5.6	7.0	7.6	7.6
Tritium (pCi/L).....	11	<1±1	14±1	15±1	22±2	57±5	67±5	73±5	74±5
Jerome/Gooding study area									
Dissolved organic carbon (mg/L).....	30	<0.10	<0.10	0.20	0.30	0.40	0.70	0.80	0.90
Dissolved oxygen (mg/L).....	30	NA	6.6	7.5	7.8	8.2	8.5	8.8	9.3
Dissolved oxygen (percent saturation) ..	30	NA	76	85	88	92	96	100	100
Methylene blue active substances (mg/L).....	30	<.02	<.02	<.02	<.02	<.02	<.02	<.02	<.02
Kjeldahl nitrogen (ammonia plus organic), dissolved, as nitrogen (mg/L).....	30	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20
Nitrite, dissolved, as nitrogen (mg/L)....	30	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N) (mg/L).....	30	<.05	.50	.60	.70	.90	1.7	2.2	2.5
Nitrogen ammonia, dissolved, as nitrogen (mg/L)	30	<.01	<.01	<.01	<.01	.01	.02	.03	.04
Phosphorus, dissolved, as phosphorus (mg/L).....	30	<.01	<.01	<.01	<.01	<.01	.02	.20	.30
Orthophosphorus, dissolved, as phosphorus (mg/L)	30	<.01	<.01	<.01	<.01	<.01	.02	.02	.03
Hydrogen isotope (δ ² H) (±2 permil).....	30	NA	-138	-138	-137	-135	-130	-129	-124
Oxygen isotope (δ ¹⁸ O) (±0.2 permil) ...	30	NA	-18.01	-17.94	-17.86	-17.72	-16.85	-16.60	-16.14
Nitrogen isotope (δ ¹⁵ N) (±0.2 permil)..	21	NA	3.0	4.1	4.8	5.2	5.8	6.5	7.2
Tritium (pCi/L).....	28	<1±1	<2±1	6±1	8±1	18±2	54±3	61±4	64±4

Table 4. Summary statistics for selected constituents in ground water, local study areas, eastern Snake River Plain, 1993–95—Continued

Constituent	No. of wells sampled	Reporting level	Minimum concentration measured	Percentile					Maximum concentration measured
				10	25	50	75	90	
Minidoka study area									
Dissolved organic carbon (mg/L).....	29	<0.10	0.60	0.80	0.95	1.4	3.2	5.7	63
Dissolved oxygen (mg/L).....	28	NA	0	0	.20	1.8	5.5	7.2	7.4
Dissolved oxygen (percent saturation) ..	28	NA	0	0	2.0	21	62	80	82
Methylene blue active substances (mg/L).....	29	<.02	<.02	<.02	<.02	<.02	<.02	.02	.03
Kjeldahl nitrogen (ammonia plus organic), dissolved, as nitrogen (mg/L).....	29	<.20	<.20	<.20	<.20	<.20	.30	.50	1.2
Nitrite, dissolved, as nitrogen (mg/L).....	29	<.01	<.01	<.01	<.01	<.01	<.01	.03	.09
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N) (mg/L).....	29	<.05	<.05	.30	2.2	7.1	13	25	58
Nitrogen ammonia, dissolved, as nitrogen (mg/L)	29	<.01	.01	.01	.02	.02	.03	.07	.20
Phosphorus, dissolved, as phosphorus (mg/L).....	29	<.01	.03	.04	.05	.07	.10	.10	.40
Orthophosphorus, dissolved, as phosphorus (mg/L)	29	<.01	.03	.03	.04	.06	.09	.10	.40
Hydrogen isotope (δ ² H) (±2 permil)....	28	NA	-129	-128	-126	-125	-125	-124	-122
Oxygen isotope (δ ¹⁸ O) (±0.2 permil) ...	28	NA	-16.77	-16.59	-16.51	-16.30	-16.23	-15.93	-15.62
Nitrogen isotope (δ ¹⁵ N) (±0.2 permil)..	0	NA	—	—	—	—	—	—	—
Tritium (pCi/L).....	15	<1±1	50±3	53±3	59±4	66±4	81±5	89±6	90±6

River Plain aquifer. Once the aquifer is contaminated, natural degradation of NO₂+NO₃-N through denitrification is minor.

Ground water in the local alluvial aquifer in the Minidoka study area contained lower dissolved-oxygen concentrations than in the other study areas; the median concentration was 1.8 mg/L and median saturation was 21 percent (table 4). The higher organic carbon and absence of dissolved oxygen suggest favorable conditions for denitrification in parts of the Minidoka study area.

Methylene Blue Active Substances

Ground water was analyzed for methylene blue active substances (MBAS) to determine whether domestic septic system effluent contributed to NO₂+NO₃-N concentrations. The analysis tests for the presence of anionic sulfate- and sulfonate-based surfactants (Burkhardt and others, 1995) that are present in some soaps. Detections

of MBAS were extremely rare in samples analyzed (table 4). Data on MBAS suggest that domestic septic system effluent did not appreciably affect NO₂+NO₃-N concentrations in the study areas.

Dissolved Nutrients

NO₂+NO₃-N concentrations in ground water (table 4, fig. 20) were highest in the Minidoka study area. Concentrations were the next highest in the A&B study area and progressively decreased in the Eden, Jerome/Gooding, and Background study areas. Concentrations of dissolved organic carbon, ammonia plus organic nitrogen, nitrite, ammonia, phosphorus, and orthophosphorus also were higher in the Minidoka study area (table 4).

Ammonia plus organic nitrogen and nitrite were not detected in any of the samples from the eastern Snake River Plain aquifer, and ammonia concentrations were low. The high concentrations of dissolved oxygen and the general lack of ammonia plus organic nitrogen,

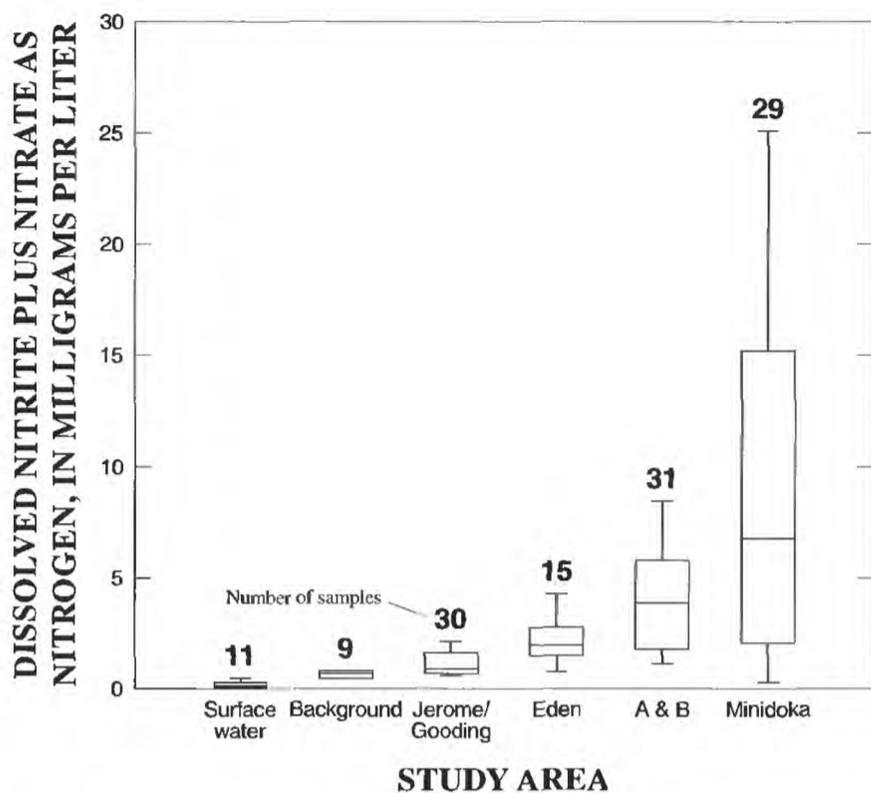


Figure 20. Concentrations of dissolved nitrite plus nitrate as nitrogen in surface and ground water, eastern Snake River Plain, 1993–95.

nitrite, and ammonia suggest that nitrogen species in the eastern Snake River Plain aquifer are readily oxidized to $\text{NO}_2 + \text{NO}_3 - \text{N}$. However, samples from the local alluvial aquifer (Minidoka study area) contained higher concentrations of ammonia plus organic nitrogen, nitrite, and ammonia, and lower concentrations of dissolved oxygen. This suggests that conditions in the local alluvial aquifer may not be as conducive to nitrification of ammonia plus organic nitrogen, nitrite, and ammonia to $\text{NO}_2 + \text{NO}_3 - \text{N}$.

Water samples from the Snake River near Minidoka and the Snake River near Milner Dam also were analyzed for $\text{NO}_2 + \text{NO}_3 - \text{N}$, as shown in figure 20. Data for surface water were included because substantial amounts of Snake River water are diverted for irrigation in the Eden, Jerome/Gooding, and Minidoka study areas. Recharge from excess irrigation water from the Snake River greatly affects ground-water quality. $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in the Snake River were less than those from the Background study area, which suggests that elevated $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in the A&B, Eden, Jerome/Gooding, and Minidoka study areas are from anthropogenic sources within each area, not from recharge of imported surface water.

$\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in the eastern Snake River Plain aquifer were highest near the south-

western edge of the A&B study area (fig. 21). Lines of equal $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations could not be drawn for the Minidoka study area because concentrations were highly variable over small areas.

Major Ions

Major ion chemistry of ground water in all study areas and in water samples from the Snake River was similar, but concentrations differed; the dominant ions were calcium and bicarbonate. Bicarbonate concentrations in ground water were highest in the Minidoka study area (fig. 22) and lowest in the Background study area. Calcium, chloride, magnesium, potassium, sodium, and sulfate concentrations differed in a similar way. Elevated concentrations of these ions can be attributed to the evaporation of some water diverted for irrigation prior to recharge of excess irrigation water, and to leaching of salts from soils during recharge. Wood and Low (1988, p. D44) confirmed that evapotranspiration of irrigation water has increased the concentrations of calcium and bicarbonate in the eastern Snake River Plain aquifer.

Bicarbonate and $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in ground water in the local study areas were positively correlated (fig. 23), as shown by a LOWESS smoothing curve calculated using the locally weighted scatterplot smoothing method (Helsel and Hirsch, 1992, p. 288). The p-value calculated by the Spearman's rho rank-order nonparametric statistical test (Helsel and Hirsch, 1992, p. 217) was less than 0.01, which suggests a significant relation between $\text{NO}_2 + \text{NO}_3 - \text{N}$ and bicarbonate at a greater-than-99-percent confidence level. Specific conductance, alkalinity, calcium, magnesium, chloride, and sulfate were similarly correlated with $\text{NO}_2 + \text{NO}_3 - \text{N}$. The relation between high $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations and high major ion concentrations suggests that high $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations may be associated with water that had undergone evaporation prior to recharge and with leaching of salts from soils by recharge water.

Isotopes

The hydrogen (^2H and ^3H) and oxygen (^{18}O) isotopic concentrations in ground water and the isotopic composition of $\text{NO}_2 + \text{NO}_3 - \text{N}$ (^{15}N) dissolved in ground water were examined in this study. Isotopes are atoms of

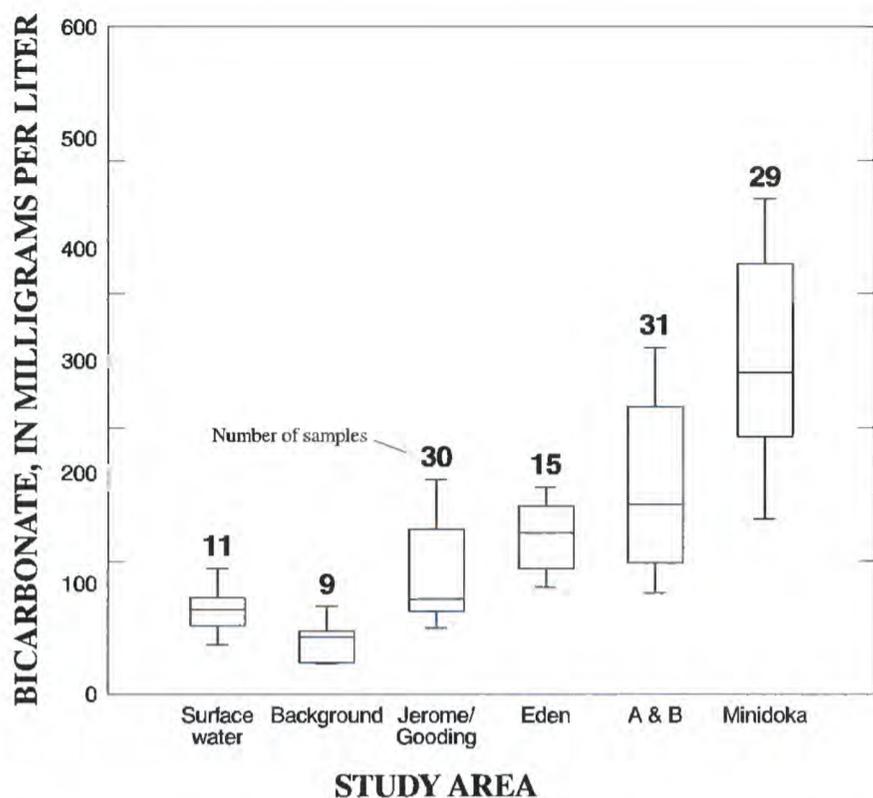


Figure 22. Concentrations of bicarbonate in surface and ground water, local study areas, eastern Snake River Plain, 1993–95.

the same element that differ in mass because of a difference in the number of neutrons in the nucleus. For example, deuterium (^2H) is hydrogen with one proton and one neutron in the nucleus and is distinguished from tritium (^3H), a radioactive isotope of hydrogen with one proton and two neutrons in the nucleus. There are many potential uses of stable and radioactive isotopes in hydrogeologic investigations (Coplen, 1993). In application to ground water in the eastern Snake River Plain, ^2H and ^{18}O can be used to trace ground water along a flowpath, determine the amount of mixing of different types of water, and identify water that has undergone evaporation since precipitation in the source area. Isotopes of nitrogen sometimes can be used to identify the source of $\text{NO}_2 + \text{NO}_3 - \text{N}$ in ground water. Tritium can be used to help determine the presence of water from precipitation that formed prior to or subsequent to the advent of atmospheric testing of nuclear weapons.

The isotopic compositions of stable isotopes ^2H , ^{18}O , and ^{15}N are expressed in permil units, or parts per thousand, as deviation of the isotope ratio relative to a standard, by using delta notation (δ):

$$\delta = \left[\frac{R_{\text{sample}}}{R_{\text{reference}}} - 1 \right] \times 1,000, \quad (1)$$

where R is the measured isotopic ratio. The delta symbol in this report is followed by the chemical symbol for the heavier isotope of the isotopic pair (for instance $\delta^{18}\text{O}$, because ^{18}O is heavier than ^{16}O). Permil values in this report are presented relative to the standardized reference compounds, Vienna Standard Mean Ocean Water (Coplen, 1994) for hydrogen ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) analyses, and air for nitrogen ($\delta^{15}\text{N}$). As an example, an $^{18}\text{O}/^{16}\text{O}$ measurement that is +50 permil ($\delta^{18}\text{O} = +50$) is enriched in ^{18}O by 5 percent relative to the standard; the sample is isotopically “heavy” relative to the standard. All isotope analyses were performed by the USGS.

Tritium (^3H), the radioactive isotope of hydrogen, commonly is measured in picocuries per liter. Tritium substitutes for a hydrogen (^1H) atom in the water molecule and can serve as an excellent tracer because water containing a ^3H atom follows the same pathway through the environment as water containing no ^3H atoms (Plummer and others, 1993, p. 256–257). The half-life of ^3H is 12.43 years.

HYDROGEN AND OXYGEN

Deuterium and ^{18}O are part of the water molecule; isotopic variations of both are usually covariant. The isotopic composition of precipitation varies glo-

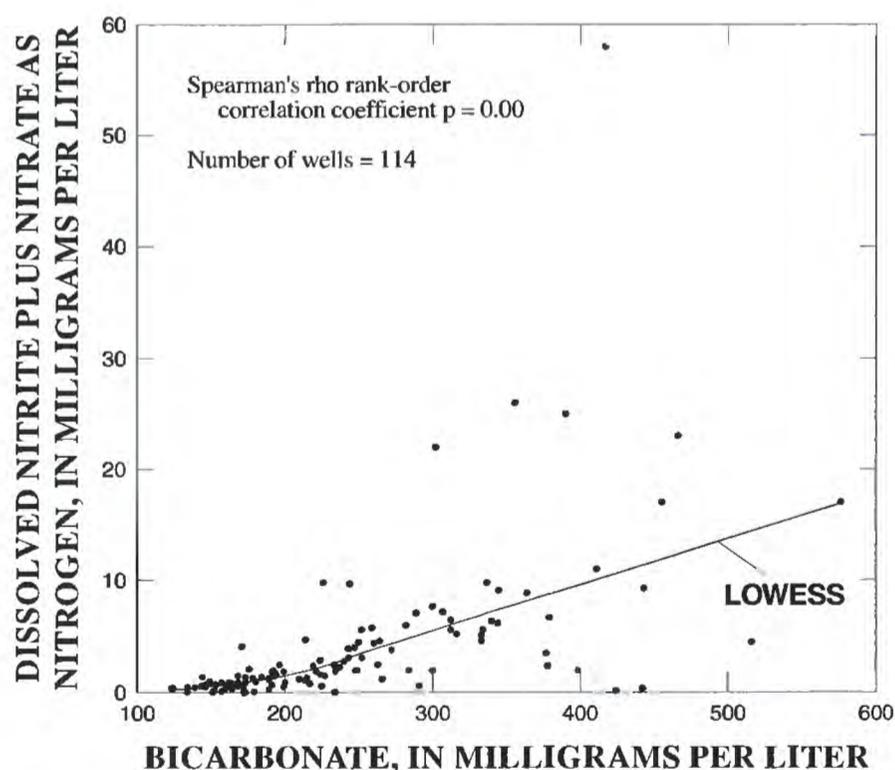


Figure 23. Relations between concentrations of dissolved nitrite plus nitrate as nitrogen and bicarbonate in ground water, local study areas, eastern Snake River Plain, 1993–95.

bally according to the World Meteoric Line (Craig, 1961):

$$\delta^2\text{H (permil)} = 8\delta^{18}\text{O (permil)} + 10 \quad (2)$$

Although the isotopic composition of most precipitation varies with a slope of 8 on plots of $\delta^2\text{H}$ and $\delta^{18}\text{O}$, the intercept of $\delta^{18}\text{O}$ at 0 permil, known as the deuterium excess (Dansgaard, 1964) can vary widely depending on local climatic conditions where precipitation forms. As water evaporates, the lighter isotopes ^{16}O and ^1H in water vapor are preferentially removed, and the stable isotopic compositions of the remaining water are shifted toward greater enrichment in ^{18}O and ^2H . Because of

the kinetic isotope fractionation effect of evaporation, the isotopic composition of the residual water typically shifts off the World Meteoric Line along slopes of 3 to 6, owing partly to a complicated function of humidity, temperature, salt concentration, and other factors (Coplen, 1993, p. 235). The residual water undergoing evaporation becomes enriched in ^{18}O and ^2H . Water undergoing multiple cycles of evaporation is further enriched along the evaporation path as a function of $\delta^2\text{H}$ and $\delta^{18}\text{O}$. Data shown in figure 24 deviate from the World Meteoric Line on a trend that coincides with the expected evaporation path.

Ground water in the Background study area contained some of the lightest isotopic compositions (fig. 24, table 4); water from the Snake River was en-

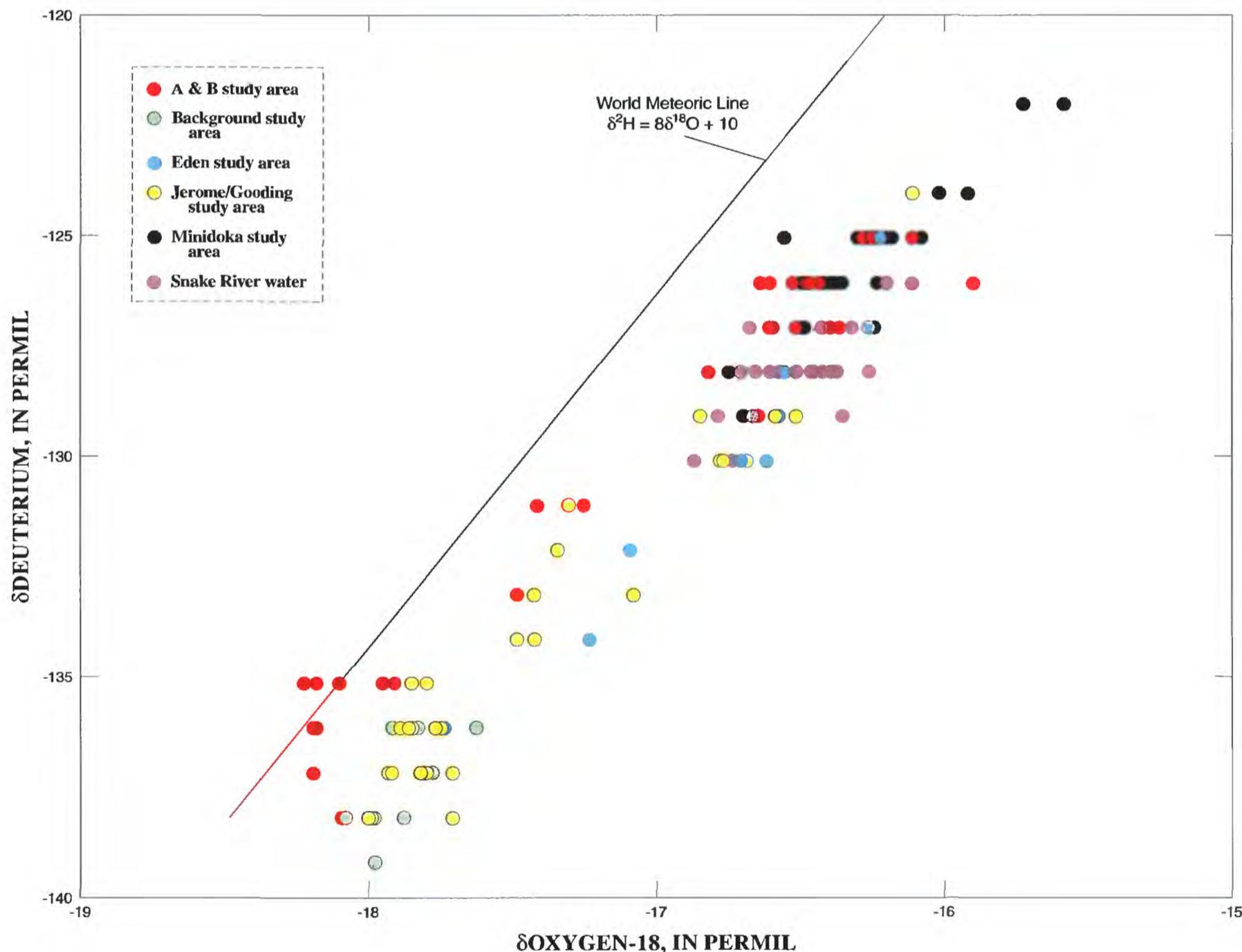


Figure 24. Relations between relative hydrogen isotope ratios and relative oxygen isotope ratios in ground water, local study areas, eastern Snake River Plain, 1993–95. (^2H , deuterium; ^{18}O , oxygen-18)

Table 5. Summary statistics for selected constituents in water from the Snake River downstream from Lake Walcott, the North Side and Main Canals near Milner Dam, the Snake River near Kimberly, the Snake River near Twin Falls, and the Snake River near Buhl, eastern Snake River Plain, 1993–95

[pCi/L, picocuries per liter; NA, not applicable; <, less than]

Constituent	No. of samples	Re-reporting level	Minimum concentration measured	Percentile					Maximum concentration measured
				10	25	50	75	90	
Hydrogen isotope ($\delta^2\text{H}$) (± 2 permil)	22	NA	-130	-130	-128	-128	-128	-126	-126
Oxygen isotope ($\delta^{18}\text{O}$) (± 0.2 permil)	22	NA	-16.89	-16.80	-16.71	-16.52	-16.40	-16.25	-16.14
Nitrogen isotope ($\delta^{15}\text{N}$) (± 0.2 permil) ...	9	NA	3.4	3.4	4.4	5.8	7.4	8.1	8.1
Tritium (^3H) (pCi/L)	21	<1 \pm 1	<43 \pm 3	45 \pm 3	54 \pm 4	57 \pm 4	61 \pm 5	61 \pm 5	62 \pm 5

riched in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (table 5) (Clark, 1997). Ground water in the Minidoka study area contained isotopic compositions slightly heavier than Snake River water, which suggests that most recharge to the local alluvial aquifer is irrigation water from the Snake River. Most irrigation water used in the Minidoka study area is, in fact, diverted from the Snake River and, according to local accounts, the local alluvial aquifer did not exist prior to construction of the irrigation network from Lake Walcott in 1907 (Rupert, 1994, p. 11). The heavier isotopic composition of ground water in the Minidoka area suggests that surface water used for irrigation had undergone additional evaporation prior to infiltration.

Compositions of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in the Eden and Jerome/Gooding study areas (fig. 24, table 4) show the effects of native ground water mixing with water that either was diverted from the Snake River for irrigation (table 5), or otherwise had undergone evaporation prior to infiltration. For the most part, the isotopic composition of ground water in the Eden area was similar to that of surface water. A logical conclusion is that a significant amount of recharge in the Eden area is from surface-water irrigation, because most of the irrigation water used in this area is diverted from the Snake River. Compositions of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in ground water in the Jerome/Gooding area were similar to those in the Background study area. Isotopic compositions were heavier in the southern part of the Jerome/Gooding area (fig. 25), which suggests a greater proportion of recharge from surface-water irrigation. This area is irrigated predominantly with water diverted from the Snake River (fig. 6) and also had the highest $\text{NO}_2+\text{NO}_3-\text{N}$ concentrations in the Jerome/Gooding study area (fig. 21). These high $\text{NO}_2+\text{NO}_3-\text{N}$ concentrations are presumably due to leaching of $\text{NO}_2+\text{NO}_3-\text{N}$ from the soil horizon by the irrigation water during infiltration.

Processes that affect $\delta^2\text{H}$ and $\delta^{18}\text{O}$ compositions in the A&B study area are different from those in the Eden and Jerome/Gooding areas because most of the A&B area is irrigated with ground water. Isotopic compositions in ground water in the northern part of the A&B area were similar to those in the Background study area (figs. 24 and 25). Isotopic compositions become progressively heavier in a southwesterly (downgradient) direction (fig. 25) because of the additive effects of evaporation as ground water is subjected to several irrigation cycles. The heaviest water from the A&B study area plots in the same general location on figure 24 as Snake River water and heavy water from the Eden and Minidoka study areas. This similarity suggests that evaporated ground water and background water mixed with local surface-water recharge cannot be distinguished by isotopic composition alone.

Concentrations of $\text{NO}_2+\text{NO}_3-\text{N}$ in the A&B, Background, Eden, and Jerome/Gooding areas increased with increasing $\delta^2\text{H}$ (fig. 26), similar to the relation between $\text{NO}_2+\text{NO}_3-\text{N}$ and $\delta^{18}\text{O}$. Elevated $\text{NO}_2+\text{NO}_3-\text{N}$ concentrations, therefore, presumably are the result of local recharge by irrigation water that had undergone evaporation.

NITROGEN

Nitrogen isotopes were analyzed to more accurately determine sources of nitrogen in the A&B, Background, Eden, and Jerome/Gooding study areas; budgetary constraints precluded sampling for nitrogen isotopes in the Minidoka study area. Values of $\delta^{15}\text{N}$ are determined specifically for nitrogen within the $\text{NO}_2+\text{NO}_3-\text{N}$ molecule; they can serve as an indicator of the source of that $\text{NO}_2+\text{NO}_3-\text{N}$. Coplen (1993, p. 239) suggested that typical $\delta^{15}\text{N}$ values for commercial inor-

EXPLANATION

— -125 — Line of equal relative hydrogen isotope composition—Interval is 5 permil

• -132 Well—Number is relative hydrogen isotope composition, in permil

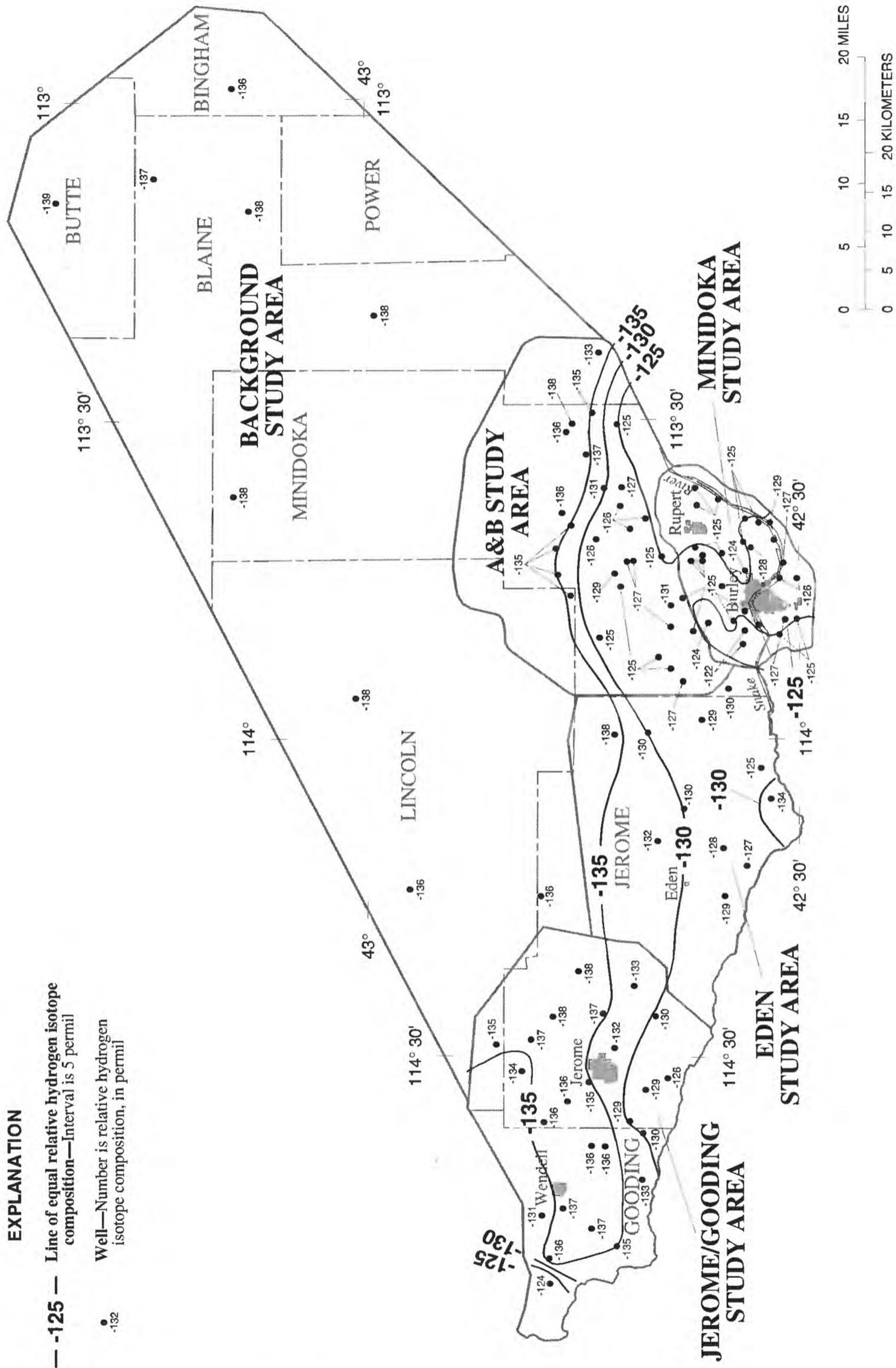


Figure 25. Relative hydrogen isotope compositions in ground water, local study areas, eastern Snake River Plain, 1993–95.

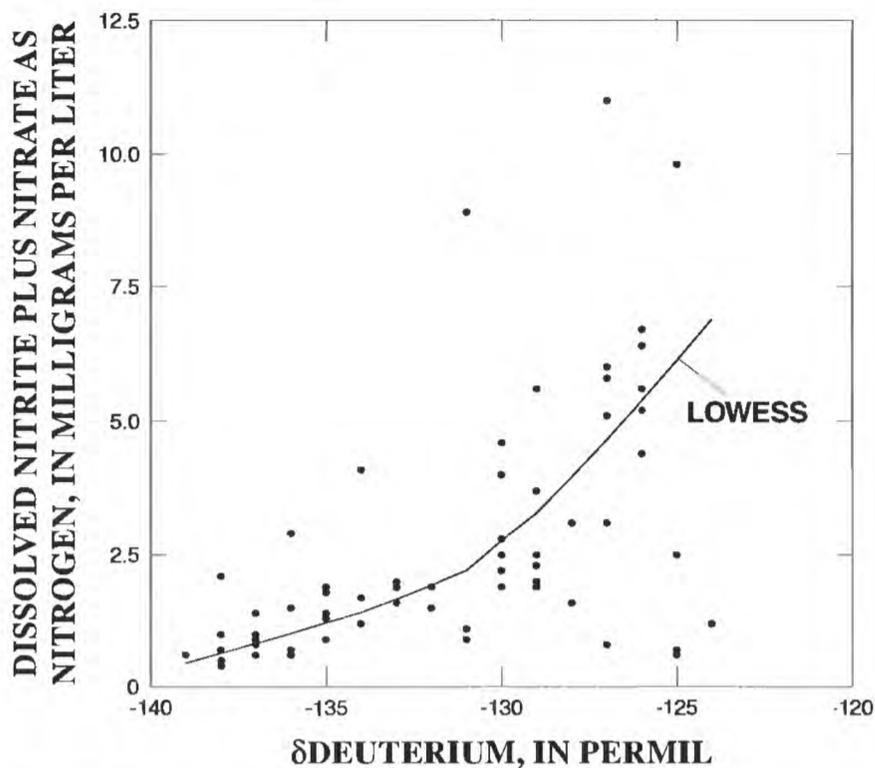


Figure 26. Relations between concentrations of dissolved nitrite plus nitrate as nitrogen and relative hydrogen isotope ratios in ground water, local study areas, eastern Snake River Plain, 1993–95. [LOWESS, Locally Weighted Scatterplot Smoothing (Helsel and Hirsch, 1992)]

ganic fertilizer are less than +3.5 permil; Komor and Anderson (1993) suggested that $\delta^{15}\text{N}$ values for commercial inorganic fertilizer are less than 2. Both investigators suggested that $\delta^{15}\text{N}$ values for animal wastes are greater than +10. Kreitler (1975) determined that natural soil $\delta^{15}\text{N}$ values in areas not affected by anthropogenic $\text{NO}_2 + \text{NO}_3 - \text{N}$ sources are from +2 to +8 permil; Komor and Anderson (1993) measured $\delta^{15}\text{N}$ values of about +3 permil.

Median $\delta^{15}\text{N}$ values for ground water in the Background study area were about +4 permil (fig. 27), corresponding with those anticipated by Kreitler (1975). The median $\delta^{15}\text{N}$ value in the A&B study area was +3.6 permil. Although median $\delta^{15}\text{N}$ values in the A&B study area were lower than in the Background study area, the difference is not statistically significant. The slightly lower value may be the result of the addition of nitrogen from commercial inorganic fertilizer. The $\delta^{15}\text{N}$ values in the A&B study area were much lower than the +10 permil value suggested by Coplen (1993, p. 239) and Komor and Anderson (1993) for $\delta^{15}\text{N}$ from animal waste, which helps to confirm that domestic septic systems and cattle manure provide minimal nitrogen in that area.

Median $\delta^{15}\text{N}$ values for ground water in the Eden and Jerome/Gooding areas exceeded +5 permil (fig. 27), which was significantly higher than background concentrations. The heavy $\delta^{15}\text{N}$ values in these areas might be attributable to input of nitrogen from cattle manure and (or) recharge from surface water used for irrigation. Median $\delta^{15}\text{N}$ values for water from the Snake River were +5.8 permil (fig. 27, table 5). Few cattle are raised in the Eden area, so the most probable reason for the heavy $\delta^{15}\text{N}$ values is recharge from surface water used for irrigation. High values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in the Eden area (fig. 24) also reflect recharge from surface water.

Elevated $\delta^{15}\text{N}$ values for ground water in the Jerome/Gooding area may be partly from leaching of cattle manure from the many dairies, particularly in Gooding County. Values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for ground water in the Jerome/Gooding area were similar to those in the Background area (fig. 24), which suggests less recharge from surface water used for irrigation than in the Eden area. In spite of less recharge, the $\delta^{15}\text{N}$ values were much higher than values in the Background area, which suggests that leaching of cattle manure from dairies may play a greater role in elevating $\delta^{15}\text{N}$ values in the Jerome/Gooding area.

A possible deterrent to determining the source of $\text{NO}_2 + \text{NO}_3 - \text{N}$ using $\delta^{15}\text{N}$ is the potential change in iso-

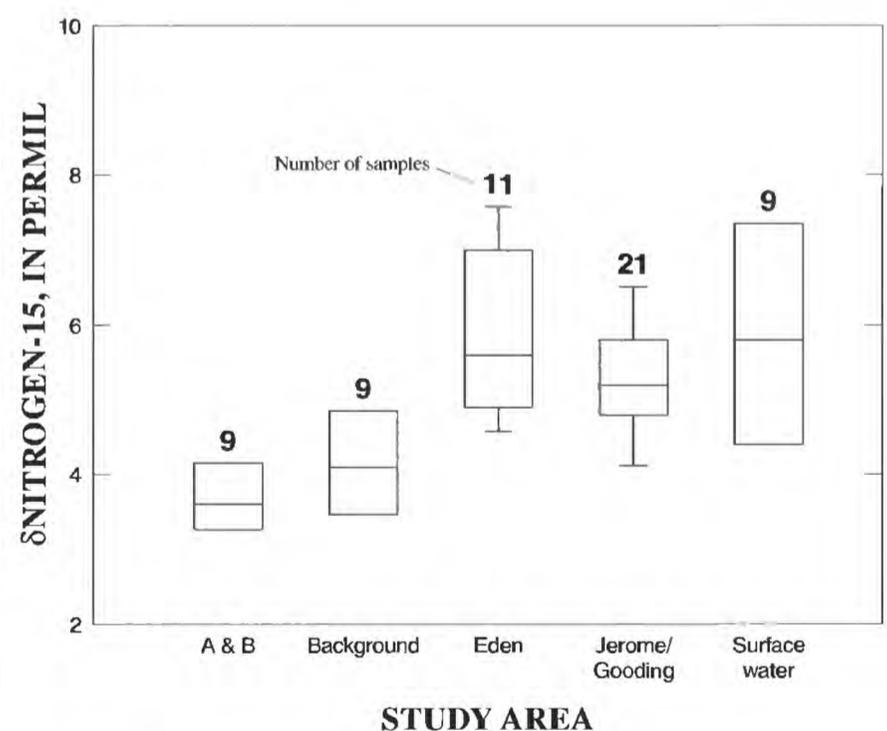


Figure 27. Nitrogen isotope ratios in ground and surface water, local study areas, eastern Snake River Plain, 1993–95. (The 10th and 90th percentiles are not shown on boxplots if fewer than 10 wells were sampled)

topic composition during denitrification. However, denitrification is not believed to be a significant process in the eastern Snake River Plain aquifer because of the high dissolved oxygen and low dissolved organic nitrogen concentrations (table 4).

TRITIUM

Tritium (^3H) can be used to identify recent ground-water recharge or ground-water mixtures containing some recent water. Low concentrations of tritium are produced naturally by the interaction of the atmosphere with cosmic rays from the solar wind. Atmospheric thermonuclear weapons testing from 1952 to the mid-1960's introduced a large amount of tritium to the atmosphere that was incorporated directly into water molecules of precipitation. Mann and Low (1994, fig. 2) calculated concentrations in precipitation at the Idaho National Engineering and Environmental Laboratory as high as 4,000 pCi/L in 1963; concentrations in precipitation have been decreasing since that time because of the short half-life of tritium and because most atmospheric thermonuclear weapons testing has been discontinued. Because the concentration of tritium in the atmosphere was high for a relatively short period of time, its presence in ground water can identify water that has been recharged during the last 40 years. Tritium concentrations in precipitation prior to thermonuclear weapons testing are not well known but probably did not exceed 6.5 to 26 pCi/L (Plummer and others, 1993, p. 260). Because tritium has a half-life of 12.43 years, water derived from precipitation before thermonuclear weapons testing would contain a maximum tritium concentration of 0.6 to 2.6 pCi/L by the early 1990's. Gellenbeck (1994, p. 20) suggested a similar estimate of 4.5 pCi/L for water older than 1952. Consequently, if tritium in a ground-water sample is higher than 4.5 pCi/L, a significant fraction of the water must have been derived since the advent of nuclear testing.

The tritium concentration map (fig. 28) helps define areas where some or all of the recharge has been from recent (post-1950's) water. The median tritium concentration in ground water from the Background study area was 1 pCi/L (table 4), which indicates little recent recharge from the immediate land surface. The median concentration in ground water from the Minidoka study area was 66 pCi/L, and the lowest concentration was 50 pCi/L (table 4). These values indicate that ground water in the Minidoka study area was recharged after 1952. Tritium concentrations in ground

water from the Eden area were lower, but high enough to suggest recent recharge. The median tritium concentration in the Jerome/Gooding area was lower than that in A&B, Eden, and Minidoka areas, which suggests much less mixing with recent recharge water. The cultivation density, crop types, irrigation methods, and soils in the Jerome/Gooding study area are relatively similar to those in the A&B, Eden, and Minidoka areas, so the reason for less recharge is unknown. Geologic materials composing the unsaturated zone in the Jerome/Gooding area may be less transmissive than materials in A&B, Eden, and Minidoka areas and, thus, may be limiting recharge of irrigation water.

The median tritium concentration in water from the Snake River was 57 pCi/L; the minimum was 43 and the maximum was 62 pCi/L (table 5) (Clark, 1997). Concentrations of that magnitude are expected in recent recharge water. Historically, tritium concentrations in water from the Snake River were much higher. Mann (1989, p. 19) reported that tritium concentrations during 1974–88 ranged from 100 to 900 pCi/L. Concentrations in precipitation peaked at 4,000 pCi/L in 1963. Tritium concentrations in the southwestern part of the A&B study area that were higher than present-day concentrations in water from the Snake River (fig. 28) suggest significant mixing with water older than present day, but younger than 1952.

The distribution of tritium concentrations (fig. 28) correlated well with the distributions of $\text{NO}_2+\text{NO}_3-\text{N}$ concentrations (fig. 21) and $\delta^2\text{H}$ values (fig. 25). These correlations indicate that areas where $\text{NO}_2+\text{NO}_3-\text{N}$ concentrations are elevated were recharged with recent irrigation water that had undergone some evaporation.

Hypothesis for Observed Ground-Water Quality in Local Study Areas

The following sequence of events, based on information in table 6, can explain the elevated concentrations of $\text{NO}_2+\text{NO}_3-\text{N}$ in the local study areas. Ground water that flows into the A&B area from the northeast side is of background water quality ($\text{NO}_2+\text{NO}_3-\text{N}$ less than 1 mg/L, $\delta^2\text{H}$ less than -135 permil, $\delta^{18}\text{O}$ generally less than 17.5 permil, tritium less than 4.5 pCi/L). As water moves southwestward under the A&B study area, some is pumped to the surface and used for irrigation. After field application, water contains heavier hydrogen and oxygen isotopic compositions and higher major ion concentrations because of

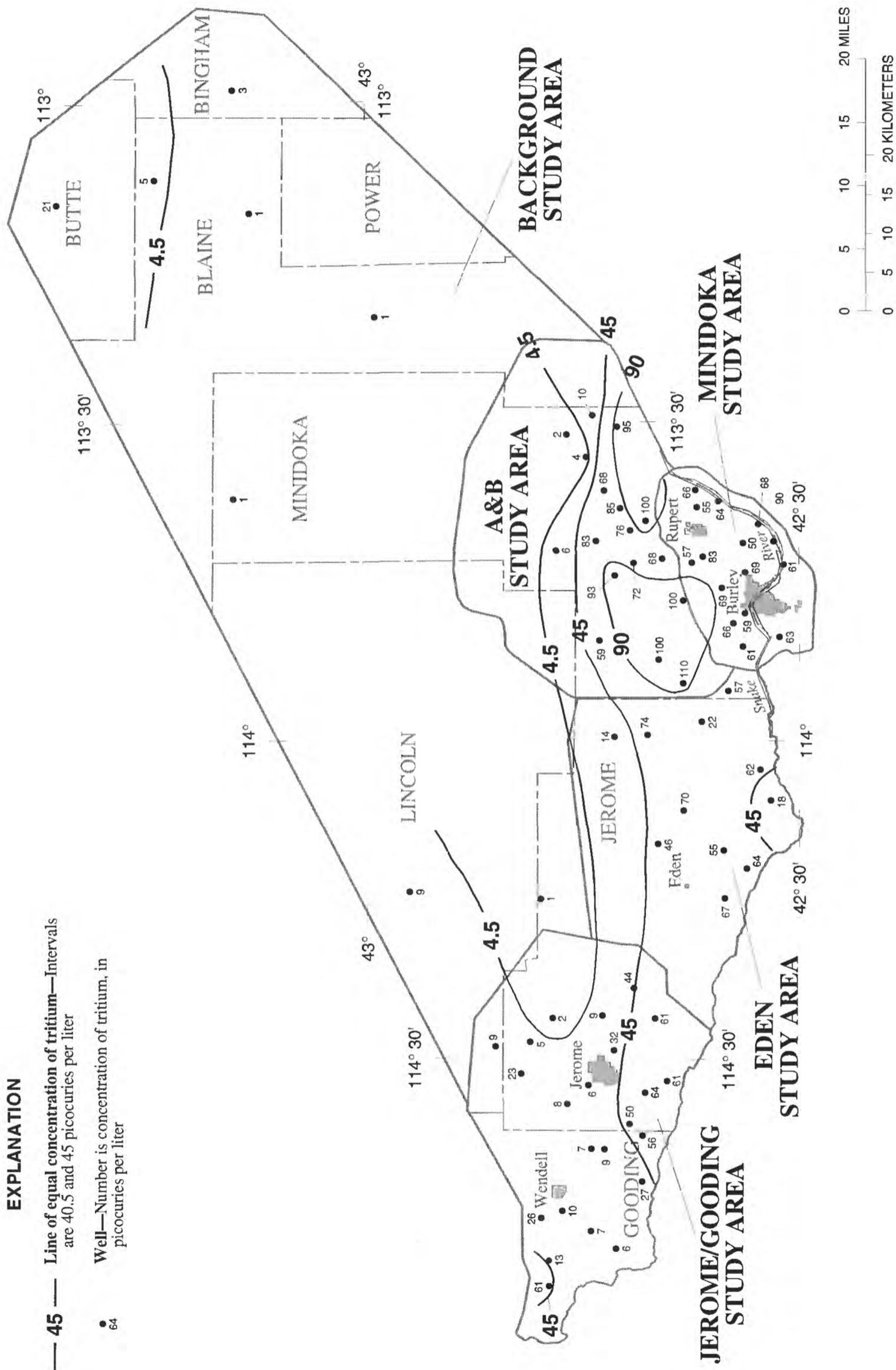


Figure 28. Concentrations of tritium in ground water, local study areas, eastern Snake River Plain, 1993–95.

Table 6. Summary of selected characteristics of ground water in local study areas, eastern Snake River Plain

[Depth to water, in feet, is ranked in order of decreasing depth to water, 5 being the shallowest and 1 being the deepest; dissolved oxygen is ranked either high or low, high is near 100 percent saturation and low is near 0 percent saturation; major ions and nitrite plus nitrate as nitrogen are ranked in order of increasing median concentrations, 1 being the lowest and 5 being the highest; relative hydrogen and oxygen isotopic compositions are ranked in order of increasing isotopic weight, 1 being the lightest and 5 being the heaviest; nitrogen isotopes are ranked as light, medium, or heavy — light isotopic composition is deficient in nitrogen-15, medium isotopic composition is midway between heavy and light, heavy isotopic composition is enriched in nitrogen-15; tritium is ranked as either young or old — young denotes significant mixing with recharge water younger than 1952, old denotes minor mixing with recharge water younger than 1952; —, insufficient data]

Characteristic	A & B study area	Back-ground study area	Eden study area	Jerome/Gooding study area	Minidoka study area
Depth to water.....	4	1	2	3	5
Dissolved oxygen.....	high	high	high	high	low
Major ions.....	4	1	3	2	5
Nitrite plus nitrate, dissolved, as nitrogen (NO ₂ +NO ₃ -N).....	4	1	3	2	5
Relative hydrogen and oxygen isotopic composition.....	4	1	3	2	5
Nitrogen isotope.....	light	medium	heavy	heavy	—
Tritium.....	young	old	young	mixed, old & young	young

evaporation and leaching of salts. Concentrations of NO₂+NO₃-N increase because of leaching of nitrogen from irrigated fields, and tritium concentrations increase because of mixing with recent water. Irrigation water in excess of plant needs percolates back to ground water and mixes with the native water. As ground water travels downgradient, it is pumped and applied to fields several times. Each time, NO₂+NO₃-N and major ion concentrations increase, and hydrogen and oxygen isotopic compositions become heavier. As a result, NO₂+NO₃-N concentrations are highest and isotopic compositions heaviest on the downgradient side of the A&B study area.

On the south-central edge of the A&B study area, recharge to the eastern Snake River Plain aquifer is from two probable sources: surface-water irrigation (fig. 6) and water from the local alluvial aquifer in the Minidoka study area. This recharge causes the sharp, westward bend of the 4,050-ft contour shown in figure 3. It is not known to what extent this recharge affects

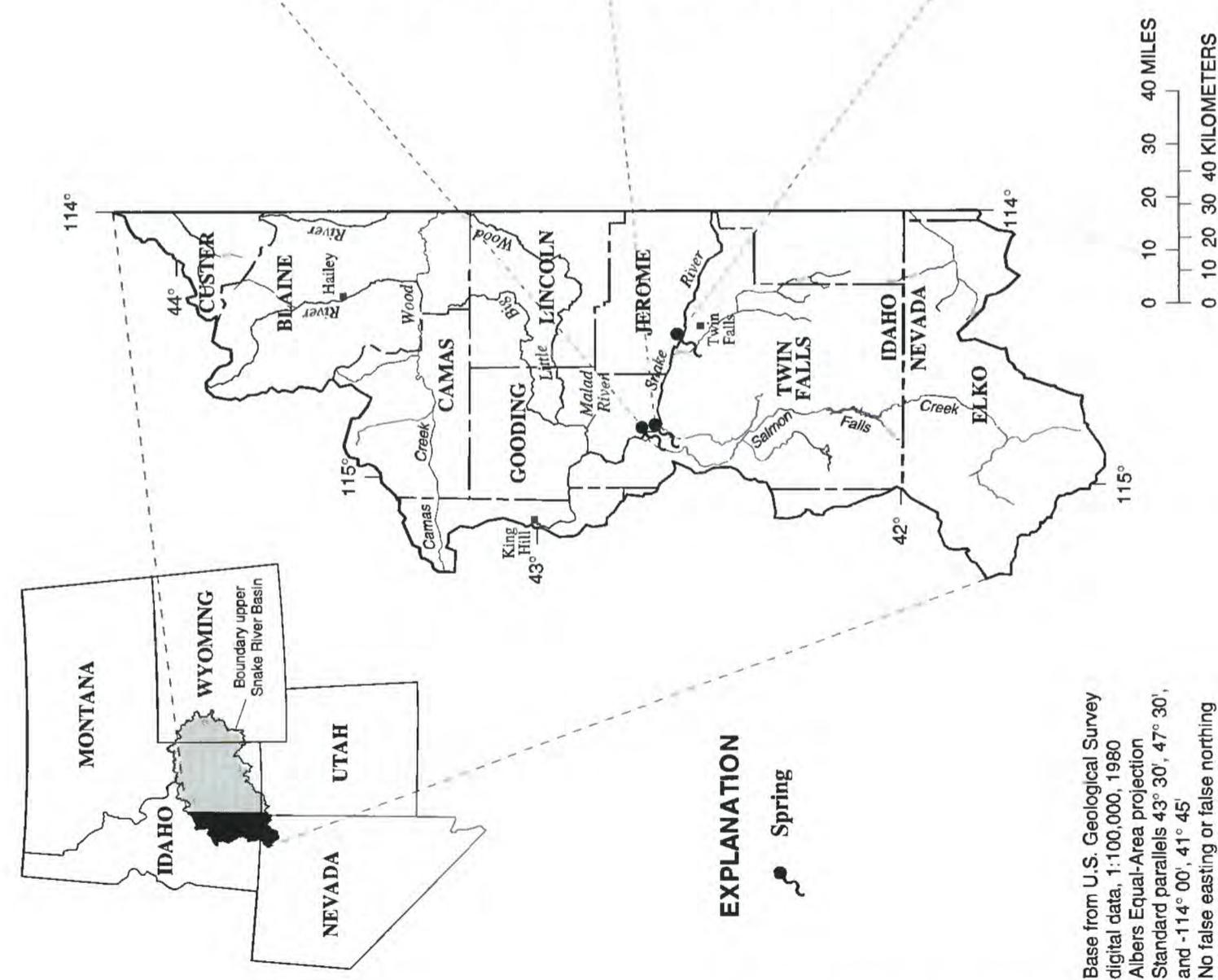
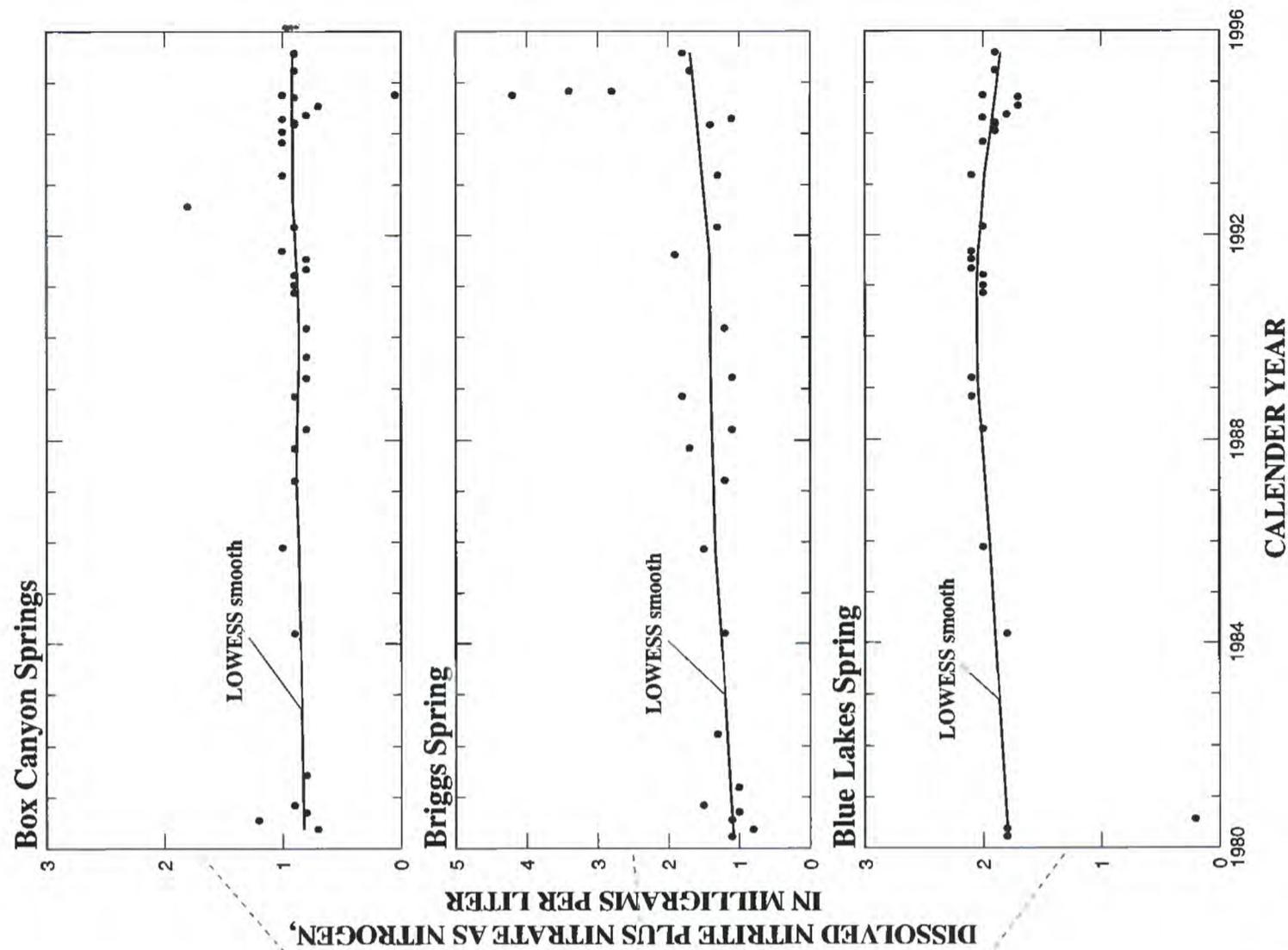
ground-water quality at the southern edge of the A&B study area.

Ground water moves from the A&B study area to the Eden area, where NO₂+NO₃-N concentrations generally are lower and stable isotope ratios are near those of surface water. Tritium concentrations suggest that most ground water is younger than 1952 (tables 4 and 5; fig. 28). The Eden study area is irrigated predominantly with water diverted from the Snake River (fig. 6). A logical hypothesis is that NO₂+NO₃-N and major ion concentrations in ground water entering the Eden area decrease as the result of mixing with surface-water recharge. However, stable isotope values and tritium concentrations remain high in ground water because they are high in the surface water that becomes recharge.

Ground-water quality in the Jerome/Gooding study area also is affected by recharge from surface-water irrigation, particularly in the southeastern part. Quality of ground water that enters the Jerome/Gooding area on the northeastern side is similar to background water quality. As ground water moves under the Jerome/Gooding area, its water chemistry changes and reflects the mixing with recharge from surface water used for irrigation. Stable isotope ratios become heavier because of evaporation prior to recharge, and tritium concentrations increase because of mixing with recent irrigation water. NO₂+NO₃-N concentrations increase slightly in a downgradient direction as a result of input from irrigated agriculture and dairy operations. The rate of recharge seems to be less than that in the A&B, Eden, and Minidoka areas because of the lower values of NO₂+NO₃-N, stable isotopes, and tritium. The distribution of stable isotope ratios and tritium concentrations in the Jerome/Gooding study area correlates well with those in springs on the southern and western margins of the area that drain the eastern Snake River Plain aquifer. Mann and Low (1994) and Clark and Ott (1996) attributed the concentrations in these springs to recharge from irrigation water upgradient from the springs.

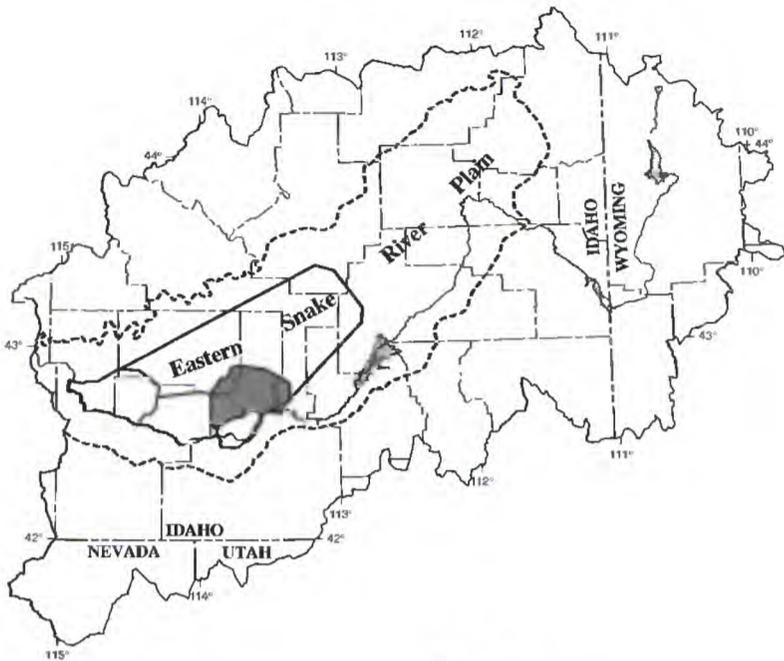
Long-Term Trends of Nitrite Plus Nitrate as Nitrogen in Ground Water

Long-term (1980–96) NO₂+NO₃-N data are available for two areas in the basin—Blue Lakes, Briggs, and Box Canyon Springs (fig. 29), and several wells in the A&B study area (fig. 30). Blue Lakes, Briggs, and Box Canyon Springs discharge water from the east-

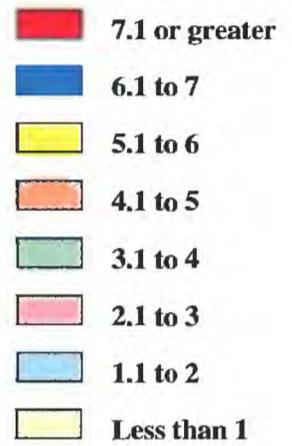


Base from U.S. Geological Survey digital data, 1:100,000, 1980
 Albers Equal-Area projection
 Standard parallels 43° 30', 47° 30', and -114° 00', 41° 45'
 No false easting or false northing

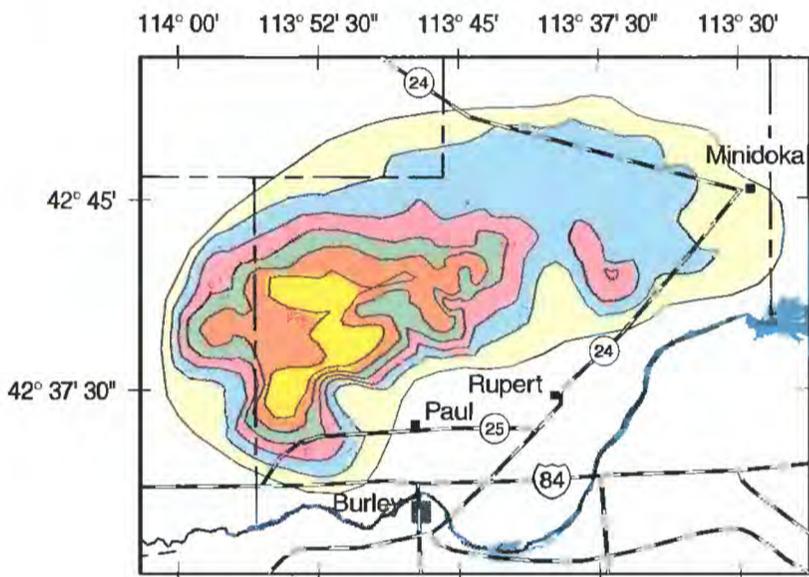
Figure 29. Long-term concentrations of dissolved nitrite plus nitrate as nitrogen in water from Box Canyon, Briggs, and Blue Lakes Springs, upper Snake River Basin, 1980–96. [LOWESS, Locally Weighted Scatterplot Smoothing (Helsel and Hirsch, 1992)]



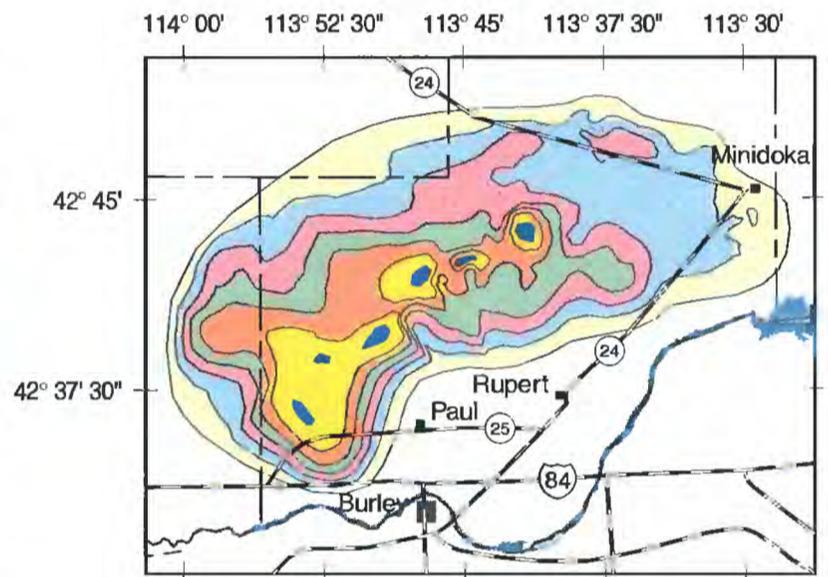
EXPLANATION
NITRITE PLUS NITRATE AS NITROGEN, IN MILLIGRAMS PER LITER



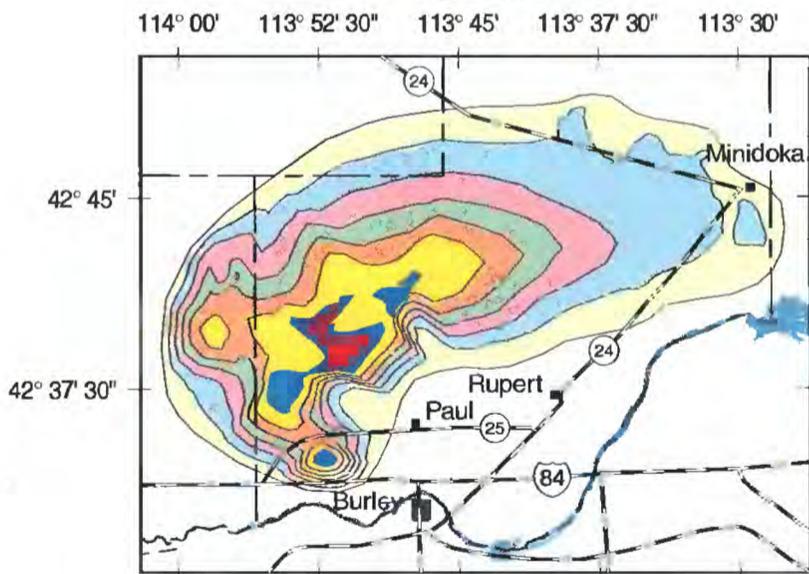
1980



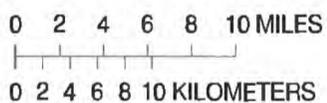
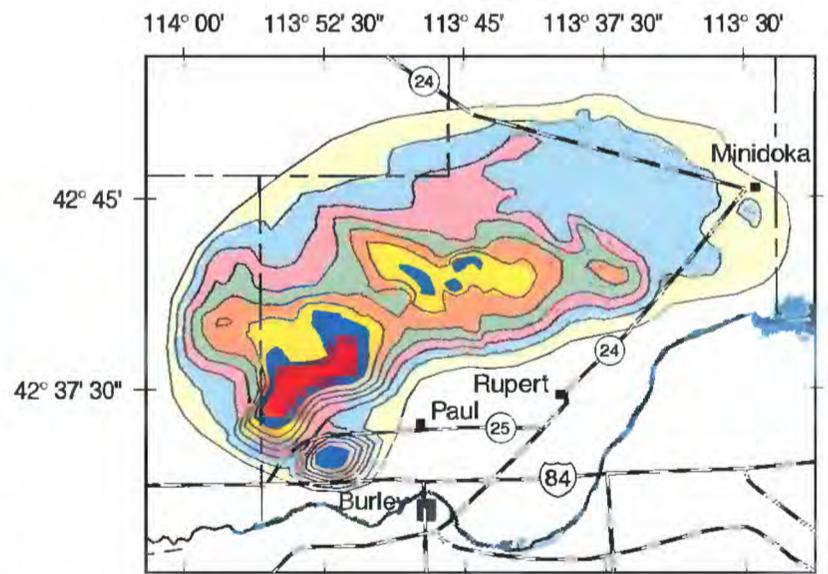
1985



1990



1995



Maps by John Mitchell (Idaho Department of Water Resources, written commun., 1996), based on data from Dave Zimmer (Bureau of Reclamation, oral commun., 1996)

Figure 30. Long-term concentrations of nitrite plus nitrate as nitrogen in ground water, A & B study area, eastern Snake River Plain, 1980–95.

ern Snake River Plain aquifer on the downgradient side of the Jerome/Gooding study area and are good indicators of water quality in the western part of the basin. Although long-term concentrations of $\text{NO}_2 + \text{NO}_3 - \text{N}$ in water from the springs do not appear to have changed significantly since 1980 (fig. 29), a seasonal variation in the $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations from Briggs and Box Canyon Springs is apparent (Clark, 1997). Concentrations are highest in the fall, shortly after the irrigation season ends. $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in samples collected from Briggs Spring during the irrigation season have increased since the mid-1980's; concentrations in samples collected during the preirrigation season have not increased. Spring discharge also is greatest in the fall due to greater recharge from irrigation water, which suggests that high $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in the fall are due to a greater proportion of irrigation water. The dairy industry in Gooding and Jerome Counties has grown tremendously in recent years; the number of dairy cattle increased from 49,000 in 1990 to 90,000 in 1995 (Idaho Agricultural Statistics Service, 1990, 1991, 1992, 1993, 1994, 1995). It is unknown if and when the additional nitrogen input from these dairies will increase the $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations in water discharging from the springs.

Rupert (1994, fig. 23) reported that $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations increased in four wells in the A&B study area during 1980–89. Using additional data collected in the same area, John Mitchell (Idaho Department of Water Resources, written commun., 1996) reported major increases in $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations over a longer period, 1980–95 (fig. 30). Data used by Rupert and Mitchell originally were collected by the Bureau of Reclamation in the A&B Irrigation District (Dave Zimmer, Bureau of Reclamation, oral commun., 1996). Concentrations of $\text{NO}_2 + \text{NO}_3 - \text{N}$ increased at a fairly constant rate; Mitchell calculated an increase of about 0.17 mg/L per year in the area of greatest concentration. Mitchell then back-calculated $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations to 1954, when irrigated agriculture first began in the A&B Irrigation District. The estimated $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentration at the start of irrigation was about 0.88 mg/L, which is about equivalent to the background $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentration in the eastern Snake River Plain aquifer. Should $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations continue to increase at the observed rate, Mitchell suggested that concentrations in parts of the A&B Irrigation District could exceed the maximum contaminant level of 10 mg/L within the next 10 to 15 years.

Although $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations have increased over time in the A&B study area, the general location of highest concentrations has not (fig. 30). This suggests a constant input of nitrogen to ground water over time from a large, stationary source, such as irrigated fields. The source of nitrogen in this area is most likely inorganic fertilizer and legume crops; few cattle are raised in the A&B study area, and Rupert (1996, p. 1) reported that nitrogen input from domestic septic systems, geologic sources, and precipitation was negligible. Low concentrations of MBAS and low nitrogen isotope values also confirm that domestic septic systems and cattle manure provide negligible $\text{NO}_2 + \text{NO}_3 - \text{N}$ to ground water in the A&B study area.

SUMMARY

In 1991, the U.S. Geological Survey began full-scale implementation of the National Water-Quality Assessment Program. The long-term goals of the program are to (1) provide a nationally consistent description of current water-quality conditions for a large part of the Nation's water resources; (2) define long-term trends in water quality; and (3) identify, to the extent possible, the major factors that affect observed water-quality conditions and trends. Sixty study units across the United States were selected to assess between 60 and 70 percent of the Nation's usable water supply. The upper Snake River Basin was selected as one of the first study units.

Concern about nitrite plus nitrate as nitrogen ($\text{NO}_2 + \text{NO}_3 - \text{N}$) in ground water of the upper Snake River Basin has generated interest in determining the factors that cause elevated $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations. Data were examined at regional and local scales. Regional-scale relations between $\text{NO}_2 + \text{NO}_3 - \text{N}$ in ground water and depth to first-encountered ground water, land use, precipitation, and soils were examined using a geographic information system. Regionally, where depth to first-encountered water was between 0 and 300 ft, $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations were significantly higher than where depth to water was between 301 and 900 ft. Ground water in urban areas contained the highest $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations; ground water in irrigated agriculture areas contained the next-highest concentrations. Ground water in rangeland, dry-land agriculture, and forest areas contained similar low $\text{NO}_2 + \text{NO}_3 - \text{N}$ concentrations. There was no correlation between precipitation and $\text{NO}_2 + \text{NO}_3 - \text{N}$ concen-

trations in ground water. Ground water in areas with excessively drained soils contained the highest $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations; ground water in areas with poorly drained soils contained the lowest $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations. Ground water in counties where residual nitrogen input was greater than 3,000,000 kilograms contained significantly higher $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations than in counties where residual nitrogen input was less than 3,000,000 kilograms.

Excessive aquatic plant growth in surface water is a major concern in the basin, particularly in the Snake River between Milner Dam and King Hill. Ground water adds nitrogen and phosphorus to surface water where ground water discharges to the Snake River. Water from more than 78 percent of the regional wells contained $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations higher than 0.3 mg/L, which is the critical limit for stimulation of aquatic plant growth in surface water in the presence of adequate phosphorus. This suggests that nitrogen is not a limiting factor for aquatic plant growth in most streams that receive ground water. Less than 8 percent of the regional wells contained orthophosphorus concentrations higher than the critical limit of 0.05 mg/L for stimulation of aquatic plant growth in the presence of adequate nitrogen. Orthophosphorus concentrations were higher than 0.05 mg/L near Twin Falls, southeast of Pocatello, and in the Rexburg/Idaho Falls area.

Two maps showing the probability of ground-water contamination by $\text{NO}_2 + \text{NO}_3\text{-N}$ were developed; one was developed using depth to first-encountered ground water, land use, and soils data. The second probability map incorporated additional data on nitrogen input. Probability categories were based on correlations between $\text{NO}_2 + \text{NO}_3\text{-N}$ and those four hydrogeologic and land-use factors. Correlations between $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in ground water and probability categories demonstrated significant differences at a greater-than-99-percent confidence level. Because the probability maps are calibrated to actual ground-water quality data, they are a significant improvement over ground-water vulnerability maps generated using the DRASTIC technique.

High concentrations of dissolved oxygen and the general lack of ammonia plus organic nitrogen, nitrite, and ammonia in the local study areas suggest that nitrogen species in the eastern Snake River Plain aquifer are readily oxidized to $\text{NO}_2 + \text{NO}_3\text{-N}$. Low dissolved organic carbon and high dissolved oxygen concentrations suggest unfavorable conditions for denitrification in the eastern Snake River Plain aquifer. Once the aquifer is

contaminated, natural degradation of $\text{NO}_2 + \text{NO}_3\text{-N}$ through denitrification is minor.

Local-scale evaluation involved five areas with different hydrogeologic settings, land use, and sources of irrigation water. Evaluation determined that high $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in ground water were correlated with high major ion concentrations, heavy hydrogen and oxygen isotopes, and ground-water ages that postdate atmospheric nuclear testing (1952). The heavy hydrogen and oxygen isotope values indicated that $\text{NO}_2 + \text{NO}_3\text{-N}$ was associated with water that had undergone evaporation; high major ion concentrations indicated that concentrated ions and $\text{NO}_2 + \text{NO}_3\text{-N}$ also may be leaching from soils during recharge. $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in ground water in parts of the A&B study area were high because of continual recycling of ground water as it is pumped from the ground, applied to fields, and then leached back to the water table. $\text{NO}_2 + \text{NO}_3\text{-N}$ and major ion concentrations decrease as ground water travels from the A&B area to the Eden area because of dilution from Snake River irrigation water. $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations and stable isotope ratios increase from background concentrations as ground water travels through the Jerome/Gooding area, similar to the increase observed in the A&B area, but at a lesser rate, possibly due to less infiltration of contaminated recharge water.

Cattle manure, inorganic fertilizer, and legume crops were the principal sources of $\text{NO}_2 + \text{NO}_3\text{-N}$ in local study areas. Data on methylene blue active substances and fecal coliform indicated that domestic septic system effluent did not appreciably affect $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations. Nitrogen isotope values for ground water in the A&B study area confirmed that input from domestic septic systems and cattle manure was minimal. A greater percentage of $\text{NO}_2 + \text{NO}_3\text{-N}$ in the Jerome/Gooding study area may be from cattle manure.

Long-term $\text{NO}_2 + \text{NO}_3\text{-N}$ data are available for three springs that discharge water from the eastern Snake River Plain aquifer and for several wells in the A&B study area. Long-term overall $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations from all three springs do not appear to have changed significantly since 1980. However, $\text{NO}_2 + \text{NO}_3\text{-N}$ concentrations in samples collected from Briggs and Box Canyon Springs during the fall months have increased since the mid-1980's. It is unknown whether the concentrations will change as the result of a large increase in the number of dairy cattle from 1990 through 1995 in areas upgradient from these springs.

NO₂+NO₃-N concentrations in parts of the A&B study area increased dramatically during 1980–95. Should the rate of increase continue, concentrations in parts of the A&B study area could exceed the maximum contaminant level of 10 mg/L in the next 10 to 15 years.

REFERENCES CITED

- Ackerman, D.J., 1995, Analysis of steady-state flow and advective transport in the eastern Snake River Plain aquifer system, Idaho: U.S. Geological Survey Water-Resources Investigations Report 94–4257, 25 p.
- Aller, Linda, Bennett, Truman, Lehr, J.H., and Petty, R.J., 1985, DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings: U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, EPA/600/2–85/018, 163 p.
- American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1985, Standard methods for the examination of water and wastewater, 16th ed.: Washington, D.C., American Public Health Association, 1268 p.
- Bouwer, Herman, 1978, Groundwater hydrology: New York, McGraw-Hill Book Company, 480 p.
- Brennan, T.S., Jones, M.L., O'Dell, I., Lehmann, A.K., and Tungate, A.M., 1995, Water resources data, Idaho, water year 1994: U.S. Geological Survey Water-Data Report ID–94–1, v. 1, 409 p.
- Brennan, T.S., O'Dell, I., Lehmann, A.K., and Tungate, A.M., 1996, Water resources data, Idaho, water year 1995: U.S. Geological Survey Water-Data Report ID–95–1, v. 1, 452 p.
- Burkhardt, M.R., Cinotto, P.J., Frahm, G.W., Woodworth, M.T., and Pritt, J.W., 1995, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—determination of methylene blue active substances by spectrophotometry: U.S. Geological Survey Open-File Report 95–189, 16 p.
- Clark, G.M., 1997, Assessment of nutrients, suspended sediment, and pesticides in surface water of the upper Snake River Basin, Idaho and western Wyoming, water years 1991–95: U.S. Geological Survey Water-Resources Investigations Report 97–4020, 45 p.
- Clark, G.M., and Ott, D.S., 1996, Springflow effects on chemical loads in the Snake River, south-central Idaho: American Water Resources Association, Water Resources Bulletin, v. 32, no. 3, p. 553–563.
- Coplen, T.B., 1993, Uses of environmental isotopes, in Alley, W.M., 1993, Regional ground-water quality: New York, Van Nostrand Reinhold, 634 p.
- 1994, Reporting of stable hydrogen, carbon, and oxygen isotopic abundances: Pure and Applied Chemistry, v. 66, no. 2, p. 273–276.
- Craig, H., 1961, Isotopic variations in meteoric waters: Science 133, p. 1702–1703.
- Crockett, J.K., 1995, Idaho Statewide Ground Water Quality Monitoring Program—summary of results, 1991 through 1993: Idaho Department of Water Resources Water Information Bulletin no. 50, Part 2, 67 p.
- Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, p. 436–468.
- Gellenbeck, D.J., 1994, Isotopic compositions and sources of nitrate in ground water from western Salt River Valley, Arizona: U.S. Geological Survey Water-Resources Investigations Report 94–4063, 53 p.
- Gilliom, R.J., Alley, W.M., and Gurtz, M.E., 1995, Design of the National Water-Quality Assessment Program—occurrence and distribution of water-quality conditions: U.S. Geological Survey Circular 1112, 33 p.
- Harenberg, W.A., Jones, M.L., O'Dell, I., Brennan, T.S., and Lehmann, A.K., 1992, Water resources data, Idaho, water year 1991: U.S. Geological Survey Water-Data Report ID–91–1, v. 1, 337 p.
- Harenberg, W.A., Jones, M.L., O'Dell, I., Brennan, T.S., Lehmann, A.K., and Tungate, A.M., 1993, Water resources data, Idaho, water year 1992: U.S. Geological Survey Water-Data Report ID–92–1, v. 1, 377 p.
- 1994, Water resources data, Idaho, water year 1993: U.S. Geological Survey Water-Data Report ID–93–1, v. 1, 401 p.
- Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier Science Publishing Company, Inc., 522 p., 1 diskette.
- Hirsch, R.M., Alley, W.M., and Wilber, W.G., 1988, Concepts for a National Water-Quality Assessment Program: U.S. Geological Survey Circular 1021, 42 p.

- Idaho Agricultural Statistics Service, 1990, Idaho agricultural statistics, 1890–1990, centennial issue: Boise, Idaho Agricultural Statistics Service, 72 p.
- 1991, Idaho agricultural statistics: Boise, Idaho Agricultural Statistics Service, 72 p.
- 1992, Idaho agricultural statistics: Boise, Idaho Agricultural Statistics Service, 72 p.
- 1993, Idaho agricultural statistics: Boise, Idaho Agricultural Statistics Service, 72 p.
- 1994, Idaho agricultural statistics: Boise, Idaho Agricultural Statistics Service, 76 p.
- 1995, Idaho agricultural statistics: Boise, Idaho Agricultural Statistics Service, 72 p.
- Idaho Department of Water Resources, 1991, Idaho's Statewide Ground Water Quality Monitoring Program—the first six months and beyond: Boise, Idaho Department of Water Resources, 24 p.
- Kjelstrom, L.C., 1992, Assessment of spring discharge to the Snake River, Milner Dam to King Hill, Idaho: U.S. Geological Survey Water Fact Sheet, Open-File Report 92–147, 2 p.
- Komor, S.C., and Anderson, H.W., 1993, Nitrogen isotopes as indicators of nitrate sources in Minnesota sand-plain aquifers: *Ground Water GRWAAP*, v. 31, no. 2, p. 260–270.
- Kreitler, C.W., 1975, Determining the source of nitrate in ground water by nitrogen isotope studies: Austin, University of Texas, Bureau of Economic Geology, Report of Investigations 83, 57 p.
- Leahy, P.P., Rosenshein, J.S., and Knopman, D.S., 1990, Implementation plan for the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 90–174, 10 p.
- Lindholm, G.F., 1996, Summary of the Snake River Plain Regional Aquifer-System Analysis in Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408–A, 59 p.
- Lindholm, G.F., Garabedian, S.P., Newton, G.D., and Whitehead, R.L., 1988 [1987], Configuration of the water table and depth to water, spring 1980, water-level fluctuations, and water movement in the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Hydrologic Investigations Atlas HA–703, 1 sheet, scale 1:500,000.
- Mackenthun, K.M., 1969, The practice of water pollution biology: United States Department of the Interior, Federal Water Pollution Control Administration, Division of Technical Support, 281 p.
- Mann, L.J., 1989, Tritium concentrations in flow from selected springs that discharge to the Snake River, Twin Falls-Hagerman area, Idaho: U.S. Geological Survey Water-Resources Investigations Report 89–4156, 20 p.
- Mann, L.J., and Low, W.H., 1994, Tritium, stable isotopes, and nitrogen in flow from selected springs that discharge to the Snake River, Twin Falls-Hagerman area, Idaho, 1990–93: U.S. Geological Survey Water-Resources Investigations Report 94–4247, 21 p.
- Mansfield, G.R., 1915, Nitrate deposits in southern Idaho and eastern Oregon: U.S. Geological Survey Bulletin 620–B, p. 19–44.
- Maupin, M.A., 1992, Depth to water in the eastern Snake River Plain and surrounding tributary valleys, southeastern Idaho, calculated using water levels from 1980 to 1988: U.S. Geological Survey Water-Resources Investigations Report 90–4193, 1 sheet, scale 1:750,000.
- 1995, Water-quality assessment of the upper Snake River Basin, Idaho and western Wyoming—environmental setting, 1980–92: U.S. Geological Survey Water-Resources Investigations Report 94–4221, 35 p.
- Molnau, Myron, 1995, Mean annual precipitation, 1961–1990, Idaho: Moscow, University of Idaho, Agricultural Engineering Department, State Climate Office, scale 1:1,000,000.
- Moreland, J.A., 1976, Digital-model analysis of the effects of water-use alternatives on spring discharges, Gooding and Jerome Counties, Idaho: Boise, Idaho Department of Water Resources Water Information Bulletin 42, 46 p.
- Mundorff, M.J., Crosthwaite, E.G., and Kilburn, Chabot, 1964, Ground water for irrigation in the Snake River Basin in Idaho: U.S. Geological Survey Water-Supply Paper 1654, 224 p., 6 pls.
- Neely, K.W., 1994, Idaho Statewide Ground Water Quality Monitoring Program network design: Boise, Idaho Department of Water Resources Water Information Bulletin no. 50, Part 1, 35 p.
- Neely, K.W., and Crockett, J.K., 1992, Idaho's Statewide Ground Water Quality Monitoring Program—status report 1991: Boise, Idaho Department of Water Resources, 22 p.
- Ott, R.L., 1993, An introduction to statistical methods and data analysis: Belmont, Calif., Duxbury Press, Wadsworth Publishing Company, 1051 p.

- Parlman, D.J., and Young, H.W., 1987, Selected water-quality data for the Murtaugh Lake area, south-central Idaho, June 1987: U.S. Geological Survey Open-File Report 87-466, 1 sheet, scale 1:37,250.
- 1988, Selected water-quality data for the Fort Hall Indian Reservation, southeastern Idaho, July 1988: U.S. Geological Survey Open-File Report 88-496, 1 sheet, scale 1:100,000.
- 1989, Selected ground-water quality data for the area near Fort Hall, Fort Hall Indian Reservation, southeastern Idaho, June 1989: U.S. Geological Survey Open-File Report 89-594, 1 sheet, scale 1:100,000.
- Plummer, L.N., Michel, R.L., Thurman, E.M., and Glynn, P.D., 1993, Environmental tracers for age dating young ground water, *in* Alley, W.M., 1993, Regional ground-water quality: New York, Van Nostrand Reinhold, 634 p.
- Pritt, J.W., and Raese, J.W., 1995, Quality assurance/quality control manual, National Water Quality Laboratory: U.S. Geological Survey Open-File Report 95-443, 35 p.
- Robertson, J.B., Schoen, Robert, and Barraclough, J.T., 1974, The influence of liquid waste disposal on the geochemistry of water at the National Reactor Testing Station, Idaho, 1952-70: U.S. Geological Survey Open-File Report IDO-22053, 231 p.
- Rupert, M.G., 1994, Analysis of data on nutrients and organic compounds in ground water in the upper Snake River Basin, Idaho and western Wyoming, 1980-91: U.S. Geological Survey Water-Resources Investigations Report 94-4135, 40 p.
- 1996, Major sources of nitrogen input and loss in the upper Snake River Basin, Idaho and western Wyoming, 1990: U.S. Geological Survey Water-Resources Investigations Report 96-4008, 15 p.
- Rupert, M.G., Dace, Tana, Maupin, M.A., and Wicher-ski, Bruce, 1991, Ground-water vulnerability assessment, Snake River Plain, southern Idaho: Boise, Idaho Department of Health and Welfare, Division of Environmental Quality, 25 p.
- Rupert, M.G., Stone, M.A.J., and Ott, D.S., 1996, National Water-Quality Assessment Program—nitrate and pesticides in ground water, Blaine, Cassia, Lincoln, and Minidoka Counties, south-central Idaho: U.S. Geological Survey Fact Sheet FS-246-95, 4 p.
- Scott, J.C., 1990, Computerized stratified random site-selection approaches for design of a ground-water-quality sampling network: U.S. Geological Survey Water-Resources Investigations Report 90-4101, 109 p.
- Snedecor, G.W., and Cochran, W.G., 1967, Statistical methods: Ames, Iowa State University Press, 593 p.
- Thurman, E.M., 1985, Organic geochemistry of natural waters: Dordrecht/Boston/Lancaster, Martinus Nijhoff/Dr. W. Junk Publishers, 497 p.
- U.S. Department of Agriculture, 1991, State soil geographic data base (STATSGO): U.S. Department of Agriculture, Soil Conservation Service, Miscellaneous Publication Number 1492, 88 p.
- U.S. Environmental Protection Agency, 1995, EPA drinking water regulations and health advisories: U.S. Environmental Protection Agency, Office of Water, EPA 822/R-95-001, 11 p.
- Weisenburger, D.D., 1991, Potential health consequences of ground-water contamination by nitrates in Nebraska, *in* Bogardi, I., Kuzelka, R.D., and Ennenga, W.G., Nitrate contamination—exposure, consequence, and control: Berlin, Springer-Verlag, p. 309-315.
- Whitehead, R.L., 1992, Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-B, 32 p., 6 pls.
- Wood, W.W., and Low, W.H., 1988, Solute geochemistry of the Snake River Plain regional aquifer system, Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-D, 79 p.
- Young, H.W., 1984, Potentiometric-surface contours, directions of ground-water movement, and perched-water zones, Oakley Fan, southeastern Idaho, March-April 1984: U.S. Geological Survey Water-Resources Investigations Report 84-4231, 1 sheet, scale 1:100,000.
- Young, H.W., Parlman, D.J., and Jones, M.L., 1987, Selected water-quality data for the Burley Irrigation District, south-central Idaho, March-April, 1987: U.S. Geological Survey Open-File Report 87-240, 1 sheet, scale 1:100,000.
- Young, H.W., Parlman, D.J., and O'Dell, I., 1987, Selected water-quality data for the Minidoka Irrigation District, south-central Idaho, June 1987: U.S. Geological Survey Open-File Report 87-465, 1 sheet, scale 1:100,000.

