

Prepared in cooperation with the  
State of Nevada Department of Conservation and Natural Resources  
Division of Environmental Protection

# **Quality of Nevada's Aquifers and their Susceptibility to Contamination, 1990–2004**

**Scientific Investigations Report 2006–5127**

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



# **Quality of Nevada's Aquifers and their Susceptibility to Contamination, 1990–2004**

By Thomas J. Lopes

**Scientific Investigations Report 2006–5127**

Prepared In cooperation with the  
State of Nevada Department of Conservation and Natural Resources  
Division of Environmental Protection

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

**U.S. Department of the Interior**

Dirk Kempthorne, Secretary

**U.S. Geological Survey**

P. Patrick Leahy, Acting Director

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

Carson City, Nevada, 2006

For additional information write to:

U.S. Geological Survey

Director, USGS Nevada Water Science Center

2730 N. Deer Run Road

Carson City, NV 89701

Email: [GS-W-NVpublic-info@usgs.gov](mailto:GS-W-NVpublic-info@usgs.gov)

URL: <http://nevada.usgs.gov/>

For more information about the USGS and its products:

Telephone: 1-888-ASK-USGS

World Wide Web: <http://www.usgs.gov/>

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Scientific Investigations Report 2006-5127

## Contents

Executive Summary .....	1
Introduction .....	2
Purpose and Scope .....	3
Acknowledgments .....	3
Previous Studies of Ground-Water Quality .....	3
Nitrate and Synthetic Organic Compounds in the Environment .....	6
Aquifer Susceptibility and Vulnerability .....	7
Aquifer Systems in Nevada .....	7
Precipitation .....	7
Recharge .....	8
Unsaturated Zone .....	12
Hydrogeologic Units .....	15
Ground-Water-Flow Paths and Velocities .....	15
Methods .....	17
Chemical Techniques .....	17
Chlorofluorocarbons .....	17
Dissolved Gases .....	19
Isotopes of Hydrogen and Oxygen .....	19
Well Selection .....	20
Sampling Procedures .....	20
Quality Assurance .....	21
Statistical Techniques .....	21
Correlations and Comparisons .....	21
Logistic Regression .....	22
Water-Quality Data Compilation .....	22
Geographic Information System Datasets .....	23
Ground-Water Quality .....	26
Dissolved Solids .....	26
Nitrate .....	26
Concentrations in Undeveloped Areas .....	26
Relations Between Nitrate and Explanatory Variables .....	29
Synthetic Organic Compounds .....	31
Co-Occurrence of Nitrate and Synthetic Organic Compounds .....	33
Aquifer Susceptibility .....	35
Chemical Results .....	35
Chlorofluorocarbons .....	35
Dissolved Gases .....	35
Stable Isotopes of Hydrogen and Oxygen .....	39
Logistic Regression .....	41
Summary .....	43
References .....	46

## Figures

<b>Figure 1.</b>	Nevada and locations of wells sampled for this study .....	4
<b>Figure 2.</b>	Deviation from mean annual precipitation for selected stations in Nevada.....	9
<b>Figure 3.</b>	Typical ground-water flow and recharge patterns perpendicular to the long axis of valleys in Nevada for mountain blocks with different permeability and annual precipitation .....	11
<b>Figure 4.</b>	Concentrations of soil organic material. ....	14
<b>Figure 5.</b>	Ranges in the horizontal hydraulic conductivity of aquifers in Nevada. ....	16
<b>Figure 6.</b>	Atmospheric mixing ratios of CFC-11, CFC-12, and CFC-113 for the northern hemisphere.....	18
<b>Figure 7.</b>	Locations of wells in Nevada with water-quality data.....	24
<b>Figure 8.</b>	Dissolved-solids concentrations in ground water, playas, and ground-water discharge areas in Nevada .....	28
<b>Figure 9.</b>	Nitrate concentrations for domestic, monitoring, and production wells in undeveloped areas .....	29
<b>Figure 10.</b>	Concentrations of nitrate in ground water.....	30
<b>Figure 11.</b>	Nitrate concentrations versus well category.....	31
<b>Figure 12.</b>	Nitrate concentrations versus A, depth to water and B, well depth.....	32
<b>Figure 13.</b>	Nitrate concentrations versus well category in Eagle Valley.....	33
<b>Figure 14.</b>	Number of A, pesticides and B, volatile organic compounds detected versus well depth .....	34
<b>Figure 15.</b>	Apparent recharge date versus A, water level above the top of the screen and B, well depth. ....	36
<b>Figure 16.</b>	Nitrate concentration versus apparent recharge date. ....	37
<b>Figure 18.</b>	Apparent recharge dates versus hydrologic setting. ....	38
<b>Figure 17.</b>	Apparent recharge dates versus aquifer type. ....	38
<b>Figure 19.</b>	Recharge temperature estimated from dissolved gases versus estimated mean annual air temperature.....	39
<b>Figure 20.</b>	Locations of wells and springs where isotopes have been sampled.....	40
<b>Figure 21.</b>	Deuterium versus $^{18}\text{O}$ measured in ground water and springs in Nevada .....	41
<b>Figure 22.</b>	Deuterium in ground water and springs versus A, latitude; B, well depth; and C, altitude.....	43

## Tables

<b>Table 1.</b>	Range in soil permeability for descriptive categories of unconsolidated sediments and corresponding geomorphic features (from Maurer and others, 2004).....	12
<b>Table 2.</b>	Summary statistics of soil organic material in selected western states and the United States.....	13
<b>Table 3.</b>	Number of wells sampled in hydrologic landscape regions of Nevada .....	20
<b>Table 4.</b>	Summary of water-quality data compilation.....	23
<b>Table 5.</b>	Explanatory variables used in logistic regression.....	25
<b>Table 6.</b>	Dissolved-solids concentrations in unconsolidated sediment and ground-water discharge areas.....	27
<b>Table 7.</b>	Spearman rank correlations between nitrate, clay, and depth to water in selected areas .....	32
<b>Table 8.</b>	Pearson correlations between binary nitrate data using a background concentration of 2 milligrams per liter and explanatory variables .....	42

## Supplemental Information

Worksheets are available as PDF files linked from each item.

Worksheet 1. Station information

Worksheet 2. Chlorofluorocarbon data

Worksheet 3. Dissolved gas data

Worksheet 4. Isotope Data

## Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
<b>Length</b>		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<b>Area</b>		
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
<b>Volume</b>		
quart (qt)	0.9464	liter (L)
cubic inch (in <sup>3</sup> )	16.39	cubic centimeter (cm <sup>3</sup> )
<b>Flow rate</b>		
foot per day (ft/d)	0.3048	meter per day (m/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
<b>Mass</b>		
ounce, avoirdupois (oz)	28.35	gram (g)

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

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

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$



# Quality of Nevada's Aquifers and their Susceptibility to Contamination, 1990-2004

By Thomas J. Lopes

## Executive Summary

In 1999, the U.S. Environmental Protection Agency introduced a rule to protect the quality of ground water in areas other than source-water protection areas. These other sensitive ground-water areas (OSGWA) are areas that are not currently but could eventually be used as a source of drinking water. To help determine whether a well is in an OSGWA, the Nevada Division of Environmental Protection needs statewide information on the susceptibility and vulnerability of Nevada's aquifer systems to contamination. This report presents an evaluation of the quality of ground water and susceptibility of Nevada's aquifer systems to anthropogenic contamination.

Chemical tracers and statistical methods were used to assess the susceptibility of aquifer systems in Nevada. Chemical tracers included nitrate, pesticides, volatile organic compounds (VOCs), chlorofluorocarbons (CFCs), dissolved gases, and isotopes of hydrogen and oxygen. Ground-water samples were collected from 133 wells during August 2002 through October 2003. Logistic regression was done to estimate the probability of detecting nitrate above concentrations typically found in undeveloped areas. Nitrate is one of the most common anthropogenic contaminants that degrades ground-water quality, is commonly measured and is persistent, except in reducing conditions. These characteristics make nitrate a good indicator of aquifer susceptibility. Water-quality data for 5,528 wells were compiled into a database. The area around each well was characterized using information on explanatory variables that could be related to nitrate concentrations. Data also were used to characterize the quality of ground water in Nevada, including dissolved solids, nitrate, pesticide, and VOC concentrations.

Dissolved-solids concentrations are less than the secondary maximum contaminant level (MCL) of 500 mg/L in 72 percent of the unconsolidated-sediment aquifer systems. Water that has  $\leq 3,000$  mg/L usually can be used for some purpose, such as stock watering and industry. About 97 percent of the unconsolidated-sediment aquifer systems have  $\leq 3,000$  mg/L dissolved solids and could be of some beneficial use. Dissolved-solids concentrations are lowest beneath alluvial slopes and fluvial sediments that are not in ground-water discharge areas and are higher beneath valley floors and playas. Ground-water discharge areas have the largest dissolved-solids concentrations.

A concentration of 2 mg/L nitrate, estimated from wells in unpopulated, undeveloped areas, was used to distinguish natural and anthropogenic sources of nitrate. Domestic and production wells in unpopulated, undeveloped areas had larger concentrations of nitrate compared to monitoring wells, suggesting that anthropogenic sources could affect ground-water quality even in apparently undeveloped areas. About 5 percent of 3,794 wells with nitrate data had concentrations that exceeded the MCL of 10 mg/L. Nitrate concentrations  $>10$  mg/L generally occurred in wells  $<200$  ft deep. Virtually all wells that exceeded the MCL are in large cities, such as Las Vegas, and small towns such as Pahrump, Winnemucca, Ely, and Jackpot, indicating sources of nitrate in urban areas have degraded ground-water quality.

Rank correlations between nitrate, well depth, and depth to water were weak ( $r = \leq -0.30$ ). Although weak, the negative correlations and high concentrations in shallow to intermediate depth wells suggest that nitrate is from sources near land surface. Relations between nitrate, depth to water, and clay layering for a subset of wells also were weak and, in some basins, opposite of what would be expected for nitrate migrating vertically from sources near land surface. These relations demonstrate the importance of understanding physical and chemical variables that control contaminant transport through unconsolidated-sediment aquifer systems, especially populated basins where large amounts of chemicals are used.

One to 5 pesticides were detected in 5.1 percent of the 1,159 wells with pesticide data. One to 14 VOCs were detected in 21.0 percent of 1,106 wells. Most pesticides were detected in shallow ( $<100$  ft) monitoring wells. In contrast, most VOCs were detected in production wells  $<500$  ft deep. Both pesticides and VOCs were detected in 23 wells  $>1,000$  ft deep. Pesticides and VOCs mostly were detected in the most urbanized areas of Nevada. Atrazine, a pesticide, was detected in one monitoring well above the MCL. VOCs were detected above the MCL in 16 production wells and 6 monitoring wells. VOCs that exceeded the MCL included dichloromethane, tetrachloroethene, and trichloroethene.

Wells that had nitrate concentrations  $>2$  mg/L had significantly more detections of pesticides and VOCs than wells that had nitrate concentrations  $<2$  mg/L. Nitrate concentrations had significant but weak rank correlations with the number of pesticides detected ( $r = 0.23$ ) and the number of VOCs detected ( $r = 0.21$ ). Concentrations of nitrate  $>2$  mg/L are more likely to occur with synthetic organic compounds (SOCs) than lower

concentrations of nitrate. However, the weak correlations indicate that nitrate is a poor indicator of the concentration or number of SOC's present.

CFCs were sampled from wells up to 7,000 ft deep in most types of consolidated rock and unconsolidated-sediment aquifer systems in Nevada. CFCs were detected in all samples collected by this study and previous studies. The presence of CFCs in all samples indicates that all aquifer systems in Nevada that have been sampled are highly susceptible to contamination. Recharge through fractured consolidated rock, continual pumping for public supply and mine dewatering, poorly constructed wells, and preferential flow along a well's gravel pack could explain the occurrence of SOC's and CFCs in deep unconsolidated-sediment and consolidated-rock aquifer systems. Also, recharge through unconsolidated sediments could be more widespread than previously thought. Ephemeral channels, too small to map on a statewide scale, are common around wells sampled for CFCs. Appreciable amounts of recharge could be occurring through small, ephemeral channels at low altitudes where it could be years between flow events.

Apparent recharge dates had significant rank correlations with well depth ( $r = -0.27$ ), water level above the top of the screen ( $r = -0.45$ ), and nitrate concentration ( $r = 0.28$ ). The inverse correlations between apparent recharge dates and well depth and water level above the screen are consistent with older water occurring at greater depths in aquifer systems. The positive correlation between apparent recharge dates and nitrate concentrations is consistent with recent development increasing nitrate concentrations in ground water. Currently, nitrate concentrations and the number of SOC's detected are highest in shallow ground water. With time, these contaminants could degrade deep aquifers that are used for public supply.

Recharge temperatures estimated from dissolved-gas concentrations ranged from 32° to 84° F (0 to 29° C). Most estimates of recharge temperatures were within  $\pm 9^\circ$  F ( $\pm 5^\circ$  C) of estimated mean annual air temperature, indicating recharge occurred under the current temperature regime. Few samples from wells and springs had deuterium values that are more negative than modern-day precipitation, indicating little Pleistocene-age water is present in the upper part of most aquifer systems. This is supported by estimates that indicate the total volume of recharge during the past 10,000 years equals or exceeds aquifer storage in the upper 1,000 ft of most basins in Nevada. Total recharge since 1950 has not exceeded aquifer storage in the upper 1,000 ft of any basin. This contradicts CFC data, which showed that water has entered all sampled aquifer systems since 1950.

Logistic regression correctly predicted high nitrate concentrations about 60 percent of the time. Because of the poor performance, a regression equation was not developed. All Pearson correlations between nitrate and explanatory variables were extremely weak ( $\leq 0.16$ ). Changing the concentration used to distinguish natural and anthropogenic nitrate or buffer size used to characterize the area around wells had no discern-

able effect on the strength of the correlations. The most consistently significant and strongest correlations were for alluvial slope, well density, and soil drainage. These correlations could be due to development encroaching on alluvial fans, association of septic tanks with domestic wells, and nitrate infiltrating through well-drained soils.

For water-quality parameters considered in this report, most of Nevada's aquifer systems could be used for public water supply and almost all ground water has some beneficial use. High nitrate concentrations and SOC's are infrequently detected and rarely above the MCL. High nitrate concentrations and SOC's were primarily detected in urban areas where most chemicals are used.

SOC, CFC, dissolved gas, and isotope data indicate that ground water in Nevada mostly is a mixture of Holocene-age and recent ground water that was recharged during the modern-day climatic regime. This suggests a high susceptibility for Nevada's aquifer systems. Areas with few clay layers and where ground water naturally moves downward are most susceptible to contamination. Contamination of deep aquifer systems may be enhanced by human-induced factors such as secondary recharge from irrigation and ground-water pumpage. Urbanizing areas with few clay layers and downward flow describe primary recharge on alluvial fans, secondary recharge on irrigated land, and well fields in Reno-Sparks, Carson City, and Carson Valley. Even in areas with a thick confining layer, such as Las Vegas, contaminants could migrate into deep aquifer systems from poorly constructed wells; illegal disposal in abandoned or unused wells; and over-pumping, which can cause subsidence and fracturing of confining layers and breakage of well casings. Contaminants released from point and non-point sources can quickly migrate to the water table and move through aquifer systems, as indicated by pesticides, VOCs, and CFCs in wells >1,000 ft deep. This was a reconnaissance-level study to see where water has entered aquifer systems since 1950. Additional studies need to be done to determine how water is entering the aquifers.

## Introduction

With its surface-water resources fully appropriated (Nevada Department of Conservation and Natural Resources, 1999), Nevada increasingly relies on ground water to meet the needs of its growing population. Not only is water quantity an issue, but protecting ground-water quality is more critical than ever so aquifer systems will meet water-quality standards and sustain future water needs. Programs such as the Wellhead and Source Water Protection Programs have been in place since the 1980s to protect underground sources of drinking water. The goal of these programs is to protect the quality of aquifer systems that are currently being used for public water supply. However, source-water protection areas comprise a small percentage of the aquifer systems in Nevada. It is also important to protect the quality of aquifer systems that are not currently

being used but could eventually be used as sources of drinking water. In 1999, a new rule was introduced through the Underground Injection Control Program to protect ground water in areas other than source-water protection areas (U.S. Environmental Protection Agency, 1999). These other sensitive ground-water areas (OSGWAs) are areas that could eventually be used as a source of drinking water. The rule gave regulatory agencies the option to designate specific sites or the entire State as an OSGWA. The Nevada Division of Environmental Protection (NDEP) elected to designate specific sites because of the complex hydrogeology of the State.

The OSGWA program specifically addresses existing wells that are used for underground injection of motor vehicle waste and bans new injection wells. If the injection well is in a ground-water protection area or an OSGWA, well owners must either close the well or apply for a permit. A permit is granted only if the injectate fluids meet drinking-water standards. Nevada is a large, rural, and hydrologically complex state (fig. 1). Except for populated areas, sparse data make it difficult to determine which aquifer systems could be susceptible to contamination. Rather than designate all or parts of Nevada as an OSGWA, NDEP will evaluate site-specific information from small-scale, statewide maps that were compiled for this study to determine if the aquifer at that site is susceptible (Nevada Division of Environmental Protection, 2003). Well owners also can provide large-scale, detailed information that may be available for the site.

Susceptibility, sensitivity, and vulnerability are similar terms that have been used differently by different authors. This report uses the definition of Focazio and others (2002) who state that the “susceptibility of a ground-water system depends on the aquifer properties (hydraulic conductivity, porosity, hydraulic gradients) and the associated sources of water and stresses for the system (recharge, interactions with surface water, travel through the unsaturated zone, and well discharge).” Ground-water vulnerability depends on the “susceptibility as well as the locations and types of sources of naturally occurring and anthropogenic contamination, relative location of wells, and the fate and transport of contaminant(s).” The distinction is that susceptibility assessments only evaluate the physical variables that affect the flow of water to and through an aquifer. Vulnerability assessments evaluate the sources and environmental behavior of contaminants in addition to susceptibility.

Nevada mostly is unpopulated and is the driest state in the Nation with a mean annual precipitation of 9.46 in. (Western Regional Climate Center, 2005). Thus, it is intuitive that most of Nevada has low susceptibility and vulnerability to contamination. However, Nevada’s population increased from about 1.2 million in 1990 to 2.2 million in 2002 and is projected to be 3 million by 2022 (Nevada State Demographer, 2004a and b). Water and chemical use associated with urban development, agriculture, and other land uses could result in localized areas that have become highly susceptible and vulnerable.

The U.S. Geological Survey (USGS), in cooperation with NDEP, began a study in 2001 to compile information on

variables that could control aquifer susceptibility and vulnerability and to evaluate the potential for ground-water degradation from anthropogenic contamination. This is the last of four reports from this project. Maurer and others (2004) describe the hydrogeology of Nevada and its hydrologic landscape regions, which are areas with similar horizontal hydraulic conductivity, soil permeability, precipitation, slope, and aspect. Lopes and Evetts (2004) estimated ground-water pumpage and artificial recharge for the year 2000 and compiled estimates of average annual natural recharge and interbasin flow by hydrographic area. Lopes and others (2006) describe maps of water-table levels and characterize water-table gradients in selected areas of Nevada.

## Purpose and Scope

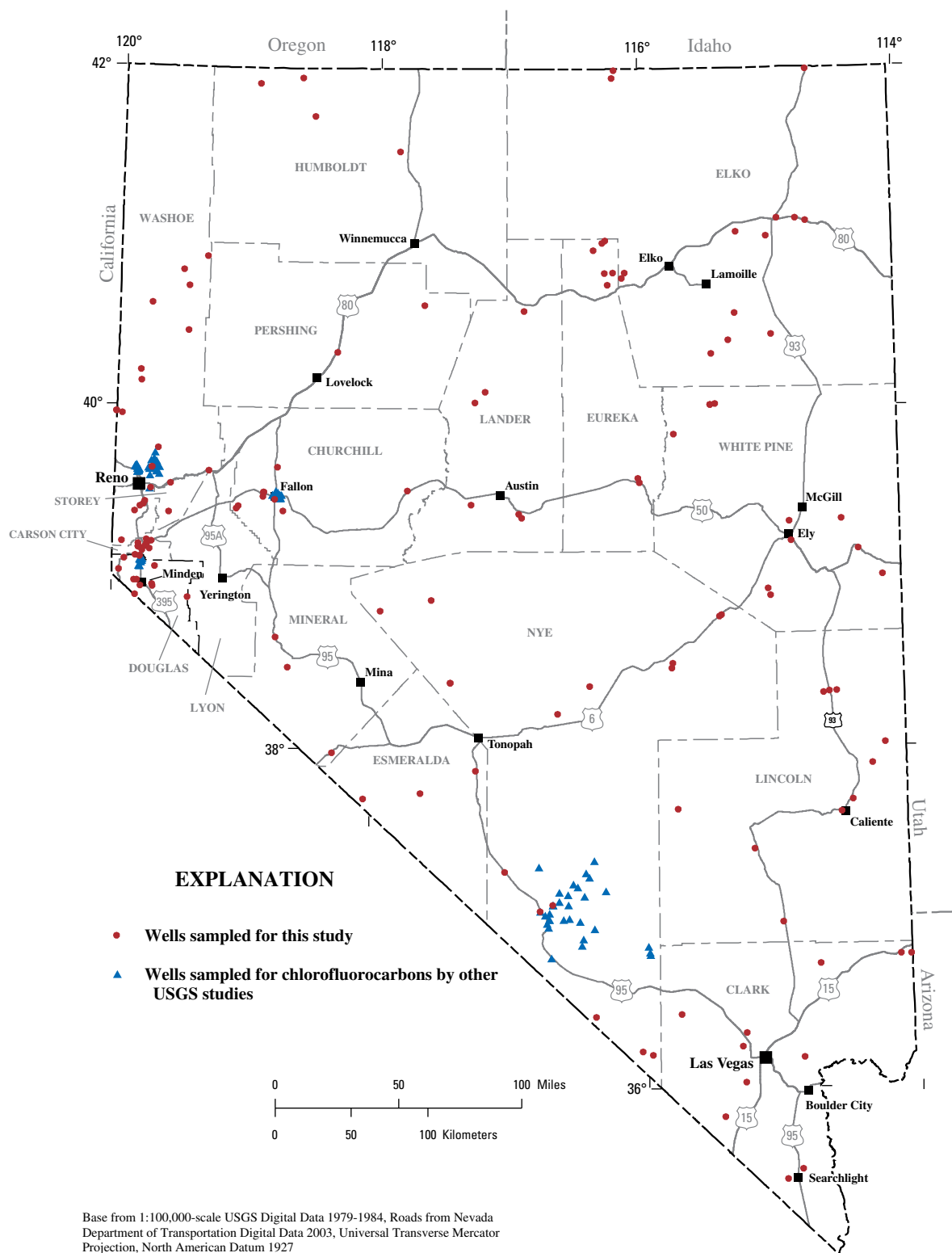
The purpose of this report is to characterize the quality of ground water and evaluate the susceptibility of Nevada’s aquifer systems to anthropogenic contamination. The evaluation determined the susceptibility of large areas of Nevada in general and was not an evaluation of specific sites, such as would be needed for a permit application. Existing chemical data collected from 1990–2004 were compiled for 5,528 monitoring, domestic, and municipal wells, including 133 wells that were sampled as part of this study. Most wells are in the Las Vegas and Reno metropolitan areas. The quality of ground water is characterized by describing the occurrence and concentrations of dissolved solids, nitrate, and synthetic organic compounds (SOCs), which includes pesticides and volatile organic compounds (VOCs). Few or no data exist for other classes of anthropogenic contaminants, such as pharmaceuticals. All concentrations of nitrate in this report are nitrate as nitrogen. Naturally occurring contaminants, such as arsenic (Welch and others, 2000), are not discussed although they are known to degrade ground-water quality in parts of Nevada.

## Acknowledgments

The author thanks James R. Land, Nevada Department of Environmental Protection; Jonathan Carpenter, Nevada Department of Agriculture; Dr. Louis Brown, Nevada State Health Laboratory; Judith Neubert, Nevada Bureau of Health Protection Services; the USGS Chlorofluorocarbon Laboratory in Reston, Virginia, for providing data from previous projects; and Sharon Watkins, USGS (retired), for assisting with statistical analyses.

## Previous Studies of Ground-Water Quality

Thompson and Chappell (1984) mapped the distribution of dissolved solids in unconsolidated-sediment aquifer systems of the Great Basin, which included most of Nevada. Dissolved-solids concentrations were computed as the sum of constituents from chemical analysis of samples from non-geo-



**Figure 1.** Nevada and locations of wells sampled for this study.

thermal springs and wells <501 ft deep. Where data were not available, dissolved-solids concentrations were estimated from other data sources, published reports, position in the ground-water flow system, and lithology of adjacent consolidated rock. Thompson and Chappell (1984) used this information to map 5 ranges of dissolved-solids concentrations: 0 to 500 mg/L; 501 to 1,000 mg/L; 1,001 to 3,000 mg/L; 3,001 to 10,000 mg/L; and >10,000 mg/L.

The first statewide characterization of ground-water quality was by Thomas and Hoffman (1988). This characterization included dissolved solids, nitrate, hardness (as calcium carbonate), fluoride, and arsenic in ground-water samples collected from 1950 to 1986 from 13 unconsolidated-sediment aquifer systems. Median dissolved-solids concentrations were <500 mg/L in most of these aquifer systems. In southeastern Las Vegas Valley, naturally occurring dissolved-solids concentrations generally were >2,000 mg/L due to dissolution of gypsum and evaporites. Ground-water discharge areas are associated with dissolved-solids concentrations of 1,000–35,000 mg/L. Except for Las Vegas Valley, median concentrations of nitrate in the 13 aquifer systems were <1 mg/L and no samples exceeded the Maximum Contaminant Level (MCL) of 10 mg/L (U.S. Environmental Protection Agency, 2005). The MCL is the maximum concentration allowed in regulated drinking-water systems. Naturally-occurring nitrate concentrations >300 mg/L were found in southeastern and north-central Las Vegas Valley (Patt and Hess, 1976) and 28 mg/L of naturally-occurring nitrate was found in Spanish Springs Valley (Seiler, 2005). Large, naturally-occurring concentrations of nitrate can be due to dissolution of nitrogen-bearing minerals, evaporative concentration, and infiltration of water through organic material.

Thomas and Hoffman (1988) also discuss anthropogenic contaminants that have been detected in unconsolidated-sediment aquifer systems, including nitrate, VOCs, pesticides, and other semi-volatile organic compounds. Disposal of explosives near Hawthorne increased nitrate from initial concentrations of <2 mg/L to 130 mg/L (Thomas and Hoffman, 1988). Septic waste-disposal effluent has elevated nitrate concentrations in Antelope and Washoe Valleys, but concentrations generally were not above the MCL (Thomas and Hoffman, 1988). SOC generally were associated with military and industrial facilities and underground fuel tanks in urban areas.

The most thorough assessment of ground-water quality in Nevada was done by the USGS National Water-Quality Assessment (NAWQA) program (Welch and others, 1997; Lawrence, 1996; Bevens and others, 1998; Lico, 1998). This assessment focused on the Truckee and Carson River Basins and Las Vegas Valley, where about 90 percent of the State's population lives (Covay and others, 1996). The assessment in Nevada was one of 51 assessments of ground-water and surface-water quality done throughout the Nation by the NAWQA program (Hamilton and others, 2004). Shallow monitoring wells in unconsolidated sediments were sampled to assess the quality of recently recharged ground water in urban and agricultural land uses. Municipal and domestic wells in unconsoli-

dated sediments were sampled to assess the quality of aquifer systems used for public and domestic supply. Samples were analyzed for many constituents, including nitrate and SOC.

The NAWQA program found that shallow ground water in urban areas had elevated concentrations of nitrate (Lawrence, 1996; Lico, 1998; Bevens and others, 1998). Shallow ground water in agricultural areas had lower concentrations of nitrate than in urban areas (Welch and others, 1997; Lico, 1998). The low concentration of nitrate in agricultural areas likely is because alfalfa is the most common crop in Nevada and it does not require fertilizers. Shallow ground water underlying the oldest part of Carson City had a median nitrate concentration of 1.1 mg/L (Lawrence, 1996); 6 of the 20 sites exceeded the MCL. In the Reno-Sparks area, the median nitrate concentration in ground water was 0.9 mg/L, about equal to the national median of the NAWQA program (Bevens and others, 1998). In Las Vegas, the median nitrate concentration of the shallow aquifer was 4.4 mg/L, more than double the national median of the NAWQA program. Median nitrate concentrations in the deep aquifer used for public supply of all areas were <1 mg/L. Nitrate contamination in urban areas can be caused by excess fertilizer application, sewage from septic waste-disposal systems, leaking sewer lines, and irrigating parks and golf courses with treated sewage effluent.

Small concentrations of SOC were commonly detected in shallow and deep aquifer systems in urban areas and infrequently detected in agricultural areas (Lawrence, 1996; Welch and others, 1997; Lico, 1998; Bevens and others, 1998). SOC were detected more frequently in the Reno-Sparks area than the Las Vegas area. For example, one or more pesticides were detected in 68 percent of shallow monitoring wells sampled in the Reno-Sparks urban area and in 28 percent of shallow monitoring wells sampled in the Las Vegas urban area (Bevens and others, 1998). Triazine herbicides, including atrazine, deethyl atrazine (a degradation product of atrazine), prometon, and simazine, were the most commonly detected pesticides. VOCs were detected in more than 50 percent of shallow monitoring wells and in 45 percent of water-supply wells in the Las Vegas and Reno-Sparks areas. Chloroform, a by-product of chlorination, was the most commonly detected VOC. Deep aquifer systems used for public supply in urban areas generally did not contain nitrate or SOC at concentrations that exceeded the MCL.

Since 1993, Nevada Department of Agriculture (NDOA) has monitored ground water for pesticides in agricultural and urban basins throughout the State (Pennington and others, 2001). Initially, NDOA sampled deep irrigation, domestic, and municipal wells and did not detect any pesticides. After the NAWQA program reported detecting pesticides in shallow ground water, NDOA modified their monitoring program to sample shallow wells to detect contamination before supply wells are affected. Shallow wells are sampled during spring before irrigation and pesticide application and during the fall after the growing season. Since 1997, NDOA has detected 10 pesticides (Pennington and others, 2001). Most detections were in the Orovada area in Humboldt County where alfalfa

seed and potatoes are the main crops. Pesticides were more frequently detected in the fall after the summer growing season. One sample had a concentration of atrazine that exceeded the MCL (3.0 µg/L).

Between 1985 and 2001, nitrate and dissolved-solids concentrations increased in 56 percent of 27 domestic and production wells sampled in Carson Valley, a rapidly growing basin in Douglas County (Rosen, 2003). Initial nitrate concentrations generally were <1 mg/L and increased to about 5 mg/L. Two wells had nitrate concentrations that exceeded the MCL. Wells with increasing nitrate concentrations were associated with septic waste-disposal systems, which are likely sources of nitrate and dissolved solids. Seiler and others (1999) found caffeine and pharmaceuticals in ground water with elevated concentrations of nitrate in Lemmon Valley, Washoe County. The occurrence of these chemicals was conclusive evidence that domestic wastewater was a source of the elevated nitrate.

A high incidence of childhood leukemia prompted a detailed investigation of ground-water quality in Fallon, Churchill County, an agricultural community in west-central Nevada (Seiler, 2004). In 2001, a total of 99 domestic and municipal wells and one industrial well were sampled for many constituents, including SOC. Results were compared to data collected in the Fallon area by the NAWQA program in 1989 (Lico and Seiler, 1994). In 1989, VOCs were not detected in either shallow or deep aquifer systems. In 2001, few VOCs were detected even though analytical reporting limits were substantially lower than in 1989. Detected VOCs included trichloroethene, chloroform, xylene, ethylbenzene, and carbon disulfide, a naturally occurring VOC that forms in reducing environments. Pesticides were not measured in 1989. In 2001, five pesticides were infrequently detected. Detected pesticides included the herbicides simazine, atrazine, dicamba, EPTC, and prometon. Phthalates, likely from PVC pipes, were detected in 21 wells. Concentrations of regulated SOC did not exceed the MCL.

## **Nitrate and Synthetic Organic Compounds in the Environment**

Nitrogen exists in many forms in the environment. Nitrate is the form of nitrogen that is a regulated contaminant because it has been associated with methemoglobinemia (Comly, 1945), also known as blue-baby syndrome. Nitrate is probably the most common contaminant that degrades ground-water quality throughout the United States (Hallberg and Keeney, 1993). Septic waste-disposal systems were identified as a potential source of contamination by 79 percent of community water systems, the most frequently identified of all potential sources (U.S. Environmental Protection Agency, 1997). Nitrate concentrations in ground water typically are less than the MCL. The concentration of nitrate in undeveloped areas throughout the Nation is about 2 mg/L (Mueller and Helsel, 1996; U.S. Geological Survey, 1999), which is similar to the median concentration of 1.6 mg/L from a national survey of

community water systems (Cohen, 1992). Previous studies have used concentrations of 2 to 5 mg/L to distinguish naturally occurring nitrate from anthropogenic nitrate (Eckhardt and Stackelberg, 1995; Tesoriero and Voss, 1997; Donato, 2000; Nolan, 2001; Nolan and others, 2002; Rupert, 2003).

Nitrate concentrations greater than the MCL can occur naturally by evaporative concentration and dissolution of evaporites, as in the Las Vegas area (Patt and Hess, 1976). Because of its high solubility, nitrate salts only are found in arid climates and have been noted in Humboldt County, Nevada (Hurlbut and Klein, 1977). However, nitrate concentrations in much of Nevada are similar to or less than national averages (Thomas and Hoffman, 1988; Welch and others, 1997; Lawrence, 1996; Bevans and others, 1998; Lico, 1998). Nitrate has been found to concentrate in desert soils of the southwestern United States (Walvoord and others, 2003). Nitrate concentrations > 2,000 mg/L were measured in soil water below the root zone at 5 sites, including the Amargosa Desert in southern Nevada (Walvoord and others, 2003). Flushing of nitrate in desert soils by urban irrigation could partly explain the high concentration of nitrate in shallow ground water compared to deep aquifers in the Las Vegas and Reno-Sparks areas (Lico, 1998).

Depending on the chemical environment, biogeochemical processes can transform nitrogen species into nitrate and transform nitrate into other forms of nitrogen. Transformation processes in the unsaturated zone and ground water include ammonification, ammonia volatilization, nitrification, and denitrification (Canter, 1997). A detailed discussion of each process is beyond the scope of this report. Briefly, ammonification is the biological transformation of organic nitrogen to ammonium in anaerobic soils. Ammonia volatilization is the physical-chemical transformation of ammonium to dissolved ammonia and subsequent volatilization of dissolved ammonia. Nitrification is the biological oxidation of ammonium to nitrate in aerobic environments. Nitrification is the process that transforms ammonia in wastewater to nitrate as it infiltrates through the unsaturated zone. Denitrification is the biological reduction of nitrate to gaseous nitrogen, carbon dioxide, and water and only occurs in anaerobic environments.

Nitrate can persist for decades in aerobic ground water (Tomer and Burkart, 2003). The persistence of nitrate in aerobic aquifer systems makes it a good indicator of anthropogenic contamination. However, this persistence also means that it can take decades to remediate nitrate contamination and that implementing new strategies to manage sources of nitrate can take years to influence ground-water quality.

SOCs are man-made compounds that are unambiguous indicators of aquifer susceptibility. Throughout the United States, the NAWQA program detected SOC more frequently in shallow aquifers in agricultural and urban areas than in deep aquifers (U.S. Geological Survey, 1999). Regulated SOC that were detected rarely exceeded the MCL. All of the pesticides and VOCs commonly detected throughout the United States were detected in either shallow or deep aquifers, or both, in

Nevada (Thomas and Hoffman, 1988; Bevans and others, 1998; Lico, 1998; Pennington and others, 2001).

Pesticides were detected in about 50 percent of shallow monitoring wells in agricultural areas and urban areas throughout the United States (U.S. Geological Survey, 1999). Herbicides were detected more frequently than insecticides for both land uses. Only atrazine, its breakdown product deethyl-atrazine, metolachlor, prometon, and simazine were detected in more than 5 percent of all wells nationally. Triazine herbicides, the most commonly detected class of pesticides nationally and in Nevada, are used for preemergent and early postemergent control of seedling broadleaf and some grass weeds. Most triazine compounds are readily sorbed to soil and slowly leach from clayey soils and soils with more than one percent organic material (Jordan and Cudney, 1987).

VOCs were detected in about 90 percent of shallow monitoring wells in urban areas throughout the United States (Hamilton and others, 2004). The most frequently detected VOCs nationally and in Nevada were the chlorinated solvents trichloroethene, tetrachloroethene, and methylene chloride; the gasoline additive methyl tert-butyl ether (MTBE); and chloroform, a solvent and disinfection by-product from chlorinating water.

The environmental behavior of SOC is controlled by many complex physical and chemical processes. In general, frequently detected pesticides and VOCs have a combination of relatively high mobility and chemical stability that allows them to move and persist in ground water. It is beyond the scope of this report to summarize the physical and chemical processes affecting the fate and transport of pesticides and VOCs. Biggar and Seiber (1987) and Barbash and Resek (1996) discuss the different classes of pesticides, their distribution, and physical and chemical processes that affect their environmental fate. Pankow and Cherry (1996) and Squillace and others (1997) discuss sources and environmental fate of dense chlorinated solvents and MTBE in ground water.

## Aquifer Susceptibility and Vulnerability

Evaluating aquifer susceptibility and vulnerability is difficult because many variables affect the hydrologic and geochemical processes that control ground-water flow and contaminant transport. Focazio and others (2002) present an overview of variables to consider when assessing ground-water susceptibility and vulnerability. Understanding how water recharges and flows through an aquifer system is a necessary step in scientifically assessing susceptibility (Focazio and others, 2002). This includes an understanding of the spatial distribution of precipitation and recharge, depositional environment of unconsolidated sediments and the interfingering and horizontal continuity of aquifer systems, physical properties of aquifer systems such as hydraulic conductivity and effective porosity, and other variables that control the velocity and direction of ground-water flow. Assessing vulnerability requires an understanding of the locations of

contaminant sources, whether contaminants are released at land surface or subsurface, the quantity of contaminant released, whether the release is continuous or discontinuous, and the physical and chemical properties of the contaminant and aquifer material that control its mobility and persistence in aquifer systems.

Focazio and others (2002) also present an overview of methods that have been used in assessing aquifer susceptibility and vulnerability and classified the methods into two main groups, subjective rating methods and statistical and process-based methods. Whether subjective, statistical, or process-based methods are used, an understanding of hydrologic and geochemical processes is needed to do an assessment. A conceptual understanding of these processes is needed to use simple, qualitative, inexpensive methods. A comprehensive understanding is needed to use quantitative, contaminant-specific, expensive methods. The method used depends on the scope of the assessment, financial resources, and the scientific defensibility and uncertainty that water-resource managers can accept. DRASTIC is a commonly used subjective method of assessing aquifer susceptibility (Aller and others, 1987). This study used statistical and process-based methods to assess susceptibility and vulnerability.

## Aquifer Systems in Nevada

This section summarizes how water recharges and flows through unconsolidated aquifer systems in Nevada and provides the basic understanding that is needed to assess aquifer susceptibility. Unconsolidated aquifer systems are the primary aquifers used for water supply in Nevada and have been the focus of most studies. The discussion follows the flow of water through an aquifer system, starting with precipitation and recharge, the unsaturated zone, saturated hydrogeologic units, and finally ground-water flow to discharge areas. More detailed discussions can be found in cited references.

## Precipitation

Precipitation in Nevada is highly variable temporally and spatially. Winter storms and summer monsoons are the two seasonal weather patterns that bring precipitation to Nevada (Houghton and others, 1975). During winter, prevailing westerly winds push cold fronts that originate in the Gulf of Alaska and northern Pacific Ocean across Nevada. Cold fronts typically are long-duration, low-intensity, broad storms that cross northern Nevada more than southern Nevada. During some winters, relatively warm storms originate from the central and tropical Pacific Ocean (Friedman and others, 2002). These storms can have large amounts of moisture and cause flooding, especially when rain falls on snow such as during the 1997 flood (Hess and Williams, 1997). During summer, prevailing southwesterly winds bring monsoonal moisture from the Gulfs of Mexico and California. Monsoons typically are short-duration, high-intensity, localized thunderstorms that are

more common in southern and eastern Nevada than in western Nevada. Months with no precipitation are common between winter storms and summer monsoons. These weather patterns are reflected in the mean annual precipitation of Nevada's four climatological divisions (Houghton and others, 1975). Mean annual precipitation is 4.56 in. in the extreme south division, 6.23 in. in the south central division, 8.43 in. in the northwest division, and 10.46 in. in the northeast division.

The spatial distribution of precipitation in Nevada is strongly influenced by latitude and altitude (Houghton and others, 1975). In general, precipitation increases with latitude and altitude. The most important variable influencing the distribution of precipitation is continentality (Houghton and others, 1975), which is more commonly called the rain-shadow effect. The rain-shadow effect is the relatively dry climate on the leeward side of a mountain range compared to the windward side. Air cools as it rises over the windward side, condensing moisture as rain and snow, resulting in the dry climate on the leeward side. The Cascade Range shields moisture from northernmost Nevada, the Sierra Nevada shields moisture from northern and central Nevada, and both the Coastal and Sierra Nevada Ranges shield moisture from southern Nevada (Houghton and others, 1975).

Type of precipitation is important because snowmelt is the primary source of recharge in Nevada (Harrill and Prudic, 1998). Rain from short, intense thunderstorms is thought to runoff and be a negligible source of recharge. Topographic slope and aspect are important variables in snow accumulation, sublimation, and soil infiltration. The 25-percent slope break is a critical condition for snow stability (Gray and Male, 1981). Slopes greater than 25 percent are less likely to have much snow accumulation due to avalanches. Aspect is the average compass direction that a slope faces and affects the rate of snowmelt and sublimation. Easterly, westerly and flat aspects receive similar amounts of solar radiation. Southerly aspects receive the most solar radiation, and northerly aspects receive considerably less radiation than non-northerly aspects (Gray and Male, 1981). As a result, snowmelt is more likely to recharge on flat, northerly slopes and sublimate and runoff from steep, non-northerly slopes.

Mean annual precipitation for 1971–2000 ranges from about 4 in. at Laughlin in Clark County to 53 in. at Mount Rose in Washoe County (Western Regional Climate Center, 2004; Natural Resources Conservation Service, 2004). However, mean annual precipitation is an average of dry and wet periods and does not usually occur during any particular year. Seventeen precipitation stations throughout the State (Austin, Boulder City, Caliente, Elko, Ely, Fallon, Lamoille, Las Vegas, Lovelock, McGill, Mina, Minden, Reno, Searchlight, Tonopah, Winnemucca, and Yerington; fig. 1) have nearly continuous records for about the past 70 years. Time-series graphs of departure from mean annual precipitation for Reno, Elko, Winnemucca, Tonopah, and Las Vegas are similar to other stations except Mina (fig. 2). Elko, Reno, Winnemucca, Tonopah, and Las Vegas have had periods of above average precipitation that lasted a median of 1 year with a maximum of

7 years. Periods of below average precipitation lasted a median of 2 years with a maximum of 7 years. The median difference between total annual precipitation and the mean for the period of record for all stations ranged from -0.04 in. for Fallon to -0.99 in. for Lamoille. Dry years occur more often than wet years; however, wet years have a larger difference from the mean than dry years. Except for Mina, there has been no increasing or decreasing trend in annual precipitation, indicating that mean annual precipitation has not changed during the past 70 years. Mina has a statistically significant increase in annual precipitation. Most of the increase has occurred since about 1965. Long-term precipitation data suggests that mean annual potential recharge has been fairly constant during the past 70 years and that recharge is episodic, mostly occurring during wet years.

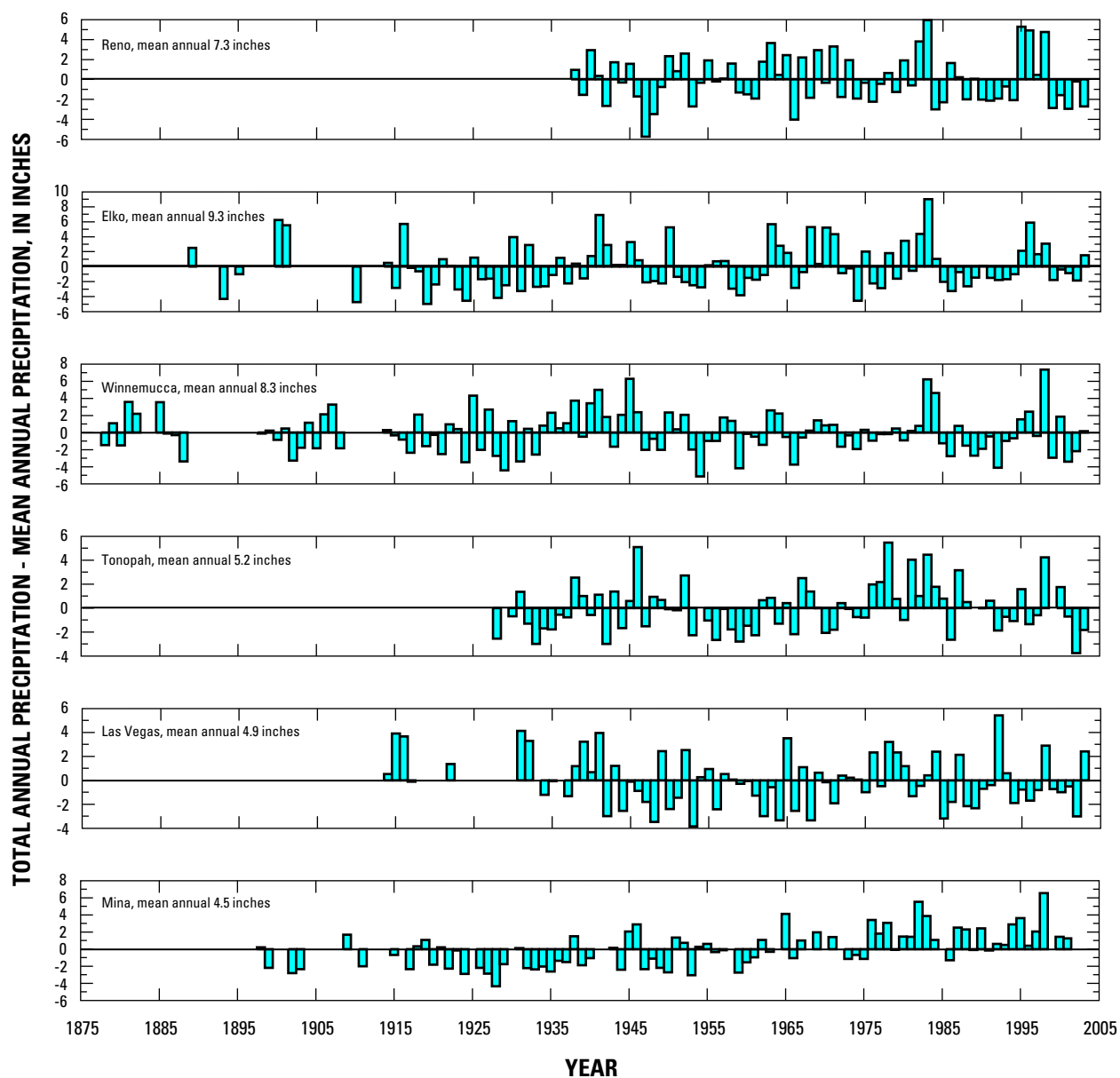
The spatial distribution of mean annual precipitation in Nevada was first mapped by Hardman (1936). Hardman (1936) mapped isohyetal contours, which are lines of equal precipitation, based on the distribution of vegetation communities, topography, and precipitation data collected during the early 1900s. The isohyetal map was published in Hardman and Mason (1949). An unpublished, modified version of Hardman and Mason (1949) also has been widely used to estimate recharge (Hardman, 1965, unpublished map). The isohyetal contours of Hardman and Mason (1949) and Hardman (1965, unpublished map) delineate areas with a broad range in mean annual precipitation, such as 12 to 16 in., 16 to 20 in., and >20 in. in the highest ranges.

The Oregon Climate Center estimated mean annual precipitation throughout Nevada (G.H. Taylor, Oregon State University, written commun., 1997) using PRISM (Precipitation-Elevation Regressions on Independent Slopes Model; Daly and others, 1994). PRISM uses the 30-yr precipitation normals and altitude of stations near an area to develop a regression equation that is intended to take into account regional influences on precipitation, such as the rain-shadow effect. However, precipitation stations are widely scattered in Nevada, so the ability of PRISM to accurately model regional influences on precipitation is uncertain. The regression equation and average altitude of 2-km grids, estimated from a digital elevation model, are used to estimate precipitation for each grid. PRISM estimates have been made using 30-yr normals for the periods 1961–1990 and 1971–2000.

## Recharge

Most estimates of mean annual recharge in Nevada have been made by assuming recharge is a percentage of the volume of mean annual precipitation within certain precipitation intervals (Lopes and Evetts, 2004). This is commonly called the Maxey-Eakin method (Maxey and Eakin, 1949) or revised Maxey-Eakin method (Nichols, 2000). The Maxey-Eakin method was developed to estimate total recharge for large basins in Nevada, Utah, and Arizona (Maxey and Eakin, 1949). The revised Maxey-Eakin method (Nichols, 2000) was developed for basins in eastern Nevada; the percentage of





**Figure 2.** Deviation from mean annual precipitation for selected stations in Nevada.

precipitation assumed to be recharge may not apply to other areas of Nevada. It would be inappropriate to use the Maxey-Eakin or revised Maxey-Eakin methods to estimate recharge at a specific site within a basin.

Both methods assume that ground-water flow is in equilibrium, which means that discharge is equal to recharge. Ground-water discharge mostly occurs by evapotranspiration from phreatophytes and is more accurate and easier to estimate than recharge. Nichols' (2000) estimates of ground-water discharge, and hence recharge, were considerably higher than previous estimates for the same basins made by Maxey and Eakin (1949). Maxey and Eakin (1949) and Nichols (2000) used their estimates of ground-water discharge as the dependent variable in regression analysis. Volumes of precipitation within 5 precipitation intervals were estimated and used as independent variables in the regression. Coefficients of the regression were forced to increase with higher precipitation intervals, which makes physical sense. However, the regression coefficients are a statistical result and are not based on physical measurements. For example, 0.8 percent of mean annual precipitation between 8 and <12 in. and 62.6 percent of precipitation  $\geq 34$  in. were assumed to recharge aquifer systems in eastern Nevada (Nichols, 2000).

Both the Maxey-Eakin and revised Maxey-Eakin methods assume that areas with mean annual precipitation <8 in. have negligible recharge. PRISM estimated about 33 percent of Nevada has <8 in., 58 percent has 8 to <16 in., and 9 percent has  $\geq 16$  in. of mean annual precipitation (Maurer and others, 2004). If the assumption of negligible recharge is correct, then about 33 percent of Nevada has a low susceptibility to contamination.

Percentages of precipitation assumed to become recharge from the Maxey-Eakin method (Maxey and Eakin, 1949) should be used with isohyetal contours from Hardman and Mason (1949) and Hardman (1965, unpublished map). Percentages of precipitation assumed to become recharge from the revised Maxey-Eakin method (Nichols, 2000) should be used with modified 1997 PRISM estimates. The 1997 version of PRISM is based on 1961–1990 precipitation normals and has isohyets with 1-in. to 4-in. contour intervals (G.H. Taylor, Oregon State University, written commun., 1997). The USGS Nevada Water Science Center interpolated between these contours to produce isohyets with 1-in. contour intervals. Nichols (2000) and Berger (2000) used these modified PRISM estimates to estimate recharge in northeastern and north-central Nevada. In general, PRISM estimates more precipitation than Hardman and Mason (1949) and Hardman (1965, unpublished map), which is consistent with higher estimates of ground-water discharge.

Relatively few studies have used mass-balance methods to directly or indirectly measure average annual recharge. The direct mass-balance method is a ground-water budget, which is an estimate of the amount of water flowing into and out of an aquifer system (Berger, 2000). A ground-water budget can include estimating recharge from precipitation and stream infiltration, subsurface inflow from and outflow to adjacent

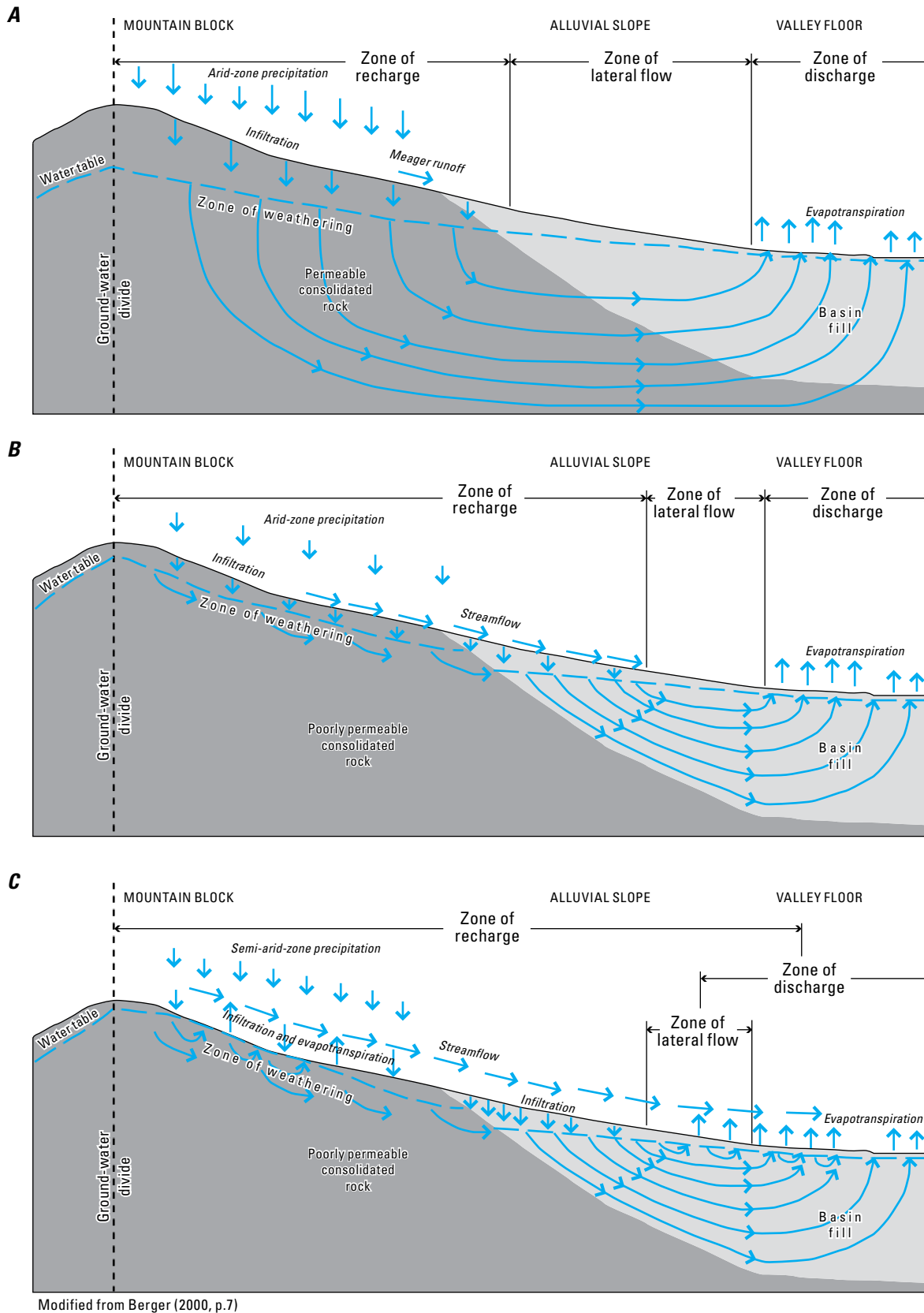
basins, and outflow by phreatophytic evapotranspiration and pumpage. For undeveloped basins with no subsurface inflow, outflow can be assumed equal to recharge and is easier to measure compared to measuring recharge (Berger and others, 2004). The chloride-balance method is an indirect method of estimating recharge (Dettinger, 1989). This technique assumes that chloride is conservative, that precipitation is the only source of chloride, and that increases in chloride in recharge compared to precipitation are due to evapotranspiration. Thus, the ratio of chloride in precipitation ( $C_p$ ) to chloride in recharge ( $C_r$ ) is the fraction of precipitation that is recharge. Recharge ( $q_w$ ) is equal to this ratio multiplied by the precipitation ( $P$ ) rate:

$$q_w = (C_p/C_r) * P \quad (1)$$

Most ground-water recharge occurs on alluvial slopes from infiltration of precipitation and snowmelt runoff from mountain-blocks (Mifflin, 1988, p. 76). Relatively little recharge occurs from infiltration on the valley floor or from infiltration into consolidated rocks that discharges directly into unconsolidated sediments (Mifflin, 1988; Freeze and Cherry, 1979). These generalized descriptions of ground-water recharge may vary somewhat depending on the permeability of consolidated rocks forming the mountain block and the amount of annual precipitation (fig. 3).

Studies have been done at various sites in the southwestern United States to understand where and how recharge occurs in desert environments (Hogan and others, 2004). Recharge rates beneath native vegetation, irrigated fields, and the Amargosa River in the Amargosa Desert of southern Nevada were estimated using the chloride mass-balance method and inferred downward velocities of chloride and nitrate peaks (Stonestrom and others, 2004). Chloride and nitrate profiles beneath native vegetation in the Amargosa Desert indicated no appreciable recharge beneath interfluvial areas, which is consistent with profiles beneath interfluvial areas in other arid alluvial basins of the southwestern United States (Walvoord and Scanlon, 2004). Profiles beneath irrigated fields and the Amargosa River channel were consistent with active recharge beneath these sites (Stonestrom and others, 2004). Chloride profiles beneath two fields irrigated since the 1960s and the upstream Amargosa River site were indicative of long-term, quasi-steady deep percolation. Chloride profiles beneath a field irrigated since 1993, the downstream Amargosa River site, and the edge of an older field were indicative of recently active deep percolation moving previously accumulated salts from the upper profile to greater depths. Recharge rates beneath irrigated fields ranged from about 6 to 22 percent of the applied water and from 12 to 15 percent of infiltration in channels (Stonestrom and others, 2004).

Only a few decades are needed for excess irrigation water to move through the unsaturated zone and recharge ground water in the Amargosa Desert (Stonestrom and others, 2003). A vertical, one-dimensional flow model estimated irrigation water reaches the water table beneath irrigated lands in about



**Figure 3.** Typical ground-water flow and recharge patterns perpendicular to the long axis of valleys in Nevada for mountain blocks with different permeability and annual precipitation.

10 to 70 years. In contrast, the estimated time for water to reach the water table beneath the ephemeral channel ranged from 140 to 1,000 years. These values represent minimum times because lateral flow was not taken into account.

Maurer and Thodal (2000) used chloride profiles in undeveloped and irrigated lands in Eagle Valley and had similar results to studies in the Amargosa Desert. Estimated recharge rates in undeveloped areas were small but measurable and ranged from 0.7 to 1.6 percent with an average of 1.3 percent of the mean annual precipitation (10 in/yr). This estimate compares well with the revised Maxey-Eakin method (Nichols, 2000), which assumes 0.8 percent of mean annual precipitation between 8 and <12 in. is recharge. Secondary-recharge rates beneath irrigated lawns and a golf course were estimated to be about 10 to 200 times greater, respectively, than recharge rates beneath areas with native vegetation (Maurer and Thodal, 2000). Secondary-recharge rates beneath irrigated land ranged from 4 to 44 percent with an average of 17 percent of the applied water plus precipitation. Secondary recharge also can occur by infiltration of urban stormwater through channels, detention and retention basins, dry wells, and other pathways in urban areas.

## Unsaturated Zone

Precipitation must infiltrate through the soil horizon and underlying unsaturated materials to recharge the aquifer. The soil horizon has the largest biological activity in the unsaturated zone, consisting of plants that transpire soil moisture and uptake nutrients and bacteria that can degrade some organic and inorganic contaminants. Weathering of rocks in the soil horizon can also produce clay, which is capable of adsorbing contaminants and impeding the downward movement of water. Soil permeability, organic material, clay layering, hardpan, and unsaturated thickness are important properties that affect the flow of water and contaminant transport through the unsaturated zone.

The soil horizon in Nevada decreases in thickness from about 60 in., the maximum thickness measured, on flat slopes to about 30 in. on 40-percent slopes (Maurer and others, 2004). Average soil permeability ranges from about 0.02 to 30 ft/d (Schwarz and Alexander, 1995). Average soil permeability was grouped into five descriptive categories ranging from very

high to very low, which generally correspond to mapped geomorphic features such as playas, alluvial slopes, flood plains, and stream channels (table 1). In general, soil permeability is low to moderate in northern, northeastern, and eastern Nevada, which has a relatively wet climate. Soil permeability is high to very high in western, southwestern, and southern Nevada, which are relatively dry. Within a particular basin, soil permeability decreases down slope from the bedrock contact. The type of parent rock, climate, and streamflow velocities are factors that likely cause these spatial patterns (Maurer and others, 2004).

Soil organic material (SOM) is an important variable because it can sorb contaminants and limit their transport through the unsaturated zone. Summary statistics of SOM in Nevada were calculated and compared to adjacent states and the United States (table 2). Summary statistics were calculated using the average SOM concentration of soil units in each state and for all soil units in the entire United States (Schwarz and Alexander, 1995). Average concentrations were not weighted by the area of each soil unit. Average SOM concentrations for soil units in Nevada ranges from 0 to 6 percent by weight with a median of 0.4 percent. Summary statistics for SOM in Nevada are similar to that of other arid western states and is about 50 percent less than national statistics. The distribution of SOM concentrations in Nevada was mapped for five ranges in values based on quartile concentrations and the 90<sup>th</sup> percentile concentration (0.9 percent; fig. 4). SOM concentrations >0.4 percent mostly occur around mountainous areas in western, central, and eastern Nevada, the Owyhee and Modoc Plateaus, and along the Truckee and Humboldt Rivers. Comparisons with vegetation types and land cover from the GAP Analysis Program (University of Idaho, 2005) indicate that SOM concentrations >0.9 percent are associated with alpine and subalpine forests, firs, aspen, mountain riparian, mountain shrub, mountain sagebrush, and wet meadows. SOM concentrations of 0.41 to 0.6 percent are associated with Sierra mountain shrub, Sierra mixed forest, and Piñon-Juniper. All other vegetation types and urban and agricultural areas, where most chemicals are used, generally are associated with <0.4 percent SOM. The low concentrations suggest SOM may not be an important variable in reducing contaminant migration and aquifer susceptibility in Nevada.

**Table 1.** Range in soil permeability for descriptive categories of unconsolidated sediments and corresponding geomorphic features (from Maurer and others, 2004)

Descriptive category	Soil permeability (feet per day)	Corresponding geomorphic feature
Very high	20 to 30	Alluvial slope/dune sand
High	10 to 20	Alluvial slope/stream channel
Moderate	5 to 10	Valley-floor alluvium
Low	1 to 5	Flood-plain/lake deposits
Very low	0.02 to 1	Playa

**Table 2.** Summary statistics of soil organic material in selected western states and the United States. Values are in percent by weight.

State	Minimum	Maximum	25th percentile	Median	75th percentile	Mean	Standard deviation
Arizona	0.0	2.6	0.1	0.2	0.4	0.3	0.3
California	0.0	13.8	0.3	0.5	0.8	0.7	1.1
Idaho	0.0	4.6	0.5	0.7	1.0	0.8	0.5
Nevada	0.0	6.0	0.2	0.4	0.6	0.5	0.4
Oregon	0.0	31.7	0.8	1.1	1.4	1.5	2.5
Utah	0.0	3.1	0.3	0.5	0.9	0.6	0.5
U.S.A.	0.0	72.3	0.4	0.6	0.9	1.2	3.8

Vertical flow and contaminant transport through unsaturated and saturated materials may be restricted by thick clay layers and hardpan. Hardpan is “a hard, impervious, often clayey layer of soil at or just below the surface, produced by cementation of soil particles by relatively insoluble materials” (Bates and Jackson, 1984). In the southwestern United States, hardpan typically is cemented by calcium carbonate. Hardpan generally is found near exposures of carbonate rocks in eastern Nevada (Maurer and others, 2004).

Clay layers are difficult to map compared to hardpan because they can occur throughout the unsaturated zone. However, some generalizations about the distribution of clay can be made based on an understanding of depositional environments in Nevada. Alluvial slopes generally have coarse-grained and poorly-sorted sediments with few interbedded clay layers (Plume, 1996; Bedsun, 1980; Mifflin, 1988; Anderson and others, 1983). Basin-fill sediments generally become finer towards the center of the valley (Plume, 1996; Davis, 1988), and the lower parts of alluvial slopes are likely to interfinger with clay layers underlying the valley floor (Plume, 1996; Bedsun, 1980). Clay layers underlying valley floors form in lakes and low-energy environments such as oxbows and flood basins along streams (Walker and Cant, 1984).

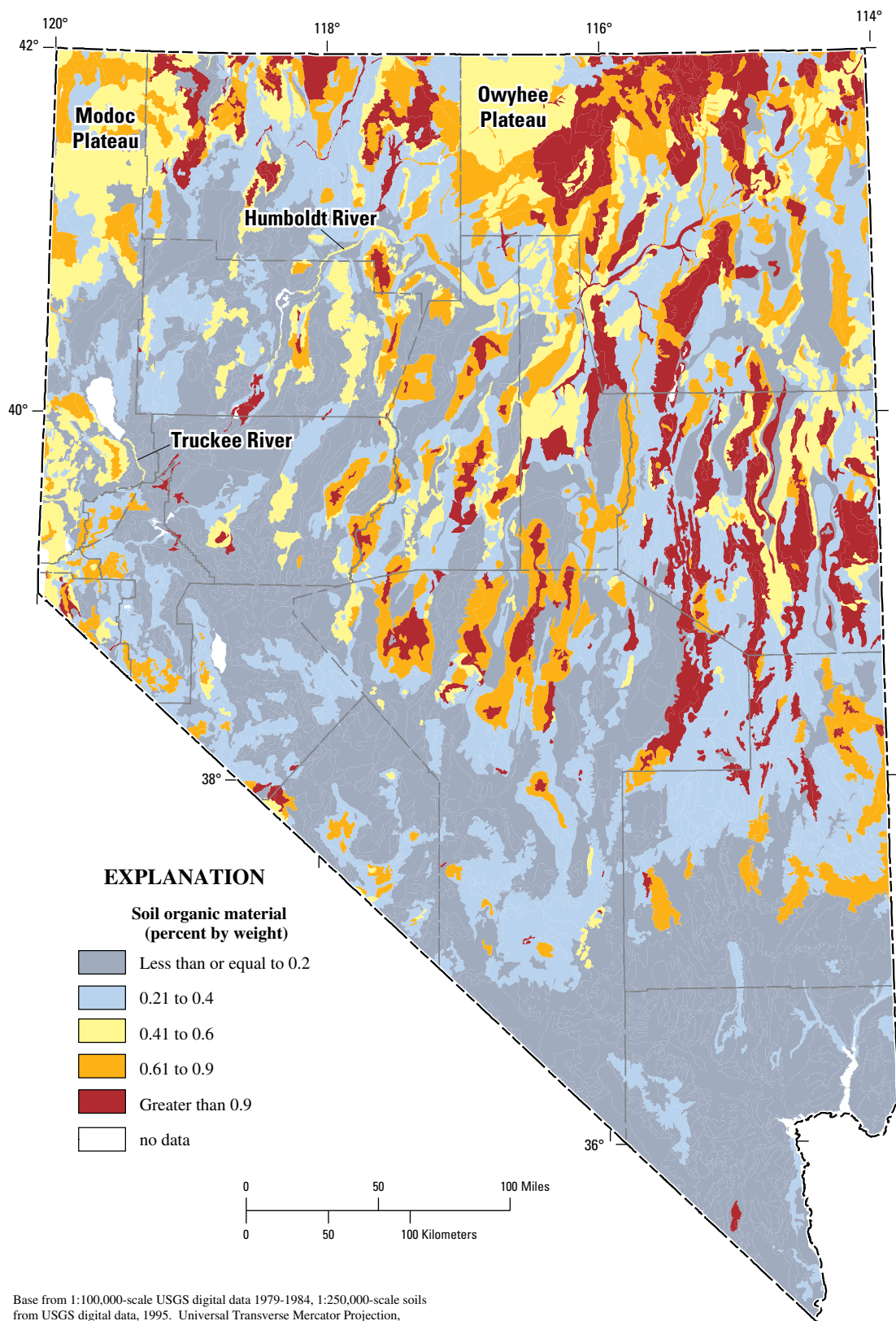
Clay layers formed along streams are discontinuous and thin compared to lake deposits. The distribution of stream channel deposits in Nevada was mapped by Maurer and others (2004). They observed that a large part of the channel that appeared active on satellite imagery was actually covered by fine-grained sediments, which likely were deposited after recession of sediment-laden high flows in the stream channels. The mapped fluvial deposits likely represent areas where well-sorted, coarse-grained fluvial sediments interfinger with clay layers at depth. Stream channels migrate laterally across the valley floor and lower alluvial slope (Plume, 1996; Bedsun, 1980). Thus, stream-channel deposits may be present at depth where stream channels are not currently active. For this reason, fluvial deposits indicate general areas having potential for both impeded and rapid vertical migration of contaminants through the unsaturated zone.

A map of Pleistocene lakes in the western Great Basin (Reheis, 1999) could indicate areas where thick, continuous

clay layers underlie valley floors. Pleistocene lakes occupied most valley floors in northwestern Nevada and some valleys in eastern Nevada. Remnants of the Pleistocene lakes include Pyramid Lake, Walker Lake, and many playas (Maurer and others, 2004). The largest late Pleistocene lake in Nevada is Lake Lahontan. Lake Lahontan extended from the present-day valleys of the Black Rock Desert, Desert Valley, and Quinn River Valley in the north; Paradise Valley, Buena Vista Valley, and the Carson Sink to the east; Mason Valley and Walker Lake to the south; and Smoke Creek Desert and Honey Lake Valley to the west. Agriculture is the primary land use in valleys that were occupied by Pleistocene lakes. Pre-late Pleistocene lakes occupied or possibly occupied the urbanized valleys of the Truckee Meadows, Eagle Valley, and Carson Valley (Reheis, 1999). These valleys could have thick, extensive clay layers, but the clay layers could be beneath aquifers currently used for water supply.

Las Vegas Valley is an example of thick, extensive clay layering protecting deep aquifer systems. The shallow and deep aquifers in Las Vegas Valley are separated by a clay layer up to 200 ft thick (Plume, 1989). The shallow aquifer, which is primarily recharged by urban irrigation, had a median dissolved-solids concentration of 3,240 mg/L, a median nitrate concentration of about 4.6 mg/L, and SOC<sub>s</sub> were commonly detected (Lico, 1998). In contrast, the underlying deep aquifer had a median dissolved-solids concentration of 565 mg/L, a median nitrate concentration of about 0.6 mg/L, and SOC<sub>s</sub> were detected less frequently. The thick clay layer has prevented downward migration of poor-quality water from the shallow to the deep aquifer.

Thick unsaturated zones increase the chance that contaminants will degrade or sorb to sediments before reaching ground water. Unsaturated thickness, which is the same as depth to water, was estimated from published maps of water-table levels in Nevada (Lopes and others, 2006). Depth to water was estimated for about 21 percent of Nevada due to lack of information in some basins and most consolidated-rock hydrogeologic units. Depth to water is commonly <50 ft beneath valley floors, 50 to 500 ft beneath alluvial fans, and is >500 ft in parts of Nevada such as the Humboldt River Basin and the Nevada Test Site (Lopes and others, 2006). In areas



**Figure 4.** Concentrations of soil organic material.

without water-table information, greasewood and mapped ground-water discharge areas are good indicators of depth to water that is <100 ft.

Roots of some plants extend tens of feet below land surface and extract soil moisture. Water that infiltrates below the root zone typically is assumed to reach the water table. Thus, susceptibility is lowered by dense vegetation with deep roots. Phreatophytes, such as greasewood, have roots that extend to and transpire ground water. Phreatophytes typically occur in ground-water discharge zones where the unsaturated zone is <100 ft (Lopes and others, 2006). Contaminants are not likely to travel far or deep in discharge zones due to vertically upward gradients.

## Hydrogeologic Units

Hydrogeologic units are geologic formations having similar lithology and assumed to have similar hydrologic properties. Where hydrogeologic units are saturated, they form aquifer systems that are used for water supply. Maurer and others (2004) grouped geologic formations into hydrogeologic units with similar lithology. Geologic formations were from Stewart and Carlson (1978), who compiled 1:250,000-scale geologic maps of Nevada's counties and other information into a single geologic map of Nevada at a scale of 1:500,000. Because the hydrologic properties of consolidated rocks and unconsolidated sediments are quite different, they comprise the two major hydrogeologic units in Nevada. Consolidated-rock hydrogeologic units form the mountain ranges and plateaus that receive the most precipitation in Nevada and unconsolidated sediments are in the intervening basins. Consolidated rocks are exposed over 56,000 mi<sup>2</sup> (51 percent) of Nevada and unconsolidated sediments are exposed over 54,000 mi<sup>2</sup> (49 percent) of the State. These two major hydrogeologic units were subdivided into more detailed hydrogeologic units (Maurer and others, 2004).

Consolidated rocks were subdivided into eight hydrogeologic units by Maurer and others (2004). In order of decreasing area, the eight consolidated-rock hydrogeologic units consist of Quaternary to Tertiary age volcanic flows of (1) basaltic, (2) rhyolitic, and (3) andesitic composition; (4) volcanic breccias, tuffs, and volcanic rocks older than Tertiary age; (5) carbonate rocks; (6) Tertiary-age consolidated and semi-consolidated tuffaceous rocks and sediments; (7) clastic rocks consisting of sandstone and siltstone; and (8) intrusive and metamorphic rocks.

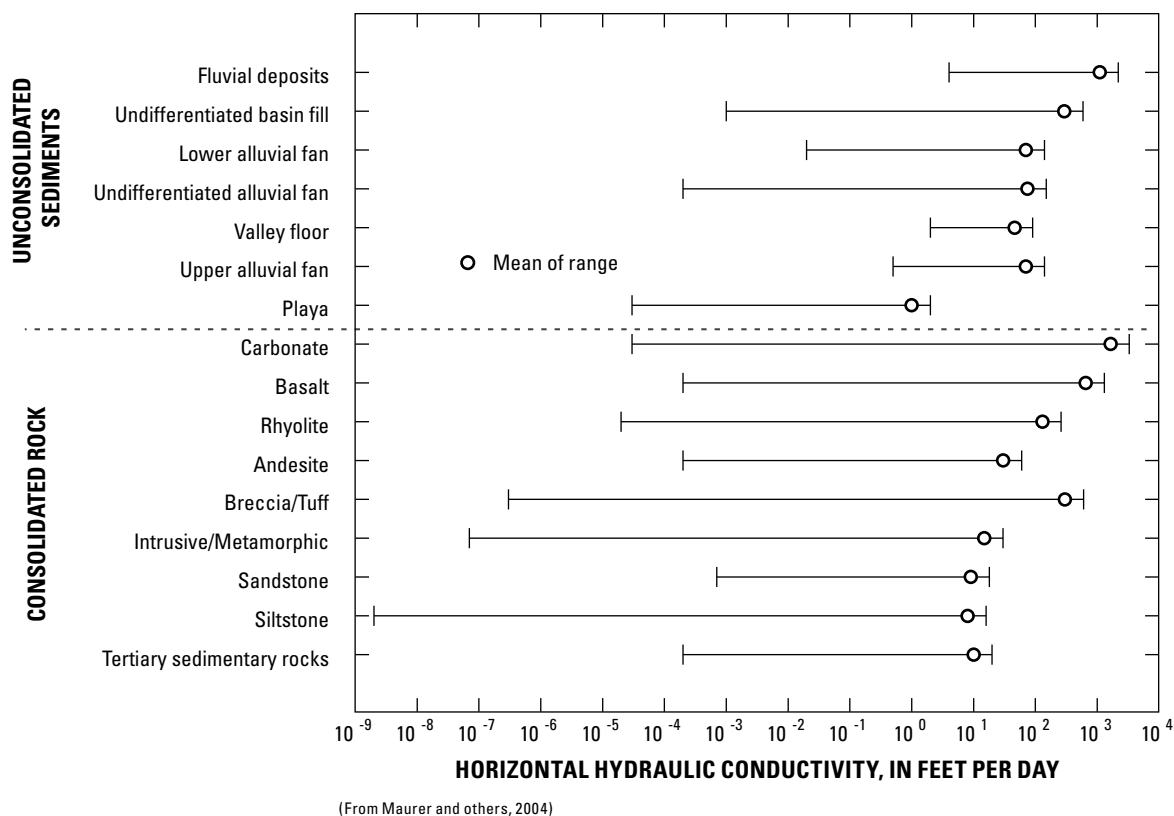
Unconsolidated sediments were subdivided into four hydrogeologic units based on topographic slope, horizontal hydraulic conductivity, and mapped stream channels (Maurer and others, 2004). Alluvial slopes and valley floors are unconsolidated sediments with a topographic slope greater than and less than 3 percent, respectively. Fluvial deposits were mapped as a separate unit and could be areas of preferential flow. Playas are topographic lows with no surface outflow and have low hydraulic conductivities.

Hydraulic conductivity is the rate at which water moves horizontally or vertically through rocks and sediments (Lohman and others, 1972). The horizontal hydraulic conductivity of each hydrogeologic unit depends on local conditions such as fracturing and can vary by several orders of magnitude. Basalt and carbonate rocks and unconsolidated sediments except playas typically have high (>40 ft/d) horizontal hydraulic conductivities that are similar to most unconsolidated sediments (fig. 5; Maurer and others, 2004). Rhyolite and volcanic breccias, tuffs and volcanic rocks older than Tertiary age seem to have high horizontal hydraulic conductivity. However, this is due to a few anomalous hydraulic conductivity values reported for these units. Playas and other consolidated rocks typically have low (<40 ft/d) horizontal hydraulic conductivities. For comparison, the hydraulic conductivity of clean sand is about 40 ft/d (Freeze and Cherry, 1979). Most of Nevada (59.8 percent) has hydrogeologic units with high horizontal hydraulic conductivity, and almost 90 percent of the population lives on hydrogeologic units with high horizontal hydraulic conductivity (Maurer and others, 2004). Thus, contaminants that migrate to the water table could quickly move through aquifer systems in most of the State.

## Ground-Water-Flow Paths and Velocities

Most ground-water recharge occurs on alluvial slopes, resulting in generally downward ground-water flow (Mifflin, 1988). On the valley floor, little ground-water recharge occurs and ground-water flow generally is parallel to land surface or upward where it discharges by evapotranspiration from plants and bare soil (Mifflin, 1988; Freeze and Cherry, 1979). These generalized descriptions of ground-water-flow paths may vary depending on the permeability of consolidated rocks forming the mountain block and the amount of annual precipitation (fig. 3).

The depth of contaminant transport is controlled by the vertical hydraulic conductivity of sediments underlying alluvial slopes and the valley floors. In general, sediments forming alluvial slopes are coarse-grained and poorly sorted with relatively few interbedded clay layers (Plume, 1996; Bedsun, 1980; Mifflin, 1988; Anderson and others, 1983). The grain size of basin-fill sediments decreases towards the center of the valley (Plume, 1996; Davis, 1988), and the lower parts of alluvial slopes are likely to interfinger with layers of well sorted sand, silt, and clay deposited on the valley floor (Plume, 1996; Bedsun, 1980). Basin-fill sediments on the valley floor may contain individual layers with high horizontal and vertical hydraulic conductivity, but the overall vertical hydraulic conductivity is relatively low because of the interbedded clay layers. Johnson and others (1968) report vertical hydraulic conductivities of valley-floor sediments in central California that range from  $9 \times 10^{-6}$  ft/d for clay layers to 90 ft/d for sand layers. Harrill and Prudic (1998) report vertical hydraulic conductivities that range from one to three orders of magnitude less than horizontal hydraulic conductivities used for modeling five alluvial basins in and near Nevada. Thus, the potential for



**Figure 5.** Ranges in the horizontal hydraulic conductivity of aquifers in Nevada.

vertical migration of contaminants likely is greater on alluvial slopes than on the valley floor.

Faults are a secondary control on ground-water flow in unconsolidated sediments and a primary control on flow in consolidated rocks. Faults usually are barriers to ground-water flow in unconsolidated sediment (Goodwin and others, 1999). However, in the unsaturated zone, fine-grained fault gouge may act as a capillary conduit to the water table (Sigda and others, 1999). In consolidated rocks, permeability and ground-water flow is reduced in directions normal to the fault zone and increased in directions parallel to the fault zone (Caine and Forster, 1999; McKee and others, 1998). During geologic time, fractures in consolidated rocks may become cemented and sealed due to precipitation of minerals, reducing the permeability. However, continued movement along the fault may form new fractures so that a fault may cycle between a zone of preferred flow and a flow barrier.

Distinctions in ground-water-flow paths between alluvial slopes and valley floors have direct implications for aquifer susceptibility and the types of wells that could be affected. Contaminants released on alluvial slopes compared to valley floors are more likely to spread quickly through large areas and reach deep aquifer systems because ground-water flow is downward and vertical hydraulic conductivity, recharge, and water-table gradients are relatively high. Contaminants released on valley floors compared to alluvial slopes are more

likely to spread slowly through small areas of shallow aquifers because ground-water flow is either parallel to land surface or upward and the recharge rate, vertical hydraulic conductivity, and water-table gradient are relatively low. Typically, deep aquifers are used for municipal supply and shallow aquifers are used for domestic supply.

Hydraulic conductivity and effective porosity are the most important aquifer properties in controlling ground-water-flow velocities. The hydraulic conductivity of sediments generally is proportional to their grain size and degree of sorting, whereas the hydraulic conductivity of consolidated rocks depends, in large part, on their degree of fracturing. Effective porosity is the interconnected pore volume that contributes to fluid flow and is less than total porosity because it excludes isolated pores. In general, effective porosity of unconsolidated sediments is greater than that of consolidated rocks because pore spaces between sediment grains may be more numerous and more interconnected than pores in consolidated rock. However, consolidated rocks that typically have very low primary porosity may develop secondary porosity from open spaces along fractures and joints, or from dissolution of rocks along fractures and joints.

The hydraulic gradient is the difference in ground-water elevation measured in two wells divided by the distance between the wells. Gradients that drive lateral ground-water flow generally are greater beneath alluvial slopes than valley



floors. Gradients beneath alluvial slopes range from 0.0003 to 0.2, and from  $6 \times 10^{-7}$  to 0.3 beneath valley floors (Lopes and others, 2006; Handman and Kilroy, 1997; Harrill and Preissler, 1994; Maurer, 1986; Prudic and Herman, 1996; Seiler and Allander, 1993; Thomas and others, 1989; Thodal, 1997). Gradients in unconsolidated sediment associated with different types of consolidated rocks are significantly different. For example, gradients in unconsolidated sediments that are near carbonate rocks are lower than gradients near andesite. The difference could be related to the horizontal hydraulic conductivity of the consolidated rocks and the sediments derived from them (Lopes and others, 2006).

The average linear velocity of ground water ( $q_x$ ) can be estimated from the gradient ( $i$ ), horizontal hydraulic conductivity ( $K$ ), effective porosity ( $n$ ), and Darcy's Law (Freeze and Cherry, 1979):

$$q_x = (K \times i) / n \quad (2)$$

Using average values in Nevada and equation 2, Lopes and others (2006) estimated the average linear velocity of ground water beneath alluvial fans to be about 14 ft/d compared to about 1 ft/d beneath valley floors. Thus, contaminants could travel approximately 10-times faster beneath alluvial fans compared to valley floors. The rate of contaminant transport also depends on the retardation factor, which is a function of the physical and chemical properties of the aquifer material and contaminant (Freeze and Cherry, 1979). Some contaminants, such as nitrate and MTBE, may travel at about the same rate as ground water because they are highly soluble, do not readily sorb to sediments, and are not easily degraded. Other contaminants, including most pesticides, move at a fraction of the ground-water velocity.

Variables that affect ground-water flow can range by orders of magnitude. Maurer and others (2004) used the concept of hydrologic landscape regions (HLRs) to group areas of Nevada with similar values of selected variables, which included horizontal hydraulic conductivity, mean annual precipitation, soil permeability, slope, and aspect. Ground-water flow presumably is similar in areas with similar characteristics. HLRs with moderate to high precipitation ( $>8$  in/yr), moderate to high soil permeability ( $>5$  ft/d), low to moderate slope ( $\leq 25$  percent), and high hydraulic conductivity ( $>40$  ft/d) could have greater recharge rates and be more susceptible to contamination relative to other regions. These characteristics describe three HLRs, which comprise 27.1 percent of Nevada and represent alluvial slopes and valley floors in most basins of eastern and central Nevada. The HLR that could be most susceptible has 38 percent of Nevada's population, so it also is vulnerable to contamination. The most susceptible HLR represents the alluvial slope and valley floor of western Las Vegas and Spanish Springs, alluvial slope and fluvial deposits of western Reno, and valley floor of Carson City, Minden, and Gardnerville. These areas could be most vulnerable due to their hydrologic characteristics and contaminants associated with urban land-use practices.

## Methods

### Chemical Techniques

Chemical tracers can be used to identify sources of ground water and contaminants, estimate the date and temperature of ground-water recharge, and to assess aquifer susceptibility. Ground water that is centuries old and has not mixed with recent recharge (since about 1950) is not currently susceptible to anthropogenic contamination. Conversely, ground water that has been recently recharged is susceptible to sources of anthropogenic contamination. Chemical tracers used for this study included nitrate, chlorofluorocarbons (CFCs), dissolved gases, and isotopes of hydrogen and oxygen. Data collected for this study were supplemented with CFC data collected by previous studies and archived at the USGS Chlorofluorocarbon Laboratory in Reston, Virginia, and isotope data retrieved from the Nevada Water Science Center National Water Information System. Previous studies collected CFC data from 1993 to 2003 and isotope data from 1974 to 2003.

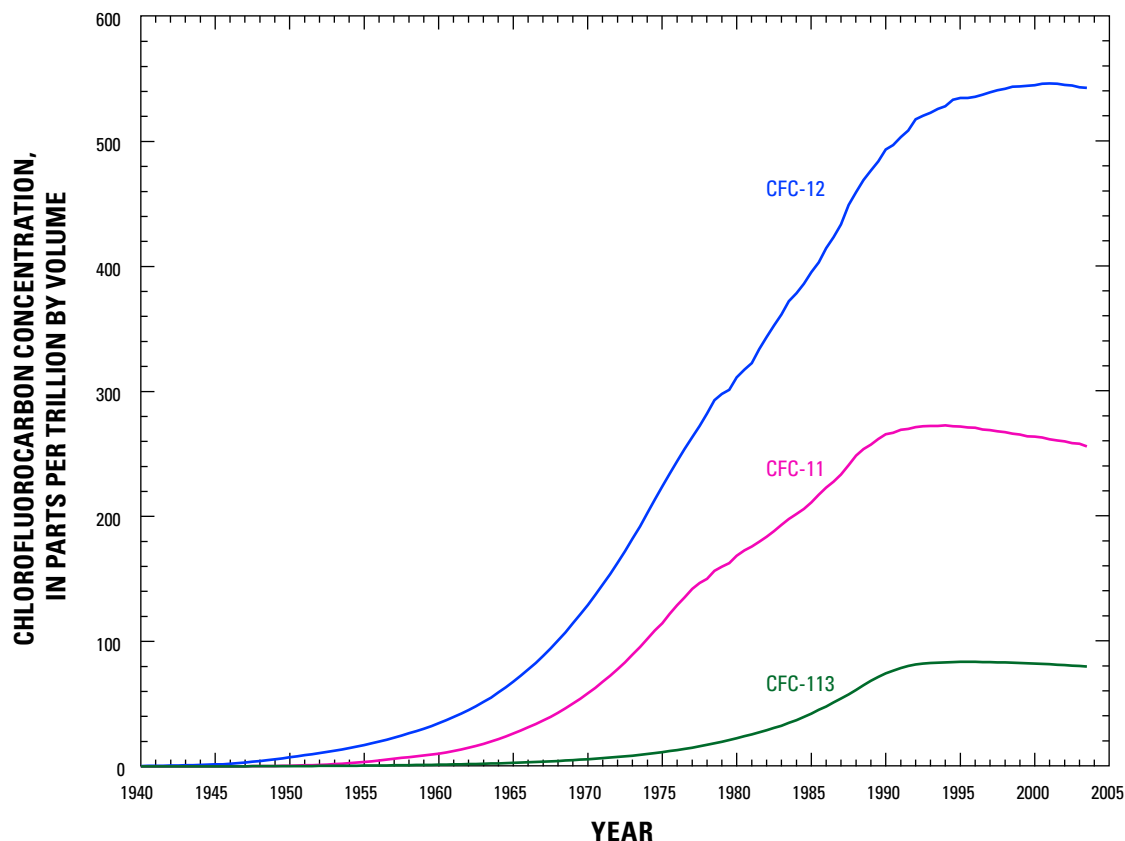
### Chlorofluorocarbons

The presence of CFCs in ground water indicates that the aquifer system has been recently recharged and, therefore, is susceptible to contamination (Nelms and others, 2003). CFCs are stable, non-toxic VOCs that primarily are used as refrigerants, blowing agents in foam, insulation, packing materials, propellants in aerosol cans, and solvents (Plummer and Busenberg, 2000). CFCs were first synthesized in the early 1930s. CFC production steadily increased until the 1990s when industrialized and developing countries agreed to phase out production. Depending on the use, most CFCs are released into the environment and enter the hydrologic cycle within 6 months to 10 years after production.

CFCs are highly volatile and quickly dispersed in the atmosphere, where their concentrations closely correspond with CFC production (Plummer and Busenberg, 2000). Atmospheric concentrations increased from the 1940s to the 1990s (fig. 6). Since then, atmospheric concentrations have decreased due to the global ban. The chemical stability, rapid dispersal, and increasing atmospheric concentrations until the 1990s make CFCs excellent tracers to date ground water recharged since about 1950. Apparent recharge dates are estimated from CFC concentrations measured in ground-water samples, atmospheric concentration-time curves (fig. 6), and Henry's Law. Henry's Law describes the partitioning of volatile liquids between water and air at equilibrium:

$$C_w / C_a = K_H \quad (3)$$

Where  $C_w$  is the concentration in ground water,  $C_a$  is the concentration in air at equilibrium, and  $K_H$  is the temperature-dependent Henry's Law constant. Recharge temperatures



**Figure 6.** Atmospheric mixing ratios of CFC-11, CFC-12, and CFC-113 for the northern hemisphere.

estimated from dissolved gases can be used to calculate the appropriate  $K_H$  at the time of recharge and refine estimates of the apparent recharge date. The CFC concentration in ground water and equation 3 are used to estimate the atmospheric CFC concentration when recharge occurred. The estimated atmospheric CFC concentration is matched with the corresponding date from the atmospheric concentration-time curves to estimate the apparent recharge date.

Of the many CFCs that have been produced, trichlorofluoromethane (CFC-11), dichlorodifluoromethane (CFC-12), and trichlorotrifluoroethane (CFC-113) have been used to date ground water (Plummer and Busenberg, 2000). Using analytical methods with a detection limit of 0.3 pg/L, CFC-12, CFC-11, and CFC-113 can date ground water recharged since about 1941, 1947, and 1955, respectively (Plummer and Busenberg, 2000). The recharge date is an apparent date because processes, such as mixing with ground water older than 1940, affect the estimate. Also, apparent recharge dates are not unique for ground water that was recharged during the 1990s due to the decline in atmospheric CFC concentrations.

Apparent recharge dates estimated using CFCs are based on the assumption that recharge is in equilibrium with tropospheric air at the time of recharge. Barometric pumping and diffusion are physical processes that move CFCs from the atmosphere through the unsaturated zone to the water table.

Barometric pumping and horizontal pressure gradients during storms can move air tens of feet into the unsaturated zone (Plummer and Busenberg, 2000). Diffusion is the primary process controlling CFC concentrations in deep unsaturated zones. However, barometric pumping can move gas hundreds of feet in fractured rock. A combination of thermal-topographic, barometric, and wind effects results in CFCs advecting through Yucca Mountain, Nye County, in  $\leq 5$  years (Plummer and Busenberg, 2000).

The thickness of the unsaturated zone is an important factor affecting apparent recharge dates in Nevada. CFC transport through thick unsaturated zones can take tens of years. Thus, present-day recharge could be in equilibrium with CFCs that were released into the atmosphere decades before. The lag time for CFCs to move to the water table would result in an apparent recharge date that is biased old. Effects of lag time on apparent recharge dates was demonstrated by Busenberg and others (1993), who measured and modeled CFCs in unsaturated playa sediments and underlying basalts to depths of about 200 ft in the Snake River Plain. In 1991, soil water equilibrated with soil air sampled just above the water table would have an apparent recharge date of 1968 using CFC-11 or 1971 using CFC-12. Thus, the apparent recharge date would be biased old by about 20 years.

## Dissolved Gases

Gases dissolved in ground water have been useful in studies of recharge temperatures, paleo-climate, ground-water dynamics, and denitrification and oxygen consumption rates (Stute and Schlosser, 2000). Nitrogen ( $N_2$ ), oxygen ( $O_2$ ), and the noble gases helium (He), neon (Ne), argon (Ar), krypton (Kr), and xenon (Xe) are the main gases that have been studied. Most gases dissolved in ground water are from the atmosphere. The dissolution of gases into ground water closely follows Henry's Law and depends on the gas solubility, barometric pressure, temperature, salinity, and other variables (Stute and Schlosser, 2000). The effect of salinity on dissolved gas concentrations is negligible for most ground water in Nevada (Stute and Schlosser, 2000).

Several techniques can be used to estimate recharge temperature. The graphical technique is used by the USGS Chlorofluorocarbon Laboratory because it is suitable for when data are available for two gases ( $N_2$  and Ar; Stute and Schlosser, 2000). This technique assumes that excess air is not fractionated. Additional noble gases need to be measured to determine if fractionation has occurred. However, argon was the only noble gas measured for this study.

Gases continually equilibrate with recharge as it infiltrates through the unsaturated zone. The concentration of gases dissolved in ground water depends on the temperature and concentration of gases in soil air at the water table. Differences in solubility changes the ratio of gases dissolved in water compared to their ratio in the atmosphere. Calculations by Stute and Schlosser (2000) suggest that recharge temperatures estimated from dissolved gases are close to the mean annual ground temperature at the water table. Exceptions are where the water table is  $\leq 5$  ft below land surface, the recharge rate is  $\geq 12$  in/yr, or where recharge does not equilibrate with soil air such as karstic aquifers. These exceptions apply to few areas in Nevada. Recharge temperatures estimated from noble gases should be within  $1.8^\circ\text{F}$  ( $1^\circ\text{C}$ ) of the mean annual ground temperature, except where depth to water is  $>100$  ft and geothermal gradients become a factor (Stute and Schlosser, 2000). Mean annual ground temperatures typically are  $1.8 \pm 1.8^\circ\text{F}$  warmer than air temperatures for the conterminous United States. However, larger temperature differences have been reported for deserts, such as Nevada, and snow-covered regions.

Dissolved gases in ground water often are in excess of what can be explained by solubility equilibria at the recharge temperature (Stute and Schlosser, 2000). Excess air occurs when the water table rises, air bubbles become entrapped in the aquifer matrix, and the bubbles dissolve into ground water. Excess air that is un-fractionated and atmospheric air will have the same ratio of gases, which can be used to estimate the amount of excess air in a sample (Stute and Schlosser, 2000). The USGS Chlorofluorocarbon Laboratory used estimates of excess air to correct estimates of recharge temperatures and apparent recharge dates.

## Isotopes of Hydrogen and Oxygen

Stable isotopes of hydrogen and oxygen in water are useful in tracking different sources of water and have been used as an indicator of paleo-ground water in the Great Basin (Smith and others, 2002). The stable isotopes measured were oxygen-18 relative to oxygen-16 ( $^{18}\text{O}/^{16}\text{O}$ ) and deuterium relative to protium ( $^2\text{H}/^1\text{H}$ ). Each ratio is determined in water and then related to the ratio of a reference standard known as Vienna-Standard Mean Ocean Water (VSMOW; Fritz and Fontes, 1980). By convention, the results are expressed by delta oxygen-18 ( $\delta^{18}\text{O}$ ) and delta deuterium ( $\delta\text{D}$ ) in parts per thousand (abbreviated "permil" or ‰). The delta notation is computed from the equation:

$$\delta = \{(R_x - R_{\text{std}})/R_{\text{std}}\} * 1,000 \quad (4)$$

where

$\delta$  is the delta notation;

$R_x$  is the ratio of  $^{18}\text{O}/^{16}\text{O}$  or  $^2\text{H}/^1\text{H}$  measured in the sample;

$R_{\text{std}}$  is the ratio of  $^{18}\text{O}/^{16}\text{O}$  or  $^2\text{H}/^1\text{H}$  in the standard.

Water that is enriched in lighter isotopes ( $^1\text{H}$  and  $^{16}\text{O}$ ) relative to VSMOW has negative delta values. Evaporation and condensation are the most important processes that affect the isotopic composition of water. Variations in  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in ground water reflect differences in latitude, altitude, seasonal precipitation, and evaporation, which are factors that affect recharge temperature. The ratios of these isotopes are virtually unaffected by low-temperature geochemical processes in ground water (Muir and Coplen, 1981).

Smith and others (2002) compared  $\delta\text{D}$  values between modern-day precipitation and ground water in the Great Basin. Iso-deuterium contours based on winter data indicate modern-day precipitation has  $-90$  to  $-120$  ‰  $\delta\text{D}$  in southern Nevada,  $-100$  to  $-120$  ‰  $\delta\text{D}$  in northwestern Nevada, and  $-120$  to  $-130$  ‰  $\delta\text{D}$  in central, northern, and northeastern Nevada. Ground water that is  $20$  ‰ more negative than modern precipitation was considered to probably be Pleistocene-age and ground water that is  $10$  to  $19$  ‰ more negative is possibly Pleistocene-age. This compares well with Lopes and Hoffman (1997) who found  $5$  ‰ to  $30$  ‰ more negative  $\delta\text{D}$  in ground water dated around  $10,000$  to  $34,000$  years in northeastern Arizona. Smith and others (2002) identified one sample in northeastern Nevada with  $<-150$  ‰  $\delta\text{D}$  that was probably of Pleistocene-age and seven samples with  $-140$  to  $-150$  ‰  $\delta\text{D}$  that is  $15$ – $20$  ‰ more negative than modern precipitation. A number of samples in northern Nevada had  $-130$  to  $-140$  ‰  $\delta\text{D}$ , which is  $5$  to  $15$  ‰ more negative than present-day precipitation. These samples also may represent Pleistocene-age water or a mixture of Pleistocene-age and Holocene-age water. Isotopic data collected for this study were compared to the iso-deuterium contours of Smith and others (2002) to determine whether the water could be of Pleistocene-age and, therefore, should not have CFCs.

## Well Selection

Ground-water samples were collected from 133 wells from August 2002 through October 2003. The HLRs of Nevada (Maurer and others, 2004) were used to select wells so that data represent ranges in natural variables that could affect aquifer susceptibility (table 3). Wells also were selected to obtain a broad distribution of data (fig. 1). HLRs 1 through 8 represent aquifers with low (<40 ft/d) horizontal hydraulic conductivity and have few wells. HLRs 9 through 16 represent aquifers with high (>40 ft/d) horizontal hydraulic conductivity and have most of Nevada's population. CFC data were available for each HLR except HLRs 3, 6, and 16. Most data are from HLRs 9 through 12, which are the largest and most populated HLRs (Maurer and others, 2004). Monitoring wells were selected first because typically they have short (<20 ft) screened intervals near the water table, which are best suited for detecting recent recharge. However, most wells sampled were domestic wells. Sampled wells had a median depth of 160 ft and median screen length of 20 ft. Some municipal wells with large screened intervals were sampled to obtain data where monitoring or domestic wells did not exist. Previous studies sampled CFCs in wells on the Nevada Test Site that are about 1,000 to 7,000 feet deep with thousands of feet of screen and open hole.

**Table 3.** Number of wells sampled in hydrologic landscape regions of Nevada

Hydrologic landscape region <sup>1</sup>	Number of wells sampled for this study	Number of wells sampled for CFCs by previous studies
1	5	7
2	2	11
3	0	0
4	6	5
5	0	3
6	0	0
7	3	13
8	6	2
9	50	38
10	23	11
11	11	9
12	15	5
13	0	1
14	4	0
15	8	7
16	0	0

<sup>1</sup>Numbers identify regions described by Maurer and others (2004).

## Sampling Procedures

Field parameters (pH, dissolved oxygen, specific conductance, and temperature) were measured and a minimum of three well volumes were pumped from each well prior to sampling. Ground water was pumped through a flow-through cell and field parameters were monitored until they stabilized (Wilde and others, 1999). Samples for dissolved solids and nutrients were filtered in the field using 0.45 micron filters and analyzed at the USGS National Water-Quality Laboratory in Lakewood, Colorado. Data were published in Stockton and others (2003).

The first 25 samples for CFC analysis were collected by fusing glass ampoules. The procedure is described in detail by Busenberg and Plummer (1992). Briefly, refrigeration-grade copper tubing is used to form a closed path from the pump to a valve system that allows flushing, filling, and fusing of borosilicate ampoules in an ultra-pure nitrogen atmosphere. This is a complex procedure which often has to be repeated to obtain properly sealed ampoules.

Most samples were collected using the bottle procedure that is essentially the same as the procedure used for sampling dissolved gases. A 125-ml bottle was placed in a 3-L stainless steel canister. The copper tubing was then placed in the bottom of the bottle and the bottle was flushed 24 times before the canister overflowed, which effectively formed a closed path from the pump to the sample bottle. The bottle was then sealed under water using a special foil-lined cap that had been flushed with sample water. The bottle was taken out of the canister, dried, and wrapped with electrical tape to prevent the cap from loosening. Ampoules can be stored for several years. However, samples collected using the bottle procedure must be analyzed within 6 months of collection.

Five replicates were collected at each site using either the ampoule or bottle procedure. Two or three of the replicates were analyzed for CFC-11, CFC-12, and CFC-113 using purge-and-trap gas chromatography with an electron capture detector at the USGS Chlorofluorocarbon Laboratory in Reston, Virginia (worksheets 1 and 2). Comparison of the ampoule and bottle procedures showed that they produce the same results (USGS Chlorofluorocarbon Laboratory, written commun., 2003). For samples collected during this study, the Wilcoxon-rank test indicated percent differences between the ampoule and bottle procedures were not significantly different for CFC-11 and CFC-12; however, CFC-113 had significantly larger differences using the ampoule method compared to the bottle method.

Measured CFC concentrations, Henry's Law (eq. 3), and atmospheric concentration-time curves (fig. 6) were used to estimate the apparent recharge date for each replicate. Apparent recharge dates can vary among CFCs measured in each replicate and among replicates due to analytical precision and variability of CFC concentrations in the aquifer. Therefore, a qualitative estimate of the apparent recharge date, such as early 1970s, was provided by the laboratory. Qualitative estimates were converted to exact dates and used in data

interpretation. For example, early 1970s was assumed to be 1972, early to mid 1970s was assumed to be 1973, mid 1970s was assumed to be 1975, mid to late 1970s was assumed to be 1977, late 1970s was assumed to be 1978, and late 1970s to early 1980s was assumed to be 1980.

For dissolved gases, the sampling procedure was essentially the same as the bottling procedure for CFCs except a 150-ml bottle was used, the bottles were sealed with a rubber stopper, and only two replicates were collected. Both replicates were analyzed for argon (Ar), nitrogen ( $N_2$ ), oxygen ( $O_2$ ), carbon dioxide ( $CO_2$ ), and methane ( $CH_4$ ) using gas chromatography with a thermal conductivity detector or flame ionization detector at the USGS Chlorofluorocarbon Laboratory (worksheet 3).

Samples for stable isotopes in water were collected by filling 60-ml bottles directly from the copper tubing and sealing with polyethylene-lined caps. Selected samples were analyzed using mass spectrometry at the USGS Stable Isotope Laboratories in Reston, Virginia (worksheet 4).

## Quality Assurance

Contamination during sampling, chemical analysis, or both, is evident from concentrations and ratios of CFCs and dissolved gases in present-day air. Nine replicates for dissolved gases were discarded due to broken bottles, leakage, or bad injection during analysis. Dissolved-gas data for these 9 samples are based on one replicate. The overall accuracy of sampling and analytical methods was evaluated by calculating the percent difference in dissolved gas concentrations between replicates. The median and mean differences were 2 and 5 percent for  $CO_2$ ; 1 and 2 percent for  $N_2$ ; 13 and 28 percent for  $O_2$ ; and 1 and 1 percent for Ar. No evaluation was done for  $CH_4$  because it was seldom detected.

No samples for CFCs were discarded due to contamination from sampling, chemical analysis, or both. However, apparent recharge dates were not estimated for some samples due to ground-water contamination. Sixteen samples had one replicate with high concentrations compared to the other two replicates (for example, worksheet 2, station 360203115163201). The other replicates had similar concentrations and apparent recharge dates based on at least 2 CFCs were similar ( $\pm 10$  years). Therefore, it was assumed that the replicate with high concentrations was contaminated during sampling, chemical analysis, or both, and that apparent recharge dates based on the other replicates were valid. Fourteen samples for CFCs had replicates with consistently high or increasing concentrations for one CFC and similar apparent recharge dates based on the other two CFCs (for example, worksheet 2, station 371647117015201). Therefore, it was assumed that ground water was contaminated with the one CFC and that apparent recharge dates based on the other two CFCs were valid. Two samples for CFCs had consistently high concentrations for one CFC and most apparent recharge dates based on the other two CFCs were different by more than 10 years, three samples had consistently high

concentrations for two CFCs, and four samples had inconsistent concentrations among all replicates (for example, worksheet 2, stations 391126119441902, 390657119492101, and 352743114591901). Therefore, it was assumed that ground water was contaminated with CFCs and that apparent recharge dates estimated for these nine samples were unreliable.

Apparent recharge dates were estimated for the remaining 124 samples. Using the same criteria, apparent recharge dates based on at least two CFCs were estimated for 94 of the 112 samples from previous studies. Apparent recharge dates were not estimated for 18 samples due to ground-water contamination or inconsistent results among replicates.

The overall accuracy of sampling, analytical methods, and estimating apparent recharge dates was evaluated by calculating the difference in CFC concentrations and apparent recharge dates among replicates. Only samples collected for this study were evaluated. CFC concentrations that indicated contamination during sampling, analysis, or both, or ground-water contamination were not used to estimate apparent recharge dates and were not included in the evaluation. The median and mean differences between concentrations among replicates were 12 and 28 percent for CFC-11; 8 and 25 percent for CFC-12; and 9 and 25 percent for CFC-113. The median and mean differences between apparent recharge dates among replicates were 1 and 1.6 years for CFC-11; 1 and 2 years for CFC-12; and 1 and 2 years for CFC-113. The median and mean differences between apparent recharge dates among CFCs were 4 and 6 years between CFC-11 and CFC-12; 6 and 9 years between CFC-11 and CFC-113; and 4 and 6 years between CFC-12 and CFC-113.

One well (station 382328117262501) was re-sampled for CFCs about one month after the first sampling to determine the repeatability of dating ground water. The apparent recharge date for the first sample was the late 1960s and the late 1950s for the second sample. The well had been pumping for several hours prior to re-sampling, which may have drawn in older water and could explain the difference. In general, replicates and re-sampling indicate CFC concentrations and estimated apparent recharge dates are accurate.

## Statistical Techniques

### Correlations and Comparisons

Parametric and non-parametric statistics were used to determine if relations exist between variables and to compare sample populations. Parametric tests assume that data have a certain distribution and use parameters, such as the mean and standard deviation, to summarize information contained in the data (Helsel and Hirsch, 1992). The most common assumption is that data are normally distributed. However, environmental data often are not normally distributed. If the assumption of normal distribution is invalid, parametric tests may lead to incorrect conclusions when testing hypotheses

because it lacks sensitivity to detect real effects (Helsel and Hirsch, 1992). Non-parametric tests do not assume a certain distribution in the data. Instead of summarizing information in parameters, information is obtained directly from the data by ranking values and comparing ranks between variables (Helsel and Hirsch, 1992). Using the ranks gives less weight to outliers and is useful in detecting relations, especially for small datasets.

The Pearson correlation, also called the linear correlation coefficient, is the most commonly used parametric test to determine if variables are related (Helsel and Hirsch, 1992). Data that are perfectly linear with a positive slope have a Pearson correlation of 1 and -1 if the slope is negative. A correlation of zero indicates there is no relation between the variables. The Spearman rank correlation is similar to the Pearson correlation, but it is a non-parametric test computed on the ranks of the data. The Wilcoxon rank-sum is a non-parametric test similar to the parametric t-test that was used to determine if there was a significant difference between two populations. The Kruskal-Wallis rank test is a non-parametric test that was used to determine if there was a significant difference between more than two populations. A level of significance ( $\alpha$  value) of 0.05 was used in all statistical tests. The  $\alpha$  value is the probability of incorrectly rejecting the null hypothesis. The p-value is a diagnostic statistic computed from the data that is compared to the  $\alpha$  value. If the p-value is less than the  $\alpha$  value, then there is a  $\geq 95$ -percent probability of correctly rejecting the null hypothesis and accepting the alternate hypothesis.

## Logistic Regression

Logistic regression has been used extensively in medical studies and is being applied in a variety of fields. In environmental studies, logistic regression has been successfully used to assess ground-water vulnerability at basin-wide, statewide, and national scales (Eckhardt and Stackelberg, 1995; Tesoriero and Voss, 1997; Nolan and others, 2002; Squillace and others, 1999; Donato, 2000; and Rupert, 2003). Logistic regression is similar to ordinary least squares regression because both regressions produce mathematical relations between dependent and independent variables (Helsel and Hirsch, 1992). However, in logistic regression the dependent variable is binary, such as detection or non-detection of an SOC. Logistic regression has advantages over process-based methods because relations between detection of contaminants and predictor variables can be investigated for areas where contaminants are infrequently detected (Squillace and others, 1999).

For this study, the dependent variable was the detection or non-detection of nitrate above a concentration that is larger than most naturally occurring concentrations in ground water. Detection of nitrate above this threshold concentration is called an event. Logistic regression produces an equation that estimates the probability of an event from independent variables, such as depth to water, that are correlated with high nitrate concentrations. An overview of logistic regression is described below. Detailed procedures and diagnostic tests for

logistic regression are described by Hosmer and Lemeshow (2000) and Helsel and Hirsch (1992).

The odds ratio is used to transform the binary, dependent variable into a continuous variable ranging from negative to positive infinity. The odds ratio is defined as the probability of an event ( $p$ ) divided by the probability of a non-event:

$$\text{Odds ratio} = (p / 1 - p) \quad (5)$$

The natural log of the odds ratio (called the logit) transforms a variable constrained between 0 and 1 into a continuous variable without bounds. The logit can be modeled as a linear function of one or more independent variables to produce the logistic regression:

$$\ln (p / 1 - p) = b_0 + bX \quad (6)$$

where

$b_0$  is the intercept,

$X$  is a vector of  $k$  independent variables, and

$b$  includes the slope coefficients for each independent variable so that  $bX = b_1X_1, b_2X_2, \dots, b_kX_k$ .

The inverse of the logit transformation is used to return the estimated value to original units:

$$p = e^{(b_0 + bX)} / (1 + e^{(b_0 + bX)}) \quad (7)$$

The equation is used to estimate the probability of detecting nitrate above the threshold concentration from values of the independent variables. For example, a logistic regression with depth to water (DTW) and population density (PD) as independent variables would be:

$$p = e^{(b_0 + b_{DTW}DTW + b_{PD}PD)} / (1 + e^{(b_0 + b_{DTW}DTW + b_{PD}PD)}) \quad (8)$$

Stepwise logistic regression using STATISTICA (StatSoft, 2004) was done on nitrate and independent variables, described below. Statistical results were considered significant at  $\alpha = 0.05$ .

## Water-Quality Data Compilation

Existing ground-water quality data were compiled into a database to characterize ground-water quality and do logistic regression (table 4). Ground-water quality data were obtained from NDEP, NDOA, NBHPS, NSHL, and the USGS. Only data collected from January 1990 to January 2004 were used to characterize recent ground-water quality. The most recent data were used for wells with multiple samples. Analytical reporting limits were not available for most data, so no comparison was done to determine if measured concentrations or frequencies of detection were different among the agencies.

Water-quality data from 5,528 wells were compiled in the database. About half of the wells were from the NSHL, which mostly are domestic wells. Data from NDEP are from shallow

**Table 4.** Summary of water-quality data compilation

[Abbreviations: NDEP, Nevada Division of Environmental Protection; NDOA, Nevada Department of Agriculture; NBHPS, Nevada Bureau of Health Protection Services; NSHL, Nevada State Health Laboratory; USGS, U.S. Geological Survey; nitrate includes nitrate and nitrate plus nitrite; VOCs, volatile organic compounds]

Agency	Total number of wells	Number of wells with chemical data			
		Dissolved solids	Nitrate	Pesticides	VOCs
NDEP	525	412	342	0	0
NDOA	252	178	0	250	0
NBHPS	1,103	965	1,008	684	753
NSHL	2,738	1,628	1,775	0	110
USGS	910	679	669	225	243
Total	5,528	3,862	3,794	1,159	1,106

monitoring wells at regulated facilities, data from NDOA are from shallow monitoring wells in urban and agricultural land uses, data from NBHPS are from production wells, and data from the USGS are from monitoring, domestic, and production wells. Information such as well depth and depth to water were not available for most wells. For wells without an exact location, it was assumed that the location was the address of the facility or residence associated with the well. Wells were categorized by either the well type or land use immediately surrounding the well. Categories for well type included monitoring, domestic, and production. Categories for land use included agriculture, commercial, golf course, industrial, and mining. Wells with available water-quality data exist throughout most of Nevada but are concentrated in the Reno and Las Vegas metropolitan areas (fig. 7).

Most pesticide and VOC data are from production wells, which are deeper than other types of wells. Data from production wells may not indicate aquifers that are susceptible because of the travel time and dilution of contaminants along flow paths. Nitrate was the only anthropogenic compound that had sufficient data for logistic regression (table 4). Nitrate typically is detected in ground water and can occur naturally at high concentrations. Therefore, a nitrate concentration that likely indicates an anthropogenic source was determined from wells in undeveloped areas of Nevada using the water-quality and explanatory variable data. Wells with nitrate concentrations greater than the threshold concentrations were an event and concentrations less than the threshold concentration were non-events.

## Geographic Information System Datasets

Information on hydrogeologic and anthropogenic variables that could be related to water quality was compiled into geographic information system (GIS) datasets and used to characterize the environment within a 1,600-ft (500-m), 3,300-ft (1,000-m), and 4,900-ft (1,500-m) radius buffer surrounding each well (table 5). Information included existing datasets created by previous projects, such as PRISM precipitation estimates. New datasets and attributes also were created for

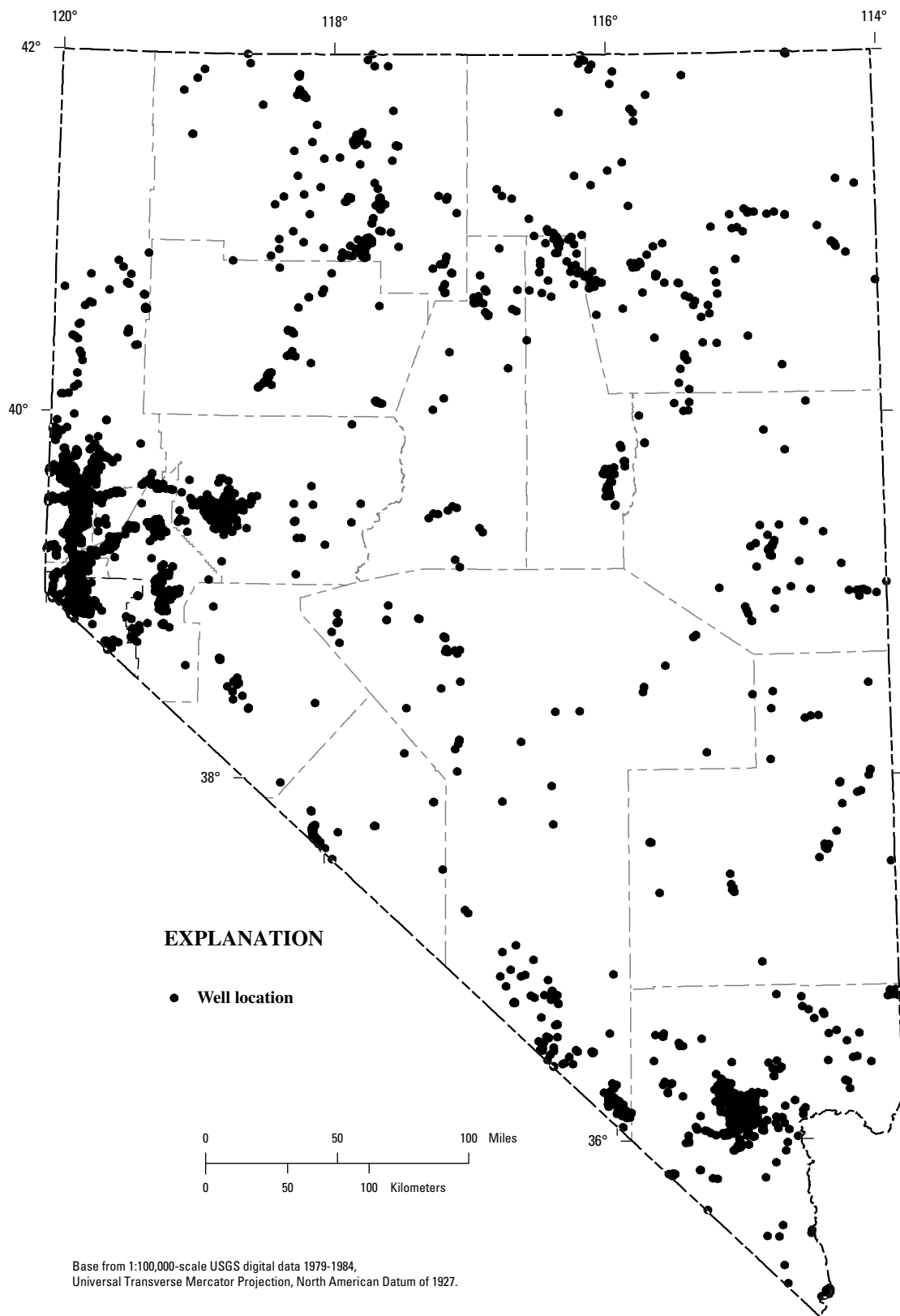
the project, such as the hydrogeology of Nevada (Maurer and others, 2004) and ground-water pumpage and recharge estimates for each hydrographic area (Lopes and Evetts, 2004). Only variables with statewide information available were compiled. Depth to water is a potential explanatory variable, but it was not used because depth to water was not available statewide. Statewide information for explanatory variables was available at a scale of  $\geq 1:250,000$ . More detailed data is available for some parts of Nevada, but not for the entire state so it was not used. The small scales reduce the ability to accurately characterize the environment around the wells.

A graphic user interface (GUI) was made for the project so NDEP could easily use the GIS datasets to obtain information on specific sites. The GUI allows the user to enter the site location, select datasets and attributes of interest, and produces a report on the selected information for the site. NDEP can use this information to evaluate a permit application, but should be aware of potentially large errors associated with using small-scale, statewide information to evaluate a specific site.

Surficial lithology and fault length were from Maurer and others (2004) who grouped geologic formations into hydrogeologic units with similar lithology. Geologic formations were from Stewart and Carlson (1978), who compiled 1:250,000-scale geologic maps of Nevada's counties and other information into a single geologic map of Nevada at a scale of 1:500,000. Surficial lithology was quantified as the percentage of each hydrogeologic unit within the buffer, which could be different than the lithology of the aquifer that the well was completed in. Fault length was the total length of faults within the buffer.

Estimates of mean annual precipitation for 1961–90 were from PRISM (G.H. Taylor, Oregon State University, written commun., 1997), which was modified by the USGS Nevada Water Science Center to produce isohyets with 1-in. contour intervals. Mean annual precipitation was the area-weighted average precipitation within the buffer.

Soil organic material, soil permeability, and soil drainage data were obtained from Schwarz and Alexander (1995), who used the STATSGO database (Natural Resources Conservation Service, 1991). STATSGO contains specific information



**Figure 7.** Locations of wells in Nevada with water-quality data.



**Table 5.** Explanatory variables used in logistic regression

Variable	Scale	Source of information
Hydrogeologic variables		
Aquifer lithology	1:500,000	Maurer and others (2004)
Fault length	1:500,000	Maurer and others (2004)
Precipitation	1:4,000,000	PRISM mean annual estimates based on 1961-1990 (G.H. Taylor, Oregon Climate Center, written commun., 1997))
Soil organic material	1:250,000	STATSGO (Schwarz and Alexander, 1995)
Soil permeability	1:250,000	STATSGO (Schwarz and Alexander, 1995)
Soil drainage	1:250,000	STATSGO (Schwarz and Alexander, 1995)
Topographic slope	1:250,000	Digital elevation model (U.S. Geological Survey, 2000)
Anthropogenic variables		
Land use	1:250,000	GIRAS updated with census information (Hitt, 1994)
Population density		Geolytics Inc. (2001)
Toxic releases	NA	U.S. Environmental Protection Agency (2005b)
Well density	NA	Nevada Division of Water Resources well log database (located at URL <a href="http://water.nv.gov/IS/wlog/wlog.cfm">http://water.nv.gov/IS/wlog/wlog.cfm</a> )

on layers within soil units, which were mapped to a maximum depth of five feet. Schwarz and Alexander (1995) used layer information to calculate a weighted average value for mapped soil units. SURGO is another soils database that contains more detailed information than STATSGO, but SURGO data are not available statewide. Organic material is the amount of organic carbon in the soil, in percent by weight. Soil permeability is the amount of water that infiltrates through the saturated soil under unit hydraulic gradient, in inch per hour. Soil drainage is a rating based on soil color and mottling that indicates how often the soil is saturated. Soil drainage has seven categories that range from excessively drained (category 1) to very poorly drained (category 7). Thus, soil drainage categories are inversely related to soil permeability. Average soil organic material, soil permeability, and soil drainage was the area-weighted average of each variable within the buffer.

Topographic slope is percent difference in altitude for a given horizontal distance. For example, a 10-percent slope rises 10 ft for a horizontal distance of 100 ft. The average topographic slope within the buffer was estimated from a digital elevation model with a resolution of 100 ft (30 m; U.S. Geological Survey, 2000).

Land-use information is based on data from the 1970s that was refined using U.S. Bureau of the Census 1990 population data to identify areas that had been recently urbanized (Hitt, 1994). A population density of  $\geq 1,000$  people per square mile was used to re-classify areas that were previously classified as another land use to urban land use. The 1970s data contains many land-use categories. For this study, these categories were simplified into urban, agriculture, and undeveloped land uses. Land use was quantified as the percentage of these three land uses within the buffer.

A demographic dataset from Geolytics, Inc. (2001) provided 2000 census population data in the form of population density blocks 328 ft (100 m) on a side. The population density value for each block represents the number of people per square mile. Population density was quantified as the area-weighted average number of people per square mile within the buffer.

Toxic release data for the year 1998 were obtained from the Toxic Release Information database (U.S. Environmental Protection Agency, 2005). This database contains information on inorganic and organic contaminants released from regulated point sources. Toxic release within each buffer was the sum of nitrogen compounds released to air, land, surface water, and ground water.

Well density information was obtained from the Nevada Division of Water Resources (NDWR) well log database (Nevada Division of Water Resources, 2005). This database mostly contains information on wells drilled since 1984. The latitude and longitude of each well was estimated from the township, range, and section provided by the driller. NDWR did a survey of wells in the Las Vegas area and obtained precise locations using a global positioning system (GPS). Comparisons between well locations from the well log database and GPS survey suggests that most locations from the well log database are within about 1,600 ft (500 m). However, during sampling for this study, some wells in other parts of the State could not be located because they had incorrect township, range, or section information. Well density was quantified as the number of wells per square mile within the buffer.

## Ground-Water Quality

### Dissolved Solids

For this study, maps of dissolved-solids concentrations (Thompson and Chappell, 1984), hydrogeology (Maurer and others, 2004), water-table levels (Lopes and others, 2005), and ground-water discharge areas (Harrill and others, 1988) were used to characterize the distribution of dissolved solids in unconsolidated sediments. Although Thompson and Chappell (1984) did not show a boundary between unconsolidated and consolidated aquifers, their map indicates that ground water had  $\leq 500$  mg/L where Maurer and others (2004) mapped consolidated-rock aquifer systems. Dissolved-solids concentrations are less than the secondary MCL of 500 mg/L in 72 percent of the unconsolidated-sediment aquifer systems (table 6, fig. 8). Water that has  $\leq 3,000$  mg/L of dissolved solids usually can be used for some purpose, such as stock watering and industry. About 97 percent of the unconsolidated-sediment aquifer systems have  $\leq 3,000$  mg/L dissolved solids and could be of some beneficial use.

Data compiled for this study are consistent with the map of Thompson and Chappell (1984) and indicate that most ground water in Nevada can be of some beneficial use. The 3,862 wells with dissolved-solids data had median and mean dissolved-solids concentrations of 290 and 820 mg/L, respectively. Dissolved-solids concentrations are  $< 500$  mg/L in 75 percent of wells and  $< 3,000$  mg/L in 96 percent of wells. Wells with dissolved-solids concentrations  $> 3,000$  mg/L are in 15 hydrographic areas, which include the Black Mountains Area, Boulder Flat, California Wash, Carson Desert, Dayton Valley, Dixie Valley, Eagle Valley, Fernley Area, Honey Lake Valley, Las Vegas Valley, Lemmon Valley, Mason Valley, Mesquite Valley, Spanish Springs Valley, and the Virgin River Valley. Most of these hydrographic areas have playas or geothermal waters, where high dissolved-solids concentrations would be expected.

Dissolved-solids concentrations were characterized for hydrogeologic units and ground-water discharge areas in unconsolidated sediments. Ground-water discharge areas, which overlap the hydrogeologic units, were considered separately. Ground-water discharge areas are comprised of about 39 percent valley floors, 33 percent playas, 15 percent alluvial fans, 6 percent fluvial sediments, and 6 percent consolidated rocks. Phreatophytes such as greasewood grow on lower alluvial fans. However, ground-water discharge areas in consolidated rocks likely are due to error from overlapping small-scale maps. Most ground-water discharge areas are where depth to water is  $< 50$  ft (Lopes and others, 2006). Ground-water discharge areas have the largest dissolved-solids concentrations due to evaporative concentration. However, dissolved-solids concentrations in 88 percent of ground-water discharge areas are  $\leq 3,000$  mg/L. Ground water flowing through sediments with gypsum can have dissolved-solids

concentrations of about 2,500 mg/L and larger concentrations when flowing through more soluble evaporites (Hem, 1985). The low percentage of dissolved-solids  $> 3,000$  mg/L in all settings, including ground-water discharge areas, suggests that soluble salts are not common in unconsolidated sediments.

The lowest dissolved-solids concentrations are beneath alluvial slopes and fluvial sediments that are not in ground-water discharge areas. These settings are where most recharge occurs (Mifflin, 1988, p. 76; Stonestrom and others, 2004). The type of consolidated rock adjacent to alluvial slopes does not appear to affect dissolved-solids concentrations but likely affects the major-ion chemistry. The percentages of unconsolidated sediment that are not in ground-water discharge areas and that have 501 to 1,000 mg/L of dissolved solids about doubles between alluvial slopes and valley floors and between valley floors and playas. About 28 percent of playas are not in ground-water discharge areas. Almost all ground water in playas that are not in ground-water discharge areas have dissolved solids  $\leq 3,000$  mg/L and could be of some beneficial use. The increase in dissolved solids between alluvial fans, valley floors, and playas likely is due to evapotranspiration and dissolution of aquifer material as ground water flows from alluvial slopes to discharge areas. Dissolution of aquifer material alone generally does not result in high dissolved-solids concentrations unless soluble salts are present.

### Nitrate

#### Concentrations in Undeveloped Areas

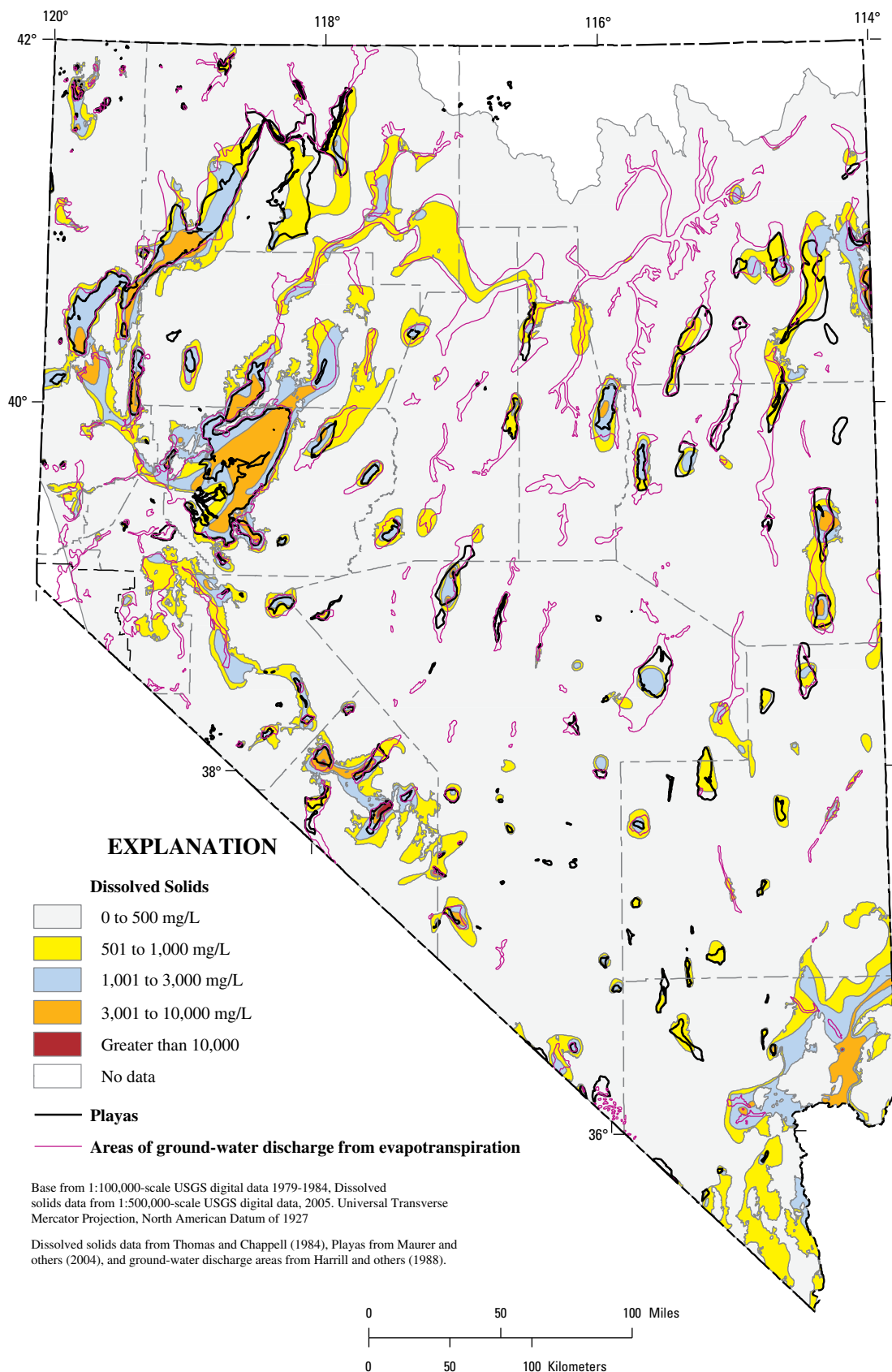
To estimate a concentration of nitrate that distinguishes natural from anthropogenic sources, wells were selected that have a population density of  $< 26$  people per square mile ( $< 10$  people per square kilometer) and  $> 80$  percent undeveloped land within a 4,900-ft (1,500-m) radius around each well. Wells that met these criteria and were associated with agricultural, commercial, golf course, industrial, and mining facilities were excluded from the analysis. These criteria resulted in 726 domestic, monitoring, and production wells being selected. Summary statistics of nitrate data from these wells were a median of 0.7 mg/L, a mean of 1.4 mg/L, an 80<sup>th</sup> percentile of 2.0 mg/L, and a maximum concentration of 20 mg/L.

The Kruskal-Wallis rank test indicated domestic and production wells in low populated, undeveloped areas had larger concentrations compared to monitoring wells (fig. 9), suggesting that anthropogenic sources could affect ground-water quality even in apparently undeveloped areas. Only 67 of the 726 wells in low populated, undeveloped areas had dissolved-solids and nitrate data. Nitrate had a significant inverse rank correlation ( $r = -0.39$ ) with dissolved solids for these wells; no significant correlation was found between dissolved-solids and nitrate data for all water-quality data. A positive correlation would be expected if evaporative concentration or nitrate salts in unconsolidated sediments were the source of high nitrate

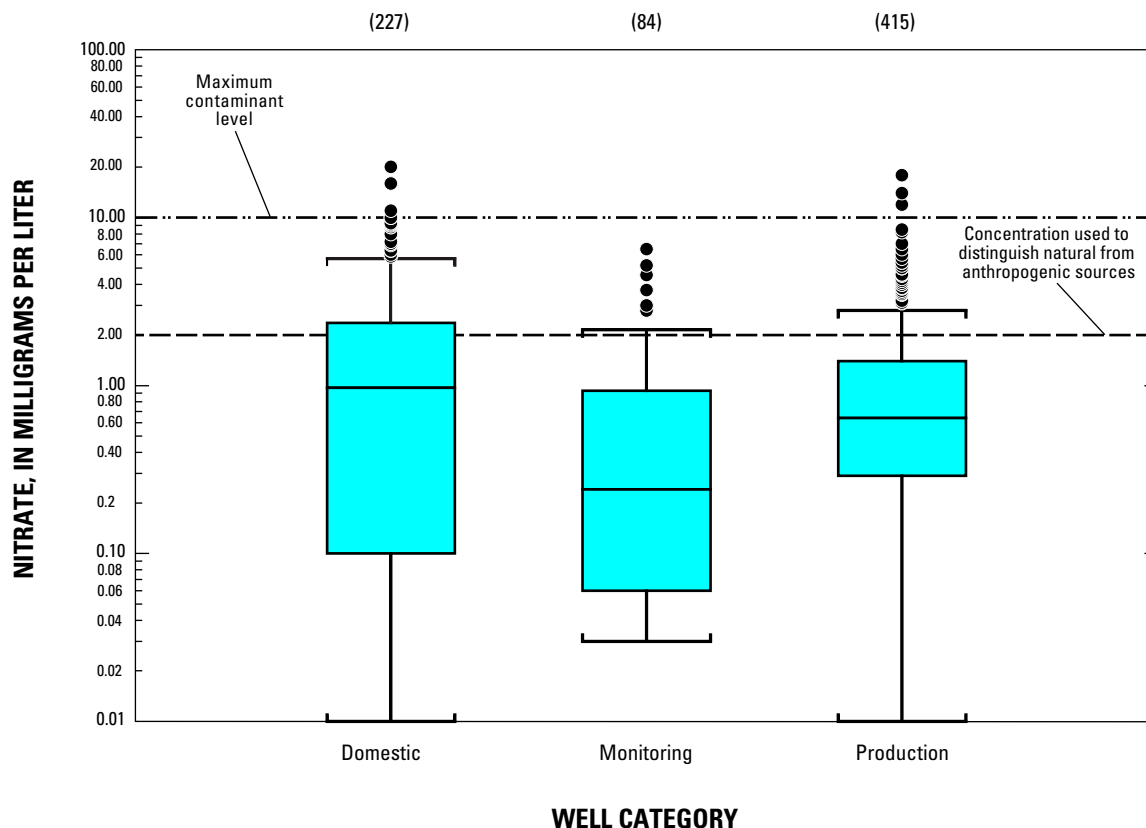
**Table 6.** Dissolved-solids concentrations in unconsolidated sediment and ground-water discharge areas

[Abbreviations: mg/L, milligrams per liter]

Hydrologic setting	Area, in square miles (percent of total setting area)	Dissolved solids range, in mg/L	Percent of setting area within dissolved-solids range
Unconsolidated sediments	54,250 (100)	<500	72
		501 to 1,000	17
		1,001 to 3,000	8
		3,001 to 10,000	3
		>10,000	<1
		Percent of area with no data	2
Ground-water discharge areas	10,300 (100)	<500	36
		501 to 1,000	29
		1,001 to 3,000	23
		3,001 to 10,000	11
		>10,000	<1
		Percent of area with no data	<1
Unconsolidated sediments other than ground-water discharge areas			
Alluvial slope	32,030 (95)	<500	85
		501 to 1,000	11
		1,001 to 3,000	4
		3,001 to 10,000	<1
		>10,000	0
		Percent of area with no data	2
Fluvial deposits	830 (54)	<500	82
		501 to 1,000	14
		1,001 to 3,000	3
		3,001 to 10,000	1
		>10,000	0
		Percent of area with no data	14
Valley floor	9,690 (69)	<500	71
		501 to 1,000	19
		1,001 to 3,000	8
		3,001 to 10,000	2
		>10,000	<1
		Percent of area with no data	1
Playas	1,400 (28)	<500	43
		501 to 1,000	44
		1,001 to 3,000	10
		3,001 to 10,000	3
		>10,000	<1
		Percent of area with no data	<1



**Figure 8.** Dissolved-solids concentrations in ground water, playas, and ground-water discharge areas in Nevada.



**Figure 9.** Nitrate concentrations for domestic, monitoring, and production wells in undeveloped areas.

concentrations in low populated, undeveloped areas. It is also possible that the small-scale information compiled for this study does not accurately characterize the environment around the wells.

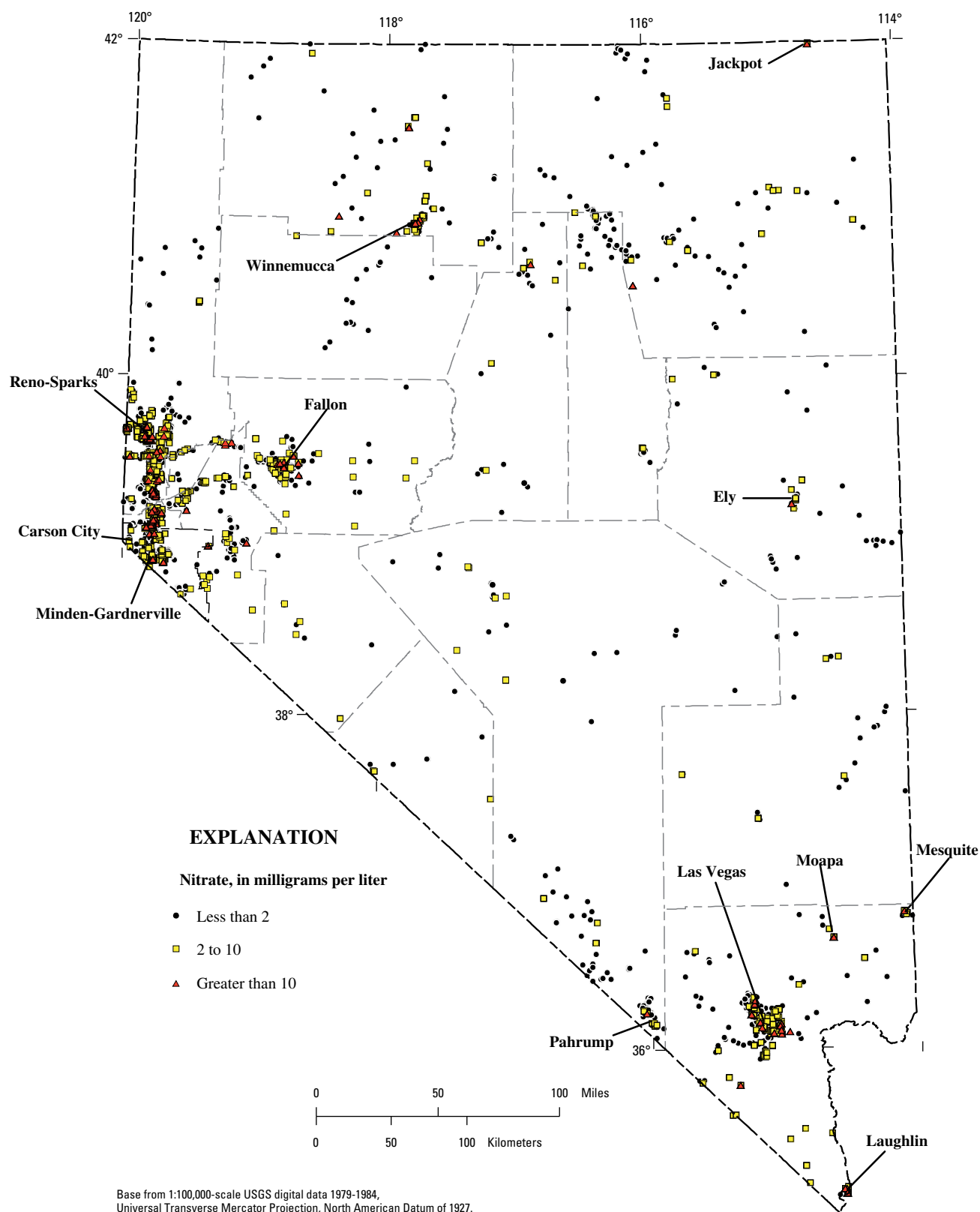
Many aquifer systems in undeveloped and developed areas throughout Nevada have median nitrate concentrations of <1 mg/L (Thomas and Hoffman 1988; Welch and others, 1997; Bevans and others, 1998; Lico, 1998). High nitrate concentrations reported by previous studies are associated with anthropogenic sources and not natural sources, except in the Las Vegas area (Patt and Hess, 1976). Based on previous studies and concentrations in undeveloped areas, a nitrate concentration of 2 mg/L was used to distinguish natural from anthropogenic sources. Nitrate concentrations >2 mg/L have a high probability of being from an anthropogenic source, but exceeding >2 mg/L is not conclusive evidence of an anthropogenic source.

## Relations Between Nitrate and Explanatory Variables

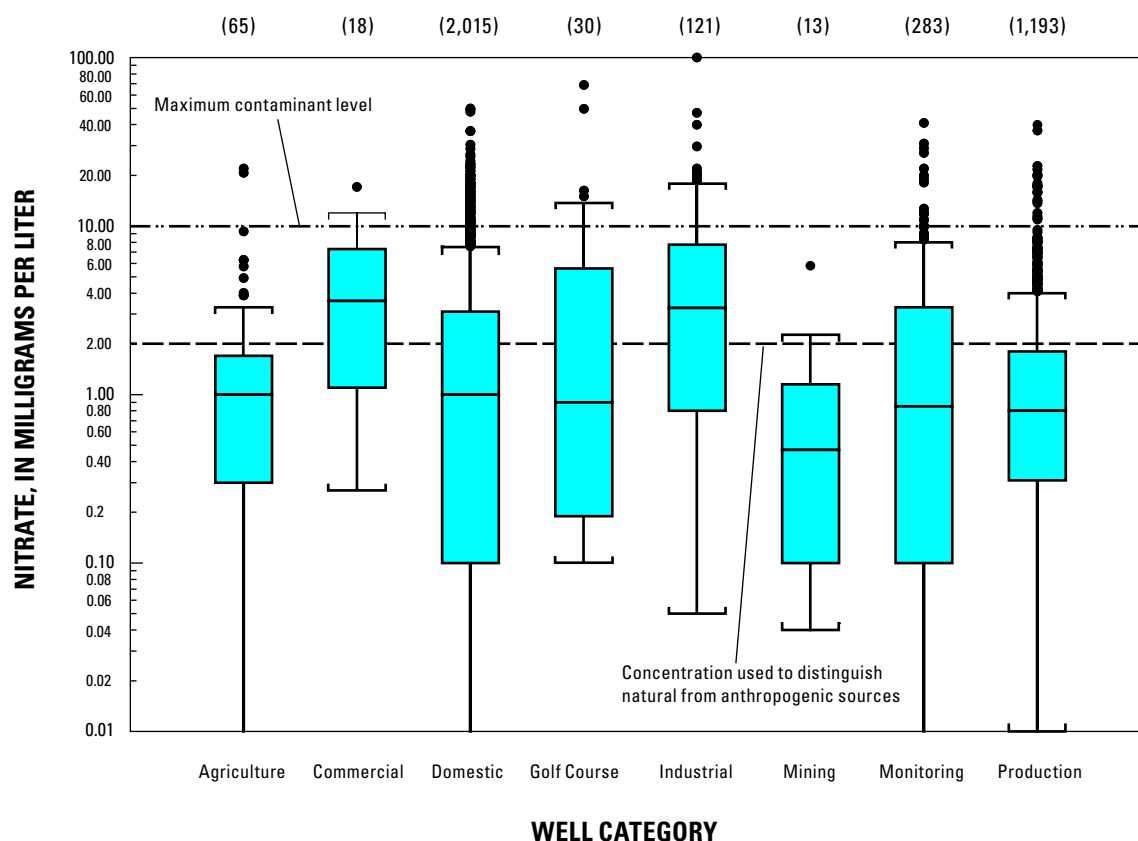
Nitrate was detected in almost all wells. In the Fallon area, nitrate was infrequently detected due to reducing conditions that result in denitrification (Welch and others, 1997).

Nitrate concentrations, where detected, ranged from 0.01 to 100 mg/L with a median and mean of 1.0 and 2.5 mg/L, respectively. About 5 percent of the 3,794 wells (table 4) had a nitrate concentration that exceeded the MCL of 10 mg/L. Almost all wells that exceeded the MCL are in cities and small towns such as Pahrump, Winnemucca, Ely, and Jackpot (fig. 10), indicating sources of nitrate in urban areas have degraded ground-water quality. Except for commercial and industrial facilities, median nitrate concentrations for all types of sites were  $\leq 1$  mg/L (fig. 11). Commercial and industrial facilities had median nitrate concentrations of about 3 mg/L. All well categories except mining had one or more wells with a nitrate concentration greater than the MCL. Most exceedences of the MCL were associated with domestic, monitoring, and production wells, golf courses, and industrial sites.

Rank correlations were calculated for wells with >2 mg/L nitrate, depth to water, and well depth data. The rank correlation between nitrate concentrations and depth to water was -0.26 and -0.30 between nitrate and well depth (fig. 12A and B). Nitrate concentrations >10 mg/L generally occurred in wells <200 ft deep. Although weak, the negative correlations and high nitrate concentrations in shallow to intermediate depth wells suggest that nitrate is from sources near land surface.



**Figure 10.** Concentrations of nitrate in ground water.



**Figure 11.** Nitrate concentrations versus well category.

Relations between nitrate, depth to water, and clay layering were investigated for a subset of wells in Las Vegas, Eagle, Carson Valleys, and the Truckee Meadows (table 7). Information on clay layering was obtained from drillers logs. Recent depth-to-water data were obtained from the Nevada Water Science Center database if available or from the well log. All rank correlations were weak, but the strongest correlations were in Las Vegas Valley. The inverse relations in Las Vegas are what would be expected for sources at land surface, where nitrate concentrations are high near the source and decrease with depth. Most development in Las Vegas Valley has been over the thick, extensive clay layer in the basin, which prevents vertical migration of contaminants and protects the deep aquifer that is used for public supply.

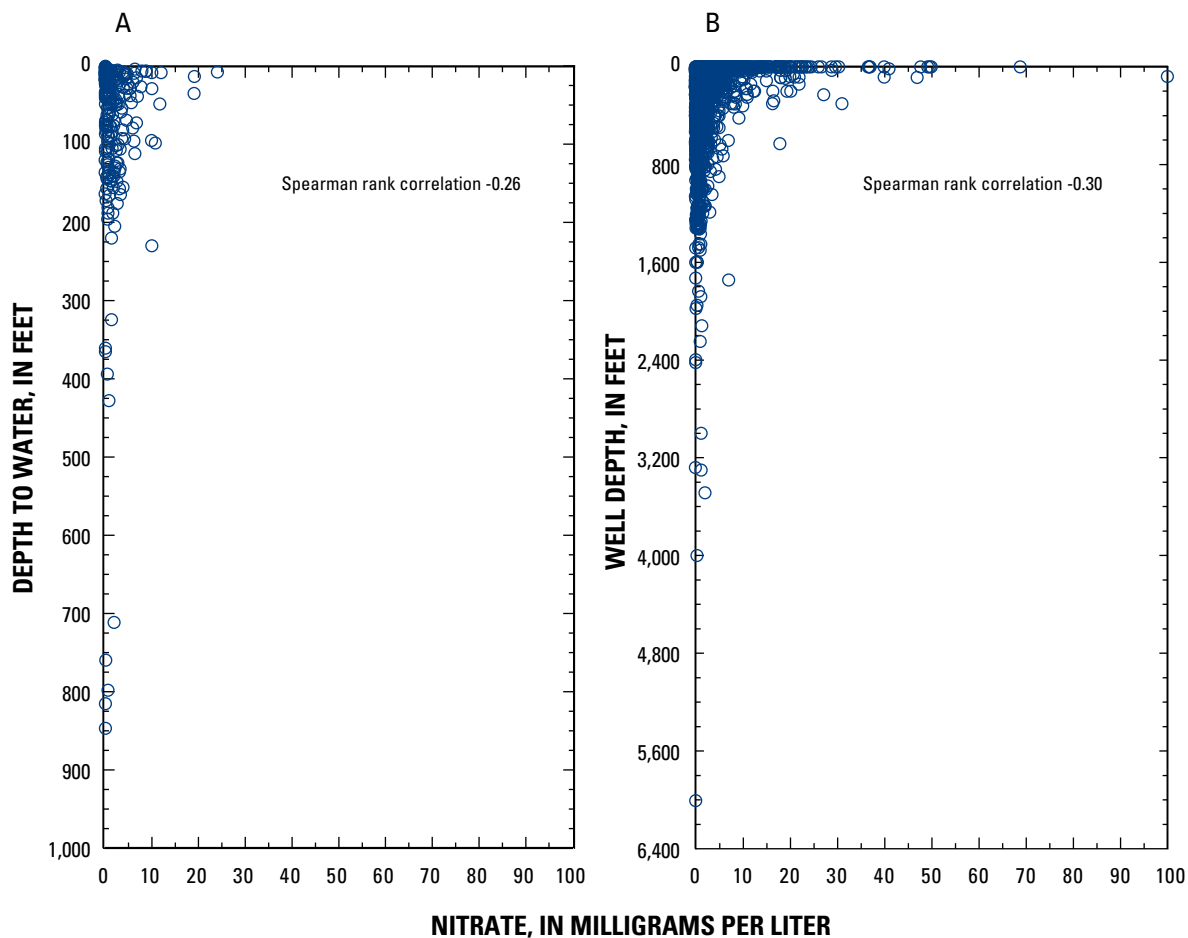
Nitrate concentrations increase with depth to water in Eagle Valley, which is opposite of what would be expected for sources near the well. This relation probably is due to residential development and use of septic waste-disposal systems on alluvial fans. Alluvial fans typically have unsaturated zones  $\geq 50$  ft thick (Lopes and others, 2006). Nitrate does not readily sorb to unsaturated sediments or degrade except in reducing environments (Canter, 1997). Although depth to water is high under alluvial fans, there is little to prevent infiltration of nitrate from anthropogenic sources. The effect of urbanization on nitrate concentrations is demonstrated for wells with different amounts of development (fig. 13). Wells were plotted on

1:24,000-scale maps that showed urban development and categorized as being in undeveloped areas, on the fringe of urban development, in fully developed areas, or production wells regardless of their location. Nitrate concentrations are lowest for wells in undeveloped areas, higher for wells on the fringe of urban development, and highest in fully developed areas. Production wells have nitrate concentrations similar to wells on the fringe of development, suggesting these wells could be capturing shallow ground water from urban areas.

The positive correlation between nitrate and clay layering in the Truckee Meadows also is opposite of what would be expected for nitrate migrating vertically from sources near the well and suggests that nitrate has migrated laterally from distant sources. Different relations could be due to the unique susceptibility and where development occurs in each basin. These relations demonstrate the importance of understanding physical and chemical variables that control contaminant transport through unconsolidated-sediment aquifer systems, especially populated basins where large amounts of chemicals are used.

## Synthetic Organic Compounds

Pesticides were measured in samples from 1,159 wells. The number of pesticides measured in each sample ranged from 3 to 78 with a median of 25 and a mean of 29. One to



**Figure 12.** Nitrate concentrations versus A, depth to water and B, well depth.

**Table 7.** Spearman rank correlations between nitrate, clay, and depth to water in selected areas

Hydrographic area	Thickness of clay layers above the water table				Depth to water
	Total <sup>1</sup>	Maximum <sup>2</sup>	Minimum <sup>3</sup>	Average <sup>4</sup>	
Las Vegas Valley	-0.25	-0.23	-0.18	-0.22	-0.39
Eagle Valley	-.14	-.15	-.11	-.15	.32
Carson Valley	-.11	-.08	-.12	-.11	.06
Truckee Meadows	.22	.23	.28	.26	-.01

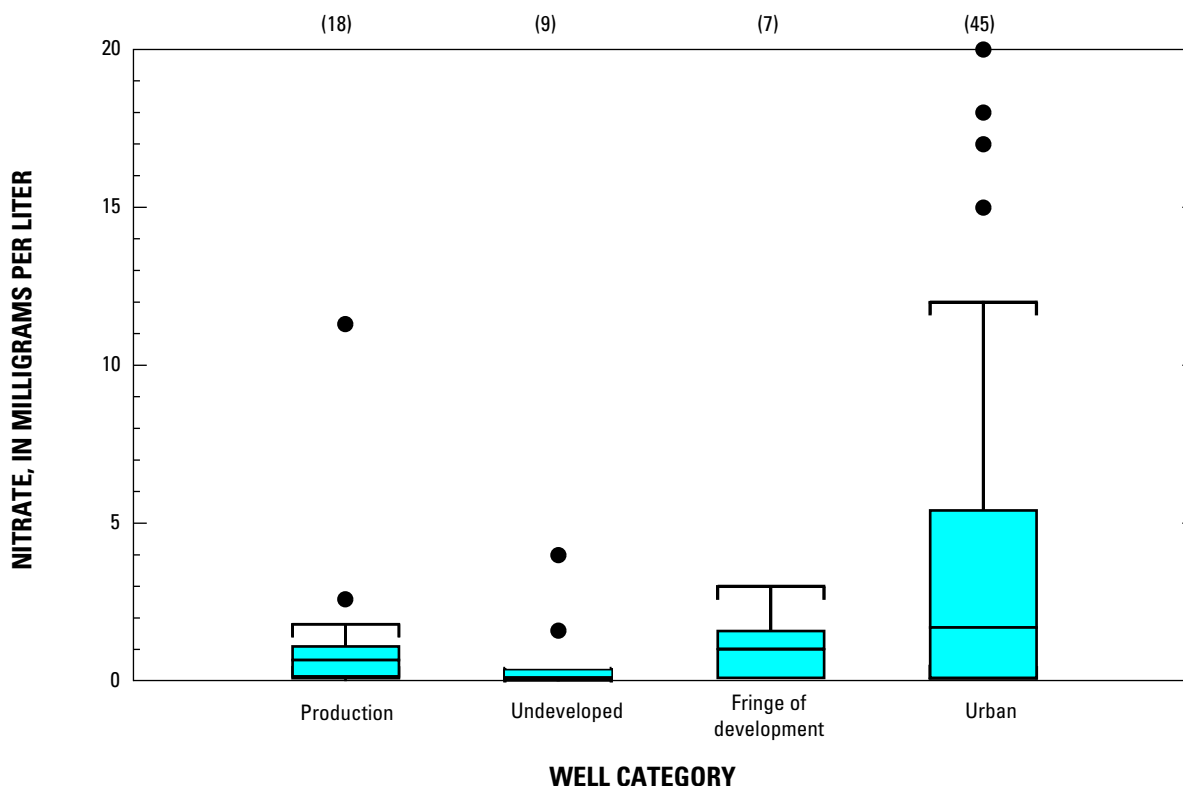
<sup>1</sup> Total thickness of clay layers identified in driller's log.

<sup>2</sup> Maximum thickness of a single clay layer identified in driller's log.

<sup>3</sup> Minimum thickness of a single clay layer identified in driller's log.

<sup>4</sup> Average thickness of clay layers identified in driller's log.





**Figure 13.** Nitrate concentrations versus well category in Eagle Valley.

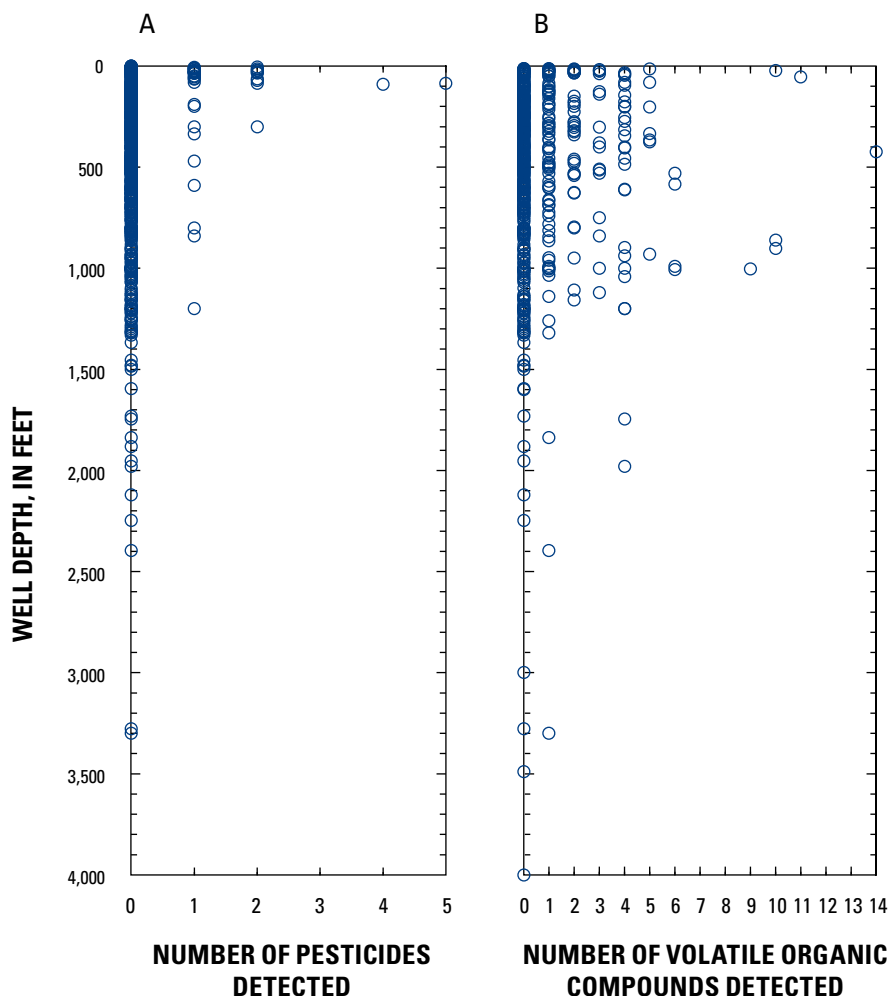
five pesticides were detected in 59 (5 percent) of the wells. Atrazine, the most frequently detected pesticide, was detected above the MCL in a monitoring well in Quinn River Valley. No other wells had pesticide concentrations that exceeded the MCL. The sum of detected concentrations ranged from 0.002 to 9.4  $\mu\text{g/L}$  and had a significant but weak rank correlation ( $r = 0.46$ ) with the number of pesticides detected. When high concentrations were detected, it typically was due to one or two pesticides. Most (47) wells with pesticides were in the Truckee Meadows area and Eagle, Carson, and Las Vegas Valleys, which are the most urbanized areas of the state. Seven wells with pesticides were in the Quinn River Valley, an agricultural basin in north-central Nevada. Most (48) wells with pesticides were monitoring wells, 10 were production wells, and one was a domestic well. For wells with depth information, most pesticides were detected in wells <100 ft deep (fig. 14A). One pesticide was detected in a well that is 1,200 ft deep.

VOCs were measured in samples from 1,106 wells. The number of VOCs measured in each sample ranged from 1 to 143 with a median of 54 and a mean of 50. One to 14 VOCs were detected in 232 (21 percent) of the wells. Chloroform, a by-product from disinfecting drinking water, was the most frequently detected VOC. VOCs were detected above the MCL in 16 production wells in Antelope Valley, Carson Valley, Diamond Valley, Pahrump, Truckee Meadows, Washoe Valley, and Willow Creek Valley. Six monitoring wells exceeded the

MCL in Las Vegas Valley and the Truckee Meadows. VOCs that exceeded the MCL included dichloromethane, tetrachloroethene, and trichloroethene. The sum of detected concentrations ranged from 0.0005 to 240  $\mu\text{g/L}$  and had a significant but fair rank correlation ( $r = 0.60$ ) with the number of VOCs detected. Most (121) wells with VOCs were in the Las Vegas Valley and the Truckee Meadows. Other wells with VOCs were in basins throughout Nevada. In contrast to pesticides, most (146) wells with detected VOCs were production wells. For wells with depth information, most VOCs were detected in wells <500 ft deep (fig. 14B). VOCs were detected in 22 wells >1,000 ft.

### Co-Occurrence of Nitrate and Synthetic Organic Compounds

Nitrate concentrations >2 mg/L were used in this study as an indicator of anthropogenic contamination. The co-occurrence of nitrate and SOC was evaluated to determine how well the occurrence of nitrate concentrations >2 mg/L represents anthropogenic contamination in general. Nitrate is one of the most common anthropogenic contaminants that degrades ground-water quality, is commonly measured, and is persistent except in reducing conditions. These characteristics make nitrate a better indicator of ground-water vulnerability than SOC.



**Figure 14.** Number of A, pesticides and B, volatile organic compounds detected versus well depth.

Nitrate and pesticides were measured in the same sample from 383 wells; pesticides were detected in 40 (10 percent) of the wells. Nitrate and VOCs were measured in the same sample from 576 wells; VOCs were detected in 125 (22 percent) of the wells. The Wilcoxon rank-sum test indicated that wells with nitrate concentrations  $>2$  mg/L had significantly more detections of pesticides and VOCs than concentrations  $<2$  mg/L. Nitrate concentrations had significant but weak rank correlations with the number of pesticides detected ( $r = 0.23$ ) and the number of VOCs detected ( $r = 0.21$ ). There was no significant correlation between nitrate concentrations and the sum of pesticide or VOC concentrations. Concentrations of nitrate  $>2$  mg/L are more likely to occur with SOC than lower concentrations of nitrate. However, the weak correlations indicate that nitrate is a poor indicator of the concentration or number of SOCs present.

Pesticides and VOCs were measured in the same sample from 252 wells. Pesticides were detected in 36 (14 percent) of the wells, VOCs were detected in 87 (34 percent) of the wells, and both pesticides and VOCs were detected in 17

(6.7 percent) of the wells. There was no significant correlation between the number of pesticides and VOCs detected or between the sum of detected concentrations. Fifteen wells containing both pesticides and VOCs were monitoring wells  $<50$ -ft deep and two wells were production wells 800-ft and 840-ft deep.

Co-occurrence data suggest there is about a 50-percent chance that VOCs will be detected where pesticides have been detected in ground water. However, there is only a 20-percent chance that pesticides will be detected where VOCs have been detected. The different chances are likely due to the more common use of VOCs compared to pesticides and their physical and chemical properties. VOCs typically are more soluble and have a lower octanol-water partitioning coefficient than pesticides. The common use of VOCs would explain their common detection and their high mobility explains the occurrence of VOCs in deep wells. The relatively low mobility of pesticides explains why VOCs and pesticides mostly co-occur in shallow ground water.

# Aquifer Susceptibility

## Chemical Results

### Chlorofluorocarbons

CFCs were detected in all 133 wells sampled for this study and in all 112 wells sampled by previous studies. Concentrations indicated ground water was contaminated with one or more CFCs at 58 (24 percent) of the wells. CFCs were sampled in most types of consolidated rock and unconsolidated-sediment aquifer systems in Nevada. The widespread occurrence of CFCs, regardless of an atmospheric or land-based source, indicates that all aquifer systems sampled by this study and previous studies are susceptible to contamination. These results are consistent with samples collected from 413 production and domestic wells throughout the United States between 1997 and 2000 (Dunkle-Shapiro and others, 2004). Three or more halogenated VOCs were detected in 100 percent of the samples at the parts-per-quadrillion level, which suggests an atmospheric source. The presence of VOCs in all samples indicates that recharge to many aquifer systems throughout the United States have been affected by anthropogenic activity during the past 60 years.

VOCs, pesticides, or CFCs were detected in 42 wells >1,000 ft deep, indicating contaminants are quickly entering unconsolidated-sediment and consolidated-rock aquifer systems in Nevada. Recharge through fractured consolidated rock, continual pumping for production and mine dewatering, poorly constructed wells, and preferential flow along a well's gravel pack could explain the occurrence of CFCs in all samples and SOC and CFCs in deep wells. Also, recharge through unconsolidated sediments could be more widespread than previously thought. Previous studies assumed that recharge is negligible for about 33 percent of Nevada with <8 in/yr of precipitation (Maurer and others, 2004). Ephemeral channels, observed using digital ortho-photo quads, are common around wells sampled for CFCs. These channels are smaller than the fluvial channels mapped by Maurer and others (2004). Appreciable amounts of recharge could be occurring through small, ephemeral channels at low altitudes where it could be years between flow events, which would be consistent with recharge studies in the southwestern United States. No appreciable recharge was found beneath interfluvial areas with native vegetation (Stonestrom and others, 2004; Walvoord and Scanlon, 2004). However, chloride and nitrate profiles beneath the Amargosa River channel were consistent with active recharge (Stonestrom and others, 2004).

Apparent recharge dates had significant rank correlations with the water level above the top of the screen ( $r = -0.45$ ), well depth ( $r = -0.28$ ), and nitrate concentration ( $r = 0.28$ ; figs. 15A and B and 16). The inverse correlations between apparent recharge dates and well depth and water level above the screen

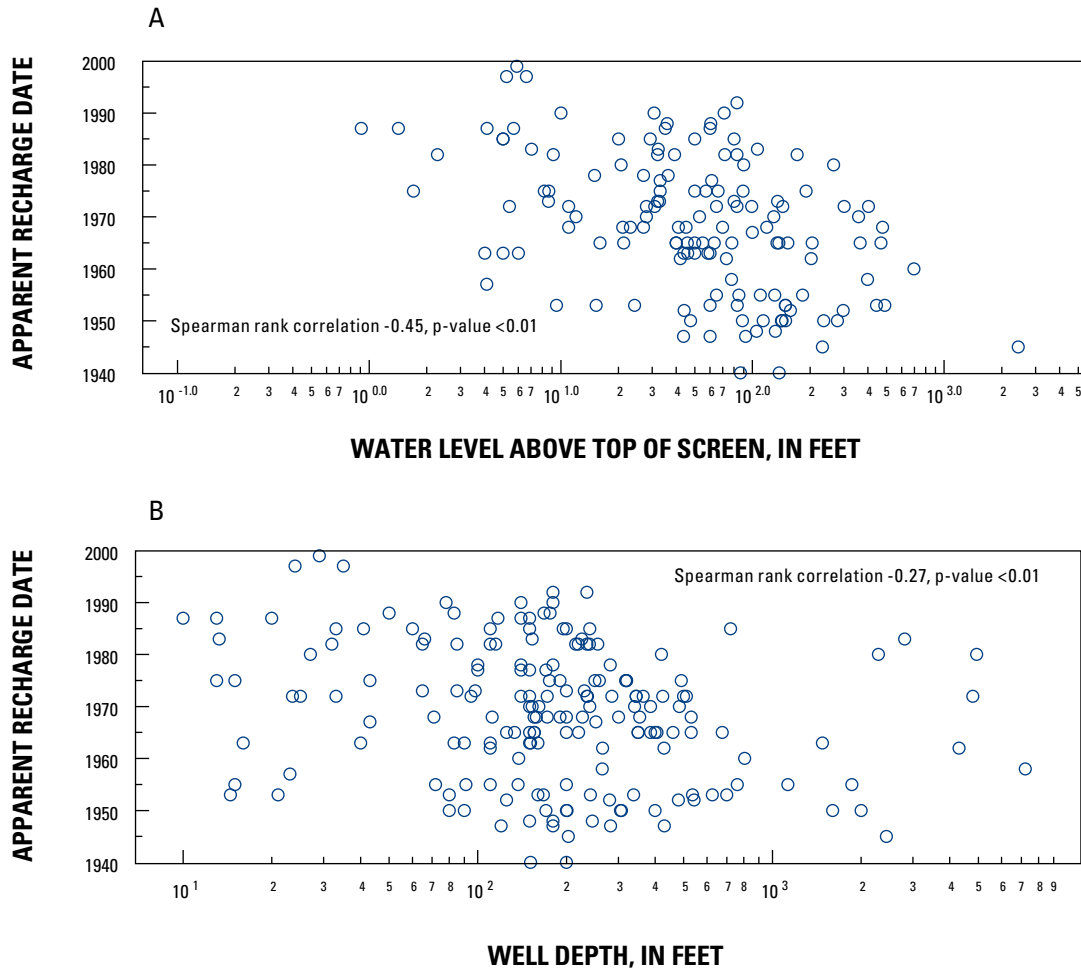
are consistent with older water occurring at greater depths in aquifer systems. The positive correlation between apparent recharge dates and nitrate concentrations is consistent with recent development increasing nitrate concentrations in ground water. Currently, nitrate concentrations are highest in shallow ground water (fig. 12). With time, nitrate and SOC could migrate to and degrade deep aquifer systems that are used for public supply. Correlations were not significant between apparent recharge dates and length of screen, depth to water, and thickness of clay above the water table. The lack of correlations with depth to water and clay layering suggests that the unsaturated zone has little effect on recharge and contaminant movement, which is counter-intuitive. The lack of correlations could be due to recharge occurring at a distance and moving laterally to the well. Also, clay layers around the well may be discontinuous and have little effect on the movement of water and CFCs through the unsaturated zone.

The Kruskal-Wallis rank test indicated a significant difference in apparent recharge dates among aquifers with different lithology. Basaltic and granitic aquifer systems appear to have younger ground water than other types of aquifers (fig. 17). This could be due to rapid movement of atmospheric air and water through fractures. Only two samples were collected from wells in Tertiary sediments, but this hydrogeologic unit appears to have older ground water than other hydrogeologic units. Older ground water in Tertiary sediments is possible because of their low horizontal hydraulic conductivity (fig. 5) and lack of fractures. Other aquifer lithologies have a wide range in apparent ages, which could be due to depth and location of wells in the ground-water-flow system.

The Kruskal-Wallis rank test did not indicate apparent recharge dates were significantly different among HLRs, but did indicate significant differences among different hydrologic settings (fig. 18). Apparent recharge dates appear to be youngest in valley floors and fluvial channels compared to other hydrologic settings, which supports the idea of appreciable recharge occurring through stream channels at low altitudes. Bedrock exposed in mountain ranges, bedrock buried under alluvial sediment, and alluvial fans have similar, wide ranges in apparent recharge dates. Unconsolidated sediments at the toe of alluvial fans appear to have two groups of apparent recharge dates. The variability could be due to the few samples that were collected or to two sources of recharge and their flow paths at the toe of alluvial fans. Infiltration on alluvial fans recharges shallow ground water and has a short flow path compared to subsurface discharge from mountain blocks into deeper unconsolidated sediments. Recharge from these two sources and convergence of flow paths near the toe of alluvial fans could result in the wide range in apparent recharge dates.

### Dissolved Gases

All but 2 of 119 samples had measurable amounts of excess air, which ranged from about 0.1 to 31 cc/L with a median and mean of about 2 and 3 cc/L, respectively. Varying recharge altitude had little effect on estimates of excess air.



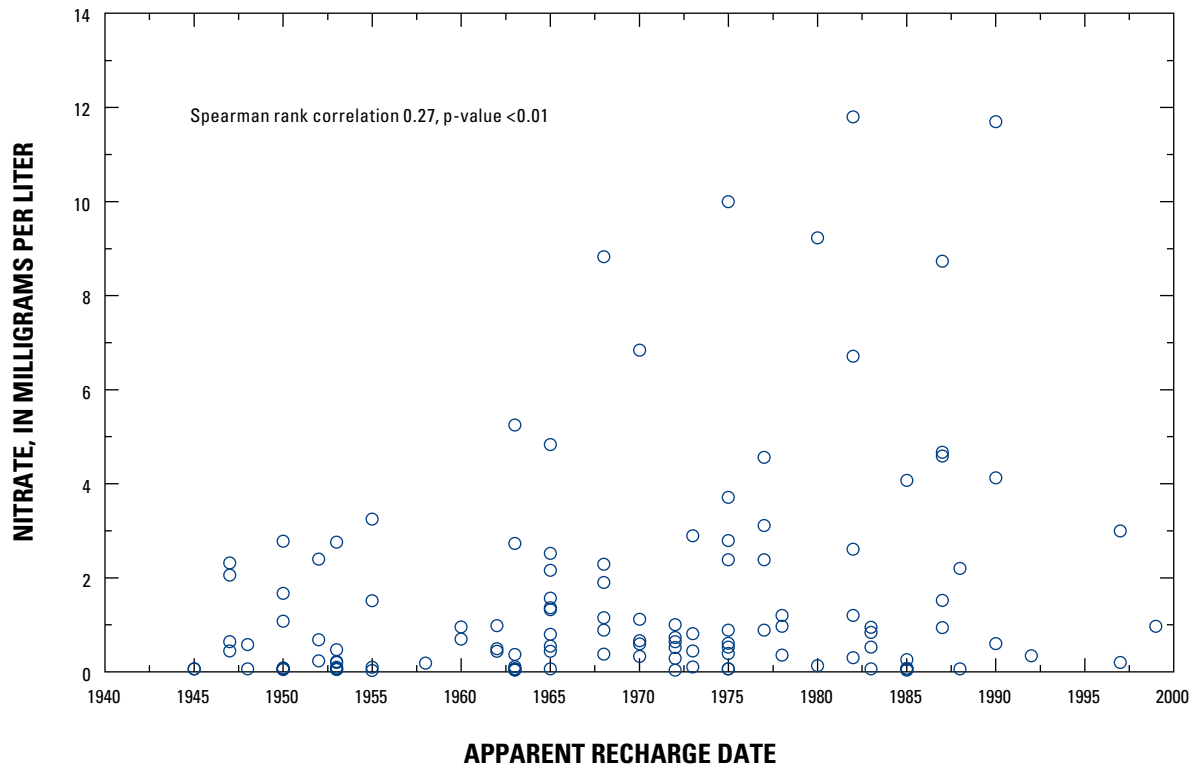
**Figure 15.** Apparent recharge date versus A, water level above the top of the screen and B, well depth.

The Wilcoxon rank-sum test indicated that wells in consolidated rock had significantly more excess air than wells in unconsolidated sediments. This could be due to movement of air through fractured consolidated rock. Excess air concentrations had a significant but weak (-0.38) rank correlation with estimated recharge temperature. The inverse correlation makes physical sense because the solubility of gases decreases with increasing temperature.

The Pearson correlation between dissolved nitrogen and argon was significant and strong (0.96). The atmosphere is the primary source of argon in ground water (Stute and Schlosser, 2000). The strong, linear relation with nitrogen indicates that dissolved nitrogen also is from the atmosphere. Nitrogen in excess of equilibrium with the atmosphere is possible where nitrate denitrifies and produces nitrogen gas. Excess nitrogen was measured in 7 of 119 samples, methane was measured in 9 samples, and 2 of the samples with methane also had excess nitrogen. The small percentage of samples with excess nitrogen and methane indicate that denitrifying and methane producing conditions are uncommon in Nevada's aquifer systems.

Dissolved-gas data and recharge altitudes were used to estimate recharge temperatures, which should be similar to the current climate because CFC data indicate that most aquifer systems have been recently recharged. Topographic maps were used to estimate a range in recharge altitude for each well. The minimum altitude was about the altitude of the well. The maximum altitude was about the highest altitude on alluvial fans up-slope from wells in unconsolidated sediment and about the highest altitude up-slope from wells in exposed bedrock. The difference between maximum and minimum recharge altitudes ranged from 300 to 4,000 ft with a mean of about 2,000 ft.

Estimated recharge temperatures ranged from 32° to 84°F (0° to 29°C) and were fairly insensitive to the estimated recharge altitude. Recharge temperatures changed about 2.7°F (1.5°C) per 1,000-ft change in recharge altitude. Estimated recharge temperatures had significant Pearson correlations with altitude (-0.48) and latitude (-0.25). The inverse correlations make physical sense because mean annual air temperatures in Nevada decrease with increasing altitude and latitude.



**Figure 16.** Nitrate concentration versus apparent recharge date.

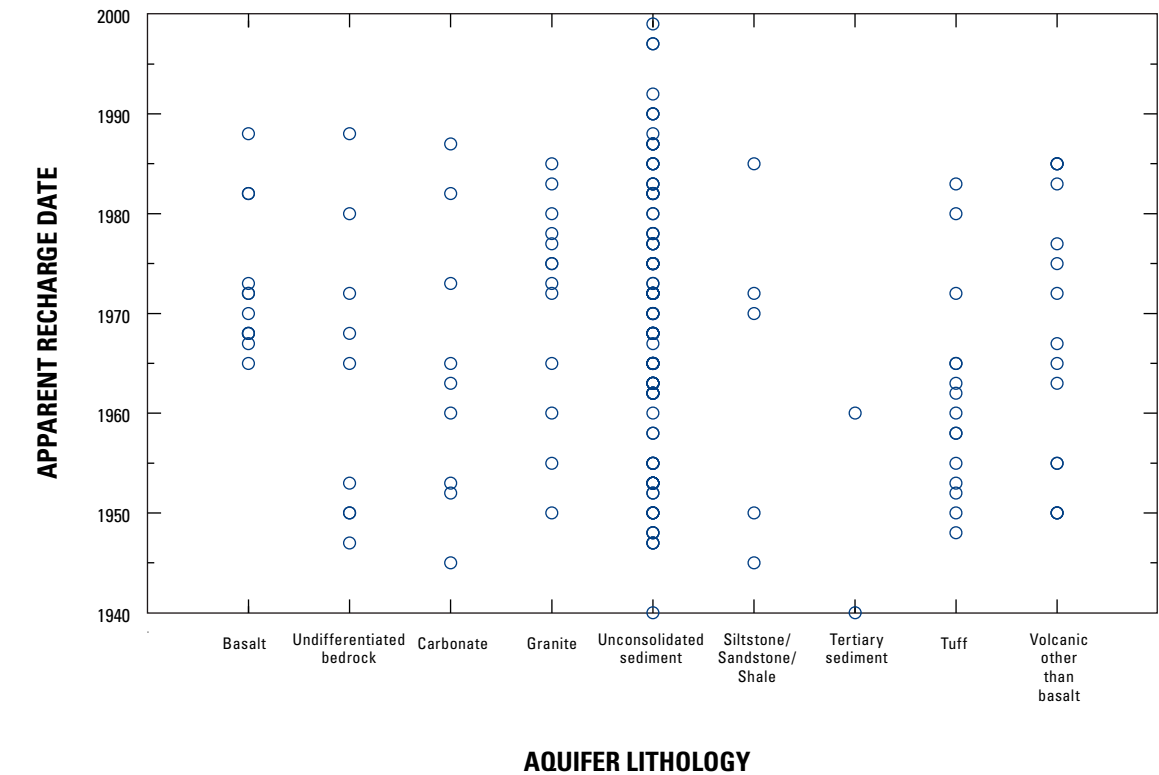
Recharge temperatures estimated from noble gases should be within 1.8° F (1° C) of the mean annual ground temperature, except where the water table is >100 ft below land surface and the geothermal gradient could affect subsurface temperatures (Stute and Schlosser, 2000). Mean annual ground temperatures typically are 1.8±1.8° F (1±1° C) warmer than air temperatures for the conterminous United States (Stute and Schlosser, 2000). However, larger temperature differences have been reported for deserts and snow-covered regions such as in Nevada. Data are not available to estimate mean annual ground temperature, so estimated recharge temperatures were compared to mean annual air temperatures estimated for average recharge altitudes. Mean annual air temperature ( $T_{ave}$ , in °F) was estimated using a regression equation of latitude (in DDMM) and altitude (in feet) developed using data from 126 weather stations throughout Nevada:

$$T_{ave} = 139.5 - 0.0186(latitude) - 0.0033(altitude) \quad (9)$$

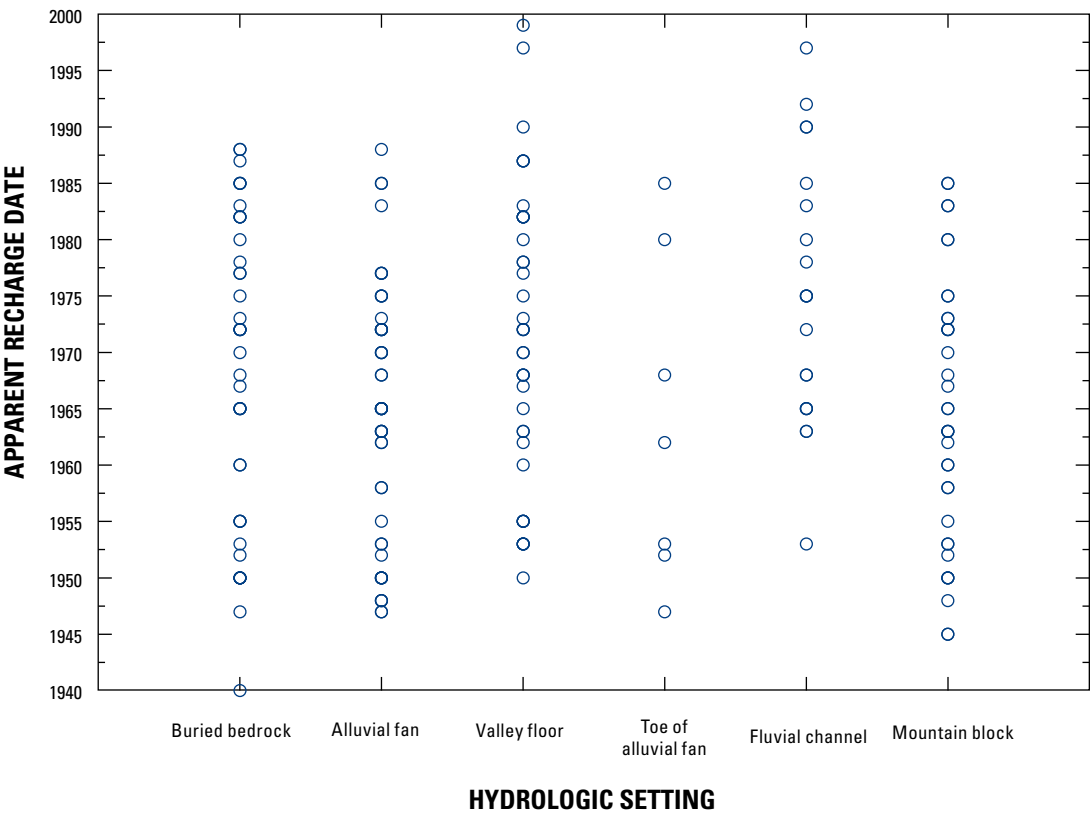
The regression equation has an R-square of 0.94, and a standard error of 1.7 °F, (3.5 percent). The estimated recharge temperatures should be within ±9° F (±5° C) of the mean annual air temperature. This assumes errors of 5.4° F (3° C) due to uncertainty in the recharge altitude and 3.6° F (2° C)

due to uncertainty in using air temperature to estimate ground temperature.

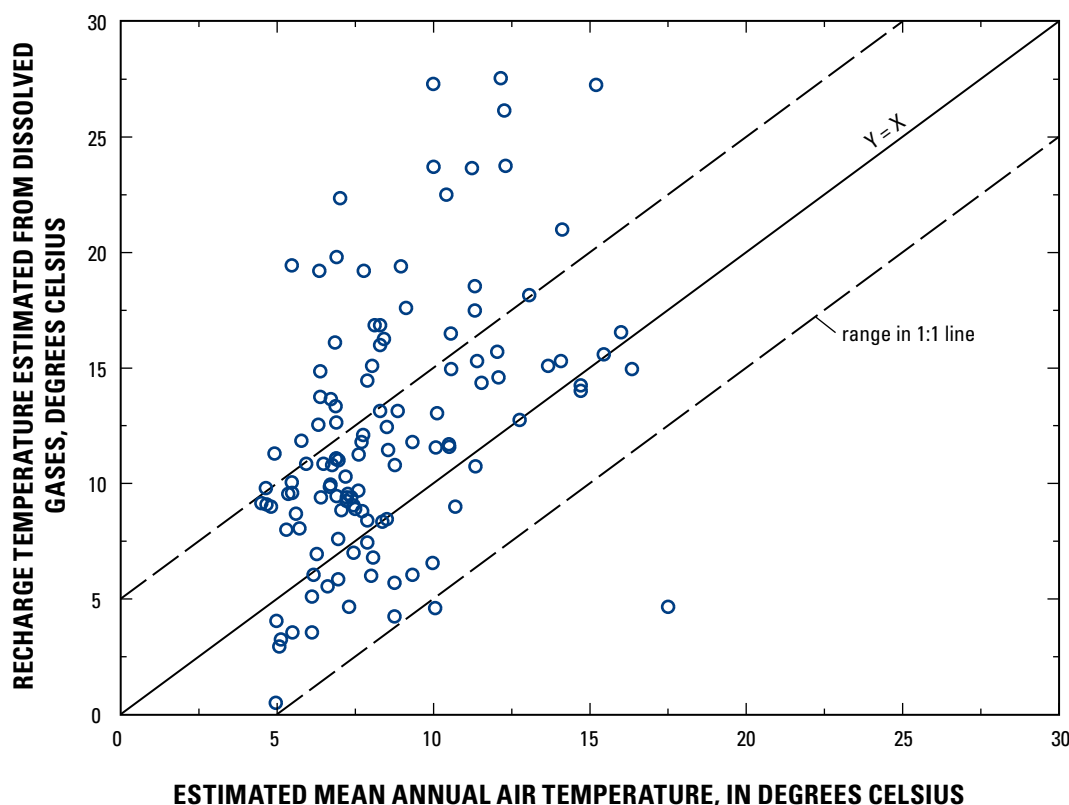
About 70 percent of the estimated recharge temperatures are within ±9° F (±5° C) of the estimated mean annual air temperature (fig. 19), which indicates that most recharge, occurred during the current climatic regime. All but two estimates that are not within ±9° F have estimated recharge temperatures that are warmer than estimated annual air temperature. Most of these wells are north of 37° latitude and between 4,000 and 6,000 ft in altitude. The rank correlation between the difference in estimated recharge and air temperatures was significant but weakly (-0.32) correlated with depth to water, suggesting the geothermal gradient could affect recharge temperatures. Warmer recharge temperatures also could be due to recharge occurring in a desert environment where mean annual ground temperatures could be >1.8° F of mean annual air temperatures. Only two wells had estimated recharge temperatures that were less than the mean annual air temperatures. Colder than expected water could indicate Pleistocene-age water has mixed with the samples. However, both of these samples were from shallow (<20 ft) monitoring wells along the Amargosa and Carson Rivers. It is unlikely that Pleistocene-age water is present along these rivers.



**Figure 17.** Apparent recharge dates versus aquifer type.



**Figure 18.** Apparent recharge dates versus hydrologic setting.



**Figure 19.** Recharge temperature estimated from dissolved gases versus estimated mean annual air temperature.

## Stable Isotopes of Hydrogen and Oxygen

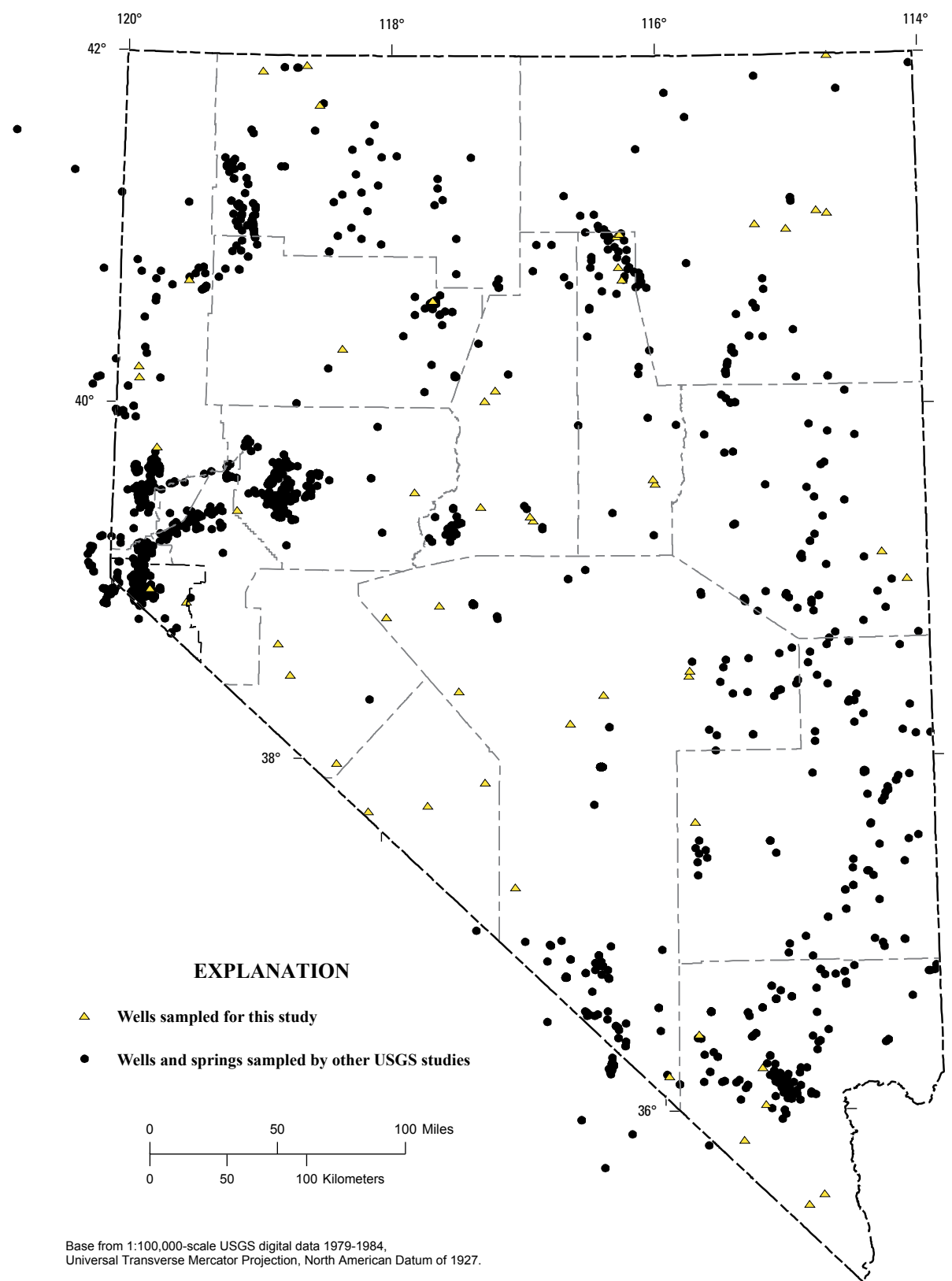
Stable isotopes of water have been measured in samples from 1,334 wells and springs throughout Nevada and along its border in adjacent states (fig. 20). Of the 53 samples analyzed for this study, five samples from northern Nevada had  $\delta D$  values between -130 and -137.17 per mil. These values are about 5 to 15 permil more negative than modern-day precipitation and suggest ground water could be a mixture of Pleistocene-age and recent recharge because CFCs were detected in samples from these wells (Smith and others, 2002). Two of the wells are in unconsolidated sediments, one well is in siltstone, and two wells are in carbonate rocks.

Previous studies collected one sample that had a  $\delta D$  value of -164 ‰, 6 samples  $\delta D$  values -140 and -150 ‰ and 81 samples had  $\delta D$  values between -130 and -140 ‰. About 40 percent of these samples were from springs with  $\delta D$  values between -130 and -145 ‰. Spring discharge could be from regional aquifers that have Pleistocene-age recharge, a mixture of Pleistocene-age and Holocene-age ground water, or modern-day precipitation has more negative  $\delta D$  values than indicated by iso-deuterium contours (Smith and others, 2002). All other ground-water samples had isotopic compositions similar to modern-day precipitation, indicating little Pleistocene-age water is present in the upper 1,000 ft of most aquifer systems where production wells are installed. Little indication of Pleistocene-age ground water is consistent with CFC

and dissolved-gas data, which indicates that ground water is a mixture of recent water and water that recharged during the current climatic regime.

To independently check results based on chemical techniques, estimates were made to compare total recharge during the past 10,000 years and 55 years to storage in the upper 1,000 ft of unconsolidated aquifer systems in each hydrographic area. Hydrographic areas where total recharge exceeds aquifer storage presumably have a mixture with mostly Holocene-age ground water in the upper part of the aquifer. The mean annual volume of recharge in each hydrographic area (Lopes and Evetts, 2004) was multiplied by 10,000 to estimate the total volume of recharge during the Holocene and by 55 to estimate recharge since 1950. These volumes were divided by the aquifer storage, which was estimated by multiplying the area of unconsolidated sediments by 1,000 ft, a porosity of 0.2, and a conversion factor. During much of the Holocene, Nevada was more than 30 percent drier than the current climate (Benson and others, 2002). Therefore, the mean annual volume recharge was multiplied by 0.5 to obtain a range in the number of hydrographic areas that presumably have mostly Holocene-age ground water.

Estimates were made for 202 of the 232 hydrographic areas due to the lack of recharge estimates or absence of unconsolidated sediment for some hydrographic areas. Estimates using current recharge rates suggest at least 62 percent (144) of all hydrographic areas have mostly Holocene-age



**Figure 20.** Locations of wells and springs where isotopes have been sampled.



ground water in the upper 1,000 ft of the aquifer. Using half the current recharge rates, at least 52 percent (122) of all hydrographic areas have mostly Holocene-age ground water. Although rough, these estimates are consistent with results based on chemical techniques that indicate little Pleistocene-age water is present in the upper part of most aquifer systems in Nevada. Total recharge since 1950 has not exceeded aquifer storage in the upper 1,000 ft of any hydrographic area, which contradicts CFC data.

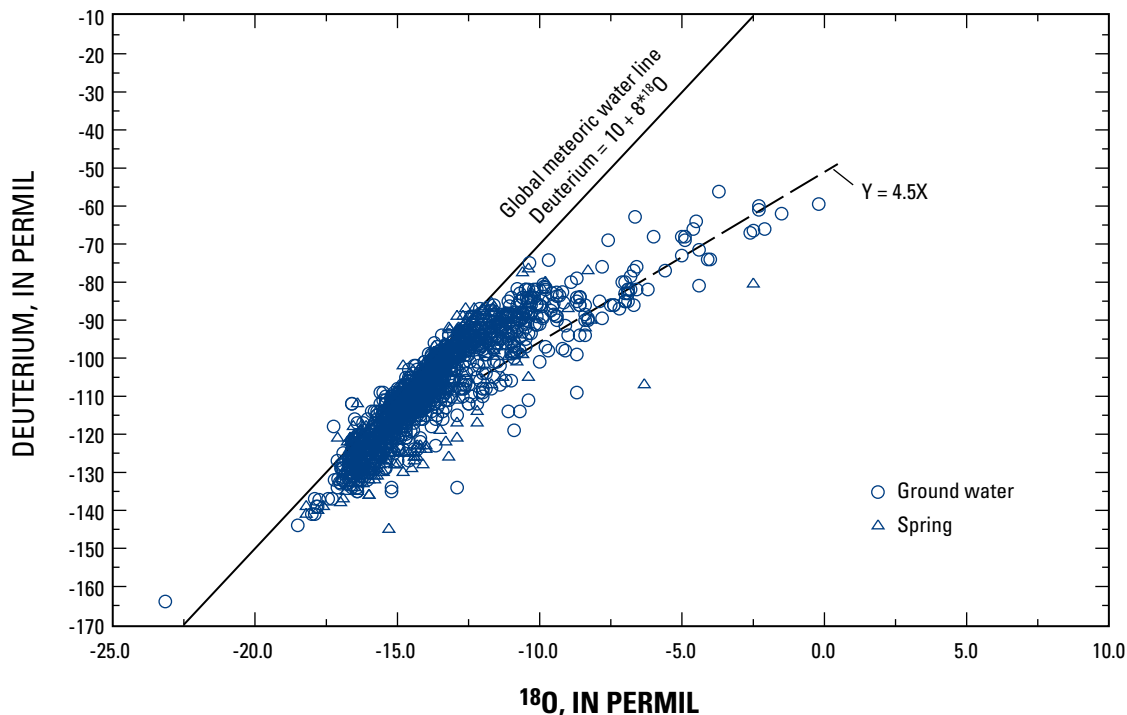
In addition to being an indicator of Pleistocene-age ground water, isotopes can indicate processes that affect recharge, such as evaporation.  $\delta D$  and  $\delta^{18}O$  values in ground water typically plot parallel to the Global Meteoric Water Line (GMWL; Craig, 1961). The intercept of the line can vary from the global average of 10, primarily depending on latitude. Most  $\delta D$  and  $\delta^{18}O$  data from Nevada are spread around the GMWL (fig. 21), which mainly is due to plotting all data which have a wide range in latitude.  $\delta D$  values become more negative with increasing latitude, altitude, and well depth (fig. 22). More negative values with increasing latitude and altitude likely are due to colder precipitation that is the source of recharge. More negative values with increasing depth could be due to partial mixing with Pleistocene-age water. There was no significant correlation between  $\delta D$  and longitude.

During intense evaporation, lighter isotopes preferentially fractionate into the vapor phase. Evaporation produces residual water that is isotopically heavier than the source water and has  $\delta D$  and  $\delta^{18}O$  values with a slope between 3 and 6 (Coplen and others, 2000). As water evaporates and values becomes more

positive along a flow path,  $\delta D$  and  $\delta^{18}O$  data plot along a line with an average slope of about 4.5. The intersection of the evaporation line with the GMWL indicates the isotopic composition of the source water. Evaporation has affected recharge to springs and ground-water in some parts of Nevada (fig. 21). Most of the samples that plot along the evaporation line were collected in the Carson Sink and Amargosa Desert, which have high evaporation rates. The isotopic composition in the Amargosa Desert could be due to recharge along ephemeral channels where a significant percentage of the streamflow may evaporate before it infiltrates. The isotopic composition in the Carson Sink likely is due to evaporation of shallow ground water in this area.

## Logistic Regression

A nitrate concentration of 2 mg/L was first used as the threshold to convert nitrate concentrations into binary data. As a preliminary analysis, Pearson correlations were calculated between the binary data and explanatory variables for the three buffer sizes around the well (table 8). All correlations were extremely weak ( $\leq 0.16$ ). Although more variables were significant using a 1,500-m buffer, buffer size had no discernable effect on the strength of the correlations. Increasing the threshold concentration to 3, 4, and 5 mg/L did not result in stronger correlations. Therefore, logistic regression was done using a threshold nitrate concentration of 2 mg/L.



**Figure 21.** Deuterium versus  $^{18}O$  measured in ground water and springs in Nevada.

**Table 8.** Pearson correlations between binary nitrate data using a background concentration of 2 milligrams per liter and explanatory variables. Only statistically significant correlations ( $p < 0.05$ ) are shown

[Symbols: —, not significant]

Explanatory variable	Pearson correlation coefficient		
	500 meter buffer	1,000 meter buffer	1,500 meter buffer
Precipitation	—	0.08	—
Slope <3 percent	—	-0.07	—
Slope 3 to 25 percent	—	0.08	0.07
Slope >25 percent	-0.05	—	-0.08
Fault length	0.05	—	—
Well density	0.14	0.14	0.10
Soil drainage	-0.10	-0.10	-0.11
Organic material	—	—	-0.04
Urban 1990	0.05	—	—
Agriculture 1990	—	—	-0.05
Agriculture 2000	—	—	-0.05
Andesite	-0.06	—	-0.05
Breccia and tuff	—	-0.06	-0.05
Carbonates	—	-0.07	-0.05
Clastics	-0.05	—	-0.06
Intrusives	—	0.11	0.07
Alluvial slope	0.16	0.12	0.15
Fluvial deposits	-0.05	—	-0.05
Playa	-0.06	-0.08	-0.08
Tertiary sediments	-0.07	-0.06	-0.05

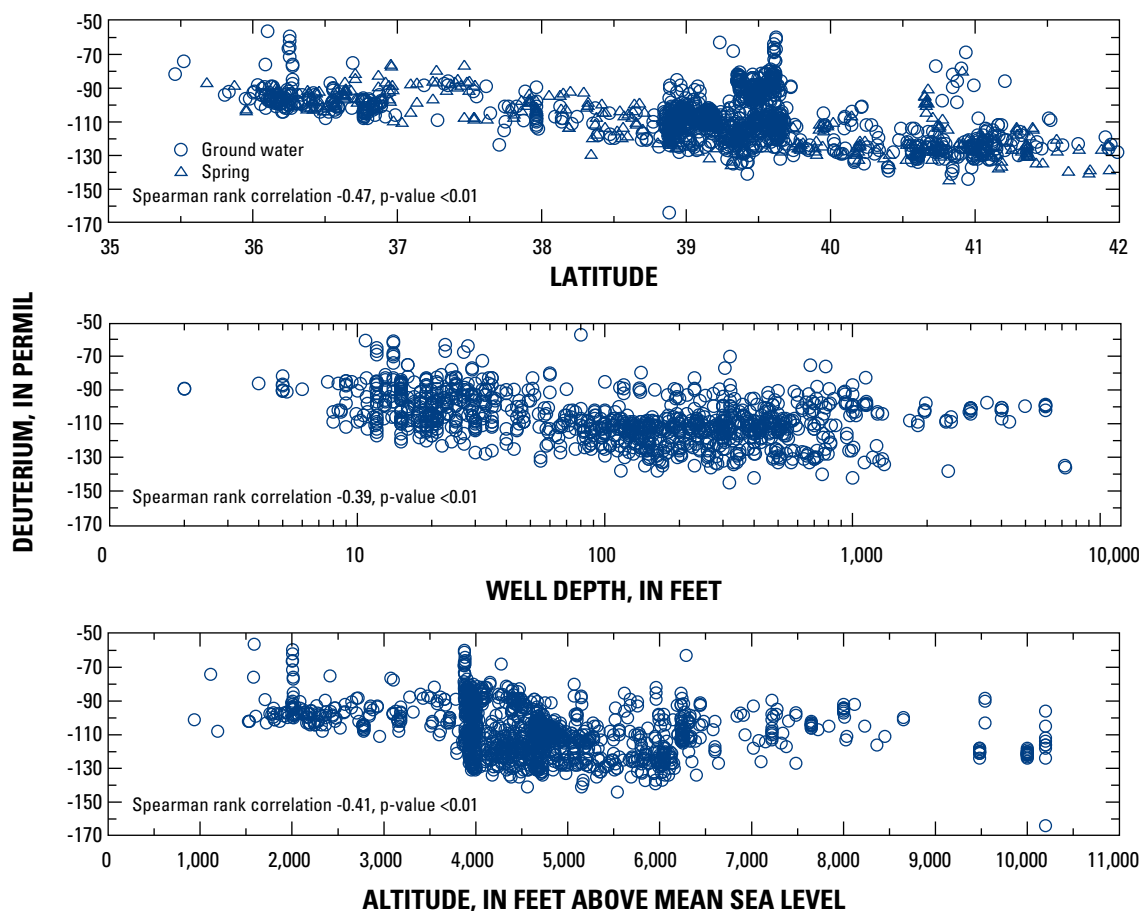
The most consistently significant and strongest correlations for the three buffer sizes were for alluvial slope, well density, and soil drainage (table 8). The positive correlation with alluvial slope could be due to development encroaching on alluvial fans. The positive correlation with well density could be due to septic tanks because houses that have a domestic well typically use septic tanks rather than sanitary sewers to dispose of wastewater. Therefore, the location of domestic wells, which are about 55 percent of wells in the Nevada well log database, could be a surrogate for the location of septic tanks. Soil drainage is a categorical variable that ranges from 1 for excessively drained soil to 7 for very poorly drained soil. Thus, the inverse correlation between binary nitrate data and soil drainage makes physical sense; high nitrate concentrations are associated with well-drained soils.

About 70 percent of the nitrate concentrations were <2 mg/L and 30 percent were >2 mg/L. Because there are a majority of non-events, classification algorithms that are designed to minimize the misclassification rate will be biased towards classifying observations as non-events. Therefore, stratified random sampling was done to obtain a data subset with equal number of events and non-events. Stepwise logistic regression then was done on the randomly selected data for the

three buffer sizes. The percent of events and non-events that were correctly predicted was used to determine how well the regression performed.

Randomly predicting a binary result should result in being correct about 50 percent of the time. Logistic regression correctly predicted high nitrate concentrations about 60 percent of the time for the three buffer sizes. Explanatory variables that had significant regression coefficients included slopes >25 percent, well density, soil drainage, and alluvial slope. Logistic regression could have been used to develop a model to predict high nitrate concentrations. However, the model would be little better than random prediction. Thus, there was no reason to develop such a model.

The poor performance of logistic regression could be due to inaccurate well locations, ancillary data that does not accurately characterize the environment around the wells, or both. For example, high nitrate concentrations in ground water near Laughlin, Nevada, likely were due to contamination from nearby mobile homes. However, land use and population density indicated that the area was undeveloped. More accurate information associated with water-quality data could improve the performance of logistic regression.



**Figure 22.** Deuterium in ground water and springs versus A, latitude; B, well depth; and C, altitude.

## Summary

In 1999, a new rule was introduced through the Underground Injection Control Program to protect ground water in areas other than source-water protection areas. OSGWAs are areas that are not currently but could eventually be used as a source of drinking water. The USGS, in cooperation with NDEP, began a project to compile information on variables that could affect aquifer susceptibility and vulnerability to contamination and to estimate the potential for ground-water degradation from anthropogenic contamination. This report presents an evaluation of the quality of Nevada's aquifer systems and their susceptibility to anthropogenic contamination.

Many variables affect the hydrologic and geochemical processes that control ground-water flow and contaminant transport. Understanding how water recharges and flows through an aquifer system is a necessary step in scientifically assessing susceptibility. This includes an understanding of the spatial distribution of precipitation and recharge, physical properties of aquifer systems such as hydraulic conductivity and effective porosity, and other variables that control the velocity and direction of ground-water flow. Assessing vulner-

ability requires an understanding of the locations of contaminant sources, how contaminants are released, the quantity of contaminants released, whether the release is continuous or discontinuous, and the physical and chemical properties of the contaminant and aquifer material that control its mobility and persistence in aquifer systems.

Mean-annual precipitation in Nevada ranges from about 4 in. at Laughlin to 53 in. at Mount Rose and increases with latitude and altitude. Winter storms and summer monsoons are the two seasonal weather patterns that bring precipitation to Nevada. Mean-annual precipitation is an average of dry and wet periods and has been fairly constant during the past 70 years. Dry periods last about 2 to 7 years and occur more often than wet periods, suggesting that recharge is episodic. Most recharge occurs on alluvial slopes from infiltration of precipitation and snowmelt runoff from mountain-blocks. Past studies concluded that relatively little recharge occurs on the valley floor or as subsurface discharge from consolidated rocks directly into unconsolidated sediments. However, recent studies indicate there could be appreciable amounts of recharge through ephemeral channels and from recharge of water used for agricultural and urban irrigation.

Soil permeability and soil organic matter are important variables affecting contaminant transport in the unsaturated zone. Average soil permeability in Nevada ranges from about 0.02 to 30 ft/d and is low to moderate in northern, northeastern, and eastern Nevada. Soil permeability is high to very high in populated areas of western, southwestern, and southern Nevada. Within a particular basin, soil permeability decreases down slope from the bedrock contact. Average soil organic matter in Nevada ranges from 0 to 6 percent by weight with a median of 0.4 percent. Soil organic matter in Nevada is about 50 percent less than the national average, indicating a relatively low capacity to sorb contaminants.

Vertical flow and contaminant transport through unsaturated and saturated materials may be restricted by thick clay layers and hardpan. Hardpan generally is found near exposures of carbonate rocks in eastern Nevada. The lower parts of alluvial slopes are likely to interfinger with clay layers underlying the valley floor. Clay layers formed along streams are discontinuous and thin compared to lake deposits. A map of Pleistocene lakes in Nevada could indicate areas where thick, continuous clay layers underlie valley floors.

Thick unsaturated zones increase the chance that contaminants will degrade or sorb to sediments before reaching ground water. Unsaturated thickness is commonly <50 ft beneath valley floors, 50 to 500 ft beneath alluvial fans, and is >500 ft in parts of Nevada such as the Humboldt River Basin and the Nevada Test Site.

Consolidated rocks and unconsolidated sediments are the two major hydrogeologic units in Nevada. Basalt and carbonate consolidated rocks and unconsolidated sediments except playas typically have high (>40 ft/d) horizontal hydraulic conductivities. Playas and consolidated rocks other than basalt and carbonates typically have low (<40 ft/d) horizontal hydraulic conductivities. Almost 90 percent of Nevada's population lives on hydrogeologic units with high horizontal hydraulic conductivity and highly permeable soils with low organic matter. Thus, most contaminants are used in areas where they could quickly move to aquifer systems that are used for public supply.

Horizontal gradients that drive lateral ground-water flow generally are greater beneath alluvial slopes than valley floors. Gradients beneath alluvial slopes range from 0.0003 to 0.2 and from  $6 \times 10^{-7}$  to 0.3 beneath valley floors. The average linear velocity of ground water beneath alluvial fans is about 14 ft/d compared to about 1 ft/d beneath valley floors. Thus, contaminants potentially could travel 10-times faster beneath alluvial fans compared to valley floors.

Alluvial slopes have coarse-grained, poorly sorted sediments with relatively few interbedded clay layers and downward ground-water flow. Contaminants released on alluvial slopes compared to valley floors are more likely to spread quickly through large areas and reach deep aquifer systems because ground-water flow is downward and vertical hydraulic conductivity, recharge, and water-table gradients are relatively high. Typically, deep aquifers are used for municipal supply and shallow aquifers are used for domestic supply.

Beneath valley floors, ground-water flow is generally parallel to land surface or upward where it discharges by evapotranspiration from plants and bare soil. Sediments on the valley floor may contain individual layers with high horizontal and vertical hydraulic conductivity, but the overall vertical hydraulic conductivity is relatively low because of the interbedded clay layers. Compared to alluvial slopes, contaminants released on valley floors are more likely to spread slowly through small areas of shallow aquifers due to low recharge rates, low water-table gradients, and low vertical hydraulic conductivity.

Chemical tracers and statistical methods were used to assess the susceptibility of aquifer systems in Nevada. Chemical tracers included nitrate, pesticides, volatile organic compounds, chlorofluorocarbons, dissolved gases, and isotopes of hydrogen and oxygen. Ground-water samples were collected from 133 wells from August 2002 through October 2003. These data were supplemented with 112 samples analyzed for CFCs by previous studies.

Water-quality data for 5,528 wells were compiled from State and Federal agencies into a database and used to characterize the quality of Nevada's aquifer systems. Information on hydrogeologic and anthropogenic variables that could be related to water quality was compiled into GIS datasets and used to characterize the environment within a 1,600-ft (500-m), 3,300-ft (1,000-m), and 4,900-ft (1,500-m) radius buffer surrounding each well. Logistic regression was done using hydrogeologic and anthropogenic information to estimate the probability of detecting nitrate above a threshold concentration that distinguishes natural from anthropogenic nitrate. Nitrate is one of the most common anthropogenic contaminants that degrades ground-water quality, is commonly measured, and is persistent except in reducing conditions. These characteristics make nitrate a good indicator of ground-water susceptibility.

Dissolved-solids concentrations were less than the secondary MCL of 500 mg/L in 72 percent of the unconsolidated-sediment aquifer systems. Water that has  $\leq 3,000$  mg/L usually can be used for some purpose, such as stock watering and industry. About 97 percent of the unconsolidated-sediment aquifer systems have  $\leq 3,000$  mg/L dissolved solids and could be of some beneficial use. Dissolved-solids concentrations were lowest beneath alluvial slopes and fluvial sediments that are not in ground-water discharge areas and higher beneath valley floors and playas. The increase likely is due to dissolution of aquifer material and evapotranspiration as ground water flows from alluvial slopes to discharge areas. Ground-water discharge areas have the largest dissolved-solids concentrations due to evaporative concentration. The low percentage of dissolved solids >3,000 mg/L in all settings, including ground-water discharge areas, suggests that soluble salts are not common in unconsolidated sediments.

A threshold concentration of 2 mg/L nitrate was estimated from wells in unpopulated, undeveloped areas and used in logistic regression to distinguish natural and anthropogenic sources. Domestic and production wells in unpopulated, undeveloped areas had larger concentrations of nitrate compared

to monitoring wells, suggesting that anthropogenic sources could affect ground-water quality even in areas that have been mapped as undeveloped.

About 5 percent of wells with nitrate data had concentrations that exceeded the MCL of 10 mg/L. Almost all wells that exceeded the MCL are in large cities and small towns such as Pahrump, Winnemucca, Ely, and Jackpot, indicating sources of nitrate in urban areas have degraded ground-water quality. Rank correlations between nitrate, well depth, and depth to water were weak ( $r = \leq -0.30$ ). Nitrate concentrations >10 mg/L generally occurred in wells <200 ft deep. Although weak, the negative correlations and high concentrations in shallow to intermediate depth wells suggest that nitrate is from sources near land surface. Relations between nitrate, depth to water, and clay layering for a subset of wells also were weak and, in some basins, opposite of what would be expected for nitrate migrating vertically from sources near land surface. These relations demonstrate the importance of understanding physical and chemical variables that control contaminant transport through unconsolidated-sediment aquifer systems, especially populated basins where large amounts of chemicals are used.

One to 5 pesticides were detected in 5.1 percent of the 1,159 wells with pesticide data; atrazine was the most frequently detected pesticide. One to 14 VOCs were detected in 21 percent of 1,106 wells; chloroform was the most frequently detected VOC. Most pesticides were detected in shallow (<100 ft) monitoring wells. In contrast, most VOCs were detected in public supply wells <500-ft deep. Both pesticides and VOCs were detected in wells >1,000-ft deep. Pesticides and VOCs mostly were detected in the most urbanized areas of Nevada. Atrazine was detected in one monitoring well above the MCL. VOCs were detected above the MCL in 16 production wells and 6 monitoring wells. VOCs that exceeded the MCL included dichloromethane, tetrachloroethene, and trichloroethene.

Nitrate concentrations >2 mg/L had significantly more detections of pesticides and VOCs than concentrations <2 mg/L. Nitrate concentrations had significant but weak rank correlations with the number of pesticides detected ( $r = 0.23$ ) and the number of VOCs detected ( $r = 0.21$ ). Concentrations of nitrate >2 mg/L are more likely to occur with SOC than lower concentrations of nitrate. However, the weak correlations indicate that nitrate is a poor indicator of the concentration or number of SOC present. There was no significant correlation between the number of pesticides and VOCs detected or between the sum of detected concentrations.

CFCs were sampled from wells up to 7,000 ft deep in most types of consolidated rock and unconsolidated-sediment aquifer systems. CFCs were detected in all samples collected by this study and previous studies. The presence of CFCs in all samples indicates that all aquifer systems in Nevada that have been sampled have a high susceptibility. Recharge through fractured consolidated rock, continual pumping for public supply and mine dewatering, poor well construction, and preferential flow along a well's gravel pack could explain the occurrence of SOC and CFCs in deep unconsolidated-sedi-

ment and consolidated-rock aquifer systems. Also, recharge through unconsolidated sediments could be more widespread than previously thought. Ephemeral channels, too small to map on a statewide scale, are common around wells sampled for CFCs. Appreciable amounts of recharge could be occurring through small, ephemeral channels at low altitudes where it could be years between flow events.

Apparent recharge dates had significant rank correlations with well depth ( $r = -0.27$ ), water level above the top of the screen ( $r = -0.45$ ), and nitrate concentration ( $r = 0.28$ ). The inverse correlations between apparent recharge dates and well depth and water level above the screen are consistent with older water occurring at greater depths in aquifer systems. The positive correlation between apparent recharge dates and nitrate concentrations is consistent with recent development, increasing nitrate concentrations in ground water. Currently, nitrate concentrations and SOC concentrations are highest in shallow ground water. With time, nitrate and SOC could degrade deep aquifers that are used for public supply.

Basaltic and granitic aquifer systems, valley floors, and fluvial channels appear to have younger ground water than other aquifer systems and hydrologic settings. This could be due to rapid movement of atmospheric air and water through fractures and appreciable recharge occurring through stream channels at low altitudes. Tertiary sediments appear to have older ground water than other hydrogeologic units, which could be due to their low horizontal hydraulic conductivity and lack of fractures. Other aquifer lithologies and hydrologic settings have a wide range in apparent ages.

Recharge temperatures estimated from dissolved-gas concentrations ranged from 32° to 84° F. Estimated recharge temperatures had significant Pearson correlations with altitude ( $r = -0.48$ ) and latitude ( $r = -0.25$ ), which is consistent with mean annual air temperatures decreasing with increasing altitude and latitude. Most estimates were within  $\pm 9^\circ$  F of estimated mean annual air temperature, indicating recharge occurred under the current temperature regime.

Few wells and springs had  $\delta D$  values that are more negative than modern-day precipitation, indicating little Pleistocene-age water is present in the upper part of most aquifer systems. This is supported by estimates that indicate total recharge during the past 10,000 years exceeds aquifer storage in the upper 1,000 ft of most basins. Total recharge since 1950 has not exceeded aquifer storage in the upper 1,000 ft of any hydrographic area, which contradicts CFC data.

Logistic regression correctly predicted high nitrate concentrations about 60 percent of the time. Because of the poor performance, a regression equation was not developed. All correlations between nitrate and explanatory variables were extremely weak ( $r = \leq 0.16$ ). The weak correlations could be due to the small scale of explanatory-variable datasets, which may not accurately characterize the area around the wells. Changing the threshold nitrate concentration or buffer size used to characterize the area around wells did not affect the strength of the correlations. The most consistently significant and strongest correlations were for alluvial slope, well density,

and soil drainage. These correlations could be due to development encroaching on alluvial fans, association of septic tanks with domestic wells, and nitrate infiltrating through well-drained soils.

For water-quality parameters considered in this report, most of Nevada's aquifer systems could be used for public water supply and almost all ground water has some beneficial use. High nitrate concentrations and SOC's are infrequently detected and rarely above the MCL. High nitrate concentrations and SOC's were primarily detected in urban areas where most chemicals are used.

SOC, CFC, dissolved gas, and isotope data indicate that ground water in Nevada mostly is a mixture of Holocene-age and recent ground water that was recharged during the modern-day climatic regime. This suggests a high susceptibility for Nevada's aquifer systems. Areas with few clay layers and where ground water naturally moves downward are most susceptible to contamination. Contamination of deep aquifer systems may be enhanced by human-induced factors such as secondary recharge from irrigation and ground-water pumpage. Urbanizing areas with few clay layers and downward flow describe primary recharge on alluvial fans, secondary recharge on irrigated land, and well fields in Reno-Sparks, Carson City, and Carson Valley. Even in areas with a thick confining layer, such as Las Vegas, contaminants could migrate into deep aquifer systems from improperly constructed wells; illegal disposal in abandoned or unused wells; and over-pumping, which can cause subsidence and fracturing of confining layers and breakage of well casings. Contaminants released from point and non-point sources can quickly migrate to the water table and move through aquifer systems, as indicated by pesticides, VOCs, and CFCs in wells >1,000 ft deep. This was a reconnaissance-level study to see where water has entered aquifer systems since 1950. Additional studies need to be done to determine how water is entering the aquifers.

## References

- Aller, L., Bennet, T., Lehr, J.H., and Petty, R.J., 1987, DRAS-TIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings, U.S. EPA Report 600/2-85/018, 163 p.
- Anderson, R.E., Zoback, M.L., and Thompson, G.A., 1983, Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range province, Nevada and Utah: Geological Society of America Bulletin, v. 94, p. 1055-1072.
- Barbash, J.E., and Resek, E.A., 1996, Pesticides in ground water: Distribution, trends, and governing factors. Chelsea, Michigan: Ann Arbor Press, Pesticides in the Hydrologic System series, v. 2, 590 p.
- Bates, R.L., and Jackson, J.A., eds., 1984, Dictionary of geological terms: Anchor Press, Garden City, New York, 3<sup>rd</sup> ed., 571 p.
- Bedsun, D.A., 1980, Geological and hydrological profiles in Missile-X valleys: Defense Nuclear Agency, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, 69 p.
- Benson, Larry, Kashgarian, Michael, Rye, Robert, Lund, Steve, Paillet, Fred, Smoot, Joseph, Kester, Cynthia, Mensing, Scott, Meko, Dave, and Lindstrom, Susan, 2002, Holocene multidecadal and multicentennial droughts affecting northern California and Nevada: Quaternary Science Reviews, v. 21, p. 659-682.
- Berger, D.L., 2000, Water-budget estimates for the 14 hydrographic areas in the middle Humboldt River Basin, north-central Nevada: U.S. Geological Survey Water-Resources Investigations Report 00-4168, 55 p.
- Berger, D.L., Maurer, D.K., Lopes, T.J., and Halford, K.J., 2004, Estimates of natural ground-water discharge and characterization of water quality in Dry Valley, Washoe County, west-central Nevada, 2002-2003: U.S. Geological Survey Scientific Investigations Report 2004-5155, 39 p.
- Bevans, H.E., Lico, M.S., and Lawrence, S.J., 1998, Water quality in the Las Vegas Valley area and the Carson and Truckee River Basins, Nevada and California, 1992-96: U.S. Geological Survey Circular 1170, 47 p.
- Biggar, J.W., and Seiber, J.N., eds., 1987, Fate of pesticides in the environment: University of California, Division of Agriculture and Natural Resources, Agricultural Experiment Station, Publication 3320, 157 p.
- Busenberg, E., and Plummer, L. N., 1992, Use of chlorofluoromethanes ( $\text{CCl}_3\text{F}$  and  $\text{CCl}_2\text{F}_2$ ) as hydrologic tracers and age-dating tools: Example- The alluvium and terrace system of Central Oklahoma: Water Resources Research, v. 28, p. 2257-2283.
- Busenberg, Eurybiades, Weeks, E.P., Plummer, L.N., and Bartholmey, R.C., 1993, Age dating ground water by use of chlorofluorocarbons ( $\text{CCl}_3\text{F}$  and  $\text{CCl}_2\text{F}_2$ ), and distribution of chlorofluorocarbons in the unsaturated zone, Snake River Plain aquifer, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water Resources Investigations Report 93-4054, 47 p.
- Caine, J.S., and Forster, C.B., 1999, Fault zone architecture and fluid flow – Insights from field data and numerical modeling, in Haneberg, W.C., Mozley, P.S., Moore, J.C., and Goodwin, L.B., eds., 1999, Faults and subsurface fluid flow in the shallow crust: American Geophysical Union Monograph, v. 113, p. 101-127.

- Canter, L.W., 1997, Nitrates in groundwater: Lewis Publishers, New York, 263 p.
- Cohen, S., 1992, Results of the National drinking water survey: Pesticides, nitrates, and well characteristics: *Water Well Journal*, v. 46, no. 8, p. 35-38.
- Comly, H.H., 1945, Cyanosis in infants caused by nitrates in well water: *Journal of the American Medical Association*, v. 29, p. 112-116.
- Coplen, T.B., Herczeg, A.L., and Barnes, Chris, 2000, Isotope engineering—Using stable isotopes of the water molecule to solve practical problems: *in* Environmental tracers in subsurface hydrology, Cook, P., and Herczeg, A.L., eds., Boston, Kluwer Academic Publishers, p. 79-110.
- Covay, K.J., Banks, J.M., Bevans, H.E., and Watkins, S.A., 1996, Environmental and hydrologic settings of the Las Vegas Valley area and the Carson and Truckee River Basins, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 96-4087, 72 p.
- Craig, 1961, Isotopic variations in meteoric waters: *Science*, v. 133, p. 1702-1703.
- Daly, Christopher, Neilson, R.P., and Phillips, D.L., 1994, A statistical—topographic model for mapping climatological precipitation over mountainous terrain: *Journal of Applied Meteorology*, v. 33, no. 2, p. 140-158.
- Davis, G.H., 1988, Western alluvial valleys and the High Plains, *in* Back, W., Rosenshein, J.S., and Seaber, P.R., eds., *Hydrogeology*, v. O-2, *Geology of North America*, 524 p.
- Dettinger, M.D., 1989, Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride-balance calculations: *Journal of Hydrology*, v. 106, no. 1/2, p. 55-78.
- Donato, M.M., 2000, Probability of detecting atrazine/des-ethyl-atrazine and elevated concentrations of nitrite plus nitrate as nitrogen in ground water in the Idaho part of the Western Snake River Plain: U.S. Geological Survey Water-Resources Investigations Report 00-4163, 25 p.
- Dunkle-Shapiro, Stephanie, Busenberg, Eurybiades, Focazio, M.J., and Plummer, L.N., 2004, Historical trends in occurrence and atmospheric inputs of halogenated volatile organic compounds in untreated ground water used as a source of drinking water: *Science of the Total Environment*, v. 321, p. 201-217.
- Eckhardt, D.A., and Stackelberg, P.E., 1995, Relation of ground-water quality to land use on Long Island, New York: *Ground Water*, v. 33, no. 6, p. 1019-1033.
- Focazio, M.J., Reilly, T.E., Rupert, M.G., Helsel, D.R., 2002, Assessing ground-water vulnerability to contamination: Providing scientifically defensible information for decision makers: U.S. Geological Survey Circular 1224, 33 p.
- Freeze, R.A., and Cherry, J.A., 1979, *Groundwater*: Prentice Hall, Inc., Englewood Cliffs, New Jersey, 604 p.
- Friedman, Irving, Harris, J.M., Smith, G.I., and Johnson, C.A., 2002, Stable isotope composition of waters in the Great Basin, United States: 1. Air Mass Trajectories: *Journal of Geophysical Research*, v. 107, no. D19, 4400, doi:10.1029/2001JD000565.
- Fritz, P., and Fontes, J. C., eds., 1980, *Handbook of Environmental Isotope Geochemistry*, v. 1, Elsevier, New York, 545 p.
- Geolytics, Inc., 2001, Geolytics Census 2000 CD Short Form Blocks: Geolytics Inc., E. Brunswick, NJ, available at URL < <http://www.censused.com/USCensus,Census-2000-Short-Form-Blocks,Products.asp>>
- Goodwin, L.B., Mozley, P.S., Moore, J.C., and Haneberg, W.C., 1999, Introduction, *in* Haneberg, W.C., Mozley, P.S., Moore, J.C., and Goodwin, L.B., eds., *Faults and subsurface fluid flow in the shallow crust: Geophysical Monograph 113*, American Geophysical Union, Washington, D.C., 222 p.
- Gray, D.M, and Male, D.H., eds., 1981, *Handbook of snow: principles, processes, management, and use*: Pergamon Press Inc., New York, 776 p.
- Hallberg, G.R., and Keeney, D.R., 1993, Nitrate: *in* Alley, W.M., ed., *Regional Ground-Water Quality*, Van Nostrand Reinhold, New York, 634 p.
- Hamilton, P.A., Miller, T.L., and Myers, D.N., 2004, Water quality in the Nation's streams and aquifers—Overview of selected findings, 1991-2001: U.S. Geological Survey Circular 1265, 20 p.
- Handman E. H., and Kilroy, K.C., 1997, Ground-water resources of northern Big Smoky Valley, Lander and Nye Counties, central Nevada: U.S. Geological Survey Water-Resources Investigations Report 96-4311, 97 p.
- Hardman, George, 1936, Nevada precipitation and acreages of land by rainfall zones: Nevada University Agricultural Experiment Station report and map, 10 p.
- Hardman, George, and Mason, H.G., 1949, Irrigated lands in Nevada: University of Nevada, Reno, Agricultural Experiment Station Bulletin 183, 57 p.

- Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-C, scale 1:1,000,000, 2 sheets.
- Harrill, J. R., and Preissler, A. M., 1994, Ground-water flow and simulated effects of development in Stagecoach Valley, a small, partly drained basin in Lyon and Storey Counties, Western Nevada: U.S. Geological Survey Professional Paper 1409-H, 74 p.
- Harrill, J.R., and Prudic, D.E., 1998, Aquifer systems in the Great Basin Region of Nevada, Utah, and adjacent states—Summary report: U.S. Geological Survey Professional Paper 1409-A, 66 p.
- Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Elsevier Science Publishers., New York, 522 p.
- Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.
- Hess, G.W., and Williams, R.P., 1997, Flood of January 1997 in the Truckee River Basin, western Nevada: U.S. Geological Survey Fact Sheet FS-123-97, 2 p.
- Hitt, K.J., 1994, Refining 1970's land-use data with 1990 population data to indicate new residential development: U.S. Geological Survey Water-Resources Investigation Report 94-4250, 15 p.
- Hogan, J.F., Phillips, F.M., and Scanlon, B.R., editors, 2004, Groundwater recharge in a desert environment: The southwestern United States: Water Science and Application Series, v. 9, American Geophysical Union, Washington, D.C, 294 p.
- Hosmer, D.W., and Lemeshow, Stanley, 2000, Applied Logistic Regression: John Wiley and Sons, Inc., New York, 373 p.
- Houghton, J.G., Sakamoto, C.M., Gifford, R.M., 1975, Nevada's climate and weather: Nevada Bureau of Mines and Geology Special Publication 2, 78 p.
- Hurlbut, C.S., Jr, and Klein, Cornelius, 1977, Manual of mineralogy (after James D. Dana): John Wiley and Sons, New York, 532 p.
- Johnson, A.I., Moston, R.P., and Morris, D.A., 1968, Physical and hydrologic properties of water-bearing deposits in subsiding areas in central California: U.S. Geological Survey Professional Paper 497-A, 71 p.
- Jordan, L.W., and Cudney, D.W., 1987, Herbicides: in Biggar, J.W., and Seiber, J.N., eds, 1987, Fate of pesticides in the environment: University of California, Division of Agriculture and Natural Resources, Agricultural Experiment Station, Publication 3320, 157 p.
- Lawrence, S.J., 1996, Nitrate and ammonia in shallow ground water, Carson City urban area, Nevada, 1989: U.S. Geological Survey Water-Resources Investigations Report 96-4224, 53 p.
- Lico, M.S., and Seiler, R.L., 1994, Ground-water quality and geochemistry, Carson Desert, western Nevada: U.S. Geological Survey Open-File Report 94-31, 91 p.
- Lico, M.S., 1998, Quality of ground water beneath urban and agricultural lands in Las Vegas Valley and the Carson and Truckee River Basins, Nevada--Implications for water supply: U.S. Geological Survey Water-Resources Investigations Report 97-4259, 24 p.
- Lohman, S.W., and others, 1972, Definitions of selected ground-water terms – revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.
- Lopes, T.J., and Hoffman, J.P., 1997, Geochemical analysis of ground-water ages, recharge rates, and hydraulic conductivity of the N aquifer, Black Mesa, Arizona: U.S. Geological Survey Water-Resources Investigation Report 96-4190, 42 p.
- Lopes, T.J., and Evetts, D.M., 2004, Ground-water pumpage and artificial recharge estimates for calendar year 2000 and mean annual natural recharge and interbasin flow by hydrographic area, Nevada: U.S. Geological Survey Scientific Investigations Report 2004-5239, 87 p.
- Lopes, T.J., Buto, S.G., and Smith, J.L., 2006, Water-table levels and gradients, Nevada, 1947-2004: U.S. Geological Survey Scientific Investigations Report 2006-3074, 23 p.
- Maurer, D. K., 1986, Geohydrology and simulated response to ground-water pumpage in Carson Valley – a river-dominated basin in Douglas County, Nevada, and Alpine County, California: U.S. Geological Survey Water-Resources Investigations Report 86-4328, 109 p.
- Maurer, D.K., and Thodal, C.E., 2000, Quantity and chemical quality of recharge, and updated water budgets, for the basin-fill aquifer in Eagle Valley, Western Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4289, 46 p.
- Maurer, D.K., Lopes, T.J., and Medina, R.L., 2004, Hydrogeology and hydrologic landscape regions of Nevada: U.S. Geological Survey Scientific Investigations Report 2004-5131, 41 p.



- Maxey, G.B., and Eakin, T.E., 1949, Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada: Nevada State Engineer, Water Resources Bulletin 8, 53 p.
- McKee, E.H., Wickham, T.A., and Wheeler, K.L., 1998, Evaluation of faults and their effect on ground-water flow southwest of Frenchman Flat, Nye and Clark Counties, Nevada: U.S. Geological Survey Open-File Report 98-580, 14 p.
- Mifflin, M.D., 1988, Region 5, Great Basin, *in* Back, W., Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology, v. O-2, Geology of North America, 524 p.
- Mueller, D.K., and Helsel, D.R., 1996, Nutrients in the Nation's waters—Too much of a good thing?: U.S. Geological Survey Circular 1136, 24 p.
- Muir, K.S., and Coplan, T.B., 1981, Tracing ground-water movement by using stable isotopes of hydrogen and oxygen, Upper Penitencia Creek alluvial fan, Santa Clara Valley, California: U.S. Geological Survey Water-Supply Paper 2075, 18 p.
- Natural Resources Conservation Service, 1991, State Soil Geographic (STATSGO) Data Base: Data use information: U.S. Department of Agriculture, National Soil Survey Center, Miscellaneous Publication Number 1492, 110 p. (Revised July 1994.)
- Natural Resources Conservation Service, 2004, SNOTEL precipitation data tables for Nevada: accessed August 20, 2004 at URL <http://www.wcc.nrcs.usda.gov/cgi-bin/state-site.pl?state=NV&report=precspotnetmon>
- Nelms, D.L., Harlow, G.E., Jr., Plummer, L.N., and Busenberg, Eurybiades, 2003, Aquifer susceptibility in Virginia, 1998-2000: Water-Resources Investigations Report 03-4278, 58 p.
- Nevada Department of Conservation and Natural Resources, 1999, Nevada state water plan: Nevada Department of Conservation and Natural Resources, Division of Water Planning, accessed July 2004 at <http://water.nv.gov/water%20planning/wat-plan/con-main.htm>
- Nevada Division of Environmental Protection, 2003, Fact Sheet: Accessed December 15, 2003, at URL <http://ndep.nv.gov/sec/uicfact.pdf>
- Nevada Division of Water Resources, 2005, Well Logs and Well Driller Information: accessed February 22, 2005, at URL <http://water.nv.gov/IS/wlog/wlog.cfm>
- Nevada State Demographer, 2004a, Nevada county population estimates, July 1, 1986 to July 1, 2003, includes cities and towns: Accessed July 14, 2004, at URL <http://www.nsbdc.org/demographer/pubs/images/popul03.pdf>
- Nevada State Demographer, 2004b, Population projections for Nevada and Nevada's counties from 2002 to 2022: Accessed July 14, 2004, at URL <http://www.nsbdc.org/demographer/pubs/images/projections02.pdf>
- Nichols, W.D., 2000, Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada: U.S. Geological Survey Professional Paper 1628, 82 p.
- Nolan, B.T., 2001, Relating nitrogen sources and aquifer susceptibility to nitrate in shallow ground waters of the United States: Ground Water, v. 39, no. 2, p. 290-299.
- Nolan, B.T., Hitt, K.J., and Ruddy, B.C., 2002, Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States: Environmental Science & Technology, v. 36, no. 10, p. 2138-2145.
- Pankow, J.F., and Cherry, J.A., 1996, Dense chlorinated solvents and other DNAPLS in groundwater: History, behavior, and remediation: Waterloo Press, Guelph, Ontario, Canada, 522 p.
- Patt, R.O., and Hess, J.W., 1976, Characterization of nitrogen sources contaminating shallow ground water in an arid basin, Las Vegas area, Nevada: University of Nevada, Desert Research Institute Technical Report H-W 26, 44 p.
- Pennington, Nyle, Adams, P.A., Moses, C.W., Bevans, H.E., Carpenter, Jon, Cichowlaz, Schott, 2001, Monitoring for pesticides in ground water in Nevada, 2001: U.S. Geological Survey Fact Sheet 094-01, 2 p.
- Plume, R.W., 1989, Ground-water conditions in Las Vegas Valley, Clark County, Nevada-Part 1, Hydrogeologic framework: U.S. Geological Survey Water-Supply Paper 2320-A, 15 p.
- Plume, R.W., 1996, Hydrogeologic framework of the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-B, 64 p.
- Plummer, L.N., and Busenberg, Eurybiades, 2000, Chlorofluorocarbons: *in* Environmental tracers in subsurface hydrology, Cook, Peter, and Herczeg, A.L., eds., Kluwer Academic Publishers, Boston, p. 441-478.
- Prudic, D.E., and Herman, M.E., 1996, Ground-water flow and simulated effects of development in Paradise Valley, a basin tributary to the Humboldt River in Humboldt County, Nevada: U.S. Geological Survey Professional Paper 1409-F, 92 p.
- Reheis, Marith, 1999, Extent of Pleistocene Lakes in the Western Great Basin: U.S. Geological Survey Miscellaneous Field Studies Map MF-2323, accessed August 19, 2004 at <http://pubs.usgs.gov/mf/1999/mf-2323/>

- Rosen, M.R., 2003, Trends in nitrate and dissolved-solids concentrations in ground water, Carson Valley, Douglas County, Nevada, 1985-2001: U.S. Geological Survey Water-Resources Investigations Report 03-4152, 6 p.
- Rupert, M.G., 2003, Probability of detecting atrazine/des-ethyl-atrazine and elevated concentrations of nitrate in ground water in Colorado: U.S. Geological Survey Water-Resources Investigations Report 02-4269, 35 p.
- Schwarz, G.E., and Alexander, R.B., 1995, State soil geographic (STATSGO) data base for the conterminous United States: U.S. Geological Survey Open-File Report 95-449, 44 p.
- Seiler, R.L., 2004, Temporal changes in water quality at a childhood leukemia cluster: *Ground Water*, v. 42, no. 3, p. 446-455.
- Seiler, R.L., 2005, Combined use of  $^{15}\text{N}$  and  $^{18}\text{O}$  of nitrate and  $^{11}\text{B}$  to evaluate nitrate contamination in ground water: *Applied Geochemistry*, v. 20, no. 9, p. 1626-1636.
- Seiler, R.L., and Allander, K.K., 1993, Water-level changes and directions of ground-water flow in the shallow aquifer, Fallon area, Churchill County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 93-4118, 74 p.
- Seiler, R.L., Zaugg, S.D., Thomas, J.M., and Howcroft, D.L., 1999, Caffeine and pharmaceuticals as indicators of waste water contamination in wells: *Ground Water*, v. 37, no. 3, p. 405-410.
- Sigda, J.M., Goodwin, L.B., Mozley, P.S., and Wilson, J.L., 1999, Permeability alteration in small-displacement faults in poorly lithified sediments: Rio Grande Rift, central New Mexico, *in* Haneberg, W.C., Mozley, P.S., Moore, J.C., and Goodwin, L.B., eds., *Faults and subsurface fluid flow in the shallow crust*, Geophysical Monograph 113, American Geophysical Union, Washington, D.C., 222 p.
- Smith, G.I., Friedman, Irving, Veronda, Guida, and Johnson, C.A., 2002, Stable isotope compositions in the Great Basin, United States: 3. Comparison of groundwaters with modern precipitation: *Journal of Geophysical Research*, v. 107, no. D19, 4402, doi:10.1029/2001JD000567, 2002.
- Squillace, P.J., Pankow, J.F., Korte, N.E., and Zogorski, J.S., 1997, A review of the environmental behavior and fate of MTBE: *Journal of Environmental Toxicology and Chemistry*, v. 16, no. 9, p. 1836-1844.
- Squillace, P.J., Moran, M.J., Lapham, W.W., Price, C.V., Clawges, R.M., and Zogorski, J.S., 1999, Volatile organic compounds in untreated ambient groundwater of the United States, 1985-1995: *Environmental Science & Technology*, v. 33, no. 23, p. 4176-4187.
- StatSoft, 2004, STATISTICA: The Small Book: StatSoft, Inc. Tulsa, OK, 164 p.
- Stewart, J.H., and Carlson, J.E., 1978, Geologic map of Nevada: U.S. Geological Survey, prepared in cooperation with the Nevada Bureau of Mines and Geology, 1:500,000 scale, 2 sheets.
- Stockton, E.L., Jones, C.Z., Rowland, R.C., and Medina, R.L., 2003, Water resources data, Nevada, Water Year 2003: U.S. Geological Survey Water-Data Report NV-03-1, 679 p.
- Stonestrom, D.A., Prudic, D.E., Lacznia, R.L., Akstin, K.C., Boyd, R.A., and Henkelman, K.K., 2003, Estimates of deep percolation beneath native vegetation, irrigated fields, and the Amargosa River channel, Amargosa Desert, Nye County, Nevada: U.S. Geological Survey Open-File Report 03-104, 83 p.
- Stonestrom, D.A., D.E. Prudic, R.J. Lacznia, and K.C. Akstin, 2004, Tectonic, climatic, and land-use controls on groundwater recharge in an arid alluvial basin: Amargosa Desert, U.S.A., *in* *Groundwater Recharge in a Desert Environment: The Southwestern United States*; Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., *Water Science and Applications Series*, v. 9, American Geophysical Union, Washington, D.C., p. 29-47.
- Stute, Martin, and Schlosser, Peter, 2000, Atmospheric noble gases: in *Environmental tracers in subsurface hydrology*, Cook, Peter, and Herczeg, A.L., eds., Kluwer Academic Publishers, Boston, p. 349-376.
- Tesoriero, A.J., and Voss, F.D., 1997, Predicting the probability of elevated nitrate concentrations in the Puget Sound Basin: Implications for aquifer susceptibility and vulnerability: *Ground Water*, v. 35, no. 6, p. 1029-1039.
- Thodal, C.E., 1997, Hydrogeology of Lake Tahoe Basin, California and Nevada, and results of a ground-water quality monitoring network, water years 1990-92: U.S. Geological Survey Water-Resources Investigations Report 97-4072, 53 p.
- Thompson, T.H., and Chappell, Richard, 1984, Maps showing distribution of dissolved solids and dominant chemical type in ground water, Basin and Range Province, Nevada: U.S. Geological Survey Water-Resources Investigations Report 83-4119-C, 4 sheets, scale 1:500,000.
- Thomas, J.M., and Hoffman, R.J., 1988, Nevada ground-water quality, *in* Moody, D.W., Carr, Jerry, Chase, E.B., and Paulson, R.W., comps., *National Water Summary 1986-Hydrologic events and ground-water quality*: U.S. Geological Survey Water-Supply Paper 2325, p. 355-362.

- Thomas, J.M., Carlton, S.M., and Hines, L.B., 1989, Ground-water hydrology and simulated effects of development in Smith Creek Valley, a hydrologically closed basin in Lander County, Nevada: U.S. Geological Survey Professional Paper 1409-E, 57 p.
- Tomer, M.D., and Burkart, M.R., 2003, Long-term effects of nitrogen fertilizer use on ground water nitrate in two small watersheds: *Journal Environmental Quality*, v. 32, p. 2158-2171.
- U.S. Environmental Protection Agency, 1997, Community water system survey—Volume 1: Overview: U.S. Environmental Protection Agency, Office of Water, EPA 815-R-97-001a, 34 p.
- U.S. Environmental Protection Agency, 1999, Revisions to the underground injection control regulations for Class V injections wells: *Federal Register*, v. 64, no. 234, p. 68546-68573, accessed February 15, 2005 at URL <http://www.epa.gov/safewater/uic/c5fedreg.pdf>
- U.S. Environmental Protection Agency, 2005, List of drinking water contaminants & MCLs: accessed February 15, 2005 at URL <http://www.epa.gov/safewater/mcl.html#mcls>
- U.S. Environmental Protection Agency, 2005, Toxic Release Inventory (TRI) Program: accessed February 22, 2005, at URL <http://www.epa.gov/tri/tridata/index.htm>
- U.S. Geological Survey, 1999, The quality of our Nation's waters—Nutrients and pesticides: U.S. Geological Survey Circular 1225, 81 p.
- U.S. Geological Survey, 2000, U.S. GeoData digital elevation models: U.S. Geological Survey Fact Sheet FS-040-00, accessed June 16, 2005, at URL <http://erg.usgs.gov/isb/pubs/factsheets/fs04000.html>
- University of Idaho, 2005, GAP Analysis Program: accessed February 15, 2005 at URL <http://www.gap.uidaho.edu>
- Walker, R.G., and Cant, D.J., 1984, Sandy fluvial systems: in *Facies Models*, Walker, R.G., ed., Geological Association of Canada, Toronto, Ontario, 317 p.
- Walvoord, M.A., Phillips, F.M., Stonestrom, D.A., Evans, R.D., Hartsough, P.C., Newman, B.D., and Striegl, R.G., 2003, A reservoir of nitrate beneath desert soils: *Science*, v. 302, no. 7, p. 1021-1024.
- Walvoord, M.A., and Scanlon, B.R., 2004, Hydrologic processes in deep vadose zones in interdrainage arid environments: in *Groundwater Recharge in a Desert Environment: The Southwestern United States*; Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., *Water Science and Applications Series*, vol. 9, American Geophysical Union, Washington, D.C., p. 15-28.
- Welch, A.H., Lawrence, S.J., Lico, M.S., Thomas, J.M., and Schaefer, D.H., 1997, Ground-water quality assessment of the Carson River Basin, Nevada and California--Results of investigations, 1987-91: U.S. Geological Survey Water-Supply Paper 2356-A, 93 p.
- Welch, A.H., Westjohn, D.B., Helsel, D.R., and Wanty, R.B., 2000, Arsenic in ground water of the United States--occurrence and geochemistry: *Ground Water*, v. 4, no. 38, p. 589-604.
- Western Regional Climate Center, 2004, Nevada climate summaries: accessed August 20, 2004 at URL <http://www.wrcc.dri.edu/summary/climsmnv.html>
- Western Regional Climate Center, 2005, Average statewide precipitation for western U.S. states: accessed February 17, 2005 at URL <http://www.wrcc.dri.edu/htmlfiles/avgstate.ppt.html>
- Wilde, F.D., Radtke, D.B., Gibbs, Jacob, and Iwatsubo, R.T., eds., September 1999, Collection of water samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4, accessed February 22, 2005 at <http://pubs.water.usgs.gov/twri9A4>



