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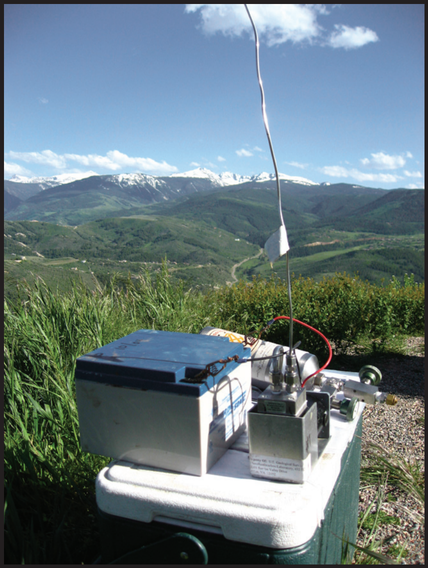
Prepared in cooperation with Eagle County, the Eagle River Water and Sanitation District, the Town of Eagle, the Town of Gypsum, and the Upper Eagle Regional Water Authority

Groundwater Quality, Age, and Probability of Contamination, Eagle River Watershed Valley-Fill Aquifer, North-Central Colorado, 2006–2007



Scientific Investigations Report 2009–5082

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

FRONT COVER:

Left: U.S. Geological Survey scientist collecting high-accuracy GPS data.

Top middle: Artesian well, Eagle County, Colorado.

Bottom middle: Collection of air sample near Bellyache Ridge, Eagle County, Colorado.

Top right: U.S. Geological Survey research hydrologist collecting groundwater age dating sample.

Bottom right: Water well, Eagle County, Colorado.

BACK COVER:

Sylvan Lake, Eagle County, Colorado.

All photographs by Michael G. Rupert, U.S. Geological Survey.

Groundwater Quality, Age, and Probability of Contamination, Eagle River Watershed Valley-Fill Aquifer, North-Central Colorado, 2006–2007

By Michael G. Rupert and L. Niel Plummer

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year ft/yr)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
	Radioactivity	
becquerel per liter (Bq/L)	27.027	picocurie per liter (pCi/L)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Hydraulic gradient	
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

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

$$°F=(1.8\times°C)+32$$

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

$$°C=(°F–32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Acronyms and Abbreviations

CFC	chlorofluorocarbon
CFC–12	dichlorodifluoromethane
CFC–11	trichlorofluoromethane
CFC–113	trichlorotrifluoroethane
CFC–114	tetrafluorodichloroethane
cc	cubic centimeters
ERWVFA	Eagle River watershed valley-fill aquifer
GIS	geographic information system
mg/L	milligrams per liter
µg/L	micrograms per liter
nitrate	nitrite plus nitrate as nitrogen
°C	degrees Celsius
PCE	tetrachloroethene (perchloroethane)
pCi/L	picocuries per liter
pg/L	picograms per liter
ppt	parts per trillion
TCE	trichloroethene
TDVOC	total dissolved low-level volatile organic compound concentration
TU	tritium units
USEPA	U.S. Environmental Protection Agency
VOC	volatile organic compound

The most recent basalt flow in Colorado (near Dotsero).

Looking south towards Arrowhead ski area (just west of Beaver Creek).

Groundwater Quality, Age, and Probability of Contamination, Eagle River Watershed Valley-Fill Aquifer, North-Central Colorado, 2006–2007

By Michael G. Rupert and L. Niel Plummer

Abstract

The Eagle River watershed is located near the destination resort town of Vail, Colorado. The area has a fast-growing permanent population, and the resort industry is rapidly expanding. A large percentage of the land undergoing development to support that growth overlies the Eagle River watershed valley-fill aquifer (ERWVFA), which likely has a high predisposition to groundwater contamination. As development continues, local organizations need tools to evaluate potential land-development effects on ground- and surface-water resources so that informed land-use and water management decisions can be made. To help develop these tools, the U.S. Geological Survey (USGS), in cooperation with Eagle County, the Eagle River Water and Sanitation District, the Town of Eagle, the Town of Gypsum, and the Upper Eagle Regional Water Authority, conducted a study in 2006–2007 of the groundwater quality, age, and probability of contamination in the ERWVFA, north-central Colorado.

Ground- and surface-water quality samples were analyzed for major ions, nutrients, stable isotopes of hydrogen and oxygen in water, tritium, dissolved gases, chlorofluorocarbons (CFCs), and volatile organic compounds (VOCs) determined with very low-level laboratory methods. The major-ion data indicate that groundwaters in the ERWVFA can be classified into two major groups: groundwater that was recharged by infiltration of surface water, and groundwater that had less immediate recharge from surface water and had elevated sulfate concentrations. Sulfate concentrations exceeded the USEPA National Secondary Drinking Water Regulations (250 milligrams per liter) in many wells near Eagle, Gypsum, and Dotsero. The predominant source of sulfate to groundwater in the Eagle River watershed is the Eagle Valley Evaporite, which is a gypsum deposit of Pennsylvanian age located predominantly in the western one-half of Eagle County.

Nitrite plus nitrate as nitrogen (nitrate) concentrations in groundwater in the ERWVFA were generally low, with the median nitrate concentration about 0.74 milligram per liter (mg/L) and a maximum concentration of 5.4 mg/L, which is less than the USEPA Maximum Contaminant Level of 10 mg/L. More than 50 percent of the nitrate concentrations in the ERWVFA were less than 1 mg/L, indicating that more than 50 percent of the wells tested in the ERWVFA had nitrate concentrations similar to precipitation. Most groundwater in the ERWVFA was under oxidized geochemical conditions, indicating that nitrate from anthropogenic sources (caused or produced by humans) could persist for several decades in groundwater of the ERWVFA.

The groundwater age-dating data indicated that most groundwater in the ERWVFA was recently recharged water and had a high probability of contamination if anthropogenic compounds were released to the environment. Based upon the CFC concentrations and tritium activities in groundwater, the median groundwater recharge date was 1989 and the standard deviation was about 9 years, indicating that most groundwater in the ERWVFA that was sampled was young water. The median percentage of young water was 83 percent, and the standard deviation was about 28 percent, indicating that only a small portion of water from most wells was composed of old (older than 1940) water.

VOCs were detected in all water samples at or above the low-level laboratory reporting limit concentrations, but VOC concentrations in all samples were at least one order of magnitude less than their USEPA Maximum Contaminant Level. Some of those VOCs can be naturally occurring at these extremely low concentrations. Total VOC concentrations above 28,000 picograms per liter were attributed to anthropogenic sources.

Logistic regression statistical modeling techniques were used to develop statistical models that predict the probability of elevated nitrate concentrations, the probability of unmixed young water (using chlorofluorocarbon-11 concentrations and tritium activities), and the probability of elevated VOC concentrations. These three models used different compounds such as nitrate and VOCs to provide an indication of the probability of groundwater contamination under a variety of conditions and contaminant inputs. The statistical parameters produced by the three logistic regression models indicated they were highly significant models;

McFadden's rho ranged between 0.490 and 0.647 and the total correct predictions ranged between 0.778 and 0.876. The logistic regression models were verified by plotting the percentage of actual detections with the predicted probability of detections using a deciles of risk calculation. R-squared values of plots of actual detections with the predicted probability of detections were between 0.995 and 0.998, verifying they are highly effective models. Although the groundwater age dating indicates that most areas of the ERWVFA have a high probability of contamination, the probability maps help to show areas with a particularly high probability of contamination if compounds of concern are released to the environment.

Introduction

The Eagle River watershed is located near the destination resort town of Vail, Colorado. The area has a fast-growing permanent population, and the resort industry is rapidly expanding. The permanent population has increased 23 percent between April 1, 2000, and July 1, 2007 (U.S. Census Bureau, 2008). The popularity of the area is largely due to the presence of relatively pristine environmental conditions that the community wishes to protect. Most of the land slated for future development within the watershed is immediately adjacent to the Eagle River or streams that are tributary to the Eagle River and overlies the Eagle River watershed valley-fill aquifer (ERWVFA), which likely has a high predisposition to groundwater contamination. As development continues, local governments need tools to manage existing environmental concerns and to evaluate potential land-development effects on ground- and surface-water resources. For instance, local governments need information to help them evaluate the most suitable locations for light industry such as automobile repair shops and dry cleaners to help protect the groundwater resources from contamination. It is not known what effect onsite wastewater-disposal (septic) systems will have on the groundwater quality. Tools are needed to identify areas with the highest predisposition to groundwater contamination so that wise land-use and source-water protection decisions can be made. To help meet these needs, the U.S. Geological Survey (USGS), in cooperation with Eagle County, the Eagle River Water and Sanitation District, the Town of Eagle, the Town of Gypsum, and the Upper Eagle Regional Water Authority, conducted a study in 2006–2007 of the groundwater quality, age, and probability of contamination in the Eagle River watershed, north-central Colorado. The goals of this study were to (1) establish baseline conditions for major ions and nutrients by summarizing groundwater quality data, (2) develop maps showing the concentrations of sulfate, total dissolved solids, and nitrate in groundwater of the ERWVFA, (3) determine the age of the groundwater in the ERWVFA, and (4) develop maps to show the probability of groundwater in the ERWVFA to contamination.

Background

Maps showing the predisposition to groundwater contamination are commonly referred to as "groundwater vulnerability maps," "groundwater susceptibility maps," or "groundwater probability maps." Different definitions of groundwater vulnerability have arisen over time. The first, and probably the most widely known groundwater vulnerability mapping procedure, is DRASTIC (Aller and others, 1985). The DRASTIC acronym refers to the seven hydrogeologic factors considered in the model: **d**epth to water, net **r**echarge, **a**quifer media, **s**oil media, **t**opography, **i**mpact of vadose (unsaturated) zone media, and hydraulic **c**onductivity of the aquifer (Aller and others, 1985, p. iv). DRASTIC used the term "vulnerability" in a generic sense, referring to the overall potential for nonpoint-source groundwater contamination with no distinction to the general classes of data layers that would be included in the map. More recently, researchers defined groundwater vulnerability as the combination of hydrogeologic susceptibility plus the input of contaminants to the land surface and delivery to the groundwater (National Research Council, 1993; Rao and Alley, 1993; U.S. Environmental Protection Agency, 1993; Vowinkel and others, 1996; Focazio and others, 2002; Gurdak and Qi, 2006). The hydrogeologic susceptibility is determined by evaluating how hydrogeologic properties such as depth to groundwater, geology, and soils influence groundwater contamination; vulnerability is the combination of susceptibility plus contaminant input. The models developed in this report can be considered susceptibility models because they are based on hydrogeologic properties.

The DRASTIC procedure has been used to develop groundwater vulnerability maps in many parts of the Nation, but the validity and accuracy of the model has had poor success because DRASTIC maps use a vulnerability point-rating system that is based upon best professional judgment instead of calibration of the point-rating system to actual contaminant concentrations (Koterba and others, 1993, p. 513; Barbash and Resek, 1996; Rupert, 2001). Rupert (2001) improved the validity and accuracy of a modified DRASTIC vulnerability map by calibrating (adjusting) the vulnerability point ratings to measured nitrite plus nitrate as nitrogen (nitrate) concentrations in groundwater using nonparametric statistical tests.

The validity and accuracy of groundwater vulnerability maps have been further improved by using statistical modeling methods such as logistic regression to relate water-quality data to anthropogenic (caused or produced by humans) and hydrogeologic factors (Koterba and others, 1993; Druliner and others, 1996; Nolan and Clark, 1997; Tesoriero and Voss, 1997; Rupert, 1998, 2003; Nolan and Hitt, 2006). Logistic regression (Hosmer and Lemeshow, 1989; Kleinbaum, 1994) is a statistical method that can be used to predict the probability of occurrence of an event of interest (such as detection of a contaminant in groundwater) as a function of a set of independent variables (such as land cover and soils). Maps developed using logistic regression are sometimes called probability maps because (1) the maps are based on the results of statistical correlations with groundwater quality, and (2) the contamination potential is stated in the terms of percent probability of a detection (Rupert, 1998, 2003). Groundwater probability maps developed using logistic regression are more accurate predictive tools (Rupert, 2003) than vulnerability maps developed with the DRASTIC mapping technique because they are statistically derived from actual contaminant concentrations, and the coefficients of the explanatory variables are automatically adjusted during model calibration.

Purpose and Scope

This report describes groundwater quality, age, and probability of contamination of the ERWVFA. The primary purpose of this report is to develop maps that show the probability of groundwater in the ERWVFA to contamination by using hydrogeologic factors such as depth to groundwater and soil characteristics. These maps are intended to help provide a sound hydrogeologic basis for the protection of groundwater in the ERWVFA and provide a tool to help resource managers to prioritize areas for groundwater-quality monitoring or implement alternative management practices. To meet the primary purpose of this report, different compounds were used to calibrate the groundwater probability maps than compounds that have been used in other areas of the Nation. Development in Eagle County has happened, for the most part, during the last 20 years or so (U.S. Census Bureau, 2008), and new land development in Eagle County is urban and not agricultural. Instead of using agriculturally derived contaminants such as atrazine, concentrations of nitrate and groundwater age-dating compounds were used to calibrate the logistic regression models under the assumption that recently recharged groundwaters have a greater predisposition to contamination than waters recharged many years earlier. Concentrations of volatile organic compounds (VOCs) determined with very low-level laboratory methods and nitrate were also used to calibrate logistic regression models because VOCs and nitrate are common urban contaminants. This report evaluated the ERWVFA; the surrounding bedrock areas were beyond the scope of this report because of the lack of sufficient hydrogeologic information.

Description of Study Area

The ERWVFA is in north-central Colorado, in Eagle County (fig. 1). The ski resort town of Vail is adjacent to the ERWVFA. Annual precipitation ranges from 915 mm (36 inches) in the surrounding mountains to less than 254 mm (10 inches) near Dotsero, on the western edge of the study area (Daly and others, 1994). Land-surface elevations of the ERWVFA range from about 2,620 m (8,600 ft) east of Vail to about 1,860 m (6,100 ft) west of Dotsero. Land-surface elevations of the surrounding mountains can exceed 3,960 m (13,000 ft) (Apodaca and others, 1996).

The ERWVFA is located in the White River Uplift (Apodaca and others, 1996), where the geology consists mostly of sedimentary rocks of Mesozoic and Paleozoic age (Lidke, 1998), which include the Leadville Limestone and Eagle Valley Evaporite. Ground- and surface-water quality in the central and western reaches of the Eagle River watershed is influenced by dissolution of gypsum and other salts from the Eagle Valley Evaporite (Apodaca and others, 1996). Quaternary- and Tertiary-age volcanic rocks occur in localized areas; one of the youngest basalt flows in Colorado is located just east of Dotsero and was dated at about 4,300 years before present (Giegengack, 1962).

Rangeland and forest lands account for the largest land area in Eagle County (Apodaca and others, 1996). Livestock (sheep and cattle) use large areas of rangeland and forest for foraging. Forest land that includes most of the mountain areas is used for some commercial lumber production from lodgepole pine, Englemann spruce, and Douglas fir. Forest land also provides wildlife habitat and recreational opportunities. Tourism and recreational activities are a major industry in the study area. Urban land use is expanding near the towns of Vail, Avon, Eagle, Gypsum, and the unincorporated area of Edwards, in response to the development by the ski and tourism industry.

Mining is another important land use in the study area. Past and present mining activities have included the extraction of metals (copper, gold, lead, molybdenum, nickel, silver, vanadium, and zinc) and gypsum (Apodaca and others, 1996). The Eagle mine, located near Minturn, is designated as a Superfund site because of contamination by heavy metals such as arsenic, cadmium, lead, manganese, and zinc associated with the mining wastes from past mining activities. Gypsum is currently (2008) being mined and processed into drywall at a plant and mine located near Gypsum, Colorado.

The study area is located in three ecoregions: high-altitude tundra, low- to high-altitude forests, and low- to middle-altitude semidesert shrublands (Apodaca and others, 1996). Ecoregions are grouped into similar areas based on landscape features such as vegetation, soils, geology, physiography, and land use (Gallant and others, 1989). High-altitude tundra has a cold, humid to arid climate with vegetation above treeline containing low-growth shrubs, cushion plants, and forbs (Apodaca and others, 1996). Along the forest/tundra interface, there are sparse stands of Engelmann spruce, subalpine fir, limber pine, and bristlecone pine. The middle- to high-altitude forests consist of Engelmann spruce and subalpine fir; some areas are locally dominated by aspen. These forests vary from cool humid to warm dry climates, depending on the altitude. In the low- to middle-altitude forests, vegetation consists of aspen, Douglas fir, ponderosa pine, gambel oak, and piñon pine-juniper woodlands. Low- to middle-altitude semidesert shrublands have a semiarid climate with vegetation consisting of greasewood, four-winged saltbrush, shadscale, and sagebrush often interspersed with grasses.

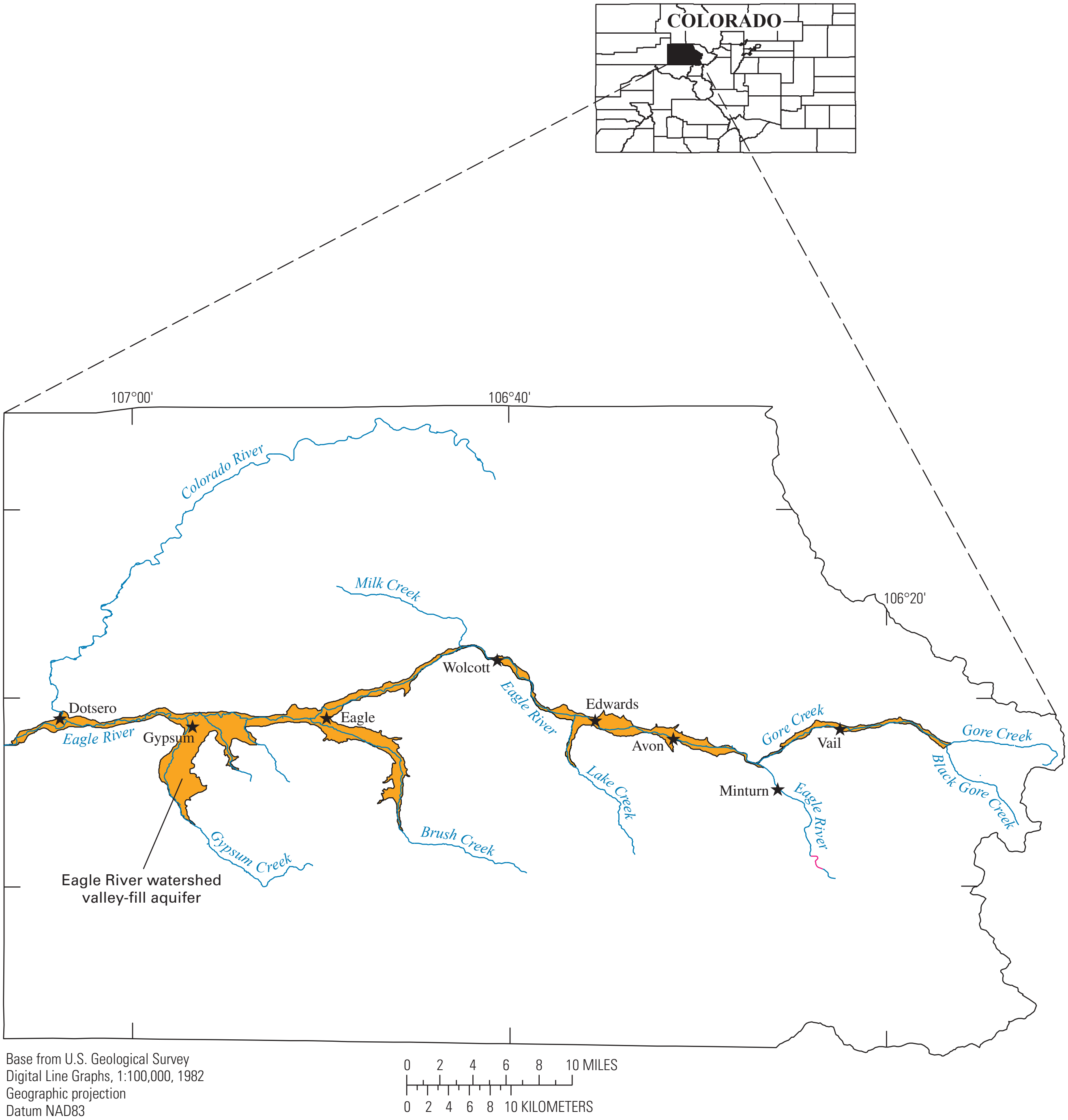


Figure 1. Locations of surface-water bodies, towns, and the Eagle River watershed valley-fill aquifer, Eagle County, Colorado.

Methods of Investigation

The following methods were used to meet the purposes of this report. Ground- and surface-water quality data were collected to establish baseline conditions for major ions and nutrients and to develop maps showing the concentrations of sulfate, total dissolved solids, and nitrate in groundwater. Groundwater-level measurements were made to provide data for a depth-to-groundwater map, which was incorporated into one of the groundwater probability maps. Chlorofluorocarbons and tritium were measured in groundwater and surface water to provide data for groundwater age dating. Low-level concentrations of VOCs were measured in groundwater and surface water to serve as one of the tracers used in one of the groundwater probability maps. Geographic Information System (GIS) data on geology, hydrography, land-surface elevations, precipitation, and soils were compiled to provide input data for the groundwater probability models. Upgradient 90-degree pie-shaped zones of influence were calculated for each well where groundwater-quality data were collected to determine the average soils properties upgradient from each sampled well, which were then incorporated into the input data sets for the logistic regression modeling. The optimum size for each pie-shaped zone was calculated using groundwater modeling and particle tracking. Three statistical models predicting the probability of groundwater contamination by various contaminants were developed using logistic regression techniques. These three models predict the probability of elevated nitrate concentrations in groundwater of the ERWVFA, the probability of unmixed young water (using chlorofluorocarbon-11 concentrations and tritium activities) in groundwater of the ERWVFA, and the probability of elevated VOCs in groundwater of the ERWVFA.

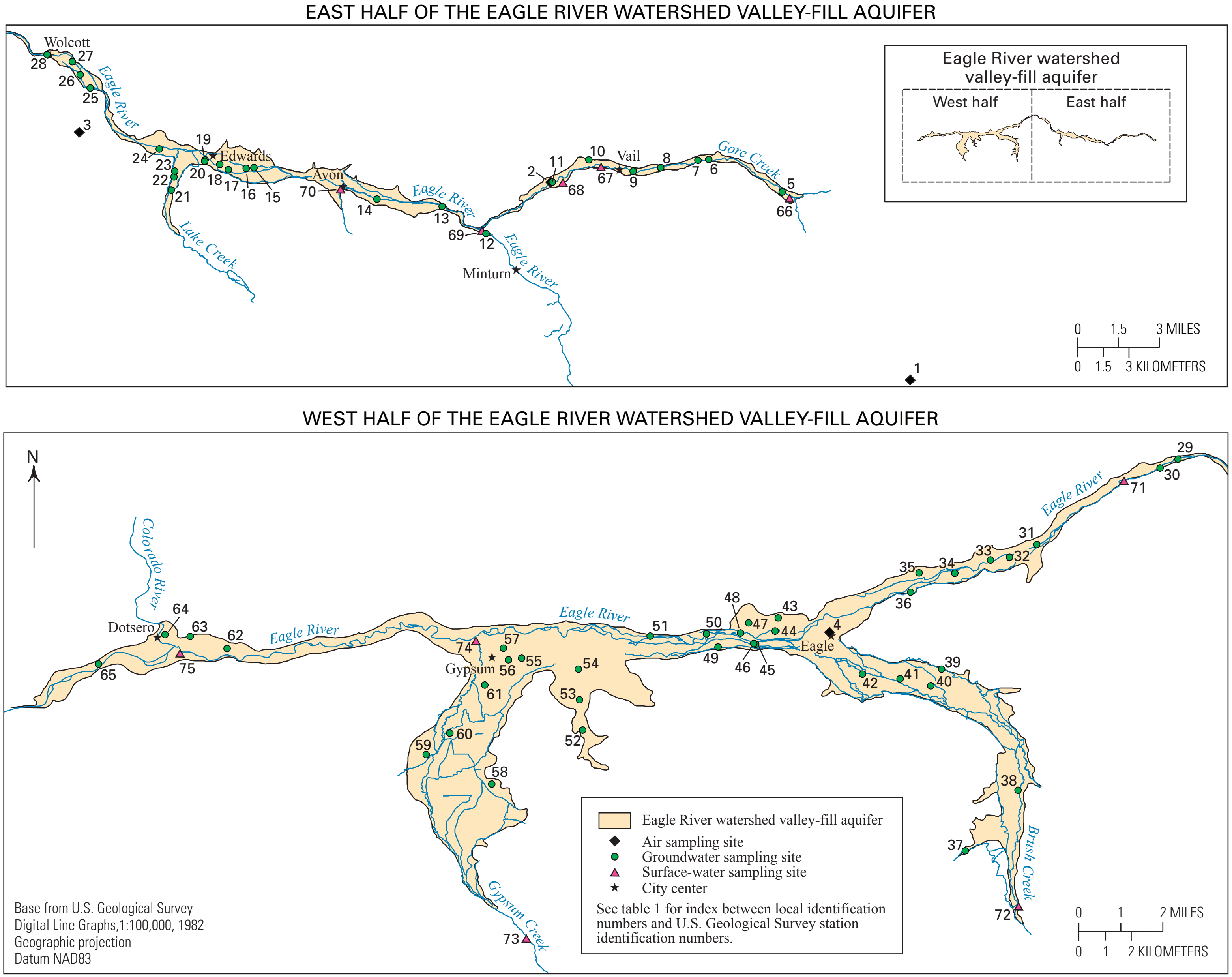
Water-Quality Sampling and Measurement of Groundwater Levels

From existing wells and surface-water sites, 61 sites for groundwater-quality sampling and 10 sites for surface-water-quality sampling were selected to provide appropriate areal coverage in the study area to meet study objectives. Well depths ranged from 17 to 543 feet. Groundwater-quality samples were collected once from 10 sites during August 2006 and once from an additional 51 sites (fig. 2, tables 1 and 2) during May through June 2007 and analyzed for major ions, nutrients, stable isotopes of hydrogen and oxygen (^{2}H and ^{18}O) in water, tritium, dissolved gases, chlorofluorocarbons (CFCs), and VOCs determined with very low-level laboratory methods (tables 2–4). Surface-water-quality samples were collected quarterly from six sites between October 2006 and September 2007 and analyzed for major ions, nutrients, ^{2}H and ^{18}O in water, and tritium (fig. 2, table 2). Additional samples were collected from the six surface-water sites, plus four additional sites, during high flow (May 2007) and low flow (August 2006 and August 2007) and analyzed for CFCs and VOCs (tables 3–4).

Water levels in wells were measured manually at the time of sampling by using a calibrated electric tape or steel tape. To prevent cross-contamination of bacteria between wells, the electric and steel tapes were disinfected immediately after measuring the water level by using a mild bleach bath followed by a deionized water rinse, according to State of Colorado regulations (State of Colorado, 2005).

Water samples were collected from wells and streams using procedures described by Koterba and others (1995), the USGS National Field Manual (U.S. Geological Survey, variously dated), and the USGS Chlorofluorocarbon and Stable Isotope Laboratories (U.S. Geological Survey, 2007a, 2007b). Water was pumped from domestic and municipal wells using existing pumps, and samples were collected prior to any pressure tanks, filtering, or treatment devices. Water was pumped from monitoring wells with a submersible electric pump constructed of stainless steel and Teflon. Water samples were processed onsite in a mobile laboratory by using methods designed to minimize changes to the water-sample chemistry. Prior to sample collection, stagnant water was flushed from the well by purging at least three casing volumes from the well. While purging, specific conductance, pH, water temperature, and dissolved oxygen were measured until readings were stable. Once readings had stabilized, water samples were collected in precleaned bottles within an enclosed chamber to prevent sample contamination. To prevent degradation of water samples and maintain the initial concentration of compounds between the time of sample collection and laboratory analyses, bottles were preserved according to the requirements of the laboratories. Preservation practices differ among analytes and may include chilling, filtration (0.45 micrometer), and(or) chemical treatment (U.S. Geological Survey, variously dated). Sampling equipment was cleaned following the collection of samples using procedures listed in the USGS National Field Manual (U.S. Geological Survey, variously dated).

Samples for alkalinity and hydrogen sulfide were analyzed in the field by using procedures listed in the USGS National Field Manual (U.S. Geological Survey, variously dated). Samples for major ions and nutrients were analyzed by the USGS National Water Quality Laboratory in Lakewood, Colorado (Fishman, 1993; Fishman and Friedman, 1989). Samples for ^{2}H and ^{18}O in water were analyzed by the USGS Stable Isotope Laboratory in Reston, Virginia (U.S. Geological Survey, 2007b; Coplen and others, 1991; Epstein and Mayeda, 1953). Tritium activities were measured at the USGS Tritium Laboratory in Menlo Park, California (Thatcher and others, 1977). Samples for CFCs and very low concentrations of VOCs were analyzed by the USGS Chlorofluorocarbon Laboratory in Reston, Va. (Plummer and Busenberg, 1999).



Base from U.S. Geological Survey
Digital Line Graphs,1:100,000, 1982
Geographic projection
Datum NAD83

Figure 2. Local identification numbers of air, groundwater, and surface-water sampling sites, Eagle River watershed, Eagle County, Colorado.

Quality Assurance and Quality Control

Field blank and replicate samples were collected at a rate of approximately 1 out of every 10 (10 percent) samples collected at ground- and surface-water sites. Field blanks were collected to determine if decontamination of the sampling equipment between sites is adequate and if sample contamination occurred during sample collection, transport, and analysis. All field blanks were collected using blank water prepared at the USGS National Water-Quality Laboratory that is certified to be free of environmental sample analytes above their reporting levels. Field blanks were processed using the same procedures and equipment as the environmental samples. Field blanks were analyzed for major ions and nutrients. It is not possible to prepare meaningful blank solutions for ^{2}H and ^{18}O, tritium, dissolved gases, CFCs, and very low concentrations of VOCs, so no field blanks for these compounds were collected.

Replicate samples were collected to assess variability due to the collection and analyses of samples. All replicates were sequential; the replicate sample was collected after the native sample and analyzed using the same method. Replicate analyses were done for major ions, nutrients, ^{2}H and ^{18}O, and tritium. Replicate samples for dissolved gases are collected at each site as part of standard sample collection, so additional dissolved gas replicate samples were not collected. Five replicate CFC and VOC samples were collected at each site as part of standard sample collection, so additional CFC and VOC samples were not collected.

Groundwater Age

Groundwater ages commonly are termed “apparent age” because the ages are modeled using simplifying assumptions regarding transport processes that may affect the age-dating constituents (such as CFCs) in the water (Plummer and Busenberg, 1999). The simplest and most common transport assumption in groundwater age dating is to assume piston flow, which assumes that the constituent concentration was not altered by transport processes (such as mixing or dispersion) from the point of entry to the measurement point in the aquifer. Some groundwater ages determined with a piston-flow model may be an oversimplification because mixing and dispersion can occur during groundwater flow.

All groundwater pumped from wells is, to some extent, water mixed within the well bore (Plummer and Busenberg, 1999). It is common to have the youngest waters near the top of an aquifer (near the source of recharge) and the oldest waters near the bottom of an aquifer. If the well screen is long, water flowing into a well can be drawn from multiple portions of the aquifer, where it mixes within the well bore. Mixing of water in the well bore produces mixed ages, which can complicate modeling of apparent age. Apparent ages of water sampled from narrow intervals of an aquifer probably are affected less by mixing than those ages interpreted from water samples pumped from large open intervals or from well bores open to multiple fractures of water-bearing zones; however, water from wells with open intervals as small as 1.5 m (5 ft) can display significant mixing (Rupert and Plummer, 2004), depending on the magnitude of age gradients over the open interval or the magnitude of pumping. The simplest case of mixing occurs if the water is a binary mixture of old (CFC-free) and young waters; the problem becomes unsolvable if more than two waters mix (Plummer and Busenberg, 1999) because an insufficient number of reliable environmental tracers can be measured in most groundwater samples.

Another approach to groundwater dating assumes a model for age distribution in the system and calculates the response of the system to input of a tracer over time. This approach, using lumped-parameter models (see for example, Małoszewski and Zuber, 1982; Małoszewski and others, 1983; Zuber, 1986; Zuber, 1994; Małoszewski and Zuber, 1996; Cook and Böhlke, 2000), yields estimates of mean residence time of water in the system. The exponential mixing model is perhaps the simplest of the lumped-parameter models and can describe discharge from an unconfined aquifer receiving uniform areal recharge. The exponential model also could apply to discharge from wells with relatively large open intervals that integrate a range of water ages, or water from springs that discharge from a large groundwater reservoir. As multiple lumped-parameter models can be considered, it is usually not possible to determine, on the basis of limited environmental tracer data, which, if any, lumped-parameter model should apply, and model selection is usually based on available geological and other technical information (Małoszewski and Zuber, 1996). When reporting estimates of groundwater age, it is necessary to qualify the age with the model on which it is based. In this study, data were insufficient to justify selection of any lumped-parameter model. Therefore, initial age estimates were based on apparent age assuming piston flow, and in cases in which CFC ratios suggested dilution with old water, a binary mixing model was applied that assumes dilution of a young fraction with old, pretracer water (International Atomic Energy Agency, 2006).

Tritium

The radioactive isotope of hydrogen, tritium, was used to identify recent groundwater recharge or groundwater mixtures that contain some recent water. In water containing tritium (^{3}H), ^{3}H substitutes for a hydrogen (^{1}H) atom or deuterium (^{2}H) atom in the water molecule and can serve as an excellent tracer because water containing a ^{3}H atom follows the same pathway through the environment as water that does not contain ^{3}H atoms (Plummer and others, 1993, p. 256–257). The half-life of tritium is 12.32 years and commonly is measured in picocuries per liter (pCi/ L) or tritium units (1 TU = 3.19 pCi/L) (Lucas and Unterweger, 2000).

Low activities of tritium are produced naturally by the interaction of the atmosphere with cosmic rays from the solar wind. Atmospheric thermonuclear weapons testing from 1952 to 1964 introduced a large amount of tritium to the atmosphere that was incorporated directly into water molecules

Table 1. Locations of air, groundwater, and surface-water sampling sites, Eagle River watershed, 2006–2007, Eagle County, Colorado.

[AIR, air sampling site; GW, groundwater sampling site; SW, surface-water sampling site; map locations using local identification numbers are shown in figure 2]

Local identification number	Site type	U.S. Geological Survey station identification number	U.S. Geological Survey site name	Latitude (in decimal degrees)	Longitude (in decimal degrees)
1	AIR	393145106130801	VAIL PASS	39.52913889	–106.21883333
2	AIR	393803106243701	DONNOVAN PARK	39.63413889	–106.41013889
3	AIR	393934106393201	BELLYACHE RIDGE	39.65930556	–106.65888890
4	AIR	393906106494201	TOWN HALL OF EAGLE	39.65155556	–106.82836111
5	GW	393743106171000	SC00508012DCD-BIGHORN PARK	39.62871944	–106.28746389
6	GW	393846106193601	SC00508003DCA	39.60000000	–106.30000000
7	GW	393844106195601	SC00508003CDA	39.60000000	–106.30000000
8	GW	393830106210600	SC00508009AAC	39.60000000	–106.30000000
9	GW	393823106215900	SC00508008BCD-GERALD R FORD PARK	39.63976389	–106.36683889
10	GW	393844106232300	SC00508006DBB-PEDESTRIAN	39.64572778	–106.39027222
11	GW	393802106243501	SC00508112CAB	39.60000000	–106.40000000
12	GW	393623106264201	SC00508122BDD	39.60655556	–106.44508333
13	GW	393715106280701	SC00508116BBD	39.62091667	–106.46847222
14	GW	393730106301101	SC00508116BAC	39.62497222	–106.50308333
15	GW	393830106340601	SC00508203CCB	39.64167778	–106.56847222
16	GW	393830106341501	SC00508204DAA	39.64127778	–106.57261111
17	GW	393826106345601	SC00508204CDB	39.60000000	–106.50000000
18	GW	393836106351201	SC00508204CBC	39.60000000	–106.50000000
19	GW	393844106354001	SC00508205DBA1	39.64570556	–106.59451944
20	GW	393842106354101	SC00508205DBA2	39.64497778	–106.59467500
21	GW	393748106364201	SC00508207DAB	39.62961111	–106.61247222
22	GW	393812106363901	SC00508207AAB	39.63675000	–106.61102778
23	GW	393823106363801	SC00508206DDC	39.63983333	–106.61061111
24	GW	393905106370801	SC00508206BAA2	39.65156111	–106.61895833
25	GW	394102106392001	SC00408323DCD	39.68396389	–106.65568889
26	GW	394127106394001	SC00408323BDD	39.69102778	–106.66111111
27	GW	394153106395501	SC00408314CCC	39.69794444	–106.66522222
28	GW	394206106404301	SC00408315CAD	39.70179722	–106.67863889
29	GW	394243106422501	SC00408308DDD	39.71194444	–106.70697222
30	GW	394232106424801	SC00408317ABC	39.70883333	–106.71333333
31	GW	394055106452301	SC00408424DCC	39.68213889	–106.75644444
32	GW	394040106455701	SC00408425BCA	39.67763611	–106.76588611
33	GW	394036106462101	SC00408426ADB	39.67672222	–106.77258333
34	GW	394019106470601	SC00408426CBD	39.67203889	–106.78504444
35	GW	394020106475101	SC00408427CAD1	39.67222222	–106.79741667
36	GW	393956106480201	SC00408434BAC	39.66547222	–106.80047222
37	GW	393431106465301	SC00508435BDB MWB-1	39.57513889	–106.78130556
38	GW	393547106454601	SC00508424CDC MWB-4	39.59630556	–106.76286111
39	GW	393819106472201	SC00508410AAB	39.63858333	–106.78958333
40	GW	393758106473601	SC00508410ACD	39.63280556	–106.79338889
41	GW	393807106481501	SC00508410BBD	39.63522222	–106.80405556
42	GW	393813106490201	SC00508409BAD	39.63686111	–106.81722222
43	GW	393923106504801	SC00408431DDB	39.65641667	–106.84666667
44	GW	393907106505201	SC00508406ABA	39.65188611	–106.84782222
45	GW	393850106511701	SC00508406BDD02	39.64725278	–106.85459167
46	GW	393851106511901	SC00508406BDD01	39.64748056	–106.85530833
47	GW	393917106512501	SC00408431CBD	39.65472222	–106.85697222
48	GW	393904106513601	SC00508406BBD	39.65113611	–106.85987500
49	GW	393847106520401	SC00508401ACD	39.64635278	–106.86768333
50	GW	393903106521901	SC00508501ABC	39.65094444	–106.87183611
51	GW	393900106532901	SC00508502BAD	39.65006667	–106.89146111
52	GW	393702106545401	SC00508515CBA	39.61730556	–106.91505556
53	GW	393740106545801	SC00508510CBD	39.62780556	–106.91608333
54	GW	393819106545901	SC00508503CDD	39.63852778	–106.91655556
55	GW	393832106561101	SC00508504CBC	39.64236111	–106.93630556
56	GW	393831106562701	SC00508505DDB	39.64186111	–106.94088889
57	GW	393845106563401	SC00508505ADC	39.64588889	–106.94272222

Table 1. Locations of air, groundwater, and surface-water sampling sites, Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

[AIR, air sampling site; GW, groundwater sampling site; SW, surface-water sampling site; map locations using local identification numbers are shown in figure 2]

Local identification number	Site type	U.S. Geological Survey station identification number	U.S. Geological Survey site name	Latitude (in decimal degrees)	Longitude (in decimal degrees)
58	GW	393554106564901	SC00508520DCB	39.59847222	–106.94683333
59	GW	393632106581101	SC00508519BAB	39.60880556	–106.96975000
60	GW	393658106574101	SC00508518DBA	39.61616667	–106.96138889
61	GW	393759106565701	SC00508508BDD	39.63305556	–106.94927778
62	GW	393845107022101	SC00508604ACC	39.64580833	–107.03918889
63	GW	393900107030701	SC00508605AAD	39.65002778	–107.05219444
64	GW	393902107033901	SC00508605BAA	39.65061111	–107.06094444
65	GW	393825107050301	SC00508606CCC	39.64033333	–107.08413889
66	SW	393737106165900	GORE CREEK BLW BLACK GORE CREEK NEAR VAIL, CO.	39.62693041	–106.28363799
67	SW	393834106230401	GORE CREEK ABOVE WASTE	39.64277778	–106.38444444
68	SW	393810106241501	GORE CREEK BELOW WASTE	39.63611111	–106.40416666
69	SW	09066510	GORE CREEK AT MOUTH, NEAR MINTURN, CO.	39.60943048	–106.44780797
70	SW	09067005	EAGLE RIVER AT AVON, CO.	39.63165271	–106.52253183
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.72583333
72	SW	09068000	BRUSH CREEK NEAR EAGLE, CO.	39.55720730	–106.76309261
73	SW	09069500	GYPSUM CREEK NEAR GYPSUM, CO.	39.54553981	–106.93476576
74	SW	09069000	EAGLE RIVER AT GYPSUM, CO.	39.64998511	–106.95226647
75	SW	09070400	EAGLE RIVER AT MOUTH, NEAR DOTSERO, CO.	39.64331767	–107.05615904

of precipitation (fig. 3). Concentrations in precipitation have been decreasing since that time because of the exchange of water with the oceans, short half-life of tritium, and because atmospheric thermonuclear weapons testing was stopped. Because the concentration of tritium in the atmosphere was high for a relatively short period, its presence in groundwater can identify water that has been recharged during the last 50 years or mixtures that contain a fraction of post-1950s water. Tritium activities in precipitation prior to thermonuclear weapons testing are not well known but probably did not exceed about 6 to 26 pCi/L (2 to 8 TU) (Plummer and others, 1993, p. 260). Because tritium has a half-life of 12.32 years, water derived from precipitation before thermonuclear weapons testing would contain a maximum ^{3}H activity of about 0.4 to 1.6 pCi/L (0.12 to 0.5 TU) by the early 2000s. Clark and Fritz (1997, p. 185) state that during the mid-1990s, waters with tritium activities above about 96 pCi/L (30 TU) contained a considerable component of recharge from the 1960s or the 1970s, and activities above 160 pCi/L (50 TU) indicate recharge predominantly from the 1960s.

Chlorofluorocarbons

CFCs were used to estimate apparent ages of recently recharged groundwater and the amounts of dilution of young (post-1940s) groundwater with old (pre-1940s) groundwater. CFCs are stable, synthetic organic compounds that were developed in the early 1930s as safe alternatives to ammonia and sulfur dioxide in refrigeration and have been used in a wide range of industrial and refrigerant applications (Plummer and Friedman, 1999). Production of CFC–12 (dichlorodifluoromethane) began in 1931, followed by CFC–11 (trichlorofluoromethane) in 1936, and then by many other CFC compounds, most notably CFC–113 (trichlorotrifluoroethane). At ordinary (room) temperatures, CFC–113 is liquid (boiling point 47.6°C [118°F]), and CFC–12 and CFC–11 are gases (boiling points –29.8°C (–21.6°F) and –23.6°C (–10.5°F) respectively). CFC–12 and CFC–11 were used as coolants in air conditioning and refrigeration; as blowing agents in foams, insulation, and packing materials; as propellants in aerosol cans; and as solvents (Plummer and Busenberg, 1999). CFC–113 has been used primarily by the electronics industry in semiconductor chip manufacturing, in vapor degreasing and cold immersion cleaning of microelectronic components, and in surface cleaning. Probably better known as Freon, CFCs are nontoxic, nonflammable, and noncarcinogenic, but they contribute to ozone depletion. Therefore, in 1987, 37 nations signed an agreement to limit release of CFCs and to halve CFC emissions by 2000. This agreement was strengthened in 1990 and 1992 to establish a cutoff date of 1996 to cease production of CFCs in industrialized nations. The United States ceased production on January 1, 1996, as a regulatory requirement under the USEPA Clean Air Act (International Atomic Energy Agency, 2006).

Table 2. Selected well-construction, major-ion, nutrient, stable isotopes of hydrogen and oxygen, and tritium data from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado.

[--, no data; na, not applicable; GW, groundwater; SW, surface water; m, month; d, day; y, year; >, greater than; <, less than; e, constituent detected, but concentration is estimated; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; pCi/L, picocuries per liter; ND, not detected; per mil, parts per thousand; pCi/L, picocuries per liter; oxidized, waters under oxidized geochemical conditions; reduced, waters under reducing geochemical conditions; mixture, mixture of waters under oxidized and reduced geochemical conditions]

Local identification number	Site type	U.S. Geological Survey station identification number	U.S. Geological Survey site name	Latitude (in decimal degrees)	Longitude (in decimal degrees)	Date of sample collection (mmddyy)	Well depth (feet below land surface)	Depth to water table (feet below land surface)	Specific conductance, field (µS/cm)
5	GW	393743106171000	SC00508012DCD-BIGHORN PARK	39.62871944	–106.2874639	06/05/07	23	7.23	282
6	GW	393846106193601	SC00508003DCA	39.60000000	–106.30000000	06/08/07	103	--	314
7	GW	393844106195601	SC00508003CDA	39.60000000	–106.30000000	06/21/07	123	--	329
8	GW	393830106210600	SC00508009AAC	39.60000000	–106.30000000	06/05/07	18	2.62	280
9	GW	393823106215900	SC00508008BCD-GERALD R FORD PARK	39.63976389	–106.3668389	06/06/07	25	13.08	451
10	GW	393844106232300	SC00508006DBB-PEDESTRIAN	39.64572778	–106.3902722	06/06/07	41	27.12	646
11	GW	393802106243501	SC00508112CAB	39.60000000	–106.40000000	08/24/06	50	--	639
11	GW	393802106243501	SC00508112CAB	39.60000000	–106.40000000	06/19/07	50	--	540
12	GW	393623106264201	SC00508122BDD	39.60655556	–106.4450833	06/11/07	65	10.29	480
13	GW	393715106280701	SC00508116BBD	39.62091667	–106.4684722	06/19/07	58	35.35	603
14	GW	393730106301101	SC00508116BAC	39.62497222	–106.5030833	06/22/07	55	26.43	376
15	GW	393830106340601	SC00508203CCB	39.64167778	–106.5684722	06/11/07	120	72.42	588
16	GW	393830106341501	SC00508204DAA	39.64127778	–106.5726111	06/06/07	73	39.72	490
17	GW	393826106345601	SC00508204CDB	39.60000000	–106.50000000	08/24/06	80	--	671
18	GW	393836106351201	SC00508204CBC	39.60000000	–106.50000000	06/08/07	61	--	745
19	GW	393844106354001	SC00508205DBA1	39.64570556	–106.5945194	05/21/07	115	46.51	584
20	GW	393842106354101	SC00508205DBA2	39.64497778	–106.5946750	05/21/07	88	53.67	911
21	GW	393748106364201	SC00508207DAB	39.62961111	–106.6124722	06/08/07	65	11.47	468
22	GW	393812106363901	SC00508207AAB	39.63675000	–106.6110278	06/21/07	25	14.17	530
23	GW	393823106363801	SC00508206DDC	39.63983333	–106.6106111	06/11/07	36	7.69	627
24	GW	393905106370801	SC00508206BAA2	39.65156111	–106.6189583	05/21/07	50	--	1,690
25	GW	394102106392001	SC00408323DCD	39.68396389	–106.6556889	06/09/07	63	42.74	239
26	GW	394127106394001	SC00408323BDD	39.69102778	–106.6611111	06/09/07	34	14.27	604
27	GW	394153106395501	SC00408314CCC	39.69794444	–106.6652222	06/09/07	543	104.08	2,202
28	GW	394206106404301	SC00408315CAD	39.70179722	–106.6786389	06/07/07	46	11.66	837
29	GW	394243106422501	SC00408308DDD	39.71194444	–106.7069722	06/07/07	20	15.35	812
30	GW	394232106424801	SC00408317ABC	39.70883333	–106.7133333	05/16/07	50	13.21	693
31	GW	394055106452301	SC00408424DCC	39.68213889	–106.7564444	05/18/07	47	12.19	1,050
32	GW	394040106455701	SC00408425BCA	39.67763611	–106.7658861	05/15/07	65	29.72	900
33	GW	394036106462101	SC00408426ADB	39.67672222	–106.7725833	05/15/07	62	--	1,021
34	GW	394019106470601	SC00408426CBD	39.67203889	–106.7850444	05/16/07	64	25.02	1,251
35	GW	394020106475101	SC00408427CAD1	39.67222222	–106.7974167	08/25/06	71	50.80	1,030
36	GW	393956106480201	SC00408434BAC	39.66547222	–106.8004722	05/16/07	28	--	2,527
37	GW	393431106465301	SC00508435BDB MWB-1	39.57513889	–106.7813056	06/12/07	19	10.67	449
38	GW	393547106454601	SC00508424CDC MWB-4	39.59630556	–106.7628611	06/12/07	17	5.58	917
39	GW	393819106472201	SC00508410AAB	39.63858333	–106.7895833	06/20/07	126	--	2,584
40	GW	393758106473601	SC00508410ACD	39.63280556	–106.7933889	06/20/07	72	9.70	903
41	GW	393807106481501	SC00508410BBD	39.63522222	–106.8040556	06/20/07	61	–2.20	901
42	GW	393813106490201	SC00508409BAD	39.63686111	–106.8172222	06/10/07	48	9.14	778
43	GW	393923106504801	SC00408431DDB	39.65641667	–106.8466667	05/17/07	137	118.03	1,916
44	GW	393907106505201	SC00508406ABA	39.65188611	–106.8478222	05/17/07	52	32.56	3,060
45	GW	393850106511701	SC00508406BDD02	39.64725278	–106.8545917	08/23/06	95	19.27	2,711
46	GW	393851106511901	SC00508406BDD01	39.64748056	–106.8553083	06/10/07	46	14.24	3,490
47	GW	393917106512501	SC00408431CBD	39.65472222	–106.8569722	08/22/06	145	126.80	5,310
47	GW	393917106512501	SC00408431CBD	39.65472222	–106.8569722	06/21/07	145	124.48	5,610
48	GW	393904106513601	SC00508406BBD	39.65113611	–106.8598750	05/23/07	48	16.29	2,042
49	GW	393847106520401	SC00508401ACD	39.64635278	–106.8676833	05/17/07	380	57.33	2,630
50	GW	393903106521901	SC00508501ABC	39.65094444	–106.8718361	08/22/06	55	13.69	2,517
51	GW	393900106532901	SC00508502BAD	39.65006667	–106.8914611	05/20/07	60	13.90	2,780
52	GW	393702106545401	SC00508515CBA	39.61730556	–106.9150556	08/23/06	52	19.21	1,856

Table 2. Selected well-construction, major-ion, nutrient, stable isotopes of hydrogen and oxygen, and tritium data from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

Local identification number	Site type	U.S. Geological Survey station identification number	U.S. Geological Survey site name	Latitude (in decimal degrees)	Longitude (in decimal degrees)	Date of sample collection (mmddyy)	Well depth (feet below land surface)	Depth to water table (feet below land surface)	Specific conductance, field (µS/cm)
53	GW	393740106545801	SC00508510CBD	39.62780556	–106.9160833	05/22/07	100	30.81	2,075
54	GW	393819106545901	SC00508503CDD	39.63852778	–106.9165556	05/18/07	116	40.69	2,082
55	GW	393832106561101	SC00508504CBC	39.64236111	–106.9363056	05/19/07	73	54.26	2,125
56	GW	393831106562701	SC00508505DDB	39.64186111	–106.9408889	05/19/07	50	32.51	1,890
57	GW	393845106563401	SC00508505ADC	39.64588889	–106.9427222	08/22/06	25	6.38	1,659
58	GW	393554106564901	SC00508520DCB	39.59847222	–106.9468333	05/20/07	92	46.99	2,464
59	GW	393632106581101	SC00508519BAB	39.60880556	–106.9697500	08/23/06	89	30.03	1,144
60	GW	393658106574101	SC00508518DBA	39.61616667	–106.9613889	05/20/07	80	3.03	594
61	GW	393759106565701	SC00508508BDD	39.63305556	–106.9492778	06/07/07	68	47.88	1,335
62	GW	393845107022101	SC00508604ACC	39.64580833	–107.0391889	08/25/06	132	86.05	8,100
63	GW	393900107030701	SC00508605AAD	39.65002778	–107.0521944	05/19/07	48	33.24	6,530
64	GW	393902107033901	SC00508605BAA	39.65061111	–107.0609444	05/22/07	56	26.98	2,905
65	GW	393825107050301	SC00508606CCC	39.64033333	–107.0841389	05/22/07	43	12.35	6,890
66	SW	393737106165900	GORE CREEK BLW BLACK GORE CREEK NEAR VAIL, CO.	39.62693041	–106.2836380	12/20/06	na	na	223
66	SW	393737106165900	GORE CREEK BLW BLACK GORE CREEK NEAR VAIL, CO.	39.62693041	–106.2836380	03/21/07	na	na	361
66	SW	393737106165900	GORE CREEK BLW BLACK GORE CREEK NEAR VAIL, CO.	39.62693041	–106.2836380	05/23/07	na	na	113
66	SW	393737106165900	GORE CREEK BLW BLACK GORE CREEK NEAR VAIL, CO.	39.62693041	–106.2836380	08/29/07	na	na	176
69	SW	9066510	GORE CREEK AT MOUTH, NEAR MINTURN, CO.	39.60943048	–106.4478080	08/24/06	na	na	356
70	SW	9067005	EAGLE RIVER AT AVON, CO.	39.63165271	–106.5225318	12/20/06	na	na	313
70	SW	9067005	EAGLE RIVER AT AVON, CO.	39.63165271	–106.5225318	03/22/07	na	na	270
70	SW	9067005	EAGLE RIVER AT AVON, CO.	39.63165271	–106.5225318	05/23/07	na	na	130
70	SW	9067005	EAGLE RIVER AT AVON, CO.	39.63165271	–106.5225318	08/28/07	na	na	248
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.7258333	08/23/06	na	na	762
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.7258333	08/25/06	na	na	754
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.7258333	12/19/06	na	na	885
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.7258333	03/22/07	na	na	560
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.7258333	05/22/07	na	na	156
71	SW	394220106431500	EAGLE RIVER BELOW MILK CREEK NEAR WOLCOTT, CO.	39.70500000	–106.7258333	08/28/07	na	na	701
72	SW	9068000	BRUSH CREEK NEAR EAGLE, CO.	39.55720730	–106.7630926	12/18/06	na	na	454
72	SW	9068000	BRUSH CREEK NEAR EAGLE, CO.	39.55720730	–106.7630926	03/20/07	na	na	448
72	SW	9068000	BRUSH CREEK NEAR EAGLE, CO.	39.55720730	–106.7630926	05/23/07	na	na	225
72	SW	9068000	BRUSH CREEK NEAR EAGLE, CO.	39.55720730	–106.7630926	08/30/07	na	na	414
73	SW	9069500	GYPSUM CREEK NEAR GYPSUM, CO.	39.54553981	–106.9347658	12/18/06	na	na	445
73	SW	9069500	GYPSUM CREEK NEAR GYPSUM, CO.	39.54553981	–106.9347658	03/20/07	na	na	490
73	SW	9069500	GYPSUM CREEK NEAR GYPSUM, CO.	39.54553981	–106.9347658	05/24/07	na	na	278
73	SW	9069500	GYPSUM CREEK NEAR GYPSUM, CO.	39.54553981	–106.9347658	08/31/07	na	na	416
74	SW	9069000	EAGLE RIVER AT GYPSUM, CO.	39.64998511	–106.9522665	12/18/06	na	na	838
74	SW	9069000	EAGLE RIVER AT GYPSUM, CO.	39.64998511	–106.9522665	03/20/07	na	na	742
74	SW	9069000	EAGLE RIVER AT GYPSUM, CO.	39.64998511	–106.9522665	05/22/07	na	na	189
74	SW	9069000	EAGLE RIVER AT GYPSUM, CO.	39.64998511	–106.9522665	08/27/07	na	na	849

Table 2. Selected well-construction, major-ion, nutrient, stable isotopes of hydrogen and oxygen, and tritium data from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

[--, no data; na, not applicable; GW, groundwater; SW, surface water; m, month; d, day; y, year; >, greater than; <, less than; e, constituent detected, but concentration is estimated; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; pCi/L, picocuries per liter; ND, not detected; per mil, parts per thousand; pCi/L, picocuries per liter; oxidized, waters under oxidized geochemical conditions; reduced, waters under reducing geochemical conditions; mixture, mixture of waters under oxidized and reduced geochemical conditions]

Local identification number	pH, water, whole, field (standard units)	Temperature, water (°C)	Oxygen, dissolved (mg/L)	Hydrogen sulfide, unfiltered (mg/L)	Alkalinity, water, dissolved, field (mg/L as $CaCO_3$)	Total dissolved solids (mg/L)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Bicarbonate, water, dissolved, field, (mg/L as HCO_3)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)
5	7.1	12.4	3.5	<0.1	136	e 155	48.5	3.93	4.46	1.20	166	4.27	3.30
6	7.9	7.0	4.0	<.1	115	e 165	49.9	4.93	5.89	1.25	140	5.25	20.9
7	7.9	7.0	3.6	<.1	122	e 172	47.9	5.57	7.42	1.20	149	5.34	23.1
8	7.8	8.0	2.2	<.1	115	148	39.5	6.11	5.54	1.30	140	5.07	13.1
9	7.8	3.9	4.2	<.1	186	e 238	67.9	9.41	8.80	1.05	227	8.26	21.2
10	7.3	9.0	3.9	<.1	277	e 351	105	16.0	7.72	1.76	338	26.3	15.1
11	7.3	9.0	2.4	<.1	177	373	91.3	18.2	9.25	1.53	--	101	33.6
11	7.5	7.4	3.0	<.1	147	298	74.9	14.6	8.14	1.29	180	73.1	27.8
12	7.7	8.0	2.9	<.1	179	e 269	60.3	19.1	9.00	1.51	218	42.9	14.2
13	7.4	9.6	4.6	<.1	168	e 345	83.3	19.6	9.59	1.40	205	86.1	30.7
14	7.3	9.1	1.7	<.1	132	e 206	53.2	10.0	5.87	1.09	162	26.4	17.4
15	7.6	9.9	5.8	<.1	222	e 370	72.3	22.3	21.6	1.59	271	83.5	9.68
16	7.3	10.2	2.0	<.1	230	e 272	79.9	13.7	4.88	1.65	281	19.8	4.59
17	7.3	9.4	3.4	<.1	197	e 410	95.6	23.8	6.85	1.81	--	127	18.4
18	7.6	9.4	4.0	<.1	197	e 466	113	25.6	7.74	1.98	240	162	19.6
19	7.7	9.4	3.1	<.1	163	337	81.3	18.9	8.16	1.55	198	83.9	28.1
20	7.5	10.4	4.4	<.1	204	e 510	118	29.0	18.4	2.14	249	94.5	101
21	7.7	9.3	4.8	<.1	144	e 281	77.8	8.88	5.68	1.51	175	80.5	6.11
22	7.6	9.6	5.4	<.1	145	332	90.0	11.5	3.98	1.39	176	123	3.59
23	7.5	9.1	5.7	<.1	175	e 390	106	13.6	3.90	1.53	213	143	4.19
24	7.6	8.4	7.5	<.1	199	e 1,040	137	34.7	159	3.66	243	384	192
25	7.5	9.9	6.0	<.1	63	137	20.6	5.56	19.2	1.00	77	30.8	13.4
26	7.8	10.2	1.0	.1	197	341	67.7	18.0	31.3	4.82	240	38.1	48.9
27	8.6	16.2	0.1	.2	421	1,260	3.84	0.72	510	0.53	513	75.0	402
28	7.5	11.1	7.2	<.1	251	488	91.8	19.9	61.3	2.34	306	79.4	70.3
29	7.5	8.4	3.0	<.1	191	e 484	80.5	20.3	61.0	2.40	233	99.3	85.9
30	7.7	9.4	4.3	<.1	247	e 424	72.7	18.8	41.8	2.30	301	65.7	58.9
31	7.6	10.7	1.9	<.1	170	e 667	133	24.6	58.1	2.68	207	270	62.2
32	7.7	11.2	3.2	<.1	224	532	110	24.0	44.8	3.28	274	140	53.6
33	7.7	10.9	6.5	<.1	231	587	106	31.7	50.4	11.1	281	125	98.2
34	7.6	11.7	2.8	<.1	198	823	186	27.3	47.4	3.60	242	349	75.4
35	7.2	13.0	4.5	<.1	273	e 627	140	16.7	46.5	3.02	--	175	64.4
36	7.1	10.6	0.4	<.1	328	e 2,270	585	43.6	84.7	5.92	399	1,164	171
37	7.3	7.5	3.8	<.1	241	e 253	65.9	17.4	3.82	1.11	293	4.39	1.08
38	7.0	8.0	0.6	<.1	277	e 602	162	20.7	7.03	1.38	338	229	2.90
39	7.1	12.4	4.6	<.1	235	e 2,190	476	99.1	36.1	11.1	286	1,368	42.5
40	7.4	10.9	5.6	<.1	195	541	111	19.9	43.1	2.85	238	177	55.2
41	7.3	10.9	6.2	<.1	201	e 535	117	20.5	33.1	2.93	245	170	55.5
42	7.4	9.4	4.7	<.1	163	475	105	16.7	29.0	2.94	198	158	51.6
43	7.3	10.5	8.6	<.1	181	e 1,580	366	65.3	27.3	3.36	221	977	10.3
44	7.2	11.1	6.3	<.1	206	e 2,670	454	184	118	4.60	251	1,672	83.2
45	7.3	10.3	0.1	<.1	194	2,260	388	153	56.6	7.59	--	1,458	71.0
46	7.0	10.1	0.8	<.1	275	2,810	613	105	104	33.5	335	1,530	240

Table 2. Selected well-construction, major-ion, nutrient, stable isotopes of hydrogen and oxygen, and tritium data from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

Local identification number	pH, water, whole, field (standard units)	Temperature, water (°C)	Oxygen, dissolved (mg/L)	Hydrogen sulfide, unfiltered (mg/L)	Alkalinity, water, dissolved, field (mg/L as CaCO$_3$)	Total dissolved solids (mg/L)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Bicarbonate, water, dissolved, field, (mg/L as HCO$_3$)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)
47	7.2	13.6	3.7	<.1	102	e 4,690	606	321	332	7.34	--	2,396	925
47	7.4	12.9	4.1	<.1	98	e 4,550	616	318	370	7.04	120	2,355	785
48	7.2	11.8	6.4	<.1	177	1,750	485	18.9	27.7	3.01	216	1,057	37.2
49	7.1	11.2	6.6	<.1	267	e 2,380	621	65.5	36.3	5.91	325	1,425	42.8
50	7.1	12.8	6.1	<.1	174	e 2,120	544	21.7	21.6	4.49	--	1,369	22.0
51	7.2	10.6	1.3	<.1	218	2,070	457	59.1	127	2.37	266	1,056	229
52	7.1	9.6	6.7	<.1	214	e 1,440	306	73.3	23.9	2.80	--	870	17.3
53	7.2	9.6	0.2	.1	195	1,750	459	48.2	16.7	2.97	238	1,076	17.0
54	7.4	11.4	6.0	<.1	235	e 1,740	350	78.6	57.3	2.41	286	1,046	42.2
55	7.1	11.4	5.5	<.1	216	e 1,830	465	55.6	8.65	3.61	264	1,132	7.20
56	7.1	11.1	4.5	<.1	307	1,610	423	40.8	7.26	3.95	375	921	2.36
57	7.0	12.5	4.2	<.1	240	1,240	309	39.8	7.28	3.42	--	712	2.67
58	7.2	11.2	4.1	<.1	224	e 2,090	461	83.1	51.6	2.61	274	1,310	24.6
59	7.4	13.5	6.2	<.1	--	e 682	67.6	29.6	118	2.70	--	253	67.1
60	7.5	8.5	3.9	<.1	199	363	88.0	22.5	4.45	1.22	243	111	1.37
61	7.4	11.6	4.8	<.1	273	e 1,040	256	44.8	6.73	2.45	333	539	2.69
62	7.4	15.1	0.1	<.1	188	5,320	471	109	1,217	12.9	--	1,380	2,000
63	7.2	12.4	0.6	<.1	289	e 4,540	534	156	756	23.3	353	1,426	1,445
64	7.4	11.0	0.3	<.1	255	2,400	425	69.2	223	12.1	311	1,375	126
65	7.5	11.7	0.1	.2	362	4,860	596	280	628	10.1	441	1,665	1,428
66	8.3	0.2	10.4	--	66	e 115	23.7	4.65	11.9	.59	80	3.31	25.6
66	8.4	1.5	10.8	--	56	e 178	26.9	5.72	32.7	.77	68	3.24	69.5
66	8.1	3.5	9.8	--	43	e 60	14.4	2.55	4.10	.44	51	1.43	7.09
66	8.5	12.6	7.9	--	62	93	22.3	4.58	7.03	.67	75	3.38	12.8
69	9.0	13.2	8.8	--	117	e 205	52.5	9.06	7.52	1.38	130	42.4	14.8
70	8.2	0.2	11.0	--	85	e 180	38.8	11.5	6.89	1.10	103	53.2	8.76
70	8.2	2.0	11.0	--	72	e 151	31.4	8.80	8.90	1.04	87	35.1	14.6
70	8.2	3.8	10.3	--	51	e 72	17.3	4.50	2.24	.55	62	8.43	2.40
70	8.6	16.3	8.1	--	76	e 139	32.2	8.20	3.71	.97	91	36.7	5.61
71	9.0	21.2	6.8	--	109	424	60.0	14.1	72.0	2.72	124	92.7	109
71	--	18.0	--	--	--	--	--	--	--	--	--	--	--
71	8.6	0.0	11.8	--	106	492	61.7	15.2	85.7	2.84	127	108	141
71	8.7	6.7	10.4	--	87	e 315	44.7	12.1	46.8	2.00	104	73.4	74.7
71	8.2	5.5	10.0	--	48	e 84	18.1	4.50	5.07	.63	58	14.7	6.08
71	8.5	15.2	11.3	--	96	e 388	55.7	12.4	68.6	2.56	114	82.5	102
72	8.2	1.7	10.6	--	106	e 287	68.4	13.9	3.09	.67	128	127	0.86
72	8.5	8.3	9.3	--	82	e 273	69.8	13.6	3.12	.71	98	126	1.10
72	8.3	3.9	10.5	--	70	130	34.0	6.30	1.63	.47	85	38.0	0.56
72	8.5	15.0	7.8	--	106	e 263	66.8	13.1	2.97	.67	126	106	0.86
73	8.3	1.1	11.0	--	114	e 288	79.9	9.30	2.45	.46	137	118	0.46
73	8.5	5.8	9.9	--	115	e 321	86.8	10.5	2.77	.55	137	142	0.60
73	8.4	8.0	9.3	--	86	e 170	46.7	5.73	1.75	.34	103	56.0	0.33
73	8.4	10.1	8.7	--	113	e 259	72.7	8.33	2.31	.40	135	98.1	0.38
74	8.6	0.9	12.8	--	118	e 501	83.5	17.5	61.3	2.57	139	155	98.8
74	8.2	7.4	9.9	--	113	436	70.4	16.2	55.6	2.67	136	126	86.2
74	8.1	6.3	10.0	--	54	e 105	23.3	4.97	5.66	.74	66	25.0	6.63
74	8.6	16.5	10.7	--	125	511	95.5	16.4	57.8	2.91	147	172	85.0

Table 2. Selected well-construction, major-ion, nutrient, stable isotopes of hydrogen and oxygen, and tritium data from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

[--, no data; na, not applicable; GW, groundwater; SW, surface water; m, month; d, day; y, year; >, greater than; <, less than; e, constituent detected, but concentration is estimated; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; pCi/L, picocuries per liter; ND, not detected; per mil, parts per thousand; pCi/L, picocuries per liter; oxidized, waters under oxidized geochemical conditions; reduced, waters under reducing geochemical conditions; mixture, mixture of waters under oxidized and reduced geochemical conditions]

Local identification number	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Nitrite, dissolved (mg/L)	Nitrite plus nitrate, dissolved, as nitrogen (mg/L)	Ammonia, dissolved (mg/L)	Orthophosphate, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Oxidation state	Hydrogen 2/1 ratio (per mil)	Oxygen 18/16 ratio (per mil)	Tritium (pCi/L)	Tritium, 2 sigma precision estimate (pCi/L)
5	e 0.05	5.42	e 0.001	0.37	<0.02	e 0.004	5	60	13.0	oxidized	–126	–17.34	27.5	0.96
6	e .07	6.62	<.002	.37	<.02	e .003	6	<6	<0.2	oxidized	–129	–17.32	24.6	.96
7	e .09	6.25	<.002	.37	<.02	e .004	7	<6	<.2	oxidized	–127	–17.28	32.3	.96
8	.12	6.77	<.002	.23	<.02	<.006	7	<6	12.2	oxidized	–126	–17.23	28.2	.96
9	e .06	6.21	<.002	.79	<.02	e .004	7	<6	<.2	oxidized	–126	–16.99	29.1	.96
10	e .06	10.6	<.002	.70	<.02	e .005	15	e 4	e .1	oxidized	–125	–16.75	21.4	.74
11	.13	7.81	<.002	.99	.01	.011	26	7	<.6	oxidized	–129	–17.33	33.9	1.31
11	.12	6.95	<.002	.62	<.02	.011	24	e 4	e .2	oxidized	–127	–17.40	27.8	.96
12	e .07	9.62	<.002	1.10	<.02	.007	42	<6	e .1	oxidized	–128	–17.18	26.2	.96
13	e .09	8.12	<.002	1.30	<.02	e .004	21	20	.6	oxidized	–128	–17.22	27.8	.96
14	e .07	8.59	<.002	.79	<.02	e .004	12	20	.6	oxidized	–127	–16.99	20.2	.96
15	e .08	13.2	<.002	2.71	<.02	.010	37	e 4	e .1	oxidized	–130	–17.50	45.8	1.28
16	e .08	7.43	<.002	.48	<.02	e .005	13	<6	e .1	oxidized	–126	–17.16	31.4	.96
17	.15	9.16	<.002	1.94	e .01	e .005	25	<6	<.6	oxidized	–126	–17.04	29.0	.96
18	.11	9.47	<.002	2.11	<.02	e .005	28	7	e .2	oxidized	–128	–17.00	29.4	.96
19	.12	9.37	<.002	1.80	<.02	<.006	23	25	2.1	oxidized	–126	–16.96	31.4	.96
20	.14	11.9	<.002	2.74	<.02	e .005	34	<6	<.2	oxidized	–121	–16.28	32.6	.96
21	.23	11.2	<.002	.57	<.02	e .005	15	7	.2	oxidized	–117	–16.25	26.6	.96
22	.18	9.15	<.002	.61	<.02	.007	11	21	.4	oxidized	–120	–16.42	30.7	1.28
23	.20	10.3	<.002	.44	<.02	e .006	14	9	.5	oxidized	–119	–16.32	31.7	1.28
24	.10	9.26	<.002	.45	<.02	e .003	46	10	22.9	oxidized	–127	–17.11	25.6	.96
25	.22	6.26	<.002	.39	<.02	.066	10	29	1.8	oxidized	–128	–17.33	31.7	1.28
26	.14	11.3	.006	.15	.59	.031	21	550	631.6	mixture	–121	–16.16	30.4	1.28
27	5.41	8.34	<.002	<.06	.18	.030	161	18	5.5	reduced	–131	–18.05	0.45	.51
28	.24	11.8	<.002	<.06	.00	.018	35	<6	98.3	mixture	–125	–16.69	24.0	.96
29	.14	9.78	<.002	2.25	<.02	.007	34	<6	e .1	oxidized	–126	–16.96	25.0	.96
30	.13	12.1	<.002	.87	<.02	.011	31	<6	e .2	oxidized	–128	–17.18	30.4	1.28
31	.13	10.7	<.002	.71	<.02	e .004	40	25	1.9	oxidized	–125	–16.96	24.3	.96
32	.17	15.1	<.002	1.43	<.02	.007	39	8	.5	oxidized	–126	–16.92	25.9	.96
33	.12	11.7	<.002	3.25	<.02	.007	40	25	1.2	oxidized	–123	–16.63	27.5	.96
34	.19	12.5	<.002	.64	<.02	.006	41	8	.6	oxidized	–125	–16.94	22.4	.74
35	.25	12.7	<.002	1.02	e .01	.007	32	e 6	e .4	oxidized	–125	–17.00	28.0	.90
36	.25	13.0	<.002	.78	<.02	e .004	76	203	5.0	mixture	–125	–16.80	29.4	.96
37	e .08	14.4	<.002	e .05	<.02	.028	16	11	6.3	oxidized	–131	–17.37	22.7	.96
38	.12	13.0	<.002	e .04	<.02	.006	29	35	2.1	oxidized	–126	–16.93	25.0	.96
39	.40	14.7	<.002	.26	<.02	e .004	65	25	14.6	oxidized	–126	–17.14	31.0	.96
40	.13	12.9	<.002	.36	<.02	.007	30	13	2.4	oxidized	–126	–17.03	25.6	.96
41	.14	13.6	<.002	.41	<.02	.009	28	e 5	.6	oxidized	–126	–17.14	22.4	.96
42	.13	11.6	<.002	.35	<.02	.008	20	151	4.3	mixture	–126	–17.17	26.9	.96
43	.31	16.8	<.002	1.19	<.02	e .006	122	102	3.0	mixture	–123	–16.32	32.0	.96
44	.31	16.7	.003	3.88	e .02	.008	332	127	5.9	mixture	–121	–16.14	28.8	.96
45	.20	8.90	<.002	<.06	.02	.007	260	2,021	118.1	reduced	–128	–17.22	36.2	.96
46	.18	12.5	<.002	.63	<.02	.007	134	115	21.2	mixture	–125	–16.83	30.4	.96

Table 2. Selected well-construction, major-ion, nutrient, stable isotopes of hydrogen and oxygen, and tritium data from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

Local identification number	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Nitrite, dissolved (mg/L)	Nitrite plus nitrate, dissolved, as nitrogen (mg/L)	Ammonia, dissolved (mg/L)	Orthophosphate, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Oxidation state	Hydrogen 2/1 ratio (per mil)	Oxygen 18/16 ratio (per mil)	Tritium (pCi/L)	Tritium, 2 sigma precision estimate (pCi/L)
47	.49	14.8	<.002	5.42	e .02	.011	328	34	<3.0	oxidized	–140	–17.71	4.00	.38
47	.48	14.6	<.002	5.39	e .02	.008	308	28	e 1.0	oxidized	–140	–17.8	4.9	.42
48	.23	14.8	<.002	.95	<.02	.006	35	16	.4	oxidized	–124	–16.89	29.4	.96
49	.19	13.9	<.002	2.39	<.02	e .003	106	20	e .4	oxidized	–127	–16.92	32.3	.96
50	.44	25.4	<.002	1.49	e .01	.019	62	<18	< 1.8	oxidized	–128	–17.48	28.0	.86
51	.18	12.8	<.002	<.06	<.02	<.006	45	108	90.7	mixture	–125	–16.98	27.8	.96
52	.28	17.3	<.002	.59	<.02	.010	88	9	e .5	oxidized	–130	–17.31	2.02	.35
53	.21	9.35	<.002	<.06	.03	<.006	171	545	88.9	reduced	–131	–17.65	1.50	.61
54	.26	14.0	<.002	1.77	<.02	.006	98	e 4	e .2	oxidized	–131	–17.38	10.5	.70
55	.25	17.6	<.002	1.27	<.02	.007	64	e 11	.6	oxidized	–125	–16.89	24.3	.83
56	.17	17.9	<.002	.88	<.02	.006	48	14	1.0	oxidized	–124	–16.89	28.2	.93
57	.22	17.1	<.002	.78	<.02	.009	54	113	3.9	mixture	–124	–16.90	33.9	.96
58	.37	14.0	<.002	2.86	<.02	e .005	155	e 14	<.6	oxidized	–128	–17.19	36.8	.96
59	.52	12.8	<.002	.74	<.02	.007	95	e 3	53.1	mixture	–124	–17.12	37.1	1.31
60	.12	13.6	<.002	.26	<.02	.006	21	65	1.7	oxidized	–125	–17.09	29.8	.96
61	e .10	15.3	.002	1.25	<.02	e .005	39	535	18.8	mixture	–123	–16.81	32.6	1.28
62	.22	14.4	<.002	<.06	.60	.016	176	3,811	1,500.0	reduced	–134	–17.93	42.9	1.31
63	.27	14.0	<.002	1.64	.03	.008	257	e 17	116.3	mixture	–130	–17.39	26.2	.96
64	.23	16.1	.007	1.10	<.02	.008	103	129	166.0	mixture	–124	–16.73	35.2	1.28
65	.27	23.8	.003	<.06	1.97	.110	227	8,364	993.0	reduced	–131	–17.21	20.0	.70
66	e .09	5.36	--	--	--	--	6	13	12.1	na	–126	–17.27	27.2	.96
66	e .08	5.34	--	--	--	--	9	11	15.3	na	–130	–17.78	19.8	.96
66	e .06	4.79	--	--	--	--	4	15	5.2	na	–126	–17.38	31.0	.96
66	.10	4.46	--	--	--	--	4	18	8.1	na	–119	–16.24	28.5	2.59
69	.10	4.46	.007	.54	e .01	.081	--	--	--	na	–125	–17.06	30.0	.93
70	.14	6.50	.005	.40	e .02	.020	--	--	59.8	na	–129	–17.22	29.8	1.28
70	e .07	6.32	.002	.35	<.02	.013	--	--	--	na	–130	–17.48	30.4	1.28
70	e .06	5.49	.001	.08	<.02	e .003	--	--	13.0	na	–128	–17.38	30.7	1.28
70	e .09	4.74	.002	.11	<.02	.009	--	--	13.3	na	–120	–16.31	28.2	2.59
71	.11	4.43	.008	.74	.02	.087	--	--	--	na	--	--	--	--
71	--	--	--	--	--	--	--	--	--	na	–122	–16.42	28.0	.86
71	.17	6.55	.014	1.34	.03	.165	--	--	22.3	na	–126	–17.02	29.1	.96
71	e .09	5.83	.006	.64	e .01	.063	--	--	--	na	–128	–17.27	27.8	.96
71	<.10	5.27	.001	.14	<.02	.008	--	--	8.8	na	–126	–17.23	31.7	1.28
71	.12	4.02	.005	.61	<.02	.073	--	--	7.9	na	–121	–16.28	29.4	2.59
72	e .06	9.25	--	--	--	--	11	e 5	3.2	na	–128	–17.39	28.8	.96
72	e .05	9.06	--	--	--	--	10	10	5.5	na	–130	–17.48	30.7	.96
72	<.10	6.90	--	--	--	--	7	20	3.5	na	–124	–16.90	28.8	.96
72	e .07	8.73	--	--	--	--	9	e 4	5.7	na	–125	–16.91	29.4	2.59
73	<.10	9.40	--	--	--	--	11	e 4	3.8	na	–126	–17.20	33.9	.96
73	e .05	9.15	--	--	--	--	12	e 6	5.7	na	–127	–17.30	33.0	.96
73	<.10	7.35	--	--	--	--	6	e 6	5.3	na	–123	–16.91	31.4	.96
73	<.10	9.04	--	--	--	--	10	e 5	2.1	na	–125	–17.03	32.0	2.59
74	.16	6.65	.007	1.04	e .02	.103	--	--	11.5	na	–125	–16.92	27.8	.96
74	.15	6.36	.011	.93	.03	.098	--	--	--	na	–128	–17.17	28.8	.96
74	<.10	5.45	.002	.14	<.02	.007	--	--	7.7	na	–125	–17.14	33.3	.96
74	.15	4.71	.004	.29	<.02	.038	--	--	19.6	na	–121	–16.22	28.8	2.59

Table 3. Selected ground- and surface-water-quality data used to interpret groundwater recharge dates using chlorofluorocarbons, Eagle River watershed, Eagle County, Colorado.

[gw, groundwater site; sw, surface-water site; m, month; d, day; y, year; cc/kg, cubic centimeters per kilogram; °C, degrees Celsius; NGVD 29, National Geodetic Vertical Datum of 1929; CFC, chlorofluorocarbon; mean concentration, mean CFC concentration normally calculated from three replicate samples collected at each site; pg/kg, picograms per kilogram; ppt, parts per trillion; pf, piston flow; na, not applicable]

Local identification number (see table 1 and fig. 2)	U.S. Geological Survey station identification number	Site type	Date of sample collection (mmddyy)	Excess air (cc/kg)	Recharge temperature (°C)	Recharge elevation (feet above NGVD 29)	CFC–11 mean concentration in solution (pg/kg)	CFC–11 calculated atmospheric mixing ratio (ppt)
5	393743106171000	gw	06/05/07	1.4	3.0	8,523	506.8	159.4
6	393846106193601	gw	06/08/07	1.4	2.5	8,287	475.0	143.5
7	393844106195601	gw	06/21/07	1.4	2.5	8,287	555.9	167.9
8	393830106210600	gw	06/05/07	1.4	2.5	8,217	316.8	95.5
9	393823106215900	gw	06/06/07	1.5	1.1	8,189	658.4	180.9
10	393844106232300	gw	06/06/07	2.2	3.5	8,180	531.5	170.1
11	393802106243501	gw	08/24/06	3.7	8.3	7,970	2,066.0	871.8
11	393802106243501	gw	06/19/07	3.7	8.3	7,970	1,997.4	842.9
12	393623106264201	gw	06/11/07	2.0	5.7	7,755	552.4	199.3
13	393715106280701	gw	06/19/07	2.1	4.1	7,611	639.4	208.1
14	393730106301101	gw	06/22/07	2.0	4.0	7,611	442.1	143.0
15	393830106340601	gw	06/11/07	2.3	5.8	7,380	536.0	191.8
16	393830106341501	gw	06/06/07	2.2	5.8	7,325	507.9	180.9
17	393826106345601	gw	08/24/06	2.1	8.1	7,267	853.0	348.1
18	393836106351201	gw	06/08/07	1.5	7.5	7,248	672.4	265.3
19	393844106354001	gw	05/21/07	1.2	6.2	7,213	2,391.0	873.0
20	393842106354101	gw	05/21/07	1.3	6.1	7,213	1,976.8	717.4
21	393748106364201	gw	06/08/07	1.7	7.2	7,387	588.3	229.1
22	393812106363901	gw	06/21/07	1.6	7.2	7,285	577.0	223.2
23	393823106363801	gw	06/11/07	1.6	7.2	7,280	543.5	210.3
24	393905106370801	gw	05/21/07	1.5	7.0	7,135	587.6	224.2
25	394102106392001	gw	06/09/07	1.5	9.9	7,061	491.1	220.6
27	394153106395501	gw	06/09/07	0.0	35	6,973	116.5	161.1
29	394243106422501	gw	06/07/07	1.3	8.4	6,915	429.8	176.5
30	394232106424801	gw	05/16/07	1.3	9.4	6,880	475.4	206.4
31	394055106452301	gw	05/18/07	1.3	8.15	6,755	285.7	115.0
32	394040106455701	gw	05/15/07	1.3	8.3	6,685	392.6	158.9
33	394036106462101	gw	05/15/07	1.3	8.15	6,726	625.1	251.3
34	394019106470601	gw	05/16/07	1.3	8.15	6,694	382.9	153.7
35	394020106475101	gw	08/25/06	4.8	3.8	6,652	3,057.7	937.9
36	393956106480201	gw	05/16/07	2.6	8.2	6,660	110.5	44.3
37	393431106465301	gw	06/12/07	1.4	5.2	7,618	242.3	84.5
38	393547106454601	gw	06/12/07	1.4	5.2	7,094	182.8	62.5
39	393819106472201	gw	06/20/07	1.5	12.4	6,871	272.4	139.2
40	393758106473601	gw	06/20/07	1.4	7.0	6,798	718.9	270.9
41	393807106481501	gw	06/20/07	9.0	7.0	6,733	735.6	271.8
42	393813106490201	gw	06/10/07	1.5	4.0	6,664	643.3	201.1
43	393923106504801	gw	05/17/07	2.0	6.2	6,707	1,892.2	676.9
44	393907106505201	gw	05/17/07	0.3	10.2	6,556	389.0	174.9
45	393850106511701	gw	08/23/06	3.5	11.9	6,500	57.0	27.8
46	393851106511901	gw	06/10/07	3.5	11.9	6,491	179.1	87.3
47	393917106512501	gw	08/22/06	1.7	13.1	6,650	206.5	108.5
47	393917106512501	gw	06/21/07	1.8	13.2	6,647	268.6	141.9
48	393904106513601	gw	05/23/07	3.0	9.3	6,493	455.1	192.8
49	393847106520401	gw	05/17/07	1.1	9.7	6,531	5,901.4	2,573.1
50	393903106521901	gw	08/22/06	3.0	9.3	6,460	493.0	208.6
51	393900106532901	gw	05/20/07	3.0	9.3	6,420	350.2	147.9
52	393702106545401	gw	08/23/06	1.6	6.9	6,722	623.7	232.9
53	393740106545801	gw	05/22/07	2.3	7.0	6,644	35.4	13.2
54	393819106545901	gw	05/18/07	1.6	7.2	6,550	295.8	111.7
55	393832106561101	gw	05/19/07	3.4	9.1	6,418	448.3	187.1
56	393831106562701	gw	05/19/07	3.3	9.0	6,395	563.5	233.7
57	393845106563401	gw	08/22/06	5.2	8.5	6,350	458.1	183.5

Table 3. Selected ground- and surface-water-quality data used to interpret groundwater recharge dates using chlorofluorocarbons, Eagle River watershed, Eagle County, Colorado.—Continued

[gw, groundwater site; sw, surface-water site; m, month; d, day; y, year; cc/kg, cubic centimeters per kilogram; °C, degrees Celsius; NGVD 29, National Geodetic Vertical Datum of 1929; CFC, chlorofluorocarbon; mean concentration, mean CFC concentration normally calculated from three replicate samples collected at each site; pg/kg, picograms per kilogram; ppt, parts per trillion; pf, piston flow; na, not applicable]

Local identification number (see table 1 and fig. 2)	CFC–12 mean concentration in solution (pg/kg)	CFC–12 calculated atmospheric mixing ratio (ppt)	CFC–113 mean concentration in solution (pg/kg)	CFC–113 calculated atmospheric mixing ratio (ppt)	Mean groundwater recharge date of young fraction	Percentage of young water	Mean groundwater recharge date based on:
5	714.0	1,019.1	98.0	70.0	1989	100	CFC–113 pf
6	864.0	1,188.5	40.9	28.0	1984	73	CFC–113/CFC–11 ratio
7	955.9	1,314.9	51.2	35.1	1985	79	CFC–113/CFC–11 ratio
8	496.6	681.4	28.1	19.2	1985	47	CFC–113/CFC–11 ratio
9	1,137.4	1,437.2	82.8	51.2	1991	73	CFC–113/CFC–11 ratio
10	1,146.2	1,651.0	73.5	53.4	1996	63	CFC–113/CFC–11 ratio
11	2,449.3	4,447.3	57.0	55.4	1987	100	CFC–113 pf
11	1,859.7	3,376.7	68.1	66.1	1988	100	CFC–113 pf
12	374.1	598.9	164.6	136.4	1983	100	CFC–11 pf
13	425.0	620.2	161.6	119.8	1984	100	CFC–11 pf
14	379.4	551.1	68.3	50.3	1986	100	CFC–113 pf
15	3,073.6	4,866.8	55.5	45.5	1987	84	CFC–113/CFC–11 ratio
16	5,070.4	7,998.2	68.1	55.7	1994	67	CFC–113/CFC–11 ratio
17	2,547.5	4,534.0	317.6	301.0	1987	100	CFC–11 pf
18	2,072.1	3,594.3	191.9	175.8	1991	100	CFC–11 pf
19	1,982.4	3,217.2	97.2	82.0	1992	100	CFC–113 pf
20	174,625.7	281,769.9	75.0	62.9	1988	100	CFC–113 pf
21	1,255.2	2,150.8	67.1	60.5	1989	91	CFC–113/CFC–11 ratio
22	571.8	974.5	75.8	68.0	1994	83	CFC–113/CFC–11 ratio
23	531.6	905.7	73.5	65.9	1991	76	CFC–113/CFC–11 ratio
24	663.0	1,116.0	75.0	66.3	1989	84	CFC–113/CFC–11 ratio
25	318.9	620.1	62.3	65.7	1992	83	CFC–113/CFC–11 ratio
27	260.5	1,404.9	48.3	179.8	<1940	0	CFC–11 pf
29	297.9	535.9	27.6	26.5	1981	100	CFC–113 pf
30	255.0	481.7	39.8	40.6	1985	100	CFC–113 pf
31	239.8	423.2	32.5	30.6	1989	46	CFC–113/CFC–11 ratio
32	544.0	964.9	55.4	52.4	1996	61	CFC–113/CFC–11 ratio
33	611.0	1,077.5	53.2	49.9	1986	100	CFC–113 pf
34	286.1	503.9	47.7	44.7	1991	58	CFC–113/CFC–11 ratio
35	360.8	490.3	73.2	50.5	1990	100	CFC–12 pf
36	245.3	427.2	13.4	12.4	1990	17	CFC–113/CFC–11 ratio
37	285.6	445.2	46.9	37.6	1984	100	CFC–113 pf
38	311.6	476.4	63.8	50.2	1986	100	CFC–113 pf
39	250.0	544.4	44.6	54.2	1987	100	CFC–113 pf
40	367.8	612.0	67.0	58.5	1988	100	CFC–113 pf
41	444.5	690.9	85.7	70.8	1989	100	CFC–113 pf
42	400.2	563.7	76.4	54.5	1989	80	CFC–113/CFC–11 ratio
43	445.2	704.3	63.1	51.9	1986	100	CFC–113 pf
44	276.6	542.7	51.6	55.1	1991	73	CFC–113/CFC–11 ratio
45	23.2	47.5	34.4	39.3	1965	100	CFC–11 pf
46	309.3	634.4	23.1	26.4	1992	32	CFC–113/CFC–11 ratio
47	171.7	382.2	27.7	34.7	1996	41	CFC–113/CFC–11 ratio
47	223.6	499.7	36.4	45.8	1995	54	CFC–113/CFC–11 ratio
48	309.5	563.6	60.5	59.6	1995	72	CFC–113/CFC–11 ratio
49	339.1	642.9	51.0	52.3	1986	100	CFC–113 pf
50	323.9	589.2	68.0	66.8	1996	79	CFC–113/CFC–11 ratio
51	318.6	578.7	52.8	51.9	1992	47	CFC–113/CFC–11 ratio
52	339.6	559.6	76.7	66.3	1990	90	CFC–113/CFC–11 ratio
53	255.4	419.2	7.1	6.1	1990	2	CFC–113/CFC–11 ratio
54	235.9	392.3	31.0	27.1	1988	47	CFC–113/CFC–11 ratio
55	333.5	597.6	63.1	61.0	1998	72	CFC–113/CFC–11 ratio
56	382.0	681.2	64.6	62.0	1989	93	CFC–113/CFC–11 ratio
57	382.2	652.2	60.8	55.7	1993	68	CFC–113/CFC–11 ratio

Table 3. Selected ground- and surface-water-quality data used to interpret groundwater recharge dates using chlorofluorocarbons, Eagle River watershed, Eagle County, Colorado.—Continued

[gw, groundwater site; sw, surface-water site; m, month; d, day; y, year; cc/kg, cubic centimeters per kilogram; °C, degrees Celsius; NGVD 29, National Geodetic Vertical Datum of 1929; CFC, chlorofluorocarbon; mean concentration, mean CFC concentration normally calculated from three replicate samples collected at each site; pg/kg, picograms per kilogram; ppt, parts per trillion; pf, piston flow; na, not applicable]

Local identification number (see table 1 and fig. 2)	U.S. Geological Survey station identification number	Site type	Date of sample collection (mmddyy)	Excess air (cc/kg)	Recharge temperature (°C)	Recharge elevation (feet above NGVD 29)	CFC–11 mean concentration in solution (pg/kg)	CFC–11 calculated atmospheric mixing ratio (ppt)
58	393554106564901	gw	05/20/07	1.5	11.2	6,760	252.4	120.4
59	393632106581101	gw	08/23/06	3.5	4.9	6,620	673.4	221.3
60	393658106574101	gw	05/20/07	1.2	1.9	6,528	447.6	121.9
61	393759106565701	gw	06/07/07	0.0	9.6	6,446	323.6	140.3
62	393845107022101	gw	08/25/06	2.9	11.4	6,250	26.5	12.5
63	393900107030701	gw	05/19/07	2.8	11.3	6,152	42.1	19.7
64	393902107033901	gw	05/22/07	2.7	11.1	6,155	627.1	290.0
65	393825107050301	gw	05/22/07	0.0	11.7	8,545	8.4	4.4
66	393737106165900	sw	05/23/07	0.0	3.5	8,545	669.7	218.2
66	393737106165900	sw	08/14/07	0.0	13.5	8,545	387.2	224.4
67	393834106230401	sw	08/14/07	0.0	14.7	8,120	545.4	331.0
68	393810106241501	sw	08/14/07	0.0	15.5	8,003	373.9	235.3
69	09066510	sw	08/24/06	0.0	15.6	7,725	424.6	265.7
70	09067005	sw	05/23/07	0.0	3.8	7,410	633.8	201.8
70	09067005	sw	08/14/07	0.0	18.1	7,410	333.8	233.5
71	394220106431500	sw	08/25/06	0.0	18.0	6,780	338.7	230.3
71	394220106431500	sw	08/14/07	0.0	19.9	6,820	299.3	222.9
72	09068000	sw	05/23/07	0.0	3.9	7,413	609.2	195.2
72	09068000	sw	08/14/07	0.0	14.8	7,413	370.7	220.2
73	09069500	sw	05/23/07	0.0	8	7,600	613.1	253.2
73	09069500	sw	08/14/07	0.0	13.8	7,600	395.6	224.8
74	09069000	sw	05/23/07	0.0	5.9	6,276	621.8	215.9
74	09069000	sw	08/14/07	0.0	20.1	6,276	281.1	207.0
75	09070400	sw	08/23/06	0.0	19.4	6,150	487.4	345.7
75	09070400	sw	05/23/07	0.0	5.9	6,150	613.6	212.1

CFCs provide excellent tracers and dating tools of young water (50-year time scale). Groundwater age dating with CFCs is based on Henry's law solubility, which is the concentration of the gas dissolved in water in equilibrium with air proportional to the partial pressure of the gas in air (Plummer and Busenberg, 1999). Under favorable conditions, sufficient concentrations of CFC–12, CFC–11, and CFC–113 can dissolve into water and allow dating of groundwater recharged since approximately 1941, 1947, and 1955, respectively. Groundwater age dating with CFC–12, CFC–11, and CFC–113 is possible because (1) the atmospheric mixing ratios (concentrations of the compounds in air) of these compounds are known and(or) have been reconstructed over the past 50 years, (2) the Henry's law solubilities in water are known, and (3) concentrations in air and young water are relatively high and can be measured (Plummer and Busenberg, 1999). Atmospheric concentrations of CFC–12, CFC–11, and CFC–113 in air peaked in about 2001, 1994, and 1996, respectively (fig. 3). Because of nearly level atmospheric input functions of CFC mixing ratios in the 1990s and early 2000s, it is not possible to resolve modern CFC ages as precisely as can be done with waters recharged earlier, when atmospheric concentrations were increasing rapidly (Plummer and others, 2006).

Dissolved Gases

Groundwater age dating with CFCs is based on gas solubility, which is affected by the recharge temperature and excess air in the water sample and the altitude at the location of recharge (Plummer and Busenberg, 1999). The recharge temperature is the temperature of the recharge water at the water table during recharge; overestimation of recharge temperature results in apparent ages that are too young, and underestimation gives apparent ages that are too old. Dissolved gases of argon (Ar), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), and oxygen (O_2) in groundwater were used to estimate recharge temperature and excess air of the water samples. The concentration, as well as the ratios of concentrations of dissolved gases, can be used to calculate the recharge temperature of a groundwater sample using Henry's law. Excess air is air dissolved in groundwater in relative proportions equal to that of the troposphere and in excess of that determined by solubility equilibrium. Excess air is trapped and dissolved under increased hydrostatic pressure in groundwater at the capillary fringe or in fractures as the water table rises. High concentrations of excess air are common in fractured rock

Table 3. Selected ground- and surface-water-quality data used to interpret groundwater recharge dates using chlorofluorocarbons, Eagle River watershed, Eagle County, Colorado.—Continued

[gw, groundwater site; sw, surface-water site; m, month; d, day; y, year; cc/kg, cubic centimeters per kilogram; °C, degrees Celsius; NGVD 29, National Geodetic Vertical Datum of 1929; CFC, chlorofluorocarbon; mean concentration, mean CFC concentration normally calculated from three replicate samples collected at each site; pg/kg, picograms per kilogram; ppt, parts per trillion; pf, piston flow; na, not applicable]

Local identification number (see table 1 and fig. 2)	CFC–12 mean concentration in solution (pg/kg)	CFC–12 calculated atmospheric mixing ratio (ppt)	CFC–113 mean concentration in solution (pg/kg)	CFC–113 calculated atmospheric mixing ratio (ppt)	Mean groundwater recharge date of young fraction	Percentage of young water	Mean groundwater recharge date based on:
58	4,255.9	8,719.1	30.8	34.8	1991	46	CFC–113/CFC–11 ratio
59	399.9	581.4	80.5	60.1	1989	88	CFC–113/CFC–11 ratio
60	299.4	373.5	56.8	35.0	1990	46	CFC–113/CFC–11 ratio
61	498.3	947.8	42.7	43.9	1995	52	CFC–113/CFC–11 ratio
62	25.4	50.7	8.5	9.4	1961	100	CFC–11 pf
63	89.4	177.5	4.7	5.2	1990	8	CFC–113/CFC–11 ratio
64	222.1	437.1	10.9	11.8	1975	100	CFC–113 pf
65	8.7	19.9	0.1	0.1	1958	93	CFC–11/CFC–12 ratio
66	368.3	547.1	95.8	71.6	na	na	surface water
66	223.1	554.7	47.6	66.7	na	na	surface water
67	557.3	1,442.0	115.6	170.7	na	na	surface water
68	204.9	547.3	43.2	66.4	na	na	surface water
69	204.5	543.0	54.7	83.7	na	na	surface water
70	337.4	488.7	86.9	63.5	na	na	surface water
70	207.0	606.6	41.0	71.1	na	na	surface water
71	184.5	525.6	47.5	79.9	na	na	surface water
71	163.5	505.4	38.3	71.3	na	na	surface water
72	323.4	471.1	82.9	61.0	na	na	surface water
72	200.1	506.5	47.5	68.7	na	na	surface water
73	311.9	570.6	84.3	81.8	na	na	surface water
73	211.2	513.9	51.1	70.2	na	na	surface water
74	341.6	532.4	85.2	68.7	na	na	surface water
74	160.1	489.1	35.8	65.9	na	na	surface water
75	197.7	583.5	50.2	88.7	na	na	surface water
75	324.2	503.0	83.1	66.7	na	na	surface water

aquifers and in aquifers in semiarid areas. Introduction of excess air adds CFCs to groundwater and, if not accounted for in age interpretation, causes a young-age bias (Plummer and Busenberg, 1999). Excess air is determined by comparing the ratio of N_2 to Ar in air to the equilibrium solubility-ratio of N_2 to Ar in water. In most cases, the altitude at location of recharge was estimated to be the altitude of the land surface at the wellhead.

Low-Level Volatile Organic Compounds

Recently, the USGS developed an analytical procedure (Plummer and others, 2008) to determine concentrations of 25 halogenated VOCs at minimum detection levels (MDLs) that typically are 2 to more than 4 orders of magnitude below the USGS purge and trap capillary column gas chromatograph–mass spectrometer (GC–MS) procedure (Rose and Schroeder, 1995; Connor and others, 1998). The GC–MS procedure corresponds closely to USEPA method 524 for drinking-water samples (Moran and others, 2006). The new analytical procedure for halogenated VOCs uses purge and trap gas chromatography with electron-capture detector (GC–ECD), similar to that of Busenberg and Plummer (1992). Details of the low-level VOC sampling and analyses from the USGS Chlorofluorocarbon Laboratory are given at *http://water.usgs.gov/lab/chlorofluorocarbons/lab/analytical_procedures/* and in Plummer and others (2008). “Low-level” detections of CFCs and other halogenated VOCs can be quite useful in determining whether fractions of post-1940s water are present in groundwater samples. The extremely low MDLs allow post-1940s water to be identified more frequently than it would be by using GC–MS VOC analysis.

Concentrations of 15 halogenated VOCs were determined in the Eagle County groundwaters by the GC–ECD analytical procedure (table 5). Although the VOC concentrations typically are very low and present no known health risk, their detections indicate post-1940s recharge, or mixtures of recharge that contain a fraction of post-1940s water. Concentrations of the 15 halogenated VOCs in groundwater expected from natural and anthropogenic atmospheric sources were estimated and used to recognize water samples that have VOC concentrations exceeding the natural and anthropogenic atmospheric threshold and, thus, identify those samples that are being affected from nonatmospheric sources.

Table 4. Mean concentrations of low-level volatile organic compounds detected in groundwater and surface water of the Eagle River watershed, 2006–2007, Eagle County, Colorado.

[m, month; d, day; y, year; gw, groundwater site; sw, surface-water site; --, not detected; pg/L, picograms per liter]

Local identification number (see table 1 and fig. 2)	Date of sample collection (mmddyy)	Site type	Dichloro-difluoro-methane (CFC–12) (pg/L)	Halon 1211 (pg/L)	Tetrafluoro-dichloro-ethane (CFC–114) (pg/L)	Trichloro-fluoro-methane (CFC–11) (pg/L)	Chloro-methane (methyl chloride) (pg/L)	1,1-dichloro-ethene (pg/L)	Bromo-methane (methyl bromide) (pg/L)	Trichloro-trifluoro-ethane (CFC–113) (pg/L)
5	06/05/07	gw	1,302	--	--	1,782	770	--	--	204
6	06/08/07	gw	1,470	--	--	595	297	67	--	81
7	06/21/07	gw	1,662	--	--	792	483	70	--	106
8	06/05/07	gw	933	--	--	349	490	--	--	60
9	06/06/07	gw	1,874	--	30	1,058	660	8	--	162
10	06/06/07	gw	1,923	--	30	736	395	63	--	150
11	08/24/06	gw	3,180	--	--	2,476	1,056	275	--	105
11	06/19/07	gw	2,786	--	--	2,653	1,264	51	--	138
12	06/11/07	gw	691	--	--	1,843	480	1,294	--	313
13	06/19/07	gw	758	--	13	1,620	--	243	--	306
14	06/22/07	gw	703	1	--	536	--	46	--	140
15	06/11/07	gw	4,093	--	--	1,819	--	--	--	112
16	06/06/07	gw	5,836	--	--	654	239	--	--	136
17	08/24/06	gw	3,541	--	--	1,519	1,347	438	--	544
18	06/08/07	gw	3,086	--	--	1,402	164	389	--	391
19	05/21/07	gw	2,809	2	--	3,105	--	121	--	191
20	05/21/07	gw	47,429	--	--	2,656	--	243	--	152
21	06/08/07	gw	1,945	--	--	820	--	--	--	131
22	06/21/07	gw	1,067	--	12	832	400	--	--	157
23	06/11/07	gw	959	--	11	760	283	--	--	146
24	05/21/07	gw	752	--	96	626	995	--	--	88
25	06/09/07	gw	633	--	--	681	--	--	--	133
27	06/09/07	gw	267	--	1,207	88	1,612	1,551	--	55
29	06/07/07	gw	574	--	--	529	--	28	--	57
30	05/16/07	gw	529	--	--	632	310	--	--	86
31	05/18/07	gw	474	--	18	328	334	19	--	67
33	05/15/07	gw	1,049	--	--	1,721	616	1,716	--	106
34	05/16/07	gw	535	--	--	444	308	--	--	95
35	08/25/06	gw	630	--	--	3,627	3,579	110	--	125
35	05/15/07	gw	977	--	--	474	194	--	--	114
36	05/16/07	gw	492	--	--	114	387	--	--	28
37	06/12/07	gw	555	--	74	270	359	--	--	96
38	06/12/07	gw	584	--	--	181	299	--	--	126
40	06/20/07	gw	587	--	--	1,102	--	11	--	111
41	06/20/07	gw	758	--	--	1,388	438	--	--	151
42	06/10/07	gw	671	--	95	943	622	--	--	141
43	05/17/07	gw	785	--	--	2,452	--	18	--	117
44	05/17/07	gw	663	--	47	541	66	99	--	128
45	08/23/06	gw	34	--	74	43	3,433	1,103	--	51
46	06/10/07	gw	601	--	--	192	349	--	--	48
47	08/22/06	gw	336	--	--	193	1,660	149	--	52
47	06/21/07	gw	470	--	--	306	1,207	--	--	78
48	05/23/07	gw	576	--	--	535	156	--	--	120
49	05/17/07	gw	684	--	--	7,933	--	47	--	106
50	08/22/06	gw	603	1	--	535	726	88	--	125
51	05/20/07	gw	633	--	67	417	896	--	--	110
52	08/23/06	gw	619	--	--	716	530	121	123	138
53	05/22/07	gw	512	--	45	35	282	--	--	15
54	05/18/07	gw	474	--	11	320	312	--	--	63
55	05/19/07	gw	631	--	--	574	269	--	--	130
56	05/19/07	gw	677	--	--	805	--	--	--	126
57	08/22/06	gw	650	--	--	475	267	69	--	102
58	05/20/07	gw	5,265	--	--	281	--	--	--	66

Table 4. Mean concentrations of low-level volatile organic compounds detected in groundwater and surface water of the Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

[m, month; d, day; y, year; gw, groundwater site; sw, surface-water site; --, not detected; pg/L, picograms per liter]

Local identification number (see table 1 and fig. 2)	Methyl iodide (pg/L)	Carbon tetra-chloride (pg/L)	Dichloro-methane (methylene chloride) (pg/L)	Trichloro-methane (chloroform) (pg/L)	Trichloro-ethene (TCE) (pg/L)	Tetrachloro-ethene (PCE) (pg/L)	1,1,1-Trichloro-ethane (methyl chloroform) (pg/L)	Total concentration of halogenated volatile organic compounds (TDVOC) (pg/L)	Number of volatile organic compounds detected (NUM_TDVOC)
5	56	2,987	--	16,097	--	363	505	24,066	18
6	129	2,392	--	11,938	127	192	3,286	20,574	16
7	135	3,421	--	91,964	--	258	1,982	100,874	19
8	138	1,795	--	33,228	--	35	1,145	38,172	16
9	118	2,417	--	29,741	1,864	196	692	38,820	23
10	264	3,290	--	104,504	--	255	1,607	113,218	18
11	72	480	--	143,887	--	49,482	3,243	204,256	17
11	99	4,616	--	241,456	--	40,105	3,688	296,855	18
12	56	29,287	--	918,340	--	7,224	84,883	1,044,410	16
13	135	3,335	--	49,610	--	34,276	10,014	100,309	19
14	169	1,744	--	23,569	--	869	7,125	34,902	16
15	218	1,462	--	7,716	23	125	711	16,280	14
16	68	3,029	--	24,166	--	765	478	35,371	15
17	1,253	2,433	--	9,048	5	830	7,771	28,729	22
18	99	3,719	--	213,502	--	764	10,742	234,259	16
19	85	3,380	--	201,159	1,083	146,252	16,951	375,139	17
20	114	2,738	--	532,755	--	8,916	11,487	606,490	15
21	102	2,380	--	10,959	--	405	646	17,387	13
22	65	2,215	--	12,386	--	236	522	17,894	15
23	200	1,683	--	7,952	--	180	554	12,729	19
24	74	2,442	--	13,816	107	111	477	19,583	16
25	48	4,311	--	42,668	--	351	336	49,161	16
27	59	414	--	107,410	--	236	899	113,798	24
29	109	349	--	15,815	--	624	1,958	20,042	18
30	138	1,382	--	7,618	--	425	945	12,064	13
31	174	1,051	--	6,778	19	72	473	9,806	17
33	148	1,816	--	11,101	--	510	51,409	70,192	13
34	88	671	--	8,325	--	33	580	11,079	15
35	282	901	--	2,526	--	193	992	12,964	16
35	159	588	--	3,245	25	31	504	6,311	15
36	118	144	--	25,331	--	30	256	26,899	18
37	264	--	--	16,199	--	79	129	18,026	13
38	244	--	--	16,215	--	111	155	17,914	13
40	132	1,388	--	11,194	62	176	1,013	15,776	17
41	160	1,108	--	5,279	--	219	727	10,229	14
42	307	4,936	--	639,527	--	1,376	584	649,202	20
43	9,464	1,859	--	3,640	--	77	1,367	19,778	20
44	319	644	--	27,577	31	41	493	30,650	20
45	9	213	--	103,445	--	7,666	--	116,071	23
46	45	67	--	10,337	--	161	194	11,993	13
47	661	242	--	890	--	44	179	4,407	20
47	453	1,764	--	13,470	--	28	250	18,026	17
48	39	1,092	--	4,091	42	145	527	7,323	14
49	365	967	--	5,083	--	77	863	16,125	18
50	254	442	--	5,098	35	123	320	8,350	18
51	28	301	--	20,967	--	141	398	23,959	18
52	171	722	--	1,537	--	1,099	1,161	6,935	17
53	22	98	--	7,969	--	23	--	9,001	14
54	1,291	1,592	--	6,708	25	28	554	11,377	20
55	188	986	--	4,820	--	99	617	8,313	15
56	187	829	--	5,976	--	82	649	9,330	16
57	217	560	--	120	--	362	519	3,342	16
58	3,182	1,042	--	329,954	--	59	291	340,141	15

Table 4. Mean concentrations of low-level volatile organic compounds detected in groundwater and surface water of the Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

[m, month; d, day; y, year; gw, groundwater site; sw, surface-water site; --, not detected; pg/L, picograms per liter]

Local identification number (see table 1 and fig. 2)	Date of sample collection (mmddyy)	Site type	Dichloro-difluoro-methane (CFC–12) (pg/L)	Halon 1211 (pg/L)	Tetrafluoro-dichloro-ethane (CFC–114) (pg/L)	Trichloro-fluoro-methane (CFC–11) (pg/L)	Chloro-methane (methyl chloride) (pg/L)	1,1-dichloro-ethene (pg/L)	Bromo-methane (methyl bromide) (pg/L)	Trichloro-trifluoro-ethane (CFC–113) (pg/L)
59	08/23/06	gw	726	--	27	1,083	1,291	173	--	143
60	05/20/07	gw	555	--	8	546	243	--	--	111
61	06/07/07	gw	958	--	55	370	221	--	--	90
62	08/25/06	gw	467	6	41	164	2,643	929	257	112
63	05/19/07	gw	196	--	--	40	1,044	46	--	10
64	05/22/07	gw	445	--	6	1,190	--	--	--	23
65	05/22/07	gw	114	--	41	54	380	--	--	20
66	05/23/07	sw	704	--	9	994	2,759	29	--	193
66	08/14/07	sw	527	--	--	527	2,060	--	--	113
67	08/14/07	sw	1,145	3	--	1,052	2,396	29	--	263
68	08/14/07	sw	483	--	17	486	1,555	--	--	107
70	05/23/07	sw	679	--	--	963	2,165	--	--	183
70	08/14/07	sw	481	--	17	428	1,498	--	--	95
71	08/14/07	sw	388	--	45	374	2,112	--	--	88
72	05/23/07	sw	637	--	14	843	2,080	34	--	169
72	08/14/07	sw	473	--	9	494	1,355	--	--	112
73	05/23/07	sw	613	--	19	826	2,269	24	--	169
73	08/14/07	sw	496	--	23	535	1,937	--	--	119
74	05/23/07	sw	698	--	18	932	2,105	38	--	179
74	08/14/07	sw	392	--	55	362	2,009	19	--	87
75	05/23/07	sw	649	--	--	881	2,047	--	--	174

Geographic Information System Data

Groundwater quality data were correlated with hydrogeologic data to develop the groundwater probability models and maps. Hydrogeologic data consisted of GIS data on depth to groundwater, geology, hydrography, precipitation, and soils.

The boundary of the ERWVFA was developed by combining information from two data sources. The first data source was a 1:250,000-scale geologic map of the Leadville quadrangle developed by Day and others (1999). The location of Quaternary sediments was used as a first approximation of the ERWVFA. The boundary of the ERWVFA was further refined by overlaying the geologic map with Digital Raster Graphic (DRG) scanned images of 1:24,000 topographic maps (U.S. Geological Survey, 2001). Where appropriate, the boundary of the ERWVFA was remapped to correspond with the abrupt change in topography at the edge of the valley floor throughout the Eagle River watershed. The boundary of the ERWVFA more closely resembles a hydrogeomorphic region presented by Rupert (2003, p. 8) because it is based upon general geographic locations of geologic materials and not on an actual aquifer location determined through rigorous hydrogeologic investigation.

A depth-to-groundwater GIS data layer was generated by subtracting a water-table map of groundwater in the ERWVFA from 10 m (32.8 ft) National Elevation Dataset (NED) data (U.S. Geological Survey, 1999a). The water-table map was generated by hand-contouring groundwater levels measured in 117 wells during May and June 2003 (*http://waterdata.usgs.gov/co/nwis/gw*). Because of inaccuracies in the NED data, a few riparian areas had negative depths to groundwater of a few feet because of the high water table. In this case, depth to groundwater was set at 0.3 m (1 ft) below land surface.

Geology data were developed by Day and others (1999), who produced a 1:250,000-scale geologic map of the Leadville quadrangle. Geologic units of interest include the Quaternary sediments, which were used to map the boundary of the ERWVFA, and the Eagle Valley Evaporite, which delineates the location of the gypsum beds in the area. Distance of wells from the gypsum beds was used as one of the independent variables in the logistic regression modeling.

The hydrography data in the Eagle River watershed were extracted from the National Hydrography Dataset (NHD) (U.S. Geological Survey, 1999b). The NHD data were edited to include only the major canals, rivers, and streams. Distance of wells from the major canals, rivers, and streams was used as one of the independent variables in the logistic regression modeling.

Table 4. Mean concentrations of low-level volatile organic compounds detected in groundwater and surface water of the Eagle River watershed, 2006–2007, Eagle County, Colorado.—Continued

[m, month; d, day; y, year; gw, groundwater site; sw, surface-water site; --, not detected; pg/L, picograms per liter]

Local identification number (see table 1 and fig. 2)	Methyl iodide (pg/L)	Carbon tetra-chloride (pg/L)	Dichloro-methane (methylene chloride) (pg/L)	Trichloro-methane (chloroform) (pg/L)	Trichloro-ethene (TCE) (pg/L)	Tetrachloro-ethene (PCE) (pg/L)	1,1,1-Trichloro-ethane (methyl chloroform) (pg/L)	Total concentration of halogenated volatile organic compounds (TDVOC) (pg/L)	Number of volatile organic compounds detected (NUM_TDVOC)
59	171	864	--	1,817	56	1,339	443	8,134	17
60	110	860	--	8,655	40	178	585	11,889	16
61	144	2,244	--	10,690	105	117	1,059	16,054	17
62	7	541	--	1,995	--	193	--	7,355	27
63	643	--	--	6,948	262	1,309	2,412	12,910	16
64	114	26	--	2,945	25	57	474	5,306	17
65	22	134	--	39,112	--	64	--	39,941	16
66	50	10,985	--	791	33	172	418	17,137	18
66	43	5,261	--	634	--	73	196	9,434	15
67	58	5,665	--	2,668	175	190	280	13,925	20
68	71	4,378	--	3,163	28	157	217	10,661	16
70	102	11,819	--	2,785	89	400	522	19,707	16
70	99	5,567	--	6,970	36	164	288	15,644	18
71	205	5,056	--	7,287	78	78	249	15,961	17
72	102	9,369	--	764	53	143	361	14,569	18
72	89	5,688	--	503	--	49	207	8,979	14
73	64	9,211	--	271	59	139	362	14,027	18
73	84	6,464	--	410	--	50	196	10,313	16
74	116	11,337	--	3,877	288	537	2,756	22,880	19
74	174	4,341	--	2,690	54	169	155	10,507	17
75	98	11,150	--	2,846	86	259	472	18,663	16

Estimates of average annual precipitation for 1961–90 were developed by Daly and others (1994), with the Parameter-elevation Regressions on Independent Slopes Model (PRISM). PRISM uses climatic point data and a digital elevation model (DEM) to generate gridded estimates of climatic parameters. PRISM has been used extensively to map precipitation and minimum and maximum temperature over the United States, Canada, and other countries.

Three sources of soils data were used. The first were the Soil Survey Geographic database (SSURGO) soils data, which were developed by the Natural Resources Conservation Service (NRCS) at approximately 1:24,000 scale (U.S. Department of Agriculture, 2008). The SSURGO soils data included a variable for depth to groundwater within the soil horizon, which is defined as “the shallowest depth to a wet soil horizon.” This is different than the depth to groundwater mentioned earlier, which used water-table elevations to calculate depth to the groundwater in the entire unsaturated zone and not just the soil horizon. In the soils data, depth to groundwater in the soils horizon was set to the maximum value of 201 cm (79 inches) if the depth was greater than the thickness of the soil horizon. The SSURGO data included a soil factor called “the soil septic suitability factor,” which rates the suitability of a certain soil for use by septic-tank absorption fields. The suitability factor is based on soil ratings of saturated hydraulic conductivity, depth to water table in soils layer, ponding, depth to bedrock in the soil layer, and flooding between soil depths of 610 and 1,829 mm (24 and 72 inches). The SSURGO data do not extend east of Vail; soils data mapped in the White River National Forest were used in the portion of the study area where SSURGO soils data were not mapped (U.S. Department of Agriculture, 1999). The SSURGO and White River National Forest soils data were checked to assure consistency between the two data sets. State Soil Geographic soils data (STATSGO), which are soils data developed at a much smaller scale (approximately 1:250,000 scale), but which cover the entire study area, also were used (U.S. Department of Agriculture, 1991). The STATSGO data were not suitable for use in raw form, so STATSGO data compiled by Schwarz and Alexander (1995) were used. The Schwarz and Alexander (1995) data included weighted averaging of many of the soil characteristics. Some SSURGO and STATSGO soil variables, such as soil hydrologic group, were categorical variables. To facilitate modeling with logistic regression, categorical variables were transformed to numerical variables. For instance, soil hydrologic group is rated in four categories from A through D, with A having the highest infiltration and D having the smallest. Soil hydrologic group A was transformed to a numerical rating of one, and soil hydrologic group D was transformed to a numerical rating of four.

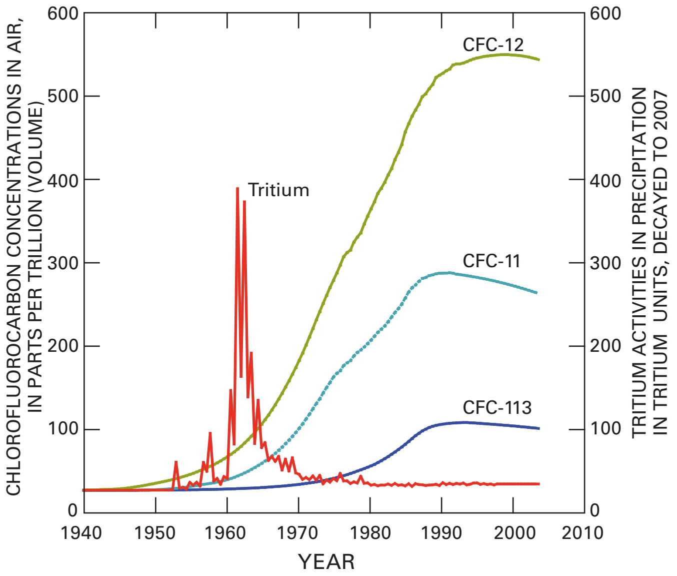


Figure 3. Concentrations of CFC–12, CFC–11, and CFC–113 in precipitation, and tritium activities in precipitation, 1940–2007.

Delineating Contributing Areas to Sampled Wells

Previous statistically based groundwater probability assessments have delineated the land cover and hydrogeologic factors potentially affecting groundwater quality by using circular buffers of various radii (Rupert, 2003). A 500-m (1,640-ft) radius has been the most common radial length for the circular buffer method (Eckhardt and Stackelberg, 1995; Nolan and others, 2002). If the groundwater flow direction is not known, circular buffers provide a first approximation of the contributing area. However, if groundwater flow directions are known, an upgradient pie-shaped buffer may provide more accurate delineation of the contributing area (fig. 4). Lorenz and others (2003), Gurdak (2008), Gurdak and others (2007), and Gurdak and Qi (2006) characterized land use near individual wells within an upgradient pie-shaped sector and determined that the sector method presented a more accurate estimate of land use affecting water quality in an individual well than the circular-buffer method.

A modified version of the sector method was developed and used to delineate the contributing area of wells. For each well, an upgradient 90-degree sector was established from GIS-based water-table and groundwater-flow maps. The radial length of each sector was determined based on hypothetical groundwater-flow modeling and particle-tracking simulations. MODFLOW-2000 (Harbaugh and others, 2000) was used for groundwater flow modeling, and MODPATH/MODPATH-PLOT (Pollock, 1994) was used for particle-tracking simulations of the results from the groundwater-flow modeling. Insufficient data exist for model calibration at each well location. Instead, hypothetical groundwater-flow simulations were conducted across an idealized section of the aquifer to evaluate model response to variations in boundary conditions and hydrogeologic parameters. The goal of the modeling was to determine the most probable radial length of a sector for a hypothetical well, and then apply this length to all of the wells in the study area. Because simulations were run for a hypothetical, idealized system, model calibration was not required (Reilly and Harbaugh, 2004).

To simulate regional groundwater flow, a 250-row by 250-column, two-dimensional model with square, 10-m (32.8-ft) cells was constructed. The east boundary was modeled as a river with constant head, and the west side was modeled as a drain with constant head. Regional groundwater gradients were calculated for major portions of the ERWVFA using measured water levels; the elevation of the river and the drain in the model were adjusted to simulate the average regional gradient (12.5 m/km [134.6 ft/mi]). A review of drillers' records on file with the State of Colorado Engineers Office indicated that only a handful of wells drilled in the ERWVFA were drilled to the bedrock, so quantitative data on the maximum depth of the ERWVFA were not available. However, a reasonable estimate of the maximum probable thickness of the ERWVFA is 100 m (328 ft), so the bottom of the aquifer in the hypothetical groundwater flow model was set to 100 m (328 ft) below the bottom of the drain.

A forward particle-tracking method was used for all simulations. In this tracking method, one particle was started at the water table and tracked forward during an 18-year simulation. Particle-tracking estimates were calculated for an 18-year travel path because, as will be presented in the "Chlorofluorocarbons and Groundwater Age" section of this report, the median groundwater age of water sampled was 18 years. As a check

Table 5. Concentrations, approximate retention times, and minimum detection levels of halogenated volatile organic compounds detected in the Eagle River watershed, 2006–2007, Eagle County, Colorado.

[MDL, minimum detection level; pg/L, picograms per liter for sample volume of 34 cubic centimeters; na, not available; GC–ECD, gas chromatography with electron-capture detector]

Compound	Retention time (minutes)	Alternate name	GC–ECD MDL (pg/L)
dichlorodifluoromethane	2.53	CFC–12	5.5
Halon 1211	3.36	none	1.3
tetrafluorodichloroethane	3.52	CFC–114	22
trichlorofluoromethane	4.34	CFC–11	1.2
chloromethane	4.88	methyl chloride	326
1,1-dichloroethene	6	none	72
bromomethane	6.64	methyl bromide	356
trichlorotrifluoroethane	7.13	CFC–113	9.4
methyl iodide	9.45	none	na
carbon tetrachloride	10.17	none	19
dichloromethane	12.42	methylene chloride	564
trichloromethane	15.93	chloroform	52
trichloroethene	16.52	TCE	20
tetrachloroethene	20.35	PCE	9.9
1,1,1-trichloroethane	23.24	methyl chloroform	161

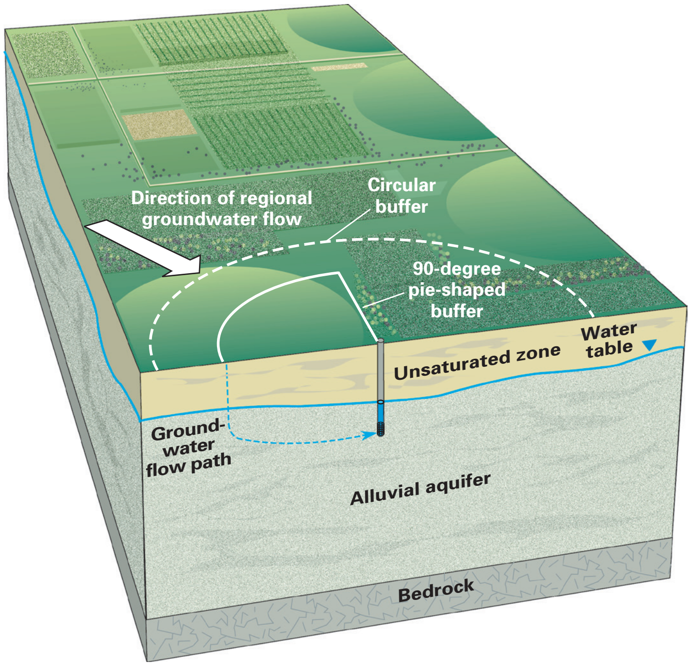


Figure 4. Conceptual diagram of 90-degree pie-shaped buffer and circular buffer for delineating areas contributing recharge to a well.

against the results of the forward-tracking simulations, backward particle-tracking simulations also were run. Because of the lack of weak or strong sinks in the simulations, backward tracking produced nearly identical results as in the forward-tracking simulations and therefore are not presented in this report.

Particles were tracked to two endpoints, the drain and a domestic well, because 72 percent of the wells sampled were domestic wells and 13 percent were monitoring wells. A hypothetical domestic well that continuously pumped water at a discharge rate of 82 m^3/d (15 gal/min) was modeled, which is conservatively large because domestic wells rarely pump continuously. Groundwater flow modeling and particle tracking indicated that there was little measurable effect on the water table or particle locations from pumping of the domestic well, indicating that groundwater quality is influenced by regional groundwater flow directions/velocities and not by induced flow paths from a single pumping domestic well. Only in the case of hydraulic conductivity (K) values of 0.1 m/d (0.3 ft/d) did the domestic well have measurable effects on groundwater flow directions. The path lines of particles to the drains were used for the final determination of the radial sector length, but any location in the study area would produce results identical to the hypothetical domestic well because the model was simulating regional flow in steady-state conditions.

Very little data exist on hydraulic conductivity and groundwater recharge values in the Eagle River watershed, so a Monte Carlo approach described by Starn and others (2000) was used to determine the probability of particles reaching the drain and domestic well under a variety of hydraulic conductivity and recharge values. The term Monte Carlo refers to a computational approach where groundwater model parameters of hydraulic conductivity and recharge are randomly varied for a large number of model simulations, and the probability of a particle being in the contributing area is calculated based upon the results of the multiple simulations. Monte Carlo simulation was useful because it allowed the most probable path lengths to be bracketed.

One hundred Monte Carlo simulations were calculated using random, normally distributed values of hydraulic conductivity and recharge, which was a sufficient number of simulations to determine the most probable path lengths and remain within reasonable computational time limits. Hydraulic conductivity values were randomly varied to fit a normal distribution between 0.1 and 10 m/d (0.3 and 32.8 ft/d) during the Monte Carlo simulations, which are reasonable values for unconsolidated aquifer materials consisting of various proportions of sand, silt, gravel, and clay (Bouwer, 1978). An unpublished report by an engineering firm working on municipal supply wells in the Eagle River watershed reported hydraulic conductivity values ranging from 0.1 to 6.5 m/d (0.3 to 21.3 ft/d) and an average value of 1.9 m/d (6.2 ft/d) (Todd Fessenden, Eagle River Water and Sanitation District, written commun., 2007), confirming that hydraulic conductivity values between 0.1 and 10 m/d (0.3 and 32.8 ft/d) are reasonable for the Monte Carlo simulations. Daly and others (1994) reported precipitation estimates for the study area; recharge estimates based on 10 percent of the zero, minimum, median, and maximum precipitation amounts were zero, 2.8, 3.3, and 6.6 mm/yr respectively (0, 1.1, 1.3, and 2.6 inches/yr). During the Monte Carlo simulations, recharge estimates were randomly varied to fit a normal distribution between zero and 6.6 mm/d (0 and 0.26 inches/yr) to bracket the precipitation estimates reported by Daly and others (1994). A porosity value of 0.3 was set as a constant value in the Monte Carlo simulations, which is an approximate median value for aquifer materials composed of various mixtures of silt, sand, and gravel (Bouwer, 1978).

The results of the Monte Carlo simulation indicated that there was a 0.90 probability that the path length to the drain during a 18-year time period was about 500 m (1,640 ft); 500 m (1,640 ft) was used in all subsequent calculations. A value of 0.90 probability was selected because this corresponds to the largest acceptable individual p-value that was used during logistic regression statistical modeling. A radial sector length of 500-m (1,640-ft) was used to determine soils properties within each pie-shaped area, which was then used in the logistic regression modeling. For each logistic regression model run, the same 500-m (1,640-ft) radial sector length was used for all wells. Gurdak and Qi (2006) used different radial sector lengths depending on estimated K values, but data are insufficient to justify using different radial sector lengths in logistic regression model runs.

Logistic Regression Statistical Method

Logistic regression (Hosmer and Lemeshow, 1989; Kleinbaum, 1994; Helsel and Hirsch, 1992) is a statistical method that predicts the probability of the occurrence of the target water-quality constituent above a certain level or threshold. For instance, logistic regression can predict the probability of detecting concentrations of nitrate in groundwater greater than or equal to 1 mg/L. A major advantage of logistic regression over multiple regression is that the former is well suited for analysis of data sets with a large number of nondetections. Logistic regression is conceptually similar to multiple linear regression because relations between one dependent variable and several independent variables are evaluated. Whereas multiple linear regression returns a continuous value for the dependent variable, logistic regression returns the probability of a positive binomial outcome (in this case, nitrate concentrations were or were not above 1 mg/L) in the form:

$$P = e^{x}/(1+e^{x}) \qquad (1)$$

where

P is the probability of nitrate concentrations above 1 mg/L;

x is $\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i$;

β_i is logistic regression coefficients;

x_i is values for the independent variables such as soil drainage or depth to groundwater;

and

i is the number of variables.

Logistic regression calculates several statistical parameters that determine the predictive success of the model. The log-likelihood ratio measures the success of the model as a whole by comparing observed values with predicted values (Hosmer and Lemeshow, 1989, p. 13); specifically, the ratio tests whether model coefficients of the entire model are significantly different from zero. The most significant model is the one with the highest log-likelihood ratio, taking into account the number of independent variables (degrees of freedom) used in the model. The log-likelihood ratio follows a chi-squared distribution, and the computed p-value indicates whether model coefficients are significantly different from zero. Therefore, the computed p-value is the significance level attained by the data; the smallest p-value indicates the best model. A p-value of 0.05 indicates a probability of a correct decision (regarding null hypothesis rejection) of 0.95; a p-value of 0.01 indicates a probability of 0.99. McFadden's rho-squared (SYSTAT Software, Inc., 2004) is a transformation of the log-likelihood statistic and is intended to mimic the r-squared of linear regression. Rho-squared is always between zero and 1; a rho-squared approaching 1 corresponds to more significant results. Rho-squared tends to be smaller than r-squared, so a small number does not necessarily imply a poor fit. Values between 0.20 and 0.40 indicate good results (SYSTAT Software, Inc., 2004). P-values are calculated for each independent variable, which indicate the statistical significance that each variable has on the overall logistic regression model. Independent variables were excluded from the models if their individual p-values were greater than 0.1. The sensitivity is calculated as the number of correctly **predicted** events (nitrate detections) divided by the total number of **observed** events (SYSTAT Software, Inc., 2004). The specificity is calculated as the number of correctly predicted **reference** events (no nitrate detections) divided by the total number of observed **reference** events. The total correct predictions is calculated as the number of correctly predicted events plus the number of correctly predicted reference events divided by the total number of all events. To verify the models, the percentage of actual detections was plotted with the predicted probability of detections by using a deciles of risk calculation, which typically involves partitioning the observations into 10 groups (SYSTAT Software, Inc., 2004, p. II–238).

During construction of the logistic regression models, all possible combinations of independent variables were evaluated to develop the most accurate logistic regression models. The models were built by including each individual variable in the model, evaluating the resulting test statistics, and deciding whether to include or reject the variable. Model validity and accuracy were determined by evaluating the log-likelihood ratio, McFadden's rho-squared, the model sensitivity and specificity, and the p-values calculated for each independent variable. During construction of the logistic regression models, the data were checked for multicolinearity by calculating the variance inflation factor (VIF). Multicolinearity means that at least one independent variable is closely related to one or more other independent variables. All VIFs in the final models were less than 10, which is the level of concern indicated by Helsel and Hirsch (1992, p. 306).

Construction of the Probability Maps

Maps showing the probability of groundwater contamination by various contaminants, or the likelihood of the presence of young water, were developed using the logistic regression models. Before constructing the maps, all GIS data were converted to grids with 10-m (32.8-ft) spacing. The soils data required an additional processing step. To create the data set for logistic regression modeling, soils data were averaged within 500-m (1,640-ft) pie-shaped buffers oriented upgradient from each well site. To create the final probability maps, the soils data within 500-m (1,640-ft) pie-shaped buffers oriented upgradient from every grid cell in each soils layer/factor were averaged. After the soils data were averaged, then the logistic regression models similar to equation 1 were entered into a GIS, and a probability rating was calculated for each grid node in the study area.

The groundwater probability models were developed as follows: (1) The groundwater quality and groundwater age data were overlaid with anthropogenic and hydrogeologic data by using a geographic information system to produce a data set in which each well had corresponding data on depth to groundwater, distance to major streams and canals, distance to gypsum beds, precipitation, soils, and well depth. These data then were downloaded to a statistical software package for analysis by logistic regression. (2) Statistical models predicting the probability of elevated nitrate concentrations, the probability of unmixed young water (using chlorofluorocarbon-11 concentrations and tritium activities), and the probability of elevated volatile organic compound concentrations were developed using logistic regression techniques. (3) The statistical models were entered into a GIS and the probability maps were constructed.

Water Chemistry and Groundwater Age

This section describes the results of water-quality sampling from sites completed in the ERWVFA and from Brush Creek, Gore Creek, Gypsum Creek, and the Eagle River. Groundwater and surface-water samples were analyzed for major ions, nutrients, ^{2}H and ^{18}O of water, tritium, CFCs, and VOCs. The results of the laboratory analyses are presented in this section; results then are synthesized in a later section entitled “Groundwater Probability Modeling.”

Quality Assurance and Quality Control

The field blank, replicate, and cation-anion balance data indicate that the major-ion and nutrient data are of high quality and suitable for quantitative analysis of ground- and surface-water quality. Concentrations of major ions and nutrients in the field blanks are mostly below laboratory reporting levels (table 6). Calcium, magnesium, nitrite, ammonia, boron, iron, and manganese were detected in a few field blanks, but in general, the concentrations were much smaller than those compounds detected in native and replicate samples (table 2, table 7). Analysis of the major-ion and nutrient field blanks indicated that the decontamination procedures of the sampling equipment were effective at cleaning the equipment between sampling sites and that there was no contamination occurring during sample collection, transport, and analysis that could affect the results of this report.

Concentrations of major ions and nutrients detected in native samples were comparable to those detected in the replicate samples (table 7). The relative percent difference (RPD) between native and replicate analyses was calculated using the following equation:

$$\mathrm{RPD} = [(\mathrm{larger\_result} - \mathrm{smaller\_result})*100]/[(\mathrm{larger\_result} + \mathrm{smaller\_result}) / 2]. \qquad (2)$$

The RPD of concentrations was very small for most analytes; the median RPD was 0.95 percent, the mean RPD was 3.4 percent, and the standard deviation was 7.8 percent. Laboratory alkalinity, orthophosphate, iron, and manganese had relatively large RPDs in a few samples (table 7). Laboratory alkalinity can sometimes display large RPDs because of the time lag from when the samples were collected to when they were analyzed in the laboratory. Overall, the replicate samples indicated that there was low variability (high precision) in the major-ion and nutrient analyses.

The accuracy of the major-ion and nutrient analyses also was checked by calculating the cation-anion balance. The difference between the sum of the cations and the sum of the anions (in milliequivalents) should be plus or minus 5 percent for the laboratory analyses to be considered “in control.” The mean cation-anion balance for all groundwater and surface-water native samples was 0.218 percent, the median was 0.450 percent, and the standard deviation was 1.814 percent. Out of 89 total analyses, only 2 analyses were larger than plus or minus 5 percent (5.02 and 6.45 percent). The cation-anion balance indicated no discrepancies with major-ion or nutrient analyses.

Major Ions

A trilinear diagram was used to represent the major-ion chemistry of surface-water samples collected from Brush Creek near Eagle, Eagle River at Avon, Eagle River at Gypsum, Eagle River at Wolcott, Gore Creek below Black Gore Creek, and Gypsum Creek near Gypsum (fig. 5). Trilinear diagrams are useful for classifying different water types and for identifying the mixing and evolution of different water types (Freeze and Cherry, 1979; Piper, 1944). A trilinear diagram shows the relative proportion of ions in a water sample, not their concentrations. The seasonal differences of surface-water chemistry in the Eagle River watershed is demonstrated by the arrows in figure 5. Surface-water samples were collected quarterly from the six surface-water sites during March, May, August, and December 2007. The samples collected during May contain a large proportion of snowmelt runoff. The August, December, and March samples from each site tend to group in a different area of figure 5 because they contain a larger proportion of base flow, which is the portion of streamflow that predominantly comes from groundwater and not snowmelt runoff. The arrows in figure 5 show the relative differences of water quality beginning in May and progressing through March of the next year.

Using a trilinear diagram, groundwaters in the ERWVFA can be classified into two major groups: groundwater that was recharged by infiltration of surface water and groundwater that had less immediate recharge from surface water and has elevated sulfate concentrations (fig. 6). Groundwater that was recharged by infiltration of surface water plots in the same vicinity as the surface-water samples (fig. 6). In many cases, these groundwaters have compositions within the seasonal fluctuations of

Table 6. Major ion and nutrient analyses of blank samples collected from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado, arranged chronologically.

[mg/L, milligrams per liter; µg/L, micrograms per liter; --, no data; m, month; d, day; y, year; <, less than; e, constituent detected, but concentration is estimated]

Local identification number	74	32	60	73	5	42	40	72
U.S. Geological Survey station identification number	09069000	394040106455701	393658106574101	09069500	393743106171000	393813106490201	393758106473601	09068000
Date of sample collection (mmddyy)	02/13/07	05/15/07	05/20/07	05/24/07	06/02/07	06/10/07	06/23/07	08/30/07
Alkalinity, dissolved, mg/L as calcium carbonate	--	<5	<5	<5	<5	<5	<5	<5
Ammonia, dissolved, mg/L as nitrogen	<0.020	<0.020	e0.012	--	e0.010	<0.020	<0.020	--
Nitrite, dissolved, mg/L as nitrogen	<0.002	<0.002	<0.002	--	e0.001	<0.002	<0.002	--
Nitrite plus nitrate, dissolved, mg/L as nitrogen	<0.016	<0.06	<0.06	--	<0.06	<0.06	<0.06	--
Orthophosphate, dissolved, mg/L as phosphorus	<0.006	<0.006	<0.006	--	<0.006	<0.006	<0.006	--
Calcium, dissolved, mg/L	<0.02	<0.02	<0.02	<0.02	0.14	0.12	0.03	<0.02
Magnesium, dissolved, mg/L	<0.014	<0.014	<0.014	<0.014	<0.014	e0.008	<0.014	<0.014
Sodium, dissolved, mg/L	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Potassium, dissolved, mg/L	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Chloride, dissolved, mg/L	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
Sulfate, dissolved, mg/L	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
Fluoride, dissolved, mg/L	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Silica, dissolved, mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Boron, dissolved, µg/L	--	<1.8	2.2	e1.6	1.9	2.6	2.4	<1.8
Iron, dissolved, µg/L	--	<6	<6	<6	11	e3	<6	<6
Manganese, dissolved, µg/L	--	<0.2	<0.2	<0.2	0.3	e0.2	<0.2	<0.2

Table 7. Analyses of replicate samples of major ions, nutrients, stable isotopes of hydrogen and oxygen, and tritium collected from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado, arranged chronologically.

[$CaCO_3$, calcium carbonate; °C, degrees Celsius; %, percent; diss., dissolved; lab., laboratory analysis; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; RPD, relative percent difference; --, no data; m, month; d, day; y, year; < less than; e, estimated]

Local identification number	**11**			**69**			**66**			**72**		
U.S. Geological Survey station identification number	**393802106243501**			**09066510**			**393737106165900**			**09068000**		
Date of sample collection (mmddyy)	**08/24/06**			**12/20/06**			**12/20/06**			**03/20/07**		
Sample type	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %
Specific conductance, lab., µS/cm at 25°C	637	637	0.0	--	--	--	230	229	0.4	469	468	0.2
pH, lab., standard units	7.5	7.5	0.0	--	--	--	8.2	8.2	0.0	8.3	8.3	0.0
Alkalinity, diss., lab., mg/L as $CaCO_3$	181	181	0.0	--	--	--	68	69	1.5	111	110	0.9
Alkalinity, diss., field, mg/L as $CaCO_3$	177	175	1.1	111	112	0.9	66	67	1.5	82	102	21.7
Ammonia, diss., mg/L as N	0.01	e0.009	--	e0.015	e0.013	--	--	--	--	--	--	--
Nitrite, diss., mg/L as N	<0.002	<0.002	--	0.03	0.03	0.0	--	--	--	--	--	--
Nitrite plus nitrate, diss., mg/L as N	0.99	0.99	0.0	1.38	1.32	4.4	--	--	--	--	--	--
Orthophosphate, diss., mg/L as P	0.011	0.01	9.5	0.154	0.153	0.7	--	--	--	--	--	--
Calcium, diss., mg/L	91.3	89.6	1.9	51	52.3	2.5	23.7	24.5	3.3	69.8	68.7	1.6
Magnesium, diss., mg/L	18.2	17.9	1.7	9.4	9.63	2.4	4.65	4.79	3.0	13.6	13.8	1.5
Sodium, diss., mg/L	9.25	9.09	1.7	10.8	11.1	2.7	11.9	12.3	3.3	3.12	3.11	0.3
Potassium, diss., mg/L	1.53	1.49	2.6	1.55	1.57	1.3	0.59	0.61	3.3	0.71	0.72	1.4
Chloride, diss., mg/L	33.7	33.6	0.3	23.3	23.5	0.9	25.6	25.8	0.8	1.1	1.08	1.8
Sulfate, diss., mg/L	101	100	1.0	45	45.3	0.7	3.31	3.3	0.3	126	125	0.8
Fluoride, diss., mg/L	0.13	0.12	8.0	0.13	0.13	0.0	e0.09	e0.08	--	e0.05	e0.06	--
Silica, diss., mg/L	7.8	7.8	0.0	4.85	4.97	2.4	5.4	5.4	0.0	9.1	9	1.1
Boron, diss., µg/L	26	27	3.8	--	--	--	6.3	6.7	6.2	10	11	9.5
Iron, diss., µg/L	7	e3	--	--	--	--	13	18	32.3	10	9	10.5
Manganese, diss., µg/L	<0.6	<0.6	--	0.8	0.8	0.0	12.1	12.2	0.8	5.5	5.3	3.7
Hydrogen 2/1 ratio, per mil	–128	–128	0.0	--	--	--	–126	–125	0.8	–130	–129	0.8
Oxygen 18/16 ratio, per mil	–17.33	–17.35	0.1	--	--	--	–17.27	–17.22	0.3	–17.48	–17.45	0.2
Tritium, pCi/L	34	32	6.1	--	--	--	27.2	28.8	5.7	30.72	30.72	0.0
Tritium 2-sigma combined uncertainty, pCi/L	1.3	1.3	0.0	--	--	--	0.96	0.96	0.0	0.96	0.96	0.0

Table 7. Analyses of replicate samples of major ions, nutrients, stable isotopes of hydrogen and oxygen, and tritium collected from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado, arranged chronologically.—Continued

[$CaCO_3$, calcium carbonate; °C, degrees Celsius; %, percent; diss., dissolved; lab., laboratory analysis; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; RPD, relative percent difference; --, no data; m, month; d, day; y, year; < less than; e, estimated]

Local identification number	**70**			**32**			**60**			**8**		
U.S. Geological Survey station identification number	**09067005**			**394040106455701**			**393658106574101**			**393830106210600**		
Date of sample collection (mmddyy)	**04/18/07**			**05/15/07**			**5/20/2007**			**06/05/07**		
Sample type	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %
Specific conductance, lab., µS/cm at 25°C	--	--	--	848	840	0.9	564	575	1.9	269	269	0.0
pH, lab., standard units	--	--	--	7.8	7.8	0.0	7.9	8	1.3	8.3	8.3	0.0
Alkalinity, diss., lab., mg/L as $CaCO_3$	--	--	--	204	173	16.4	143	175	20.1	114	114	0.0
Alkalinity, diss., field, mg/L as $CaCO_3$	72	72	0.0	224	224	0.0	199	188	5.7	115	113	1.8
Ammonia, diss., mg/L as N	<0.020	<0.020	--	<0.020	<0.020	--	<0.020	<0.020	--	<0.020	<0.020	--
Nitrite, diss., mg/L as N	e0.001	e0.001	--	<0.002	<0.002	--	<0.002	<0.002	--	<0.002	<0.002	--
Nitrite plus nitrate, diss., mg/L as N	0.164	0.166	1.2	1.43	1.42	0.7	0.26	0.27	3.8	0.23	0.24	4.3
Orthophosphate, diss., mg/L as P	e0.006	e0.006	--	0.007	0.007	0.0	0.006	0.008	28.6	<0.006	<0.006	--
Calcium, diss., mg/L	28.9	28.7	0.7	110	108	1.8	88	86.9	1.3	39.5	39.2	0.8
Magnesium, diss., mg/L	7.95	8.11	2.0	24	24	0.0	22.5	22.2	1.3	6.11	6.07	0.7
Sodium, diss., mg/L	6.19	6.13	1.0	44.8	44.4	0.9	4.45	4.42	0.7	5.54	5.47	1.3
Potassium, diss., mg/L	0.88	0.88	0.0	3.28	3.32	1.2	1.22	1.19	2.5	1.3	1.3	0.0
Chloride, diss., mg/L	10.1	10	1.0	53.6	53.6	0.0	1.37	1.35	1.5	13.1	13	0.8
Sulfate, diss., mg/L	28.4	28.3	0.4	140	140	0.0	111	111	0.0	5.07	5.17	2.0
Fluoride, diss., mg/L	0.1	0.1	0.0	0.17	0.16	6.1	0.12	0.11	8.7	0.12	0.11	8.7
Silica, diss., mg/L	6.11	6.09	0.3	15.1	15.1	0.0	13.6	13.6	0.0	6.8	6.8	0.0
Boron, diss., µg/L	--	--	--	39	38	2.6	21	20	4.9	6.7	6.9	2.9
Iron, diss., µg/L	--	--	--	8	7	13.3	65	59	9.7	<6	<6	--
Manganese, diss., µg/L	66.6	66.5	0.2	0.5	0.3	50.0	1.7	1.5	12.5	12.2	13.7	11.6
Hydrogen 2/1 ratio, per mil	--	--	--	–126	–126	0.0	–125	–124	0.8	–126	–126	0.0
Oxygen 18/16 ratio, per mil	--	--	--	–16.92	–16.98	0.4	–17.09	–17.06	0.2	–17.23	–17.08	0.9
Tritium, pCi/L	--	--	--	25.92	26.56	2.4	29.76	31.04	4.2	28.16	27.52	2.3
Tritium 2-sigma combined uncertainty, pCi/L	--	--	--	0.96	0.96	0.0	0.96	0.96	0.0	0.96	0.96	0.0

Table 7. Analyses of replicate samples of major ions, nutrients, stable isotopes of hydrogen and oxygen, and tritium collected from groundwater and surface water, Eagle River watershed, 2006–2007, Eagle County, Colorado, arranged chronologically.—Continued

[$CaCO_3$, calcium carbonate; °C, degrees Celsius; %, percent; diss., dissolved; lab., laboratory analysis; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; RPD, relative percent difference; --, no data; m, month; d, day; y, year; < less than; e, estimated]

Local identification number	**42**			**40**			**71**			**73**			**74**		
U.S. Geological Survey station identification number	**393813106490201**			**393758106473601**			**394220106431500**			**09069500**			**09069000**		
Date of sample collection (mmddyy)	**06/10/07**			**06/20/07**			**07/27/07**			**08/31/07**			**09/12/06**		
Sample type	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %	Native	Replicate	RPD, %
Specific conductance, lab., µS/cm at 25°C	778	747	4.1	867	841	3.0	--	--	--	427	428	0.2	--	--	--
pH, lab., standard units	8	7.8	2.5	7.7	7.7	0.0	--	--	--	8.3	8.3	0.0	--	--	--
Alkalinity, diss., lab., mg/L as $CaCO_3$	158	157	0.6	163	176	7.7	--	--	--	119	120	0.8	--	--	--
Alkalinity, diss., field, mg/L as $CaCO_3$	163	159	2.5	195	190	2.6	76	75	1.3	113	112	0.9	125	127	1.6
Ammonia, diss., mg/L as N	<0.020	<0.020	--	<0.020	<0.020	--	e0.016	--	--	--	--	--	e0.007	e0.009	--
Nitrite, diss., mg/L as N	<0.002	<0.002	--	<0.002	<0.002	--	0.004	--	--	--	--	--	0.004	0.004	0.0
Nitrite plus nitrate, diss., mg/L as N	0.35	0.33	5.9	0.36	0.35	2.8	0.292	--	--	--	--	--	0.41	0.407	0.7
Orthophosphate, diss., mg/L as P	0.008	0.007	13.3	0.007	0.007	0.0	0.037	--	--	--	--	--	0.038	0.037	2.7
Calcium, diss., mg/L	105	105	0.0	111	112	0.9	37	36.5	1.4	72.7	74.6	2.6	83.4	82.8	0.7
Magnesium, diss., mg/L	16.6	16.4	1.2	19.9	20.1	1.0	8.73	8.58	1.7	8.33	8.57	2.8	16.1	16	0.6
Sodium, diss., mg/L	29	29.2	0.7	43.1	43.4	0.7	35.5	35	1.4	2.31	2.41	4.2	50.5	50	1.0
Potassium, diss., mg/L	2.94	2.93	0.3	2.85	2.92	2.4	1.55	1.51	2.6	0.4	0.44	9.5	2.54	2.51	1.2
Chloride, diss., mg/L	51.6	50.5	2.2	55.2	55	0.4	53	53.3	0.6	0.38	0.38	0.0	84.3	84.2	0.1
Sulfate, diss., mg/L	158	155	1.9	177	177	0.0	50.1	50.5	0.8	98.1	98	0.1	159	159	0.0
Fluoride, diss., mg/L	0.13	0.14	7.4	0.13	0.15	14.3	e0.10	0.11	--	< 0.10	e0.06	--	0.15	0.18	18.2
Silica, diss., mg/L	11.6	11.5	0.9	12.9	13	0.8	4.53	4.52	0.2	9	9.1	1.1	5.23	5.2	0.6
Boron, diss., µg/L	20	20	0.0	30	30	0.0	--	--	--	9.6	9.8	2.1	--	--	--
Iron, diss., µg/L	151	173	13.6	13	17	26.7	--	--	--	e5	7	--	--	--	--
Manganese, diss., µg/L	4.3	5.7	28.0	2.4	4.9	68.5	--	--	--	2.1	2.1	0.0	14.3	--	--
Hydrogen 2/1 ratio, per mil	–126	–126	0.0	–126	–125	0.8	--	--	--	–125	–125	0.0	--	--	--
Oxygen 18/16 ratio, per mil	–17.17	–17.17	0.0	–17.03	–17.11	0.5	--	--	--	–17.03	–17.03	0.0	--	--	--
Tritium, pCi/L	26.88	30.72	13.3	25.6	27.2	6.1	--	--	--	32	33	3.1	--	--	--
Tritium 2-sigma combined uncertainty, pCi/L	0.96	0.96	0.0	0.96	0.96	0.0	--	--	--	2.6	2.6	0.0	--	--	--

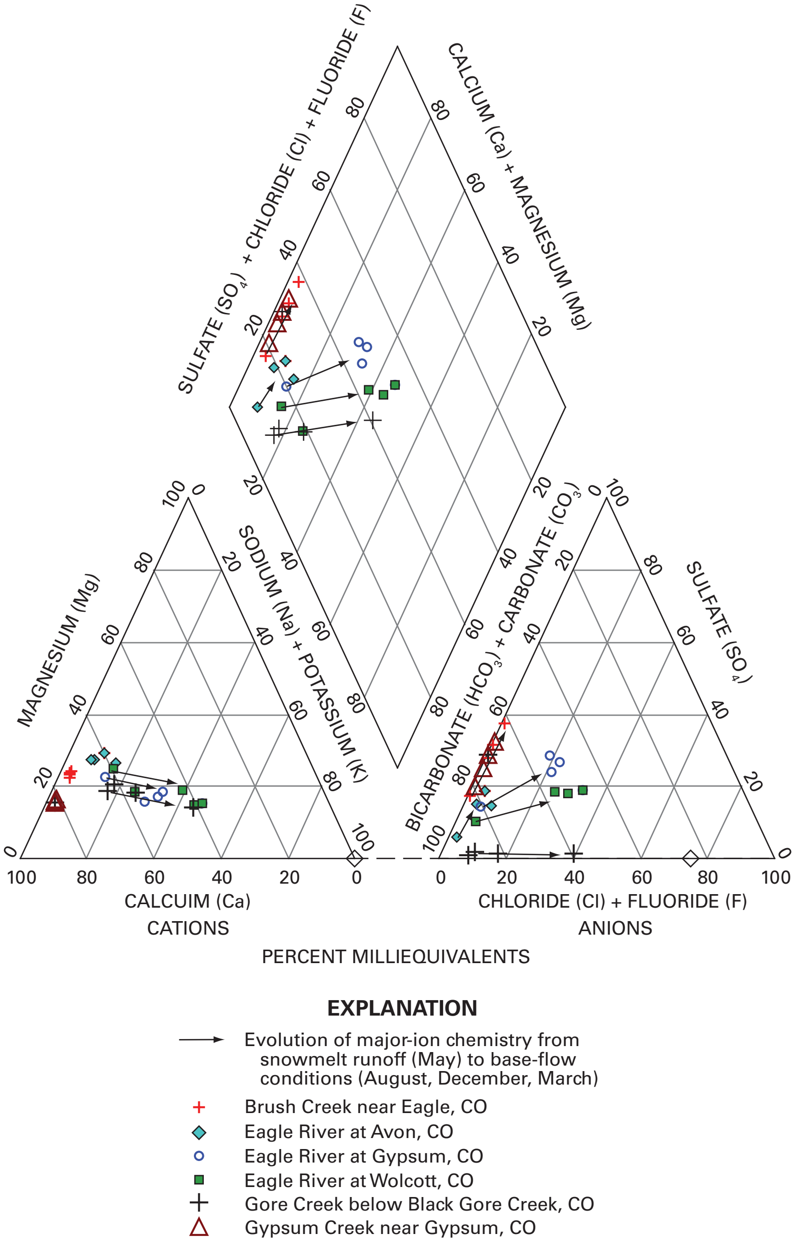


Figure 5. Major-ion chemistry of surface-water-quality samples, Eagle River watershed, 2006–2007, Eagle County, Colorado.

the surface-water chemistry (sulfate concentrations less than 750 mg/L), and the wells that produced these groundwaters are mostly located in the eastern portion of the study area and are adjacent to creeks and rivers (fig. 7). The second category of groundwater plotted in a different portion of the trilinear diagram than the surface-water samples (fig. 6) and has sulfate concentrations greater than 750 mg/L, which is three times greater than the Secondary Drinking Water Regulation of 250 mg/L (U.S. Environmental Protection Agency, 2003). The concentration of 750 mg/L was selected because it is an apparent separation point on the trilinear diagram; the 750 mg/L concentration has no hydrogeologic or health standards associated with it. The locations of wells with sulfate concentrations less than 250 mg/L, greater than 250 mg/L but less than 750 mg/L, and greater than 750 mg/L are shown in figure 7.

Groundwater samples from a subset of wells exceeded the USEPA National Secondary Drinking Water Regulations (U.S. Environmental Protection Agency, 2003) for chloride (250 mg/L), sulfate (250 mg/L), fluoride (2.0 mg/L), total dissolved solids (500 mg/L), iron (300 µg/L), and manganese (50 µg/L) (table 2, table 8). National Secondary Drinking Water Regulations (secondary standards) are guidelines for constituents that may cause cosmetic effects (such as skin or tooth discoloration [for fluoride]) or esthetic effects (such as taste,

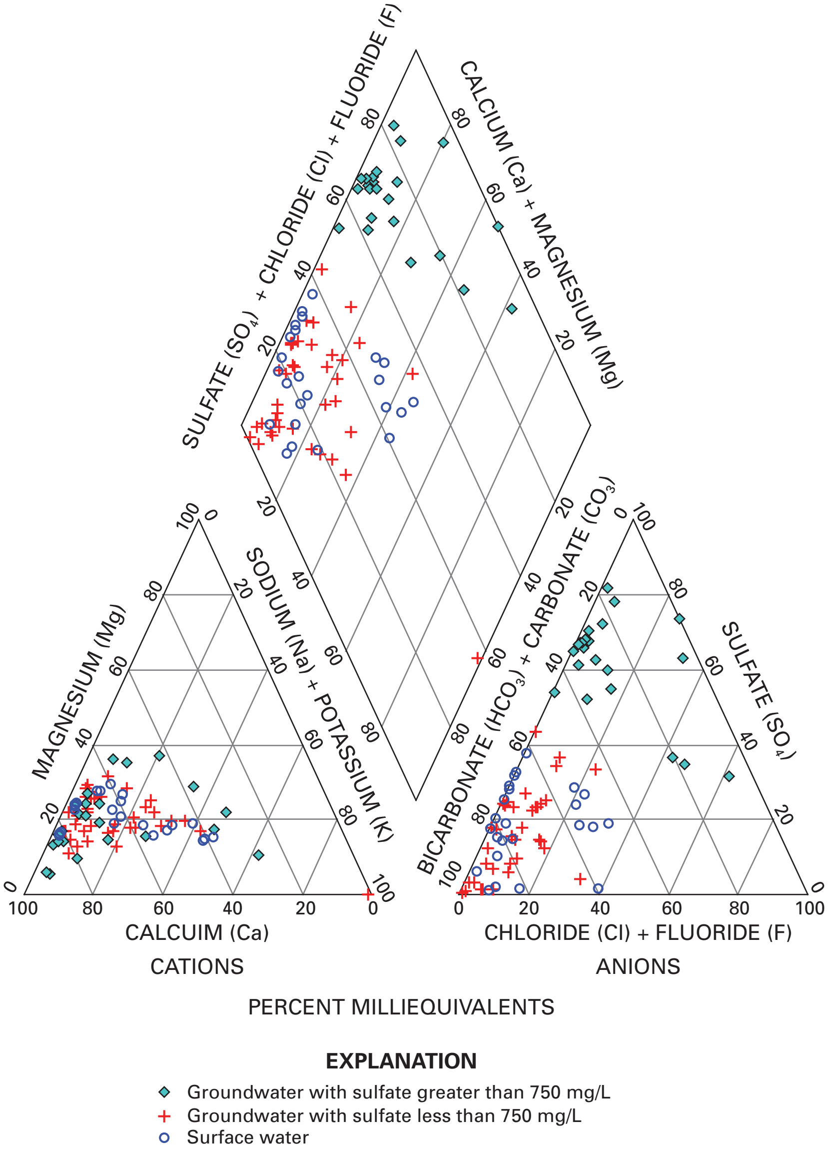


Figure 6. Major-ion chemistry of ground- and surface-water-quality samples, Eagle River watershed, 2006–2007, Eagle County, Colorado.

odor, or color [for sulfate, total dissolved solids, iron, and manganese]) in drinking water. Exceedances for sulfate and total dissolved solids were common and were mostly located west of Wolcott (fig. 7, fig. 8). Areas where sulfate and total dissolved solids exceed the secondary drinking-water standards, such as near the town of Gypsum, probably would not be suitable for development as public drinking-water supplies because of the difficulty of lowering the sulfate and total dissolved solids concentrations below the Secondary Drinking Water Regulations. Exceedances for chloride, fluoride, iron, and manganese were not common and were located in the western portion of the ERWVFA (table 2).

Sulfate exceeded the secondary standard of 250 mg/L in many wells near Eagle, Gypsum, and Dotsero (fig. 7). Health concerns regarding sulfate in drinking water have been raised because of reports that diarrhea may be associated with the ingestion of water containing high levels of sulfate (U.S. Environmental Protection Agency, 1999). Of particular concern are groups within the general population that may be at greater risk from the laxative effects of sulfate when they experience an abrupt change from drinking water with low sulfate concentrations to drinking water with high sulfate concentrations. Many domestic well owners in the western portion of Eagle County use reverse-osmosis water-treatment systems to reduce the amount of sulfate in their drinking water. The most significant source of sulfate and total dissolved solids to groundwater in the Eagle River watershed is the Eagle Valley Evaporite, which is a Pennsylvanian-age geologic deposit located in the western half of Eagle County (fig. 7). The Eagle Valley Evaporite is composed mostly of gypsum with

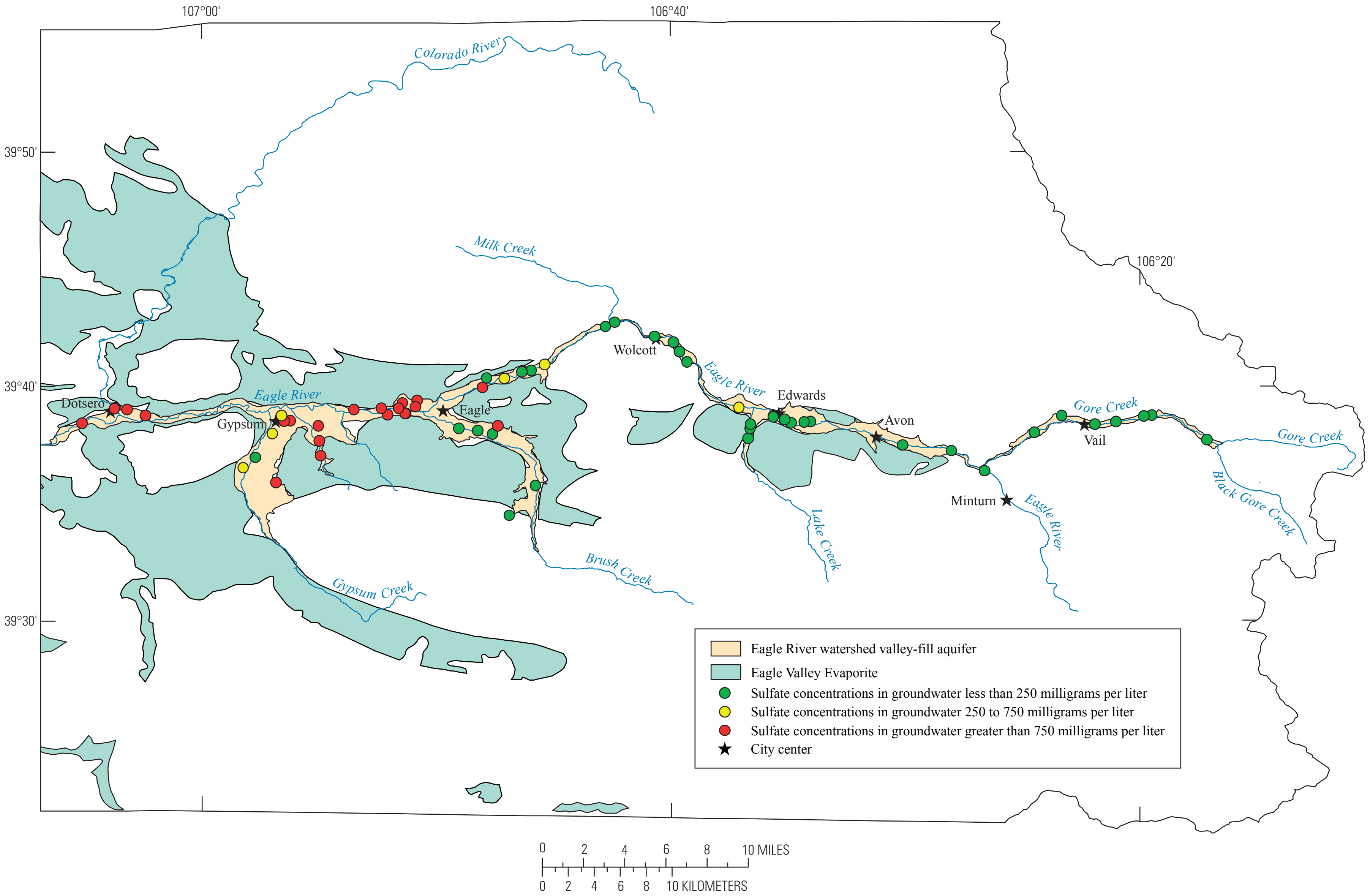
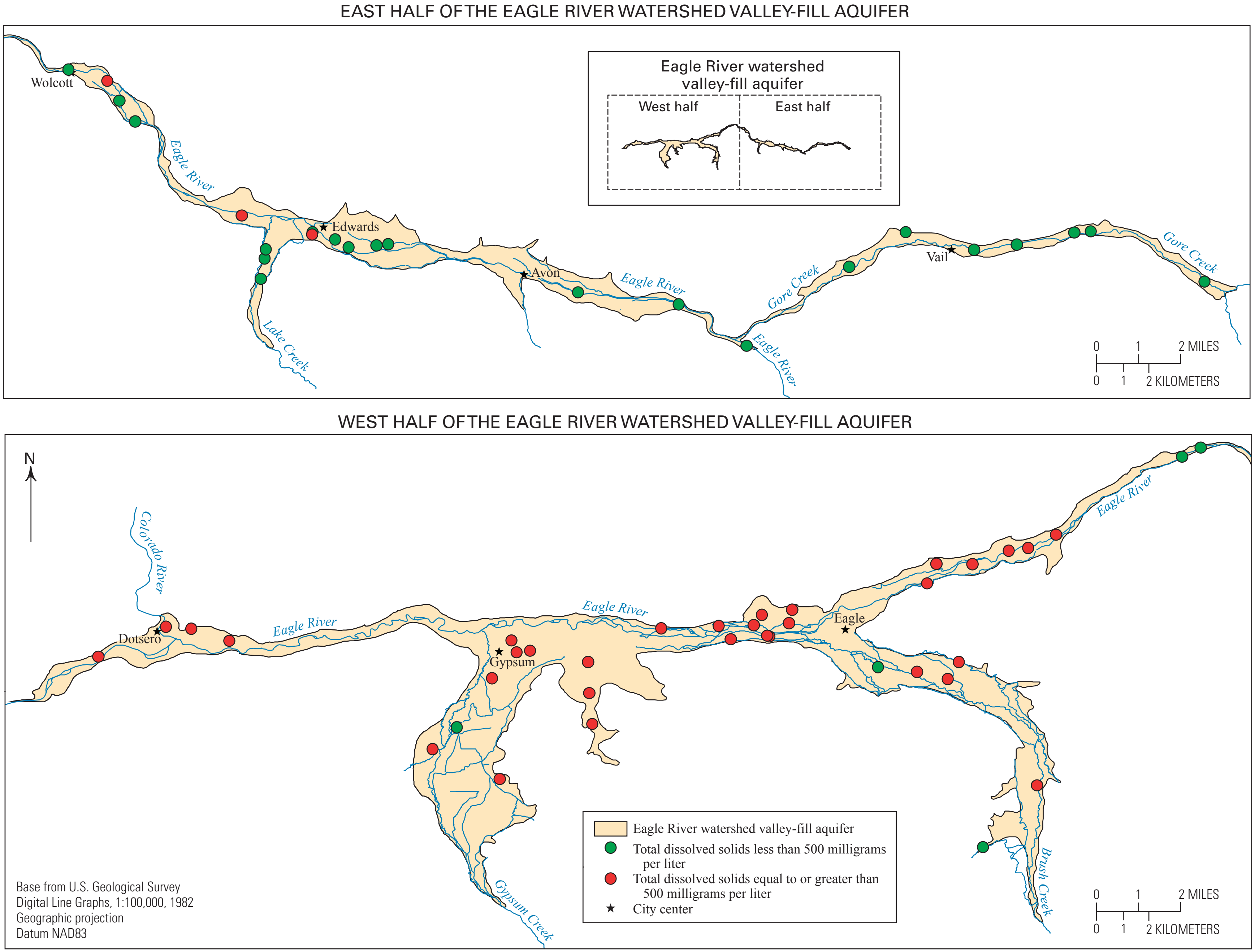


Figure 7. Sulfate concentrations in groundwater in the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

Table 8. Summary statistics for major ions, nutrients, stable isotopes of hydrogen and oxygen, and tritium in groundwater, Eagle River watershed, 2006–2007, Eagle County, Colorado.

[$CaCO_3$, calcium carbonate; °C, degrees Celsius; diss., dissolved; lab., laboratory analysis, µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter; N, nitrogen; P, phosphorus; pCi/L, picocuries per liter; RD, relative difference; --, no data; ‰, per mil; na, not applicable; <, less than; bold letters indicate concentrations above National Secondary Drinking Water Regulations (U.S. Environmental Protection Agency, 2003)]

Constituent	No. of wells sampled	Laboratory reporting level	Minimum concentration measured	Percentile					Maximum concentration measured	National Secondary Drinking Water Regulation
				10	25	50	75	90		
Specific conductance, µS/cm at 25°C	61	<3	239	420	601	917	2,140	2,967	8,100	
pH, standard units	61	<0.1	7.0	7.1	7.2	7.4	7.6	7.7	8.6	6.5–8.5
Temperature, degrees Celsius	61	na	3.9	8.0	9.4	10.4	11.4	12.6	16.2	
Dissolved oxygen, mg/L	61	<.1	<0.1	0.4	2.2	4.0	5.6	6.4	8.6	
Hydrogen sulfide, in mg/L	61	<.1	<.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.18	
Calcium, diss., mg/L	61	<.02	3.8	52	79	112	432	538	621	
Magnesium, diss., mg/L	61	<.014	0.717	7.77	17	23	56	107	321	
Sodium, diss., mg/L	61	<.20	3.8	5.3	7.4	27	58	184	1,220	
Potassium, diss., mg/L	61	<.04	0.53	1.2	1.5	2.6	3.7	11	34	
Bicarbonate, diss, field, mg/L as HCO_3	51	<5	77	164	214	245	299	344	513	
Alkalinity, diss., field, mg/L as $CaCO_3$	60	<5	63	134	176	199	241	277	420	
Sulfate, diss., mg/L	61	<.18	4.3	15	80	170	1,065	1,430	2,400	250
Chloride, diss., mg/L	61	<.12	1.1	3.1	13	34	72	233	2,000	250
Fluoride, diss., mg/L	61	<.10	<.10	< .10	0.12	0.17	0.24	0.33	5.4	2.0
Silica, diss., mg/L	61	<.20	5.4	7.2	9.4	13	14	17	25	
Total dissolved solids, mg/L	61	na	137	225	350	587	1,770	2,508	5,320	500
Ammonia, diss., mg/L as N	61	<.02	<.02	<.02	0.02	0.02	0.02	0.03	2.0	
Nitrite, diss., mg/L as N	61	<.002	<.002	<.002	<.002	<.002	<.002	<.002	0.007	
Nitrite plus nitrate, diss., mg/L as N	61	<.06	<.06	<.06	0.36	0.74	1.3	2.5	5.4	
Orthophosphate, diss., mg/L as P	61	<.006	<.006	<.006	<.006	<.006	0.008	0.018	0.110	
Boron, diss., µg/L	61	<1.8	5.4	11	21	37	90	173	332	
Iron, diss., µg/L	61	<6	3	6	6	16	61	336	8,360	300
Manganese, diss., µg/L	61	<.2	0.1	0.2	0.4	1.7	12	105	1,500	50
Hydrogen 2/1 ratio, per mil	61	<2	–140	–130.4	–128	–126	–125	–122.2	–117	
Oxygen 18/16 ratio, per mil	61	<0.20	–18.05	–17.43	–17.24	–17.03	–16.89	–16.38	–16.14	
Tritium, pCi/L	61	<1.00	<1.00	20.11	24.88	28.16	31.44	34.5	45.8	



Base from U.S. Geological Survey
Digital Line Graphs, 1:100,000, 1982
Geographic projection
Datum NAD83

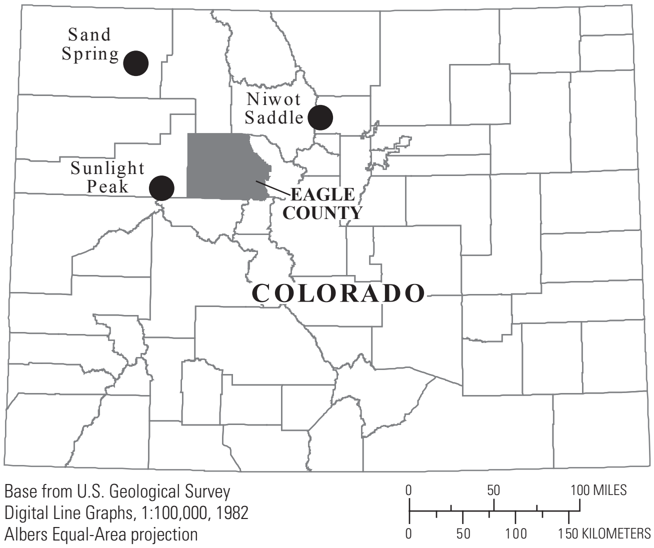
Figure 8. Total dissolved-solids concentrations in groundwater in the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

interbeds of shale, limestone, and sandstone (Day and others, 1999). Sediments eroded from the Eagle Valley Evaporite were incorporated into the aquifer materials of the ERWVFA, causing high sulfate and total dissolved solids concentrations in groundwater that flows through the aquifer.

Nutrients

Nitrate concentrations in groundwater were generally low; the median nitrate concentration was about 0.74 mg/L, and the maximum concentration measured 5.4 mg/L (table 2, table 8). Concentrations of ammonia and nitrite as nitrogen in groundwater of the ERWVFA were close to, or below, the laboratory reporting level in most samples. Most groundwater samples contained dissolved oxygen concentrations greater than 0.5 mg/L, dissolved manganese concentrations less than 50 µg/L, and dissolved iron concentrations less than 100 µg/L, indicating they have oxidized geochemical conditions (Paschke and others, 2007, p. 1–12). Under oxidized conditions, nitrate can exist in groundwater for many years. For instance, the High Plains aquifer has mostly oxidized geochemical conditions; McMahon and others (2007) estimate that it could take between 250 and 14,000 years for nitrate concentrations in the High Plains aquifer to decrease by 1 mg/L. Although there are no estimates of actual denitrification rates in the ERWVFA, the oxidized conditions observed in most areas of the ERWVFA indicate that nitrate from fertilizers and animal or human waste could persist for several decades in groundwater of the ERWVFA.

Nitrate concentrations of natural recharge water to the ERWVFA were determined by examining precipitation data collected by the National Atmospheric Deposition Program (2007). Precipitation is a good indicator of nitrate concentrations in natural recharge water to the ERWVFA because it establishes nitrate concentrations before any anthropogenic or hydrogeologic effects. There were no National Atmospheric Deposition Program (NADP) collection sites located in Eagle County, so data from three NADP sites that surround Eagle County were evaluated: Niwot Saddle, Sand Spring, and Sunlight Peak (fig. 9). Annual data on precipitation-weighted mean concentrations of ammonia and nitrate were downloaded (*http://nadp.sws.uiuc.edu/sites/sitemap.asp?state=co*) for calendar years 1988 through 2006, which was the period of record in common at the three sites. The median ammonia concentration at all three NADP sites combined was 0.10 mg/L, and the median nitrate concentration at all three sites combined was 0.20 mg/L (table 9). There were minimal differences in ammonia, nitrate, and total nitrogen concentrations among the three sites, indicating that concentrations in precipitation were relatively constant near Eagle County (table 9). Total inorganic nitrogen concentrations were calculated by adding the ammonia and nitrate concentrations; median total nitrogen concentrations of precipitation at all three sites combined was 0.30 mg/L, the maximum concentration was 0.63, and the standard deviation was 0.1. The largest



Base from U.S. Geological Survey
Digital Line Graphs, 1:100,000, 1982
Albers Equal-Area projection
37°30' and 40°30',
central meridian –105°30'
Datum NAD83

Figure 9. Locations of the National Atmospheric Deposition Program precipitation sites, north-central Colorado.

Table 9. Summary statistics for ammonia and nitrate concentrations in precipitation measured by the National Atmospheric Deposition Program (2007) at the Niwot Saddle, Sand Spring, and Sunlight Peak sites, Colorado, 1988–2006.

[N, nitrogen; mg/L, milligrams per liter]

Statistic	Ammonia as N	Nitrate as N	Total N
Niwot Saddle, Sand Spring, and Sunlight Peak combined			
Minimum concentration (mg/L)	0.04	0.12	0.17
Mean concentration (mg/L)	0.12	0.21	0.32
Median concentration (mg/L)	0.10	0.20	0.30
Maximum concentration (mg/L)	0.29	0.35	0.63
Standard deviation (mg/L)	0.05	0.05	0.10
Niwot Saddle			
Minimum concentration (mg/L)	0.04	0.13	0.17
Mean concentration (mg/L)	0.11	0.21	0.33
Median concentration (mg/L)	0.10	0.20	0.30
Maximum concentration (mg/L)	0.19	0.30	0.50
Standard deviation (mg/L)	0.04	0.04	0.08
Sand Spring			
Minimum concentration (mg/L)	0.06	0.18	0.24
Mean concentration (mg/L)	0.15	0.25	0.40
Median concentration (mg/L)	0.14	0.24	0.38
Maximum concentration (mg/L)	0.29	0.35	0.63
Standard deviation (mg/L)	0.06	0.05	0.11
Sunlight Peak			
Minimum concentration (mg/L)	0.05	0.12	0.17
Mean concentration (mg/L)	0.09	0.15	0.24
Median concentration (mg/L)	0.08	0.15	0.24
Maximum concentration (mg/L)	0.18	0.19	0.37
Standard deviation (mg/L)	0.03	0.02	0.05

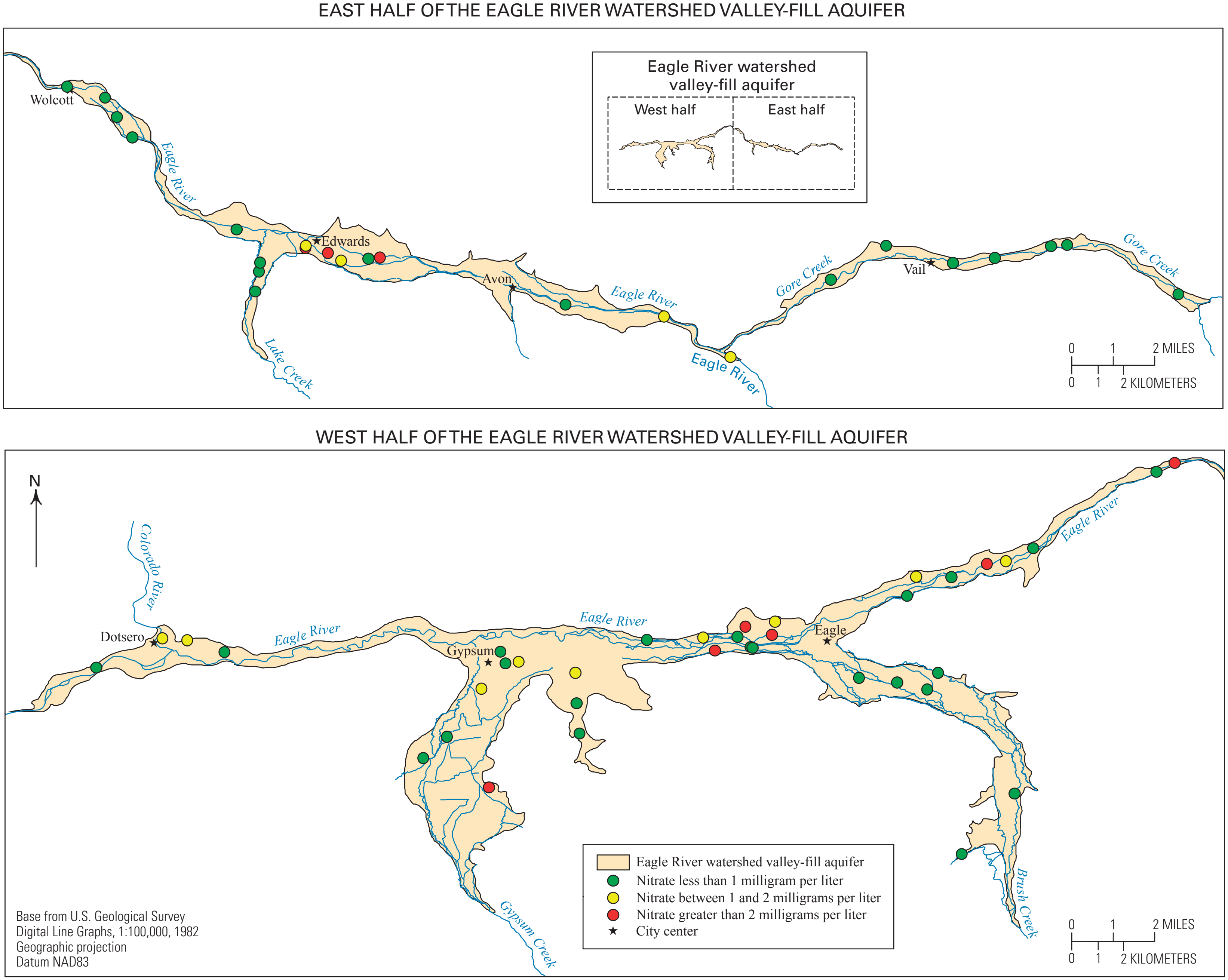
expected total nitrogen concentration of 0.74 mg/L was calculated by adding the maximum concentration measured at all three sites plus the largest standard deviation. This indicated that concentrations of nitrate in natural recharge water to the ERWVFA were less than 1 mg/L. In a national study, Nolan and Hitt (2002) also reported that concentrations of nitrate in groundwater in undeveloped forested areas of the United States were less than 1 mg/L.

More than 50 percent of the nitrate concentrations in the ERWVFA were less than 1 mg/L (table 8), indicating that water from more than 50 percent of the wells tested in the ERWVFA had nitrate concentrations similar to natural recharge water (precipitation). Nitrate concentrations were larger than concentrations of precipitation near Edwards, Eagle, Gypsum, and Dotsero (fig. 10). There were four major sources of nitrogen in the Eagle River watershed that could cause nitrate concentrations in excess of that in precipitation: fertilizers, manure, natural sources, and sewer systems. Agricultural uses of fertilizer were very limited in the Eagle River watershed, so probably the largest use of fertilizers was on turf grass, although rangeland areas are sometimes fertilized to improve winter forage for deer and elk. Manure from cattle, dogs, and horses can provide excess nitrogen to groundwater. As the result of evapotranspiration, nitrate can naturally accumulate in soils in arid environments (such as the environment near Gypsum and Dotsero), which leaves chloride and nitrate salts that can leach to groundwater following changes in land use or climate (Walvoord and others, 2003). Excess nitrogen input to groundwater can result from conventional domestic septic systems, from leaking municipal sewer systems, and from discharge of treated effluent to surface water and the land surface.

In an attempt to determine the source of elevated nitrate concentrations, boron was analyzed in groundwater samples from the ERWVFA. Boron can be an indicator of wastewater effluent from septic and sewer systems because boron is used as a bleaching additive in soaps and detergents (Westgate and others, 2000; Barber and others, 1988; Thurman and others, 1986; Verstraeten and others, 2005; Vengosh and others, 1994; Leenheer and others, 2001). Boron is a conservative tracer because it is biochemically inactive in groundwater (Barber and others, 1988; Ford and Tellam, 1994; Leenhouts and others, 1998). Boron can also be naturally concentrated in soils in arid climates, such as the climate near Dotsero, and be associated with evaporite deposits such as gypsum. Boron does not appear to be a useful indicator of nitrate from wastewater in the ERWVFA (fig. 11). There was a relatively strong relation between boron and sulfate concentrations, indicating that boron in groundwater from the ERWVFA may be associated with the same gypsum deposits that are the source of the elevated sulfate (fig. 11). To quantify this correlation, boron and sulfate were correlated using Spearman's rho. Two factors are strongly correlated when Spearman's rho approaches plus or minus one; no correlation exists as the Spearman's rho approaches zero (Helsel and Hirsch, 1992). There is a strong correlation between boron and sulfate (Spearman's rho = 0.9). Nitrate concentrations are shown as colored dots in figure 11; nitrate concentrations greater than 1 mg/L are detected in a wide range of boron and sulfate concentrations, indicating there is not a strong relation between boron and nitrate (Spearman's rho = 0.2). If a strong relation existed between boron and nitrate, most nitrate detections greater than 1 mg/L would be associated with high boron concentrations. Elevated chloride concentrations in groundwater can also be an indicator of wastewater effluent. Groundwater with significant amounts of wastewater effluent should have elevated concentrations of boron, chloride, and nitrate, but there is no clear relation between boron, chloride, and nitrate in the right-hand graph in figure 11 (Spearman's rho = 0.2). A few individual wells may have had elevated nitrate concentrations from septic or sewage effluent, but boron was not a useful indicator of that effluent. Isotopes of boron ($^{11}B/^{10}B$) can be used to differentiate between naturally occurring boron and that from sewage (Naftz and others, 2008). Forcada and Evangelista (2008) indicate that boron isotopes may be useful for identifying wastewater in high-sulfate water, so sampling for boron isotopes may be useful in future studies of the ERWVFA. Examining chloride/bromide ratios of groundwater may also be a useful indicator of effluent (Vengosh and Pankratov, 1998).

Tritium

Tritium, when plotted with one of the other CFC compounds, can be an effective tool for groundwater age dating and for determining amounts of groundwater mixing (Plummer and others, 2003). In the Eagle River watershed, tritium and CFC–11 were useful indicators of groundwater age (fig. 12). The solid blue line in figure 12 is the intersection of tritium activities in precipitation decayed to the average year of sampling (2007) with the northern hemisphere CFC–11 atmospheric mixing ratio over time and is commonly called the piston-flow line because groundwater recharged from precipitation and moving in the aquifer under unmixed piston flow will plot on that line. Points that plot near the line are composed of waters that were derived from precipitation falling at that time in history and that was recharged to groundwater. The year of recharge is shown on the line. It is common for groundwater sampled from wells to be mixtures of young and old waters that were mixed in the well bore, particularly in wells with screen lengths greater than 1.5 m. Points plotting below the piston-flow line either contain a significant fraction of old (prenuclear detonation) water or are located in areas of deep unsaturated zones and(or) low recharge rate, which moves the points toward the origin of the graph (fig. 12). Samples plotting above the piston-flow line contain fractions of water elevated in tritium from the mid-1960s period of atmospheric testing of nuclear weapons. In the Eagle River watershed, a useful indicator of the predisposition of water to anthropogenic contamination is whether the water is composed of mostly young waters (high predisposition) or contain a significant portion of older waters (lower predisposition). As will be shown later in the "Comparison of Probability Models" section of this report, an effective model was developed using logistic regression to predict the probability of detecting unmixed young groundwater in the ERWVFA by using CFC–11 concentrations and tritium activities in groundwater.



EAST HALF OF THE EAGLE RIVER WATERSHED VALLEY-FILL AQUIFER

WEST HALF OF THE EAGLE RIVER WATERSHED VALLEY-FILL AQUIFER

Base from U.S. Geological Survey
Digital Line Graphs, 1:100,000, 1982
Geographic projection
Datum NAD83

Figure 10. Nitrate concentrations in groundwater in the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

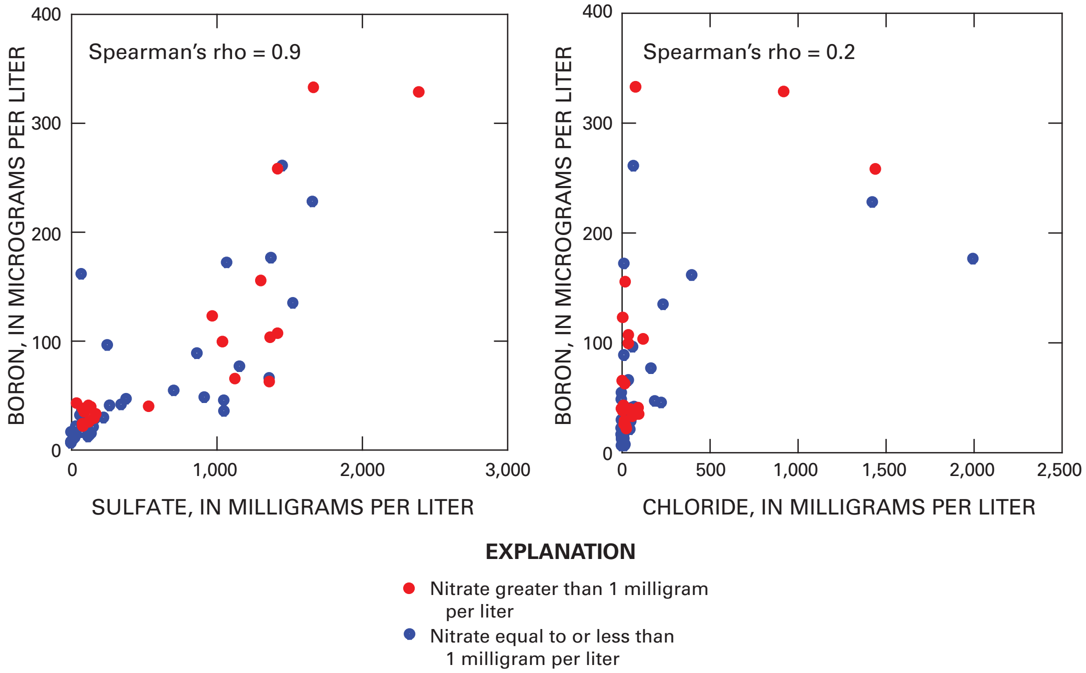


Figure 11. Boron, chloride, sulfate, and nitrate concentrations in groundwater, Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

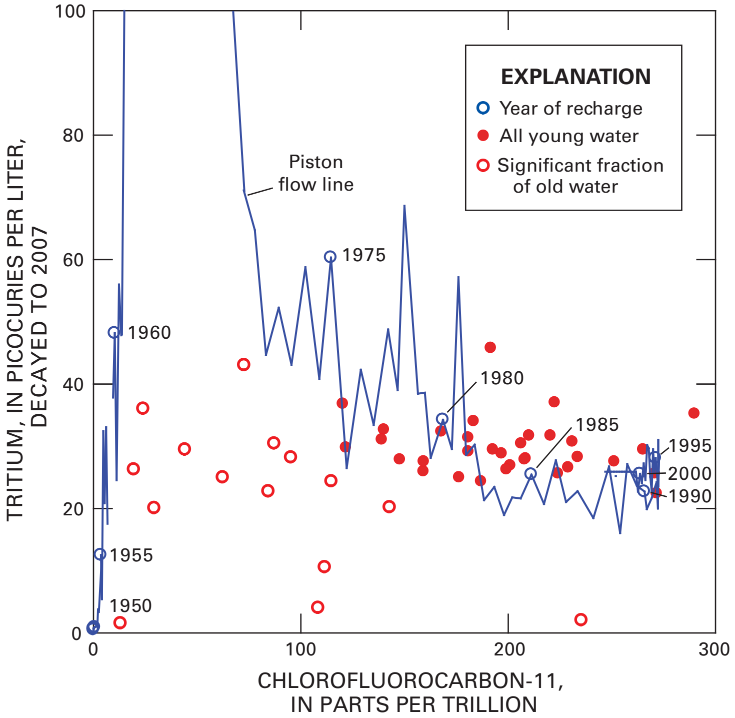


Figure 12. Measured CFC–11 concentrations and tritium activities in groundwater, Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

Dissolved Gases

Dissolved gas concentrations, as well as the ratios of concentrations, can be used to calculate the recharge temperature of a groundwater sample (table 10) because the solubility of gases in water varies as a function of temperature (Plummer and others, 2004). Determining the groundwater temperature is important because groundwater ages determined using CFCs are based on Henry's law solubility, which is dependent on the groundwater temperature at time of recharge and altitude at location of recharge. About one-half of the groundwater sites were sampled for dissolved gases, but the areal distribution of the sites was appropriate to show a range of recharge dates throughout the ERWVFA. Recharge temperatures for groundwater sites without dissolved-gas data were extrapolated from adjacent groundwater sites with dissolved-gas data. The field temperature measured at the time of sampling was used for recharge temperatures at surface-water sites. Land-surface elevations were used for recharge elevations at all sites because actual recharge locations were unknown for most sites and groundwater ages are less sensitive to recharge elevations than recharge temperatures (Plummer and Busenberg, 1999).

Dissolved-gas samples were collected in replicate from each site; samples were analyzed for Ar, CO_2, CH_4, O_2, and N_2 (table 10). Most samples contained excess air, probably from excess air being trapped and dissolved in groundwater under increased hydrostatic pressure during rapid recharge conditions. Mean recharge temperatures at each site ranged from 1.1 to 64.0°C (34 to 147°F). Median recharge temperature of all sites combined was 7.3°C (45°F) (table 10). Mean and median field water temperatures measured at the time of sampling were about 3.1°C (5.6°F) higher than the temperatures determined using dissolved gases (table 10), indicating that groundwaters at the time of sampling probably recharged at lower temperatures than current groundwater temperatures. Site 27 (table 10) had an anomalously high recharge temperature of 64°C (147°F). Water from this well contained an anomalously high concentration of methane and anomalously low concentrations of the other gases. Apparently this sample has undergone a more complex evolution than any of the other samples from the study area, and recharge temperature cannot be determined from the nitrogen and argon concentrations in this sample. If dissolved-gas data from this well are eliminated from the analysis, then the minimum, maximum, and median recharge temperatures of the groundwater samples are 1.1, 13.2 and 7.2°C (34, 56, and 45°F), respectively.

Long-term mean annual daily air temperature data collected by the Colorado Climate Center (*http://ccc.atmos.colostate.edu/dly_form.html*) were comparable to recharge temperatures determined using dissolved gases. Two sites in the Eagle River watershed have long-term temperature data: one site at the Eagle County Airport (1949 through 1993) and one site at Vail (1986 through 1999). Mean annual daily air temperature at the Eagle County Airport for calendar years 1986 through 1993, which was the period of record in common at both sites, was 6.4°C (43.5°F); the median annual air temperature was 7.5°C (45.5°F). Mean annual daily air temperature at Vail for calendar years 1986 through 1993 was 0.2°C (32.4°F); the median annual air temperature was 1.7°C (35.0°F). The differences in temperatures between Vail and the Eagle County Airport are because the Eagle County Airport is at a much lower elevation (1,980 m [6,500 ft]) than Vail (2,510 m [8,230 ft]).

Chlorofluorocarbons and Groundwater Age

Groundwater ages of water in the Eagle River watershed were estimated using CFCs, excess air, recharge temperature, and recharge elevation (table 3). Five replicate CFC samples were collected at each site, and in most cases three of those samples were analyzed for each site and the concentrations were averaged. In cases where there was high variability in CFC concentrations between each replicate sample, additional samples were analyzed for each site up to the maximum of five samples. Groundwater ages were based on CFC atmospheric mixing ratios, which were calculated from the CFC concentrations using Henry's law (Busenberg and Plummer, 1992; Plummer and Busenberg, 1999; International Atomic Energy Agency, 2006) and estimates of excess air, recharge temperature, and recharge elevation (table 3). Most groundwater ages and estimates of percentage of young water (percentage of water younger than 1940) were determined using either CFC–113/CFC–11 ratios or piston-flow apparent ages based on CFC–113 (International Atomic Energy Agency, 2006).

The median groundwater recharge date of all sites combined is 1989 and the standard deviation was about 9 years, indicating that most groundwater in the ERWVFA was young water (table 3, fig. 13). The median percentage of young water was 83 percent and the standard deviation was about 28 percent, indicating that only a portion of water from most wells was composed of old (older than 1940) water. To put the groundwater age data in the context of the probability of groundwater contamination, most groundwaters in the ERWVFA were recently recharged waters and have a high predisposition to anthropogenic contamination.

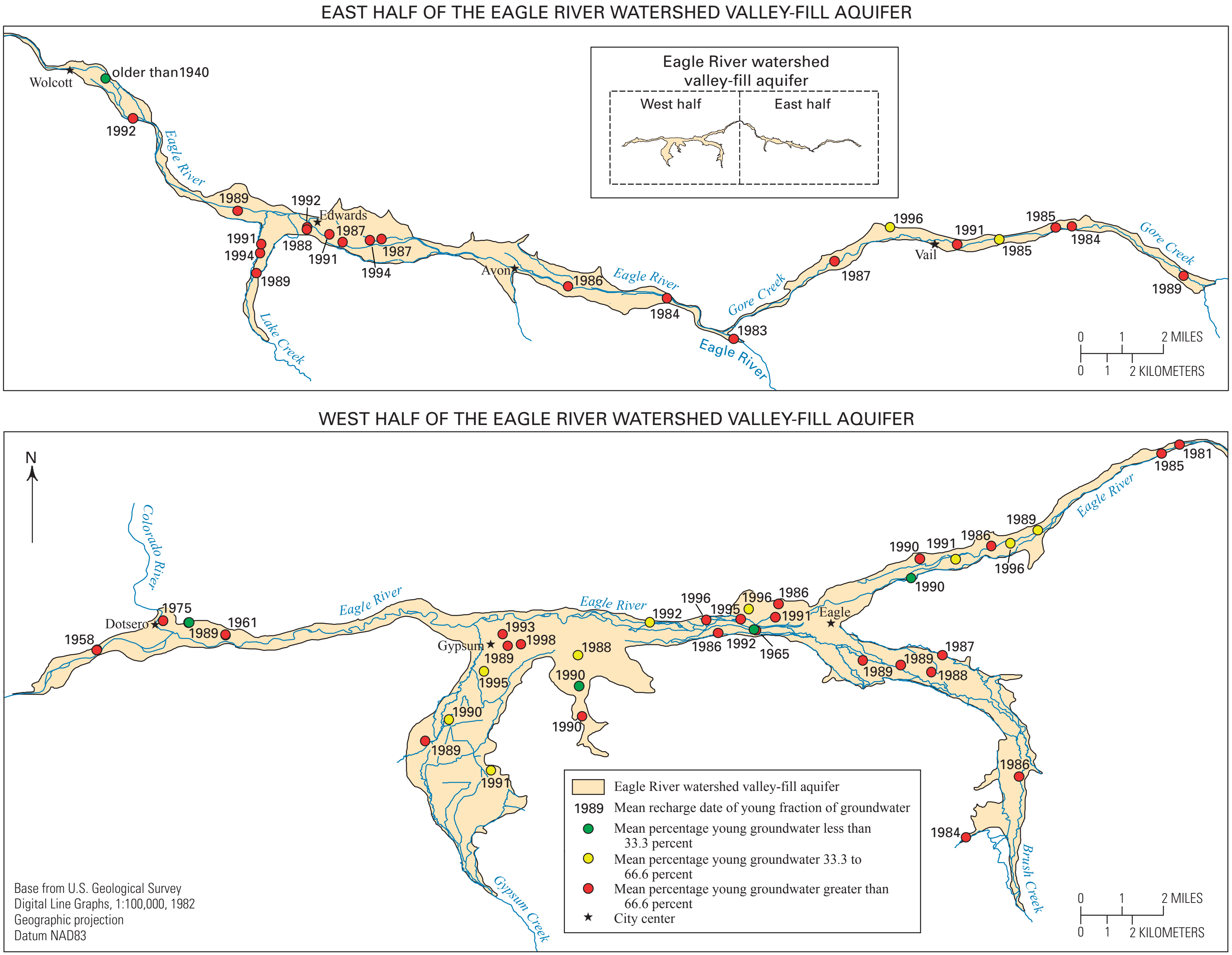
Two sites (11 and 47, table 3) were sampled during 2006 and 2007, which allowed a check on the comparability of the groundwater recharge dates between the two sampling events. The two sites were sampled about one year apart, and groundwater recharge dates were about one year different between the two sampling events, indicating there is good repeatability in the groundwater age determinations. These sites were originally selected for resampling to verify the relatively large tetrachloroethene concentrations detected at site 11 (table 4) and the relatively large nitrate concentration detected at site 47 (table 2). The resampling also confirmed the tetrachloroethene and nitrate concentrations.

CFC–12 concentrations exceeded those in water in equilibrium with the modern atmosphere in many samples, so in most cases groundwater ages could not be determined using CFC–12. The maximum expected concentration of

Table 10. Dissolved-gas data analyzed from groundwater samples collected from the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

[°C, degrees Celsius; m, month; d, day; y, year; mg/L, milligrams per liter; NAVD 29, National Geodetic Vertical Datum of 1929; trace, detected, but at very low concentration; Mean concentrations were determined by averaging replicate samples collected at each site]

Local identification number (see table 1 and fig. 2)	U.S. Geological Survey station identification number	Date of sample collection (mmddyy)	Field water temperature measured at the time of sample collection (°C)	Recharge elevation (feet above NGVD 29)	Mean argon (Ar) (mg/L)	Mean carbon dioxide (CO_2) (mg/L)	Mean methane (CH_4) (mg/L)	Mean oxygen (O_2) (mg/L)	Mean nitrogen (N_2) (mg/L)	Mean excess nitrogen (N_2) (mg/L)	Mean recharge temperature (°C)	Mean excess air in water sample (cubic centimeters per liter at standard temperature and pressure)
9	393823106215900	06/06/07	3.8	8,189	0.7	8.5	0.0	5.4	18.0	0.0	1.1	1.4
10	393844106232300	06/06/07	9.0	8,180	0.6	39.7	0.0	4.2	17.7	0.0	3.4	2.1
11	393802106243501	08/24/06	9.0	7,970	0.6	17.5	0.0	0.6	17.7	0.0	8.3	3.7
12	393623106264201	06/11/07	8.0	7,755	0.6	9.2	0.0	3.4	16.9	0.0	5.7	2.0
13	393715106280701	06/19/07	9.5	7,611	0.6	16.2	0.0	3.8	17.7	0.0	4.1	2.0
15	393830106340601	06/11/07	9.8	7,380	0.6	13.1	0.0	7.1	17.4	0.0	5.8	2.2
17	393826106345601	08/24/06	9.4	7,267	0.6	17.1	0.0	3.7	16.5	0.0	8.1	2.1
18	393836106351201	06/08/07	9.4	7,248	0.6	18.0	0.0	4.5	16.1	0.0	7.4	1.4
19	393844106354001	05/21/07	9.4	7,213	0.6	11.4	0.0	2.9	16.4	0.0	6.1	1.2
21	393748106364201	06/08/07	9.2	7,387	0.6	8.5	0.0	5.6	16.3	0.0	7.2	1.6
27	394153106395501	06/09/07	15.4	6,973	0.2	1.3	19.7	0.0	4.1	0.0	64.0	–0.6
32	394040106455701	05/15/07	11.2	6,685	0.6	24.7	0.0	2.6	15.9	0.0	8.3	1.3
35	394020106475101	08/25/06	13.0	6,704	0.7	39.1	0.0	4.8	21.1	0.0	3.8	4.8
36	393956106480201	05/16/07	10.5	6,660	0.6	61.9	0.0	0.4	17.2	0.0	8.2	2.5
37	393431106465301	06/12/07	7.5	7,618	0.6	29.8	0.0	2.8	16.5	0.0	5.2	1.3
41	393807106481501	06/20/07	10.9	6,733	0.7	24.2	0.0	5.0	23.7	0.0	7.0	8.6
42	393813106490201	06/10/07	9.4	6,664	0.6	18.9	0.0	4.3	17.7	0.0	3.9	1.4
43	393923106504801	05/17/07	10.5	6,707	0.6	30.3	0.0	7.8	17.6	0.0	6.1	2.2
44	393907106505201	05/17/07	11.1	6,556	0.5	37.7	0.0	6.9	14.4	0.0	10.2	0.3
45	393850106511701	08/23/06	10.3	6,500	0.6	24.1	trace	0.2	18.2	1.0	11.9	3.5
47	393917106512501	08/22/06	13.6	6,650	0.5	8.9	0.0	3.3	15.0	0.0	13.1	1.7
49	393847106520401	05/17/07	11.2	6,531	0.6	51.0	0.0	6.2	15.3	0.0	9.7	1.0
50	393903106521901	08/22/06	12.8	6,460	0.6	23.9	0.0	3.2	17.5	0.0	9.3	3.0
52	393702106545401	08/23/06	9.6	6,722	0.6	33.5	0.0	7.0	16.7	0.0	6.9	1.6
53	393740106545801	05/22/07	9.6	6,644	0.6	34.4	trace	0.3	17.3	0.0	6.9	2.2
55	393832106561101	05/19/07	11.4	6,418	0.6	44.3	0.0	5.3	17.9	0.0	9.0	3.3
57	393845106563401	08/22/06	12.5	6,350	0.7	40.9	0.0	3.9	20.0	0.0	8.5	5.2
59	393632106581101	08/23/06	13.5	6,620	0.7	14.5	0.0	5.7	19.5	0.0	4.9	3.5
60	393658106574101	05/20/07	8.5	6,528	0.7	18.7	0.0	3.9	18.5	0.0	1.8	1.2
61	393759106565701	06/07/07	11.6	6,446	0.5	43.4	0.0	5.6	14.1	0.0	9.7	–0.2
62	393845107022101	08/25/06	15.1	6,250	0.6	10.3	0.5	0.2	18.8	2.0	11.4	2.9
63	393900107030701	05/19/07	12.4	6,152	0.6	28.0	0.0	0.3	19.2	2.5	11.2	2.7



Base from U.S. Geological Survey
Digital Line Graphs, 1:100,000, 1982
Geographic projection
Datum NAD83

Figure 13. Mean recharge date of the young fraction of groundwater and the percentage of young groundwater from wells completed in the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

CFCs in precipitation is about 550 parts per trillion (ppt) (International Atomic Energy Agency, 2006), and the largest concentration of CFC–12 measured in air samples was 540 ppt (table 11), but 40 out of 59 wells sampled in the Eagle River watershed had concentrations greater than 550 ppt (table 3). CFC–12 was used as coolants in air-conditioning units and refrigeration, blowing agents in foams, insulation, and packing materials, propellants in aerosol cans, and as solvents (Plummer and Busenberg, 1999). It is possible that the elevated CFC–12 concentrations in groundwater in the Eagle River watershed are from a combination of point and nonpoint sources of contamination. The point sources could include spills of CFC–12 containing solvents on the ground. Nonpoint sources could include the discharge of treated wastewater that contains CFC–12 to the Eagle River, which is subsequently diverted by the irrigation networks and reapplied to the land surface. Although CFC–12 could not be used for groundwater age determination, the anomalously high CFC–12 concentrations could be a useful indicator of areas with a high predisposition to anthropogenic contamination in groundwater.

Low-Level Concentrations of Volatile Organic Compounds

VOCs were detected in all water samples using the low-level minimum detection levels (fig. 14). The low-level VOCs were analyzed from the same samples, and at the same time, using the same analytical equipment as the CFC samples. Five replicate CFC/VOC samples were collected at each site, and in most cases three of those samples were analyzed for each site and the concentrations were averaged. In cases where variability in concentrations was high between each replicate sample, additional samples were analyzed for each site. Analyzing replicate samples at each site helps to quantify the variability of analytical results at these extremely low concentrations. The values listed in table 4 are mean values from the multiple replicate samples analyzed.

Detection of halogenated VOCs in groundwater can be attributed to three general categories of source: (1) natural, atmospheric origin; (2) anthropogenic sources in the atmosphere; and (3) contaminant anthropogenic sources (Plummer and others, 2008). Methyl iodide (and methyl bromide) is detected in air and produced naturally by marine and aquatic biological processes (Sturges and others, 2001; Bell and others, 2002; Cox and others, 2005; Chuck and others, 2005). Approximately 90 percent of global emissions of chloroform is estimated to be of natural origin from sources such as volcanic gases (Isidorov and others, 1990), marine algae (Gribble, 1994; Laturnus and others, 2002), and soil fungi (McCulloch, 2003). Although most of the chloroform of natural origin is oxidized (to hydrogen chloride and carbon dioxide) in the atmosphere, some low-level detections of chloroform in rural groundwater may be of natural, terrestrial origin (McCulloch, 2003). Although a natural substance, salt concentrations (NaCl and $CaCl_2$) have increased in the environment because of the use of these compounds for roadway deicing. A recent study (Princeton Geoscience, 2005) indicated that the abundance of chloride ions in the runoff of deicing meltwaters may be enhancing the natural chloroform formation process in nearby soils. Natural emissions of other naturally occurring halogenated VOCs have been identified, including methyl chloride, tetrachloroethene, trichloroethene, and methylene chloride (Keene and others, 1999; Khalil and others, 1999), with 5 percent of the total 1998 global input of tetrachloroethene and 10 percent of that of trichloroethene attributed to natural, oceanic sources (Keene and others, 1999). Marine algae also have been identified as natural sources for bromodichloromethane, dibromochloromethane, and bromoform (Gribble, 1994).

Most of the halogenated VOCs in the atmosphere also have anthropogenic sources. For example, concentrations of chlorofluorocarbons in the atmosphere are likely entirely of anthropogenic origin, and most of the VOCs that have natural sources also can be attributed to various industrial sources. Samples containing VOCs of contaminant anthropogenic origin are of greatest concern because they represent waters that are being affected by contaminant sources in addition to atmospheric sources. By defining pre-anthropogenic and modern anthropogenic atmospheric concentrations of halogenated VOCs in groundwater, it is possible to identify those samples that exceed this threshold and thus contain anthropogenic sources of VOCs (Plummer and others, 2008).

A means of identifying samples that are being affected by contaminant sources of halogenated VOCs is to plot the sum of the total concentrations of dissolved halogenated VOCs

Table 11. Chlorofluorocarbon and volatile organic compounds analyzed from air samples collected in the Eagle River watershed, 2006–2007, Eagle County, Colorado.

[CFC, chlorofluorocarbon; m, month; d, day; y, year; ppt, parts per trillion; --, not analyzed]

Local identification number (see table 1 and fig. 2)	U.S. Geological Survey station identification number	Location	Date of sample collection (mmddyy)	Time	CFC–12, in ppt	CFC–11, in ppt	CFC–113, in ppt	Carbon tetrachloride, in ppt	Tetra-chloro-ethylene, in ppt
1	393145106130801	Vail Pass	05/24/07	14:30	527	241	78	83	2
2	393803106243701	Donnavan Park, Vail	06/22/07	15:30	530	242	78	85	2
3	393934106393201	Bellyache Ridge	08/26/06	9:00	540	247	77	--	--
3	393934106393201	Bellyache Ridge	06/08/07	17:50	534	239	77	84	2
4	393906106494201	Town of Eagle City Hall	06/22/07	11:10	526	239	76	84	2

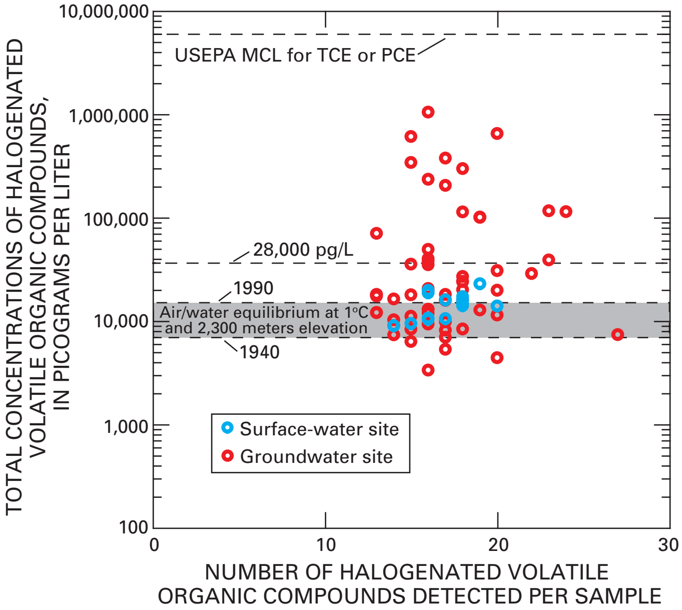


Figure 14. Relations between total concentrations of halogenated volatile organic compounds with the total number of halogenated volatile organic compounds, Eagle River watershed, 2006–2007, Eagle County, Colorado.

(TDVOC) in the sample as a function of the total number of VOC compounds detected per sample (Plummer and others, 2008) (fig. 14). Samples that are being affected by contaminant sources of halogenated VOCs have larger concentrations than concentrations of halogenated VOCs in groundwater that are only of atmospheric origin. Twenty-five halogenated VOCs were analyzed in this report. Table 4 lists concentrations of the 15 most commonly detected VOC compounds by this study and the TDVOC of those 15 compounds added together. It has been shown that TDVOC computed for these 15 selected compounds accounts for, on average, more than 95 percent of the total concentration of halogenated VOCs detected in groundwater samples (Plummer and others, 2008), as was the case for the Eagle County samples. The remaining 10 compounds were detected at very low concentrations that contribute an average of only about 5 percent to the value of TDVOC concentration in the samples. It is important to note the very low concentrations of VOCs in groundwater and surface water of the ERWVFA; all concentrations were at least one order of magnitude less than the USEPA Maximum Contaminant Level for tricholoroethene or tetrachloroethene (fig. 14).

Values of TDVOC were calculated from historical atmospheric concentrations of VOCs using Henry's law solubility data, as in Plummer and others (2008). The air/water equilibrium was calculated for 1940 (before significant anthropogenic input of VOCs to the atmosphere) and for 1990 (the estimated maximum concentration of VOCs in the atmosphere from natural and anthropogenic sources combined) at the mean annual temperature of 1°C (34°F) and at 2,300 m (7,500 ft) of elevation for the Eagle River watershed. Total concentrations of halogenated VOCs detected in surface water in the Eagle River watershed plot near values of the air/water equilibrium of water with the modern atmosphere calculated at the elevation and mean annual temperatures expected in the Eagle River watershed (fig. 14). The surface-water samples were collected from each site during high flow (snowmelt runoff) and low flow (late summer) to bracket seasonal fluctuations (table 4). Sites 393737106165900 (Gore Creek Below Black Gore Creek), 09068000 (Brush Creek Near Eagle), and 09069500 (Gypsum Creek Near Gypsum) are located upgradient from any substantial anthropogenic sources of VOCs, yet water from those sites had substantial TDVOC concentrations, confirming that substantial concentrations of TDVOCs in surface water can be from natural and anthropogenic atmospheric sources in the Eagle River watershed. The highest TDVOC concentrations at all surface-water sites were during high-flow conditions (May); the average TDVOC concentration for the high-flow (May) surface-water samples was about 18,000 pg/L. The average TDVOC concentration for low-flow (August) samples was about 12,000 pg/L. Site 393834106230401 is located on Gore Creek immediately upgradient from a wastewater-treatment plant, and site 393810106241501 is located immediately downstream from the same wastewater-treatment plant. Chloroform concentrations were higher in Gore Creek downstream from the wastewater-treatment plant, but most other VOC concentrations were lower downstream from the wastewater-treatment plant. Elevated chloroform concentrations are expected in wastewater because of the presence of chlorinated water, free chlorine, and elevated organic carbon (Carter and others, 2008; Plummer and others, 2008).

The maximum TDVOC concentration detected in surface-water samples was 22,880 pg/L, and the standard deviation of all TDVOC concentrations in surface water was 4,206 pg/L (table 4). Adding the maximum observed TDVOC concentration in surface water with the standard deviation, and then rounding up, produced a maximum likely TDVOC concentration in surface water in the Eagle River watershed of about 28,000 pg/L. Water from wells with TDVOC concentrations greater than 28,000 pg/L probably have been affected by anthropogenic contamination. Twenty-one of the 61 groundwater samples had TDVOC values that exceeded 28,000 pg/L, indicating those waters have been affected by VOCs from anthropogenic sources. Low-level detections of VOCs can provide a measure of the predisposition of an aquifer to anthropogenic contamination (Shapiro and others, 2003; Plummer and others, 2008; Carter and others, 2008). The locations of wells with TDVOC concentrations greater than 28,000 pg/L were used to identify areas with a large predisposition to contamination by VOCs in one of the logistic regression models described in the next section of this report.

Groundwater Probability Modeling

Logistic regression statistical modeling techniques were used to develop three statistical models that predict the probability of groundwater contamination by various contaminants. These three models used different compounds such as nitrate and VOCs to provide an indication of the probability of groundwater contamination under a variety of conditions and contaminant inputs. These three models are the probability of elevated nitrate concentrations, the probability of unmixed young water (using CFC–11 concentrations and tritium activities), and the probability of elevated VOC concentrations. Before using the groundwater probability maps, the results of the groundwater age dating should be recognized. The median groundwater recharge date was 1989, indicating that most groundwater in the ERWVFA was young water (younger than 1940) and had a high predisposition to contamination. The probability maps showed areas that have a greater predisposition to contamination by anthropogenic compounds than other areas, but just about all areas had a high predisposition to contamination because very few wells in the ERWVFA had large portions of water older than 1940 (table 3).

Development of Nitrate Model

A logistic regression model was developed to predict the probability of nitrate concentrations above 1 mg/L in groundwater (table 12, fig. 15), which is the maximum concentration expected in natural recharge water in the Eagle River watershed. The nitrate probability model was developed because groundwater contamination from fertilizers, manure, and wastewater from sources such as conventional domestic septic systems is a concern in Eagle County. Depth to groundwater, clay content, soil drainage, depth to groundwater in the soil layer, soil liquid limit, soil organic-matter content, soil sand content, and soil slope were significant variables in the nitrate model (table 12). Overall performance of the model was good, with a McFadden's rho-squared value of 0.490, and total correct predictions of 0.778.

The nitrate model predicted a lower probability of elevated nitrate concentrations in areas with shallower depth to groundwater and more transmissive soils, which is opposite to relations observed in other logistic regression models (Rupert, 1998; Nolan and others, 2002; Gurdak and Qi, 2006). This may be due to two reasons. The first is that some of the nitrate may be naturally occurring. As the result of evapotranspiration, nitrate can naturally accumulate in soils in arid environments (such as the environment near Gypsum and Dotsero), which leaves chloride and nitrate salts that can leach to groundwater following changes in land use or climate (Walvoord and others, 2003). Naturally occurring nitrate may be concentrated in areas with deeper depth to water and less transmissive soils. The second reason is that the areas with shallow groundwater and more transmissive soils are located near surface-water bodies such as the Eagle River. The shallow groundwater has more immediate recharge from the surface-water bodies, which provide recharge water with nitrate concentrations similar to precipitation that may dilute nitrate concentrations in groundwater to less than 1 mg/L. Nitrate in groundwater in areas with larger depth to groundwater and less transmissive soils would have less opportunity for dilution by surface-water recharge. Nitrate supplied by fertilizers, manure, or wastewater in areas of large depth to groundwater and less transmissive soils may tend to concentrate in the groundwater because of the lower amount of recharge available to dilute the nitrate. Areas such as the Brush Creek and Gypsum Creek valleys (fig. 15) have low nitrate probability ratings. Future urban development may reduce the amount of recharge from irrigation in the valley bottoms, which may increase the depth to groundwater. This may, in turn, increase the probability of nitrate contamination.

Development of Chlorofluorocarbon-11 and Tritium Model

Plotting CFC–11 concentrations with tritium activities provided an indication of water that was composed of mostly young water or contained a substantial fraction of old water (fig. 12). Points that lie close to the piston-flow line, which is the line of measured CFC–11 concentration in parts per trillion and tritium in precipitation decayed to the year 2007 through time, were composed of 100 percent young water (water younger than 1940). Points plotting below the piston-flow line were composed of a substantial portion of old water (water older than 1940), or are waters recharged through deep unsaturated zones. Water composed of 100 percent young water could have a higher probability of anthropogenic contamination at concentrations of concern than water with a portion of old water.

To construct a logistic regression model predicting the probability of unmixed young water (younger than 1940) using CFC–11 and tritium (fig. 16), the data set was coded as zero for

Table 12. Logistic regression modeling results, coefficients, and individual p-values of independent variables significantly related with the probability of nitrate concentrations greater than 1 milligram per liter, the probability of unmixed young water (using chlorofluorocarbon-11 concentrations and tritium activities), and the probability of total volatile organic compounds greater than 28,000 picograms per liter in the Eagle River watershed valley-fill aquifer, Eagle County, Colorado.

[CFC, chlorofluorocarbon; TDVOCs, total volatile organic compound concentrations; mg/L, milligrams per liter; pg/L, picograms per liter; --, no relation observed; sensitivity, the number of correctly predicted events divided by the total number of observed events; specificity, the number of correctly predicted reference events divided by the total number of observed reference events; total correct predictions, the number of correctly predicted events plus the number of correctly predicted reference events divided by the total number of all events; values not enclosed in parentheses are logistic regression coefficients; values enclosed in parentheses are individual p-values; independent variables in bold are used in equation 1 for the logistic regression models; SSURGO, Soil Survey Geographic Database; STATSGO, State Soil Geographic Database]

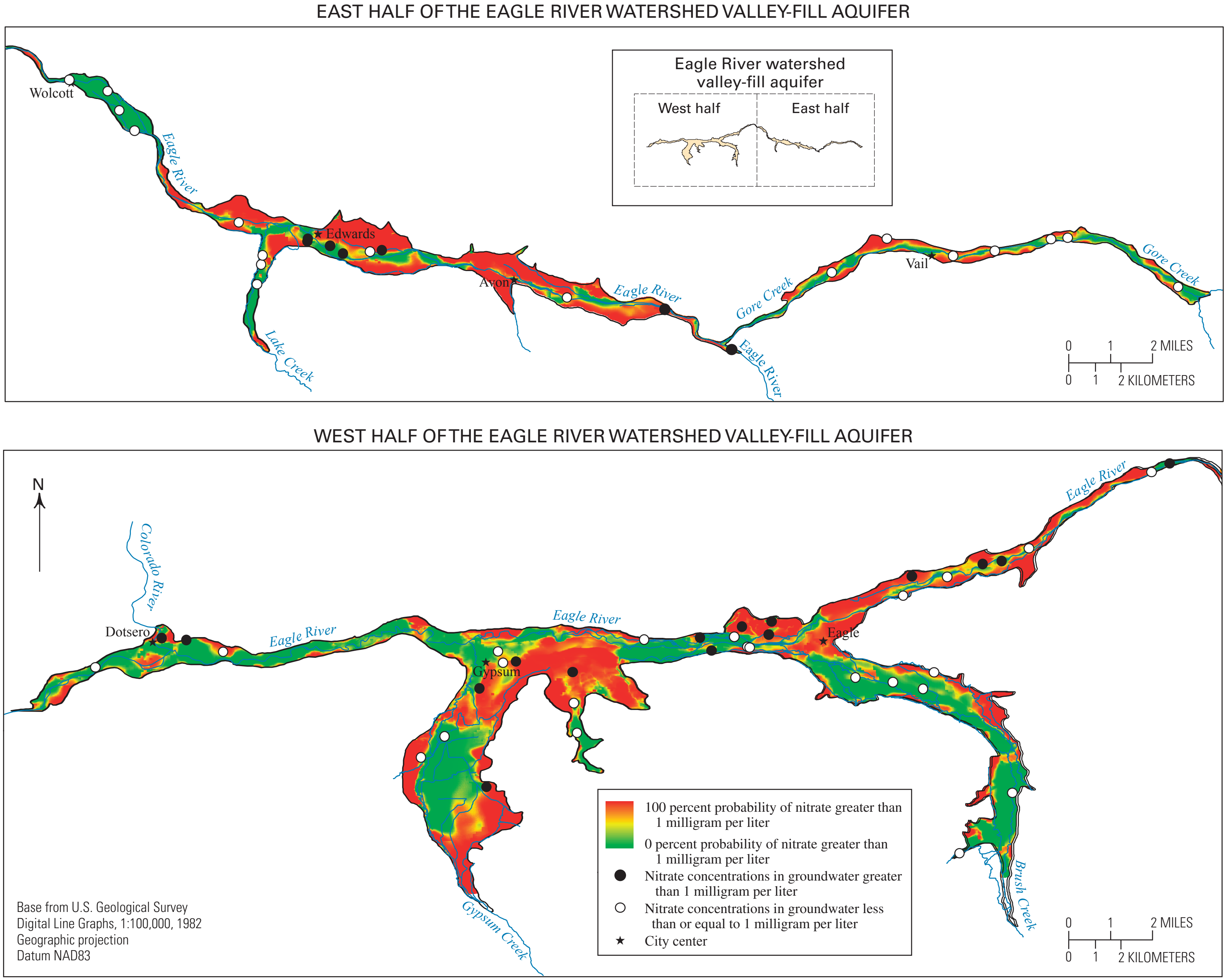
Statistical measures and independent variables	Probability of nitrate greater than 1 mg/L	Probability of unmixed young water based upon CFC–11 concentrations and tritium activities	Probability of TDVOCs greater than 28,000 pg/L
McFadden's rho-squared	0.490	0.632	0.647
Sensitivity	0.696	0.919	0.779
Specificity	0.825	0.740	0.892
Total correct predictions	0.778	0.876	0.855
Logistic regression constant	–0.742	–209.348	–289.698
Well depth	--	--	--
Depth to groundwater	0.116 (0.011)	--	--
Distance to gypsum beds	--	--	–2.803 (0.030)
Distance to surface water	--	–10.137 (0.015)	--
Precipitation	--	--	1.329 (0.036)
SSURGO soil available water capacity	--	--	–465.077 (0.018)
SSURGO soil clay content	1.565 (0.028)	--	7.875 (0.017)
SSURGO soil drainage	–8.391 (0.061)	–12.636 (0.099)	--
SSURGO depth to groundwater in soil layer	0.151 (0.013)	--	0.281 (0.023)
SSURGO soil hydrologic group	--	–11.492 (0.023)	--
SSURGO soil liquid limit	–1.969 (0.028)	4.003 (0.030)	–5.752 (0.016)
SSURGO soil septic suitability	--	–4.669 (0.053)	9.208 (0.023)
SSURGO soil organic matter content	4.338 (0.073)	--	--
SSURGO soil silt content	--	2.830 (0.027)	3.332 (0.049)
SSURGO soil sand content	0.290 (0.077)	2.833 (0.020)	2.622 (0.068)
SSURGO soil saturated hydraulic conductivity	--	–0.247 (0.016)	0.153 (0.021)
SSURGO soil slope	0.355 (0.019)	–0.409 (0.020)	--
SSURGO soil thickness	--	--	--
STATSGO soils available water capacity	--	--	1.221 (0.011)
STATSGO soils clay content	0.317 (0.042)	--	--

water containing a substantial portion of old water, and one for water composed of 100 percent young water. Water from 12 wells had CFC–11 concentrations greater than 250 ppt (table 3), which is the maximum concentration measured in air samples (table 11). Those 12 wells also were coded as one because they contain elevated concentrations of CFC–11 and have a higher probability of anthropogenic contamination. The resulting logistic regression model had a large McFadden's rho-squared (0.632), a large sensitivity (0.919), and a large total correct predictions (0.876) (table 12), indicating an effective model. Independent variables included in the model were distance to surface water, soil drainage, soil hydrologic group, soil liquid limit, soil septic suitability, soil silt content, soil sand content, soil saturated hydraulic conductivity, and soil slope (table 12).

The percentage of young water is an indicator of the predisposition of groundwater to anthropogenic contamination because groundwater composed of 100 percent young water has a greater likelihood of recharge by water containing anthropogenic compounds than water containing a substantial portion of old (older than 1940) water. Most compounds likely to cause concern in the Eagle River watershed are anthropogenic in origin that were produced mostly during the past 50 years; water composed of 100 percent young water has the greatest likelihood to contain anthropogenic compounds. Even if the young portion of water contains compounds of concern, those concentrations will be diluted by the older (uncontaminated) water, reducing the overall concentrations. For an overall measure of the predisposition to anthropogenic groundwater contamination, this probability model is probably the most useful out of the three probability models developed.

Development of Volatile Organic Compound Model

A model was developed to predict the probability of total dissolved VOC concentrations (TDVOC) in groundwater greater than 28,000 pg/L (table 12, fig. 17). Significant independent variables were distance to gypsum beds, precipitation, soil available water capacity, soil clay content, depth to groundwater in soil layer, soil liquid limit, soil septic suitability, soil silt content,



Base from U.S. Geological Survey
Digital Line Graphs, 1:100,000, 1982
Geographic projection
Datum NAD83

Figure 15. Probability of detecting nitrate concentrations greater than 1 milligram per liter in the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

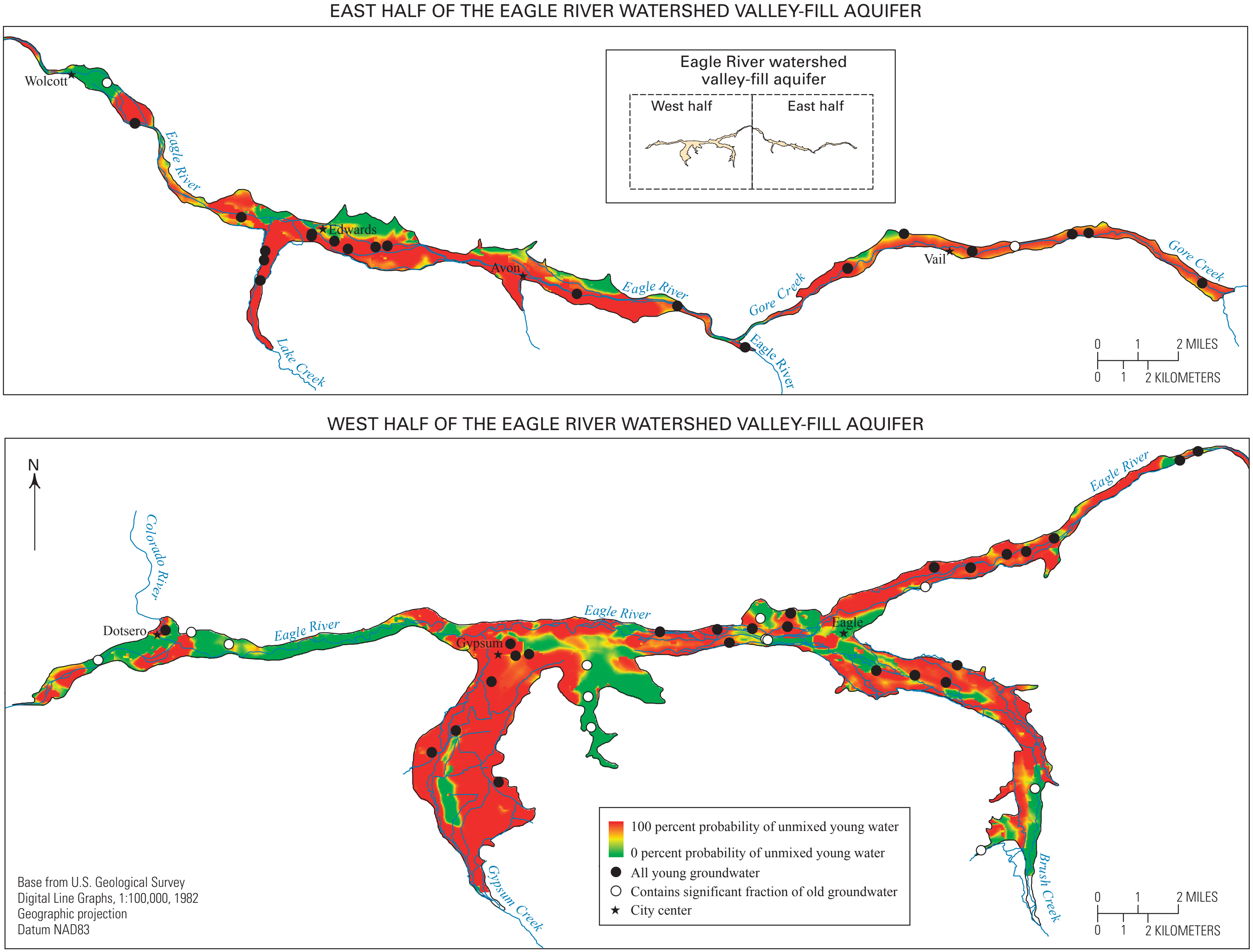


Figure 16. Probability of detecting unmixed young water in the Eagle River watershed valley-fill aquifer (using chlorofluorocarbon-11 concentrations and tritium activities), 2006–2007, Eagle County, Colorado.

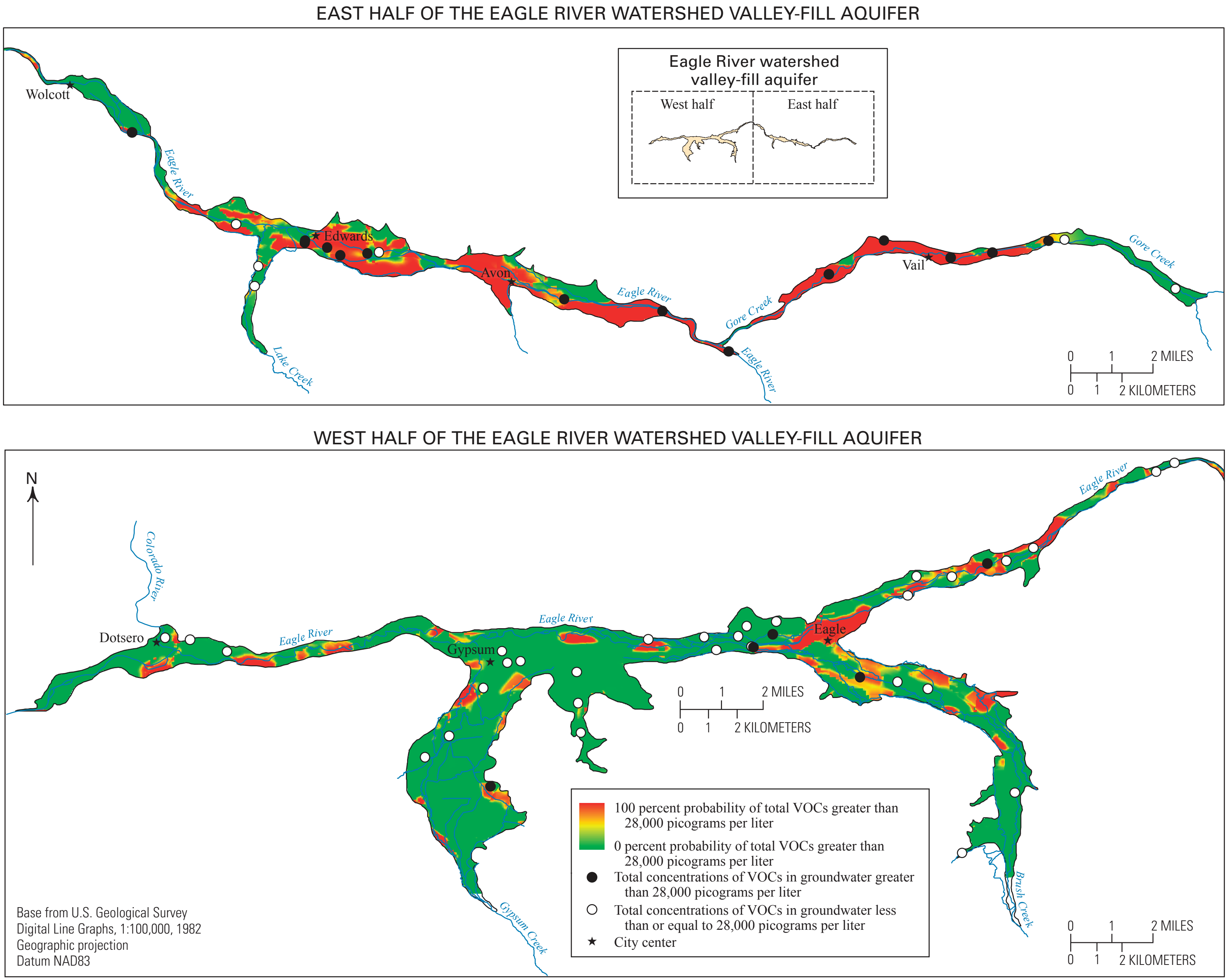


Figure 17. Probability of detecting total volatile organic compound concentrations greater than 28,000 picograms per liter in the Eagle River watershed valley-fill aquifer, 2006–2007, Eagle County, Colorado.

soil sand content, and soil saturated hydraulic conductivity. The TDVOC model was one of the most significant probability models produced (table 12). McFadden's rho-squared was 0.647, the sensitivity was 0.779, and the total correct predictions was 0.855.

Most wells with elevated TDVOC concentrations are located in the eastern portion of the ERWVFA (fig. 17), presumably because this is where the most intensive urban development has occurred. The TDVOC detections may be an indicator of light industrial and construction uses of solvents such as PCE, or the result of spills.

Verification of Probability Models

Previous probability mapping projects in other areas have validated the performance of the models by comparing them to an independent set of groundwater quality data (Rupert, 1998; Rupert, 2003; Gurdak and Qi, 2006). Unfortunately, an independent set of groundwater quality data is not available for the Eagle County watershed. To verify the models, the percentage of actual detections was plotted with the predicted probability of detections using a deciles of risk calculation. R-squared values of plots of actual detections with the predicted probability of detections were between 0.995 and 0.998, verifying they are highly effective models.

Comparison of Probability Models

The results of the groundwater age dating indicated that most areas in the ERWVFA had a high predisposition to contamination because most waters had groundwater recharge dates younger than 1980. The three probability models further delineated the probability of contamination for three different classes of compounds.

The nitrate probability model (fig. 15) showed the relative risk of elevated nitrate concentrations in groundwater from sources of nitrate such as fertilizers, manure, and wastewater. Based upon the young groundwater ages, the entire ERWVFA had a high predisposition to nitrate contamination from fertilizers, manure, and wastewater, but areas with larger depth to groundwater and less transmissive soils had a greater risk. Wells with nitrate concentrations greater than 1 mg/L in 2006–07 are shown in figure 10. Areas such as the Brush Creek and the central part of Gypsum Creek valleys (fig. 15) had low nitrate probability ratings. Future urban development may reduce the amount of recharge from irrigation in the Brush Creek and Gypsum Creek valley bottoms, which may increase the depth to groundwater, hence increasing the probability of nitrate contamination.

The model predicting the probability of unmixed young water in the ERWVFA (fig. 16) can be considered a generic model that is applicable for most contaminants. If a spill were to occur on the land surface or into the local surface water, those contaminants could be transported to the groundwater along the same pathways that the young recharge water uses. Although all areas of the ERWVFA had a high predisposition to contamination, areas with a high probability of unmixed young water (fig. 16) had the highest probability of carrying contamination with those young recharge waters into the groundwater.

Based upon the high occurrence of VOC detections observed by this study, VOC contamination is a concern in the ERWVFA. Although the entire ERWVFA had a predisposition to VOC contamination to some degree, the VOC probability map (fig. 17) indicated that the areas near Vail, Avon, and Edwards had the highest probability of groundwater contamination if a spill should occur.

Appropriate Uses of the Probability Maps

The probability models and maps are designed to portray the likelihood of groundwater in the ERWVFA to be affected by anthropogenic contamination. These models and maps do not show areas that are actually (currently) contaminated; rather, they show the areas that have a high likelihood for being contaminated if a compound of concern were released to the environment in the terms of percent probability. Probability is a statistical measure of how likely an event will occur. Probability is not the same as certainty. A well in a high-probability area is not necessarily contaminated because contamination also can depend on the type of contaminant released, how much of that contaminant was released, and other factors not taken into account by the logistic regression models. Although the probability maps show predictions of detections as a percent probability, there is inherent uncertainty within these predictions that is not shown in the probability map.

The probability models and maps are intended to be a first approximation at developing a consistent rating method for the entire study area and may have several limitations for use at the site or field scale. The models and maps do not account for local point sources of contaminants or features and processes that may promote focused recharge, preferential groundwater flow, or bypass mechanisms. Additional site-specific data are needed before site-specific decisions are made, such as the site-specific design of a wastewater-disposal system.

The probability maps should not be used at a scale any larger than 1:24,000, which is the scale of the SSURGO soils data. Some site-specific variables, such as improper well construction and local spills of contaminants, were not accounted for in the models. The Eagle River watershed is rapidly being developed. As development activities continue, some variables such as surficial soils and irrigation networks may be altered through construction activities, which may have unpredictable effects on the groundwater probability ratings.

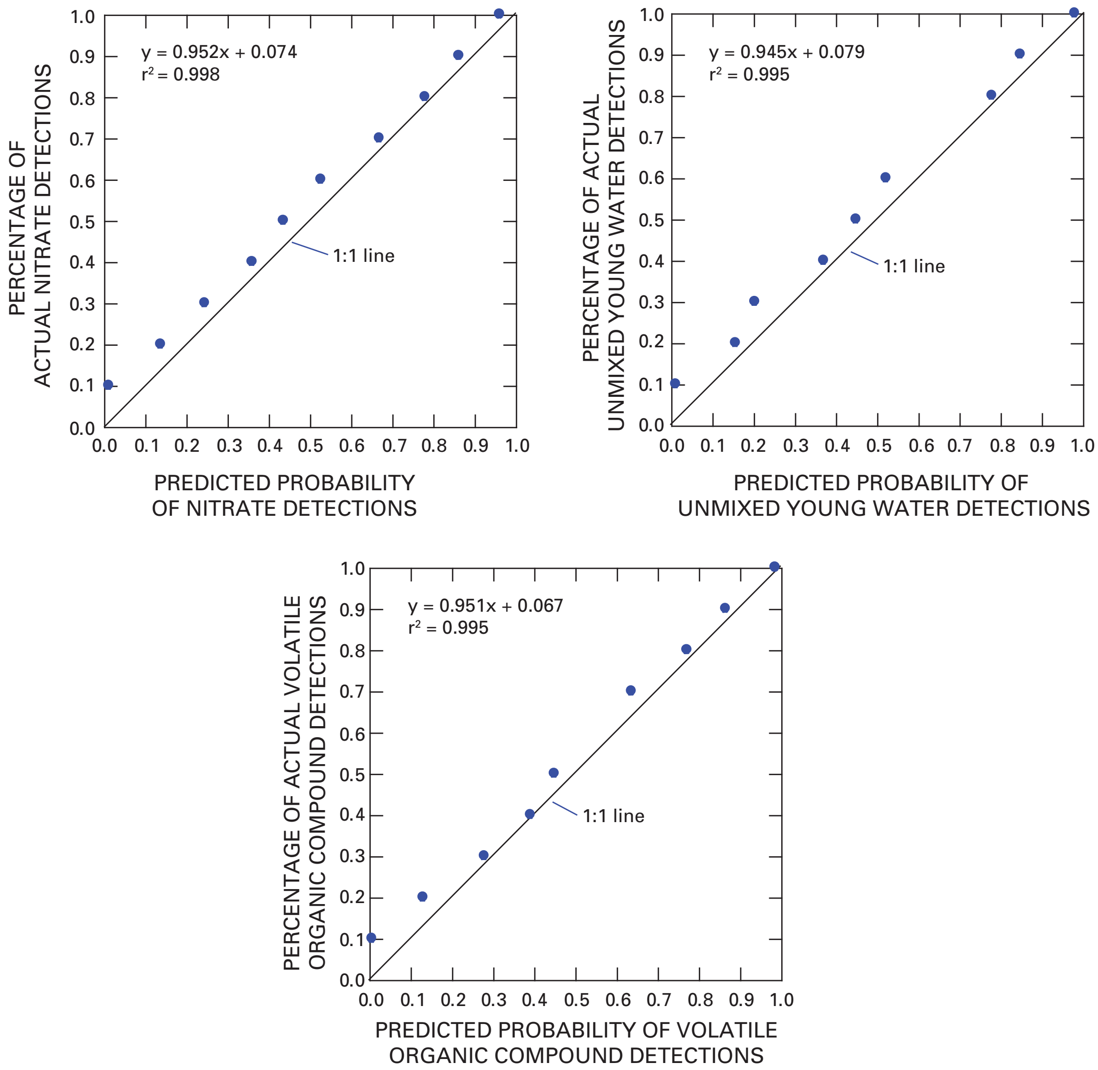


Figure 18. Percentage of actual detections of nitrate greater than 1 milligram per liter, detections of unmixed young water, and detections of total volatile organic compounds greater than 28,000 picograms per liter, plotted with the predicted probability of detections of those compounds, Eagle River watershed valley-fill aquifer, Eagle County, Colorado.

Summary

The Eagle River watershed is near the destination resort town of Vail, Colorado. The area has a fast growing permanent population, and the resort industry is rapidly expanding. The popularity of the area is largely due to the presence of high-value ecosystems and relatively pristine environmental conditions that the community wishes to protect. A large percentage of the land undergoing development is located above the Eagle River watershed valley-fill aquifer (ERWVFA), which has a high predisposition to groundwater contamination. As development continues, local organizations need tools to evaluate potential land-development effects on ground- and surface-water resources so that wise land-use decisions can be made. To help develop these tools, the U.S. Geological Survey (USGS), in cooperation with Eagle County, the Eagle River Water and Sanitation District, the Town of Eagle, the Town of Gypsum, and the Upper Eagle Regional Water Authority, conducted a study in 2006–2007 of the groundwater quality, age, and probability of contamination in the ERWVFA, north-central Colorado.

The overall purpose of this report was to develop maps that show the predisposition of the ERWVFA to contamination by anthropogenic compounds (contamination caused or produced by humans). Logistic regression statistical modeling techniques were applied to measured concentrations of environmental tracers (nitrate, tritium, chlorofluorocarbons (CFCs), and halogenated volatile organic compounds [VOCs]) in groundwater to develop statistical models that predict the probability of groundwater contamination by anthropogenic compounds in the ERWVFA. Previous groundwater probability mapping projects in other areas of the country have used agricultural contaminants such as atrazine to calibrate the statistical models. Nitrate, tritium, CFCs, and VOCs were used to calibrate the statistical models because development in Eagle County is urban and not agricultural, and development has occurred, for the most part, during the past 20 years or so.

Groundwater-quality samples were collected once from 10 sites during August 2006 and once from an additional 51 sites during May through June 2007 and analyzed for major ions, nutrients, stable isotopes of hydrogen and oxygen in water (^{2}H and ^{18}O), tritium, dissolved gases, CFCs, and VOCs determined with very low-level laboratory methods. Surface-water-quality samples were collected quarterly from six sites between October 2006 and September 2007 and analyzed for major ions, nutrients, ^{2}H and ^{18}O, and tritium. Additional samples were collected from the six surface-water sites, plus four additional sites, during high flow (May 2007) and low flow (August 2006 and August 2007) and analyzed for CFCs and VOCs.

Maps showing the probability of groundwater contamination by various contaminants, or the likelihood of occurrence of young water, were developed using the logistic regression models. Before constructing the maps, all Geographic Information System (GIS) data were converted to grids with 10-meter (32.8-feet) spacing. The soils data required an additional processing step. To create the data set for logistic regression modeling, soils data were averaged within 500-meter (1,640-foot) pie-shaped buffers oriented upgradient from each well site. To create the final probability maps, the soils data within 500-meter (1,640-foot) pie-shaped buffers oriented upgradient from every grid cell in each soils layer/factor were averaged. After the soils data were averaged, then the logistic regression models were entered into a GIS, and a probability rating was calculated for each grid node in the study area.

The groundwater probability models were developed as follows: (1) The groundwater quality and groundwater age data were overlaid with anthropogenic and hydrogeologic data by using a geographic information system to produce a data set in which each well had corresponding data on depth to groundwater, distance to major streams and canals, distance to gypsum beds, precipitation, soils, and well depth. These data then were downloaded to a statistical software package for analysis by logistic regression. (2) Statistical models predicting the probability of elevated nitrate concentrations, the probability of unmixed young water (using chlorofluorocarbon-11 concentrations and tritium activities), and the probability of elevated volatile organic compound concentrations were developed using logistic regression techniques. (3) The statistical models were entered into a GIS and the probability maps were constructed.

The major-ion data indicated that groundwaters in the ERWVFA can be classified into two major groups: groundwater that was recharged by infiltration of surface water, and groundwater that had less immediate recharge from surface water and had elevated sulfate concentrations. Sulfate exceeded the U.S. Environmental Protection Agency National Secondary Drinking Water Regulations for sulfate (250 milligrams per liter [mg/L]) in many wells near Eagle, Gypsum, and Dotsero. The most significant source of sulfate to groundwater in the ERWVFA is the Eagle Valley Evaporite, which is a Pennsylvanian-age gypsum deposit located in the western half of Eagle County. Many domestic well owners in the western portion of the watershed use reverse-osmosis water-treatment systems to reduce the amount of sulfate in their drinking water.

Nitrite plus nitrate as nitrogen (nitrate) concentrations in groundwater in the ERWVFA were low, with the median nitrate concentration about 0.74 mg/L, and the maximum concentration measured 5.4 mg/L. More than 50 percent of the nitrate concentrations in the ERWVFA were less than 1 mg/L, indicating that more than 50 percent of the wells tested in the ERWVFA had nitrate concentrations similar to natural recharge water (precipitation). Most groundwater in the ERWVFA was under oxidized geochemical conditions, indicating that nitrate from anthropogenic sources (caused or produced by humans) could persist for several decades in the groundwater of the ERWVFA.

Apparent groundwater ages were estimated from the CFC and tritium data by using models that assume either piston flow or binary mixing (dilution of a young component with old, tracer-free water). The median groundwater recharge date was 1989 and the standard deviation was about 9 years, indicating that most groundwater in the ERWVFA was young water. The median percentage of young water was 83 percent and the standard deviation was about 28 percent, indicating that only a small portion of water from most wells was composed of old (older than 1940) water. To put the groundwater age data in the context of the probability of groundwater contamination, most groundwater in the ERWVFA was recently recharged water and had a high predisposition to contamination by anthropogenic compounds.

VOCs were detected in all water samples at the low-level minimum detection level concentrations, but all VOC concentrations were at least one order of magnitude less than their U.S. Environmental Protection Agency Maximum Contaminant Level. Although VOCs are commonly associated with anthropogenic sources, several VOCs are produced naturally in the environment, and, if not degraded or otherwise altered, can be found in water that was not affected by human sources. A useful indicator of VOC concentrations larger than those produced naturally in the environment is to sum the total concentrations of halogenated VOCs. Water from wells in the ERWVFA with total VOC concentrations greater than 28,000 picograms per liter (pg/L) probably had total VOC concentrations larger than that produced naturally in the environment. Wells with total VOC concentrations greater than 28,000 pg/L can be used to identify areas that had a high predisposition to anthropogenic contamination by VOCs.

Logistic regression statistical modeling techniques were used to develop three statistical models that predict the probability of groundwater contamination by various contaminants. These three probability models used different compounds such as nitrate and VOCs to provide an indication of the predisposition to groundwater contamination by anthropogenic compounds under a variety of conditions and contaminant inputs. These three models predict the probability of elevated nitrate concentrations, the probability of unmixed young water (using CFC–11 concentrations and tritium activities), and the probability of elevated VOC concentrations.

The statistical parameters produced by the three logistic regression models indicated they were statistically significant models. McFadden's rho ranged between 0.490 and 0.647, and the total correct predictions ranged between 0.778 and 0.876, meaning they were highly effective models. The logistic regression models were verified by plotting the percentage of actual detections with the predicted probability of detections using a deciles of risk calculation. R-squared values of plots of actual detections with the predicted probability of detections were between 0.995 and 0.998, verifying they were highly effective models.

Although the results of the groundwater age dating indicated that most areas in the ERWVFA had a high predisposition to contamination because most waters had groundwater recharge dates younger than 1980, the three probability models further delineated the probability of contamination for three different classes of compounds. The nitrate probability model showed the relative risk of elevated nitrate concentrations in groundwater from sources of nitrate such as fertilizers, manure, and wastewater. The entire ERWVFA had a predisposition to nitrate contamination from fertilizers, manure, and wastewater, but areas with larger depth to groundwater and less transmissive soils had a greater risk. The model predicting the probability of unmixed young water in the ERWVFA can be considered a generic model that is applicable for most contaminants. If a spill were to occur on the land surface or into the local surface water, those contaminants could be transported to the groundwater along the same pathways that the young recharge water uses. Although the entire ERWVFA had a predisposition to VOC contamination to some degree, the VOC probability map indicates that the areas near Vail, Avon, and Edwards had the highest probability of groundwater contamination if a spill should occur. Based upon the high occurrence of VOC detections observed by this study, VOC contamination is a concern in the ERWVFA.

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