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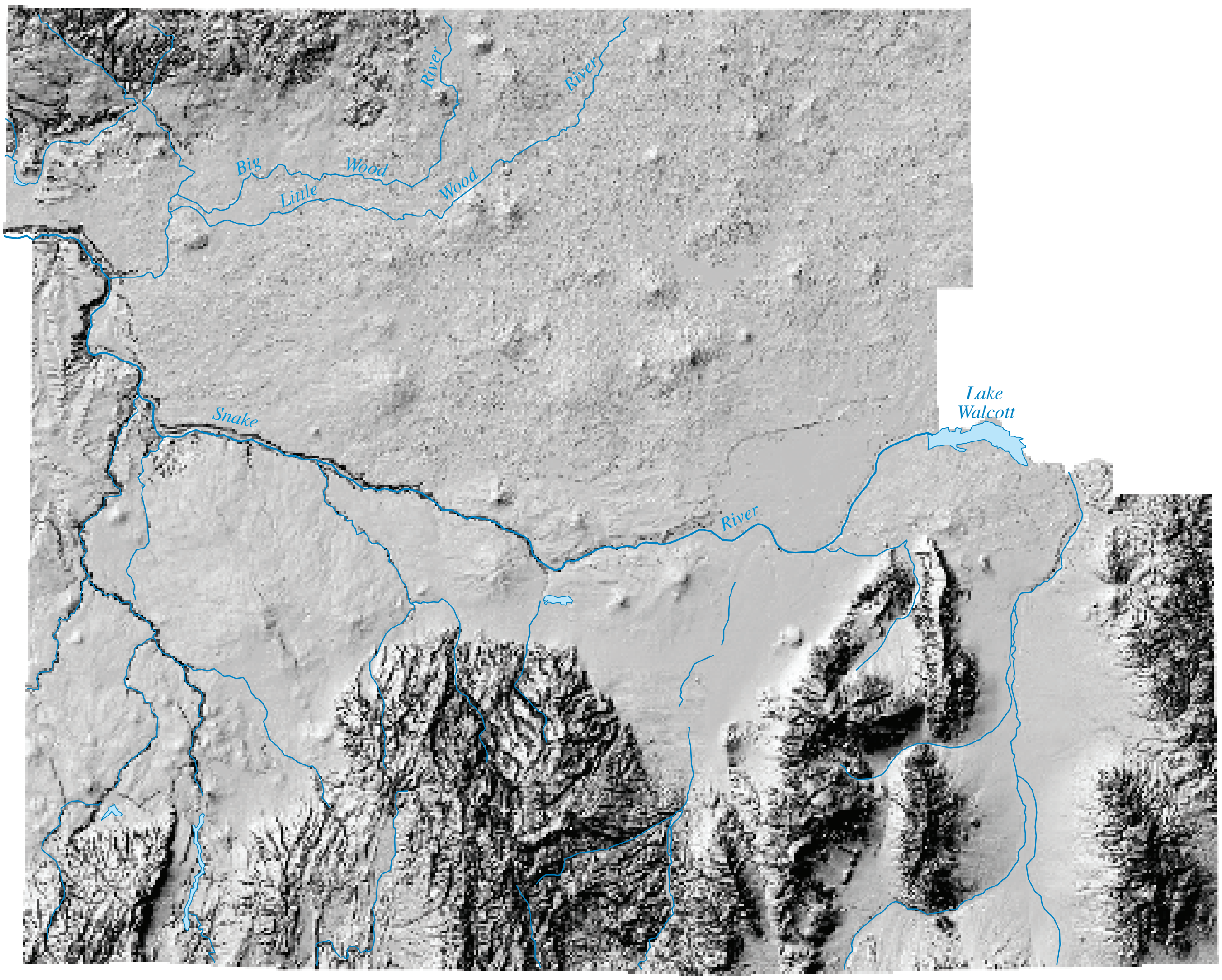
Prepared in cooperation with
Idaho Department of Environmental Quality and
Cassia, Gooding, Jerome, Lincoln, Minidoka, and Twin Falls Counties

Probability of Detecting Elevated Concentrations of Nitrate in Ground Water in a Six-County Area of South-Central Idaho

Water-Resources Investigations Report 03–4143



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By Kenneth D. Skinner *and* Mary M. Donato

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NOTE: On June 23, 2005, a correction was made on page 10, third paragraph, first sentence, by the addition of the line, "...from the ISDA for 1998. Crops belonging to the legume... "

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IDAHO DEPARTMENT OF ENVIRONMENTAL QUALITY and
CASSIA, GOODING, JEROME, LINCOLN, MINIDOKA, AND TWIN FALLS COUNTIES

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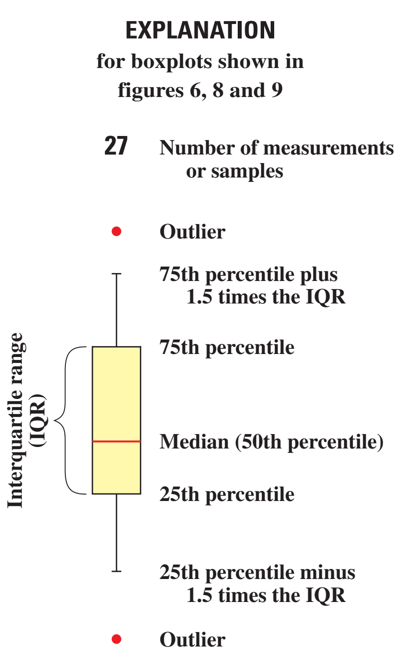
CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNIT, AND BOXPLOT EXPLANATION

Multiply	By	To obtain
acre	4,047	square meter (m^2)
foot (ft)	0.3048	meter (m)
foot per hour (ft/hr)	0.3048	meter per hour (m/hr)
foot squared per day (ft^2/d)[1]	0.09290	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
pound (lb)	0.4536	kilogram (kg)
pound per acre (lb/acre)	1.121	kilogram per square meter (kg/m^2)
pound per acre per year [(lb/acre)/yr]	1.121	kilogram per square meter per year [(kg/m^2)/yr]
pound per day (lb/d)	0.4536	kilogram per day (kg/d)
square mile (mi^2)	2.590	square kilometer (km^2)

[1] The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. This mathematical expression reduces to foot squared per day (ft^2/d).

Abbreviated water-quality unit:

mg/L milligram per liter



Probability of Detecting Elevated Concentrations of Nitrate in Ground Water in a Six-County Area of South-Central Idaho

By Kenneth D. Skinner *and* Mary M. Donato

Abstract

A probability map constructed for this study identi ed se veral areas in a six-county region of south-central Idaho with high probabilities of detecting elevated concentrations (greater than 2 milligrams per liter) of nitrate. An increasing proportion of Idaho's ground water being used for drinking water and large increases in the inputs of nitrogen to ground water in Cassia, Gooding, Jerome, Lincoln, Minidoka, and Twin Falls Counties have prompted concerns about the quality of the resource. The probability map was constructed to assist regulatory and resource agencies in managing land use and protecting water resources.

To construct the probability map, hydrogeologic and anthropogenic data were integrated with ground-water quality data in a geographic information system. The resulting data set contained land use, geology, precipitation, soil characteristics, depth to ground water, nitrogen input, and ground-water velocity information for each of the 1,365 samples collected from 1991 to 2001. Logistic regression analysis was used to determine the most statistically signi cant v ariables related to the detection of elevated nitrate concentrations.

The resulting multivariate probability model showed that ground-water velocity, nitrogen input, precipitation, soil drainage, land use, and depth to ground water were signi cantly correlated with elevated nitrate concentrations. A subset of the water-quality data set was used to verify these results. Linear regression of the percentage of predicted probabilities of elevated nitrate concentrations and the actual percentage of elevated nitrate concentrations with the model data set and the veri cation data set both sho wed good correlations: r-squared values were 0.96 and 0.97, respectively. Statistical comparisons of both data sets showed that ground-water samples containing elevated nitrate concentrations had signi cantly higher probabilities of detection ($p < 0.001$) than samples without elevated nitrate concentrations. On the basis of these results, a map identifying the probability of detecting elevated nitrate concentrations was constructed. High-probability areas on the map coincided with regions of agricultural land use and high nitrogen input, except in southern Gooding County and western Jerome County. In these areas, high ground-water velocities representing a predominance of regional ground water resulted in a low probability of detecting elevated nitrate concentrations. Areas of poor prediction tended to be congregated along the transition zone between high and low ground-water velocities in Jerome and Gooding Counties, indicating a mix of regional and recently recharged ground water.

INTRODUCTION

Ground-water quality is an ongoing concern in Idaho. In 1990, ground water accounted for nearly 85 percent of the State's drinking water; in 1995, it accounted for almost 95 percent (Solley and others, 1993, 1998). Previous studies have detected high concentrations of nitrate in many aquifers in the State (Rupert, 1994; Crockett, 1995; Rupert and others, 1996). Predominant sources of nitrate in much of the State are inorganic fertilizer, cattle manure, and legume crops (Rupert, 1997). Because of the stable agricultural industry and large increases in the dairy industry, especially in Gooding, Jerome, and Twin Falls Counties (Idaho Agricultural Statistics Service, 1999; U.S. Department of Agriculture, 1999), resource managers and planners are in need of tools to aid in land-use planning and water-resource management and protection.

Maps showing the probability of detecting elevated nitrate concentrations can be important tools to aid regulatory and resource-protection agencies. Ground-water probability maps indicate the predisposition of areas to ground-water contamination on the basis of natural and anthropogenic factors. These maps also can assist other organizations such as agricultural producers; city governments; planning and zoning commissions; and State programs related to Wellhead Protection, Drinking Water, and Best Management Plans.

For this study, elevated nitrate concentrations or nitrate detections are considered greater than 2 mg/L. A nitrate concentration of 2 mg/L was chosen because it was the concentration used in other similar studies in the area (Rupert, 1998; Donato, 2000) and is high enough above local background concentrations, typically below 1 mg/L, to indicate an anthropogenic in uence on ground water.

Background

Most maps showing the vulnerability of areas to ground-water contamination are created using a geographic information system (GIS) to combine hydrogeologic and anthropogenic data such as land use, soil properties, and depth to ground water. One of the most widely used methods for producing such maps is the DRASTIC model (Aller and others, 1985). The **DRASTIC** model uses point ratings assigned to seven factors: **D**epth to ground water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone media, and hydraulic **C**onductivity of the aquifer. The ratings are added together in data layers in a GIS to make a vulnerability map. DRASTIC models usually are not calibrated to actual ground-water contaminant concentrations.

Another method of vulnerability mapping uses statistical correlations between environmental factors and water-quality data. A statistical method used to calibrate nitrate vulnerability maps with water-quality data was developed by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program for the upper Snake River Basin, southeastern Idaho (Rupert, 1997). This method differs from the DRASTIC method by calculating the probability of contamination on the basis of statistical correlations between measured nitrate concentrations in ground water and land use, soils, and depth to ground water.

The statistical method was improved by using logistic regression to relate water-quality data to hydrogeologic and anthropogenic data. Two probability maps for detecting the herbicide atrazine have been created, one for the upper Snake River Basin and one for the western Snake River Plain (Rupert, 1998; Donato, 2000). These maps are called probability maps because they delineate areas according to the probability of detecting a contaminant in that area. Calibrated contaminant probability maps are a superior predictive tool over maps produced using the modi ed DRASTIC method because the actual probabilities of contaminant detection can be quanti ed.

The probability map developed in this study encompasses a smaller area than those of Rupert (1998) and Donato (2000). To compensate for the difference in study area size, a larger scale soil data set was used than in the previous two studies. In addition, an aquifer property data layer was incorporated to provide another explanatory factor for the probability of detecting elevated nitrate concentrations in ground water.

Purpose and Scope

The main purpose of this report is to document the construction and veri cation of a map sho wing the probability of detecting elevated nitrate concentrations in ground water in south-central Idaho. A GIS was utilized to examine relations between elevated nitrate in ground water and hydrogeologic and anthropogenic factors. The data set consisted of 1,365 ground-water samples collected from 1991 to 2001. This report also documents the construction of three GIS layers—a nitrogen input layer, a ground-water velocity layer, and a depth-to-water layer—used to construct the probability map. Logistic regression was used to develop the statistical model that predicts the probability of detecting elevated nitrate concentrations in ground water.

Acknowledgments

The author wishes to thank the following people and agencies: Dave Clark and Patrick Lambert (USGS) for valuable discussions leading to improvements in the probability model, and Idaho State Department of Agriculture (ISDA) and Idaho Department of Environmental Quality (IDEQ) for providing an extensive additional nitrate concentration data set.

STUDY AREA DESCRIPTION AND GEOHYDROLOGY

Cassia, Gooding, Jerome, Lincoln, Minidoka, and Twin Falls Counties compose the study area, approximately 7,800 mi^2 (fig. 1) in south-central Idaho. Most of the study area is in the downstream part of the eastern Snake River Plain and is bounded on the south by mountains and tributary valleys. About 57 percent of the area is rangeland, 17 percent is flood-irrigated land, 11 percent is sprinkler-irrigated land, and the remaining 15 percent is composed of six other land-use types. Most of the agricultural land in the study area is near the Snake River. The area is predominantly semiarid; mean annual precipitation ranges from 10 in. on the Snake River Plain to 40 in. on the mountains in central Cassia County.

The study area ground-water system is made up of three types of aquifers: a regional basalt aquifer, a local perched alluvial aquifer, and tributary valley aquifers. The regional basalt aquifer underlying the eastern Snake River Plain provides most of the ground water that moves through the study area. The local perched alluvial aquifer (fig. 1) overlying the eastern Snake River Plain near Minidoka and Cassia Counties and the tributary valley aquifers in the southern part of the study area are lesser sources of ground water.

Snake River Plain Aquifer

North of the Snake River in the study area is the eastern Snake River Plain aquifer, composed primarily of vesicular and fractured olivine basalt flows (Quaternary age) of the Snake River Group (Whitehead, 1992). Individual flows average 20 to 25 ft in thickness. The top of the basalt is generally less than 100 ft below land surface throughout this part of the plain, and the thickness of the basalt is more than 1,000 ft in places.

Layered basalt flows in the eastern Snake River Plain aquifer yield exceptionally large volumes of water to wells and springs. Individual well yields are some of the highest in the Nation and typically range from 2,000 to 3,000 gal/min to 7,000 gal/min with minimal drawdown (Whitehead, 1992; Lindholm, 1996). Transmissivity can be as high as 1,000,000 ft^2/d and is commonly 100,000 ft^2/d (Whitehead, 1992). Locally, aquifer properties can vary greatly; however, on a regional scale, the variability is minimal.

Regional ground-water movement in the eastern Snake River Plain aquifer is from the northeast to the southwest (Rupert, 1997). Ground water is discharged as springs and seeps to the Snake River along the reach bordering Twin Falls, Jerome, and Gooding Counties. Ground-water discharge to this reach of the Snake River increased considerably from about 1910 through the early 1950s (Kjelstrom, 1992). The increase is attributed to recharge from surface-water irrigation north of the Snake River. Since the early 1950s, ground-water discharge to the Snake River has decreased as a result of increased ground-water withdrawals for irrigation (Moreland, 1976), the introduction of more efficient irrigation practices such as conversion from flood to sprinkler irrigation, and local droughts (Kjelstrom, 1992). Changes in ground-water levels reflect the same long-term downward trend as does spring discharge (Kjelstrom, 1992; Rupert, 1997).

Perched Aquifer

An alluvial aquifer is perched above a blue-clay layer about 60 to 120 ft below land surface in the Burley area (fig. 1) (Rupert, 1997). The top of the clay layer was previously mapped on the basis of data from several hundred well-driller records. Water in the perched aquifer moves northward at the southern boundary of the perched aquifer and westward near the western boundary. The water level in the perched aquifer is about 100 ft above that of the Snake River Plain aquifer. Recharge to the perched aquifer is predominantly infiltration of irrigation water. According to local accounts, the perched aquifer was formed in 1907 when a canal network was constructed through the area to transport irrigation water. Reportedly, several wells completed in this aquifer go dry seasonally after irrigation ceases and become operational again after the start of the next irrigation season.

Tributary Valley Aquifers

Tributary valley aquifers south of the Snake River recharge the regional Snake River Plain aquifer in the study area. They are predominantly alluvial deposits that interfinger with the Snake River Group near the mouths of the valleys. A more complete description of these valley aquifers is provided by Mundorff and others (1964).

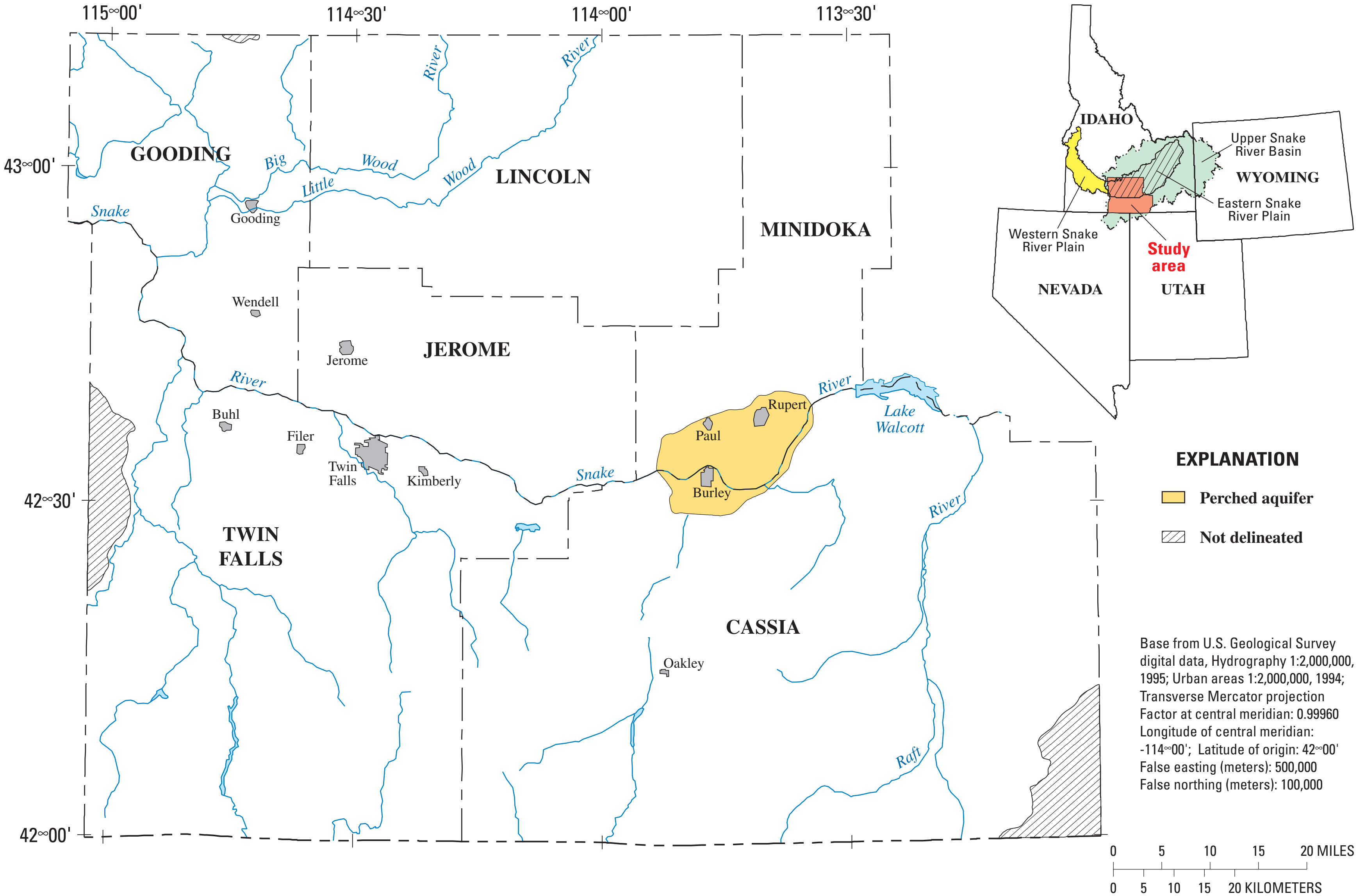


Figure 1. Location of the study area and the perched aquifer in the Burley area, south-central Idaho.

MODEL DEVELOPMENT APPROACH

The creation of the elevated nitrate probability model closely followed the methodologies of Rupert (1998) and Donato (2000). These studies were based on water-quality data from the Idaho Statewide Ground-Water Monitoring Program (ISGWMP), a cooperative program between the USGS and the Idaho Department of Water Resources (IDWR). Rupert (1998) used additional data collected as part of the USGS NAWQA Program. Because of poor spatial distribution of ISGWMP and NAWQA nitrate data in the study area, it was uncertain whether a statistically valid model for producing the probability maps could be built. Thus, additional nitrate data from the USGS National Water Information System (NWIS) data base, the IDEQ, and the ISDA were used for this study.

The elevated nitrate probability map was constructed using mostly existing data and published interpretation of o w, statistical methods that model the probability, and a GIS to process the data and produce the nal map. First, all the nitrate data from the multiple data bases were combined. Next, relations between the occurrence of elevated nitrate concentrations and hydrologic and anthropogenic data were evaluated using a GIS and statistical methods, including logistic regression. Univariate relations between elevated nitrate concentrations and land use, geology, precipitation, soil characteristics, depth to ground water, nitrogen input, and ground-water velocity were examined to identify explanatory variables. Multivariate logistic regression was used to determine the best probability model using a forward-stepwise approach with a backward check for elimination. The nal model then w as entered into a GIS to produce the probability map.

GROUND-WATER QUALITY DATA

Initial phases of model development incorporated nitrate data collected as part of the ISGWMP, the USGS NAWQA Program, and a 70-well network established in Cassia and Twin Falls Counties speci cally for this study. Primary objectives of the ISGWMP are to characterize the quality of water in Idaho's aquifers, identify temporal trends in water quality in individual aquifers, and identify potential ground-water quality problem areas (Idaho Department of Water Resources, 1995; Neely, 2001). The goals of the NAWQA Program are to (1) describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers; (2) describe water-quality trends; and (3) improve understanding of the primary natural and human factors that affect water-quality conditions. The purpose of the additional 70-well network was to aid in calibrating nitrate probability maps in areas of Cassia and Twin Falls Counties where the data were sparse. All the nitrate data used for this study were collected during 1993 to 2001. If multiple data were available from a single well, the most recent data value was used. All programs used a random well-selection process and similar sampling methods.

Spatial distribution of wells in the data sets indicated that most of the sampled wells were located in agricultural and urban areas. Thus, initial statistical models based on these data were of limited use for describing the probability of detecting elevated nitrate concentrations in other land-use areas. To create a more robust statistical model, additional nitrate data collected during previous USGS studies and stored in the USGS NWIS data base were used. Nitrate data from the following data bases also were added to the data set used in nal statistical modeling: ISD A — ground-water monitoring networks and a one-time analysis of water from wells at dairies statewide; and IDEQ — individual ground-water quality investigations statewide and the Drinking Water Information Management System public water-supply data base (g. 2). Samples collected and analyzed by the USGS were reported as nitrite plus nitrate as nitrogen ($NO_2 + NO_3 - N$), whereas the remainder of the samples were analyzed by the Idaho State Laboratory and reported as nitrate as nitrogen ($NO_3 - N$). Concentrations of nitrite in ground water in the study area are typically negligible; therefore, USGS, IDEQ, and ISDA analyses were considered equivalent. Some of the additional nitrate data did not have associated well depths and water levels, so a generalized depth-to-water map was used instead of well depth and water-level measurements during statistical analysis. Also, some of the additional samples were collected from wells that were not randomly selected; however, these samples accounted for only a small proportion of the total data set. The entire data set consisted of 1,365 samples, collected from 1991 to 2001.

A random selection process in the statistical software was used to extract 20 percent of the sample set for external veri cation of the statistical model. The veri cation data set w as viewed in a GIS to ensure a good spatial distribution.

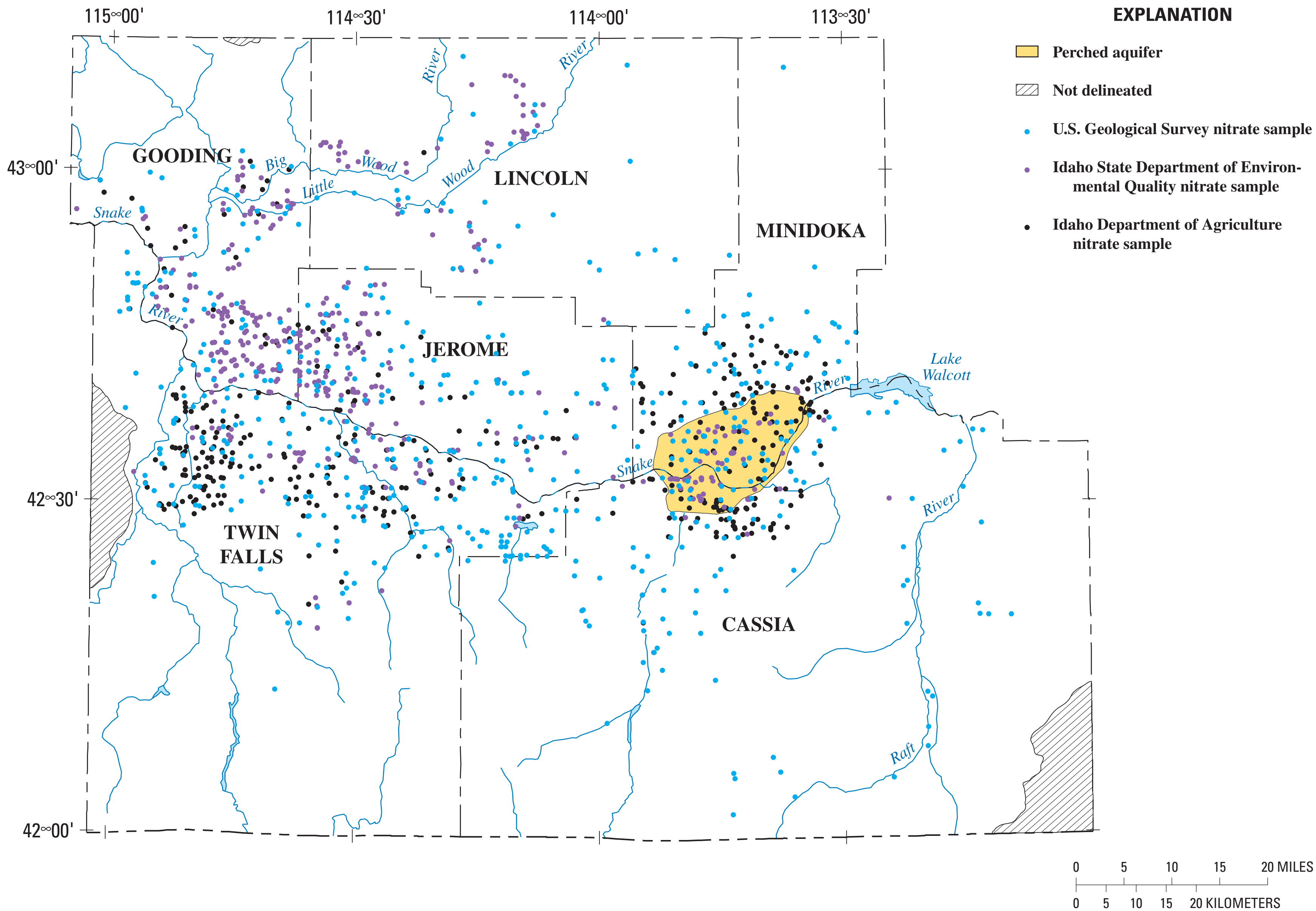


Figure 2. Sources and locations of ground-water samples analyzed for nitrate, south-central Idaho.

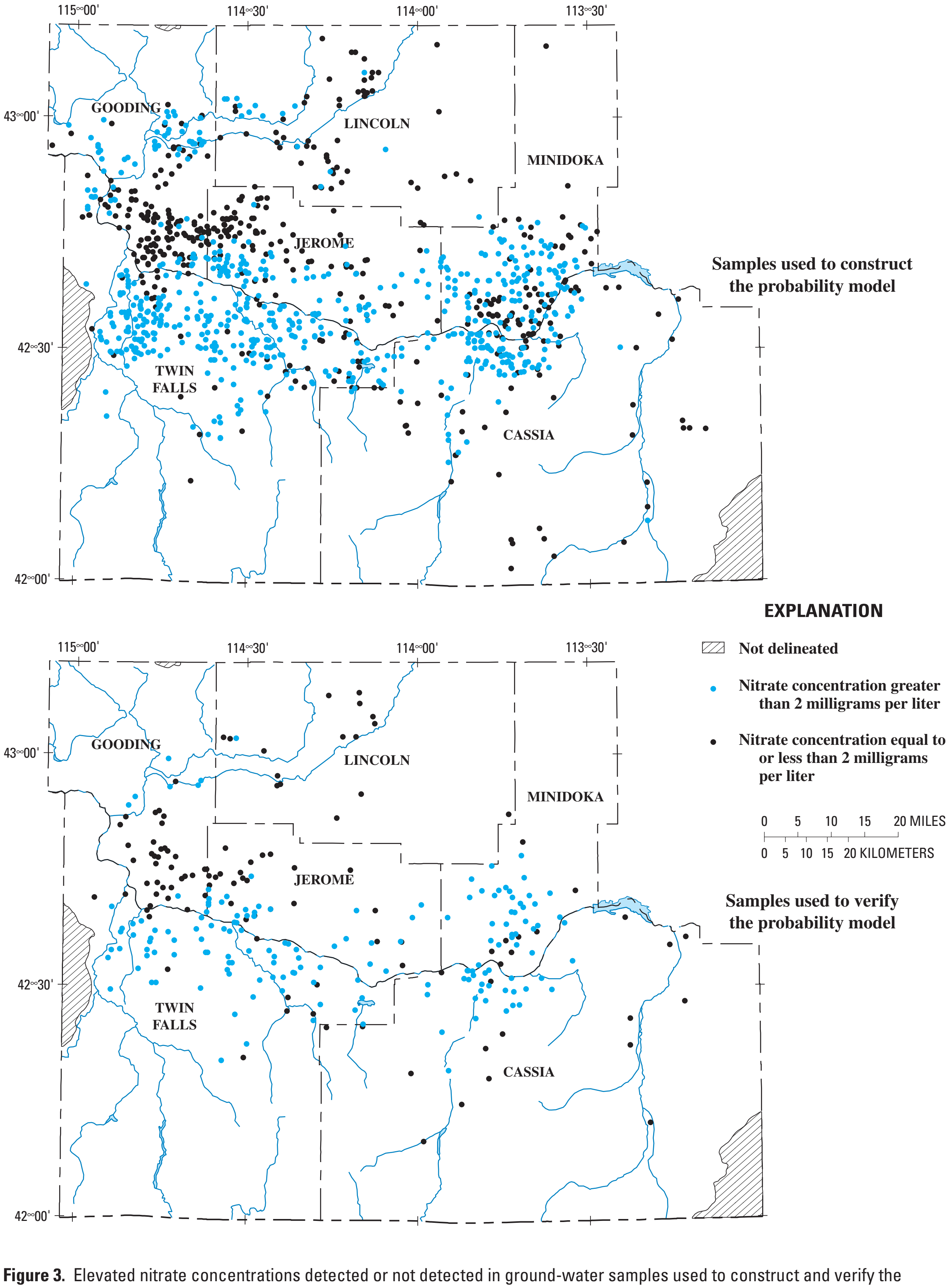


Figure 3. Elevated nitrate concentrations detected or not detected in ground-water samples used to construct and verify the probability model, south-central Idaho. (Elevated, greater than 2 milligrams per liter)

Of the 1,095 samples used to create the statistical model and probability map, 656 contained an elevated nitrate concentration; 161 out of 270 samples in the verification data set contained an elevated nitrate concentration (fig. 3). Nitrate concentrations in both data sets ranged from less than 0.05 to 26 mg/L as N; concentrations in 56 of the 1,365 samples exceeded the U.S. Environmental Protection Agency (EPA) maximum contaminant level of 10 mg/L.

HYDROGEOLOGIC AND ANTHROPOGENIC DATA

Hydrogeologic and anthropogenic data used in this study included land use, precipitation, surficial geology, soil characteristics, nitrogen input, relative ground-water velocity, and depth to water. These data are available in GIS format from a variety of sources.

Two sets of land-use data were evaluated for use in the probability model, one from IDWR and one from the Bureau of Reclamation (BOR). The IDWR land-use data were combined from three maps: one showing vegetation type, one differentiating between sprinkler and flood irrigation, and one differentiating between dryland and irrigated agriculture. The BOR mapped land cover at 1:40,000 scale from digitized high-altitude aerial photographs taken in 1987 and field checked in 1992. Each land-use data set has unique advantages. The IDWR data were mapped at a scale of 1:100,000 and included classifications for lava flows, dryland agriculture, rangeland, and forest land. The BOR data were mapped at a larger scale but combined forest, lava flows, and rangeland into one classification, native lands. Each land-use data set was evaluated separately to determine which produced the best correlation with elevated nitrate concentrations.

A precipitation GIS data set (1:250,000) was obtained from the Water and Climate Center of the Natural Resources Conservation Service (NRCS) and represents mean annual precipitation from 1961 to 1990.

The surficial geology GIS data set is from a digitized geologic map by Whitehead (1986) at a scale of 1:100,000.

Soils data were obtained from the NRCS Soil Survey Geographic (SSURGO) data base. SSURGO soil maps are made at scales ranging from 1:12,000 to 1:63,360. Previous analyses of the Snake River Plain by Rupert (1998) and Donato (2000) incorporated data from the State Soil Geographic Database (STATSGO), which are mapped at a scale of 1:250,000. Use of the SSURGO soils data set provided a significant improvement over the STATSGO data set as a result of the small size of the study area. The soil characteristics evaluated in the statistical model were percentage of clay content, drainage, hydrologic group (infiltration), percentage of organic matter, permeability, and soil depth. Clay content, organic matter, and permeability were assigned values for each soil horizon. A weighted average for the entire soil column was used for the statistical analysis.

The method used to estimate nitrogen input and losses for the study area followed that of Rupert (1996). Five sources of nitrogen were considered: fertilizer, cattle manure (dairy and beef), septic systems, atmospheric deposition (precipitation), and legume crops. Nitrogen losses resulting from crop uptake; decomposition of previous-year nonleguminous crop residue (chaff); and storage, volatilization, denitrification, and inorganic nitrogen availability of cattle manure were estimated.

Most nitrogen sources, including cattle inventories and crop acreages, were determined using 1998 data. Exceptions were fertilizer sales data, which were available only for 1997, and population household estimates for septic systems, which were adjusted to approximate 1998 data.

Because specific nitrogen application maps were not available, nitrogen input values were distributed according to the BOR's land-use coverage. For example, nitrogen input from fertilizer was applied only to land classified as residential or agricultural (dry farmed and flood- or sprinkler-irrigated land), whereas nitrogen from septic systems was applied only to residential or commercial land, because actual septic system locations are not available. The nitrogen input categories are county-level estimates distributed by land-use type in each county, so artificial discontinuities occur at county boundaries (fig. 4).

Nitrogen fertilizer use for the six counties in the study area were estimated using a method similar to that of Battaglin and Goolsby (1995). The ratio of expenditures for commercial fertilizer in the county to expenditures for commercial fertilizer in the State was multiplied by the number of pounds of nitrogen applied in the entire State to obtain the number of pounds of nitrogen applied in each county, as follows:

$$\left(\frac{\textit{\$ spent in county}}{\textit{\$ spent in State}}\right) \; X \textit{ pounds of nitrogen applied in State} = \textit{pounds of nitrogen applied in county} \qquad (1)$$

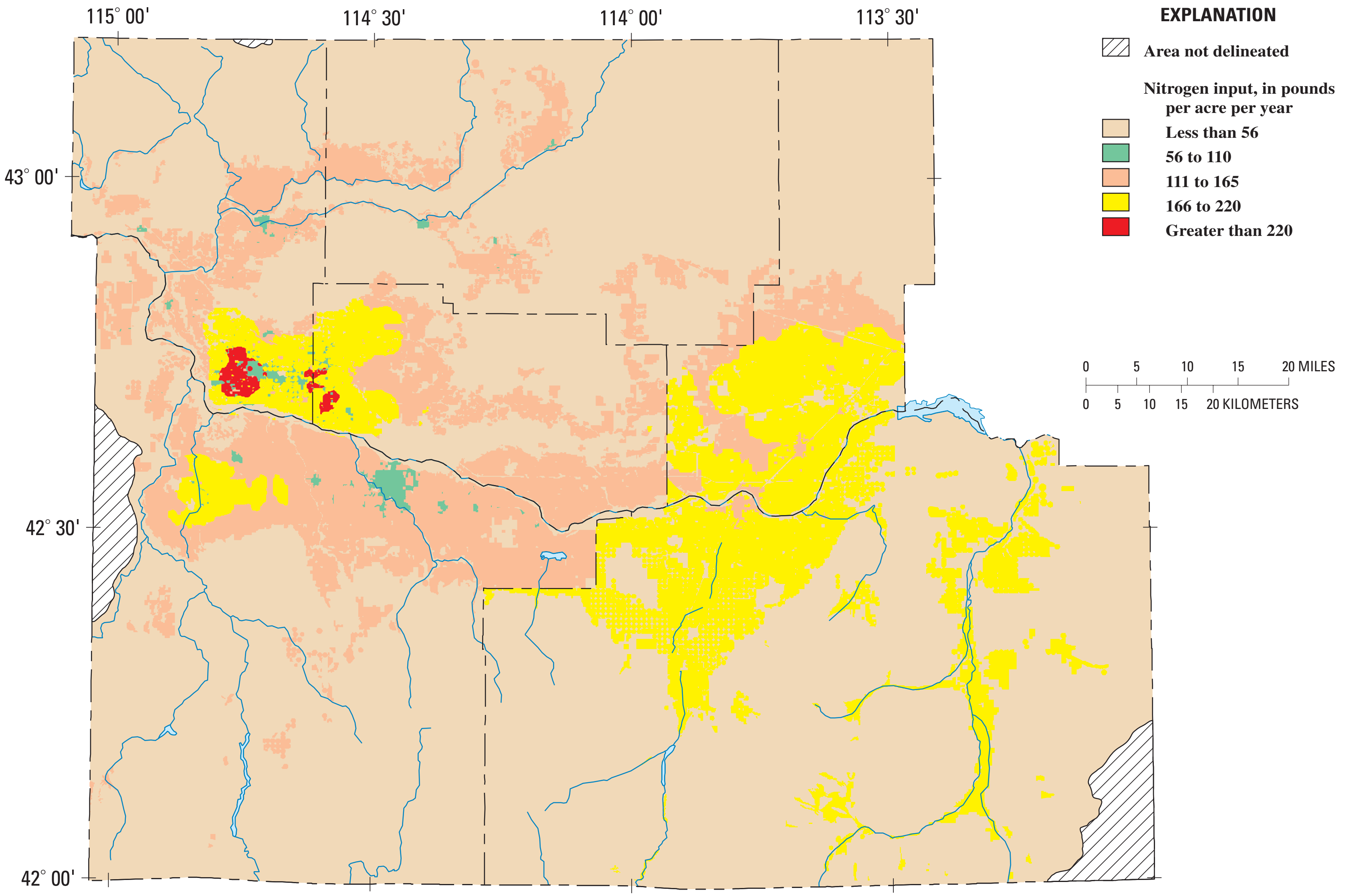


Figure 4. Nitrogen input, south-central Idaho.

The calculations of nitrogen fertilizer use are based on State and county fertilizer sales gures from the 1997 U.S. Department of Agriculture's Census of Agriculture. The nitrogen from fertilizer data then were divided by the total number of agricultural and residential acres in each county to obtain the number of pounds of nitrogen applied per acre. The resulting county-level nitrogen inputs for the six counties in the study area are reasonable when compared with those reported for the six-county study area in 1991 by Battaglin and Goolsby (1995).

Nitrogen losses from crop uptake were applied only to agricultural land-use types. Estimated nitrogen losses from crop uptake were calculated by determining the amount of nitrogen required for a given crop and yield and dividing by the acres of that crop in a county. Crop uptake was estimated for the major crops grown in each county based on 1998 data (barley, sugar beets, potatoes, oats, wheat, and corn).

For this study, nitrogen input from legumes was estimated using alfalfa and dry bean crop data by county from the ISDA for 1998. Crops belonging to the legume family, such as clovers, alfalfa, and beans, establish a symbiotic relationship with microbes that reside in nodules on the roots of the host plant and x atmospheric nitrogen. The nitrogen xation rates were from a report by Goolsby and others (1999): 194.5 lb/acre for alfalfa and 53.7 lb/acre for dry beans.

Nitrogen input resulting from dairy cattle was estimated for areas with known dairy operations and weighted by the average number of dairy cattle per facility. These data were provided by ISDA for 429 dairies in the study area, probably a fraction of the total number of dairies (Danielle Bruno, Idaho State Department of Agriculture, oral commun., 2000). A contour map, based on the dairy locations and number of dairy cattle, was created in intervals of 50 animals, ranging from 1 to 450 animals/mi^2. This allowed a range of nitrogen input values, in pounds per acre, to be assigned spatially on the basis of the estimated number of animals per acre. It was assumed that dairy cattle produce 0.45 lb/d of nitrogen per animal (Lander and others, 1998).

Ranges of nitrogen losses from storage and application of dairy cattle manure summarized by Rupert (1996) were used. The type of manure storage system determines the amount of loss, ranging from 80 percent in open lagoons to 15 percent by spreading. Volatilization losses (mostly as ammonia) during eld application range from 5 to 30 percent. Denitri cation losses (loss of inorganic nitrogen by biological conversion to nitrogen gas) range from 0 to 40 percent depending upon soil drainage properties. Rupert (1996) summarized a range of estimates of organic nitrogen from cattle manure that is not available for plant uptake or leaching. This organically bound nitrogen breaks down in the soil over time and forms inorganic nitrogen, which then is available for plant uptake and leaching. Nitrogen availability ranges from 45 to 96 percent after the rst year of application. The mean of these nitrogen loss ranges was subtracted from the nitrogen inputs.

Because information on the spatial distribution of beef cattle was not available, it was assumed that all beef cattle were located on agricultural land, although this necessary simpli cation does not account for cattle on rangeland. The number of beef cattle in each county, obtained online from the Idaho Agricultural Statistics Service, was multiplied by the average daily amount of total nitrogen in feces and urine produced by each animal (0.305 lb/d/animal).

Nitrogen losses from beef cattle manure differ from those of dairy cattle manure only in the method of manure storage and application. Losses resulting from storage of cattle manure range from 0 to 80 percent, depending on whether the cattle were grazing on open rangeland or in feedlots and pens. Rupert (1996) indicated that 85 percent of the total nitrogen remains when manure is applied directly to the ground. This is between the range of 70 to 95 percent retained by mechanical spreading methods. Because denitri cation and organic nitrogen losses occur once the manure is applied to the ground, they are the same for both dairy and beef cattle.

Nitrogen concentration data from the National Atmospheric Deposition Program/National Trends Network were combined with long-term average precipitation data to compute the annual amount of nitrogen input by precipitation at any point in the study area. Precipitation contains small but measurable amounts of nitrogen. The GIS data set (Molnau, 1995) showing 30-year average precipitation ranging from less than 5 to 40 in/yr was used to calculate a precipitation-weighted mean deposition of nitrogen, in pounds per acre.

Total nitrogen input from domestic septic tank systems was estimated by multiplying the average amount of total nitrogen generated per person by the average number of persons per household and the number of households using domestic septic systems in each county. Estimates for the number of households were based on 1990 census data and 1998 updated population estimates. The exact distribution of septic systems in the study area is not well known. Therefore, it was assumed that nitrogen input from domestic septic systems occurs chie y in areas designated as residential or commercial lands, according to the BOR land-use maps.

Relative ground-water velocity data were obtained from an adaptation of a three-dimensional, nite-dif ference, numerical model of the eastern Snake River Plain regional aquifer system (Garabedian, 1992; David Clark, U.S. Geological Survey, written commun., 2002)(g. 5). Velocity data had not been used in previous probability models for the Snake River Plain (Rupert, 1998; Donato, 2000). However, it was hypothesized during this study that the probability of detecting elevated nitrate concentrations at any given location in the study area might be related to the rate of ground-water and solute movement through the study area's aquifer systems. Conceptually, areas of high ground-water velocity result in a greater amount of regional ground water containing low nitrate concentrations that mixes with surface recharge containing higher nitrate concentrations. Thus, areas of high nitrogen input and high ground-water velocity will result in a lower nitrate concentration than will areas of high nitrogen input and low ground-water velocity. Water-quality samples collected from spring discharge originating from high ground-water velocity areas indicate a greater proportion of regional water than do samples from spring discharge originating from middle to low ground-water velocity areas (Clark and Ott, 1996).

Ground-water velocity values for the areas outside the o w model were determined by visually de ning aquifer boundaries based on topography and using ordinary kriging to statistically interpolate velocity values from the o w model to the outside areas. The nal ground-water velocity layer resulted in either high or low velocity values with a small transitional zone (g. 5).

Depth to ground water was based on a map developed from more than 1,000 water-level measurements. The water-level data were compiled from the USGS NWIS data base. Water-level measurement reselection followed the methods of Maupin (1991). Ordinary kriging then was used to interpolate water-level values at 0.5-mi grid intersections. The resulting raster data set was converted to a vector GIS data set, and 20-ft water-level contours were created.

ESTIMATING THE PROBABILITY OF DETECTING ELEVATED NITRATE CONCENTRATIONS IN GROUND WATER

A map showing the probability of detecting elevated nitrate concentrations was constructed using a GIS and logistic regression statistical methods (Hosmer and Lemeshow, 2000) in the following steps:

1. Data describing nitrate concentrations and hydrogeologic and anthropogenic variables were combined into one GIS data set providing each sample location with all of the corresponding GIS data. The GIS data set was then exported to a statistical software program for logistic regression analysis.

2. The data set was statistically analyzed to evaluate individual (univariate) correlations between nitrate in ground water and hydrologic and anthropogenic characteristics and to identify those variables that correlated signi - cantly with elevated nitrate concentrations.

3. Multivariate forward-stepwise regression with a backward check for elimination was performed to identify the most signi cant variables to include in the probability model, after which each variable's signi cance w as veri ed.

4. Various tests, including an external data veri- cation check, were conducted to determine how well the probability model represented the data.

5. The nal multi variate model was entered into a GIS and the probability map was constructed.

For this study, the nitrate concentration in ground water was converted to a binary dependent variable, elevated nitrate detection, whereby the nitrate concentration was either greater than 2 mg/L or less than or equal to 2 mg/L. For logistic regression analysis, the dependent variable is categorical.

Independent categorical variables included geology, land use, soil hydrologic group, and soil drainage. To prevent divergence of the logistic regression model

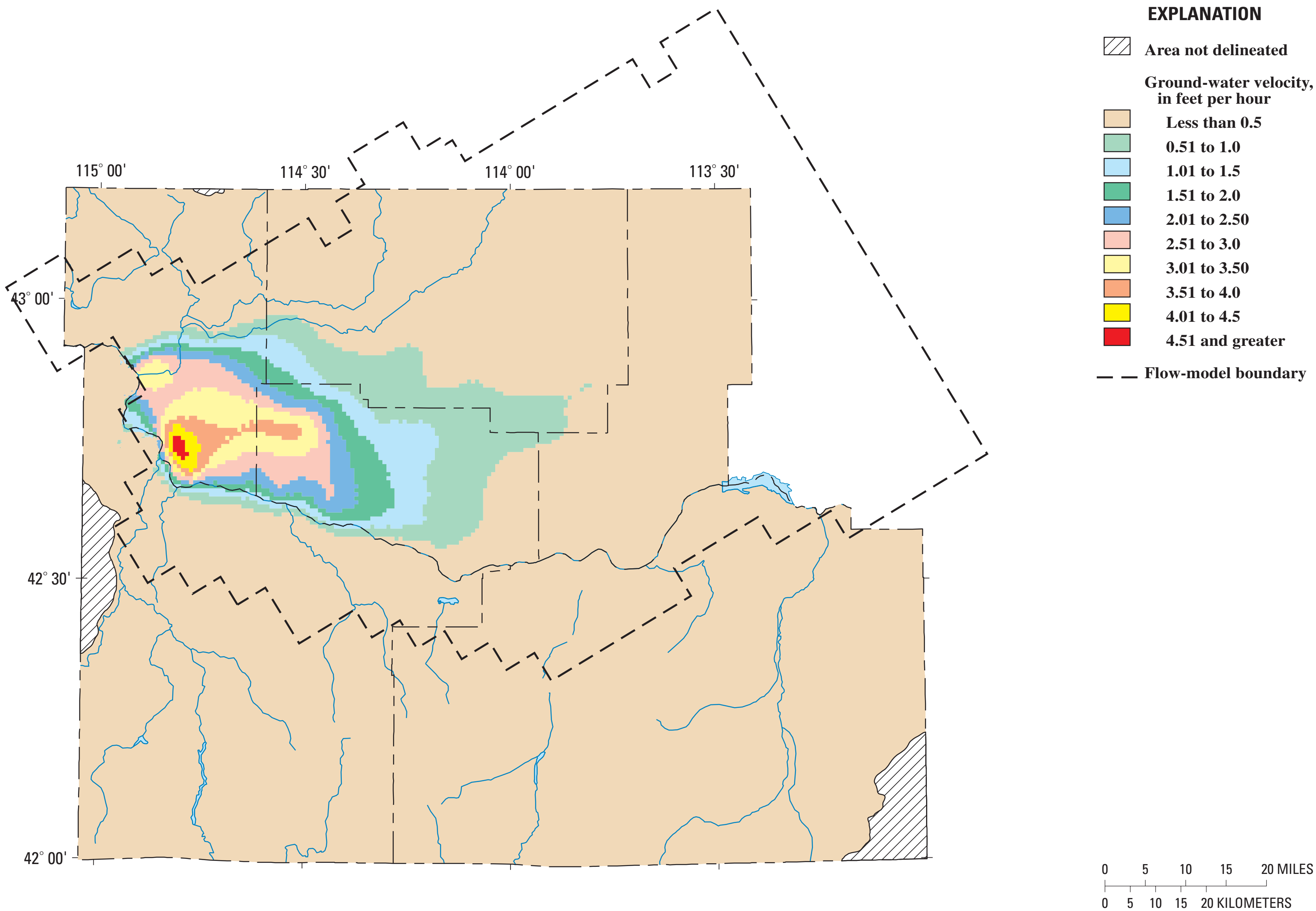


Figure 5. Location of the flow-model boundary and rates of ground-water velocity, south-central Idaho.

resulting from small populations of data in some categories, similar categories within the geology and land-use data sets were combined to provide an approximately even distribution of data per independent variable. For example, the BOR's land-use categories — native, gravel pit, idle, and public land — each contained few nitrate samples but, when combined into one category termed native, the amount of samples was adequate to compare with the agricultural categories. By generalizing some of the categories, a meaningful logistic regression model was obtained.

The other independent variables were modeled as continuous; therefore, precipitation and depth-to-water values at sample sites were assigned midpoint values between contours. For example, sample locations between depth-to-water contours of 40 and 60 ft were assigned a depth-to-water value of 50 ft.

Statistical Methods and the Logistic Regression Model

A variety of statistical methods was used to evaluate correlations between the nitrate concentration, or the binary-variable elevated nitrate detection, and the independent variables. Spearman correlation tests were used to determine signi cant correlations between continuous variables and nitrate concentrations or elevated nitrate detections. The Wilcoxon rank-sum test (Ott, 1993) was used to determine whether differences between nitrate concentrations and the different categories of a variable were signi cant (for e xample, signi - cant differences between nitrate concentrations and different land-use types). This test also evaluated whether differences between elevated nitrate detections and non-detections for a continuous variable were signi cant.

Logistic regression was used to predict the probability of detecting nitrate concentrations greater than 2 mg/L in ground water. Logistic regression is a statistical method similar to linear regression. However, in logistic regression, the output variable is binary, and any number of the independent variables can be categorical (discrete).

Multiple logistic regression (more than one independent variable) software generates several parameters that determine the predictive success of the model, including the likelihood ratio statistic (LR), rho-squared value (similar to an r-squared value in linear regression), standard error, and p-value of the model parameter coef cients. The model prediction success table also was used to evaluate the probability model's classi catory power. These evaluation parameters are described in a report by Rupert (1998). For a thorough description of how these parameters are created, refer to Hosmer and Lemeshow (2000) or SPSS Inc. (2000). An example multiple regression model follows, showing the calculation of the probability of detecting elevated nitrate concentrations in ground water:

where

$$p = \frac{e^{[a + b_1(V) + b_2(LU_1) + b_3(LU_2) + b_4(S) + b_5(WL)]}}{1 + e^{[a + b_1(V) + b_2(LU_1) + b_3(LU_2) + b_4(S) + b_5(WL)]}} \quad (2)$$

p = the probability of detecting elevated nitrate concentration in ground water;
a = intercept;
b_1 = slope coef cient for ground-w ater velocity;
V = ground-water velocity;
b_2 = slope coef cient for land-use type 1;
LU_1 = land-use type 1;
b_3 = slope coef cient for land-use type 2;
LU_2 = land-use type 2;
b_4 = slope coef cient for soils property;
S = soils property;
b_5 = slope coef cient for depth to w ater; and
WL = depth to water.

Univariate Analysis

Univariate analysis was performed on all variables to determine initial correlations with nitrate concentrations and elevated nitrate detections and to identify key variables that were likely to be signi cant in the nal model. Logistic regression, Spearman correlation tests, and the Wilcoxon rank-sum test were performed on all data (table 1). After the land-use categories were regrouped to account for small populations of wells in certain land-use types, comparisons were made to determine whether statistical differences between nitrate concentrations among the land-use categories were signi cant ($p < 0.05$). Dif ferences between nitrate concentrations and each of the three land uses classi ed by BOR, and between nitrate concentrations and two of the three land uses classi ed by ID WR were statistically signi cant (g. 6); ho wever, the IDWR data resulted in a better t of the logistic re gression model.

Table 1. Results from univariate correlations between independent variables and elevated nitrate detections or nitrate concentrations in ground water, south-central Idaho

[Q-T, Quaternary-Tertiary; ref, reference; BOR, Bureau of Reclamation; IDWR, Idaho Department of Water Resources]

Independent variable	Logistic regression coefficient	Logistic regression coefficient p-value	Likelihood ratio	Likelihood ratio p-value	McFadden's rho-squared	Degrees of freedom	Spearman's correlation coefficient	Wilcoxon p-value
Nitrogen input	0.004	0.000	17.184	0.000	0.012	1	0.085	0.059
Ground-water velocity	-0.665	0.000	151.460	0.000	0.103	1	-0.310	0.000
Geology (Q-T basalt)	1.389	0.026					0.315	0.000
Geology (Q-T sediments)	0.413	0.505					0.051	0.000
Geology (other)	0.000	ref .					-0.011	0.357
Geology (Q basalt)	-0.682	0.267					-0.357	0.000
Geology (Q sediments)	0.464	0.482	170.896	0.000	0.116	4	0.029	0.789
Gravity-irrigated land (BOR)	0.458	0.001					0.157	0.000
Native land (BOR)	-0.567	0.001					-0.160	0.000
Sprinkler-irrigated land (BOR)	0.000	ref.	38.039	0.000	0.026	2	-0.032	0.459
Flood-irrigated land (IDWR)	1.116	0.000					0.265	0.000
Rangeland (IDWR)	-0.122	0.597					-0.145	0.000
Sprinkler-irrigated land (IDWR)	0.000	ref.	76.862	0.000	0.052	2	-0.193	0.000
Precipitation	-0.205	0.000	13.881	0.000	0.009	1	-0.118	0.004
High in ltration rates (soil hydrologic group)	-1.113	0.001					-0.060	0.074
Moderate in ltration rates (soil hydrologic group)	-0.516	0.005					0.005	0.428
Slow in ltration rates (soil hydrologic group)	-0.716	0.000					-0.071	0.009
Very slow in ltration rates (soil hydrologic group)	0.000	ref.	19.240	0.000	0.013	3	0.113	0.001
Excessively drained (soil drainage)	0.000	ref.					-0.016	0.159
Well drained (soil drainage)	0.179	0.506					0.071	0.005
Poorly drained (soil drainage)	-0.226	0.497	3.733	0.155	0.003	2	-0.055	0.121
Soil layer depth	0.000	0.994	0.000	0.994	0.000	1	-0.008	0.151
Soil clay content	-0.030	0.003	9.071	0.003	0.006	1	-0.106	0.000

Table 1. Results from univariate correlations between independent variables and elevated nitrate detections or nitrate concentrations in ground water, south-central Idaho—Continued

Independent variable	Logistic regression coefficient	Logistic regression coefficient p-value	Likelihood ratio	Likelihood ratio p-value	McFadden's rho-squared	Degrees of freedom	Spearman's correlation coefficient	Wilcoxon p-value
Soil organic matter content . .	1.118	0.000	24.493	0.000	0.017	1	0.183	0.000
Soil permeability.	-0.013	0.185	1.744	0.187	0.001	1	-0.074	0.000
Depth to water.	-0.004	0.000	29.422	0.000	0.020	1	-0.176	0.000

Among the best predictors of detecting elevated nitrate concentrations using univariate analysis were ground-water velocity, geology, both land-use data sets, depth to water, and soil organic matter content (table 1). Except for soil depth, the other variables were weak predictors of elevated nitrate concentrations. Due to a logistic regression coef cient p-v alue of 0.994 and Spearman and Wilcoxon p-values of 0.155 and 0.151, respectively, soil depth was omitted from further analysis. The remaining variables were carried forward for multivariate logistic regression analysis.

Multivariate Logistic Regression Analysis

Several methods can be used to create a multivariate logistic regression model. Most involve a stepwise procedure, whereby variables are added to or deleted from the model one at a time on the basis of statistical signi cance until the model that best ts the data is achieved. Statistical signi cance is assessed by the lik elihood ratio chi-square test (Hosmer and Lemeshow, 2000), which commonly is used to compare nested models.

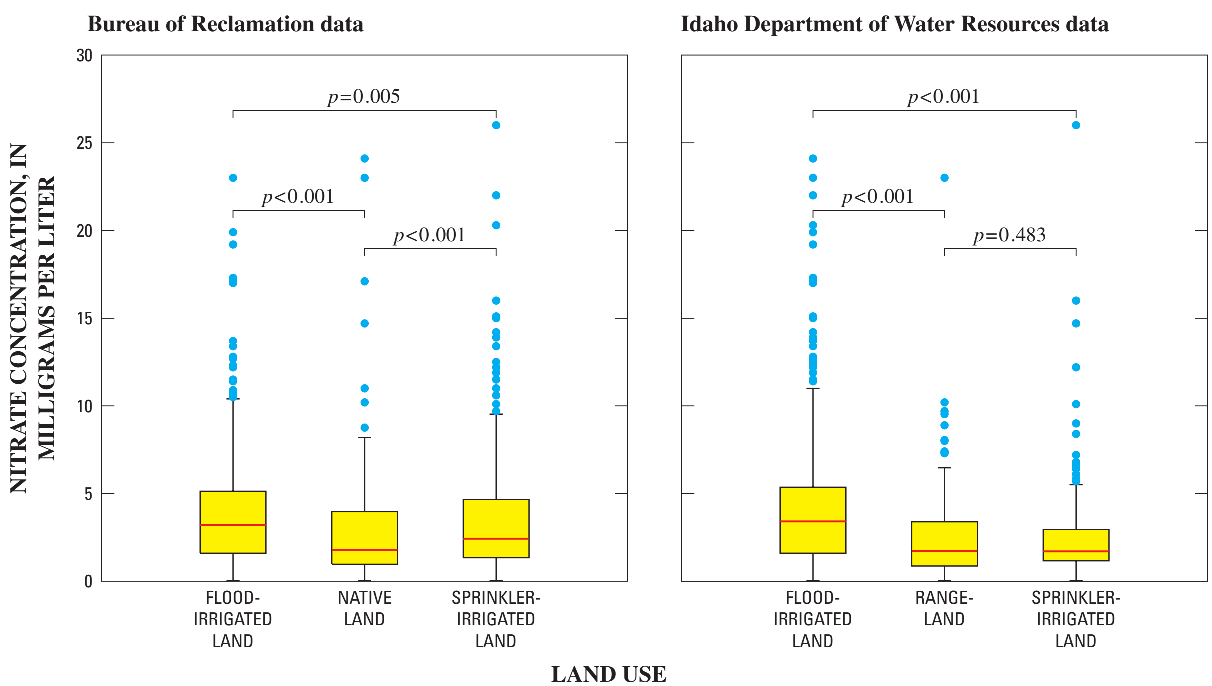


Figure 6. Correlation between nitrate concentrations and land use classified by the Bureau of Reclamation and the Idaho Department of Water Resources, south-central Idaho.

The method utilized to develop the preliminary model was a manual forward-stepwise selection of variables with a backward test for elimination. This method uses a statistical algorithm to determine the initial variable with the highest statistical signi cance to create the best single-variable model. A two-variable model then is created by adding each of the remaining variables one at a time to the single-variable model and determining which, if any, signi cantly impro ved the one-variable model's predictive capabilities. This process of adding variables continues until no remaining variables signi cantly improve the model. After each successive variable is added, each variable included in the present model is individually tested for removal, because a variable found to be signi cant at an early step could become insigni cant at a later step. In de veloping the model, variables were considered signi cant at the 95-percent con dence le vel (p-value < 0.05).

The variables selected for the preliminary model were ground-water velocity, nitrogen input, precipitation, soil drainage, land use (IDWR), and depth to water. After the preliminary model was created, several steps were taken to verify the suitability of the selected variables. First, the variable coef cients were compared with those produced by the univariate model to check for large differences in magnitude that would indicate that an excluded variable was needed to adjust the t of the variables that remained in the model. Another method to identify intervariable in uences is to reenter all the unselected variables one at a time into the model to check for large changes in coef cient magnitudes, then reevaluate the likelihood ratio test to check for signi cant model impro vement from the unselected variables. Each continuous variable then is checked for linearity in the logit (a transformation of equation 2). Linearity in the logit is assumed in the beginning stages of model development and needs to be veri ed for the continuous variables in the nal model. Lastly , interactions between variables are checked. Variables interact when one independent variable is not constant over levels of another independent variable (Hosmer and Lemeshow, 2000). Interactions are checked by adding an interaction term into the model and checking for a statistically signi cant impro vement by the likelihood ratio chi-square test. Interactions need to be scienti cally sound to remain in the probability model. For the present model, all the preselected variables remained after the veri cation tests were conducted and no interactions were added. The nal probability model is listed in table 2.

Construction of the Elevated Nitrate Concentration Probability Map

Multivariate analysis resulted in a best- t probability regression model that incorporated variables for ground-water velocity, nitrogen input, precipitation, soil drainage, land use (IDWR), and depth to water. The regression model then was used to construct the probability map. Each of the nal data layers were combined into one GIS data set, and a probability value was calculated using equation 2 for each of the 251,000 polygons that resulted from intersecting the GIS data layers (g. 7).

EVALUATION AND TESTING OF PROBABILITY MODELS

Several tests were conducted to evaluate how well the model t the data as a whole. The likelihood ratio statistic tests the hypothesis that all coef cients e xcept the constant are zero, similar to the F test reported for linear regression. The log likelihood ratio for the nal probability model was 297.305, which is chi-squared with eight degrees of freedom and a p-value of < 0.001, indicating a signi cance le vel greater than 99 percent.

Table 2. Variables selected for use in the final probability model, south-central Idaho

[IDWR; Idaho Department of Water Resources]

Variable	Coeffi-cient	Stan-dard error	Wald test (z)	p-value
Ground-water velocity	-0.860	0.073	-11.781	0.000
Nitrogen input	0.006	0.001	4.661	0.000
Well drained (soil drainage)	-0.559	0.315	-1.775	0.076
Poorly drained (soil drainage)	-2.454	0.393	-6.244	0.000
Precipitation	-0.357	0.081	-4.407	0.000
Flood-irrigated land (IDWR)	0.583	0.180	3.239	0.001
Rangeland (IDWR)	-0.106	0.276	-0.384	0.701
Depth to water	-0.002	0.001	-2.489	0.013
Constant	4.671	0.840	5.561	0.000

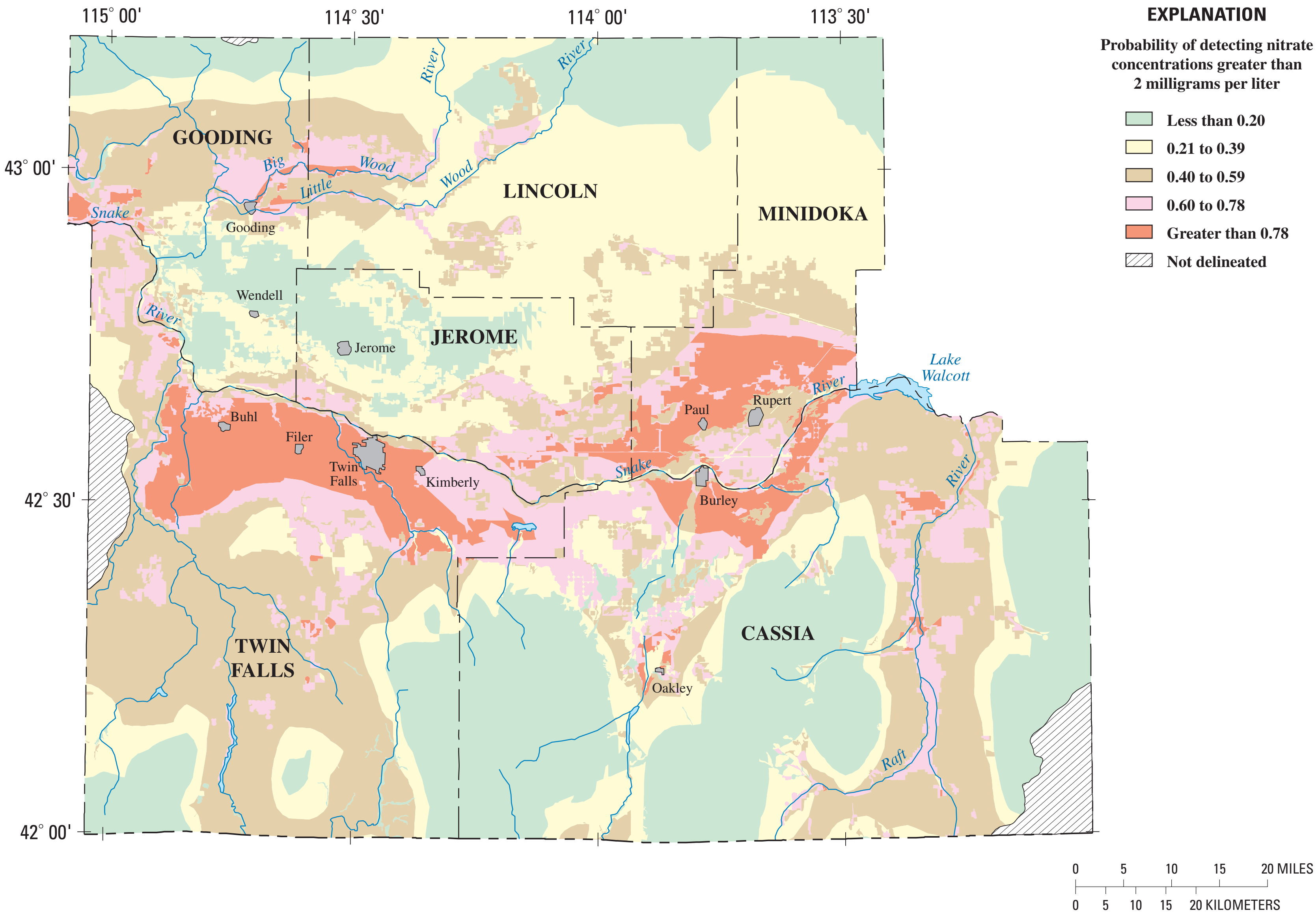


Figure 7. Probability of detecting elevated nitrate concentrations in ground water, south-central Idaho. (Elevated, greater than 2 milligrams per liter)

McFadden’s rho-squared is a transformation of the likelihood ratio and is similar to the r-squared value in linear regression. McFadden’s rho-squared values between 0.20 and 0.40 are considered satisfactory (SPSS Inc., 2000). The rho-squared value for the final probability model was 0.202. For the 1,095 samples in the model data set, the model correctly predicted 64 percent of the data; 70 percent of the samples that contained elevated nitrate concentrations were correctly predicted and 55 percent of the samples that did not contain elevated nitrate concentrations were correctly predicted, also known as the sensitivity and specificity, respectively. A probability cutpoint of 0.50 was used to determine the data set’s sensitivity and specificity. Probability values ranged from 0.04 to 0.95. The results of this model closely match those of Rupert (1998) and Donato (2000).

The range of the model’s predicted probabilities of detecting elevated nitrate was evaluated by comparing groupings of predicted probabilities with percentages of actual elevated nitrate detections in each group. This was done by performing a linear regression between the percentage of actual elevated nitrate detections in a group and the predicted probability of elevated nitrate detections in a group. The probability of detecting elevated nitrate concentration was calculated for each sample, and the data set was sorted by ascending probability and divided into categories of 10 percent (0 to 9, 10 to 19, 20 to 29, and so on). The percentage of elevated nitrate detections in each group was calculated, and linear regression was used to compare the percentage of actual elevated nitrate detections with the predicted probability of elevated nitrate detections in each group (fig. 8). A perfectly fit model is one in which linear regression produces a slope = 1, y-intercept = 0, and an r-squared value of 1. The probability model resulted in a slope = 0.958, y-intercept = 0.007, and an r-squared value of 0.959. The Wilcoxon test was used to determine whether differences in probability ratings between samples with elevated nitrate detections and samples without elevated nitrate detections were significant (fig. 8). The difference between the high-probability values for elevated nitrate detections and the low-probability values for nondetections was significant ($p < 0.001$).

The probability model also was compared with the extracted verification data set of 270 samples. The verification data set was randomly selected from the combined data sets of the USGS, ISDA, and IDWR. The verification samples were combined with the GIS data sets, and the probability for detecting nitrate was calculated for each sample using the logistic regression

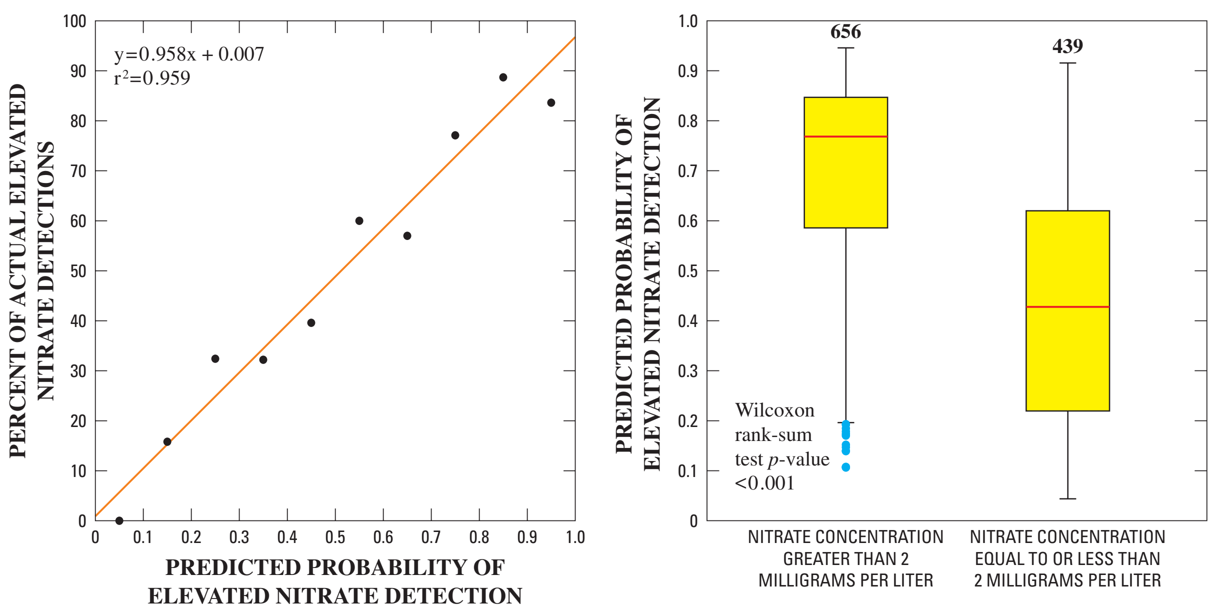


Figure 8. Correlation between groups of predicted probabilities of detecting elevated nitrate concentrations and actual detections of elevated nitrate concentrations in ground-water samples used in the model data set, south-central Idaho.

ing probability of elevated nitrate detection, and the percentage of actual elevated nitrate detections in each interval was calculated. Linear regression was used to compare the predicted probability of detection in each group with the actual percentage of detections. The predicted and detected values (g. 9) were strongly correlated with a slope = 1.060, y-intercept = -0.039, and an r-squared value of 0.973. The Wilcoxon rank-sum test for the veri cation data set, as for the model data set, indicated that the difference between the high-probability values for elevated nitrate detections and the low-probability values for nondetections was signi cant ($p < 0.001$). For the 270 samples in the veri cation data set, the model correctly predicted 74 percent of the data; 83 percent of the samples with elevated nitrate were correctly predicted, and 63 percent of the samples without elevated nitrate were correctly predicted. Probability values for the veri cation data set ranged from 0.06 to 0.91. As with the model data set, a probability cutpoint of 0.50 was used in determining a correct or incorrect prediction.

Although the study areas and data sets for developing probability models in the two previous studies (Rupert, 1998; Donato, 2000) were different from those used for this study, several of the signi cant e xplanatory variables were the same—land use, soil drainage, and depth to water.

The areas of predicted high probability for elevated nitrate detection (g. 6) coincide with areas of high nitrogen input and agricultural land use in northern Twin Falls, northern Cassia, and southern Minidoka Counties. An exception to the correlation between predicted high probability of elevated nitrate detection and areas of high nitrogen input occurs in southern Gooding and western Jerome Counties. This area is characterized by agricultural land use and high nitrogen input but was predicted by the model to have a low probability for elevated nitrate detection. The low-probability prediction is a result of high ground-water velocity, which represents the large amount of regional ground water moving through the aquifer. The model correctly predicted that high nitrate concentrations are less likely to occur in areas where regional ground water predominates and moves relatively faster through the aquifer than in areas where ground water moves slower and has a larger component of recent recharge from the surface.

Areas of lowest probability, primarily in Cassia and Twin Falls Counties, relate to high-precipitation, high-elevation areas with no agricultural land use, but the low-probability areas in northern Minidoka County and northeastern Lincoln County result from deeper ground water.

The effect of the soil drainage variable is most prominent in southern Minidoka County, a region of

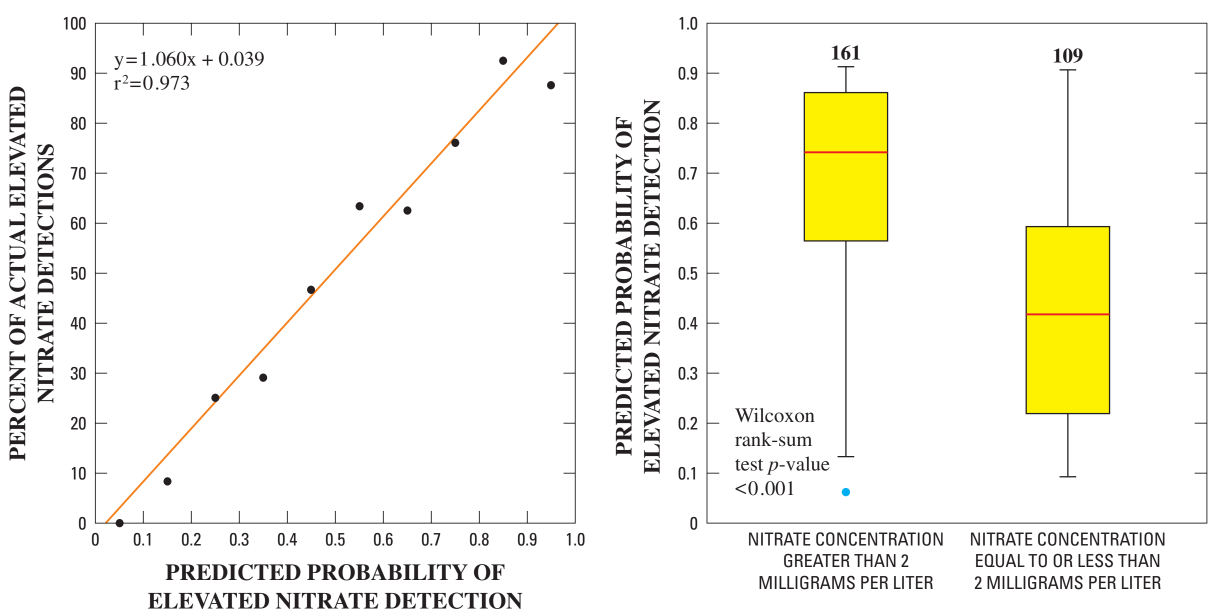


Figure 9. Correlation between groups of predicted probabilities of detecting elevated nitrate concentrations and actual detections of elevated nitrate concentrations in ground-water samples used in the verification data set, south-central Idaho.

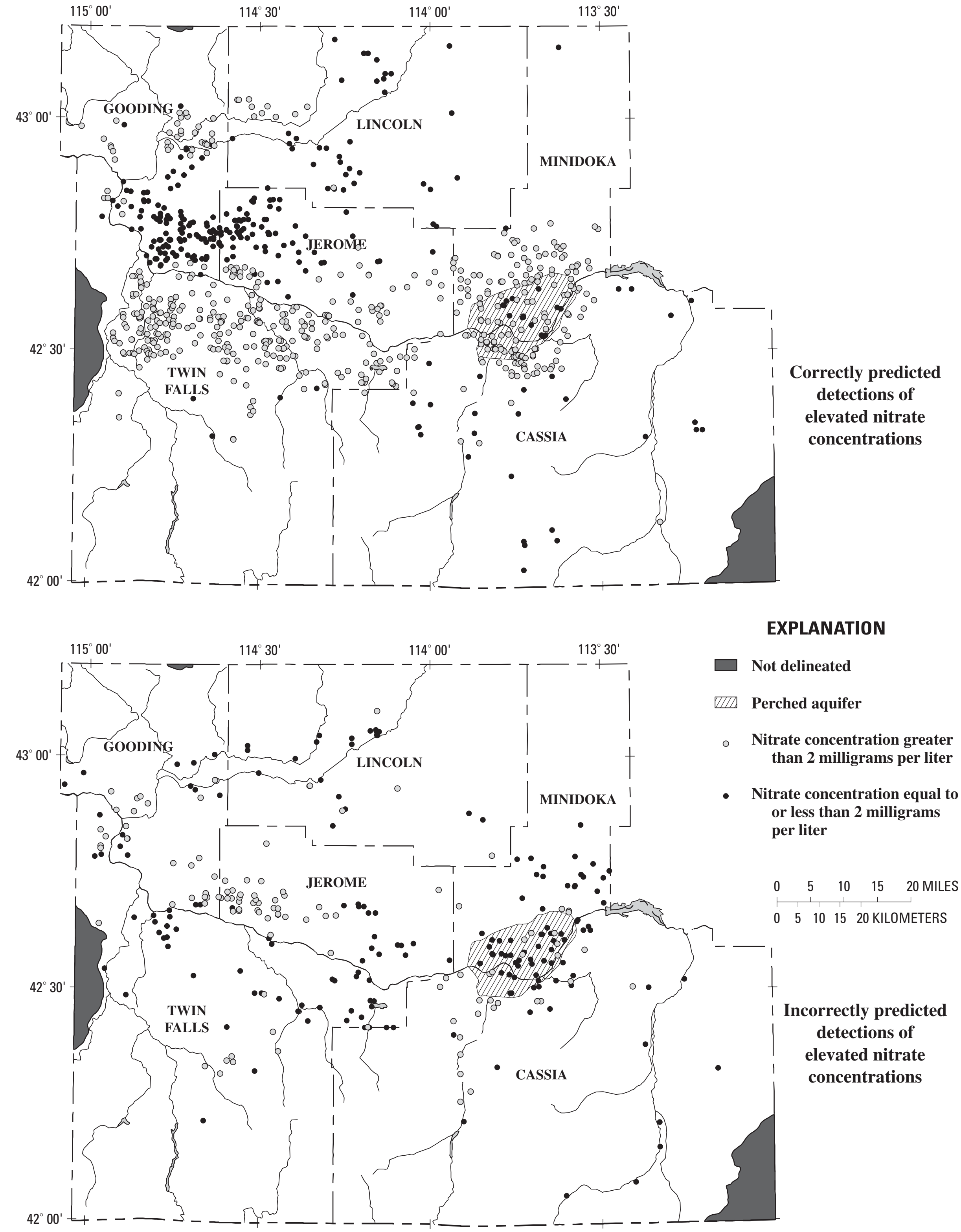


Figure 10. Correctly and incorrectly predicted detections of elevated nitrate concentrations in ground water using a probability cutpoint of 0.50, south-central Idaho. (Elevated, greater than 2 milligrams per liter)

The effect of the soil drainage variable is most prominent in southern Minidoka County, a region of predicted low probability, where the soil above the perched aquifer is poorly drained. Soil drainage describes the frequency and duration of wet periods of the soil (U.S. Department of Agriculture, 1995). Soils with poor drainage are typically water saturated and can have reducing conditions that may lead to denitri cation, which reduces nitrate concentration (Goolsby and others, 1999).

Incorrectly predicted elevated nitrate detections tend to congregate along a transition zone between high and low ground-water velocity areas in Jerome and Gooding Counties, where the probability model underpredicts the probability of detecting elevated nitrate concentrations (g. 10). Although this area does have high nitrogen input, the ground-water velocities are in the middle range, which indicates a mix of regional ground water and surface recharge that results in nitrate concentrations above 2 mg/L.

The probability model slightly overpredicts elevated nitrate detections in the perched aquifer area (g. 10). Probability v alues in this area range between 0.50 and 0.60, just slightly over the cutpoint of 0.50 for correctly predicted elevated nitrate detections.

SUMMARY

Ground-water quality is an ongoing concern in Idaho because of rising nitrate concentrations in an increasing number of wells. The concentration of nitrate in ground water is related to anthropogenic factors; therefore, planning tools are needed to aid local managers in assessing the potential effects of land-use decisions on nitrate concentrations in ground water.

Ground-water probability maps can be an important tool for resource-protection and regulatory agencies to help protect ground-water quality. In previous studies (Rupert, 1998; Donato, 2000), the U.S. Geological Survey developed preliminary maps showing the probability of detecting elevated nitrate in ground water of the upper Snake River Basin and the western Snake River Plain. This study used similar methodologies while compensating for differences in study area scale. The resultant probability map provides an additional tool for managing the increase of nitrate concentrations in south-central Idaho ground water.

The elevated nitrate probability map was produced by overlaying ground-water quality data on hydrogeologic and anthropogenic geographic information system (GIS) layers. The GIS layers consisted of two land-use data sets (Bureau of Reclamation and Idaho Department of Water Resources), precipitation, geology, nitrogen input, six soil characteristics, ground-water velocity, and depth to water. A statistical software program was used to conduct a variety of statistical tests, including logistic regression and the Wilcoxon rank-sum test. A forward-stepwise logistic regression and subsequent model- t assessment with model diagnostic e valuations resulted in a nal probability model based on ground-water velocity, nitrogen input, precipitation, soil drainage, land use (Idaho Department of Water Resources), and depth to water.

The nal probability model performed well in predicting areas of elevated nitrate concentration (greater than 2 mg/L). A linear regression of the grouped predicted probabilities of detecting elevated nitrate concentrations with the percentage of actual elevated nitrate detections showed strong correlation with an r-squared value of 0.96. A similar linear regression of a veri cation data set also showed a strong correlation with an r-squared value of 0.97. There was a signi cant difference ($p < 0.001$) between samples with and without elevated nitrate detections for both the model data set and the veri cation data set. Areas of high probability of elevated nitrate detections coincide with areas of agricultural land use and high nitrogen input except in southern Gooding and western Jerome Counties, where high ground-water velocities predominate resulting in low probabilities of elevated nitrate detection. This nding reinforces the concept that high nitrate concentrations are less likely to occur in areas where regional ground water moves relatively quickly through the aquifer than in areas where ground water moves more slowly and is recharged from the surface. Incorrectly predicted elevated nitrate detections tend to be congregated along a transition zone between areas of high and low ground-water velocity in Jerome and Gooding Counties indicating a mix of regional ground water and surface recharge.

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