

Uranium and Radon in Ground Water in the Lower Illinois River Basin

Water-Resources Investigations Report 01-4056

National Water-Quality Assessment Program



U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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By William S. Morrow

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Urbana, Illinois
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FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity and quality, even more critical to the long-term sustainability of our communities and ecosystems.

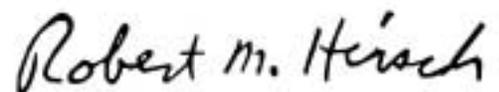
The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings.

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.



Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
square foot (ft ²)	0.09290	square meter
square mile (mi ²)	2.590	square kilometer
Volume		
gallon (gal)	3.785	liter
Flow rate		
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06309	liter per second
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day

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

Altitude, as used in this report, refers to distance above or below sea level.

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

Abbreviations

AMCL	Alternate Maximum Contaminant Level
BRP	Bloomington Ridged Plain
BRP N/O BV	Bloomington Ridged Plain not overlying a buried bedrock valley
BRP O/L MBBV	Bloomington Ridged Plain overlying the Mahomet Buried Bedrock Valley
GSP N/O BV	Galesburg/Springfield Plain not overlying a buried bedrock valley
MBBV	Mahomet Buried Bedrock Valley
MCL	Maximum Contaminant Level
ml	milliliter
MRL	Maximum Reporting Limit
Rn	radon
µm	micrometer
U	uranium

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Abstract

Uranium and radon are present in ground water throughout the United States, along with other naturally occurring radionuclides. The occurrence and distribution of uranium and radon are of concern because these radionuclides are carcinogens that can be ingested through drinking water. As part of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) program, water samples were collected and analyzed for uranium and radon from 117 wells in four aquifers in the lower Illinois River Basin (LIRB) from 1996 to 1997. The aquifers were the shallow glacial drift deposits of the Bloomington Ridged Plain (BRP) not overlying a buried bedrock valley (BRP N/O BV), shallow glacial drift deposits of the BRP overlying the Mahomet Buried Bedrock Valley (BRP O/L MBBV), shallow glacial drift deposits of the Galesburg/Springfield Plain not overlying a buried bedrock valley (GSP N/O BV), and the deep glacial drift deposits of the Mahomet Buried Bedrock Valley (MBBV).

Uranium was detected in water samples from all aquifers except the MBBV and ranged in concentration from less than 1 microgram per liter ($\mu\text{g/L}$) to 17 $\mu\text{g/L}$. Uranium concentrations did not exceed 20 $\mu\text{g/L}$, the proposed U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) at the time of sampling (1996–97). The current (2001) promulgated MCL is 30 $\mu\text{g/L}$ (U.S. Environmental Protection Agency, 2000). The highest median uranium concentration (2.0 $\mu\text{g/L}$) among the four

aquifers was in the BRP N/O BV. Uranium most often occurred in oxidizing and sulfate-rich water.

Radon was detected in water samples from all aquifers in the LIRB. Radon concentrations in all aquifers ranged from less than 80 picocuries per liter (pCi/L) to 1,300 pCi/L. Of 117 samples, radon concentrations exceeded 300 pCi/L (the proposed USEPA MCL) in 34 percent of the samples. Radon concentrations exceeded 300 pCi/L in more than one-half of the samples from the GSP N/O BV and the BRP O/L MBBV. No sample exceeded the proposed Alternative Maximum Contaminant Level (AMCL) of 4,000 pCi/L. Concentrations of uranium and radon were not correlated.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) implemented the full-scale National Water-Quality Assessment (NAWQA) program to assess the quality of the ground- and surface-water resources of the United States, characterize the trends in the quality of these resources, and identify natural and anthropogenic factors that affect water quality. The lower Illinois River Basin (LIRB) (fig. 1) is one of more than 50 study units throughout the United States where water-quality data are being collected in the NAWQA program.

Uranium (U) and radon (Rn) are among naturally occurring radionuclides present in ground water throughout the United States (Szabo and Zapecza, 1987). The occurrence and distribution of U and Rn in ground water are of concern because these radionuclides are carcinogens that can be ingested through drinking water and because naturally occurring radionuclides, such as radium, have been

found at levels above drinking-water standards in Illinois (Kay, 1999). Uranium concentrations, however, are low in northern Illinois (Gilkeson and Cowart, 1982). From 1996 to 1997, the USGS collected and analyzed samples from 117 wells in the LIRB to evaluate the distribution of U and Rn in ground water.

Purpose and Scope

This report presents the results of sampling and analysis of ground water for concentrations of U and Rn in the LIRB, 1996–97. Radon and U concentration data may be useful for designing (1) future monitoring in problem areas and (2) maps and programs for multi-media mitigation programs for Rn similar to the maps and programs suggested by dePaul and others (2000), as well as a U abatement program if necessary. Samples were collected from 117 randomly selected wells completed in four separate physiographic areas within the LIRB. For this study, radon-222 (^{222}Rn) and uranium-238 (^{238}U) were collected and analyzed. Relations among U and Rn with sampled inorganic chemical constituents and physical properties of the water were examined.

Description of Study Area

The LIRB covers an area of 18,000 mi² in western and central Illinois and consists of the drainage area from Ottawa, Ill., to the confluence of the Illinois and Mississippi Rivers at Grafton, Ill. (fig. 1). The primary land use is agricultural—mostly corn and soybeans. The largest population centers in the basin are Peoria, Springfield, Bloomington-Normal, and Decatur. The major aquifers underlying the basin are composed of glacial deposits of Quaternary age and Pennsylvanian- to Mississippian-age bedrock. Some major Quaternary aquifers are present in buried bedrock valleys (Warner, 1998).

The LIRB is part of the Till Plains Section of the Central Lowland Province and the Ozark Plateaus Province. The main physiographic areas (about 98 percent) of the LIRB are the Bloomington Ridged Plain subsection, the Galesburg Plain subsection, and the Springfield Plain subsection; all are within the Till Plains Section. About 2 percent of the LIRB comprises the Kankakee Plain subsection (also within the Till Plains Section), the Lincoln Hills Section (Ozark Plateaus Province), and the Salem Plateau

Section (Ozark Plateaus Province) (fig. 2) (Warner, 1998).

The Bloomington Ridged Plain (BRP) is in the northeast region of the LIRB and is surficially covered by Wisconsinan glacial drift with prominent glacial moraines and topography. The Galesburg Plain and Springfield Plain are in the southwest region of the LIRB and are surficially covered with Illinoian glacial drift. Most Illinoian glacial features are subdued, although some localized glacial topography is evident (Willman and others, 1975). Buried bedrock valleys are underneath the overlying surficial glacial deposits in areas of these subsections. The four aquifers described in this report are within the Bloomington Ridged Plain and the Galesburg/Springfield Plain subsections in the LIRB (fig. 3, table 1).

Acknowledgments

Thanks are extended to the private homeowners and land managers in the LIRB who allowed the USGS to sample their supply wells or allowed access to install and sample monitoring wells. Thanks also are extended to USGS hydrologists Zoltan Szabo and Robert Kay for extensive colleague reviews and numerous constructive comments.

STUDY DESIGN AND SAMPLING, AND ANALYTICAL METHODS

Four aquifers were defined by depth and physiography. The well depth and physiographic relations are shown in table 1. The first defined aquifer is the shallow glacial drift in the Bloomington Ridged Plain not overlying a buried bedrock valley (BRP N/O BV), and is in the northeastern part of the basin. The BRP N/O BV consists of the shallowest water-producing Wisconsinan-age deposits in the BRP that are not over buried bedrock valleys (fig. 3, table 1). This aquifer is of interest because many communities within the area have difficulty obtaining potable ground water and, commonly, are dependent on surface-water supply. These shallow deposits, used for primarily private domestic supply, may become more important as surface-water supplies approach maximum potential use. The BRP N/O BV underlies approximately 21 percent of the LIRB.

The second aquifer is the shallow glacial drift in the Bloomington Ridged Plain overlying the Mahomet

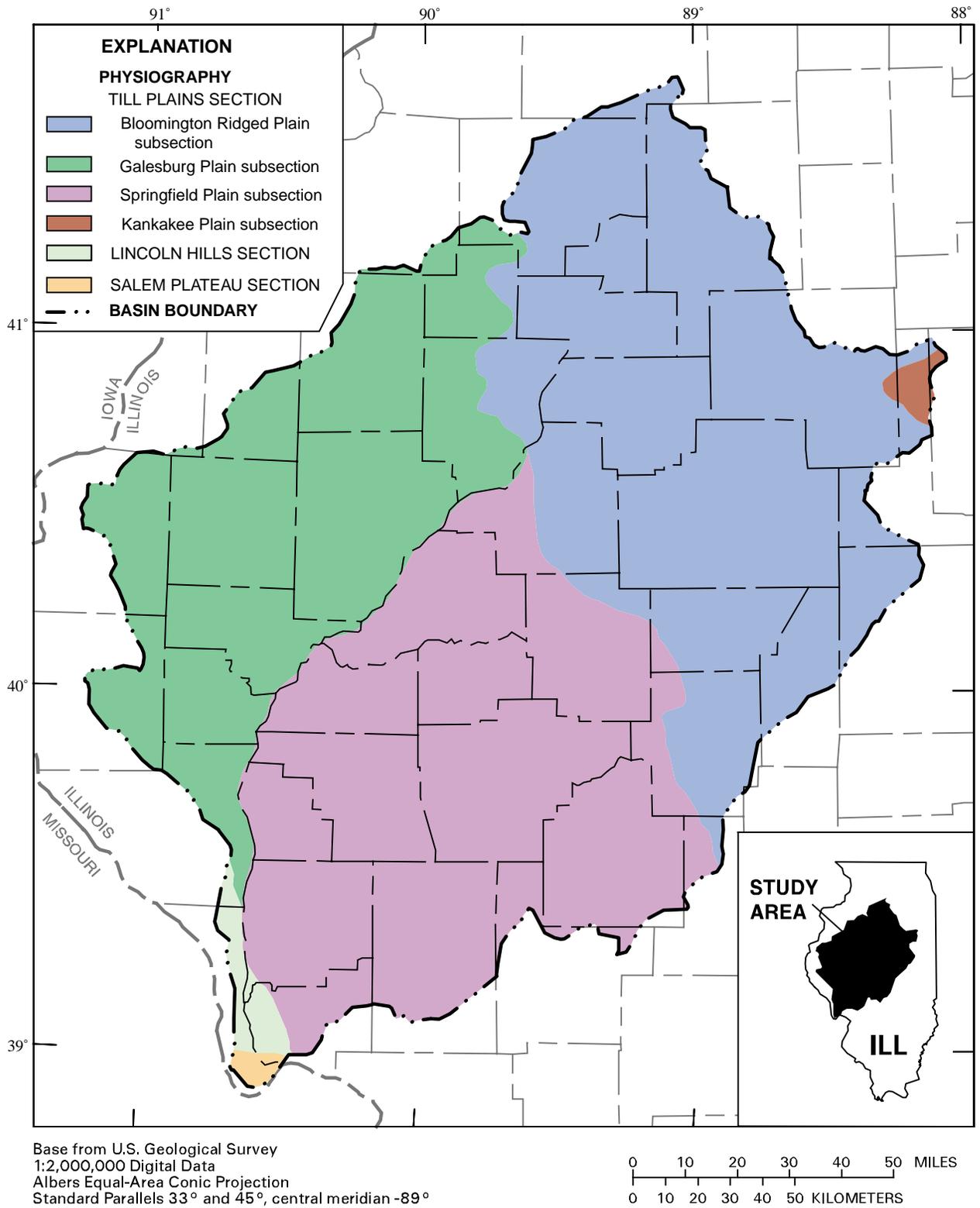


Figure 2. Physiography in the lower Illinois River Basin.

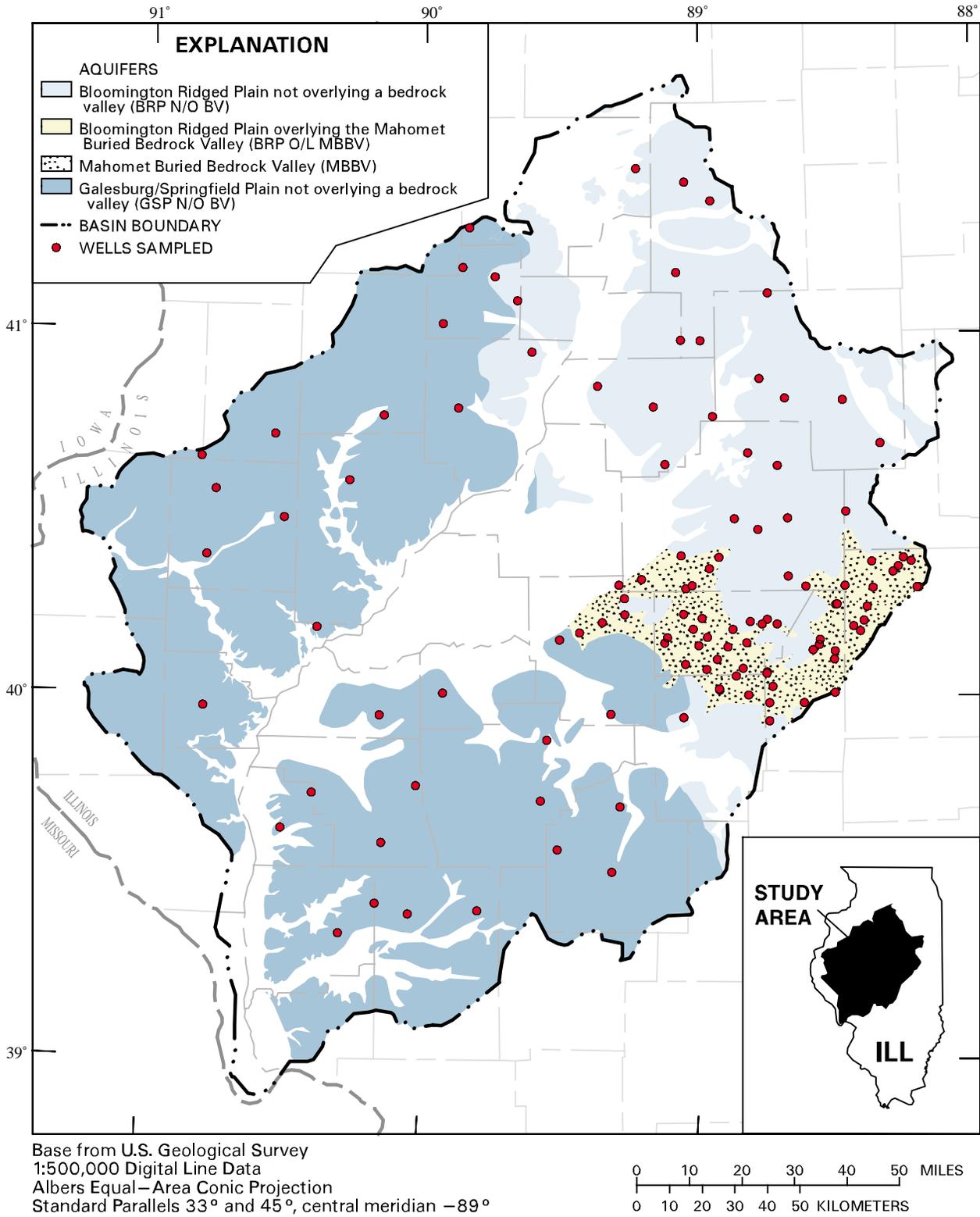


Figure 3. Locations of aquifers and wells sampled in the lower Illinois River Basin.

Table 1. Relations of aquifers with glacial stage, physiographic area, well depth, and well type in the lower Illinois River Basin

Aquifer	Aquifer abbreviation	Glacial stage	Physiographic area	Range of well depth, in feet below land surface	Well type
Bloomington Ridged Plain not overlying a buried bedrock valley	BRP N/O BV	Wisconsinan	Bloomington Ridged Plain	12–59	Monitoring
Bloomington Ridged Plain overlying the Mahomet Buried Bedrock Valley	BRP O/L MBBV	Wisconsinan	Bloomington Ridged Plain	13–59	Monitoring
Galesburg/Springfield Plain not overlying a buried bedrock valley	GSP N/O BV	Illinoian	Galesburg and Springfield Plains	30–108	Supply
Mahomet Buried Bedrock Valley	MBBV	Pre-Illinoian	Bloomington Ridged Plain	200–365	Supply

Buried Bedrock Valley (BRP O/L MBBV) (fig. 3, table 1). The BRP O/L MBBV is near the eastern edge of the basin. The aquifer consists of the shallowest water-producing Wisconsinan-age deposits in the BRP overlying the Mahomet Buried Bedrock Valley. This aquifer is of interest because shallow ground water may be recharging the deep glacial aquifer in the Mahomet Buried Bedrock Valley, a very productive and heavily used water supply. The BRP O/L MBBV underlies approximately 6 percent of the LIRB.

The third aquifer is the shallow glacial drift in the Galesburg/Springfield Plain not overlying a buried bedrock valley (GSP N/O BV). The GSP N/O BV is in the southwestern part of the basin. The GSP N/O BV consists of the shallowest water-producing Illinoian-age deposits capable of domestic supply (fig. 3, table 1). This aquifer is of interest because many communities have difficulty obtaining potable ground water from the deeper bedrock; the water from the bedrock aquifers is commonly highly mineralized. The GSP N/O BV underlies approximately 42 percent of the LIRB.

The fourth aquifer is the deep glacial drift in the Mahomet Buried Bedrock Valley (MBBV) in the Bloomington Ridged Plain (fig. 3, table 1). The MBBV lies near the eastern edge of the LIRB and trends towards southwestern Tazewell County in the center of the LIRB, where the MBBV joins another buried bedrock valley beneath the Illinois River. The MBBV comprises primarily pre-Illinoian glacial deposits and is overlain by Wisconsinan glacial deposits at the surface. Confining clays and silts in the Wisconsinan, Illinoian, and pre-Illinoian drift overlying the deep glacial drift aquifer are commonly greater than 100 ft thick. The aquifer underlies approximately 6 percent of the LIRB but is the largest source of ground

water for irrigation, industrial, and municipal water supplies in east-central Illinois. At least 40 municipalities and water districts withdraw water from the MBBV (Kempton and others, 1991).

Well Selection and Installation

Samples were collected from 60 existing supply wells and 57 monitoring wells installed specifically for this study (fig. 3). In each aquifer, water from 28 to 30 wells was sampled. All wells were in rural agricultural areas. Wells or well locations were selected for sampling on the basis of a computer-based random site-selection method developed by Scott (1990).

The supply wells selected for sampling were completed in glacial drift and constructed after 1980 to ensure that modern well-construction techniques were used. Of the 60 wells sampled, 59 were private-supply wells and 1 was a public-supply well. Water samples were obtained prior to passing through residential or public water-treatment systems to avoid any chemical modifications introduced by these systems.

Of the 60 existing supply wells, 30 were 200 ft or greater in depth and screened in the deep glacial drift aquifer. Wells selected were in the Mahomet Buried Bedrock Valley area where the top of the bedrock was below an altitude of 500 ft. Wells were completed in the sands and gravels of the glacial drift. Well depths ranged from 200 to 365 ft, with a median depth of 256 ft. The well diameters ranged from 4 to 5 inches; 80 percent were 5-inch-diameter wells. Well-screen lengths ranged from 4 to 12 ft, with a median screen length of 5.5 ft (table 2).

The remaining 30 supply wells were less than 110 ft deep and screened in the shallow glacial drift

Table 2. Well dimensions for sampled wells in the lower Illinois River Basin

Aquifer	Aquifer abbreviation	Well depth, in feet below land surface	Median well depth, in feet	Well diameter, in inches	Well screen length, in feet	Well screen median, in feet
Bloomington Ridged Plain not overlying a buried bedrock valley	BRP N/O BV	12–59	26.5	2	5	5
Bloomington Ridged Plain overlying the Mahomet Buried Bedrock Valley	BRP O/L MBBV	13–59	19.0	2	5	5
Galesburg/Springfield Plain not overlying a buried bedrock valley	GSP N/O BV	30–108	50	4–36	0–78	26
Mahomet Buried Bedrock Valley	MBBV	200–365	256	4–5	4–12	5.5

of the Galesburg/Springfield Plain, where no buried bedrock valleys were located. Wells were completed primarily in the sands and gravels, but also in silty-sands of the glacial drift. Well depths ranged from 30 to 108 ft, with a median value of 50 ft. Well diameters ranged from 4 to 36 inches. Seventeen wells were 36 inches in diameter, and one well was 24 inches in diameter. The large-diameter (24 and 36 inches) wells were constructed because the water-producing units in this area are thin and poorly permeable. Well-screen lengths ranged from open ended casing to 78 ft, with a median screen length of 26 ft (table 2).

During the study, 57 monitoring wells were installed. Well locations were selected by use of the random site-selection program and the well sited within 0.5 mi of the selected point. Occasionally, going slightly beyond 0.5 mi was necessary if the local hydro-geologic conditions were consistent. All monitoring wells were constructed of 2-inch-diameter polyvinyl chloride (PVC) with 5-ft-long screens. Wells were constructed according to NAWQA protocols (Lapham and others, 1995) using the hollow-stem augering drilling method at the first water-producing unit and installed on private land and rural agricultural roadsides. Wells were completed in primarily sands and gravels but also were completed in less productive silts and clayey-silts of the glacial drift.

In the shallow glacial drift of the BRP N/O BV, 29 monitoring wells were installed, with well depths ranging from 12 to 59 ft and a median well depth of 26.5 ft, whereas 28 wells were installed in the shallow glacial drift of the BRP O/L MBBV, with well depths ranging from 13 to 59 ft and a median well depth of 19.0 ft (table 2).

Uranium and Radon Sampling and Analysis Methods

Water samples for U and Rn analysis were collected after the field-measured parameters (pH, dissolved oxygen, water temperature, and turbidity) had stabilized to ensure that a representative sample from the aquifer was obtained. The readings usually stabilized after three well volumes were purged or, in the case of some large-diameter wells, approximately 2 hours of purge time had elapsed. Where sampling wells by bailing was necessary, the wells also were purged by bailing. After sufficient water had recharged the well, samples were collected using primarily Teflon and stainless-steel sampling equipment. Samples also were analyzed for a comprehensive set of nutrient, trace element, and other inorganic constituents (table 3).

Samples for analysis of U were obtained by collecting 250 ml of water through a 0.45- μ m high-capacity tortuous flow polysulfone capsule filter and preserved with 1 ml of nitric acid (HNO₃). Samples were shipped to the USGS National Water-Quality Laboratory (NWQL) in Denver, Colo., and analyzed for ²³⁸U (Natural U consists almost entirely of the ²³⁸U isotope (Berlin and Rudell, 1986).) by inductively coupled plasma-mass spectrometry (ICPMS), with a minimum reporting level (MRL) of 1 μ g/L (Faires, 1993, Ivahnenko and others, 1996).

Water samples for Rn analysis consisted of 10 ml of water injected under a mineral-oil cocktail to eliminate contact with the atmosphere (Mullin and Wanty, 1991). The 10-ml samples were obtained by collecting 15 ml of water with a hypodermic syringe. To prevent degassing of Rn by aeration of the sample, the needle was inserted through a Teflon septum on the sampling line. After filling and purging the syringe twice, 15 ml of water was collected again and 5 ml was eliminated from the syringe. If the sampled well was not capable

Table 3. Sampled inorganic constituents, field parameters, and well characteristics correlated with uranium and radon using the Spearman Rank Correlation test

Inorganic constituents	Field parameters and well characteristics
Aluminum	Alkalinity
Antimony	Dissolved oxygen
Arsenic	pH
Barium	Specific conductivity
Beryllium	Turbidity
Bromide	Water temperature
Cadmium	Well depth
Calcium	Well diameter
Chloride	
Chromium	
Cobalt	
Copper	
Fluoride	
Iron	
Lead	
Magnesium	
Manganese	
Molybdenum	
Nickel	
Nitrogen, ammonia	
Nitrogen, ammonia + organic nitrogen	
Nitrogen, nitrite	
Nitrogen, nitrite + nitrate	
Phosphate, ortho	
Phosphorus	
Potassium	
Selenium	
Silica	
Silver	
Sodium	
Sulfate	
Zinc	

of being pumped at a rate less than or equal to recharge, the sample was collected using a Teflon bailer from the well by filling the bailer with water and inserting a hypodermic syringe into the lower quarter of the bailer to minimize aeration and atmospheric contact. The sample was then injected under a mineral-oil cocktail and shipped overnight to the NWQL. All Rn samples were analyzed for ^{222}Rn using liquid scintillation methodology, with an MRL of 80 pCi/L (Prichard and Gessell, 1977, Mullin and Wanty, 1991).

Hydraulic Conductivity Analysis

Hydraulic conductivity results were obtained by conducting slug tests on 42 of the 57 (74 percent) monitoring wells. A 3-ft long, 1-inch diameter PVC rod

was inserted and removed from the water in the well casing to effect a water-level change; the change in water level was measured by use of a pressure transducer. Hydraulic conductivity values were calculated from water-level data change over time using the Bouwer and Rice (1976) method of analysis for unconfined aquifer conditions, and Cooper and others (1967) method of analysis for confined aquifers.

Quality-Assurance/Quality-Control Plan

A quality-assurance plan for samples analyzed for U was developed and consisted of 32 quality-assurance samples collected in the field, including 17 field blanks, 3 equipment blanks, and 12 replicates. The quality-assurance plan for samples analyzed for Rn consisted entirely of 13 quality-assurance replicate samples collected in the field. Blanks were not collected because of the short half-life of Rn and its degassing properties, which leads to low, not high, bias.

No U was detected at an MRL of 0.2 $\mu\text{g/L}$ in any of the 17 field blanks. No U was detected in the two bailer blank samples. No U concentration bias due to random sampling contamination is expected.

The range of the percent difference for the 12 replicate sample pairs for U concentrations was from 0 to 20 percent. Median and mean percent differences were 0 and 2 percent, respectively. All but one pair had 0 percent differences between the pairs, with identical replicate sample concentrations ranging from less than 1 $\mu\text{g/L}$ to 7 $\mu\text{g/L}$. The only pair that differed in U concentration had an environmental sample concentration of 2 $\mu\text{g/L}$, with a replicate concentration of 1.6 $\mu\text{g/L}$ (a difference of 20 percent). The one replicate concentration pair collected by bailing had 0 percent difference. Precision of U concentrations, therefore, should not differ substantially between pumped or bailed samples.

The range of the percent difference for the 13 replicate samples for Rn concentrations was 0 to 17 percent. Median and mean percent differences were 4 and 5 percent, respectively. The one replicate concentration pair collected by bailing had a 4 percent difference. Precision of Rn concentrations did not differ substantially between pumped or bailed samples.

Statistical Analysis

Although sample sizes ranged from 28 to 30 samples for each aquifer, the Rn and U data were not normally distributed; therefore, nonparametric methods were used in the statistical analyses.

The nonparametric Spearman Rank method (r_s) was used to calculate the coefficient of correlation between U and Rn with inorganic constituents, field parameters, and well characteristics (table 3). For the purposes of this report, the terms used to describe statistically significant correlations are strong (± 0.50 to ± 1.00), moderate (± 0.35 to ± 0.49), and weak, or not correlating (less than ± 0.35). Correlations are evaluated as to the degree of significance (p) and reported with the correlation value.

Relations between U and Rn with type of deposit, well location, and sampling method were evaluated using the nonparametric Mann-Whitney test with a null hypothesis of equal medians (Helsel and Hirsch, 1995).

URANIUM

Geochemistry

Uranium is present in ground water in three naturally occurring isotopes: ^{238}U , uranium-234 (^{234}U), and uranium-235 (^{235}U). The predominant forms, in terms of activity, found in natural waters are ^{238}U and ^{234}U . Uranium-238 has a half-life of 4.5×10^9 years; U-234 has a half-life of 247,000 years. The ^{238}U isotope constitutes the majority of the mass (99 percent) of natural U (Aieta and others, 1987), but, in general, a higher ^{234}U to ^{238}U activity ratio is found in ground water relative to the source material (Osmond and Cowant, 1976). The higher ^{234}U to ^{238}U activity ratio in ground water than in adjoining rock is hypothesized to be a result of ^{234}U being ejected into solution from alpha (α) recoil from decay of ^{238}U and thorium-234 (^{234}Th) parents in the source rock (Osmond and Cowant, 1976; Aieta and others, 1987). Natural U also includes ^{235}U , but it constitutes only 0.7 percent by weight of natural U. Uranium-235 is important for use in nuclear reactors and nuclear weapons (Wrenn and others, 1987).

The solubility of U in ground water is affected by local oxidizing-reducing conditions. Uranium is most soluble in oxidizing conditions. Uranium in the

+6 oxidation state becomes mobile and occurs in the form of uranyl (UO_2^{2+}) complexes, or where bicarbonate is present (most ground water), as $\text{UO}_2(\text{CO}_3)_3^{-4}$ complexes (Hsi and Langmuir, 1985). In reducing conditions, U in the +4 or +5 oxidation state is immobile. Uraninite (UO_2) is usually the end product of U precipitation. The precipitation of U where oxidation-reduction potential greatly decreases over a short distance has resulted in the formation of economically important U-rich deposits (Hostetler and Garrels, 1962).

Concentrations of dissolved oxygen were used in this study as an indication of the oxidizing-reducing conditions of the aquifers and as an indicator of the potential solubility of U. In northern New Jersey, where U concentrations greater than 20 $\mu\text{g/L}$ in ground water were present, dissolved-oxygen concentrations were greater than 1 mg/L in all but one case. Uranium concentrations less than 1 $\mu\text{g/L}$ occurred more frequently in ground water containing less than 1 mg/L of dissolved oxygen than in ground water containing greater than 1 mg/L of dissolved oxygen (Szabo and Zapecza, 1991). In the LIRB, U concentrations did not exceed 20 $\mu\text{g/L}$ in any of the 117 samples; however, U concentrations equaling or exceeding 1 $\mu\text{g/L}$ were more frequent (64 percent) where dissolved-oxygen concentrations were greater than 1 mg/L. Uranium concentrations less than 1 $\mu\text{g/L}$ were more frequent (86 percent) where dissolved-oxygen concentrations were less than 1 mg/L. The highest U concentration detected in the LIRB, however, was in a sample with a dissolved-oxygen concentration less than 1 mg/L. The distribution of U relative to oxygen-rich and oxygen-poor waters is similar for the LIRB and other areas, such as northern New Jersey (Szabo and Zapecza, 1991). The concentration range, median, and percentage of concentrations greater than 1 $\mu\text{g/L}$ for oxygen-rich and oxygen-poor water is shown in table 4.

The solubility of U in ground water is also affected by pH. The pH of all samples was between 6.3 and 8.0, with 85 percent between 6.7 and 7.3. At these pH levels, uranyl ions form dissolved complexes, predominantly with carbonates and biophosphates. Adsorption of uranyl ions may occur on some aquifer materials in oxidizing conditions, especially iron hydroxides (Hsi and Langmuir, 1985), with adsorption strongest at near-neutral pH (7.0 pH) (Wanty and Schoen, 1991). Complexation can mobilize U even in the presence of adsorptive iron hydroxides (Hsi and Langmuir, 1985).

Table 4. Relations of uranium concentrations with dissolved oxygen in ground water[$\mu\text{g/L}$, micrograms per liter]

Uranium concentration variables	Water with dissolved oxygen less than or equal to 1 milligram per liter	Water with dissolved oxygen greater than 1 milligram per liter
Uranium concentration range, in $\mu\text{g/L}$	0–17	1–15
Uranium concentration median, in $\mu\text{g/L}$	0	1
Percentage of uranium concentrations equal or greater than 1 $\mu\text{g/L}$	14	64

Sources of Uranium

Geologic sources for U in water for the four aquifers are the glacial drift deposits. For the wells completed in the deep aquifer, the bedrock surrounding the glacial deposits also may be a source. Gilkeson and Cowart (1982), in their assessment of U in water in northern Illinois, suggest that glacial sediments may be a significant source of U. The glacial deposits in the shallow glacial drift aquifers are Wisconsinan and Illinoian in age; source rocks may have originated locally or from the north/northeast. Origin of glacial deposits may be as far north as areas north of Lake Michigan and Lake Superior in Canada. Wisconsinan glacial deposits in the LIRB are from mainly the Lake Michigan lobe, which advanced from the Hudson Bay region. The tills are from primarily shales, sandstones, and carbonate rocks of southern Wisconsin, the western Michigan Basin, and the northern Illinois Basin (Schumann, 1993). Illinoian glacial deposits in central Illinois advanced mainly south-southwesterly from the Lake Michigan Basin. These Illinoian tills generally contain greater amounts of illite and dolomite (Killey, 1998; Matsch, 1976). Based on the occurrence of U in the tills, some glacial material containing U of Canadian origin (Lang and others, 1970) may be a partial source for the Wisconsinan and Illinoian glacial deposits. Gilkeson and Cowart (1982) also suggest that local black shale deposits ground up and incorporated into glacial debris could be a significant source of soluble U.

The age of glacial deposits in the MBBV is primarily pre-Illinoian. The source direction for these pre-Illinoian glacial deposits probably is from the northeast (Killey, 1998). Supply wells in the MBBV usually are screened to glacial drift deposits composed of sand from glaciofluvial sources. Sands contain abundant hornblende, garnet, and epidote composition similar to that of overlying tills (Kempton and others, 1991).

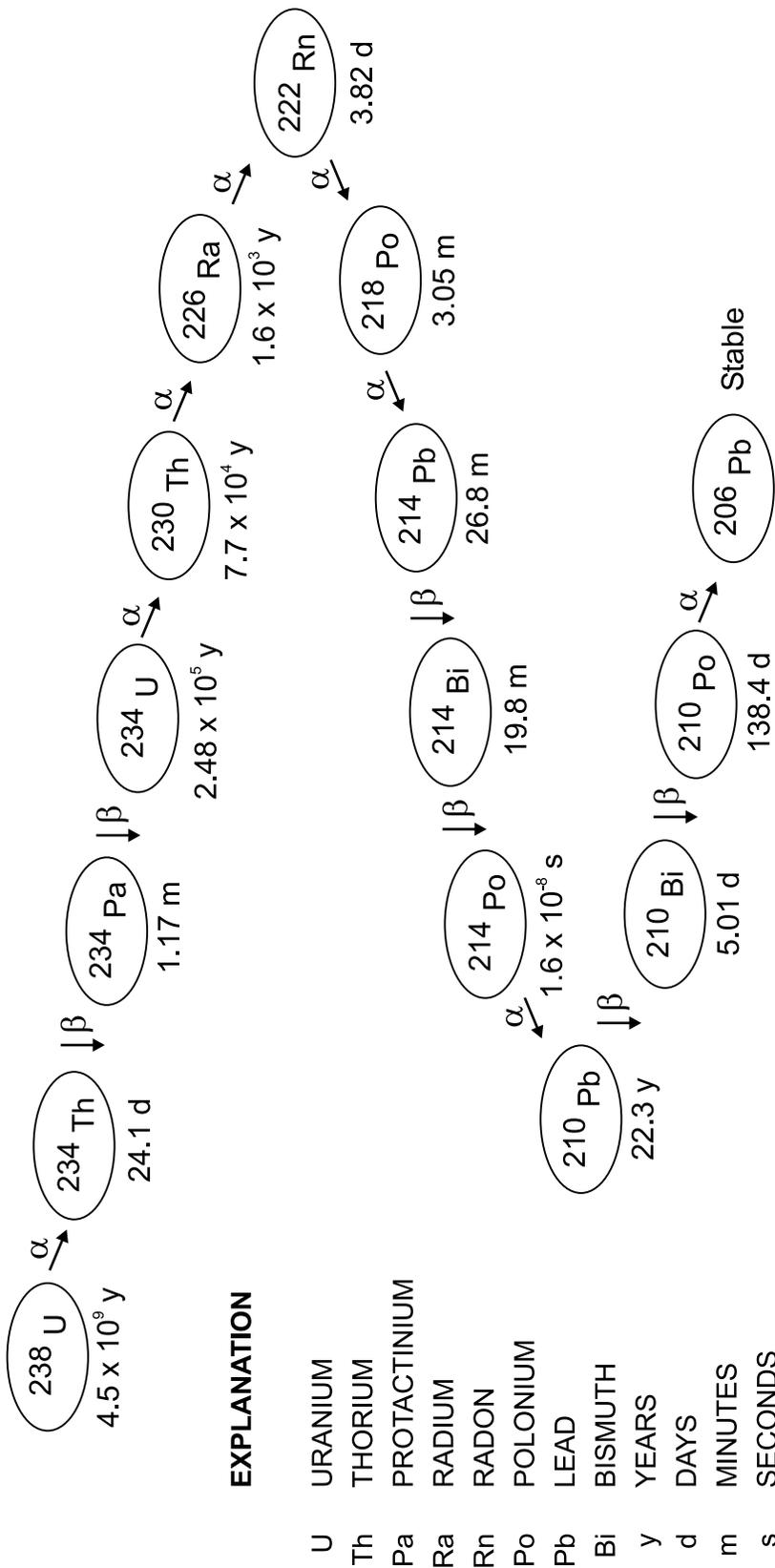
The bedrock surrounding the glacial deposits may affect water quality of the MBBV. In the MBBV, the bedrock is primarily Pennsylvanian shale with some sandstone and limestone, mainly from the Mattoon, Bond, and Modesto Formations (Kempton and others, 1991). The average U content for Pennsylvanian shales throughout Illinois is slightly more than 0.004 percent equivalent U. The Pennsylvanian shale in the basin has been found to contain U in the range from 0.000 to 0.014 percent equivalent U (Ostrom and others, 1955). Gilkeson and Cowart (1982) suggest that the grinding of black shale to fine debris may liberate some U.

In the LIRB, U may be derived from phosphate-bearing fertilizers used for agricultural purposes. Uranium can be present in many phosphate-bearing fertilizers and can contribute dissolved U through leaching (Zielinski and others, 1997). Uranium concentrations in fertilizers have been found to correlate positively with phosphorus compounds in the Mississippi River drainage system (Spalding and Sackett, 1972).

RADON

Decay Series

Radon is a radioactive gas that occurs naturally in ground water as an intermediate step in the decay of ^{238}U to lead-206 (^{206}Pb). Uranium-238 decays through a number of steps to radium-226 (^{226}Ra), which decays to ^{222}Rn by releasing an alpha particle from its nucleus. Radon-222 decays through a number of radionuclides with short half-lives until stable ^{206}Pb is formed (fig. 4). Radon is soluble in water, odorless, and tasteless. The only Rn isotope analyzed in this study was ^{222}Rn . The other two isotopes of Rn, ^{220}Rn and ^{219}Rn , were not analyzed. Their occurrence in ground water is difficult to determine because their half-lives are short



EXPLANATION

- U URANIUM
- Th THORIUM
- Pa PROTACTINIUM
- Ra RADIUM
- Rn RADON
- Po POLONIUM
- Pb LEAD
- Bi BISMUTH
- y YEARS
- d DAYS
- m MINUTES
- s SECONDS

α ALPHA DECAY

β BETA DECAY

Figure 4. Radioactive decay series of uranium-238 with half-lives.

(seconds), whereas ^{222}Rn has a comparatively long half-life at 3.82 days.

Sources of Radon

The glacial drift immediately surrounding the well borehole is the primary source for Rn in ground-water samples. The Rn source is in the zone immediately surrounding the borehole because the slow traveltime of typical ground water, coupled with the relatively short half-life (3.82 days) of Rn, limits the distance that Rn can travel in ground water before decay (Hoehn and others, 1992). The glacial drift deposits in the LIRB may have originated from local sources or as distant as the original area of glacier formation, such as Canada. The origin of the deposits is partly dependent on the type of glacial deposits encountered: subglacial, end moraine, or other types of glacier deposition. Typical glacial sediments are rarely homogeneous; this heterogeneous composition, coupled with variable U concentrations, results in varying Rn concentrations.

In general, the geologic Rn potential for indoor air concentrations, based on the permeability and U content of geologic deposits for the LIRB, is “high” (fig. 5) (Schumann, 1993). In areas of glacial deposits, soil permeability (and presumably porosity) typically is high, allowing the Rn to be mobile (Gundersen and others, 1992; Gundersen and Schumann, 1996). For Rn in water in porous media, however, high porosity tends to correspond to low Rn content (Wanty and others, 1992). In the LIRB, the factors most likely to result in high Rn content in ground water are high U content of the sediment, or high Rn emanation coefficient, or both. Neither factor is well defined for these shallow sediments. Despite the heterogeneous nature of glacial deposits, the critical variables that affect Rn concentration in ground water, such as U content, porosity, and emanation coefficient (Wanty and others, 1992), are distributed fairly uniformly resulting in little variation in Rn content.

URANIUM DETECTIONS AND CORRELATIONS

Uranium was analyzed in water samples collected from 117 wells completed in four separate aquifers. Of the 117 wells, 22 were sampled by bailing and 95 were sampled by pumping. Of the 22 wells bailed, all were completed in the BRP N/O BV and

the BRP O/L MBBV. Uranium concentrations ranged from less than 1 $\mu\text{g/L}$ to 17 $\mu\text{g/L}$. The median and mean values were 0 and 1.4 $\mu\text{g/L}$, respectively. The maximum measured concentration of 17 $\mu\text{g/L}$ did not exceed the USEPA proposed Maximum Contaminant Level (MCL) drinking-water standard at the time of sampling (1996–97) of 20 $\mu\text{g/L}$ (U.S. Environmental Protection Agency, 1996). The current (as of December 2000) promulgated MCL is 30 $\mu\text{g/L}$ (U.S. Environmental Protection Agency, 2000). Locations of wells that were sampled for analysis of U and ranges of U concentrations are shown in fig. 6. Uranium distribution by aquifer is given in table 5.

Mahomet Buried Bedrock Valley (MBBV)

Uranium concentrations were less than 1 $\mu\text{g/L}$ in the 30 samples from the MBBV. This lack of detection at a concentration of less than 1.0 $\mu\text{g/L}$ is interpreted to be the result of reducing conditions in the aquifer. Under reducing conditions, U is precipitated in the immobile +4 valence state. The presence of reducing conditions in all sampled wells of the aquifer was inferred on the basis of dissolved-oxygen concentrations at less than 0.1 mg/L throughout the aquifer.

Uranium is likely present, but precipitated or sorbed onto the aquifer matrix, as indicated by the presence of Rn in all water samples from the MBBV. This presence implies that there are radionuclide parents (U and Rn) in the aquifer material in concentrations great enough to produce the measured concentrations of Rn.

Galesburg/Springfield Plain Not Overlying a Buried Bedrock Valley (GSP N/O BV)

Uranium was detected at concentrations greater than 1.0 $\mu\text{g/L}$ in 10 of 30 (33 percent) samples collected from the GSP N/O BV. Concentrations ranged from less than 1.0 $\mu\text{g/L}$ to 17 $\mu\text{g/L}$. Oxidizing conditions, which enable U to become mobile in the +6 valence state, generally were present in at least some parts of the GSP N/O BV as indicated by dissolved-oxygen concentrations. Dissolved-oxygen concentrations ranged from less than 0.1 to 6.8 mg/L. Dissolved-oxygen concentrations were greater than 0.1 mg/L in 18 of 30 samples (60 percent) and were greater than 1.0 mg/L in 15 of 30 samples (50 percent). The median

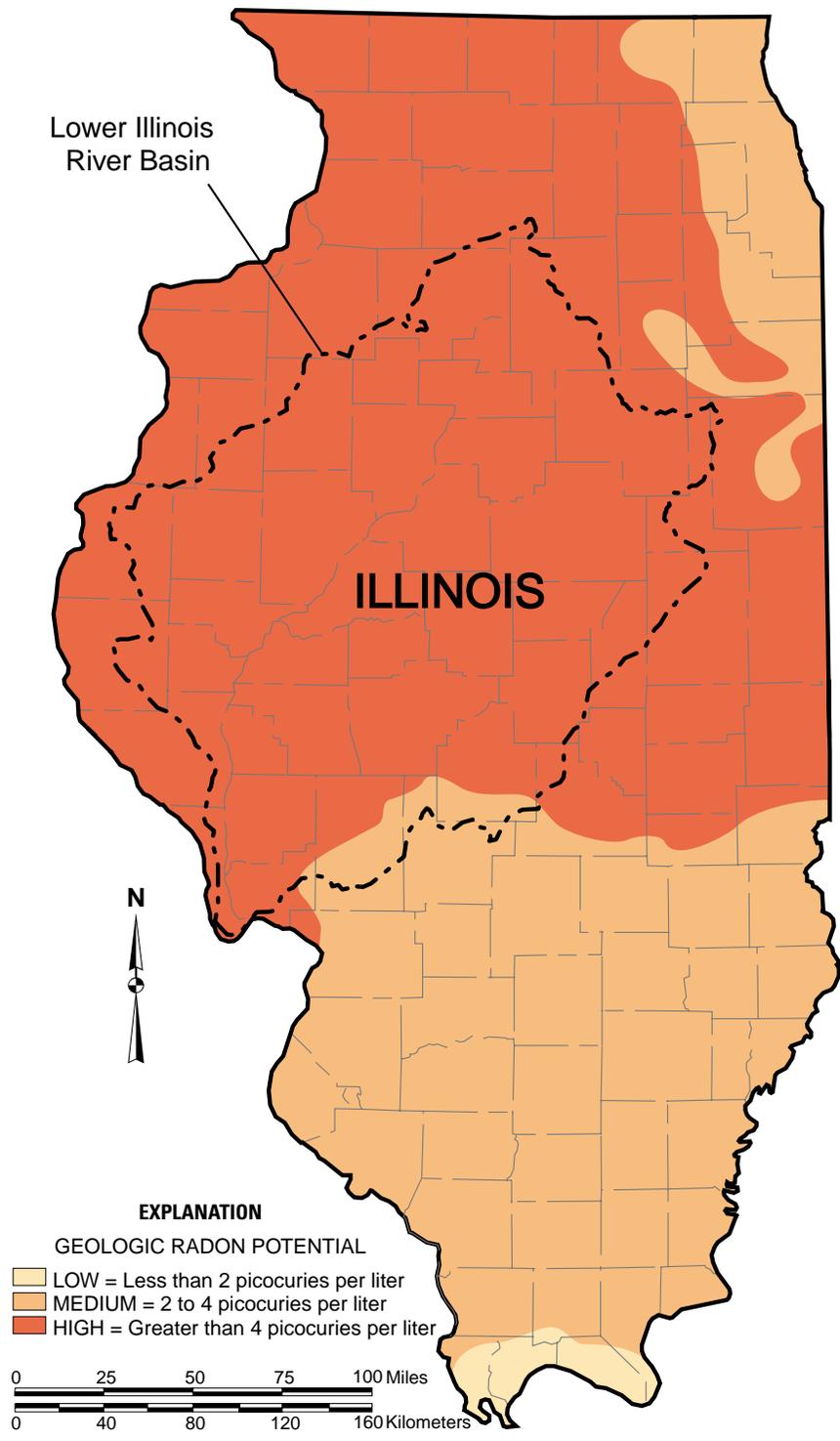


Figure 5. Generalized geologic radon potential for indoor air concentrations of Illinois, based on permeability and uranium content of geologic deposits (modified from Schumann, 1993).

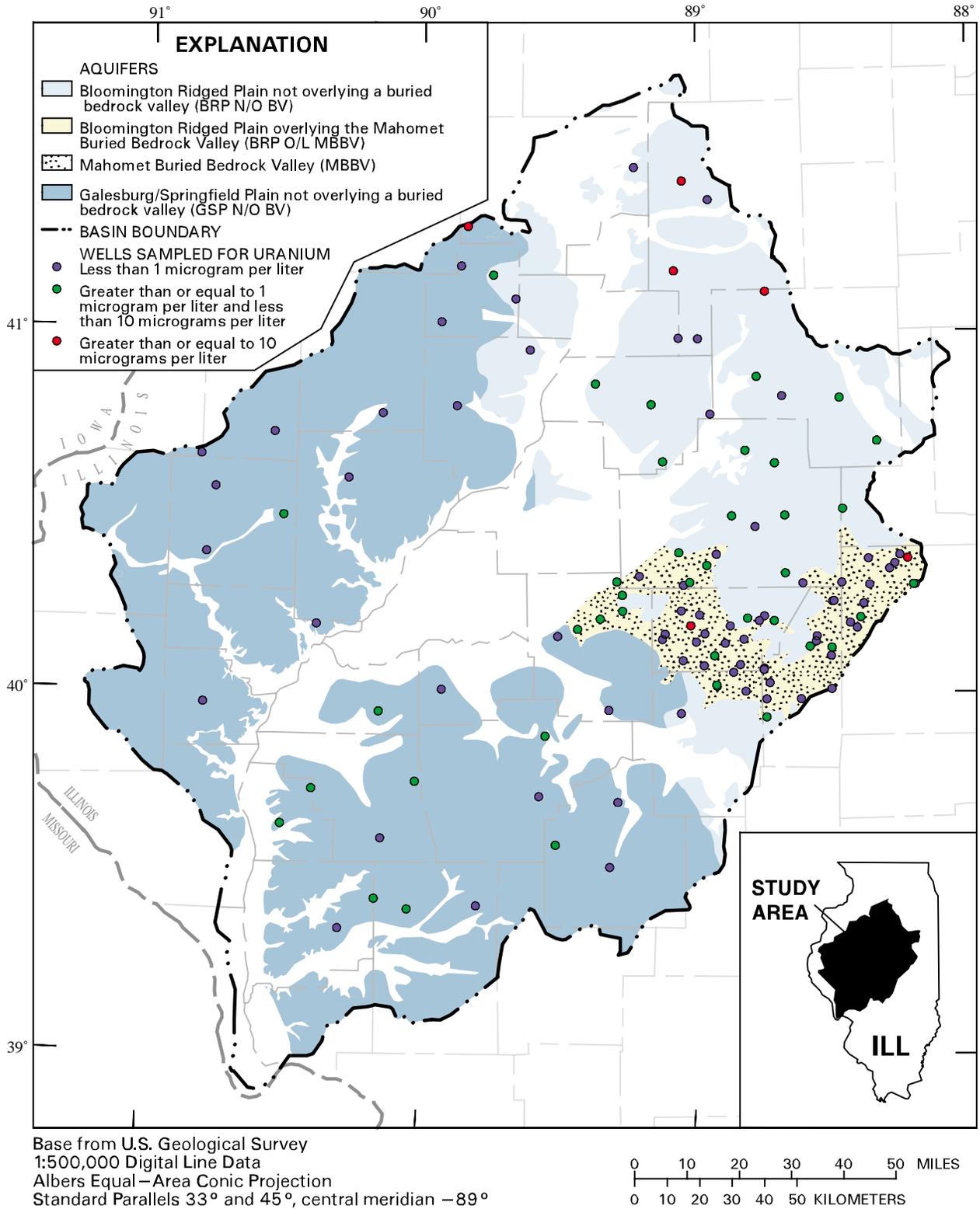


Figure 6. Locations of wells and ranges of uranium concentrations in ground water in the lower Illinois River Basin.

Table 5. Uranium concentrations, range, mean, and median, by aquifer
[$\mu\text{g/L}$, micrograms per liter]

Aquifer	Aquifer abbreviation	Uranium concentration range ($\mu\text{g/L}$)	Uranium concentration, median value ($\mu\text{g/L}$)	Uranium concentration, mean value ($\mu\text{g/L}$)
Bloomington Ridged Plain not overlying a buried bedrock valley	BRP N/O BV	Less than 1.0–15	2.0	2.8
Bloomington Ridged Plain overlying the Mahomet Buried Bedrock Valley	BRP O/L MBBV	Less than 1.0–12	1.0	1.6
Galesburg/Springfield Plain not overlying a buried bedrock valley	GSP N/O BV	Less than 1.0–17	1.0	1.4
Mahomet Buried Bedrock Valley	MBBV	Less than 1.0	Less than 1.0	Less than 1.0

dissolved-oxygen concentration was 1.4 mg/L and the mean was 2.0 mg/L.

Concentrations of U did not correlate significantly with those of Rn ($r_s = 0.31$, $p = 0.11$). Uranium and Rn concentrations did not correlate above an r_s of an absolute value of 0.28 ($p = 0.16$) in any of the other aquifers. This result is likely because of the different chemical behavior of these elements. The concentration and mobility of Rn is related to the concentration of U in the sediment, specifically the sources of U near the well screen. The solubility of Rn is not dependent upon the oxidation/reduction potential of the water, whereas the mobility of U is dependent on the oxidation/reduction potential and pH. Under similar hydrologic flow conditions and favorable oxidizing alkaline conditions, U can travel substantial distances relative to Rn because the half-life of U is so much longer than that of Rn. Thus, under oxidizing conditions where U is mobile, it is possible that U can be found at higher concentrations in ground water where the aquifer matrix has little U in the aquifer matrix than in areas where the water is reducing, even if plenty of U is in the aquifer matrix. The Rn concentrations, which are primarily proportional to the U content of the aquifer matrix, may be low in the areas of rapidly flowing oxidizing water because of the potential long-term leaching of U from the aquifer matrix, especially that in soluble grain coatings. Conversely, under reducing conditions, Rn may be present in high concentrations in an area of uraniferous deposits, whereas U would not be present in the water because U is immobilized, possibly as a precipitate in the aquifer matrix. Szabo and Zapezca (1991) noticed a lack of correlation between U and Rn concentrations in water from fractured rock aquifers in northern New Jersey. They further indicated that long distance transport of U occurs in oxidizing waters, resulting, on occasion, in

elevated concentrations of U in areas with moderate or low U content in the aquifer matrix and relatively low Rn concentration in the water.

Uranium correlated strongly with sulfate and nickel ($r_s = 0.63$ ($p = 0.0002$) and $r_s = 0.52$ ($p = 0.0036$), respectively; see fig. 7). The correlation of sulfate with U is an indicator of oxidizing conditions where U is soluble. Sulfate is the stable form of dissolved sulfur in oxidizing water. In northern New Jersey, a similar strong correlation is noted between the concentrations of sulfate and U; Szabo and Zapezca (1991) concluded that both accumulated (increasing in concentration along the flow path) in oxidizing water.

The correlation of U and nickel concentrations could be an indication that the source rock is the same for both and potentially contains elevated concentrations of both. The southern Precambrian Canadian Shield area, the Superior and Grenville Provinces, are the probable origin of glacial debris transported from the north. Rocks in these areas contain U and nickel deposits (Lang and others, 1970). Glacial sediments derived from this source area, thus, may contain abundant U and nickel. Extremely high and variable concentrations of U in rock and concentrations of Rn in water have been documented in the southwestern portion of the Canadian Shield (Steck, 1987), the likely source of some glacial debris in the LIRB. Another possibility is that the oxidizing conditions are favorable for U and nickel to be in solution as these trace elements are among the most mobile of trace elements. The weak correlations of dissolved-oxygen concentrations with U ($r_s = 0.35$, $p = 0.059$) and of nickel ($r_s = -0.22$, $p = 0.24$) indicate the oxidizing geochemical conditions may not be the primary reason for the correlation between U and nickel concentrations. Also, possibly, the correlation between the concentrations of U and nickel is simply fortuitous with no

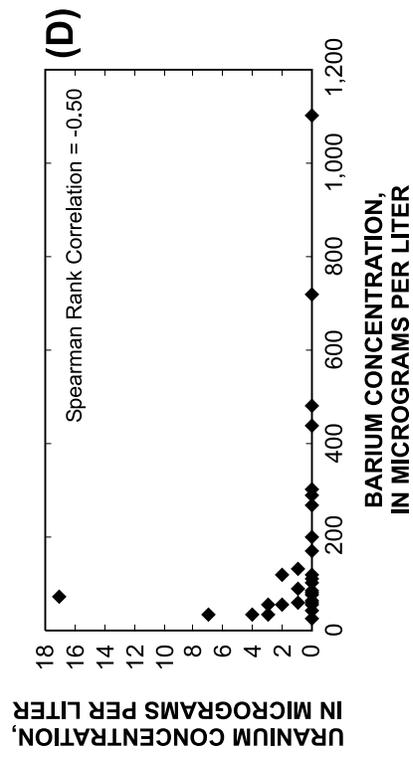
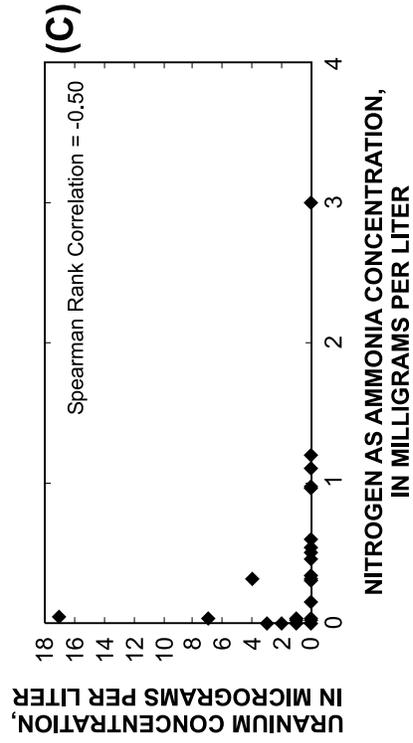
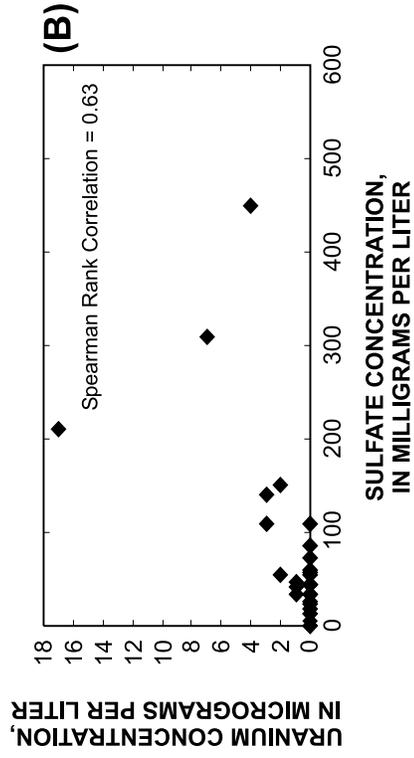
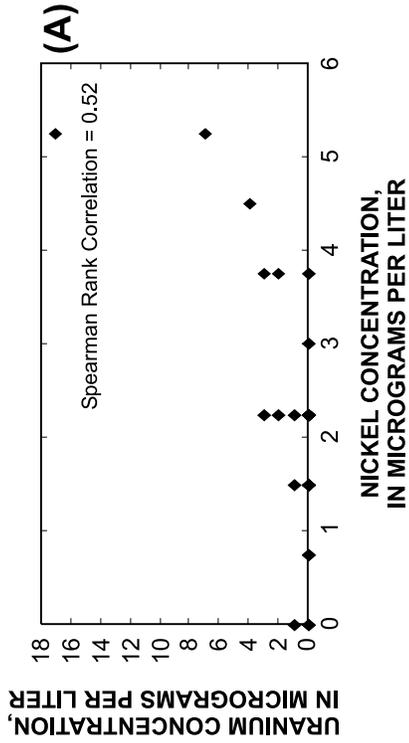


Figure 7. Concentration of uranium as a function of the concentration of (A) nickel, (B) sulfate, (C) nitrogen as ammonia, and (D) barium in water from the Galesburg/Springfield Plain not overlying a buried bedrock valley (GSP N/O BV), lower Illinois River Basin, with Spearman Rank Correlation.

hydrologic or geochemical significance. Correlation between these two elements in ground water is not widely documented in the scientific literature.

Strong inverse correlations were noted among the concentrations of U with those of barium ($r_s = -0.50$, $p = 0.0054$) and ammonia ($r_s = -0.50$, $p = 0.032$). In general, in water when one of these constituents is present, U is absent (fig. 7). Ammonia is a reduced species of nitrogen that is most stable under reducing conditions, conditions that favor U precipitation. The divalent cations, barium and radium, are often released into solution under reducing conditions when the iron hydroxides, to which these cations are sorbed, dissolve (Szabo and Zapecza, 1991); again, these conditions are likely to immobilize U.

Concentrations of U do not correlate with those of dissolved phosphorus ($r_s = -0.08$, $p = 0.64$). Phosphorus sorbs strongly to soil. Phosphorus was detected in 33 percent of the samples with a maximum concentration of 0.28 mg/L. The water-quality data do not indicate the source of dissolved U is leachate from anthropogenic phosphate fertilizer application.

Bloomington Ridged Plain Not Overlying a Buried Bedrock Valley (BRP N/O BV)

Uranium was present at concentrations greater than 1.0 $\mu\text{g/L}$ in 18 of the 28 (64 percent) water samples collected from the BRP N/O BV. Concentrations ranged from less than 1.0 $\mu\text{g/L}$ to 15 $\mu\text{g/L}$. The median value was 2 $\mu\text{g/L}$, and the mean was 2.8 $\mu\text{g/L}$.

Oxidizing conditions generally were present as indicated by dissolved-oxygen concentrations. Dissolved-oxygen concentrations ranged from 0.3 to 5.9 mg/L. Dissolved-oxygen concentrations were greater than 0.1 mg/L in all samples (100 percent) and were greater than 1.0 mg/L in 19 of 27 samples (70 percent). The median and mean concentrations were 1.4 and 2.9 mg/L, respectively. The oxidizing conditions allow U to become mobile in the +6 valence state.

Uranium had a strong ($r_s = 0.73$, $p = <0.0001$) correlation with nickel (fig. 8). This correlation may be an indication of a similar source for the U and nickel as the GSP N/O BV source. The deposits containing U and nickel from the Superior and Grenville Provinces in the general pre-Cambrian Canadian Shield area (Lang and others, 1970) are considered a possible origin because the Wisconsinan glaciation came from a generally north/northeast direction. Local black

shales ground up in the till may be another possible U-containing source. Often, black shales also contain high concentrations of trace elements (Leventhal and Hosterman, 1982), including U and nickel. Gilkeson and Cowart (1982) suggest the black shale component in glacial debris could be a source of dissolved U. Dissolved oxygen correlated weakly with U ($r_s = 0.26$, $p = 0.19$), but dissolved oxygen did correlate strongly with nickel ($r_s = 0.63$, $p = 0.0004$). This result indicates that oxidizing conditions may affect the occurrence and co-occurrence of nickel and U.

Although the correlation of U with sulfate was moderate ($r_s = 0.39$, $p = 0.038$), a noticeable general trend of increasing concentrations of both is evident (fig. 8). Tritium had a strong ($r_s = 0.50$, $p = 0.0084$) correlation with U (fig. 8). This correlation is assumed to indicate the proximity between oxidizing conditions near the land surface (favorable to dissolved U and sulfate) and young water with high tritium concentrations.

Concentrations of U do not correlate with those of dissolved phosphorus ($r_s = -0.20$, $p = 0.19$). Phosphorus sorbs strongly to soil. Phosphorus was detected in 14 percent of the samples with a maximum concentration of 0.06 mg/L. The water-quality data do not indicate the source of dissolved U is leachate from anthropogenic phosphate fertilizer application.

Bloomington Ridged Plain Overlying the Mahomet Buried Bedrock Valley (BRP O/L MBBV)

Uranium was detected in the BRP O/L MBBV in 17 of the 29 (59 percent) samples collected. Concentrations ranged from less than 1.0 $\mu\text{g/L}$ to 12 $\mu\text{g/L}$. The median and mean values were 1.0 and 1.6 $\mu\text{g/L}$, respectively.

Oxidizing conditions generally were present as indicated by dissolved-oxygen concentrations. Dissolved-oxygen concentrations ranged from 0.1 to 7.4 mg/L. All but 1 of 29 samples analyzed (96 percent) had concentrations greater than 0.1 mg/L and greater than 1.0 mg/L in 23 of 29 (79 percent) samples, indicating oxidizing conditions that would allow U to be dissolved and mobile in the +6 valence state. The median and mean values were 3.1 and 3.2 mg/L, respectively.

Uranium shows no correlation with Rn ($r_s = 0.00$, $p = 0.99$), nor with nickel ($r_s = 0.18$, $p = 0.36$) (fig. 9). Neither concentrations of U nor nickel correlate with the concentrations of dissolved

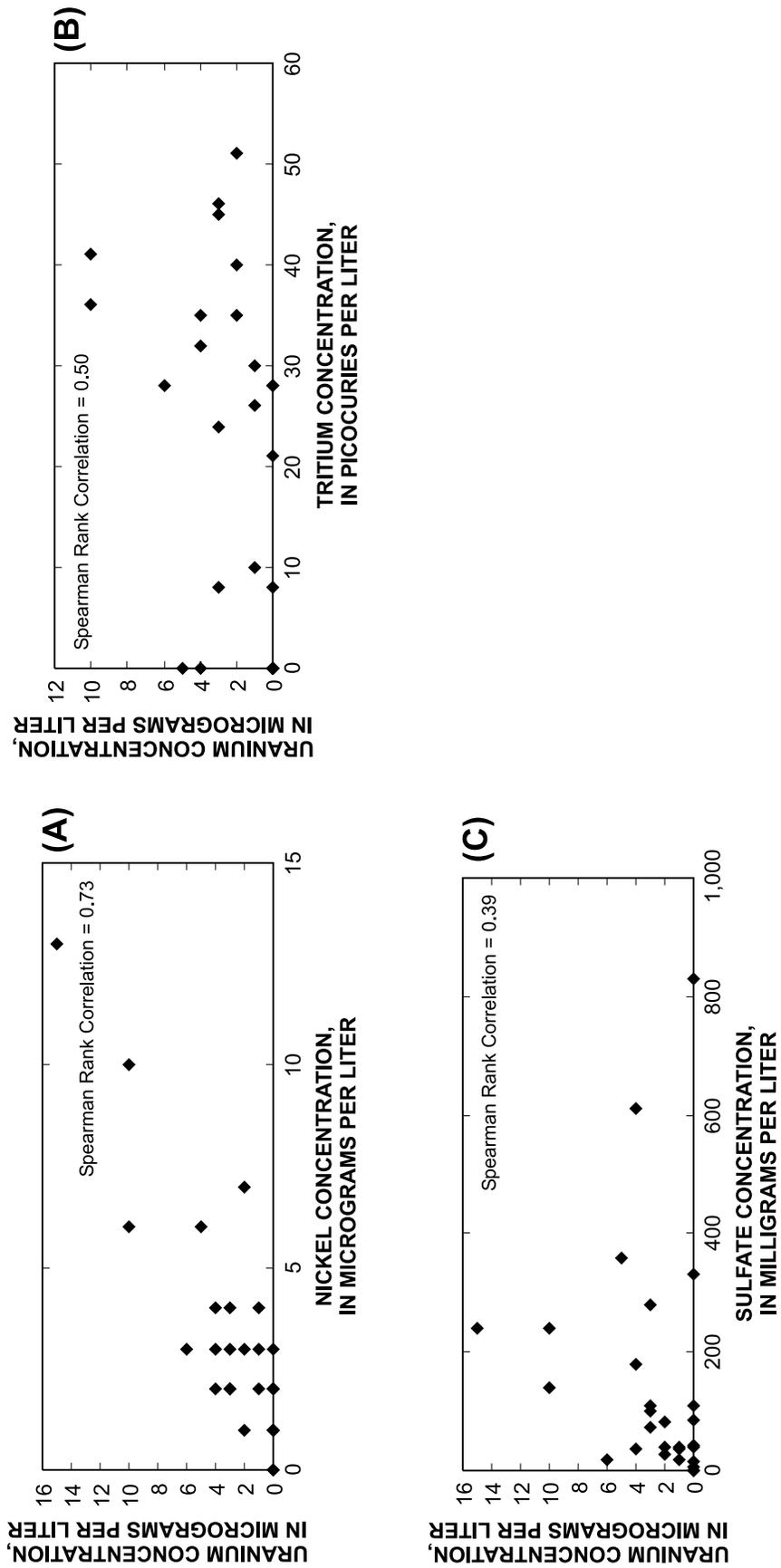


Figure 8. Concentration of uranium as a function of the concentration of (A) nickel, (B) tritium, and (C) sulfate in water from the Bloomington Ridged Plain not overlying a buried bedrock valley (BRP N/O BV), lower Illinois River Basin, with Spearman Rank Correlation.

oxygen. Oxidizing conditions are prevalent throughout the BRP O/L MBBV, indicating no gradient from oxidizing to reducing conditions in this aquifer. The concentration of U does correlate strongly with that of sulfate ($r_s = 0.52$, $p = 0.0043$) (fig. 9). This correlation is again indicative of the accumulation of U and sulfate with increasing mineralization of the water in oxidizing environments (see previous discussions and Szabo and Zapecza, 1991).

The absence of correlation of the concentrations of U and nickel may be the result of the different distribution of wells in the BRP O/L MBBV relative to the other glacial deposits of the LIRB. The majority of the sampled wells in the BRP O/L MBBV (24 of 29, or 83 percent) were completed in off-moraine lobe deposits as opposed to the BRP N/O BV, where 13 of 28 wells (46 percent) were completed in off-moraine lobe deposits. Glacial deposits from the moraine lobes may contain more sediment from northern (Grenville Province, Canadian Shield) areas that may contain U and nickel. The moraines contain supraglacial deposits with material from the accumulation zone that may have originated from northern areas. The glacial deposits off the moraine lobes may contain a greater proportion of local bedrock debris than on the moraine lobes. The absence of correlation between U and nickel concentrations are believed to reflect the absence of the potential source material for these trace elements, the U- and nickel-rich material from the Canadian Shield.

The concentrations of U also correlated strongly with that of manganese ($r_s = 0.52$, $p = 0.0035$) in the BRP O/L MBBV (fig. 9). Manganese is soluble in reducing environments (Hem, 1985) where U would tend to be insoluble. The aquifer, however, is oxidizing. Reduced forms of manganese may be stabilized in solution by organic carbon in oxidizing water (Hem, 1985). Manganese also can be solubilized in mildly acidic water. Manganese can be stable in solutions with less extreme geochemical conditions (in terms of reduction potential and acidity) than can iron. Thus, possibly, the correlation between U and manganese concentrations does not contradict known geochemical behavior of either U or manganese.

RADON DETECTIONS AND CORRELATIONS

Radon was analyzed in water samples collected from 117 wells completed in four separate aquifers. Of the 117 wells, 22 were sampled by bailing and 95 were sampled by pumping. Of the 22 wells bailed,

all were completed in the BRP N/O BV and the BRP O/L MBBV. Radon concentrations ranged from less than 80 pCi/L to 1,300 pCi/L. The median and mean values were 225 and 304 pCi/L, respectively. At the time of sampling (1996–97), an MCL of 300 pCi/L was proposed by the U.S. Environmental Protection Agency (USEPA) for the drinking-water standard. This proposal was rescinded by the USEPA on July 30, 1997. The current proposed (as of October 1999) standard is 300 pCi/L for an MCL, with an additional Alternative Maximum Contaminant Level (AMCL) of 4,000 pCi/L if there is a developed multimedia mitigation (MMM) program. An MMM program also addresses the Rn risks in indoor air (U.S. Environmental Protection Agency, 1999). Concentrations of greater than 300 pCi/L were detected in 40 samples (34 percent); no samples had concentrations greater than 4,000 pCi/L. One of the most critical inputs to any MMM program is the development of regional maps delineating concentrations in ground water (dePaul and others, 2000). Locations of wells sampled for Rn and ranges of Rn concentrations are shown in figure 10. Radon distribution by aquifer is given in table 6.

Mahomet Buried Bedrock Valley (MBBV)

Radon was detected in all 30 samples from the MBBV. Radon concentrations ranged from 110 to 730 pCi/L. Concentrations of greater than 300 pCi/L were detected in two samples (7 percent); no sample had concentrations greater than 1,000 or 4,000 pCi/L. The median and mean values were 160 and 192 pCi/L, respectively (table 6). Radon did not significantly correlate with any chemical constituent.

Galesburg/Springfield Plain Not Overlying a Buried Bedrock Valley (GSP N/O BV)

Radon was detected in 29 of 30 (97 percent) samples taken from wells in the GSP N/O BV. Radon concentrations ranged from less than 80 to 1,200 pCi/L. Concentrations greater than 300 pCi/L were detected in 16 of 30 (53 percent) samples, one sample had a concentration greater than 1,000 pCi/L, and no sample was greater than 4,000 pCi/L. The median and mean were 340 and 387 pCi/L, respectively (table 6). Again, concentrations of Rn did not significantly correlate with any chemical constituent.

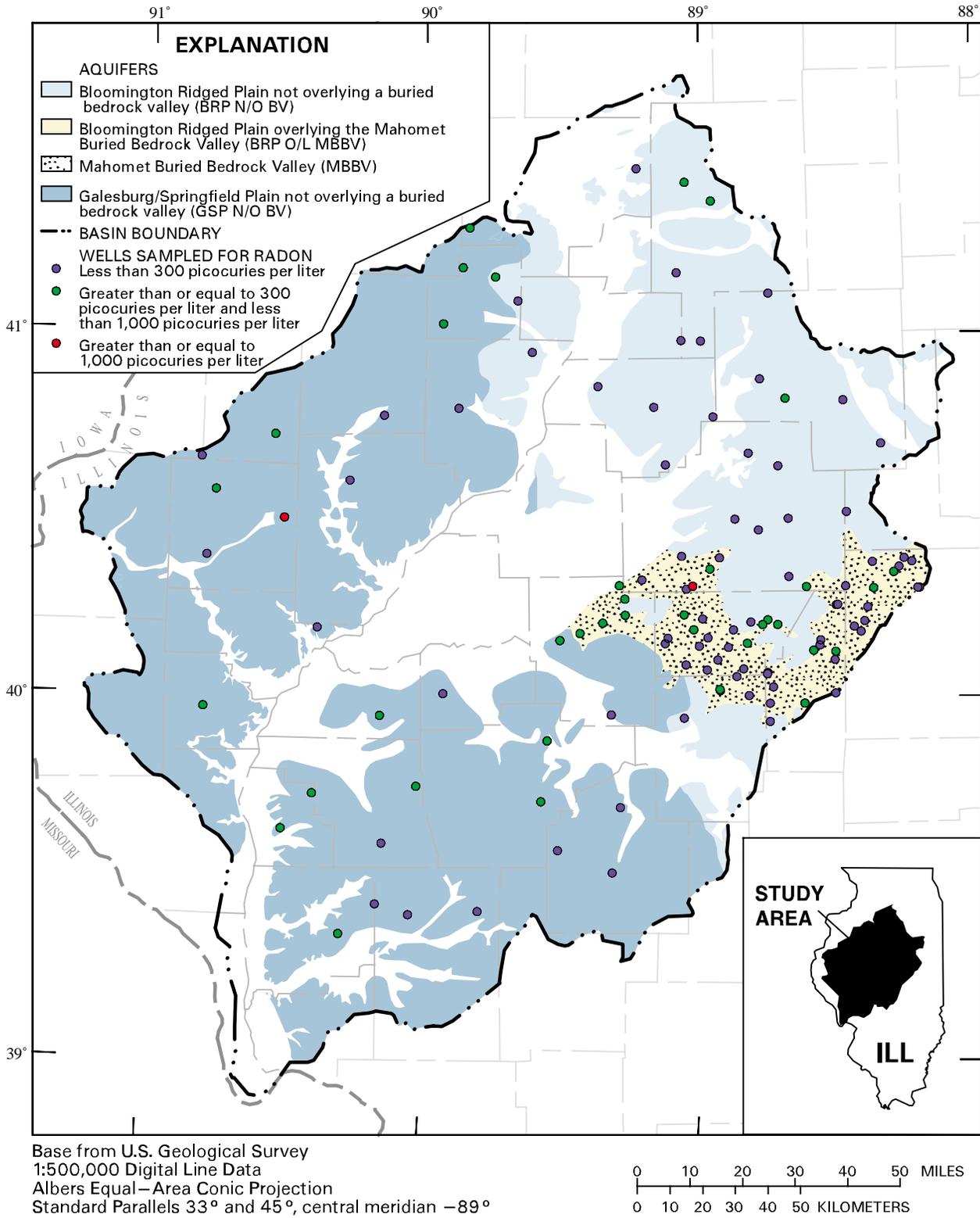


Figure 10. Locations of wells and ranges of radon concentrations in ground water in the lower Illinois River Basin.

Table 6. Radon concentrations, range, mean, and median, by aquifer
[pCi/L, picocuries per liter]

Aquifer	Aquifer abbreviation	Radon concentration range (pCi/L)	Radon concentration median value (pCi/L)	Radon concentration mean value (pCi/L)
Bloomington Ridged Plain not overlying a buried bedrock valley	BRP N/O BV	Less than 80–680	215	251
Bloomington Ridged Plain overlying the Mahomet Buried Bedrock Valley	BRP O/L MBBV	Less than 80–1,300	350	387
Galesburg/Springfield Plain not overlying a buried bedrock valley	GSP N/O BV	Less than 80–1,200	340	387
Mahomet Buried Bedrock Valley	MBBV	110–730	160	192

Bloomington Ridged Plain Not Overlying a Buried Bedrock Valley (BRP N/O BV)

Radon was detected in 25 of 28 (89 percent) samples taken from wells in the BRP N/O BV. Radon concentrations ranged from less than 80 to 680 pCi/L. Concentrations greater than 300 pCi/L were detected in 5 of 28 (18 percent) samples, and no sample was greater than 1,000 or 4,000 pCi/L. The median and mean were 215 and 251 pCi/L, respectively (table 6). Radon concentrations did not correlate significantly with any chemical constituent.

Bloomington Ridged Plain Overlying the Mahomet Buried Bedrock Valley (BRP O/L MBBV)

Radon was detected in 28 of 29 (97 percent) samples taken from wells in the BRP O/L MBBV. Radon concentrations ranged from less than 80 to 1,300 pCi/L. Concentrations greater than 300 pCi/L were detected in 17 of 29 (59 percent) samples, one sample was greater than 1,000 pCi/L, and no sample was greater than 4,000 pCi/L. The median and mean were 350 and 387 pCi/L, respectively (table 6). Radon concentrations did not correlate significantly with any chemical constituent.

It is not surprising that most investigations find no relation between the concentrations of Rn and those of other constituents in water (Szabo and Zapecza, 1991; Brutsaert and others, 1981). Radon is chemically inert. Radon concentration in water is controlled by the solubility of Rn, the amount of U present in the aquifer, and an emanation or transfer factor from sediment to water (Wanty and others, 1992). The geochemical environment does not affect Rn concentrations unless it affects the distribution of the U and radium precursor of the Rn. Possibly,

the Ra-226 precursor of the Rn is mobilized (desorbed) in anoxic (reducing) environments, as documented in northern New Jersey (Szabo and Zapecza, 1991). Sorbed radium at mineral-grain surfaces generally contribute the most Rn to water (Tanner, 1964).

FACTORS AFFECTING URANIUM AND RADON DISTRIBUTION AND CONCENTRATIONS

Type of Glacial Deposit

The data sets of U concentrations from the Wisconsin age BRP N/O BV and BRP O/L MBBV were combined (57 wells) and compared with U concentrations from the 30 wells sampled from the Illinoian age GSP N/O BV. The Mann-Whitney test indicated a statistically significant difference between the two groups ($p = 0.013$). This difference is an indication of different geochemistry of the deposits. The median and mean of the Wisconsin (BRP N/O BV and BRP O/L MBBV) U concentration data sets (1 and 2.2 $\mu\text{g/L}$, respectively) are higher than that of the Illinoian (GSP N/O BV) U concentration data sets (less than 1.0 and 1.4 $\mu\text{g/L}$, respectively). The result is consistent with oxidizing geochemical conditions in the Wisconsin glacial deposits and mixed oxidizing/reducing conditions (40 percent of samples have less than or equal to 0.1 mg/L dissolved oxygen in the GSP N/O BV) in water from the Illinoian glacial deposits.

The combined Wisconsin age BRP Rn concentration data set (median = 240 pCi/L) was compared with the Illinoian age GSP N/O BV Rn concentration data set (median = 340 pCi/L). The Mann-Whitney test ($p = 0.15$) indicated no significant difference at the 95th percent confidence level. If only

the Rn concentration data set from the BRP N/O BV (median = 215 pCi/L) was used in the comparison, the Mann-Whitney test did indicate a statistically significant difference ($p = 0.01$) with the GSP N/O BV (median = 340 pCi/L).

The combined Wisconsinan age BRP Rn concentrations (median = 240 pCi/L) compared with the MBBV Rn concentrations (median = 160 pCi/L) were significantly different ($p = 0.0007$). The BRP O/L MBBV, which directly overlies the MBBV, has a median Rn concentration of 350 pCi/L, which is greater than the median Rn concentration of 160 pCi/L in the MBBV ($p < 0.0001$). The Illinoian age GSP N/O BV deposits also contained Rn concentrations (median = 340 pCi/L) that were significantly greater ($p < 0.0001$) than those from the MBBV deposits (median = 160 pCi/L). These differences likely indicate the highest concentration of U-series radionuclides are in the shallow Wisconsinan and Illinoian sediments. The degree that the highest Rn in the shallowest youngest glacial deposits also is a function of the permeability and porosity of these deposits and high Rn emanation capacity is not clear.

The concentration of U in the water is a poor indicator of the U concentration of the glacial deposits surrounding the well screen because of the great mobility of U in oxidizing environments but immobility in reducing environments. The presence of high concentrations of U in the ground water may indicate the presence of abundant U concentration in the sediment but only under oxidizing conditions. Furthermore, U concentrations may be elevated in mineralized sulfate-rich oxidizing water even if the sediment is not strongly enriched in U. Nevertheless, the presence of high U concentrations in shallow oxidizing water in Wisconsinan deposits indicates the geochemical solubility of U in this environment is likely a major factor in U distribution in the LIRB.

Well Locations

Examination of well locations in relation to glacial moraines indicated that 54 percent of the BRP N/O BV deposits were on a moraine, whereas only 17 percent of the BRP O/L MBBV deposits were on a moraine (fig. 11). Wells were grouped by their location relative to being on a moraine (ON) or off a moraine (OFF), and their relations were evaluated. Well depth means (ON = 30.1 ft, OFF = 22.5 ft) and medians

(ON = 26.5 ft, OFF = 19.0 ft) differed significantly ($p = 0.0066$).

Uranium concentrations from the BRP N/O BV and the BRP O/L MBBV were not significantly different ($p = 0.17$) among water from wells, whether the wells were on or off moraines. Uranium concentrations show a strong correlation with those of nickel ($r_s = 0.72$, $p = 0.0003$) for water from wells on a moraine, whereas for water from wells off a moraine, the correlation ($r_s = 0.36$, $p = 0.0312$) is only moderate. This result indicates that the on-moraine materials deposited as an end moraine may contain U and nickel in more easily soluble forms from a different source than the off-moraine materials.

Radon concentrations in the BRP N/O BV and BRP O/L MBBV were significantly different between the ON/OFF data sets ($p = 0.002$). The median concentrations are ON = 160 pCi/L and OFF = 330 pCi/L. Either the U concentrations, physical properties associated with porosity, Rn emanation, or a combination of these factors are significantly different between the two deposit types.

Slug tests were conducted on 42 of the 57 (74 percent) monitoring wells on and off moraines to estimate the hydraulic conductivity. Wells screened in locations off a moraine (31 wells) had an average hydraulic conductivity of 31 ft/d. Wells screened in locations on a moraine (11 wells) had an average hydraulic conductivity of 3.3 ft/d, approximately an order of magnitude lower than wells screened in locations off a moraine. This result indicates that the physical properties of the deposits are different. For example, poorly sorted but porous deposits could result in physical conditions that may result in lower Rn concentrations than other sediments with similar U concentrations.

Sampling Method

Differences in U and Rn concentrations between pumped and bailed samples were significant. Uranium samples collected by pumping had median and mean values of less than 1 $\mu\text{g/L}$ and 1.6 $\mu\text{g/L}$, respectively, whereas U samples collected by bailing had median and mean values of 1.5 and 3.2 $\mu\text{g/L}$, respectively. The population concentrations differed significantly for U ($p = 0.025$). The wells with lower producing capacity may be completed in clays and silts that have high U content. As long as the water is oxidizing, the U can solubilize.

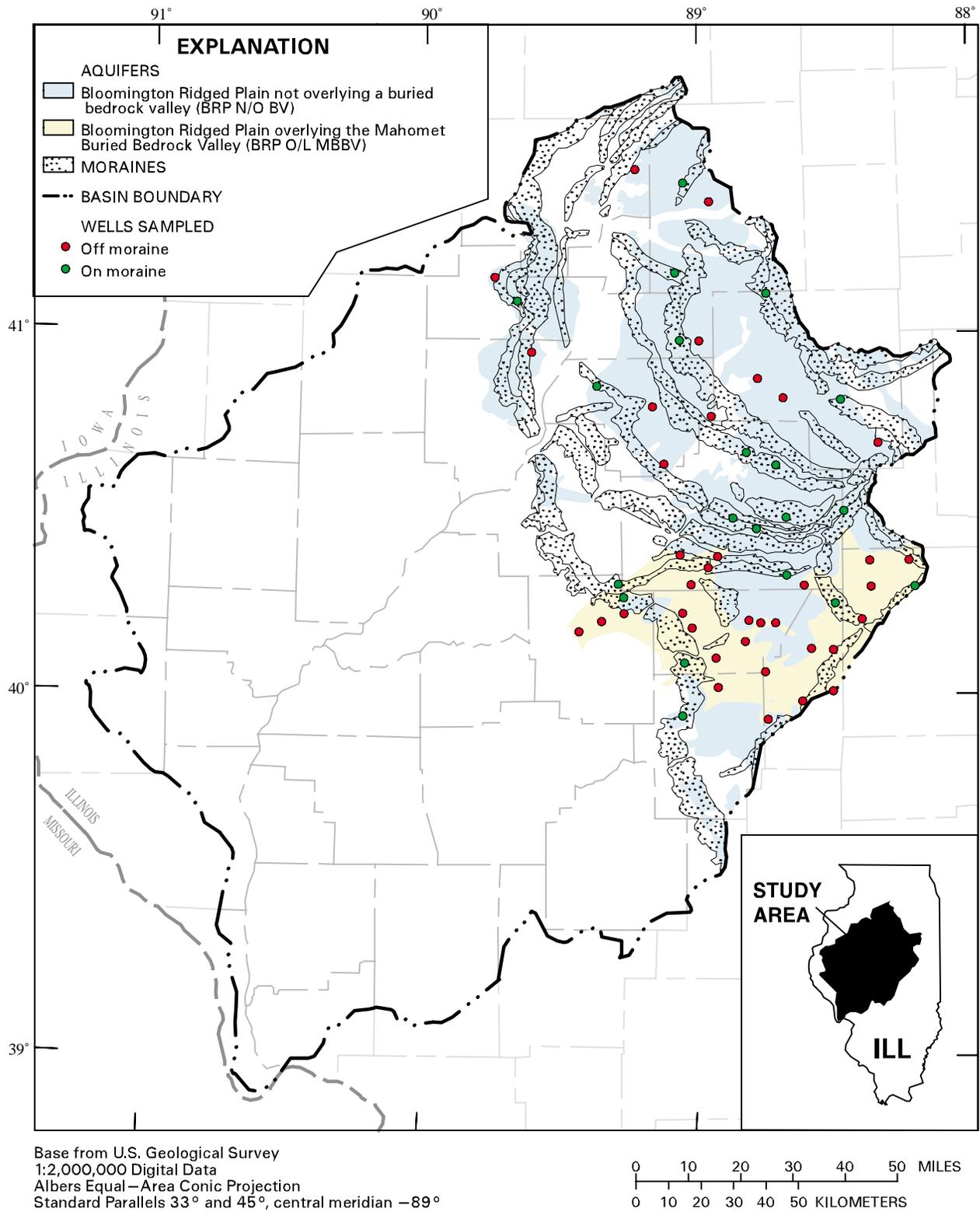


Figure 11. Locations of wells in the lower Illinois River Basin and Wisconsin moraine locations.

Bailed samples can deviate from pumped samples in turbidity but also by altering the sampling zone through introduction of freshly exposed reactive surfaces by precipitation, particle detachment, or disaggregation. Turbid samples generally contain higher concentrations of trace elements than nonturbid samples (Gibs and others, 2000; Puls and Powell, 1992; Puls and others, 1992). The higher U concentrations in bailed as opposed to pumped samples may be an artifact of the bailing process.

Differences for Rn concentrations between pumped and bailed samples ($p = 0.019$) also were significant. Radon samples collected by pumping had median and mean values of 260 and 373 pCi/L, respectively; bailed Rn samples had median and mean values of 195 and 236 pCi/L, respectively. This result may be attributed to multiple causes. Most likely, differences caused by physical Rn loss is from aeration alteration. The low hydraulic conductivity that makes bailing necessary could generally result in increased Rn concentration, all other factors being equal, based on analogy with fractured rock (Rumbaugh, 1983; Folger and others, 1996, Szabo and others, 1997). In porous media, the effect is not so clear cut. Impermeable sediments may be porous as well, a fact that may minimize, not maximize, Rn concentration in the water (Wanty and others, 1992). Because the bailed samples contained the lowest Rn concentrations, Rn concentrations appear to be most affected by the physical processes involved with bailing. Agitation caused by collecting the Rn sample with a bailer increases the potential for Rn degassing. Furthermore, when samples were collected by bailing, recharge rates were insufficient to maintain the water level in the well. After the initial purge, water refilled the borehole during a lengthy interval. Possible cascading of recharging water with the well screen may have allowed degassing of Rn prior to sampling. The wells that can be pumped likely are screened in coarser material than that present in the wells that need to be bailed; differences in physical properties of the sediments may affect Rn emanation and porosity, both of which affect Rn concentration in the water.

Concentrations of U in samples from pumped wells indicated no statistical difference ($p = 0.53$) between the BRP N/O BV and the BRP O/L MBBV. Concentrations of U in samples from bailed wells, however, indicated a significant difference ($p = 0.025$) between the two aquifers. Uranium concentrations from the bailed wells of the BRP N/O BV had a higher

median (4 $\mu\text{g/L}$) and mean (5.3 $\mu\text{g/L}$) U concentration than the U concentrations from the bailed wells of the BRP O/L MBBV median (1 $\mu\text{g/L}$) and mean (1.8 $\mu\text{g/L}$). This result may be an indication of differences in geologic material between the primarily “on-moraine” well locations of the BRP N/O BV and the primarily “off-moraine” well locations of the BRP O/L MBBV. The high U content of water from the lowest producing wells of the BRP N/O BV may indicate that the aquifer material surrounding the boreholes contain more uraniferous clay and silt than the possibly more porous and permeable aquifer material surrounding the boreholes of the more productive wells. Turbid samples contain more trace elements than nonturbid samples from the same well. Finer-grained deposits in the BRP N/O BV may be agitated into colloidal suspension by bailing that can pass through a 0.45- μm filter by bailing the wells, but pumping the wells with the low (approximately 0.1 gal/min) flow rate used may not agitate the samples enough to bring these colloids into suspension (Puls and other, 1992). The pumped wells also may be screened in a coarser aquifer material than in the wells that needed to be bailed. The differences in the physical properties of the sediments may affect Rn emanation and porosity (Wanty and others, 1992), and, thus, the concentration of Rn in these deposits.

The sample population Rn concentration medians for the BRP O/L MBBV collected by pumping (415 pCi/L) and bailing (250 pCi/L) were significantly greater than the BRP N/O BV pumped (230 pCi/L) and bailed (160 pCi/L) Rn concentration population medians. Bailed well water samples did not indicate significant differences in Rn concentration at the 95th percent confidence level ($p = 0.06$) for samples from the BRP N/O BV and BRP O/L MBBV. Radon concentrations obtained by pumping did indicate a significant difference between the two aquifers ($p = 0.02$). If all Rn concentration data, regardless of sampling technique, are combined, a significant difference ($p = 0.01$) is exhibited between the concentrations from the BRP N/O BV and BRP O/L MBBV aquifers. Combining the Rn sample results obtained by pumping and bailing for comparison is based on the assumption that Rn is not affected by colloidal transport, which is true for Rn gas. Combining the Rn sample results also requires the assumption that any resulting changes from degassing that occur are not significantly different among the aquifers. If significant degassing has occurred, bailing has resulted in considerable low bias.

To study the differences in the factors that may affect the Rn concentrations is one way to assess the differences in Rn concentrations between the BRP O/L MBBV and the BRP N/O BV aquifers. Such data could include the U content of the aquifer materials (Sloto and Senior, 1998), areal gamma surveys (Gundersen and others, 1992; Gundersen and Schumann, 1996), gamma ray geophysical logging (Szabo and dePaul, 2000), determining indoor air concentrations (Steck, 1987), sediment mineralogy, and aquifer porosity. Some data may be available already and can be assembled onto regional maps for further evaluation.

Significance of Results

Radon exceeds the MCL of 300 pCi/L in more than one-half of the wells in the Illinoian deposits of the GSP N/O BV and the Wisconsinan deposits of the BRP O/L MBBV. This data indicates that public-supply wells in these deposits will likely be involved in an MMM program to achieve Rn risk reduction. Further investigation and monitoring is needed to better characterize the deposits.

Uranium does not exceed the current MCL of 30 µg/L in any well sample. Some oxidizing sulfate-rich water samples, however, have U concentrations of up to 17 µg/L, which may be of concern for some areas and may warrant further study for future water-supply development.

SUMMARY

The lower Illinois River Basin (LIRB) is one of more than 50 study units throughout the United States where water-quality data are being collected by the U.S. Geological Survey, National Water-Quality Assessment (NAWQA) program to assess water quality at a regional and national level. Uranium (U) and radon (Rn) are found in ground water throughout the United States, and the occurrence and distribution of these radionuclides are of concern because they are carcinogens that can be ingested through drinking water. Radionuclides are of special concern in Illinois because some, such as radium, have been detected at levels above drinking-water standards in Illinois.

Uranium and Rn were sampled in four aquifers defined by physiography and depth in the LIRB in 1996 and 1997. The aquifers were the shallow glacial drift

deposits of the Bloomington Ridged Plain (BRP) not overlying a buried bedrock valley (BRP N/O BV), the shallow glacial drift deposits of the BRP overlying the Mahomet Buried Bedrock Valley (BRP O/L MBBV), the shallow glacial drift deposits of the Galesburg/Springfield Plain not overlying a buried bedrock valley (GSP N/O BV), and the deep glacial drift deposits of the Mahomet Buried Bedrock Valley (MBBV). A total of 117 wells were sampled: 57 monitoring wells installed for the study and 60 previously installed supply wells.

Uranium was detected in all aquifers except the deep glacial drift aquifer in the MBBV. Uranium concentrations for all aquifers ranged from less than 1.0 µg/L to 17 µg/L. Maximum U concentrations did not exceed 30 µg/L, the proposed U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL). The absence of detectable U in water from the deep glacial drift is probably because reducing conditions were present as indicated by dissolved-oxygen concentrations. The presence of Rn indicates that radionuclides are present in the MBBV. Precipitated U may be present in the aquifer material.

Concentrations of U correlated strongly with those of sulfate in oxic environments. Generally, concentrations of U were highest in water where the water is oxidizing and the concentrations of U correlated with those of nickel. The source of these glacial deposits may have been U- and nickel-rich material to the north, such as the Grenville Province of the Canadian Shield.

Bailed well water samples have higher U concentrations than those samples collected by pumping from the same glacial deposit. Concentrations of U may be positively biased for samples collected by bailing from the lowest producing glacial deposits. Bailing tends to result in turbid samples; turbid water has been shown to have higher concentrations of trace elements than nonturbid samples.

Concentrations of Rn ranged from less than 80 to 1,200 pCi/L. Of the 117 samples, 40 (34 percent) exceeded 300 pCi/L, the proposed USEPA MCL, but no sample exceeded the proposed Alternative Maximum Contaminant Level of 4,000 pCi/L. Concentrations of Rn were highest in the water from the Wisconsinan BRP O/L MBBV and Illinoian GSP N/O BV glacial deposits and were lowest in the water from the deposits in the MBBV. This distribution indicates that additional data needs necessary to develop a multimedia mitigation (MMM)

program for Rn likely will center on the Wisconsin and Illinoian glacial deposits.

Concentrations of U and Rn did not significantly correlate. This result is expected because of the different chemical properties and half-lives whereby, U, but not Rn, is available for long-distance transport.

Concentrations of U in water from the BRP N/O BV are highest because of the oxidizing geochemical environment. Concentrations of U in water from the MBBV are low because of the anoxic geochemical environment, but the corresponding low concentrations of Rn in these deposits indicate that these deposits may actually contain low concentrations of U relative to the younger glacial deposits.

The lowest individual Rn concentrations from any sample were in water from wells finished in low-permeability deposits in the BRP N/O BV and the BRP O/L MBBV where samples were bailed. The low concentrations probably were due to physical loss of Rn as a result of degassing because of bailing.

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