

Ground-Water Quality Beneath an Urban Residential and Commercial Area, Montgomery, Alabama, 1999–2000

By James L. Robinson

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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.

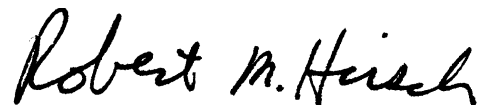
Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water 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, DEFINITIONS, AND ABBREVIATIONS
and ACRONYMS

Multiply	By	To obtain
<i>Length</i>		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
<i>Area</i>		
square mile (mi ²)	2.590	square kilometer
<i>Volume</i>		
gallon (gal)	3.785	liter
<i>Flow rate</i>		
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per day per square mile [(Mgal/d)/mi ²]	1,460	cubic meter per day per square kilometer
<i>Hydraulic conductivity</i>		
foot per day (ft/d)	0.3048	meter per day

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

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

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.

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

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

Additional abbreviations and acronyms used in this report:

CFC	chlorofluorocarbon
CaCO ₃	calcium carbonate
CFC-11	trichlorofluoromethane (CFCl ₃)
CFC-12	dichlorodifluoromethane (CF ₂ Cl ₂)
CFC-113	trichlorotrifluoroethane (C ₂ F ₃ Cl ₃)
CO ₂	carbon dioxide
CO ₃	carbonate ion
DCPA	dacthal
ECD	electron capture detector
<i>E. coli</i>	<i>Escherichia coli</i>
FeS ₂	Iron sulfide
HCO ₃	bicarbonate ion
MCL	U.S. EPA drinking water maximum contaminant level
MTBE	methyl <i>tert</i> butyl ether
m-FC	fecal coliform method
m-TEC	Escherichia coli method
NAWQA	National Water-Quality Assessment
NWQL	National Water Quality Laboratory
<i>p,p'</i> -DDE	dichlorodiphenyldichloroethylene
QA/QC	quality assurance and quality control
RSD	USEPA risk-specific dose health advisory for drinking water
SF ₆	sulfur hexafluoride
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UV	ultraviolet
VOC	volatile organic compound

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ABSTRACT

The Black Warrior River aquifer, which is composed of the Coker, Gordo, and Eutaw Formations, supplies more than 50 percent of the ground water used for public water supply in the Mobile River Basin. The city of Montgomery, Alabama, is partially built upon a recharge area for the Black Warrior River aquifer, and is one of many major population centers that depend on the Black Warrior River aquifer for public water supply. To represent the baseline ground-water quality in the Black Warrior River aquifer, water samples were collected from 30 wells located in a low-density residential or rural setting; 9 wells were completed in the Coker Formation, 9 wells in the Gordo Formation, and 12 wells in the Eutaw Formation. To describe the ground-water quality beneath Montgomery, Alabama, water samples also were collected from 30 wells located in residential and commercial areas of Montgomery, Alabama; 16 wells were completed in the Eutaw Formation, 8 wells in alluvial deposits, and 6 wells in terrace deposits. The alluvial and terrace deposits directly overlie the Eutaw Formation with little or no hydraulic separation. Ground-water samples collected from both the rural and urban wells were analyzed for physical properties, major ions, nutrients, metals, volatile organic compounds, and pesticides. Samples from the urban wells also were analyzed for bacteria, chlorofluorocarbons, dissolved gases, and sulfur hexafluoride. Ground-water quality beneath the urban area was compared to baseline water quality in the Black Warrior River aquifer.

Compared to the rural wells, ground-water samples from urban wells contained greater concentrations or more frequent detections of chloride and nitrate, and the trace metals aluminium, chromium, cobalt, copper, nickel, and zinc. Pesticides and volatile organic compounds were detected more frequently and in greater concentrations in ground-water samples collected from urban wells than in ground-water samples from rural wells.

The Spearman rho test was used to check for statistically significant covariance among urban ground-water quality and land-use type. The number of pesticides and volatile organic compounds detected and concentrations of nickel increased as the percentage of residential land use increased. Greater nickel concentrations also were associated with a greater number of volatile organic compounds detected. As the percentage of commercial land use increased, the numbers of pesticides and volatile organic compounds detected decreased. The number of pesticides detected in the urban ground-water samples increased as concentrations of nitrite plus nitrate increased; the number of pesticides detected and the concentrations of nitrite plus nitrate decreased as the age of the ground water increased. These correlations may indicate that, with time, pesticides and nitrate are removed from the ground-water system by physical, chemical, or biological processes.

The effects of surficial geology on the occurrence of pesticides and volatile organic compounds was investigated by calculating frequencies of detection. The detection frequency for pesticides was greater for urban samples collected from wells where the surficial geology is sand than

for urban samples collected from wells where the surficial geology is clay. The frequency of detection of volatile organic compounds did not show this relation.

INTRODUCTION

Ground water is the source of drinking water for approximately 50 percent of the Nation (U.S. Geological Survey, 1999a). Degradation of ground-water quality as a result of urban land use is a major concern not only because of its use for public water supply, but also because of the potential for ground water to affect surface-water quality, as well as ecological and recreational resources. The U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program was designed to assess the status of, and trends in, the quality of the ground- and surface-water resources in 59 of the Nation's major river basins (also referred to as Study Units); and to link the status and trends with an understanding of the natural and human factors that affect the quality of water (Gilliom and others, 1995).

Ground-water studies performed for the NAWQA Program are classified as (1) major aquifer studies, designed to assess the water quality of major aquifer systems within the study unit; (2) land-use studies, which are intended to assess the quality of recently recharged shallow ground water associated with regionally extensive combinations of land use and hydrogeologic conditions; or (3) flowpath studies, designed to examine specific relations among land-use practices, ground-water flow, contaminant occurrence and transport, and surface- and ground-water interactions (Gilliom and others, 1995). The land-use study described in this report is part of the NAWQA Program investigation of the Mobile River Basin in Alabama, Georgia, Mississippi, and Tennessee (fig. 1).

Purpose and Scope

The objectives of this report are to (1) describe the quality of ground water beneath an urban area in Montgomery, Alabama, and compare it to regional ground-water quality in the same aquifer system; and (2) describe selected environmental factors that may be influencing ground-water quality beneath the urban area. Hydrologic and geologic data collected during the drilling of 30 wells were used to describe the hydrogeology of the shallow aquifer underlying the urban area. Water quality was determined in samples collected from the 30 urban

wells. Ground-water quality in the urban area was compared and contrasted to the water quality of samples collected from 30 wells completed in the same aquifer but located in rural (low-density residential to forested land use) settings in Mississippi and Alabama. All ground-water samples were analyzed for physical properties, major ions, nutrients, metals, volatile organic compounds, and pesticides. Samples from the urban wells also were analyzed for bacteria, chlorofluorocarbons, dissolved gases, and sulfur hexafluoride. Ground-water samples were collected from the rural wells from June through September 1999, and from the urban wells from October 1999 through January 2000. Correlation analysis was used to investigate possible relations between selected environmental factors and ground-water quality.

Previous Investigations

Reports that describe the geology of the study area date back approximately 140 years when Tuomey (1858) included a report on part of the Cretaceous Formations of Alabama in the second biennial report of the Geological Survey of Alabama. Bicker (1969) prepared the current geologic map of Mississippi; Osborne and others (1989) prepared the current geologic map of Alabama; and King and Biekman (1974) prepared a geologic map of the conterminous United States, which was used for this report.

Reports describing the ground-water resources of the study area date back at least to Smith (1907) who published a report on the underground water resources of Alabama. The Layne Central Company (1941) prepared a report for the city of Montgomery describing ground-water conditions in and adjacent to the city as part of an exploratory drilling program to expand the municipal wellfield. Carlston (1942, 1944) authored reports on fluoride in the ground water of the Cretaceous area of Alabama and on the ground-water resources of the Cretaceous area of Alabama. Knowles and others (1960, 1963) published the results of an exhaustive study of the geology and ground-water resources of Montgomery County. Ground-water resources of the Cretaceous aquifers in Mississippi were discussed in Crider and Johnson (1906); Stephenson and others (1928); Boswell (1963, 1977, 1978); Boswell and others (1965); Mallory (1993); and Strom and Mallory (1995). Scott and others (1987) prepared a report describing the geohydrology and susceptibility of major aquifers to surface contamination. Reports prepared by CH2M Hill, Inc. (1997a,b), describe the hydrogeology of the Cretaceous aquifers in the vicinity of Montgomery. The nomenclature documented

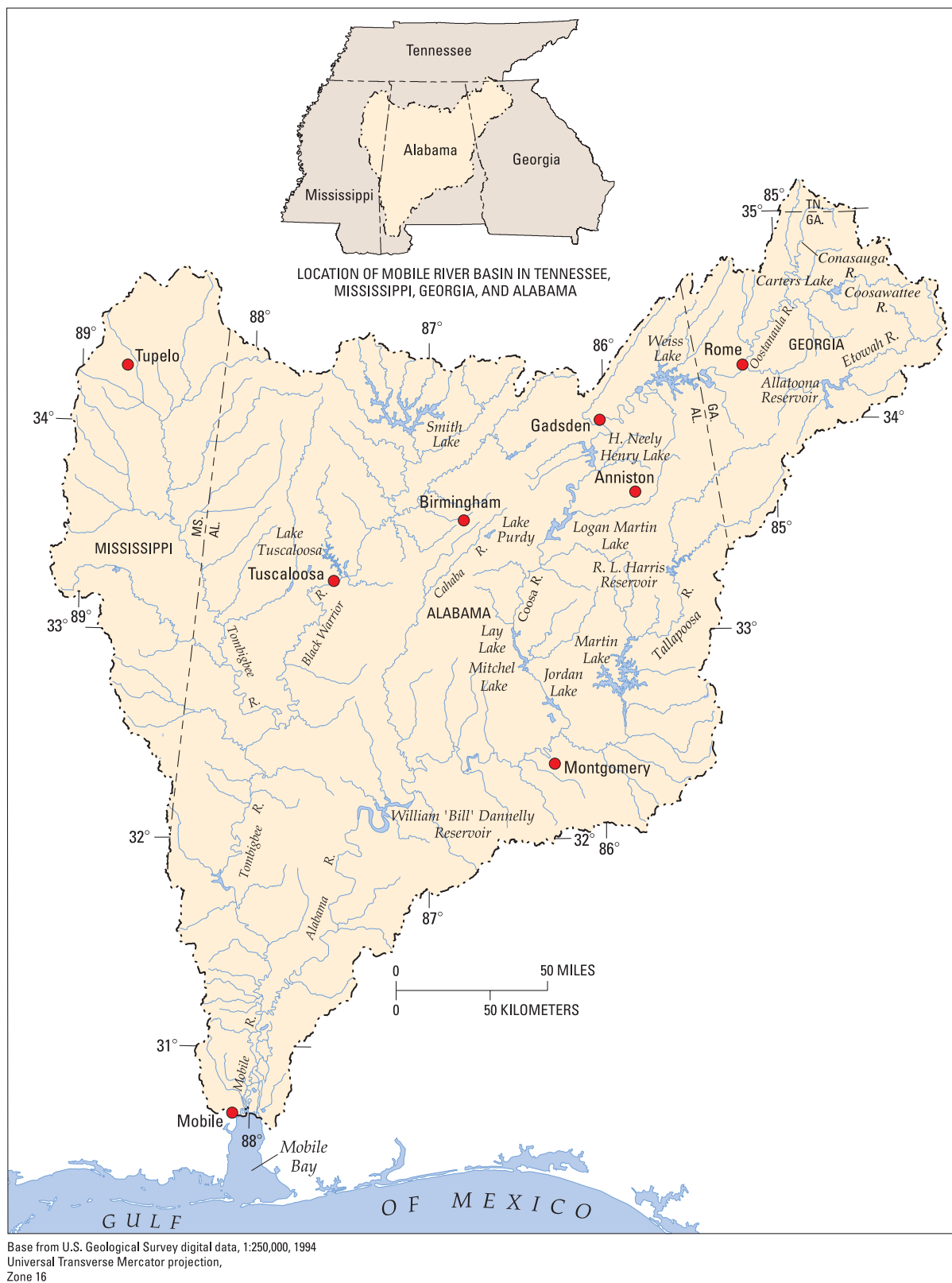


Figure 1. Locations of major rivers and cities in the Mobile River Basin.

by Miller (1990) and Renken (1998) for the ground-water systems in the Mobile River Basin Study Unit is used herein.

Acknowledgments

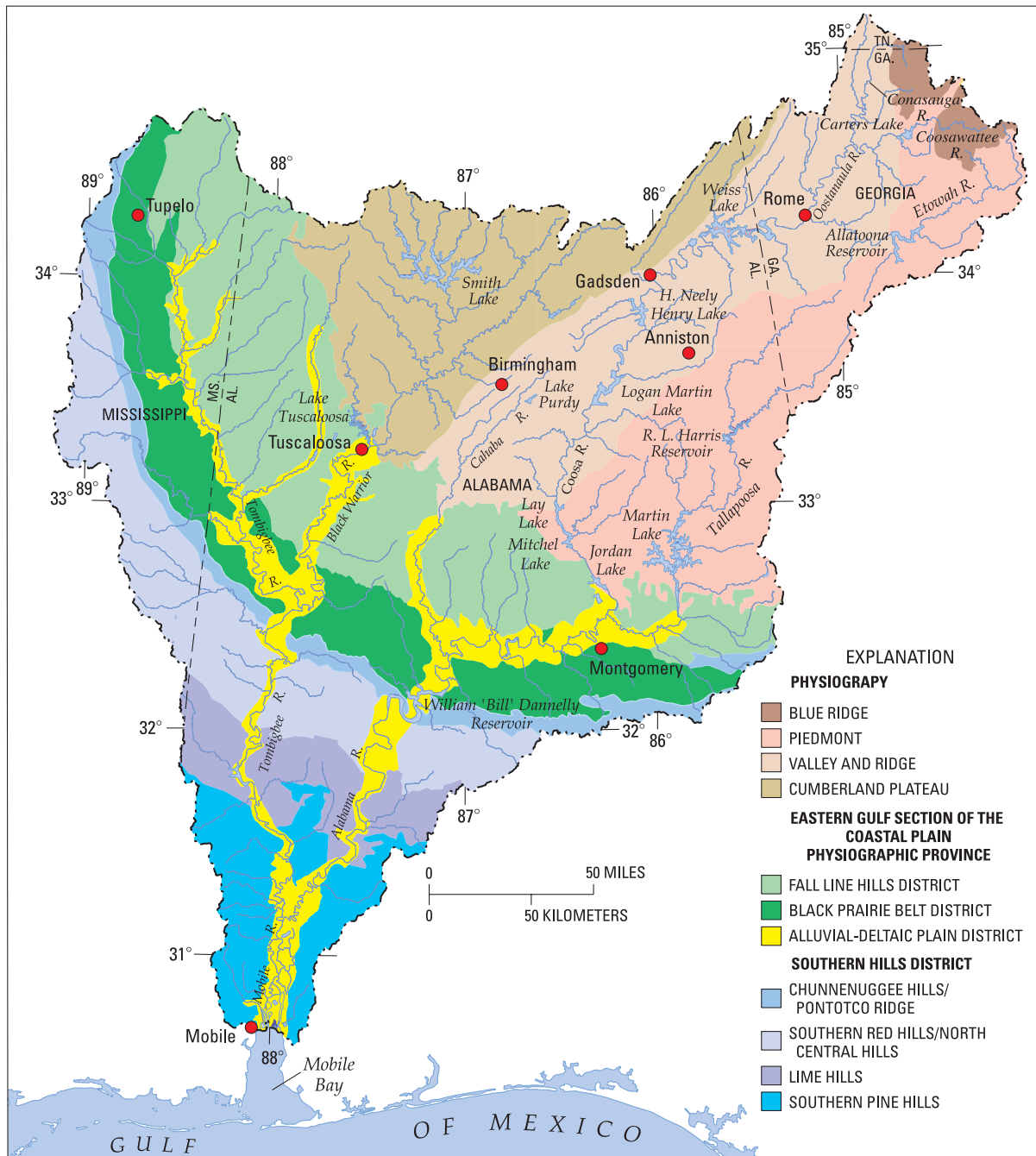
The author is grateful for the cooperation and assistance provided by the Montgomery Water Works and Sanitary Sewer Board and the City of Montgomery Engineering Department. The following organizations were helpful by allowing access to their properties for data collection: the State of Alabama, the Alabama Baptist State Convention, Alabama Christian Academy, Aldersgate Methodist Church, the First Assembly of God, Auburn University of Montgomery, Landmark Church of Christ, Montgomery County School Board, Trinity Presbyterian School, Vaughn Park Church of Christ, and YMCA of Montgomery. Finally, gratitude is expressed to the many private citizens of Alabama and Mississippi who allowed access to their wells and properties for data collection.

ENVIRONMENTAL SETTING

The Mobile River Basin includes about 44,000 square miles (mi²) in Alabama, Georgia, Mississippi, and Tennessee (fig. 1). The major surface-

water systems are the Cahaba, Coosa, and Tallapoosa, which are tributary to the Alabama River; and the Black Warrior River, which is tributary to the Tombigbee River (fig. 1). The Alabama and Tombigbee Rivers join to form the Mobile River in the southern part of the basin (fig. 1). The Mobile River Basin Study Unit has diverse physiography (fig. 2) and geology (fig. 3). The study area is located in the Fall Line Hills, Alluvial-Deltaic Plain, and Black Prairie Belt physiographic districts (fig. 2). The geology of the study area is primarily unconsolidated clastic sediments, limestone, and chalk that dip to the southwest toward the coast and form gently curved, east-west trending bands through Alabama and Mississippi.

Ground water is an important resource in the Mobile River Basin. Total ground-water use in 1995 was estimated to be about 328 million gallons per day (Mgal/d; table 1) by Strom and Mallory (1995), Fanning (1997), and Mooty and Richardson (1998). This accounted for about 24 percent of the total water use in the basin. Ground-water withdrawals are concentrated in the Black Warrior River aquifer (166 Mgal/d), which is composed of clastic sediments of Cretaceous age, and in the Valley and Ridge aquifers (83 Mgal/d), which are solution-conduit aquifers developed in carbonate rocks of Devonian through Cambrian age (fig. 3). Fifty-one percent of the ground water used for public water supply in the Mobile River Basin is withdrawn from the Black Warrior River aquifer.



Base from U.S. Geological Survey digital data, 1:2,000,000, digital data, 1972
 Modified from Stephenson and Monroe, 1940; Sapp and Emplainscourt, 1975;
 and O'Hara, 1996

Figure 2. Physiographic units of the Mobile River Basin (modified from Sapp and Emplainscourt, 1975).



Figure 3. Generalized geology of the Mobile River Basin.

Table 1. Ground-water resources of the Mobile River Basin

[Modified from Miller (1990) and Renken (1998); Mgal/d, million gallons per day]

Physiographic district (fig. 2)	Regional aquifer subunit	Primary geology (fig. 3)	Total population served (1995), in thousands	Total withdrawals (1995), in Mgal/d
Fall Line Hills	Black Warrior River aquifer	Cretaceous clastic sediments	885	166
Valley and Ridge	Valley and Ridge aquifers	Devonian through Cambrian carbonate rocks	429	83
Southern Hills	Pearl River, Chickasawhay River, surficial aquifers	Oligocene, Eocene, and Paleocene clastic sediments and carbonate rocks	179	41
Blue Ridge and Piedmont	Piedmont and Blue Ridge aquifers	Igneous and metamorphic rocks of various and uncertain age	192	21
Cumberland Plateau	Appalachian Plateaus aquifers	Pennsylvanian and Mississippian sandstone and carbonate rocks	130	17

Description of the Study Area

The rural wells sampled for this study (fig. 4) are randomly distributed following the outcrop of the Cretaceous clastic sediments that comprise the Black Warrior River aquifer (fig. 3). The urban wells sampled for this study are located in eastern Montgomery, Alabama (fig. 5). The population of the Montgomery metropolitan area in 1998 was approximately 321,000 (U.S. Census Bureau, 2000). Land use in eastern Montgomery is primarily a mixture of high- to low-density residential, commercial, light industry, and forested areas.

Hydrogeology of the Shallow Aquifer

The city of Montgomery is underlain, north to south, by alluvial and terrace deposits of gravel, sand, and clay; sands and clays of the Eutaw Formation, which is the uppermost unit of the Black Warrior River aquifer; and by clay and clayey soils developed from the Mooreville Chalk (fig. 6). The alluvial and terrace deposits range from about 30 to more than 100 feet (ft) thick, and form a shallow aquifer (fig. 7) that overlies the Eutaw Formation with little or no hydraulic separation in the northern part of the urban study area (Scott and others, 1987). In Montgomery County, the Eutaw Formation ranges from approximately 250 to 400 ft thick, and dips 30 to 40 ft per mile (fig. 6) to the south, southeast, and

southwest (Knowles and others, 1960, 1963; Scott and others, 1987). The Mooreville Chalk, part of the Selma confining unit, is the surficial geologic unit in the southern third of the urban study area (figs. 5 and 6).

Rainfall in Montgomery County averages 55.4 inches (in.) annually (National Oceanic and Atmospheric Administration, 1995). There is a distinct seasonality to the distribution of rainfall, with the months of December through March having the highest rainfall (about 5–6 in. per month) and the months of August through October having the least (about 2–4 in. per month). Surface-water runoff in the city of Montgomery drains to the Alabama and Tallapoosa Rivers. North of the Selma confining unit (figs. 5 and 6), recharge to the Black Warrior River aquifer can occur directly from precipitation because the uppermost unit, the Eutaw Formation, is exposed at land surface or is overlain by permeable sand and gravel with no intervening unit of low permeability (Hinkle and others, 1983; Scott and others, 1987). In the southern part of the study area, the Selma confining unit prevents direct recharge to the Black Warrior River aquifer. Ground water flows north away from the recharge area and toward the Tallapoosa River, west toward the Alabama River, and along dip to the south and southeast.

The Black Warrior River aquifer is heavily used for public and private water supply in Montgomery County. The Montgomery Water Works and Sanitary Sewer Board operates two well fields in the vicinity of Montgomery, Alabama, which utilize the Black Warrior River aquifer.

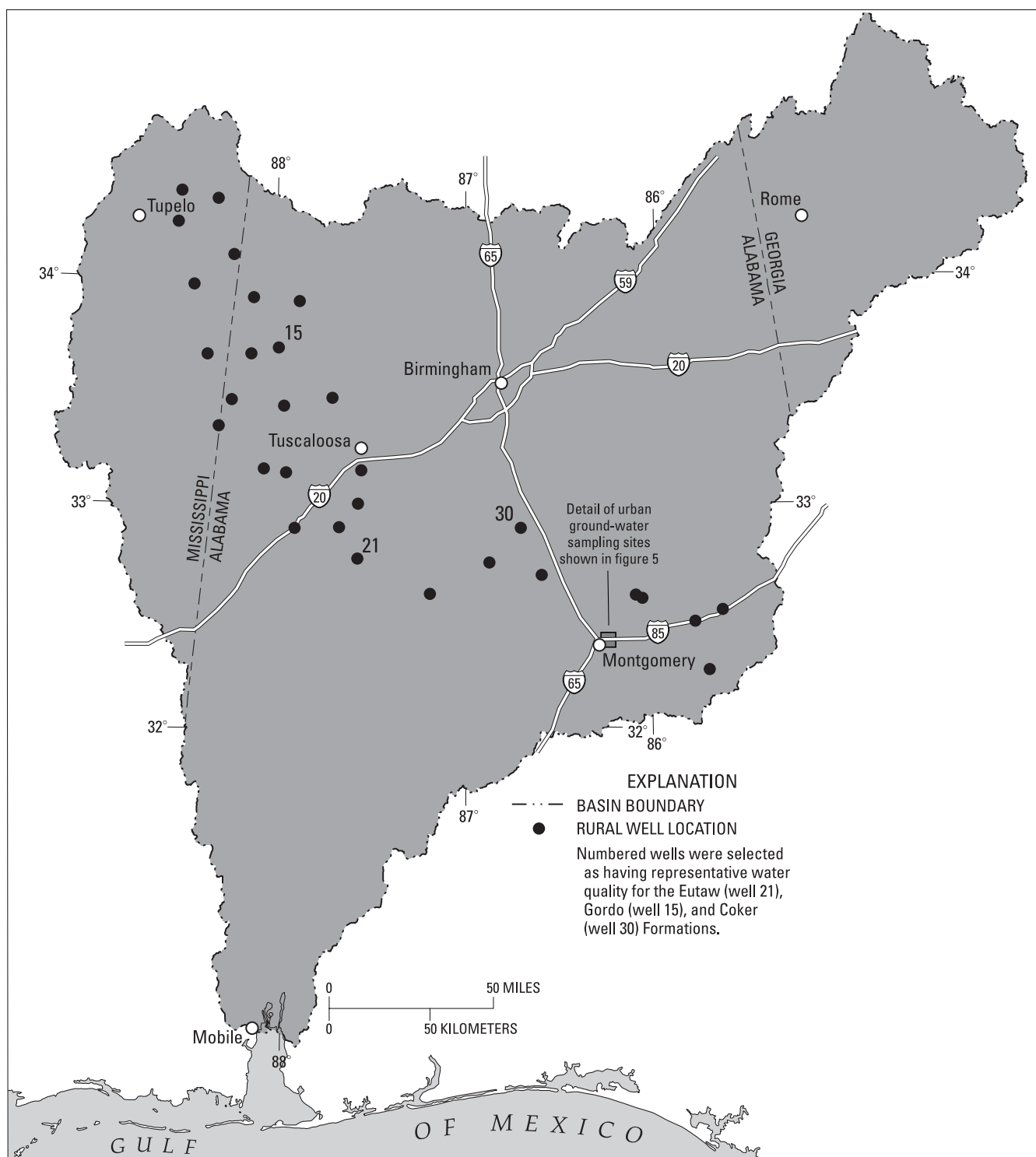


Figure 4. Locations of wells sampled in the Mobile River Basin for this study.

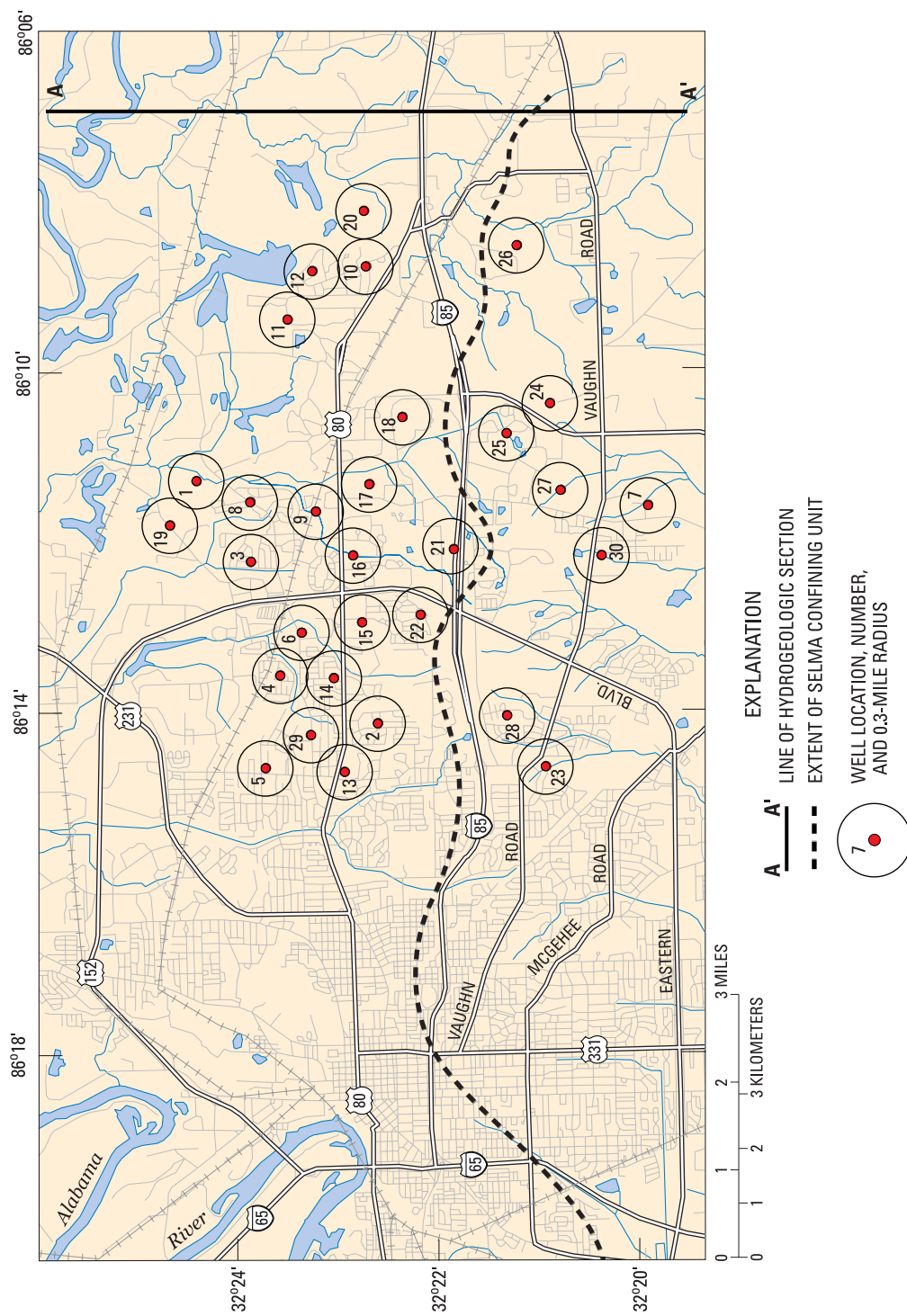


Figure 5. Location of urban wells sampled for the land-use study, line of section A–A', and the northern extent of the Selma confining unit, Montgomery, Alabama.

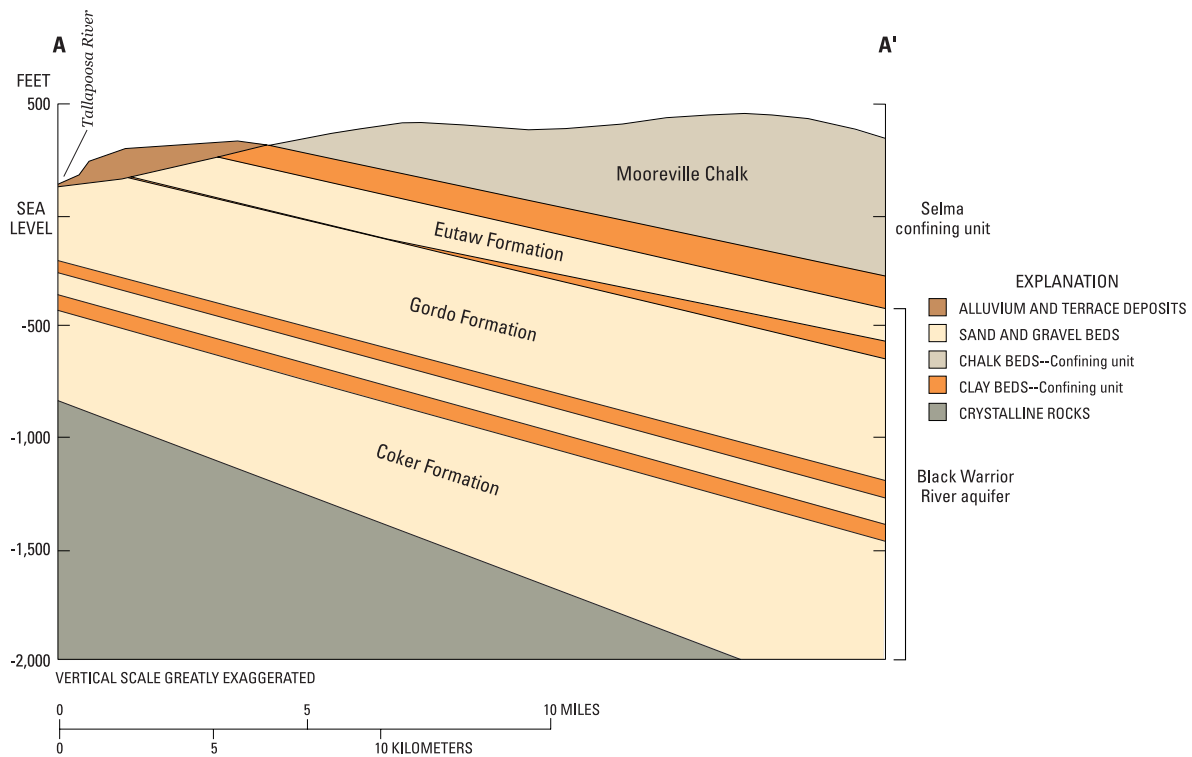


Figure 6. Hydrogeologic section showing stratigraphic units underlying the urban land-use study area, Montgomery, Alabama (modified from Scott and others, 1987).

System	Stratigraphic unit		Major lithology	Thickness (feet)	Hydrogeologic unit	Regional aquifer system
Quaternary	Alluvial and terrace deposits		Sand, gravel, silt, and clay	30–100 +	Shallow aquifer	Southeastern Coastal Plain aquifer system
Cretaceous	Selma Group	Mooreville Chalk	Chalk and limestone	0–500 +	Selma confining unit	
	Eutaw Formation		Upper and lower marine sand separated by clay; consists of glauconitic sand interbedded with calcareous sandstone and sandy limestone	0–400 +	Black Warrior River aquifer	
	Tuscaloosa Group	Gordo Formation	Basal zone of gravel and sand overlain by lenticular beds of sand and clay	300 +		
		Coker Formation	Basal zone of non-marine sand, gravel, and clay; upper zone of marine sand and clay	500 +		
Pre-Cretaceous			Schist, gneiss	1,000 +	Base of fresh-water flow system	

Figure 7. Generalized section of stratigraphic and hydrogeologic units underlying Montgomery, Alabama [from Knowles and others (1963), Scott and others (1987), Miller (1990)].

The Black Warrior River aquifer is also used by many other public water-supply systems (fig. 8) and domestic wells in Montgomery County. Total ground-water use in Montgomery County in 1995 was 34.8 Mgal/d (Mooty and Richardson, 1998).

STUDY DESIGN AND METHODS

The urban land-use study was designed by using NAWQA guidelines (Gilliom and others, 1995; Squillace and Price, 1996). NAWQA ground-water protocols (Lapham and others, 1997; Koterba, 1998) were followed during data collection. Standardization of data-collection procedures is intended to produce a nationally consistent database that can be used to produce statistically valid interpretations. Modification of national protocols is sometimes necessary because of local conditions. The following sections describe how the national protocols were applied and, when necessary, modified for the urban land-use study.

Land-Use Selection

The criteria used to select urban land-use study areas are outlined in Squillace and Price (1996). Of primary concern are the criteria specifying that the shallow aquifer in the study area be used as a source of drinking water, a potential source of drinking water, or hydraulically connected to surface water or deeper ground water that is used as a source of drinking water; and that land use within the study area be residential and commercial developed between 1970 and the 1990's. The urban land-use study area in eastern Montgomery meets these criteria; however, the last criterion was modified to extend the period of residential development in the study area from 1960 to 1998.

Well Network

Ground-water samples were collected from 30 wells in rural areas and 30 wells in an urban area of the Mobile River Basin. The rural wells were sampled to

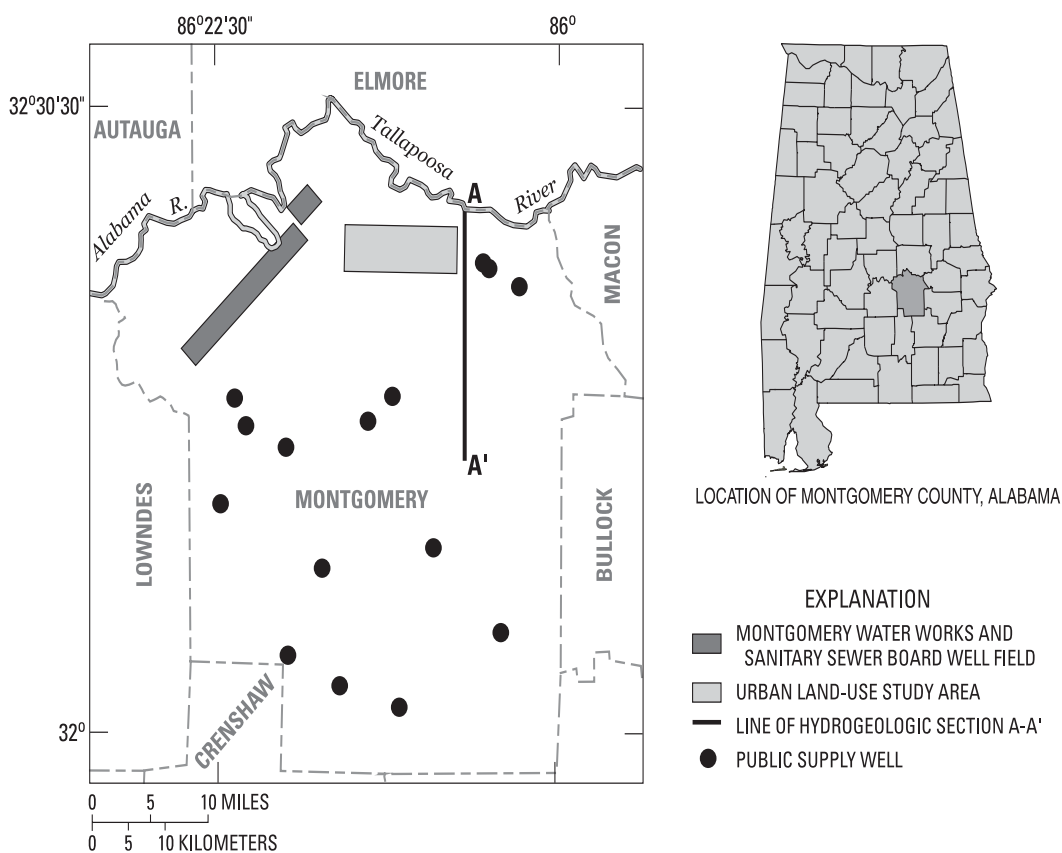


Figure 8. Locations of public water-supply wells, urban land-use study area, and line of section A–A', Montgomery County, Alabama

provide a regional assessment of baseline water-quality conditions in the Black Warrior River aquifer (Gilliom and others, 1995). The rural wells were selected from existing domestic or stock wells, and are randomly distributed throughout the Fall Line Hills and Black Prairie Belt physiographic districts (figs. 2 and 4). Nine rural wells are completed in the Coker Formation, 9 are completed in the Gordo Formation, and 12 wells are finished in the Eutaw Formation.

The urban wells were designed to sample shallow ground water beneath a specific land-use type (Squillace and Price, 1996). The wells are located in eastern Montgomery, Alabama, in recharge areas or directly downgradient of recharge areas for the Black Warrior River aquifer. The urban wells are completed in the Eutaw Formation (16 wells), the alluvial deposits (8 wells), and the terrace deposits (6 wells; figs. 5 and 6).

The part of a well through which water is withdrawn from the ground is referred to as the “open” interval because it is open to the transmission of water. Screened wells have sections of pipe with thin slots cut in them through which water may flow into the well. In open-hole well construction, no pipe or screen is placed in the part of borehole through the aquifer, and a pipe or “surface casing” is installed in the borehole above the open-hole section. Water enters the well directly through the borehole. The depth-to-open interval of a well is the depth to the top of the screens or the open borehole. The importance of this measurement relates to the susceptibility of a well to contamination. The less the depth-to-open interval, the greater the susceptibility of the well to contamination from sources at land surface. The depth-to-open interval of the rural wells ranged from about 60 to 405 ft, with a median depth of 121 ft (fig. 9). The depth-to-open interval of the urban wells ranged from about 8 to 88 ft, with a median depth of 29 ft (fig. 9).

The urban wells were randomly distributed throughout the urban land-use study area to avoid biasing the data (fig. 5). NAWQA guidelines (Squillace and Price, 1996) specify that land use within a 0.3-mile radius of the wells must be at least 75 percent residential and commercial and stable for approximately 5 years. Well locations are at least 0.6 mile from heavy industry or any known source of ground-water contamination. Although it is desirable that well locations be no closer than 0.6 mile to each other, two pairs of wells were located at a spacing slightly less than 0.6 mile. This was necessary to meet all other NAWQA requirements for urban land-use studies.

The 30 urban wells (fig. 5) were installed by the USGS in accordance with national NAWQA protocols (Lapham and others, 1997). A hollow-stem auger rig was used to drill 6-in.-diameter boreholes. The wells were

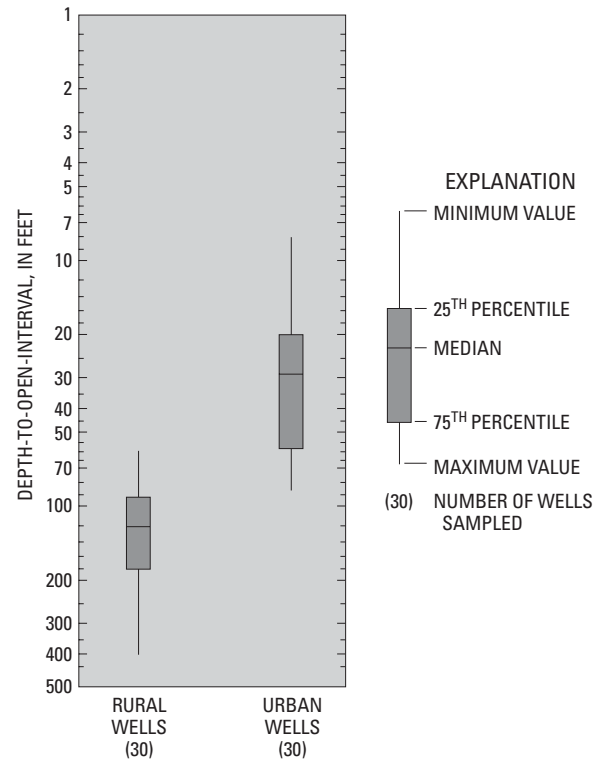


Figure 9. Range and distribution of depth-to-open interval of rural wells in the Mobile River Basin and urban wells in Montgomery, Alabama, sampled for this study.

constructed within the hollow-stem augers using threaded, 2-in.-diameter polyvinyl-chloride casing having 10-ft-long, 0.010-in. slotted screens. A sand pack of washed 10/30 silica sand was placed around the screens where possible. The aquifer material flowed into the hollow-stem auger at some drill sites, making it impossible to place a sand pack around the well screens. The 10/30 sand pack was placed to a depth of about 5 ft above the well screens. Bentonite was used to form a seal in the annulus around the well casing, and a cement grout and steel protective wellhead was installed to form a surface seal. All equipment used to drill the monitoring wells was decontaminated prior to the drilling of each well by scouring with a high pressure steam cleaner. Well casings and screens were cleaned with the high pressure steam cleaner and then rinsed with deionized water.

Sediment samples were collected from every major lithologic unit drilled during well installation, and geologist’s logs of the samples were prepared. When possible, sediment cores were collected from each lithologic unit present. Representative samples of each lithology cored were chilled and sent to the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, for organic carbon analyses. The methods

specified by Squillace and Price (1996) were used to determine soil pH values for sediment core samples. Representative sediment cores were taken to a geotechnical laboratory for grain-size and in situ sediment core analyses to determine the porosity and permeability of the material.

Land-Use Classification

The type of land use within a 0.3-mile radius of each well (table 2) was determined by using aerial photography and field reconnaissance. The contributing area for a well is unlikely to be defined by the 0.3-mile

Table 2. Percentages of predominant land-use types within a 0.3-mile radius around the urban wells in Montgomery, Alabama

[Site identification number is latitude-longitude-well sequence number]

Map reference number (fig. 5)	Site identification number	Residential, churches, schools, and developed parks	Commercial and light industry	Undeveloped parks and forests	Other
1	32242108611170	57		22	21
2	32223308614080	87	3	9	1
3	32235008612150	60	30	10	0
4	32233208613340	96			4
5	32234308614390	94		2	4
6	32232008613030	79	12	5	4
7	32195108611360	46		11	43
8	32234908611320	69		30	1
9	32230708611420	71	20	6	3
10	32223908608450	87		2	11
11	32232608609240	76		15	9
12	32231108608500	77			23
13	32225308614440	63	27		10
14	32230208614420	74	19		7
15	32224208612570	70	28		2
16	32224708612110	41	58		1
17	32223708611210	80	8	11	1
18	32221708610310	51	5	43	1
19	32243708611480	47		36	17
20	32224008608080	87			13
21	32214808612060	47	31		22
22	32221008612520	46	16	25	13
23	32205408614380	94			6
24	32205508610300	51	19		30
25	32211508610450	82		13	5
26	32210908608330	61	2	32	5
27	32204108611280	85	4		11
28	32204108611280	71	19		10
29	32211608614060	98	1		1
30	32231508614150	89			11

radius around the well; however, the land use within that area should have some effect on the ground-water quality (Squillace and Price, 1996). The land-use data were compared to ground-water-quality data to determine relations between land-use type and ground-water quality.

Water-Quality Samples

Ground-water samples collected during the urban land-use study were analyzed for major ions, nutrients, trace metals, pesticides, volatile organic compounds (VOCs), bacteria, chlorofluorocarbons (CFCs), dissolved gases, and sulfur hexafluoride (SF₆). The constituents tested for and the laboratory analytical methods used are listed in table 3.

Sampling procedures were consistent with NAWQA ground-water sampling protocols (Koterba and others, 1995; U.S. Geological Survey, 1999c). All ground-water samples analyzed for organic compounds were collected by using sampling equipment constructed of stainless steel and Teflon. Before sampling began, at least three well volumes of water were purged, and field measurements of specific conductance, pH, water temperature, dissolved oxygen, and turbidity were stable within 10 percent for 15 minutes. Bacteriological samples were analyzed in the USGS Alabama District laboratory in Montgomery. Samples to be analyzed for CFCs, SF₆,

and dissolved gases were hand delivered to the CFC laboratory in Reston, Virginia. All other ground-water samples were chilled and shipped overnight to the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado.

The USGS NWQL reports analysis values for constituent concentrations as measured or estimated (censored). These terms indicate the confidence the NWQL places in the accuracy of the measurement. Estimated values are reported for concentrations less than the reporting level but above the long-term method detection level (Childress and others, 1999) or for concentrations greater than the calibrated range of the apparatus. Measured values are reported for concentrations above the reporting level and within the calibration range of the apparatus.

Quality-Assurance and Quality-Control Procedures

Three types of quality-assurance and quality-control (QA/QC) samples (table 4) were collected during sampling of the urban land-use study monitoring wells—blanks, spikes, and replicates. Seven field blanks, three source-water blanks, and one trip blank were collected. Three field spikes and three field-spike

Table 3. Constituents analyzed and analytical methods used in ground-water-quality samples collected during the urban land-use study in Montgomery, Alabama

[UV, ultra-violet; C-18, octadecyl; *E. coli*, *Escherichia coli*; m-TEC, two-step membrane-filtration method for *E. coli*; m-FC, one-step membrane-filtration method for fecal coliform; CFC, chlorofluorocarbons; ECD, electron capture detector; SF₆, sulfur hexafluoride]

Constituent	Analysis method	Reference
Major ions	Atomic absorption spectrometry	Fishman (1993)
Nutrients	Various methods	Fishman (1993)
Organic carbon	UV-promoted persulfate oxidation and infrared spectrometry	Brenton and Arnett (1993)
Trace metals	Atomic absorption spectrometry	Fishman (1993)
Pesticides	Solid-phase extraction using a C-18 cartridge and gas chromatography/mass spectrometry	Zaugg and others (1995)
Volatile organic compounds	gas chromatography/mass spectrometry	Connor and others (1998)
<i>E. coli</i>	m-TEC	Myers and Sylvester (1997)
Fecal coliform	m-FC	Myers and Sylvester (1997)
CFC	gas chromatography with ECD detector	Busenberg and Plummer (1992)
SF ₆	gas chromatography with ECD detector	Busenberg and Plummer (2000)

Table 4. Summary of quality-assurance and quality-control samples collected during the urban land-use study in Montgomery, Alabama

[TM, trace metals; I, major ions; N, nutrients; V, volatile organic compounds; P, pesticides; OC, organic carbon; A, alkalinity]

Map reference number (fig. 5)	Quality-control sample type	Date sampled	Analytical coverage
Inorganic blank			
6	Field blank	12/13/1999	TM, I, N
7	Field blank	12/28/1999	TM, I, N
12	Field blank	11/17/1999	TM, I, N
17	Field blank	10/27/1999	TM, I, N
Organic blank			
15	Source-water blank	12/07/1999	V
15	Field blank	12/07/1999	P, V, OC
16	Field blank	11/08/1999	P, V, OC
16	Source-water blank	11/08/1999	V
19	Trip blank	01/05/2000	V
19	Source-water blank	01/05/2000	V
19	Field blank	01/05/2000	P, V, OC
Spike			
9	Field spike	12/02/1999	V
20	Field spike	01/04/2000	P
28	Field spike	11/22/1999	P
Replicate			
1	Environmental	11/15/1999	P, V, OC, TM, I, N, A
3	Environmental	12/06/1999	P, V, OC, TM, I, N, A
9	Field spike	12/02/1999	V
27	Environmental	12/01/1999	P, V, OC, TM, I, N, A
20	Field spike	01/04/2000	P
20	Pesticide	01/04/2000	P
28	Pesticide	11/22/1999	P
28	Field spike	11/22/1999	P
29	Environmental	01/06/2000	P, V, OC, TM, I, N, A

replicates were collected in addition to four environmental replicate samples.

A blank is a water sample that has no analytes of interest. A blank sample is analyzed to determine if contamination of the environmental sample has occurred during (1) sample collection and processing, (2) sample handling and transportation, and (or) (3) sample analysis

(Mueller and others, 1997). Field blanks are used to test for all three of the sources of contamination listed above; equipment blanks are used to test for contamination sources 1 and 2 only. Source-water blanks are collected to determine if the sample-processing equipment is a source of contamination. A trip blank is prepared in the laboratory, taken to the field, and shipped with the environmental sample to test for contamination sources 2 and 3 only. Spiked samples are environmental samples that are injected with a known mass of the analyte of interest for use in determining the accuracy and precision of organic analyses, the stability of analytes during typical holding times, and whether characteristics of the environmental sample may interfere with the analysis for analytes (Mueller and others, 1997). Replicates are two or more samples that are split or are collected in sequence or concurrently. They are considered to have identical composition. Replicates provide a measure of the variability resulting from sample collection, processing, and analysis (Mueller and others, 1997).

Interpretation of the data provided by the field blanks collected during the urban land-use study indicated no systematic bias or source of contamination attributable to the sampling equipment or procedures used to collect the ground-water samples. No detections were noted in the organic blank samples. Chromium, copper, and zinc were detected in two inorganic blank samples. With the exception of one copper detection, concentrations of these trace metals in the inorganic blank samples were less than 10 percent of the chromium, copper, and zinc concentrations in the environmental sample collected the same day as the blank. Detections of copper are attributed to the copper tubing used to collect the CFC samples. Blank samples were collected from a glass cylinder in a procedure that exposed the inorganic blank water sample to the copper tubing. Environmental samples, however, did not come in contact with the copper tubing because they were collected directly from the well by using Teflon tubing. Detections of chromium and zinc in the inorganic blank samples are attributed to the stainless steel sample pump and line fittings.

Samples from three wells were spiked—one with VOCs and two with pesticides. Three field-spike replicates also were collected. Mean recovery of VOCs from the field spike and the field-spike replicate was 78 and 71 percent, respectively (table 5). The mean difference in recovery between the field spike and the field-spike replicate was 14 percent. Analyses of the field spikes indicated that the results of analyses for VOCs in the urban samples may be conservative. Mean recovery of pesticides from the field spikes and the field-spike replicates ranged from 89 to 107 percent (table 5). The

Table 5. Descriptive statistics for quality-assurance and quality-control field spikes
[V, volatile organic compounds; P, pesticides]

Map reference number (fig. 5)	Sample type	Date sampled	Analytical coverage	Mean recovery (percent)	Mean difference in recovery (percent)
9	Field spike	12/02/1999	V	78	
9	Field-spike replicate	12/02/1999	V	71	14
20	Field spike	01/04/2000	P	104	
20	Field-spike replicate	01/04/2000	P	107	5
28	Field spike	11/22/1999	P	89	
28	Field-spike replicate	11/22/1999	P	91	3

mean difference in recovery between the field spikes and the field-spike replicates was 5 and 3 percent.

Four environmental replicate samples were collected. The variance between the environmental samples and the corresponding replicate samples typically was less than 7 percent. One set of environmental and replicate samples had variances of 14 percent for manganese, 12 percent for organic carbon, and 19 percent for cobalt. Increased concentrations of copper in two replicate samples and nickel in one replicate sample are attributed to increased time of exposure of the sample water to the metal of the sample pump and fittings of the sample line. Interpretation of the data provided by the blanks, spiked samples, and replicate samples indicated no systematic bias in the sample analyses; therefore, none of the environmental data were adjusted based on interpretation of the results of the QA/QC samples.

Graphical and Statistical Methods

Three common graphical techniques were used to present and analyze results of water-quality sampling from the urban land-use study—the Piper (1944) trilinear diagram, boxplots (Tukey, 1977), and the Stiff (1951) diagram. The Piper (1944) diagram is used to graphically present water-quality data based on cation and anion content. Percentages of total milliequivalents per liter of cations or anions of interest are plotted in separate triangles. Each side of each triangle provides an axis to plot ions; a single point is plotted in each triangle. The two points are then projected as a single point onto a diamond-shaped diagram. Piper diagrams permit the ionic content of many samples to be represented on a single graph. The dominant ion type in each sample is

easily determined by where the sample plots. However, because ion concentrations are converted to total composition percentages before plotting, waters with very different total concentrations may plot closely together.

Boxplots are vertical rectangles the top of which represents the 75th percentile and the bottom the 25th percentile for the range of values for a set of samples. The median value is represented as a line drawn across the rectangle. Vertical lines extend from the top and bottom of the rectangle to represent values that are outliers. Alley (1993) lists three ways boxplots illustrate the distribution of data: (1) the sample median is a robust measure of the central tendency of the data that is not influenced by outliers; (2) the difference between the top and bottom of the rectangle, the interquartile range, is a robust measure of the spread of the data; and (3) the distance from the top of the rectangle to the median compared to the distance from the bottom of the rectangle to the median is a measure of the skewness of the data. The top and bottom of a rectangle for normally distributed data are roughly equidistant from the median. Boxplots are useful in presenting data for individual constituents in large numbers of samples. Different groups of data can be compared and contrasted by placing boxplot analyses side by side.

A Stiff diagram is a polygon created by plotting cation and anion milliequivalents along a horizontal axis divided by a vertical center line. Cations are plotted on one side of the vertical center line; anions are plotted on the opposite side. Stiff diagrams are useful for rapid comparisons of water-quality analyses from different sources because the Stiff diagram for each source will be a distinctive graphical shape. They are not useful for large numbers of analyses.

Descriptive statistics, such as the range, maximum, minimum, median, and interquartile range of data, were used in this study to summarize the distribution of chemical data for ground-water samples collected from wells completed in the same land-use setting or aquifer. Descriptive statistics for data sets that contained censored values were estimated by using log-probability regression (Maddy and others, 1990).

Nonparametric hypothesis tests were used to evaluate significant differences between water-quality variables in ground-water samples collected from different land-use settings or aquifers. Censored data are represented by ranks in nonparametric tests; estimation of data values below reporting limits is not necessary. The Wilcoxon rank-sum test was used to test the null hypothesis that independent, random ground-water samples from two populations were identical. Rejection of the null hypothesis, at a confidence level of 95 percent, supported the alternative hypothesis that the samples were drawn from different populations.

The relations between selected physical properties and chemical constituents in ground-water samples collected from the urban wells and land use surrounding the urban wells was examined by using statistical correlation. Correlation analysis assesses not only the relation between two variables, but also the strength of the relation (Ott, 1988, p. 319). The Spearman rho rank correlation test was chosen because the data are likely to be nonparametric and the number of samples was greater than 20 (Helsel and Hirsch, 1992, p. 217–218).

Correlation tests calculate a probability statistic and a correlation coefficient. The probability statistic relates to the confidence level. A confidence level of 95 percent, as used in this report, means that there is a 95-percent probability that the correlation is statistically significant. The correlation coefficient describes the strength of the correlation and how the correlated parameters (physical properties and chemical constituents of the water and selected land use) vary. For this report, parameters with a correlation coefficient of 0.6 and greater is considered strongly correlated. Parameters with a correlation coefficient between 0.4 and 0.6 are considered somewhat correlated. Parameters with a correlation coefficient of 0.4 and less are considered weakly correlated. A positive correlation coefficient means that as the value of one parameter increases, the value of the other parameter also increases. A negative correlation means that the value of one parameter decreases as the value of the other parameter increases. Scatterplots were made of all correlated parameters to ensure that the parameters possessed a monotonic correlation (Helsel and Hirsch, 1992, p. 209–211).

CHEMICAL AND PHYSICAL PROPERTIES OF THE SHALLOW AQUIFER

The chemical and physical properties of sediments through which ground water flows can affect ground-water quality. Soils with low organic carbon content may increase the potential for nitrate (U.S. Geological Survey, 1999c) and pesticides (Barbash and Resek, 1996) to enter ground water. Soils with low pH contribute to low pH conditions in ground water, which has been correlated with increased nitrate and trace element concentrations (van Duijvenbooden, 1993). Soil pH and organic carbon content also can affect concentrations of methyl *tert*-butyl ether (MTBE) and ethyl *tert*-butyl ether, which degrade only in soil having a low organic carbon content and a pH of about 5.5 (Yeh and Novak, 1994). Coarse-grained sediments permit more rapid infiltration of water than fine-grained sediments; therefore, aquifers overlain by coarse-grained sediments may be more vulnerable to contamination than aquifers overlain by fine-grained sediments.

Soil Characteristics

The clayey soils that develop from weathering of the Selma confining unit are very poorly drained, have soil pH values ranging from 4.5 to 8.5, and have organic carbon content ranging from 0 to 7 percent (Burgess and others, 1960). This relatively high organic carbon content and moderate pH may reduce the potential for pesticides, nitrate, and trace elements to enter the Black Warrior River aquifer. The soils developed from the alluvial and terrace deposits and from the Eutaw Formation are well drained, have lower soil pH values ranging from 3.6 to 6.5, and have comparatively low organic carbon content ranging from 0 to 4 percent (Burgess and others, 1960). These characteristics may increase the potential for pesticides, nitrate, and trace elements to enter the Black Warrior River aquifer; however, they may decrease the potential for MTBE and ethyl *tert*-butyl ether to enter the aquifer.

Sediment Core Analyses

Sediment core samples of the Selma confining unit, the shallow aquifer, and the Eutaw Formation were collected during the installation of the urban land-use monitoring wells. Core samples of the Selma confining unit had a soil pH range from 4.5 to 7.5, with a median value of 6.5. Organic carbon content ranged from less than 0.01 to 0.85 percent. The vertical hydraulic

conductivity and porosity, determined for three core samples of the Selma confining unit, ranged from 1.9×10^{-2} to 1.36×10^{-6} feet per day (ft/d) and 36.3 to 46.9 percent, respectively. These analyses indicate that the Selma confining unit is likely to hydraulically isolate the underlying Black Warrior River aquifer from sources of contamination at land surface, and the moderate pH of the sediments may lessen the potential for nitrate and trace metals to enter the Black Warrior River aquifer (van Duijvenbooden, 1993).

Core samples from the shallow aquifer had a soil pH range from 5.5 to 6.0, with a median value of 5.5. Organic carbon content ranged from 0.03 to 0.16 percent. The vertical hydraulic conductivity, determined for two core samples, was 2.7 and 6.2 ft/d, and the porosity was 26 and 35 percent. Core samples from the Eutaw Formation had a soil pH that ranged from 5.5 to 7.0, with a median value of 6.0. Organic carbon content ranged from less than 0.01 to 0.24 percent. The vertical hydraulic conductivity of six core samples ranged from 0.48 to 35 ft/d. Porosity values of five samples ranged from 44 to 47 percent. The results of these analyses indicate that there is little hydraulic separation between the ground water and sources of contamination where the shallow aquifer and Eutaw Formation are exposed at land surface. The relatively low pH and organic carbon content of the sediments have little potential to prevent the transport of nitrate, trace metals, and pesticides into the aquifer (van Duijvenbooden, 1993; Barbash and Resek, 1996; U.S. Geological Survey, 1999b); however, these properties may enhance the degradation of MTBE and ethyl *tert*-butyl ether (Yeh and Novak, 1994).

Lithology of the Shallow Aquifer

Representative sediment samples were collected from all materials drilled during the installation of the 30 urban wells, and lithologic descriptions of the samples were prepared. Samples of the alluvial deposits typically were composed of very fine- to very coarse-grained quartz sand that was clear, white, red, and yellow in color. Pebbles were sometimes present. Muscovite was common. Red, brown, and gray silt and clay were mixed with the sand but also was present as separate layers. The lithology of the terrace deposits is similar, but quartz gravel up to 100 millimeters in diameter typically was present in the samples.

Samples of the Eutaw Formation were composed of very fine- to medium-grained quartz sand, glauconite, calcium carbonate, and trace amounts of muscovite and pyrite. Where the Eutaw Formation is at or near land surface, the quartz sand has a clear, white, and tan color.

Green and gold colored muscovite is commonly present, but the glauconite, calcium carbonate, and pyrite have been dissolved and transported (weathered) away by acidic rainwater as it enters the ground and moves downdip. The Eutaw Formation in the urban study area has been weathered as deep as 100 ft below land surface. The Eutaw Formation has not been weathered where it is overlain by the Selma confining unit, or is not near land surface. The presence of glauconite causes the quartz sand to appear deep to light green in color. Pyrite, calcium carbonate, and muscovite also are present. Gravel was not found in any of the Eutaw Formation samples.

WATER QUALITY IN THE SHALLOW AQUIFER

During 1999–2000, ground-water samples were collected from 30 urban monitoring wells installed by the USGS in eastern Montgomery, Alabama. These samples were analyzed at the USGS NWQL for major ions, nutrients, trace metals, pesticides, and VOCs. The results of the analyses were compared to baseline water quality in the Black Warrior River aquifer.

Chemistry of Natural Ground Water

Natural ground-water quality is a term used to describe water quality unaffected by man. The natural water quality must be known before the effects of specific land-use practices can be determined. Natural water-quality conditions in the Black Warrior River aquifer were determined by analyzing ground-water samples collected from 30 wells (fig. 4) located in low-density residential and rural settings (Pearman and others, 2000). With the exception of bacteria, CFCs, and SF₆, the ground-water samples were analyzed at the USGS NWQL for the constituents listed in table 3. Minimum, median, and maximum concentrations of selected chemical constituents in ground-water samples collected from the rural wells are listed in table 6.

The major ion composition of ground-water samples collected from the rural wells is illustrated by the Piper diagram in figure 10. The ion content of ground-water samples collected from the Gordo and Coker Formations plot near the center of the Piper diagram, indicating no dominant ion. The ion content of ground-water samples collected from the Eutaw Formation, however, plot primarily within the area of the Piper diagram indicating water quality dominated by calcium, bicarbonate (HCO₃), and carbonate (CO₃) ions. The sources of the calcium, HCO₃, and CO₃ ions in ground-

Table 6. Minimum, median, and maximum values for physical properties and concentrations of selected chemical constituents in ground-water samples collected from rural wells in the Mobile River Basin and urban wells in Montgomery, Alabama

[MIN, minimum; MED, median; MAX, maximum; $\mu\text{S}/\text{cm}$ at 25 °C, microsiemens per centimeter at 25 degrees Celsius; none, no drinking-water standard; mg/L, milligrams per liter; °C, degrees Celsius; <, less than; *, value is estimated by using a log-probability regression to predict the values of data below the detection limit (Maddy and others, 1990); nd, not present above long-term detection level; $\mu\text{g}/\text{L}$, micrograms per liter; —, too few detections to estimate statistic; P, phosphorus; C, carbon]

Property or constituent	MCL ^a SS ^b AL ^c	Rural data set (30 wells)			Rural data set Eutaw Formation (12 wells)			Urban data set (30 wells)			Urban data set, by formation						
		MIN	MED	MAX	MIN	MED	MAX	MIN	MED	MAX	Unweathered Eutaw (8 wells)			Weathered Eutaw (8 wells)			
											MIN	MED	MAX	MIN	MED	MAX	
Physical properties																	
pH (standard units)	6.5–8.5 ^b	5.1	5.8	8.5	5.4	7.4	8.5	4.6	5.6	7.7	6.7	7.1	7.5	4.7	5.3	5.7	4.6
Specific conductance (µS/cm at 25 °C)	none	14	51	835	42	186	835	28	74	2,670	306	621	2,670	28	53	269	33
Alkalinity (mg/L)	none	3	14	290	5	88	290	2	8	380	88	214	381	3	7	15	2
Dissolved solids residue 180 °C (mg/L)	500	19	46	455	46	129	455	27	48	2,240	192	406	2,240	27	42	148	29
Major ions																	
Calcium (mg/L)	none	4	1.9	110	1.6	13	110	1.2	3.4	520	29	105	523	1.3	2.6	16	1.2
Magnesium (mg/L)	none	.3	.6	7.8	.4	2.2	7.8	.3	1.4	9	1	3	9	.3	1.2	7.1	.5
Potassium (mg/L)	none	.1	2	8.6	.7	2.6	8.6	.2	1.4	2.8	1	2	3	.9	1.6	2.3	<.24
Sodium (mg/L)	none	.8	2.2	163	1.8	9.2	163	.9	4.6	228	9	25	228	.9	3.4	15	1.6
Chloride (mg/L)	250 ^b	.5	2.5	150	1.7	3.2	150	1.3	6.8	120	6	28	123	1.3	4.6	30	2
Fluoride (mg/L)	2 ^b	<.1	*.02	.9	<.1	*.12	.9	<.1	*.09	.9	.2	.4	1	nd	nd	nd	nd
Silica (mg/L)	none	8.3	14	55	10	20	36	8.2	14	42	23	29	42	11	15	25	8.2
Sulfate (mg/L)	250 ^b	<.1	*.5	35	<.1	*4.3	35	<.1	*.6	1,100	9	53	1,100	<.1	*.4	.7	<.1
Bromide (mg/L)	none	<.01	*.02	.9	.02	.05	.9	<.01	*.03	1	.04	.2	1	<.01	*.04	.1	<.01
Iron (µg/L)	300 ^b	<.10	*.17	17,900	<.10	*205	14,300	<.10	16	2,500	10	500	2,500	<.10	*10	330	<.10
Nutrients																	
Nitrite plus nitrate (mg/L)	10 ^a	<.05	*.06	2.3	<.05	—	2.3	<.05	*.13	15	<.05	—	11	.4	1.5	15	<.05
Phosphorus (mg/L as P)	none	<.006	*.01	.8	<.006	*.2	.8	<.006	*.005	.2	<.006	*.006	.2	nd	nd	nd	<.006
Phosphate, ortho (mg/L as P)	none	<.01	*.02	.8	<.01	*.2	.8	<.01	*.002	.2	<.01	*.014	.2	nd	nd	nd	<.01
Dissolved organic carbon (mg/L) as C	none	<.33	*.15	.8	.1	.35	.8	<.33	*.28	1.2	.2	.6	1.2	<.33	*.3	.4	<.33
Metals																	
Aluminum (µg/L)	50–200 ^b	<.1	*1.2	14	<.1	*.8	2.4	1	12	136	<.1	4	13	3	28	118	3
Barium (µg/L)	2,000 ^a	6.3	27	155	10	60	155	6	47	368	6	22	368	10	40	84	10
Chromium (µg/L)	100 ^a	<.1	—	2.3	nd	nd	nd	<.8	*.569	1.8	nd	nd	nd	<.8	—	1.4	<.8
Cobalt (µg/L)	none	<.1	—	9.6	nd	nd	nd	<.1	*.15	7.3	<.1	—	4	<.1	*.1	4	<.1
Copper (µg/L)	1,000 ^b	<.1	*1.8	29	<.1	—	1.9	<.1	*3.4	30	<.1	—	4	1	4	30	<.1
Lead (µg/L)	0 ^a , 15 ^c	<.1	*.5	2.8	nd	nd	nd	<.1	—	1.4	nd	nd	nd	nd	nd	nd	<.1
Manganese (µg/L)	50 ^b	1	9.9	999	4.7	118	724	10	80	382	14	84	382	25	89	379	10
Nickel (µg/L)	none	<.1	*.3	12	<.1	—	1.6	<.1	*1.4	13	<.1	—	13	<.1	*.2	3	<.1
Zinc (µg/L)	5,000 ^b	<.1	*1.5	216	<.1	*1.1	5.5	<.1	*4.8	23	<.1	—	9	2	14	21	3

^a Maximum contaminant level for drinking water established by the U.S. Environmental Protection Agency.

^b Secondary drinking-water standard established by the U.S. Environmental Protection Agency.

^c Action level established by the U.S. Environmental Protection Agency.

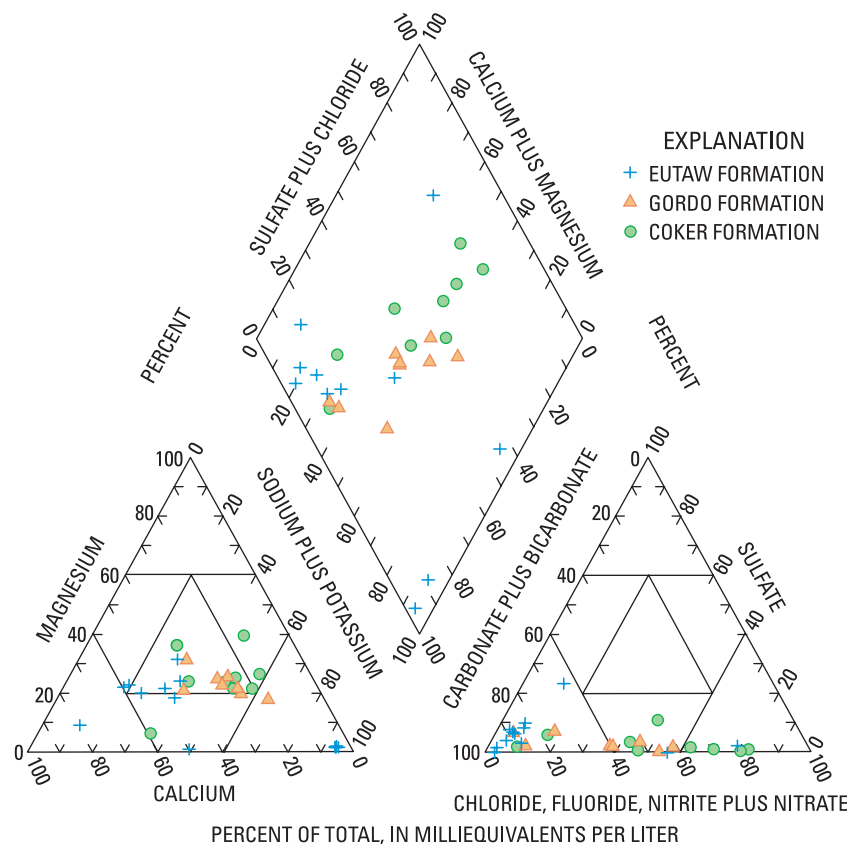


Figure 10. Piper trilinear diagram showing major ion composition of ground-water samples collected from rural wells completed in the Coker, Gordo, and Eutaw Formations in the Mobile River Basin.

water samples collected from the Eutaw Formation are calcareous sandstone and limestone interbedded with glauconitic sand (Cook, 1993).

Concentrations of selected anions and cations in representative ground-water samples from the Coker, Gordo, and Eutaw Formations were used to create Stiff diagrams. The Stiff diagrams for ground-water samples collected from the Gordo and Coker Formations are elongated along the vertical central axis with no single ion producing a large horizontal departure from the central axis (fig. 11), indicating no dominant ion in the sample. The pattern generated by the ion content of ground-water samples collected from the Eutaw Formation is elongated along the bottom horizontal axis for the calcium, HCO_3 , and CO_3 ions (fig. 11). This pattern indicates greater concentrations of these ions relative to the other ions plotted in the diagram.

Analyses of water samples collected from urban wells completed in the unweathered Eutaw Formation indicate that the ground water is calcium-bicarbonate type (fig. 12), similar to samples collected from the rural wells completed in the Eutaw Formation (fig. 10).

The ion content of ground-water samples collected from the alluvial and terrace deposits and the weathered Eutaw Formation plot near the center of the Piper diagram, indicating no dominant cation; however, ground water collected from these formations was dominated by chloride, fluoride, and nitrate anions. Minimum, median, and maximum concentrations of selected chemical constituents in ground-water samples collected from the urban wells are listed in table 6.

The chemical composition of water changes as it moves through the ground and interacts with soil and sediments. These changes often follow a predictable pattern. Recently recharged ground water is likely to have greater dissolved oxygen levels because it contains atmospheric oxygen; in addition, recharge water typically is acidic because atmospheric or microbial carbon dioxide (CO_2) dissolved in the water produces a weak carbonic acid in solution. Recently recharged ground water also is typically low in dissolved solids because insufficient time has passed for the carbonic acid to dissolve minerals. As

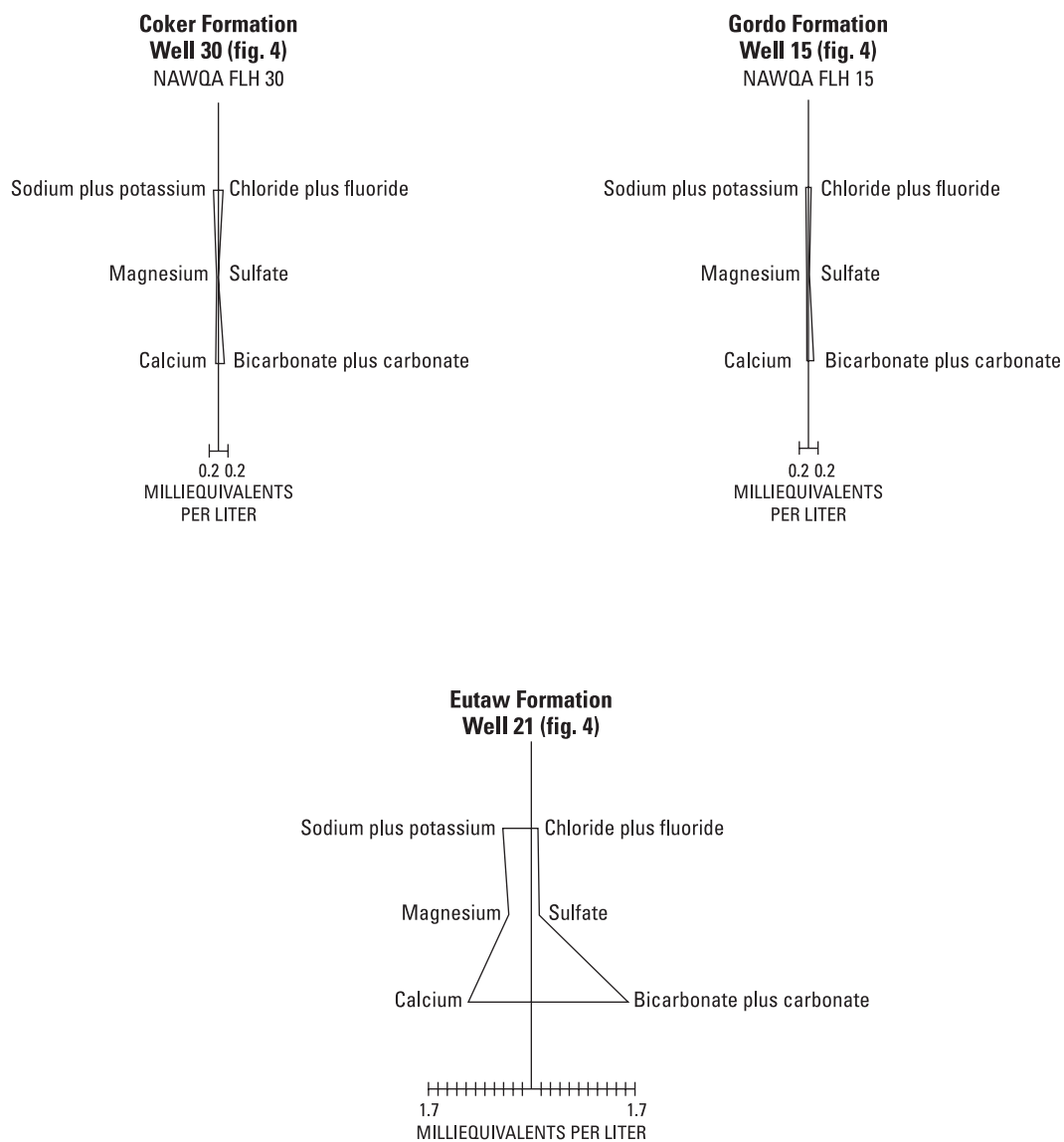


Figure 11. Stiff diagrams representing water quality of samples collected from rural wells completed in the Coker, Gordo, and Eutaw Formations in the Mobile River Basin.

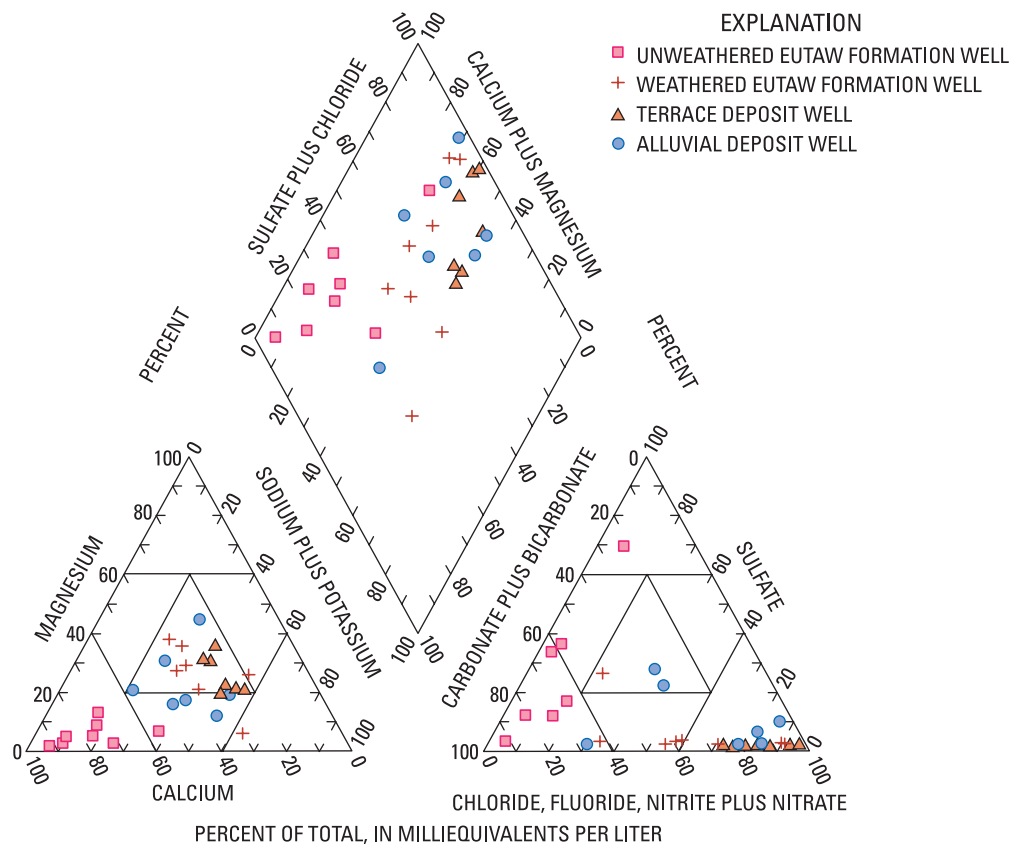


Figure 12. Piper trilinear diagram showing major ion composition of ground water collected from urban wells in Montgomery, Alabama.

ground water moves away from the recharge area, readily soluble minerals, such as carbonates and sulfides, are dissolved, increasing the dissolved solids content of the water. Dissolved oxygen concentration in the water also decreases as biological and chemical reactions consume the oxygen. Once dissolved oxygen in the water has been removed, denitrification may occur, causing nitrogen concentrations to decrease (Chapelle, 1993, p. 246). Iron concentrations may increase due to iron III reduction. The dissolved solids content of ground water increases with time as a result of the dissolution of readily soluble minerals, such as calcite (CaCO_3) and pyrite (FeS_2). Both of these minerals were found in drill cuttings collected during the installation of the urban wells sampled for this study. As a result of these natural chemical processes, ground water typically becomes less acidic and increases

in alkalinity as it ages and moves away from the area of recharge.

The geochemical evolution of ground water in the urban study area is illustrated by the trilinear diagram of water-quality analyses of samples collected from the urban wells completed in the Eutaw Formation (fig. 13). Where the Eutaw Formation is exposed at or near land surface, recently recharged, acidic ground water has dissolved and transported away calcium-rich minerals, producing a major-ion composition similar to that of the alluvial and terrace deposits. As ground water flows down dip, the major-ion composition becomes more similar to that of ground-water samples collected from the rural wells completed in the Eutaw Formation. This geochemical evolution is further illustrated by the Stiff diagrams in figure 14.

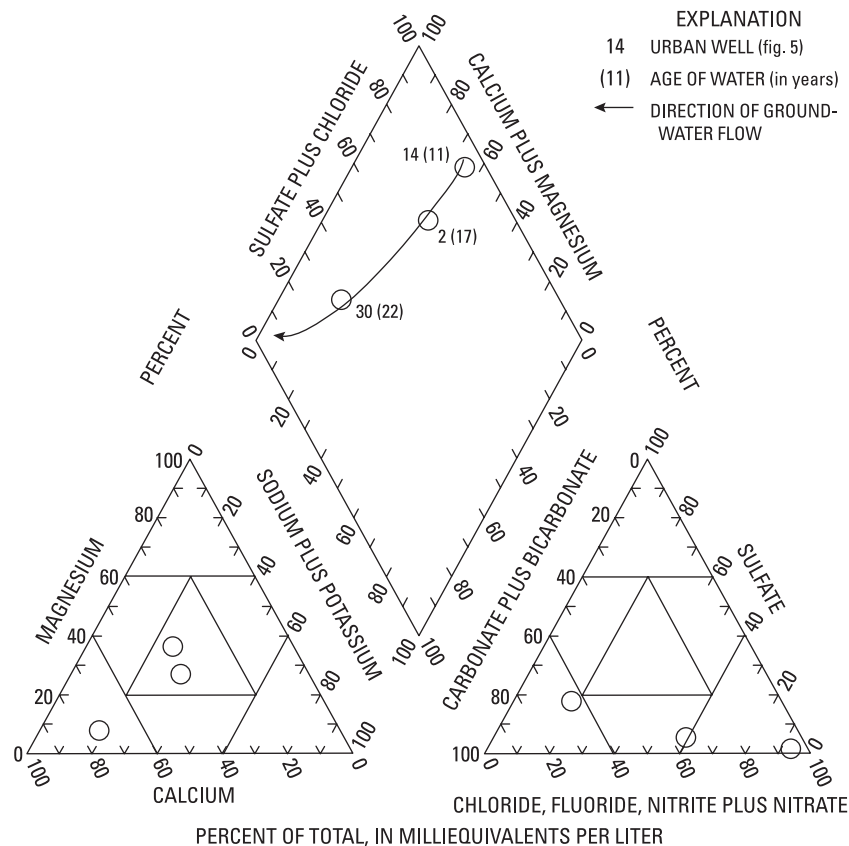


Figure 13. Piper trilinear diagram showing geochemical evolution of ground water in the Eutaw Formation beneath Montgomery, Alabama.

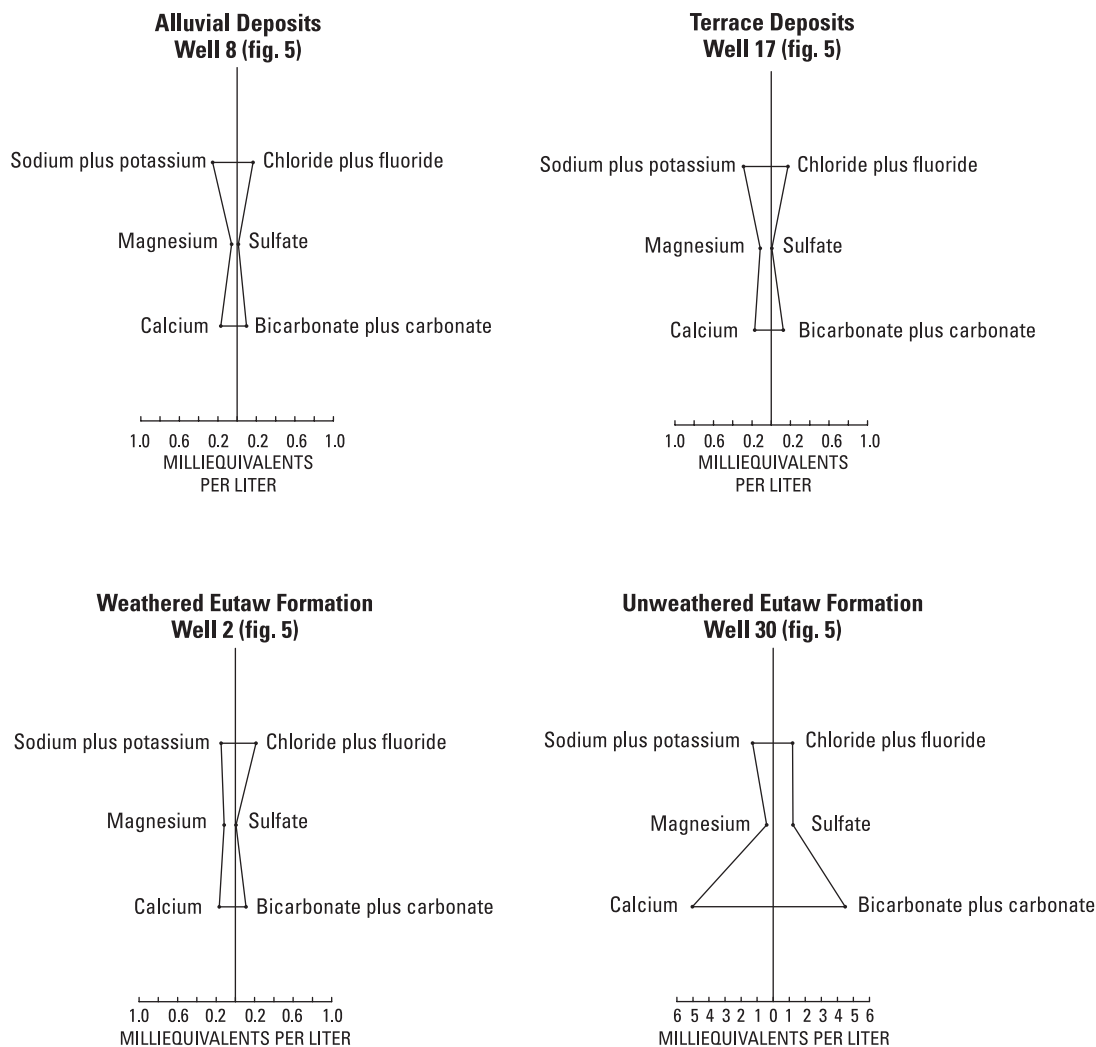


Figure 14. Stiff diagrams representing water quality of samples collected from urban wells completed in the Eutaw Formation, alluvial deposits, and terrace deposits beneath Montgomery, Alabama.

Ground-Water Quality Beneath an Urban Area of Montgomery, Alabama

Urban ground-water quality, represented by samples collected from 30 wells in Montgomery, Alabama, was compared to regional ground-water quality represented by samples collected from 30 wells located in rural areas of the Mobile River Basin. All of the wells in the urban area produce water from the Eutaw Formation or from overlying deposits in direct hydraulic contact with the Eutaw Formation. Most of the urban wells are shallow relative to wells in the rural area (fig. 9), and many are completed in different formations. As a result, the direct effects of urbanization cannot be easily evaluated due to the complicating factors of position in the flow system and differing mineralogy. Despite these

complicating factors, however, 12 rural wells completed in the Eutaw Formation, the same formation in which 16 of the 30 urban wells are completed, allowed for a broad comparison based on these two data subsets. Graphical methods and the Wilcoxon rank-sum test were used to evaluate the significance of water-quality differences between the data sets.

Values of pH, dissolved solids, specific conductance, and alkalinity of the water samples from the 30 rural wells, the 12 rural wells completed in the Eutaw Formation, and the 30 urban land-use study wells were illustrated and compared by using boxplots (fig. 15). The urban ground-water samples had lower median values but a larger range in values for pH, specific conductance, total dissolved solids, and alkalinity compared to the water quality of ground-water samples collected from the rural

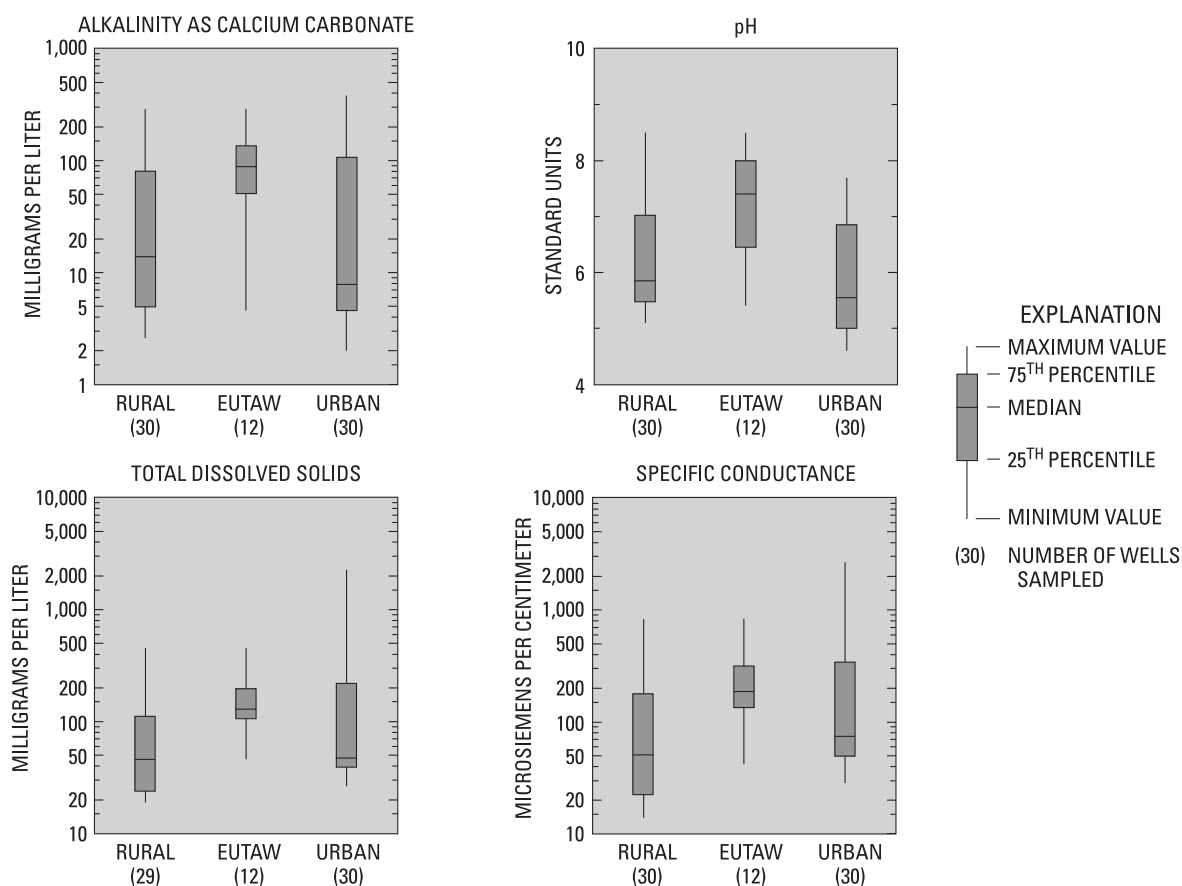


Figure 15. Concentrations of selected water-quality constituents in ground-water samples collected from rural wells in the Mobile River Basin, rural wells completed in the Eutaw Formation, and urban wells in Montgomery, Alabama.

wells. The distribution of physical properties measured in the urban ground-water samples is consistent with those of samples collected from recently recharged ground water, the water-quality of which reflects diverse influences such as are found in an urban setting.

Occurrence and Distribution of Major Ions

A comparison of median values for major ions measured in rural water samples and urban water samples (table 6) indicated that the chloride concentration was greater in water samples collected from urban wells compared to rural wells (fig. 16). The apparent relation

between greater chloride concentrations and the urban ground-water samples was tested by using the Wilcoxon rank-sum test. Three separate tests were run—the 12 rural water samples collected from the Eutaw Formation were compared to all 30 urban water samples; the 12 rural water samples collected from the Eutaw Formation were compared to the 16 urban water samples collected from the Eutaw Formation; and all 30 rural water samples were compared to all 30 urban water samples. Results of these three tests indicated that chloride concentrations in urban water samples was statistically greater than in the rural water samples.

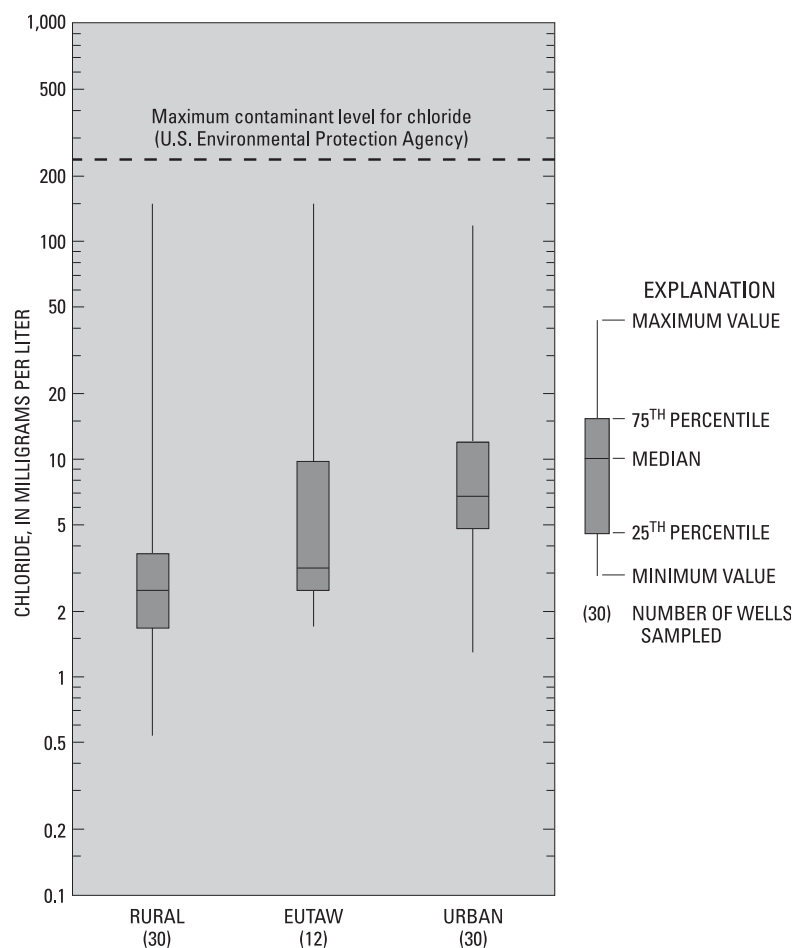


Figure 16. Concentrations of chloride in ground-water samples collected from rural wells in the Mobile River Basin, rural wells completed in the Eutaw Formation, and urban wells in Montgomery, Alabama.

Occurrence and Distribution of Nutrients

Comparison of nutrient concentrations in ground-water samples collected from the rural wells and the urban wells (table 6) suggests that concentrations of nitrite plus nitrate were greater in samples collected from the urban wells. The frequency of detection of nitrite plus nitrate in the urban water samples (22 detections) was greater than in the 30 rural water samples (16 detections) and greater than in the 12 rural water samples collected from the Eutaw Formation (1 detection). The apparent relation

between greater concentrations of nitrite plus nitrate and urban ground-water samples (fig. 17) was tested by using the Wilcoxon rank-sum test. Two tests were run—the 30 rural water samples were compared to the 30 urban water samples; and the 30 rural water samples were compared to the 16 urban water samples collected from the Eutaw Formation. Results of both tests indicated that concentrations of nitrite plus nitrate in the urban water samples were statistically greater than in the rural water samples.

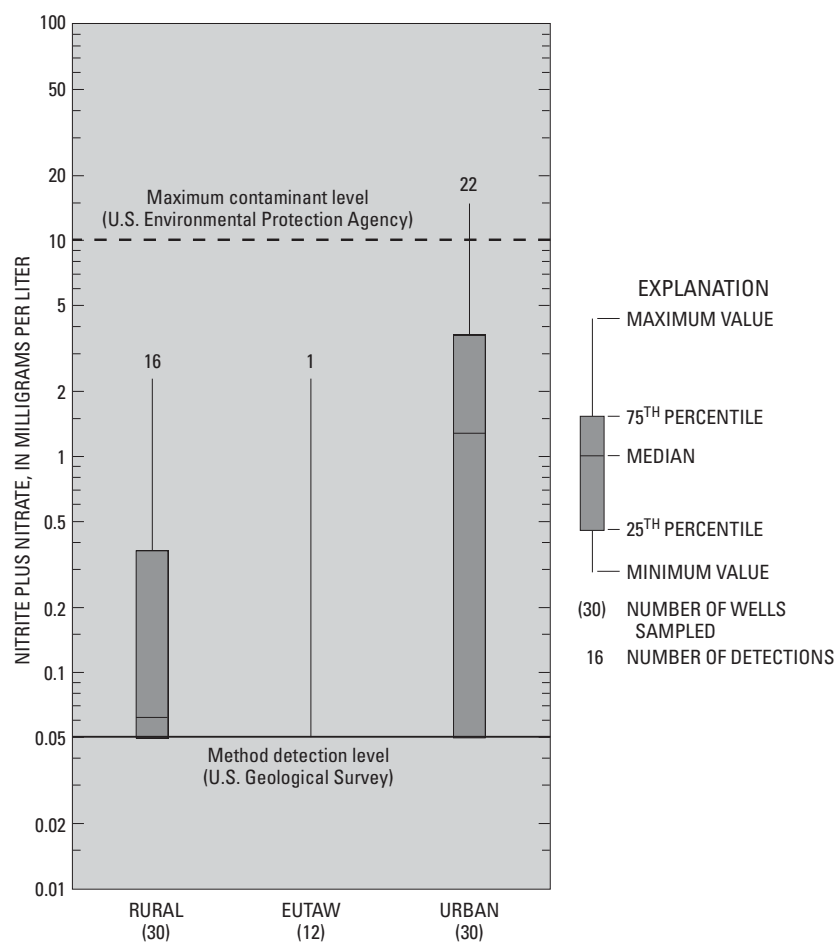


Figure 17. Concentrations of nitrite plus nitrate in ground-water samples collected from rural wells in the Mobile River Basin, rural wells completed in the Eutaw Formation, and urban wells in Montgomery, Alabama.

Occurrence and Distribution of Trace Metals

Median concentrations of some trace metals were greater in urban ground-water samples than in rural ground-water samples collected from the same aquifer (table 6). Boxplots of the data are of limited use, however, because of the large number of non-detections of trace metals (fig. 18). Aluminum, chromium, cobalt, copper, nickel, and zinc were detected more frequently in the urban ground-water samples than in the rural ground-water samples. The Wilcoxon rank-sum test was used to evaluate the apparent differences in concentrations of aluminum, cobalt, copper, zinc, and nickel in the urban and rural ground-water samples. No statistical analysis was performed on the occurrence and distributions of chromium because it was detected only twice in the rural wells; however, chromium was detected more frequently in the urban samples (11 detections).

The apparent differences in aluminum and zinc concentrations in three sets of ground-water samples were evaluated. The 30 rural water samples were compared to the 30 urban water samples; the 12 rural water samples collected from the Eutaw Formation were compared to 16 urban water samples collected from the Eutaw Formation; and the 12 rural water samples collected from the Eutaw Formation were compared to all 30 urban water samples (fig. 18). Results of these analyses indicated that the concentration of aluminum in the ground-water samples collected from the urban wells was statistically greater than in the rural samples. Concentrations of zinc in the ground-water samples collected from the urban wells were statistically greater than in water samples collected from the rural wells when all 30 samples were analyzed; but the zinc concentrations in the rural Eutaw samples were not significantly different from those in the urban Eutaw samples.

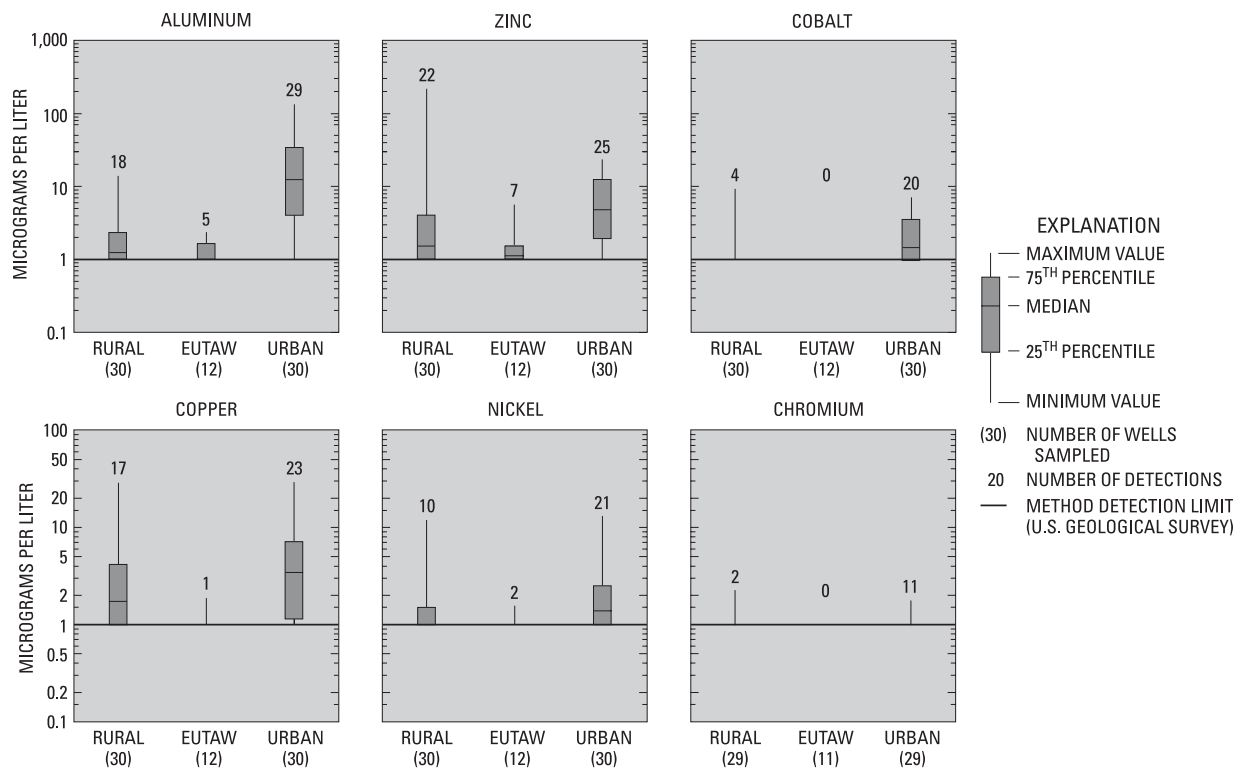


Figure 18. Concentrations of selected trace metals in ground-water samples collected from rural wells in the Mobile River Basin, rural wells completed in the Eutaw Formation, and urban wells in Montgomery, Alabama.

The apparent differences in cobalt, copper, and nickel concentrations also were evaluated. The 30 rural ground-water samples were compared to the 30 urban ground-water samples. The samples collected from the Eutaw Formation were not independently analyzed because cobalt, copper, and nickel were detected infrequently in ground-water samples collected from the rural wells (fig. 18). Results of the analysis indicated that concentrations of cobalt, copper, and nickel in ground-water samples collected from the urban wells were statistically greater than in ground-water samples collected from the rural wells.

Occurrence and Distribution of Pesticides

Pesticides were detected in greater variety and more frequently in ground-water samples collected from the urban land-use study wells than in ground-water samples from the rural wells. Samples from only two rural wells contained pesticides, and these two samples contained three different pesticides. Samples from 21 urban wells contained pesticides, and these 21 samples

contained 12 different pesticides. Pesticides were detected 3 times in the rural ground-water samples, but 54 times in the urban ground-water samples. The most commonly detected compounds in the urban samples were deethyl atrazine (16 detections), atrazine (10 detections), dieldrin (7 detections), and simazine (6 detections). The range and distribution of concentrations of the most commonly detected pesticides in rural and urban wells are shown in figure 19; however, many of the concentrations are similar and when plotted do not appear as individual points on the graph. Herbicides were the most frequently detected class of pesticides in the urban samples (fig. 20). The highest measured concentration of any pesticide in the rural samples was 0.008 microgram per liter (µg/L) for atrazine. The highest measured concentration of any pesticide in the urban samples was also atrazine at 0.55 µg/L. The minimum and maximum concentrations of selected pesticides detected in ground-water samples collected from the urban and rural wells are listed in table 7.

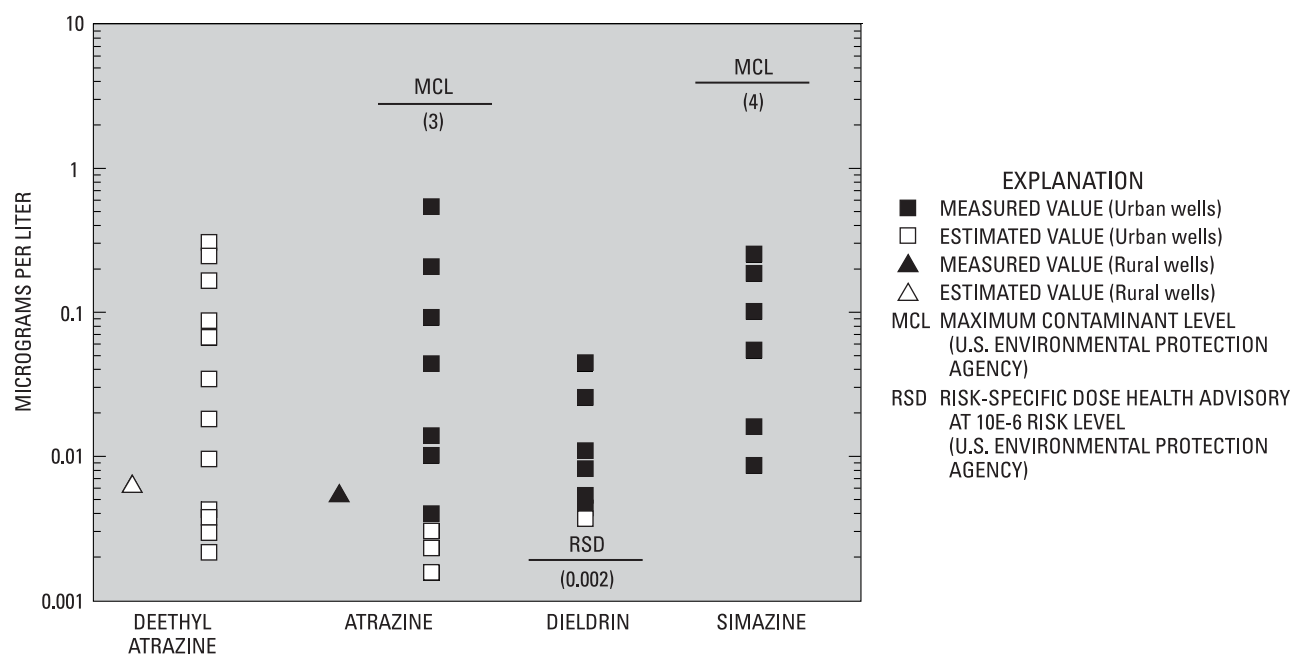


Figure 19. Range and distribution of concentrations of the most commonly detected pesticides in ground-water samples collected from rural wells in the Mobile River Basin and urban wells in Montgomery, Alabama.

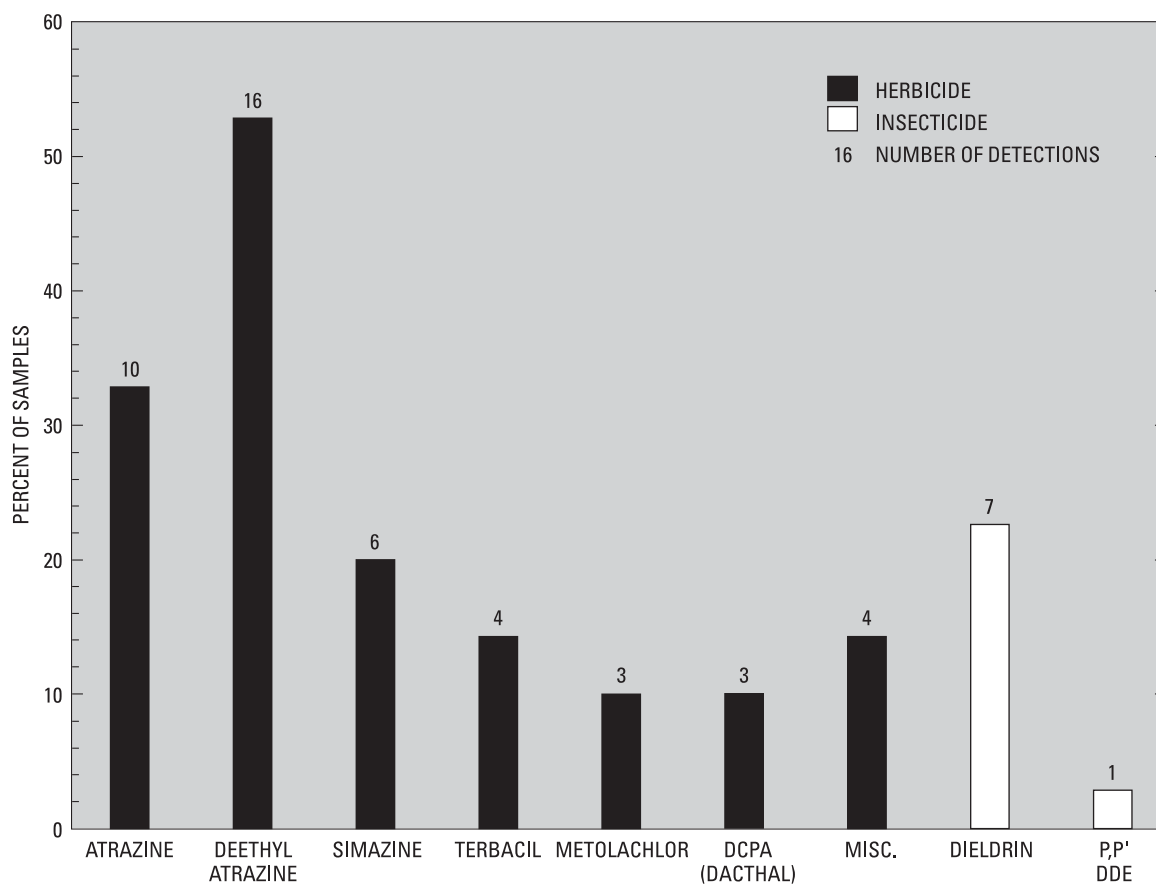


Figure 20. Detection frequencies of pesticides in ground-water samples collected from urban wells in Montgomery, Alabama.

Table 7. Minimum and maximum concentrations of selected pesticides and volatile organic compounds in ground-water samples collected from rural wells in the Mobile River Basin and urban wells in Montgomery, Alabama

[MIN, minimum; MAX, maximum; µg/L, micrograms per liter; E, concentration less than the reporting level but above the long-term method detection level; *p,p'*-DDE, dichlorodiphenyldichloroethylene; none, no drinking-water standard]

Constituent	MCL ^a RSD ^b HA ^c	Number of detections		Rural data set (30 wells)		Urban data set (30 wells)	
		Rural wells	Urban wells	MIN	MAX	MIN	MAX
Pesticides							
Atrazine (µg/L)	3 ^a	1	10	0.008	0.008	E0.002	0.55
Dacthal (µg/L)	4,000 ^c	1	3	E.0009	E.0009	.002	.01
Deethyl atrazine (µg/L)	none	1	16	E.007	E.007	E.003	E.3
Dieldrin (µg/L)	.002 ^b	0	7			E.004	.06
Metolachlor (µg/L)	100 ^c	0	3			E.003	.008
<i>p,p'</i> -DDE (µg/L)	.1 ^b	0	1			E.002	E.002
Simazine (µg/L)	4 ^a	0	6			.009	.28
Terbacil (µg/L)	90 ^c	0	4			E.007	E.009
Volatile organic compounds							
Benzene (µg/L)	5 ^a	0	8			E.008	E.06
Chloroform (µg/L)	100 ^a	11	20	E.008	E.1	E.03	1.5
Tetrachloroethylene (µg/L)	5 ^a	2	9	E.01	E.07	E.01	45.5
1,1,1-Trichloroethane (µg/L)	200 ^a	1	8	E.007	E.007	E.008	.25
Toluene (µg/L)	1,000 ^a	1	12	E.009	E.009	E.006	E.08
Carbon disulfide (µg/L)	none	8	11	E.022	E.238	E.01	.13

^a Maximum contaminant level for drinking water established by the U.S. Environmental Protection Agency.

^b Risk-specific dose health advisory at 10E-6 level established by the U.S. Environmental Protection Agency.

^c Health advisory level established by the U.S. Environmental Protection Agency.

Occurrence and Distribution of Volatile Organic Compounds

Volatile organic compounds (VOCs) were detected in greater variety and more frequently in ground-water samples collected from the urban land-use study wells than in the ground-water samples from the rural wells. Seven different VOCs were detected in water samples from 19 of the rural wells. Twenty-nine different VOCs were detected in water samples from 29 of the urban wells. VOCs were detected a total of 25 times in the rural samples, but 121 times in the urban samples. Chloroform was the most commonly detected VOC in the rural samples (11 detections). The most commonly detected VOCs in the urban samples were chloroform (20 detections), toluene (12 detections), carbon disulfide (11 detections), tetrachloroethylene (9 detections), and

benzene and 1,1,1-trichloroethane (8 detections). The range and distribution of concentrations of the most commonly detected VOCs in rural and urban wells are shown in figure 21; however, many of the concentrations are similar, and when plotted do not appear as individual points on the graph. Alkanes were the most frequently detected class of VOCs in the urban samples (fig. 22).

Concentrations of all VOCs in the rural samples were reported as estimated because values were below the reporting limit but above the long-term method detection level. The highest measured concentration of any VOC in the urban land-use study samples was 45.5 µg/L for tetrachloroethylene. The minimum and maximum concentrations of selected VOCs detected in ground-water samples collected from the urban and rural wells are listed in table 7.

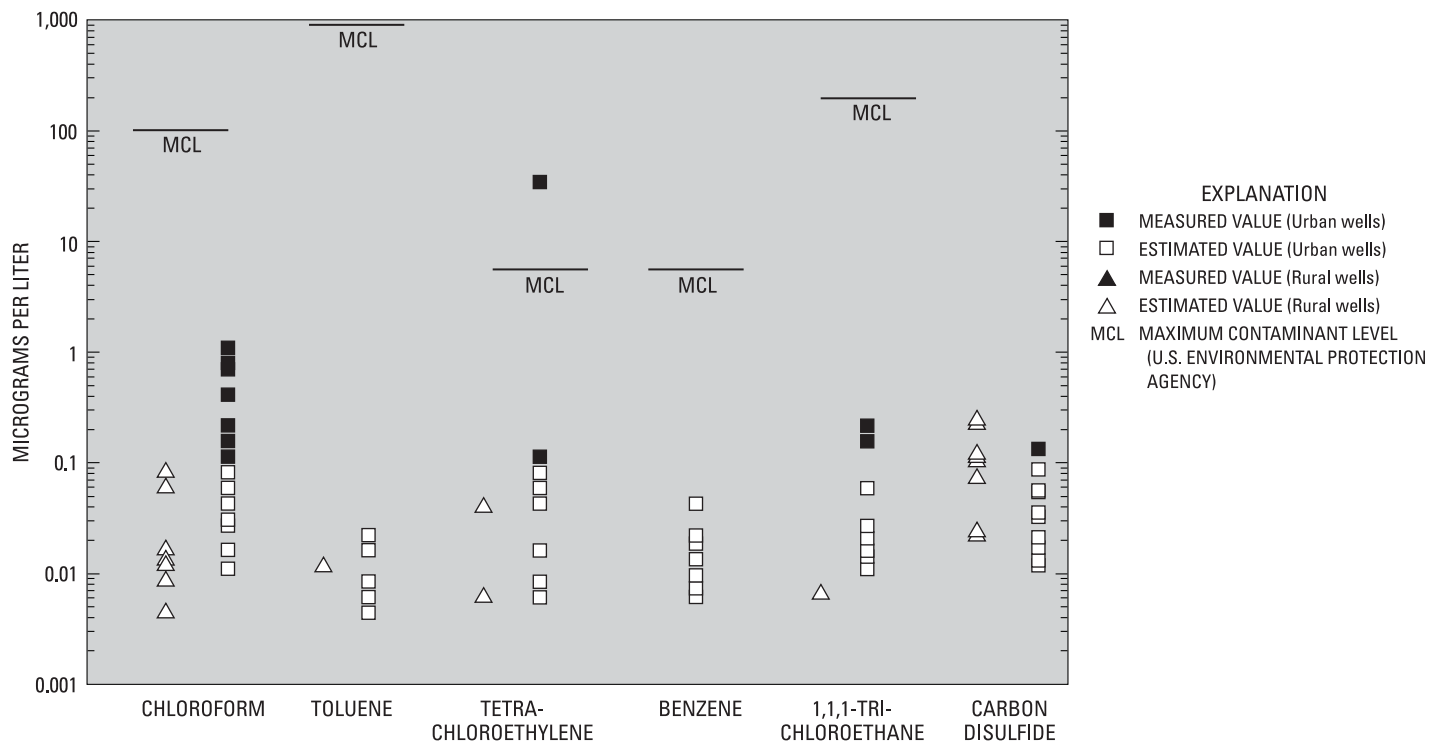


Figure 21. Range and distribution of concentration of most commonly detected volatile organic compounds in ground-water samples collected from rural wells in the Mobile River Basin and urban wells in Montgomery, Alabama.

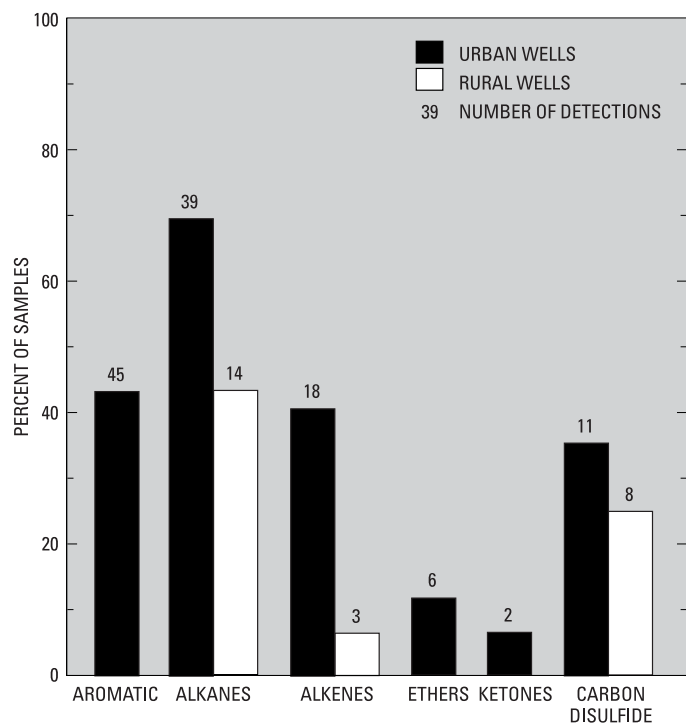


Figure 22. Frequency of detection of volatile organic compounds, by compound class, in ground-water samples collected from rural wells in the Mobile River Basin and urban wells in Montgomery, Alabama.

Age of Ground Water

Ground-water samples collected from the urban land-use study wells were analyzed for the environmental tracers, CFCs and SF_6 . Ground-water age is estimated by relating the measured concentration of the environmental tracer in ground-water samples to the reconstructed historical atmospheric concentration and/or to calculated concentrations expected in water in equilibrium with air (Busenberg and Plummer, 1992, 2000; U.S. Geological Survey, 1999d). The age estimated for the water refers to the time period in which CFCs and SF_6 are introduced into the water prior to entering the subsurface. Environmental processes, such as microbial degradation, sorption, and excess dissolved gases, may affect the concentration of environmental tracers in water.

Chlorofluorocarbons are synthetic compounds first produced in the early 1930's (Cook and Herczeg, 2000). The presence of measurable concentrations of CFCs in a water sample indicates that the sample contains some post-1940 water. Sulfur hexafluoride is a trace atmospheric gas that occurs naturally in some minerals, igneous rocks, and volcanic and igneous fluids; however, SF_6 is primarily of anthropogenic origin. Large-scale

production of SF₆ began in the 1960's, and dating is possible from about 1970 (Busenberg and Plummer, 1997). Ground-water samples collected from the urban land-use study wells were analyzed for CFC-11 (trichlorofluoromethane or CFCI₃), CFC-12 (dichlorodifluoromethane or CF₂Cl₂), CFC-113 (trichlorotrifluoroethane or C₂F₃Cl₃), and SF₆.

The age of the ground water was determined for samples from all 30 urban land-use study wells (table 8). In addition to the CFC and SF₆ age date estimates, the

process of assigning an age to ground-water samples included consideration of the concentration of dissolved oxygen, the presence or absence of bacteria, the presence or absence of chemical compounds that can be used as date markers such as MTBE, and the hydrogeologic setting of the well. In general, factors that support a younger water age are the presence of fecal bacteria, which is assumed to be from a source at land surface, a dissolved oxygen concentration greater than 1 milligram per liter (mg/L), sandy surficial geology, and the presence

Table 8. Ages of ground water in samples collected from urban wells in Montgomery, Alabama

[SF₆, sulfur hexafluoride; CFC, chlorofluorocarbon; CFC-11, trichlorofluoromethane; CFC-12, dichlorodifluoromethane; CFC-113, trichlorotrifluoroethane; mg/L, milligrams per liter; MTBE, methyl *tert*-butyl ether; contam., contaminated by contact with atmosphere during sampling; <, less than; ~, approximately; >, greater than; ns, no sample]

Map reference number (fig. 5)	Surficial geology	Open interval (feet below land surface)	SF ₆ age (years)	CFC age (years)			Dissolved oxygen (mg/L)	Date marker chemical or bacteria present	Age used in this report (years)
				CFC-11	CFC-12	CFC-113			
1	sand	12.5–22.5	14	42	37	45	0.24	MTBE	14
2	sand	87.9–97.9	17	contam.	contam.	17	4.9	bacteria	17
3	sand	17.0–27.0	6	contam.	contam.	contam.	5.5	bacteria	6
4	sand	30.0–40.0	22	contam.	contam.	28	4.4		28
5	sand	22.5–32.5	9	12	< 1	2–5	2.3		2
6	sand	26.5–36.5	< 1	contam.	contam.	contam.	1.1	bacteria	~ 1
7	clay	70.0–80.0	22	45	52	> 45	.6	bacteria	> 45
8	sand	8.3–18.3	12	contam.	contam.	13	5.2	MTBE	12
9	sand	25.5–35.5	10	contam.	contam.	contam.	7.0	bacteria	10
10	sand	28.9–38.9	2	contam.	contam.	contam.	5.9	MTBE	2
11	sand	10.5–20.5	5	14	22	10	.8	bacteria	5
12	sand	52.5–62.5	8	4	contam.	9	5.1		8
13	sand	57.0–67.0	7	contam.	contam.	contam.	4.6	bacteria	7
14	sand	71.5–81.5	6	contam.	contam.	11	4.2		11
15	sand	29.0–39.0	18	contam.	< 1	contam.	4.5		~ 1
16	sand	28.0–38.0	19	ns	ns	ns	4.0	MTBE	19
17	sand	21.0–31.0	6	contam.	contam.	5	5.2	bacteria	6
18	clay	21.5–31.5	12	19	19	18	4.5	bacteria	18
19	gravel	16.2–26.2	5	14	12	8	1.4		5
20	sand	16.2–26.2	7	contam.	6	7	4.8	bacteria	7
21	sand	70.0–80.0	11	contam.	contam.	14	1.4		14
22	sand	81.0–91.0	< 1	contam.	contam.	10	5.5		10
23	clay	19.5–20.5	14	37	30	17	.31	bacteria	17
24	clay	76.0–86.0	2	20	50	21	.10		20
25	clay	50.0–60.0	20	ns	ns	ns	.25	bacteria	20
26	clay	30.5–40.5	21	39	44	> 45	.49		> 40
27	clay	56.5–66.5	14	46	45	20	.07	bacteria	14
28	clay	21.0–31.0	12	45	31	> 45	.12		12
29	sand	74.4–84.4	12	contam.	contam.	12	6.0		12
30	clay	47.0–57.0	25	contam.	53	22	.15	bacteria	22

of chemicals whose first manufacture and use is known to be recent. The opposite of these factors supports an older age for ground water.

The age assigned to the ground-water sample collected from urban land-use study well 1 (table 8) provides a useful example of the age dating process. The CFC data suggests a ground-water age of 37 to 45 years. The SF₆ data, however, yields an age of 14 years. The sandy surficial geology and the detection in the sample of MTBE, which was first used in 1979 as an octane booster in gasoline, supports the SF₆ age of less than 20 years. Urban ground water sampled for this study ranged in age from about 1 to greater than 45 years, with a median age of about 12 years. The ages estimated for the ground water are consistent with the geology and hydrology of the urban study area and the design of the urban wells.

RELATIONS AMONG GROUND-WATER QUALITY, GROUND-WATER AGE, LAND USE, AND GEOLOGY

Selected factors that may influence ground-water quality in the shallow aquifer underlying the urban study

area were examined using the Spearman rho correlation test. Analyses were run for covariance between physical properties, major ions, nutrients, trace metals, the number of pesticides and volatile organic compounds detected, depth-to-open interval, ground-water age, soil organic carbon content, soil pH, and land-use type. The Spearman rho correlation test is based on ranks. Concentrations of major ions and trace metals less than the reporting level were assigned a value of one-half the reporting level so they would not have a rank equal to that of a measured value at the reporting level. Correlated physical properties and parameters that relate to this study are listed in table 9.

Some of the correlations listed in table 9 reflect the natural geochemical evolution of ground water. The decrease in dissolved oxygen and in the concentration of nitrite plus nitrate as ground-water age increases, and the increase in pH and in the concentration of iron and sulfate as ground-water age increases, are common changes in ground-water quality that occur with time. These correlations support the accuracy of the ground-water age estimates in urban land-use areas.

Some correlations may reflect the fate of constituents in the ground-water system. The number of

Table 9. Spearman rank correlation coefficients for selected physical properties and parameters of ground-water samples collected from urban wells in Montgomery, Alabama

[>, greater than; *, correlation test performed using only samples of ground water less than 20 years old; VOC, volatile organic compound]

Variables	Number of sample pairs	Correlation coefficient	Probability statistic
Ground-water age and dissolved oxygen	30	- 0.43	0.017
Ground-water age and concentration of nitrite plus nitrate	30	- .57	.001
Ground-water age and pH	30	.53	.002
Ground-water age and concentration of iron	30	.38	.038
Ground-water age and concentration of sulfate	29	.50	.005
Ground-water age and concentration of aluminum	30	- .54	.002
Ground-water age and concentration of copper	30	- .58	.001
Ground-water age and concentration of zinc	30	- .40	.026
Ground-water age and number of pesticides detected	30	- .56	.001
Number of pesticides detected and concentration of nitrite plus	30	.36	.049
Concentration of aluminum and pH	30	- .85	> .001
Concentration of zinc and pH	30	- .63	> .001
*Percentage of residential land use and concentration of nickel	24	.53	.007
*Percentage of residential land use and number of pesticides	24	.49	.013
*Percentage of residential land use and number of VOCs	24	.41	.047
*Percentage of commercial land use and number of pesticides	24	- .63	.001
*Percentage of commercial land use and number of VOCs	24	- .44	.033
*Number of VOCs detected and concentration of nickel	24	.47	.019

pesticides detected and the concentration of nitrite plus nitrate decreased as ground-water sample age increased. These data may indicate that, with time, pesticides and nitrogen are being removed from the ground-water system. Likewise, concentrations of aluminum, copper, and zinc decreased as the age of ground water and pH increased. These correlations may indicate that as water moves through sediments, changing pH and redox potential (Eh) conditions cause these elements to form insoluble compounds, removing them from solution. This may explain why the Wilcoxon test indicated that the greater median concentration of zinc in the urban samples was statistically significant when all 30 samples were tested, but not statistically significant for the rural and urban samples collected from the Eutaw Formation only. Although urban land use is indicated as a source of the greater median concentrations of aluminum, copper, and zinc in the urban ground-water samples, these trace metals were detected less frequently and in lower concentrations in ground-water samples collected from the unweathered portion of the Eutaw Formation (table 6).

Correlation between land use and ground-water quality beneath the urban study area was evaluated by applying the Spearman rho correlation test to the 24 samples of ground water having an age of less than 20 years (table 8). The concentration of nickel and the number of pesticides and VOCs detected increased somewhat as the percentage of residential land use increased. The number of pesticides and VOCs detected decreased as the percentage of commercial land use increased. No other statistically significant correlations were found between land use and the water quality of urban ground-water samples (table 9).

The effect of surficial geology on the occurrence of pesticides and VOCs was investigated by calculating frequencies of detection. The detection frequency of pesticides and VOCs in the urban ground-water samples was compared to the surficial geology (fig. 23). The detection frequency for pesticides was greater for urban samples collected from wells where the surficial geology is sand than for urban samples collected from wells where the surficial geology is clay. The frequency of detection of VOCs did not show a similar relation (fig. 23).

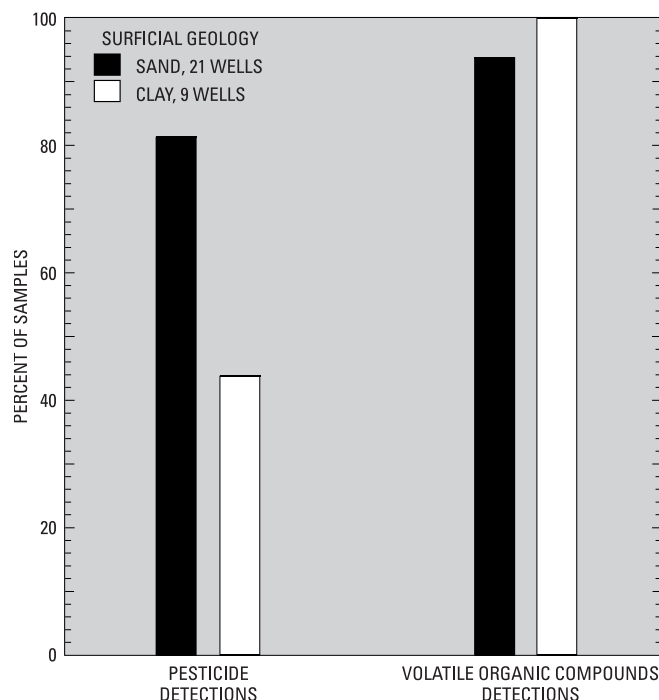


Figure 23. Detection frequencies of pesticides and volatile organic compounds in ground-water samples collected from urban well in Montgomery, Alabama.

SUMMARY

The city of Montgomery, Alabama, is underlain, north to south, by a shallow aquifer composed of alluvial and terrace deposits of gravel, sand, and clay; sands and clays of the Black Warrior River aquifer, and by the Selma confining unit, which consists of clay and clayey soils developed from the Mooreville Chalk. Montgomery is one of many major population centers in the Mobile River Basin that rely on the Black Warrior River aquifer for public supply. The chemical and physical characteristics of soils developed from the alluvial and terrace deposits and the Black Warrior River aquifer may increase the potential for nutrients, trace metals, and pesticides to enter the aquifer. The chemical and physical characteristics of soils developed from the Selma confining unit may decrease the potential for contamination of the aquifer.

Thirty wells were installed in eastern Montgomery, where the Black Warrior River aquifer is overlain by residential and commercial land use. Ground-water samples collected during this urban land-use study were

analyzed for major ions, nutrients, trace metals, pesticides, volatile organic compounds (VOCs), bacteria, chlorofluorocarbons, dissolved gases, and sulfur hexafluoride. Ground-water quality beneath the urban area was compared to the water quality of ground-water samples collected from 30 wells located in low-density residential and rural areas, which represent regional ground-water quality in the Black Warrior River aquifer.

The median concentrations of chloride, nitrite plus nitrate, aluminum, chromium, cobalt, copper, zinc, and nickel were greater in ground-water samples collected from the urban land-use study wells than in samples collected from the rural wells. Pesticides and VOCs were detected more frequently and in greater concentrations in ground-water samples collected from the urban wells compared to ground-water samples collected from the rural wells. The most commonly detected pesticides in the urban samples were deethyl atrazine (16 detections), atrazine (10 detections), dieldrin (7 detections), and simazine (6 detections). Herbicides were the most frequently detected class of pesticides. The most commonly detected VOCs in the urban samples were chloroform (20 detections), toluene (12 detections), carbon disulfide (11 detections), tetrachloroethylene (9 detections), and benzene and 1,1,1-trichloroethane (8 detections each). Alkanes were the most frequently detected class of VOCs in the urban samples.

Correlation analyses provided insight into the occurrence of chemical constituents in the ground-water system beneath the urban area. Concentrations of nitrite plus nitrate, aluminum, copper, zinc, and the number of pesticides decreased as the ground-water age increased. These correlations indicated that with time, these constituents may be removed from the ground-water system.

Statistically significant correlations were found between residential and commercial land use and three water-quality constituents. Concentrations of nickel and the number of pesticides and VOCs detected in a ground-water sample increased as the percentages of residential land use increased. The number of pesticides and VOCs detected decreased as the percentages of commercial land use increased.

The effect of surficial geology on the occurrence of pesticides and VOCs was investigated by calculating frequencies of detection. Pesticides were detected more frequently in urban ground-water samples collected where the surficial geology was sand than in urban ground-water samples collected where the surficial geology was clay. The frequency of detection of VOCs did not show a similar relation.

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