GEOCHEMICAL CHARACTERIZATION OF SHALLOW GROUND WATER IN THE EUTAW AQUIFER, MONTGOMERY, ALABAMA[1]

James L. Robinson and Celeste A. Journey[2]

ABSTRACT: Ground water samples were collected from 30 wells located in, or directly down gradient from, recharge areas of the Eutaw aquifer in Montgomery, Alabama. The major ion content of the water evolves from calcium-sodium-chloride-dominated type in the recharge area to calcium-bicarbonate-dominated type in the confined portion of the aquifer. Ground water in the recharge area was undersaturated with respect to aluminosilicate and carbonate minerals. Ground water in the confined portion of the aquifer was at equilibrium levels for calcite and potassium feldspar. Dissolved oxygen and nitrite-plus-nitrate concentrations decreased as ground water age increased; pH, iron, and sulfate concentrations increased as ground water age increased. Aluminum, copper, and zinc concentrations decreased as ground water age and pH increased. These relations indicate that nitrate, aluminum, copper, and zinc are removed from solution as water moves from recharge areas to the confined areas of the Eutaw aquifer. The natural evolution of ground water quality, which typically increases the pH and decreases the dissolved oxygen content, may be an important limiting factor to the migration of nitrogen based compounds and metals.
(KEY TERMS: ground water hydrology; statistical analysis; water quality; water resources planning; geochemistry.)

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INTRODUCTION

The chemical composition of ground water changes as it interacts with the soil, rock, and sediments along the flow path. Understanding this change in the chemical composition, or evolution, of ground water quality is important in understanding the transport and fate of contaminants. The purpose of this paper is to present data and interpretations that explain how the chemical composition of ground water evolves as it moves from a recharge area of the Eutaw aquifer to a confined area of the aquifer.

The Eutaw aquifer is used for public and private water supply by numerous municipalities in central Alabama. Eastern Montgomery, Alabama, is partially built upon a recharge area of the Eutaw aquifer (Figure 1). Potential degradation of ground water quality in the Eutaw aquifer as a result of urban land use (Robinson, 2002) is a major concern because of the effects on drinking water supplies in central Alabama. Robinson (2002) determined that urban land use in eastern Montgomery may have increased the occurrence and concentration of chloride, nitrate, and metals in shallow ground waters recharging the Eutaw aquifer.

The chemistry of water in the Coastal Plain aquifers was characterized in previous studies on a regional scale (Foster, 1950; Back, 1960; Lee, 1985, 1993; Cook, 1993), and the geochemical processes responsible for changes in ground water chemistry in the Eutaw aquifer were evaluated (Lee, 1985, 1993). Foster (1950) determined that water with high sodium bicarbonate ion content in the Atlantic and Gulf Coastal Plain was the result of calcium replacement by sodium through cation exchange. Back (1960) identified distinct chemical zones (hydrochemical facies) in the Atlantic Coastal Plain aquifer system that resulted from geochemical processes responding to the aquifer lithology and hydrologic flow pattern in a particular region. Similarly, Lee (1993) and Cook (1993) identified distinct zones that represented

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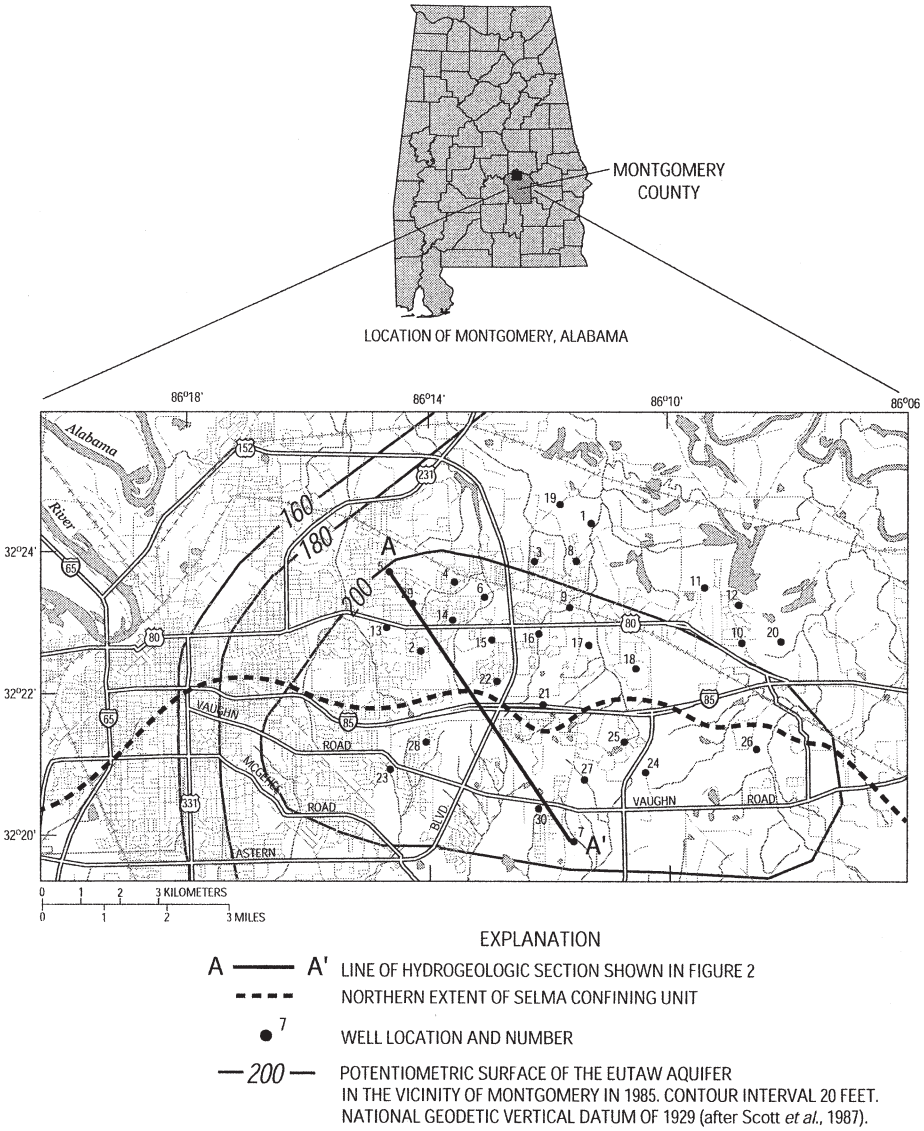

Figure 1. Locations of Sampled Wells, Line of Generalized Hydrogeologic Section, Northern Extent of the Selma Confining Unit, and Potentiometric Surface of the Eutaw Aquifer in 1985, Eastern Montgomery, Alabama.

changes in the ground water chemistry from recharge areas to the deeper confined flow system in the Eutaw aquifer.

HYDROGEOLOGIC SETTING

The City of Montgomery, Alabama, is underlain north to south by alluvial and terrace deposits of gravel, sand, and clay; by sands and clays of the Eutaw aquifer; and by clay and clayey soils developed from the Mooreville Chalk (Table 1). Alluvial and terrace deposits ranging from about 10 meters to more than 30 meters thick form a shallow aquifer that overlies and recharges the Eutaw aquifer in northeastern Montgomery (Scott *et al.,* 1987). Ground water flows radially away from this area (Scott *et al.,* 1987). The Mooreville Chalk, part of the Selma confining unit, is the surficial geologic unit in southern Montgomery. A generalized section illustrating the vertical distribution of hydrogeologic units is presented in Figure 2.

Representative samples were collected from the material drilled during the installation of 30 wells in eastern Montgomery, Alabama (Figure 1). Samples of the alluvial deposits typically were composed of very fine grained to very coarse grained quartz sand and pebbles. Muscovite was common. Silt and clay were mixed with the sand and also were present as

TABLE 1. Generalized Section of Stratigraphic and Hydrogeologic Units Underlying Montgomery, Alabama (from Knowles *et al.,* 1963; Scott *et al.,* 1987; Miller, 1990).

System	Stratigraphic Unit	Major Lithology	Thickness (meters)	Hydrogeologic Unit	Regional Aquifer System
Quaternary	Alluvial and terrace deposits	Sand, gravel, silt, and clay	10 to 30 +	Shallow aquifer	
		Unconformity			
Cretaceous	Selma Group Mooreville Chalk	Chalk and limestone	0 to 150 +	Selma confining unit	Southeastern Coastal Plain Aquifer System
	Eutaw Formation	Upper and lower marine sand separated by clay; consists of glauconitic sand interbedded with calcareous sandstone and sandy limestone	0 to 120 +	Eutaw aquifer	Southeastern Coastal Plain Aquifer System
	Tuscaloosa Group Gordo Formation	Basal zone of gravel and sand overlain by lenticular beds of sand and clay	100 +	Gordo aquifer	Southeastern Coastal Plain Aquifer System
	Coker Formation	Basal zone of nonmarine sand, gravel, and clay; upper zone of marine sand and clay	150 +	Coker aquifer	Southeastern Coastal Plain Aquifer System
Pre-Cretaceous		Schist, gneiss	300 +	Base of freshwater flow system	Southeastern Coastal Plain Aquifer System

separate layers. The lithology of samples of the terrace deposits was similar to that of samples of the alluvial deposits, but quartz gravel up to 100 millimeters in diameter was present in the terrace samples. The Eutaw aquifer is weathered to a depth of up to 30 meters below land surface in eastern Montgomery. Samples of weathered Eutaw aquifer were composed of white and tan, fine grained to medium grained quartz sand with trace amounts of pyrite, muscovite, and calcite. Where the Eutaw aquifer is either overlain by the Selma confining unit or is not near land surface, minerals in the aquifer are not altered or weathered. Samples of unweathered Eutaw aquifer were composed of green, glauconitic sand. A bed of sandstone, generally less than 1 meter thick and cemented with calcium carbonate, is present in some places in the first few meters of the unweathered Eutaw aquifer. Gravel was not found in any lithologic samples from the Eutaw aquifer. The dominant mineral phases of the Eutaw aquifer include quartz, albite (sodium feldspar), orthoclase (potassium feldspar), kaolinite, illite, and montmorillonite (Lee, 1985, 1993; Cook, 1993). Minor amounts of glauconite, calcium carbonate, and pyrite also have been reported (Lee, 1985, 1993; Cook, 1993).

Geochemical reactions occurring along the ground water flow path from recharge areas to the deeper, confined part of the Eutaw aquifer (Lee, 1985, 1993) are alterations of primary mineral phases and formations of secondary mineral phases. Alteration of primary mineral phases includes dissolution of calcite, hydrolysis of feldspars, and oxidation or reduction of iron species. Formation of secondary mineral phases includes kaolinite in the oxygenated part of the aquifer and montmorillonite in the reduced part of the aquifer for aluminosilicate mineral species and goethite in the oxygenated part of the aquifer, then siderite, and finally pyrite in the reduced part of the aquifer as a result of the leaching of iron containing mineral species (Table 2).

The main alteration occurring in the Eutaw aquifer (Lee, 1985, 1993) is detrital sodium feldspars altering to kaolinite, which is the dominant aluminosilicate mineral reaction in the unconfined part of the aquifer. This reaction releases sodium, bicarbonate, and silica to the ground water. Formation of montmorillonite

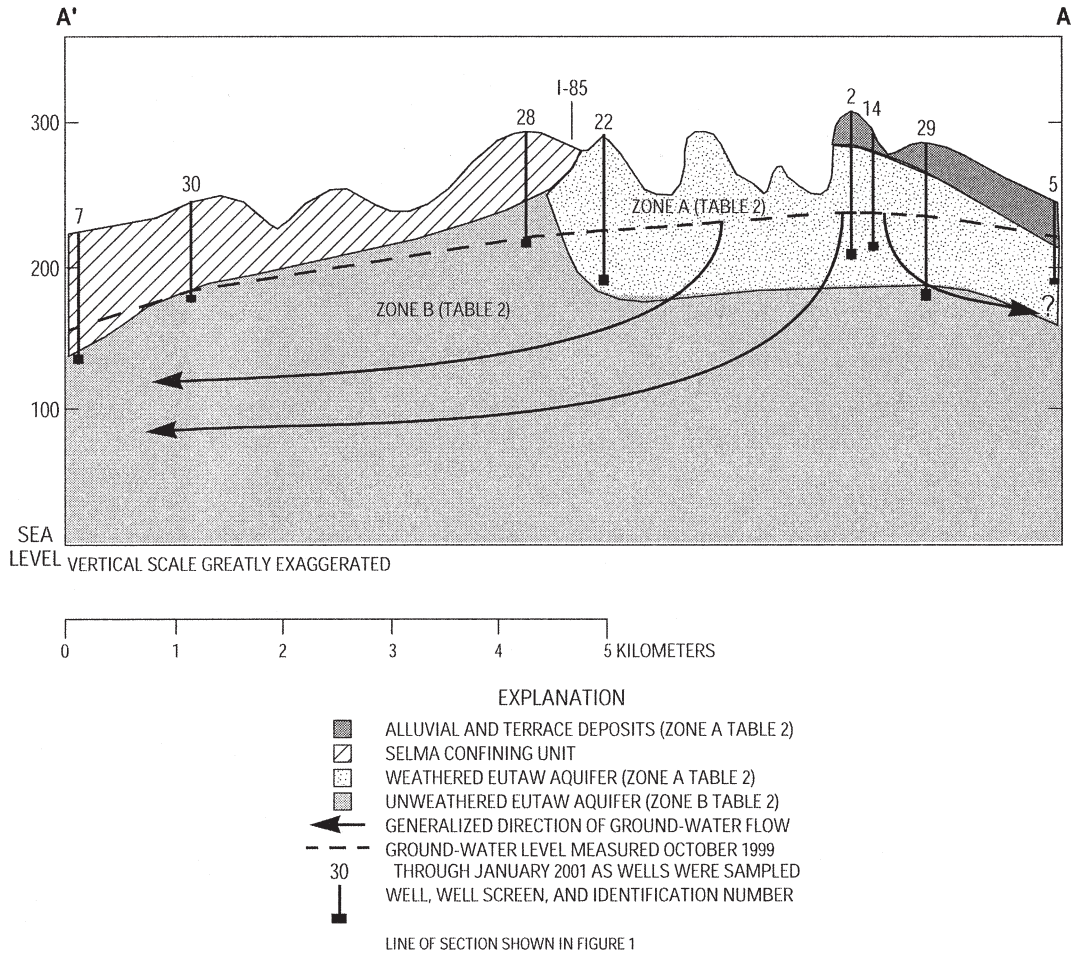

Figure 2. Generalized Hydrogeologic Section Along Dip of Eutaw Aquifer.

potentially occurs in the deeper, confined parts of the aquifer. Oxidation of reduced iron species in minerals, such as pyrite, biotite, and glauconite, occurs in the unconfined part of the aquifer; but secondary iron mineral formation generally is absent. Along the flow path toward the confined part of the aquifer, iron reduction and precipitation of siderite were observed. In very deeply confined areas, pyrite was present with no siderite. Lee (1993) noted that spatial differences in aquifer lithology on a regional and local scale, such as the presence or absence of calcite or pyrite or differences in carbon dioxide input in the recharge areas, may result in slightly different reactions and water chemistry in the aquifer. The local scale of the present study made it possible to identify spatial differences in aquifer lithology, hydrology, and water chemistry in the Eutaw aquifer that were not noted by Cook (1993) and Lee (1993).

Lee (1993) and Cook (1993) reported that ground water chemistry in the Eutaw aquifer evolved from calcium-chloride-sulfate and calcium-bicarbonate water in the recharge area to calcium-bicarbonate and sodium-calcium-bicarbonate water in the confined area of the aquifer, and then to sodium-chloride water in the deepest part of the aquifer (Table 2). However, both Lee (1993) and Cook (1993) described the occurrence of a sodium-chloride influence in ground water in the recharge area of the Eutaw aquifer in the Montgomery area. Lee (1993) suspected that the occurrence of sodium-chloride waters resulted from the migration of deeper ground water towards centers of ground water withdrawal.

METHODS

The wells sampled for this study are distributed randomly throughout a residential and commercial area of eastern Montgomery, Alabama (Figure 1). The wells were designed for sampling shallow ground water beneath or directly downgradient from

TABLE 2. Selected Geochemical Reaction Sequences in Geochemical Zones in the Eutaw Aquifer (modified from Lee, 1985, 1993).

Geochemical Zone	Geochemical Reaction	Expected Change in Ground Water Chemistry
ZONE A	Calcite dissolution	Increase in calcium and bicarbonate.
	Sodium feldspar hydrolysis to kaolinite	Increase in sodium, silica, and bicarbonate.
ZONE B	Calcite dissolution	Increase in calcium and bicarbonate.
	Sodium feldspar hydrolysis to kaolinite	Increase in sodium, silica, and bicarbonate.
	Iron (III) reduction to iron (II) to saturation with siderite	Change in reduction-oxidation potential in aquifer from oxic to anoxic.
ZONE C	Silica precipitation	Decrease in silica.
	Calcite dissolution	Increase in calcium and bicarbonate.
	Sodium feldspar hydrolysis to kaolinite	Increase in sodium, silica, and bicarbonate.
	Iron (III) reduction to iron (II)	Change in reduction-oxidation potential in aquifer.
	Siderite precipitation	Decrease in iron and bicarbonate.
	Silica precipitation	Decrease in silica.
ZONE D	Montmorillonite precipitation	None
	Calcite dissolution	Increase in calcium and bicarbonate.
	Calcium for sodium cation exchange	Sodium enrichment.
	Gypsum dissolution	Increase in calcium and sulfate.
	Sulfate reduction	Change in the reduction-oxidation potential.
	Pyrite precipitation	Decrease in iron and sulfur.
	Iron (III) reduction to iron (II)	Change in reduction-oxidation potential in aquifer.
	Silica dissolution	Decrease in silica.
ZONE E	Mixing with saline waters	Increase in sodium and chloride.

recharge areas of the Eutaw aquifer. The wells are completed in the Eutaw aquifer (16 wells), the alluvial deposits (eight wells), and the terrace deposits (six wells). The depth-to-open interval of the wells ranges from about 2 to 27 meters, with a median value of about 9 meters. The wells were constructed by using threaded, five-centimeter diameter polyvinyl chloride casing with 3-meter long, 0.025-centimeter slotted screens. All equipment used to drill the monitoring wells was decontaminated with a steam cleaner prior to the drilling of each well. The well casing and screen were cleaned with the steam cleaner and then rinsed with deionized water.

Ground water samples were analyzed for physical properties, major ions, nutrients, trace metals, dissolved gases, chlorofluorocarbons, and sulfur hexafluoride. Sampling procedures were consistent with U.S. Geological Survey ground water sampling protocols (Koterba *et al.,* 1995). The major ion concentrations and results of dissolved carbon dioxide, methane, and oxygen analyses were used to determine the basic geochemistry and the dominant reduction oxidation process in the aquifer. Analytical results were published in Pearman *et al.* (2000) and Robinson (2002).

Chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) were used to estimate the age of ground water in the aquifer (Busenburg and Plummer, 1992, 1997). Production of CFC-12 (dichlorodifluoromethane, CF_2Cl_2) began in 1931, followed by CFC-11 (trichlorofluoromethane, $CFCl_3$) in 1936, and then CFC-113 (trichlorotrifluoroethane, $C_2F_3Cl_3$). Sulfur hexafluoride has been accumulating rapidly in the atmosphere since 1953 (Busenberg and Plummer, 1997, 2000). Ground water age dates were based on the historical atmospheric mixing ratios of these compounds. The CFC and SF_6 sampling techniques were consistent with the methods described by the U.S. Geological Survey (1999). The CFC age dating technique was described in Busenburg and Plummer (1992) and Plummer *et al.* (1993). The SF_6 age dating technique was described in Busenburg and Plummer (1997).

The chemical composition of ground water in the Eutaw aquifer underlying eastern Montgomery, Alabama, was characterized by plotting the major ion concentration of the ground water on a Piper trilinear diagram (Figure 3) (Piper, 1944; Hem, 1992). Changes in the chemical composition of ground water along a theoretical flow path in the Eutaw aquifer

were characterized by plotting the major ion concentrations from selected wells that represent different locations along the flow path, based on age (Figure 4). Changes in the location of sample points on the Piper diagram demonstrate changes in the chemical character of the ground water. These data were compared to previous studies to identify geochemical zones. Aqueous speciation and saturation indices were determined for the three wells that represent change in ground water chemistry along the flow path (Figure 4).

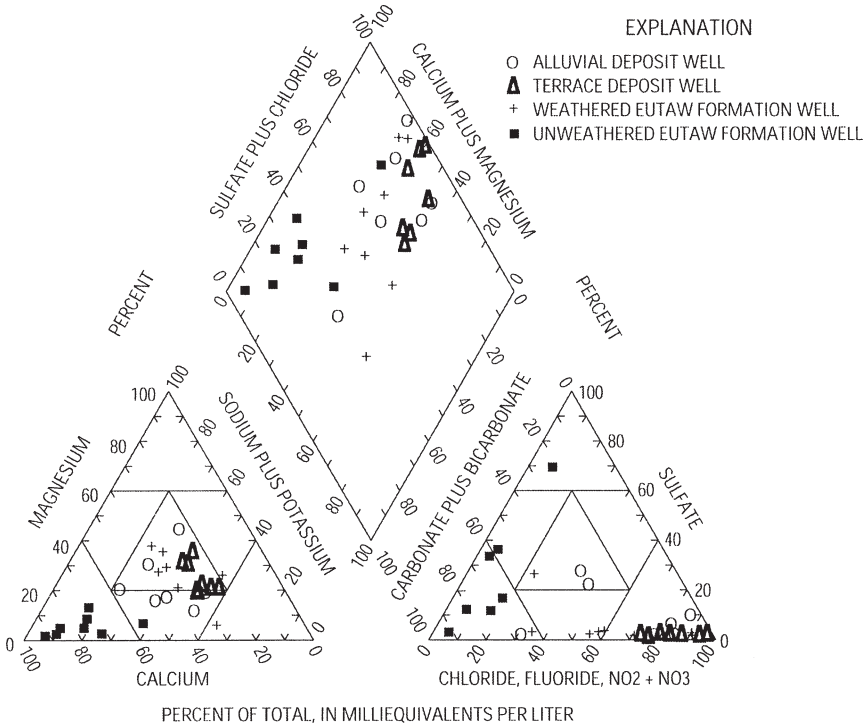

Figure 3. Major Ion Composition of Ground Water Collected From Wells in Montgomery, Alabama.

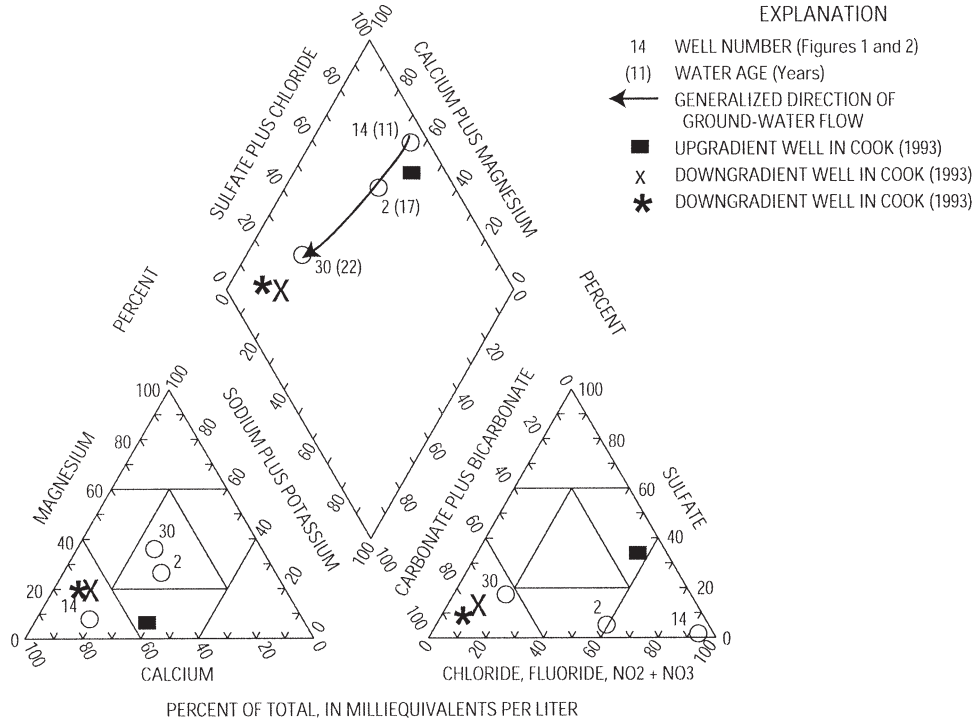

Figure 4. Geochemical Evolution of Ground Water in the Eutaw Aquifer Beneath Eastern Montgomery, Alabama.

Aqueous speciation and saturation indices were calculated by using the PHREEQE geochemical model, which is designed to perform a wide variety of low temperature aqueous geochemical calculations (Parkhurst *et al.,* 1980). Input to the model is the chemical composition of the ground water solution. The model calculates the distribution of the aqueous species and saturation indices for possible mineral phases.

Covariance among selected factors that may influence ground water quality in the shallow aquifer underlying the study area was determined by using the Spearman-rho rank correlation test. Correlation tests are used to calculate a probability statistic (*p*-value) and a correlation coefficient. The probability statistic is compared to α, or the significance level selected by the investigator. For this report, a *p*-value less than $\alpha = 0.05$ or 5 percent was the criterion selected for statistically significant correlations. The correlation coefficient indicates the strength of the correlation between two independent variables, where 1.0 and -1.0 indicate a perfect positive and negative correlation, respectively.

Scatterplots were made of all correlated parameters to assure that the parameters possessed a monotonic correlation (Helsel and Hirsch, 1992). Tests were run for covariance among physical properties, major ions, nutrients, metals, depth-to-screened interval, ground water age, soil organic carbon content, and soil pH. For the purposes of correlation, concentrations of major ions and metals less than the reporting level were assigned a value of one-half the reporting level so that values less than the reporting level would not receive equal rank to measured values equal to the reporting limit.

CHEMICAL EVOLUTION OF SHALLOW GROUND WATER

The chemical composition of water changes as it flows through the ground and interacts with soil, rock, and sediments. Natural processes that cause changes in water chemistry include mixing with older ground water, reduction oxidation (redox) reactions, ion exchange, dissolution of undersaturated minerals, and precipitation of oversaturated compounds. Recently recharged ground water is likely to have greater dissolved oxygen levels because it contains atmospheric oxygen and has an acidic pH, and because atmospheric or microbial carbon dioxide (CO_2) dissolved in the water produces carbonic acid. Recently recharged ground water also is typically low in dissolved solids because insufficient time has passed for the carbonic acid to dissolve minerals. As ground water moves away from the recharge area, readily soluble minerals, such as carbonates (calcite – $CaCO_3$, dolomite – Ca, $MgCO_3$, siderite – $FeCO_3$), are dissolved. Iron rich minerals, such as sulfides (pyrite – FeS_2), are altered either by dissolution or by redox reactions. Aluminosilicate minerals, such as albite, orthoclase, glauconite – $K_2(Mg,Fe)_2Al_6(Si_4O_{10})$, muscovite, and biotite, undergo hydrolysis to clay minerals, such as kaolinite and montmorillonite. These reactions tend to increase the dissolved solids content and alkalinity of the ground water.

Redox conditions within the aquifer must be defined to understand the geochemistry in the aquifer because they determine the species and solubility of dissolved constituents in water at a given pH. Equilibrium redox couples at a pH value of seven include (in order of decreasing Eh) O_2/H_2, Mn^{4+}/Mn^{2+}, NO_3^-/NO_2^-, NO_2^-/NH_4^+, Fe_3^+/Fe_2^+, $SO_4 2^-/S^-$, SO_4^{2-}/H_2S, S^0/H_2S, HCO_3/CH_4, and H_2O/H_2. Dissolved oxygen in the ground water is consumed during some geochemical reactions that can be biologically mediated and that define zones based on the dominant electron-accepting process (Chapelle, 1993; Chapelle *et al.,* 1995). Once the dissolved oxygen is depleted, a denitrifying zone is defined based on the reduction of nitrate concentrations, which represent oxidized species in the ground water (Baedecker and Back, 1979; Bulger *et al.,* 1989). Increased dissolved iron concentration defines the iron reducing zones (Langmuir, 1969; Chapelle and Lovley, 1992) when (or where) Fe^{3+} is reduced to the more soluble form Fe^{2+}. Sulfate reducing zones are based on the removal of sulfate (Thorstenson *et al.,* 1979) or production of sulfide (Jackson and Patterson, 1982), and methanogenic zones are based on the accumulation of methane (Thorstenson *et al.,* 1979). However, the consumption of electron acceptors (e.g., removal of sulfate) and accumulation of the final product (e.g., release of sulfide) in the ground water is not always definitive of the redox process because of dissolution and precipitation processes that could be occurring conjunctively (Chapelle *et al.,* 1995).

Calcareous sandstone and limestone interbedded with glauconitic sand, detrital feldspar, and mica are the sources of iron (Fe), sodium (Na), calcium (Ca), silicic acid (H_4SiO_2), carbonate (CO_3), and bicarbonate (HCO_3) ions in the Eutaw aquifer (Cook, 1993). These minerals are altered or dissolved by recently recharged, acidic water in areas where the Eutaw aquifer is at or near land surface. Some of the dissolved solids and especially nitrate in the recently recharged ground water could come from anthropogenic sources, such as fertilizers and wastewater. The lack of reactive mineral species in the weathered Eutaw aquifer produces a major ion composition similar to that of the alluvial and terrace deposits.

The characterization of the evolution of ground water along its flow path is illustrated by using major ion and dissolved gas analyses of samples collected from three wells completed in the Eutaw aquifer (Table 3). These three wells were selected to represent different locations along the flow path based on the ground water age as determined by CFC and SF_6 techniques and the presence of the confining unit (Figures 1 and 2). Of the three wells, Well 14 represents the most upgradient well in the unconfined, weathered part of the Eutaw aquifer. In the downgradient direction, Well 2 also is in the unconfined, weathered part of the Eutaw aquifer, and Well 30 is in the confined, unweathered part of the Eutaw aquifer. At Wells 14 and 2, the dominant water types are calcium-sodium-chloride and calcium-sodium-magnesium-chloride-bicarbonate, respectively (Figure 4). This water type is somewhat similar to the calcium-chloride-sulfate type described by Cook (1993) in the recharge area of the Eutaw aquifer near Montgomery, Alabama, except for the absence of sulfate. A small increase in the percentage of magnesium and bicarbonate is observed as the ground water moves downgradient from Well 14 to Well 2 (Figure 4). Ground water in Well 30, from the confined, unweathered part of the Eutaw aquifer, is a calcium-bicarbonate water type, again similar to the calcium-bicarbonate zone described by Cook (1993).

The downgradient increase in iron and bicarbonate concentrations and decrease in nitrite-plus-nitrate and dissolved oxygen concentrations from Well 14 to Well 30 (Table 3) indicate that the downgradient extent of the flow path may be in Zone B or Zone C described by Lee (1993) (Table 2). The presence of nitrous oxide (N_2O) in Wells 14 and 2, an intermediate compound formed by microbial respiration process where nitrate is used as a terminal electron acceptor and is reduced to nitrogen gas (N_2) (Tesoriero *et al.,* 2000), may indicate active denitrification. The dominant terminal electron accepting process probably

TABLE 3. Values for Physical Properties and Concentrations of Selected Chemical Constituents in Ground Water Collected From Three Wells in the Eutaw Aquifer, Montgomery, Alabama.

Water Quality Property or Constituent	Well 14 (Figure 1)	Well 2 (Figure 1)	Well 30 (Figure 1)
pH	5.1	5.1	7.3
Specific conductance (µS/cm)	271	56	650
Alkalinity (mg/l as $CaCO_3$)	5.4	5.5	25
Water temperature (degrees Celsius)	22	20	19
Dissolved oxygen (mg/l)	4.2	4.9	0.15
Ground water age (years)	11	17	22
Ammonia (mg/l)	< 0.02	0.02	0.03
Aluminum (µg/l)	38	19	2.9
Bicarbonate (mg/l as HCO_3)	6.6	6.7	270.0
Calcium (mg/l)	16.0	3.4	101.0
Chloride (mg/l)	30	7	42
Copper (mg/l)	1	5	< 1
Iron (µg/l)	9	127.0	535.0
Fluoride (mg/l)	< 0.10	< 0.10	0.4
Magnesium (mg/l)	7.1	1.4	4.9
Nitrite plus nitrate (mg/l)	14.8	1.38	< 0.05
Nitrite (mg/l)	< .01	< .01	< .01
Nitrogen gas (mg/l)	15	Not measured	22
Nitrous oxide (N_2O) present	yes	yes	no
Potassium (mg/l)	2.3	1.6	2.0
Silica (mg/l)	13.3	17.8	29.7
Sodium (mg/l)	15	2.5	28
Sulfate (mg/l)	0.49	0.28	59.0
Zinc (µg/l)	13	21	1

changes from denitrification to iron reduction in the confined portion of the aquifer. The relatively high concentrations of sulfate and iron in water collected from Well 30 indicate that sulfate reduction and pyrite precipitation occur farther downgradient (Zone D, Table 2).

ESTIMATION OF SATURATION INDICES

Saturation indices for selected mineral phases were calculated by using the PHREEQE geochemical model. Mineral phase selection was based on reported mineralogical data (Cook, 1993; Lee, 1993) and descriptions of lithologic samples collected during the drilling of wells for this study. The chemical constituent values in Table 3 served as input to the model. For the model, the mass of water was assumed to be 1.0 kilogram per liter and the activity of the water was estimated to be 1.0 (default options). Redox couples of O^{2-}/O^{0} and N^{3+}/N^{5+} were defined in the input.

Saturation indices indicate whether the mineral phase is oversaturated (positive saturation index), undersaturated (negative saturation index), or in equilibrium (zero or near zero saturation index) with respect to the ground water chemistry in the wells (Table 4). Oversaturated conditions result in precipitation of the mineral phase and undersaturated conditions result in dissolution or alteration of the mineral phase.

TABLE 4. Saturation Indices for Water From Selected Wells in the Eutaw Aquifer in Montgomery, Alabama (wells located on Figure 1).

Mineral Species	Well 14	Well 2	Well 30
Albite (sodium feldspar)	-4.98	-5.64	-1.51
Potassium feldspar	-3.41	-3.43	-0.25
Calcite	-5.54	-6.20	0.07
Dolomite	-11.12	-12.49	-0.89
Siderite	-13.50	-12.40	-9.09
Gypsum	-3.87	-4.66	-1.25
Muscovite	3.39	2.76	6.37
Quartz	0.37	0.52	0.76
Amorphous silica	-0.92	-0.78	-0.54
Kaolinite	2.75	2.46	3.37
Calcium-montmorillonite	0.30	0.03	2.33
Gibbsite	0.60	0.31	0.52
Amorphous iron hydroxide	-0.86	0.41	2.83
Goethite	4.94	6.13	8.50

Saturation indices indicate that the aluminosilicate minerals albite (sodium feldspar) and potassium feldspar were undersaturated with respect to the ground water in Wells 2 and 14, indicating that hydrolysis of these minerals could be occurring in the Eutaw aquifer. In Well 30, however, the saturation indices for aluminosilicate minerals, especially potassium feldspar, appeared to be approaching equilibrium levels. Kaolinite was oversaturated in all wells, supporting the hydrolysis of albite to kaolinite reported by Lee (1993) (Table 2). Ground water in Wells 2 and 14 was undersaturated with respect to carbonate minerals, creating the possibility of calcite dissolution. However, the ground water in Well 30 was in equilibrium with calcite, suggesting that calcite dissolution was not occurring in this section of the ground water flow path. Calcium montmorillonite was oversaturated in Well 30, indicating the potential for montmorillonite formation in lieu of kaolinite. Goethite was oversaturated in all three wells.

CORRELATION ANALYSIS

The results of correlation analysis (Table 5) are consistent with the results of geochemical modeling of the chemical evolution of ground water in the Eutaw aquifer. The pH, alkalinity, and dissolved solids content of the ground water increased as ground water age increased; dissolved oxygen content decreased as ground water age increased. Concentrations of iron, sulfate, sodium, and calcium increased as ground water age increased, suggesting dissolution of carbonate, reduction of iron from sulfide bearing rocks, and hydrolysis of aluminosilicates. These processes raise the pH, alkalinity, and dissolved solids content of the ground water. Decreases in concentrations of aluminum (Figure 5), copper, and zinc (Tables 3 and 5) as ground water age increased may indicate that increasing pH and changing pH-Eh conditions cause these metals to form insoluble compounds, thus removing them from solution. Dissolved oxygen and nitrite-plus-nitrate concentrations decreased as ground water age increased, whereas dissolved nitrogen gas and iron concentrations increased as ground water age increased. These data may indicate that natural phenomena, such as denitrification, are removing nitrate from solution.

CONCLUSIONS

The major ion content of ground water in the Eutaw aquifer in eastern Montgomery, Alabama,

TABLE 5. Spearman-Rho Rank Correlation Coefficients for Selected Parameters.

Variables	Number of Sample Pairs	Correlation Coefficient	Probability Statistic
Significant Correlations of Water Quality Properties and Ground Water Age			
pH	30	0.53	0.002
Alkalinity ($CaCO_3$, mg/l)	30	0.49	0.005
Solids, residue at 180°C (mg/L))	30	0.56	0.001
Dissolved oxygen (mg/l)	30	-0.43	0.017
Dissolved nitrogen gas (mg/l)	28	0.51	0.009
Significant Correlations of Ions and Ground Water Age			
Iron (µug/l as Fe)	30	0.54	0.002
Sulfate (mg/l as SO_4)	30	0.51	0.005
Sodium (mg/l as Na)	30	0.50	0.005
Calcium (mg/l as Ca)	30	0.47	0.009
Significant Correlations of Dissolved Metals and pH			
Aluminum (µg/l)	30	-0.85	0.0001
Zinc (µg/l)	30	-0.63	0.0002
Copper (µg/l)	30	-0.49	0.006
Significant Correlations of Dissolved Metals and Ground Water Age			
Aluminum (µg/l)	30	-0.54	0.002
Zinc (µg/l)	30	-0.41	0.026
Copper (µg/l)	30	-0.59	0.0007
Significant Correlations of Water Quality Properties and Nitrite Plus Nitrate			
Alkalinity ($CaCO_3$, mg/l)	30	-0.80	0.0001
pH	30	-0.75	0.0001
Ground water age (years)	30	-0.57	0.001
Dissolved oxygen (mg/l)	30	0.64	0.0001

evolves from calcium-sodium-chloride water in the recharge area to calcium-bicarbonate water in the confined portion of the aquifer. The results of geochemical modeling indicate that ground water in the recharge area was undersaturated with respect to aluminosilicate and carbonate minerals. Ground water in the confined portion of the aquifer was at equilibrium levels for calcite and potassium feldspar, and oversaturated with respect to calcium montmorillonite, indicating the potential for montmorillonite formation in lieu of kaolinite. Kaolinite and goethite were oversaturated in ground water samples collected from all portions of the aquifer. This distribution of water chemistry is similar to geochemical zones described in regional studies (Cook, 1993; Lee, 1993). Minor differences between historical data sets and this data set are the result of the local scale of this study, which identified changes in aquifer lithology, hydrology, and water chemistry over short distances.

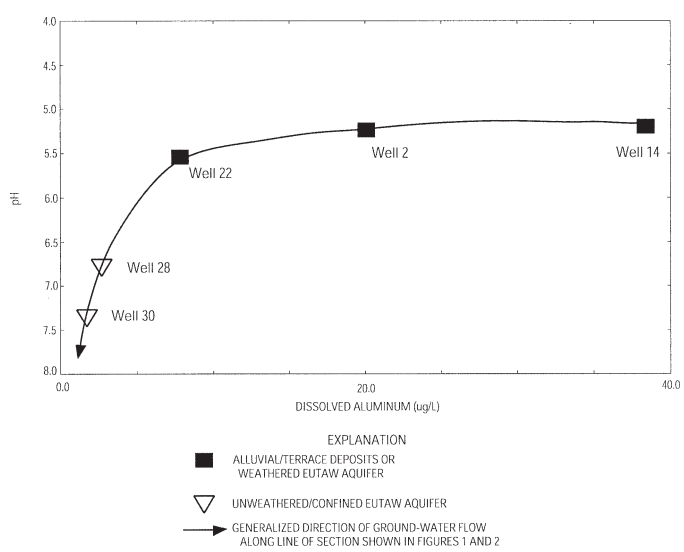

Figure 5. Covariance Between Dissolved Aluminum and pH Along a Generalized Ground-water Flow Path.

Spearman-rho rank correlation analyses indicate that concentrations of dissolved oxygen, nitrate, aluminum, copper, and zinc in water collected from the Eutaw aquifer in eastern Montgomery, Alabama, were inversely correlated to ground water age. The pH and dissolved solids concentration of water in the Eutaw aquifer were directly correlated to ground water age. The results of correlation analyses are consistent with the results of geochemical modeling of the evolution of shallow ground water quality in the Eutaw aquifer.

The results of geochemical and statistical analyses illustrate how changing physical and chemical conditions in an aquifer may determine the fate and migration potential of contaminants. Accurate interpretation of water quality data, and planning effective monitoring and remediation strategies depend on having an understanding of the natural variability of ground water quality in an aquifer and a thorough knowledge of the mineralogy, hydrology, and geochemical conditions of the aquifer. Although urban land use in the recharge area of an aquifer may introduce nitrates and metals into the ground water, data presented here demonstrate how the downgradient transport of nitrate and metals may be limited by geochemical constraints.

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