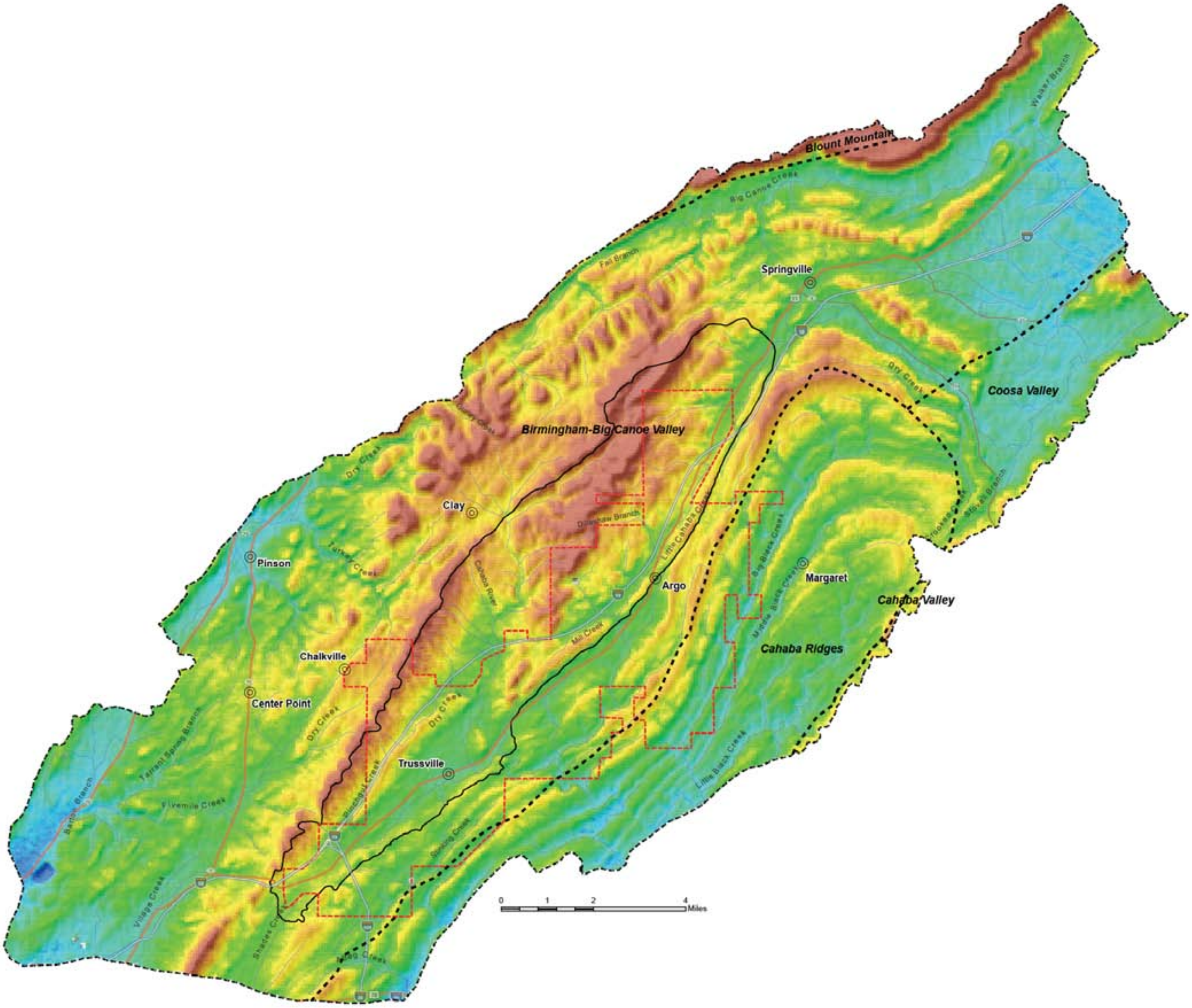
GROUNDWATER HYDROGEOLOGIC CHARACTERIZATION, PRESERVATION, AND DEVELOPMENT IN THE TRUSSVILLE AREA, JEFFERSON AND ST. CLAIR COUNTIES, ALABAMA



Trussville Utilities
TRUSSVILLE UTILITIES WATER & NATURAL GAS

GEOLOGICAL SURVEY OF ALABAMA

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GROUNDWATER HYDROGEOLOGIC CHARACTERIZATION, PRESERVATION, AND DEVELOPMENT IN THE TRUSSVILLE AREA, JEFFERSON AND ST. CLAIR COUNTIES, ALABAMA

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CONTENTS

CONTENTS—CONTINUED

ILLUSTRATIONS

CONTENTS—CONTINUED

ILLUSTRATIONS—CONTINUED

TABLES

PLATES

CONTENTS—CONTINUED

PLATES—CONTINUED

EXECUTIVE SUMMARY

All public-water supplies in the Trussville area of northeastern Jefferson County are produced from groundwater sources. Due to increasing population, land-use change, and concerns about the long-term viability of current water sources, the Geological Survey of Alabama (GSA) initiated the Groundwater Hydrogeologic Characterization, Preservation, and Development Project in July 2009. The study was a cooperative effort between Trussville Utilities and the GSA.

The hydrogeologic investigation addresses six major topics including stratigraphy and structure; land-use/land-cover; physical, chemical, and isotopic characteristics and composition; groundwater age dating and movement; recharge; and groundwater exploration. The area of investigation is located in the Appalachian fold-thrust belt, characterized by Paleozoic sedimentary rocks ranging in age from Cambrian to Pennsylvanian, deformed into a series of thrust sheets and thrust-related folds during the late Paleozoic Alleghanian orogeny. There are four potential aquifers and five confining units, although all of Trussville Utilities current water production is from the Bangor Limestone and the Tuscumbia Limestone/Fort Payne Chert. The investigated area is at the northeast terminus of the Birmingham Anticlinorium and includes major geologic structures such as the Argo and Happy Hollow Thrust Faults and Cahaba Mountain Syncline.

Land-use/land-cover in the recharge area is dominated by mixed forest (75.3%) and grass/pasture (13.0%). Much of this undeveloped land is in the central and northeastern parts of the recharge area. All of the current Trussville Utilities water production wells are in the southwestern part of the area, dominated by developed/residential, roads, and parking spaces and developed/commercial land-use classifications.

Groundwater levels, drawdown, and geochemical parameters were used to characterize groundwater movement and climate and production impacts. Based on chlorofluorocarbon analyses, apparent groundwater ages in the investigated aquifers ranged from 17.5±2 to 30.5±2 years. Sulphur hexafluoride-based ages determined for W-6 and P-1 were 28±2 and 1±2 years, respectively.

Analysis of groundwater age distribution with depth indicated that water in the Tuscumbia Limestone/Fort Payne Chert aquifer flows from northeast to southwest along the Cahaba Mountain Syncline at a rate of about 2.4 miles per year.

Unlike the Coastal Plain where groundwater recharge can move long distances in aquifers that exceed depths of 2,500 feet (ft) or the Tennessee River watershed area where aquifers are relatively thin and shallow with local recharge, the Valley and Ridge is characterized by large, complex structures with faults and fractures that create local and long distance pathways for groundwater movement. Recharge rates are controlled by a number of factors including porosity, which in Paleozoic aquifers is primarily secondary and tertiary and is the result of leached fossils, bedding plane conduits, fractures, and solution cavity development and permeability, and relies on the magnitude of interconnectedness of pore spaces.

Average precipitation in the Trussville area is 56 inches per year and is distributed as runoff, evapotranspiration, and groundwater recharge. Since most groundwater recharge is discharged to streams as baseflow in aquifer recharge areas, estimates of baseflow may be used to approximate groundwater recharge rates. This is accomplished by separating baseflow and runoff components of stream flow. GSA used the automated hydrograph separation program WHAT (Web Based Hydrograph Analysis Tool) to estimate baseflow and then calculated recharge rates and volumes using estimated baseflow values. The investigated area was divided into two recharge zones to evaluate the Tuscumbia Limestone/Fort Payne Chert aquifer along the Cahaba Mountain Syncline and the Bangor Limestone and Tuscumbia Limestone/Fort Payne Chert aquifers along and southeast of the Argo Fault.

One of the primary purposes of this investigation was to recommend sites for test well drilling in the Trussville Utilities service area. The GSA Ground-water Assessment Program (GAP) research resulting in possible test well locations included field assessments and evaluation of available published data. GSA GAP recommended seven test well locations in the Trussville Utilities service area. Three of the recommended sites were drilled between January 2011 and January 2012. A fourth well was drilled to evaluate the potential for economic quantities of water on a tract of land owned by Trussville Utilities north of I-59 and east of Deerfoot Parkway along the Cahaba River. The primary objective for the first three wells was the Tuscumbia Limestone/Fort Payne Chert.

The first test well was drilled near the intersection of U.S. Highway 11 and Deerfoot Parkway. The well encountered 30 ft of Hartselle Sandstone underlain by 363 ft of Pride Mountain Formation before penetrating the Tuscumbia Limestone. The well was terminated in the Tuscumbia Limestone at a depth of 485 ft with no economic quantities of water encountered. An unexpected steepening of dips in the Pride Mountain Formation caused the Fort Payne Chert to be at excessive depth at the drilled location.

Test well 2 was drilled just north of the Happy Hollow Fault, 0.5 mile south of Happy Hollow Road and I-59 and 0.5 mile west of Deerfoot Parkway. The primary objective was the Tuscumbia Limestone/Fort Payne Chert. The well penetrated 59 ft of Pride Mountain Formation, 32 ft of extremely karstified Tuscumbia Limestone, and 54 ft of Fort Payne Chert. The well was terminated at a depth of 145 ft. The Tuscumbia Limestone contained water in several karst zones. However, it was too shallow to be considered for testing. The entire Fort Payne Chert

The third test well was drilled in the Argo community near the intersection of U.S. Highway 11 and Micklewright Road. The well was drilled into an overturned section adjacent to the Argo Fault with the Fort Payne Chert as the primary objective. The well penetrated 190 ft of Red Mountain Formation underlain by 347 ft of Fort Payne Chert. No Tuscumbia Limestone was recognized and the well was terminated in the Pride Mountain Formation at a depth of 555 ft. The entire Fort Payne Chert section was deeply weathered to clay with remnant chert beds. There was no economic quantity of water encountered.

section was deeply weathered and consisted of clay with thin, remnant chert beds.

The fourth test well was drilled 1 mile north of I-59, just east of Deerfoot Parkway and the Cahaba River on a tract of land owned by Trussville Utilities. The Fort Payne Chert in this area consists of erosional remnants and was not considered a viable exploration target. Therefore, the primary objective was the Sequatchie Formation and Chickamauga Limestone. The well penetrated 30 ft of Fort Payne Chert, 230 ft of Red Mountain Formation, and 246 ft of Sequatchie Formation and Chickamauga Limestone. The well was terminated at a depth of 506 ft. The well encountered several carbonate water bearing zones in the lower Red Mountain Formation and upper Sequatchie Formation and Chickamauga Limestone but quantities were considered inadequate for testing.

Recommendations based on the hydrogeologic investigation and test well drilling involve protection of aquifer recharge areas and potential for groundwater source development. Land use is a major issue impacting current and future water supplies for the Trussville area. All of Trussville Utilities current groundwater production is in or near heavily developed areas. Although current water-quality impacts are minor, future water source development should occur in less developed areas where water quality can be more easily protected. The recharge area for aquifers in the Trussville Utilities Service area covers about 40 mi^2. Much of this area is undeveloped or has only sparse commercial and residential development, particularly northeast of the city. Due to the shallow, karst character of available aquifers, these areas must be protected in the future to insure high quality water sources. Protective measures may include land purchases, cooperative efforts with state and federal agencies to implement protective incentive programs, and legislation or ordinances to guide planning and development.

Based on recent strategic test well drilling, it appears that the U.S. Highway 11 corridor northeast of the city of Trussville has limited potential for future groundwater development for public water supplies. Although the Tuscumbia Limestone/Fort Payne Chert is a prolific aquifer in many areas of the Alabama Valley and Ridge, it is extremely weathered in outcrop and appears to be similarly weathered in the subsurface from Argo (where test well number 2 was drilled) southwestward to Deerfoot Parkway. The same situation exists in the Happy Hollow Road area where test well number 3 was drilled. Therefore, other than high risk test wells to evaluate the Knox Group or Bangor Limestone, the most viable area for test well drilling is along the Cahaba Mountain Syncline, northeast of the city of Trussville, to evaluate the Tuscumbia Limestone/Fort Payne Chert.

INTRODUCTION

All public-water supplies in the Trussville area of northeastern Jefferson County are produced from groundwater sources. Due to increasing population, land-use change, and concerns about the long-term viability of current water sources, the Geological Survey of Alabama (GSA) initiated the Groundwater Hydrogeologic Characterization, Preservation, and Development Project in July 2009. The study was a cooperative effort between Trussville Utilities and the GSA.

The purpose of the project was to generate data that can be used by Trussville Utilities to develop and protect groundwater sources. Hydrogeologic, land-use, geochemical, and isotope data were used to evaluate groundwater recharge, movement, aquifer storage, and the potential for developing additional groundwater sources from Paleozoic aquifers in the Trussville Utilities service area. The data were also used to evaluate current and potential future impacts on groundwater sources from land-use changes resulting from economic and population growth in the Trussville area.

ACKNOWLEDGMENTS

The Geological Survey of Alabama acknowledges those individuals whose participation and cooperation made this study possible. The Honorable Gene Melton, Mayor of Trussville; Trussville Utilities Board of Directors, Mr. Gordon Flynn, Chairman, Mr. Bill Wingate, General Manager, Mr. Mike Strong, Chief Financial Officer, and Mr. Brian Smith, Chief Engineer, were instrumental in providing assistance for the completion of this research.

AREA OF INVESTIGATION

The area of investigation covers about 450 square miles (mi^2) in north-central Alabama (northeastern Jefferson and southwestern St. Clair Counties, and includes the Trussville Utilities service area (approximately 44 mi^2), and the aquifer recharge areas for current and potential future aquifers (approximately 40 mi^2) (plate 1). The Trussville Utilities service area is a northeast trending irregular rectangle, approximately 8.5 miles wide, extending from Roebuck Plaza on the southwest to 2.9 miles southwest of Springville on the northeast. The investigation area lies in the Birmingham-Big Canoe Valley district of the Alabama Valley and Ridge physiographic section, characterized by narrow limestone valleys 4 to 8 miles wide developed on faulted anticlinorium (Sapp and Emplaincourt, 1975). Regional geology is dominated by Paleozoic stratigraphy common to the Alabama Valley and Ridge physiographic section (plate 2). Topography in the area is dominated by local geologic structures in the Appalachian fold-thrust belt, including the Cahaba Mountain syncline and the Echo Lake and Argo thrust faults (plate 3).

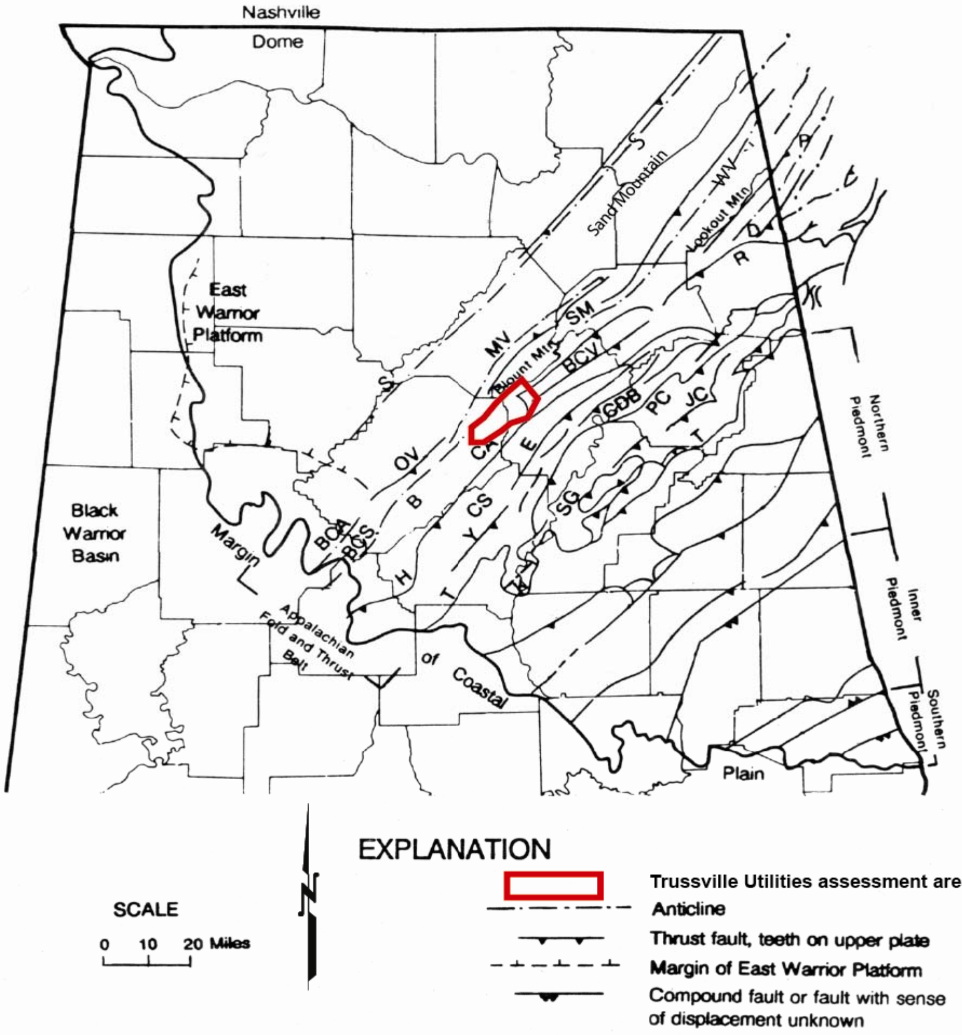
STRATIGRAPHY AND STRUCTURE

The area of investigation is located in the Appalachian fold-thrust belt, characterized by Paleozoic sedimentary rocks ranging in age from Cambrian to Pennsylvanian, deformed into a series of thrust sheets and thrust-related folds during the late Paleozoic Alleghanian orogeny (Osborne and Raymond, 1992). The fold and thrust belt includes parts of 10 counties in northeast and north-central Alabama and is bounded on the northwest by the Black Warrior basin, East Warrior platform, and the Nashville dome and on the southeast by the Appalachian Piedmont (fig. 1).

The investigation area is situated at the northeast terminus of the Birmingham anticlinorium and is bounded on the north by the northeast-striking and northwestward translated Echo Lake thrust fault and on the south by the Pottsville Formation (fig. 1, plate 3). The area is underlain by clastic and carbonate geologic units with the lower part of the sequence composed primarily of limestone and chert and the upper part composed of sandstone and shale. Any sediment deposited in the area in the past 315 million years has been eroded, with the exception of some thin alluvial deposits along the Cahaba River (Raymond and others, 2003). Karst terrains are observed, particularly in Mississippian carbonates along the Cahaba River.

KNOX GROUP UNDIFFERENTIATED

The Knox Group in Alabama can be comprised of several units including the Late Cambrian Copper Ridge Dolomite and the Early Ordovician Chepultepec Dolomite, Longview Limestone, Newala Limestone, and Odenville Limestone. However, all exposures of the Knox Group observed during this investigation were undifferentiated and consisted of chert and dolomite (plate 3). Raymond and others (2003) reported that the Knox Group undifferentiated in the Argo quadrangle, including part of the investigation area, is thought to be comprised of the Copper Ridge and Chepultepec Dolomites. The Longview Limestone or younger units in the



B	Birmingham anticlinorium	MV	Murphrees Valley anticline
BCA	Blue Creek anticline	OV	Opossum Valley fault
BCS	Blue Creek syncline	P	Peavine anticline
BCV	Big Canoe Valley fault	PC	Pell City fault
CA	Cahaba synclinorium	R	Rome fault
CDB	Coosa deformed belt	S	Sequatchie anticline
CS	Coosa synclinorium	SG	Sleeping Giants klippe
D	Dirtseller Mountain syncline	SM	Straight Mountain fault
E	Eden fault	T	Talladega fault system
H	Helena fault	WV	Wills Valley anticline
JC	Jacksonville fault complex	Y	Yellowleaf fault
K	Kelley Mountain window		

Figure 1.—North Alabama major faults and geologic structures (modified from Osborne and Raymond, 1992).

The Knox Group undifferentiated crops out in the core of a breached anticline northeast from the Argo fault along Interstate 59 from Deerfoot Parkway to the northeastern boundary of the investigated area in southwestern St. Clair County (plate 2). It generally underlies areas of relatively low topography, wetlands, and major tributaries to the Cahaba River. The Knox Group undifferentiated was observed along Happy Hollow Road near the intersection of Interstate 59 and Deerfoot Parkway (plate 2). It consists of highly fractured, bedded, dark-gray chert. Raymond and others (2003) report the thickness of the Knox Group in the Argo quadrangle is about 1,300 ft. Although the Knox Group undifferentiated in the area of investigation is not a major aquifer, abundant fractures and cavity development cause the unit to be considered as a test well target.

SEQUATCHIE FORMATION AND CHICKAMAUGA LIMESTONE UNDIFFERENTIATED

The Chickamauga Limestone is of Middle Ordovician age and generally consists of light-gray variably bioturbated, variably fossiliferous limestone (calcareous mudstones, peloidal grainstones, and grainstones). Calcareous siltstone and calcareous shale are locally present at the base of the formation (Raymond and others, 2003).

The overlying Sequatchie Formation is of Late Ordovician age and is estimated to be about 27 ft thick in the Argo quadrangle where it is mapped with the Chickamauga. The Chickamauga-Sequatchie was observed along Deerfoot Parkway south of Interstate 59 in the NE¼NW¼ sec. 18, T. 16 S., R. 1 E. The exposed unit consisted of thick bedded limestone with extensive solution cavity development. A second outcrop was observed west of Deerfoot Parkway in the NE¼SW¼ sec. 7, T. 16 S., R. 1 E., along the base of a narrow valley where it overlies the younger Ft. Payne Chert along a previously unnamed thrust fault (designated as the Happy Hollow fault) (plate 3) at an elevation of about 880 ft above mean sea level. The unit at this location dips from 8 to 13 degrees to the southwest and the top of the formation is at an elevation of about 1,000 ft above mean sea level where it conformably underlies the Red Mountain Formation. Although the Chickamauga-Sequatchie is about 100 ft thick at this location, Raymond and others (2003) report that the average thickness is about 280 ft in the Argo quadrangle. The Chickamauga-Sequatchie is not currently a water producing zone in the area of investigation. However, cavity development observed in outcrops cause it to be considered as a test well target.

RED MOUNTAIN FORMATION

The Red Mountain Formation of Silurian age is a heterogeneous clastic unit, composed of purple-red, dark-red-brown, olive-gray, and light-gray variably ferruginous and fossiliferous, fine- to medium-grained sandstone interbedded with siltstone and shale and containing minor pebbly sandstone and fossiliferous limestone to oolitic ironstone (Butts, 1926; Chowns and McKinney, 1980).

The Red Mountain Formation is a confining unit in the investigated area where it outcrops in three structural settings. The first outcrop is observed in the footwall of the Argo and Echo Lake faults where it dips about 55 degrees southeast, except in the Argo community where the rocks are overturned and dip about 60 degrees to the northwest. The formation in these areas forms the crests of ridges due to its resistant nature. The Red Mountain Formation crops out on the crest of two ridges south of Happy Hollow Road and Interstate 59. Raymond and others (2003) observed the Happy Hollow fault along the northwestern flank of the southernmost ridge in the S½ sec. 7, T. 16 S., R. 1 E., where the Red Mountain overlies the Chickamauga-Sequatchie and dips to the southeast at 8 degrees (plate 3). The crest of the northernmost ridge was previously mapped as Hartselle Sandstone. However, recent mapping indicates that the crestal formation is Red Mountain Formation that dips about 40 degrees northwest and overlies the younger Tuscumbia Limestone/Fort Payne Chert. This interpretation leads to the conclusion that the Happy Hollow fault extends northwestward where the Red Mountain Formation was thrust over the younger rocks in the W½ sec. 7, T. 16 S., R. 1 E. (plate 3).

The formation is observed at higher elevations on the southeast limb of the Cahaba Mountain syncline or northwest flank of a breached anticline in the center of the Argo quadrangle where overlying Mississippian rocks were removed by erosion. The Red Mountain Formation in this area dips about 12 degrees to the northwest (plate 3).

The third outcrop has been observed at relatively low elevations in the Cahaba River Valley in the Cahaba Mountain syncline where overlying Mississippian rocks were removed by erosion. The thickness of the Red Mountain Formation in the area of investigation varies widely due to erosion, from about 500 ft at the southwestern end of the Argo fault to about 100 ft near the intersection of Deerfoot Parkway and Happy Hollow Road (NW¼ sec. 7, T. 16 S., R. 1 E.) (plate 3).

FROG MOUNTAIN SANDSTONE

The Frog Mountain Sandstone of Devonian age was observed at two locations in the investigated area, near the crest of a ridge about 0.5 mile northeast from Deerfoot Parkway in the SW¼SE¼ sec. 7, T. 16 S., R. 1 E. (plate 3). The unit is about 5 ft thick and is composed of medium- to thick-bedded sandstone. The second outcrop occurs on the Trussville Utilities Cahaba River property in the SW¼NW¼ sec. 6, T. 16 S., R. 1 E., where the Frog Mountain is about 3 ft thick (plate 3).

MAURY FORMATION

The Maury Formation of Early Mississippian age unconformably overlies the Red Mountain Formation due to the absence of Devonian sediments in the Trussville area. The unit consists of relatively thin, pale green shale. Outcrops were observed in the area of investigation near the intersection of Deerfoot Parkway and U.S. Highway 11 (SW¼NW¼ sec. 18, T. 16 S., R. 1 E.) where the unit was about 2 ft thick and near the Cahaba River along Deerfoot Parkway north of Interstate 59 (NW¼ sec. 6, T. 16 S., R. 1 E.) (plate 3).

FORT PAYNE CHERT

The Fort Payne Chert consists primarily of thin- to medium-bedded, light-gray to dark-gray, light-yellowish-gray to pale-gray, red-yellow- and black-stained, variably fossiliferous chert (Raymond and others, 2003). Most outcrops in the investigated area are deeply weathered grayish-orange to yellowish-orange clay. Despite deep weathering, the original fabric of the unit is intact including highly fractured, thin chert bedding, nodular chert, and abundant molds of invertebrate fossils, primarily brachiopods, and bryozoans. Exposures of the Fort Payne Chert were observed in the Trussville metropolitan area, along Deerfoot Parkway near U.S. Highway 11 and near the Interstate 59 intersection, and in the Argo community (plate 2). The Fort Payne Chert is the primary aquifer in the Valley and Ridge characterized by relatively high porosity and permeability due to frequent fractures and leached fossils.

TUSCUMBIA LIMESTONE

The Fort Payne Chert is conformably overlain by cherty bioclastic limestone of the Late Mississippian Tuscumbia Limestone (Thomas, 1972). Tuscumbia Limestone is a medium- to thick-bedded, dark-gray, very fossiliferous, sparry limestone with minor shale and nodular chert

(Raymond and others, 2003). Raymond and others (2003) found exposures of the Tuscumbia Limestone in the area of investigation but since the Fort Payne Chert and Tuscumbia Limestone are not easily distinguished, they are mapped as a single unit. Although Raymond and others (2003) reported a thickness of 275 ft in a drill hole on Chalkville Road, test holes drilled during the current investigation indicate that the unit thickness is highly variable or is absent. Eight water supply wells operated by Trussville Utilities are constructed in the Tuscumbia Limestone/Fort Payne Chert on the northeast side of the Trussville metropolitan area in the Cahaba River Valley (plate 4).

PRIDE MOUNTAIN FORMATION

The Pride Mountain Formation of Late Mississippian age conformably overlies the Tuscumbia Limestone/Fort Payne Chert and is exposed in numerous locations in the investigated area. The unit is composed of alternating thinly bedded dark-gray shale and thinly bedded fine-grained sandstone. Easily accessible exposures are observed in excavated areas in the NW¼SW¼ sec. 18, T. 16 S., R. 1 E., near the intersection of Deerfoot Parkway and U.S. Highway 11, where the unit is composed of alternating thin beds of sandstone and shale dipping about 45 degrees southeast (plate 3). It is also exposed in the NW¼SW¼ sec. 34, T. 15 S., R. 1 E., near the intersection of Micklewright Road and U.S. Highway 11 in the Argo community, where the unit consists of deeply weathered, folded white, tan, gray, orange, and purple clay and thinly bedded sandstone (plate 3). The unit is overturned at this location, dipping 56 degrees northwest. Evidence of an ancient landslide was observed in sec. 8, T. 16 S., R. 1 E., where steeply dipping beds in the Pride Mountain Formation and the Hartselle Sandstone along the ridge southeast from the Argo fault collapsed southeastward resulting in a large area of sandstone, shale, and clay rubble (plate 3). Although limited water moves along fractures and bedding planes, the Pride Mountain Formation is the major confining unit in Trussville area.

HARTSELLE SANDSTONE

The Hartselle Sandstone of Late Mississippian age is generally a hard, quartzitic fine- to medium-grained, thin- to thick-bedded medium-gray quartzose sandstone and minor gray to purple-gray shale. The sandstone is in part laminated and commonly crossbedded with common ripple marks (Raymond and others, 2003). The Hartselle Sandstone is resistant to erosion and forms the southeastern flank of a linear ridge that extends along the Argo fault, northeastward from Trussville past the northeastern boundary of the investigated area in southwestern St. Clair County (plate 2). Dips along the ridge vary from 45 to 60 degrees southeast, except in the Argo community where the Hartselle is overturned and dips 35 degrees northwest. It also forms the crest of Little Sand Mountain that extends through the southwestern part of the area of investigation from the Cahaba River, northeast of Trussville, southwestward through Mountain Brook and Homewood in southeastern Jefferson County. The Hartselle Sandstone is a major confining unit about 200 ft thick, overlying previously described carbonate aquifers except in the Argo area where the stratigraphic section is overturned along the Argo fault. Field observations in the investigated area indicate that the unit has little or no primary porosity but stores and transmits limited water along fractures and bedding planes.

BANGOR LIMESTONE

The Bangor Limestone (upper Mississippian) forms a long, narrow valley that extends from the city of Trussville northeastward into St. Clair County (plate 2). It was described in Raymond and others (2003) as medium-light-gray peloidal and fossiliferous grainstone containing crinoids and a few ramose bryozoans and shells. Observations in Blount and Jefferson Counties indicate that the formation is generally massive with little primary porosity (M. R. Cook and S. P. Jennings, unpublished data, 2010). A thickness of 304 ft was measured by Thomas (1972) in the Trussville area. The Bangor Limestone is not considered to be a major source of water supplies in the Trussville Utilities service area and was not evaluated during this investigation.

OTHER UNITS IN THE AREA OF INVESTIGATION

The Floyd Shale, Parkwood Formation, and the Pottsville Formation outcrop in the southeastern part of the Trussville Utilities service area and the investigated area. However, none of these units supply adequate water for public water sources. Therefore, they were not considered during this assessment.

HYDROGEOLOGY

Geologic units capable of yielding adequate quantities of water in the investigated area consist of limestone, dolomite, and chert with little primary porosity and permeability. However, secondary porosity and permeability results from leached fossils, bedding plane conduits, abundant fractures, and karst development. Surface-water discharge and flow directions and groundwater recharge and migration pathways are influenced by karst terrains and complex folds and faults characteristic of the Valley and Ridge.

Water bearing geologic units in the investigated area occur in three hydrogeologic settings with distinctive stratigraphic, structural, and topographic characteristics including the Mississippian Tuscumbia Limestone-Fort Payne Chert outcropping at relatively low elevations along the axis of the Cahaba Mountain syncline; the Ordovician and Cambrian undifferentiated Sequatchie Formation and Chickamauga Limestone and the undifferentiated Knox Group, outcropping at varying elevations along the southeast limb of the Cahaba Mountain syncline and outcropping and overlain by clastic units at relatively high elevations, adjacent to thrust faults along the southeast limb of the Cahaba Mountain syncline (plate 3).

The Tuscumbia Limestone-Fort Payne Chert aquifer in the Cahaba River Valley along the axis of the Cahaba Mountain syncline is exposed at land surface and is under unconfined or semi-confined hydrologic conditions. Eight water supply wells operated by Trussville Utilities are constructed in the Tuscumbia Limestone/Fort Payne Chert aquifer and are located in this setting (plate 4). The Tuscumbia Limestone/Fort Payne Chert aquifer is the primary objective for exploratory drilling in the Trussville Utilities service area due to the brittle character of the Fort Payne Chert that facilitates extensive fracturing and large amounts of water storage over wide areas. However, the absence of adequate aquifer confinement of the aquifer in some areas of the Cahaba River Valley limit test well drilling.

The undifferentiated Knox Group, Chickamauga Limestone, and Sequatchie Formation outcrop at varying elevations on the southeast limb of the Cahaba Mountain syncline, southeastward to the hanging wall of the Argo fault (plate 3). These potential aquifers are fractured and have undergone karst development that was observed during field investigations. These units may be water supply exploration targets along the axis of Little Cahaba Mountain Syncline where they are overlain by the Red Mountain Formation. However they are considered to be secondary objectives for test well drilling due to a lack of proven production.

The Tuscumbia Limestone/Fort Payne Chert aquifer was the primary objective for most test wells in close proximity to the Argo and Happy Hollow thrust faults. However, recent test wells have shown that the Ft. Payne chert is highly weathered and is not a suitable exploration target in this area. The undifferentiated Knox Group, Chickamauga Limestone, and Sequatchie

Formation serve as primary and secondary objectives in some areas of this hydrogeologic setting characterized by relatively high elevations and steep dips in most cases overlain by clastic confining units.

PHYSIOGRAPHY AND TOPOGRAPHY

The investigation area is located in the Alabama Valley and Ridge section of the Valley and Ridge physiographic Province (Sapp and Emplaincourt, 1975). The physiographic districts in this area include the Birmingham-Big Canoe Valley (the aquifer recharge and service areas) and the Cahaba Ridges (the service area) (plate 1). The Birmingham-Big Canoe Valley district, encompassing most of the investigated area (plate 1), is a narrow limestone valley, about 4 to 8 miles wide, developed on a faulted anticlinorium (Sapp and Emplaincourt, 1975) with shale, sandstone, and chert outcroppings. Elevations in this area vary from 298 to 1,522 ft (Esri-Digital Elevation Model, 1998) (plate 1). The Cahaba Ridges district, located southeast of the Birmingham-Big Canoe Valley, represents a series of parallel northeast-prominent ridges underlain by gently folded sandstone and conglomerate beds with prevailing shale valleys. Elevations in this district vary from 550 to 1,139 ft (Esri-Digital Elevation Model, 1998) (plate 1). The relief in the investigation area is characterized by gentle (0 to 5%) to very steep slopes (5 to 29%) (fig. 2). Gentle slopes are mainly confined to developed areas and river bottoms.

SOILS

Soils are formed as a result of the interaction of factors such as climate, animal and plant life, parent material, relief, and time acting simultaneously as destructive and constructive forces (McBride and Burgess, 1964). Depending on the location and the parent material, one of these factors may dominate soil formation and consequently is accountable for the majority of soil properties (McBride and Burgess, 1964). In most cases, weathered geologic materials as well as underlying geologic materials provide a good foundation for soils (McBride and Burgess, 1964). A detailed classification of soil types is offered by the U.S. Department of Agriculture-Natural Resources Conservation Services (USDA-NRCS, 2010), **Soil Survey Geographic**-certified dataset (SSURGO) for Jefferson and St. Clair Counties.

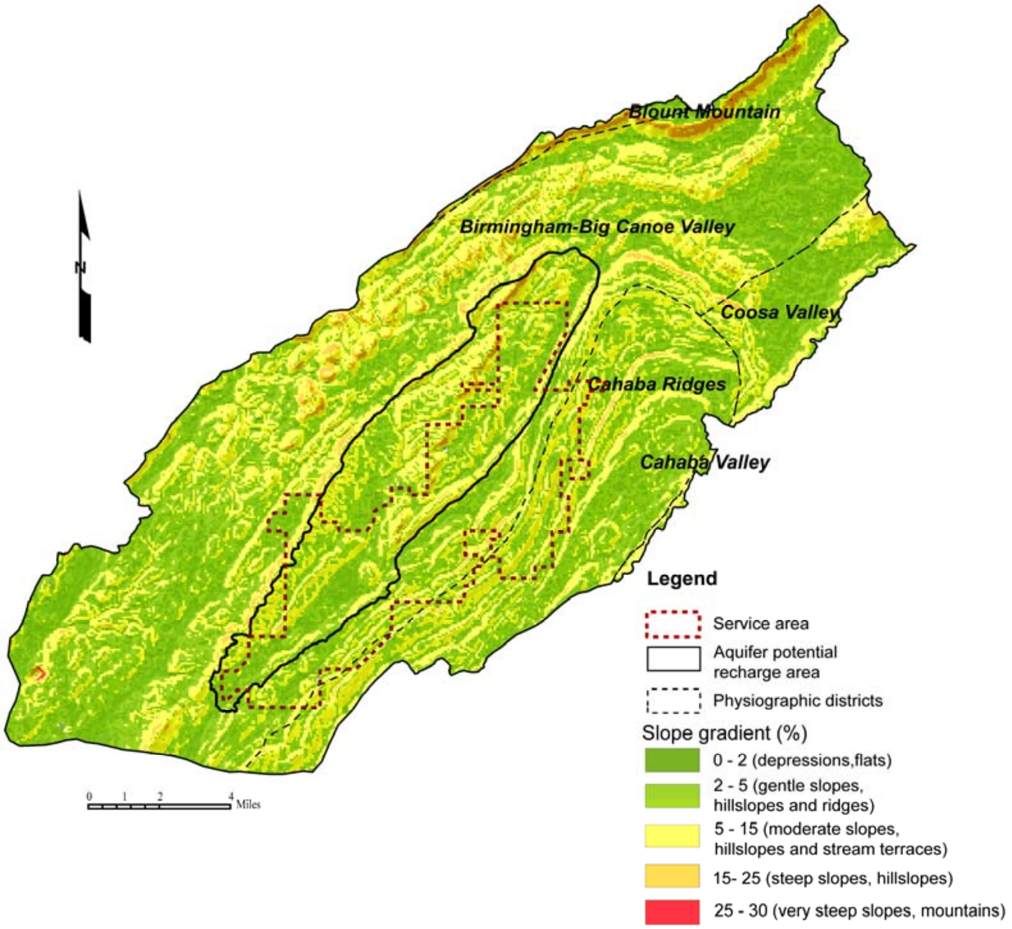


Figure 2.—Physiographic districts and slope gradients.

It is not the purpose of this study to provide a thorough description of soil characteristics but to present a rather simplistic classification of soil orders and taxonomy and their relationship with areas of potential aquifer recharge. The NRCS-SSURGO dataset offers sufficient information to fulfill the objectives of this study.

Soils in the investigated area are divided between four orders: ultisols, inceptisols, alfisols, and mollisols (USDA-NRCS, 2010) (fig. 3). In the aquifer recharge and water supply service areas, ultisols are the most pervasive soils, followed by inceptisols (fig. 3). Alfisols and mollisols have extremely low occurrence in the investigated area (fig. 3) and are not described in this section. Ultisols are solely of the Udults suborder (USDA-NRCS, 2010). Udults are freely drained, relatively humus poor, and udic moisture regime ultisols (USDA-NRCS, 2010). Currently, in the investigated area most of these soils support mixed forest vegetation. However,

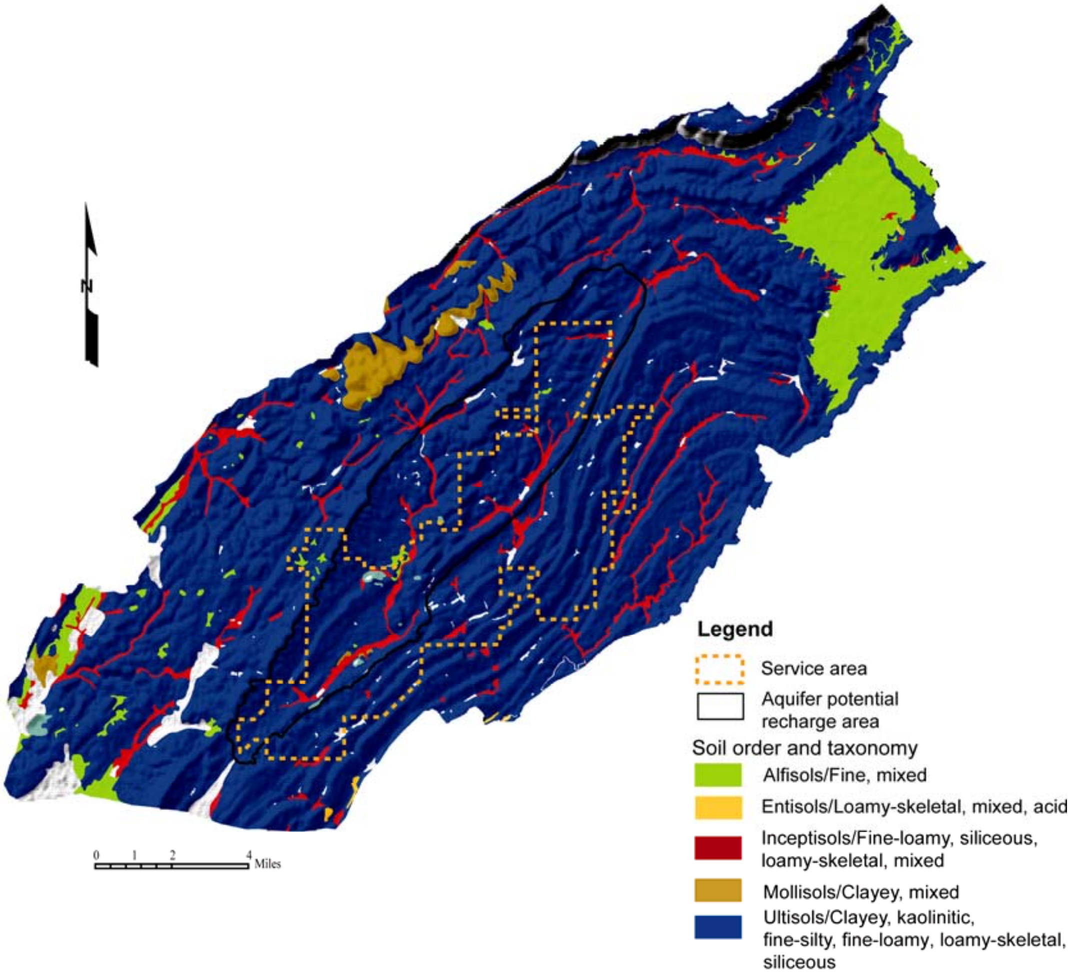


Figure 3.—Soil order (SSURGO, USDA-NRCS, 2010).
Gray-colored areas represent missing data.

some areas of the lower elevation or flat areas have been cleared and converted to pasture or residential and commercial land uses.

The presence of ultisols generally is an indication of soils with long-term wetting and drying periods and insignificant fertility and ability to replenish nutrients (Lal, 2005). These soils occur in warm and humid areas and are characterized by the properties of their parent material, in this case predominantly the Bangor Limestone, Hartselle Sandstone (quartzose sandstone with minor shale interbeds), Pride Mountain Formation, Tuscumbia Limestone/Fort Payne Chert (limestone silicified near surface with minor shale and chert), Knox Group undifferentiated (cherty dolomite), Parkwood Formation, Pottsville Formation and Red Mountain Formation (sandstone interbedded with shale and lesser siltstone) (plate 2).

Soils texture ranges from fine, fine-loamy to fine-silty siliceous, clayey and kaolinitic and are formed on sloping topography, ridges, and stream terraces in the Birmingham-Big Canoe Valley and Cahaba Ridges districts (USDA-NRCS, 2010). Ultisols in the investigated area exhibit high saturated hydraulic conductivities (approximately 8 ft/d) and are very well to excessively drained (for example, in the area of aquifer recharge) (USDA-NRCS, 2010). Inceptisols, not extensive in the area of investigation, are mainly developed from alluvium sediments composed of unconsolidated quartz silt, sand, and gravel containing clasts of local bedrock (Raymond and others, 2003) deposited on flood plains and terraces (fig. 3). To some extent these soils underlie commercial and residential areas located along stream valleys.

LAND-USE/LAND-COVER

Land-use practices are important factors that influence water quality and availability and therefore, although difficult to accurately determine at a large scale, their impact should be closely monitored. Landscape patterns are influenced by both natural processes and those related to human activity (anthropogenic). However, in recent decades, human-generated processes have been the dominant force in shaping landscape patterns in the United States. As a region's population and rate of development increases, landscape usage is altered to accommodate growing needs. Inappropriate distribution and placement of industrial, commercial, agricultural, high intensity residential, and other human developments, can adversely impact the regional environment. Specifically, these land practices are not only major sources of contamination to the environment, but represent a measureless threat to groundwater recharge. Polluted effluents resulting from developed areas can degrade surface-water and indirectly groundwater quality wherever there is a connection between the two entities. Sustainable groundwater development is imperative to urban planning, particularly in communities that utilize groundwater for drinking water. Development and implementation of measures intended for management and protection of natural resources requires land use/land cover (LULC) analysis. The 2009 National Agricultural Statistics Service (NASS) U.S. Department of Agriculture (USDA) Cropland Data Layer (CDL) (USDA-CDL, 2010) for Alabama was used in delineating LULC classes and identify potential contaminant source zones and in predicting future impacts (fig. 4).

The CDL containing crop specific digital data layers is a digital categorized geo-referenced output product compiled from the Resources at-1 AWiFS and the Landsat 5 TM

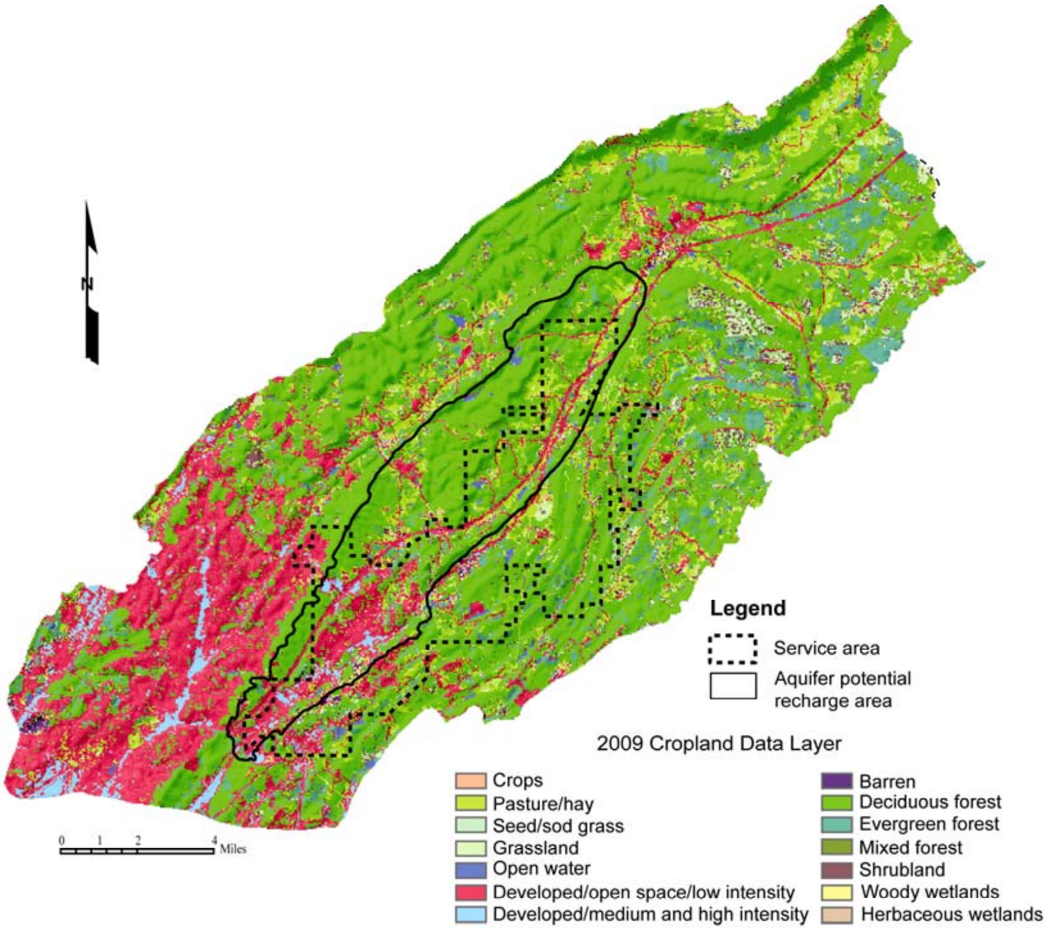


Figure 4.—Land-use/land-cover classification for the Trussville Utilities recharge area (modified from USDA, 2009 Cropland Data Layer).

satellites (USDA, 2010a). This data layer was incorporated into a Geographic Information System (GIS) and 14 Level II LULC classes, depicted in figure 4, were identified for the area under investigation. The classification includes the following classes: crops, pasture/hay, seed/sod grass, grassland, open water, developed/open space/low intensity, developed/medium and high intensity, barren, deciduous forest, evergreen forest, mixed forest, shrubland, woody wetlands, and herbaceous wetlands (fig. 4). Most of the investigated area is dominated by forest, followed by residential and commercial, and to a lesser extent by pasture land uses (fig. 4). However, because this study is mainly concerned with protection and identification of potential additional groundwater sources, the investigation focuses mainly on the designated area of aquifer recharge. Consequently, in order to characterize this critical area in more detail, a more comprehensive LULC was produced for the recharge area.

AQUIFER RECHARGE AREA LULC CLASSIFICATION

One of the primary tasks associated with this project was to develop a potential aquifer recharge area classification. The first step toward accomplishing this objective was to create a comprehensive LULC classification that will facilitate the development of a hydrological LULC. For this purpose, the 2009 high-resolution, natural color and color-infrared (four-band) aerial photography acquired by the National Agriculture Imagery Program (NAIP) for the state of Alabama was utilized. This imagery is collected annually by the Farm Service Agency (FSA) through NAIP and with cooperating state agency partners such as GSA, for the entire conterminous United States to monitor the USDA farm programs. However, other organizations and citizens use NAIP photos for innumerable other applications. NAIP imagery has a 1-meter ground sample distance (GSD) with a horizontal accuracy of approximately 5 meters of reference ortho-imagery that translates in an accuracy of 6 meters at a 95% confidence level (USDA, 2010a). The reference ortho-imagery (orthorectified aerial image) consists of mosaicked digital ortho quarter quads (DOQQs). Spectrally, the imagery is a RGB natural color with red, green, and blue bands. In addition, a fourth near-infrared band is available as a “buy-up” option (USDA, 2010a). Radiation scattered by the cellulose structure of healthy vegetation appears bright in the near-infrared spectrum allowing for a more precise delineation of vegetation (for example, grasslands). The advantage of using aerial photography as opposed to satellite imagery is that it provides a pictorial view of the ground that no other map can equal.

The four-band ortho-imagery was first imported into a GIS with other baseline data such as the 2009 CDL, roads, water bodies, and topography. GIS mosaics from several DOQQs were prepared to create the recharge area scene, which was clipped to the recharge area. Though care is taken to acquire the photography at high sun angle, extended shadows occurred, particularly in images of mountainous or developed areas (terrain due to the steep slopes or taller buildings). Furthermore, tree shadows are visible on surface water bodies, which can obscure other features otherwise identifiable. In the given image, examples of shadows are those projected by trees on water and ground surfaces or by commercial buildings. Shadows have impacts on the tone/color characteristic to certain features (for example, the different tones within a water body or shaded grassland). While image interpretation is possible, given the high resolution of the photography, image classification based on spectral reflectance becomes challenging. Shadow effects caused class confusion, which occurred on water bodies, in forested and developed areas, and on parking lots and roads. In order to overcome this problem water bodies and commercial buildings were subset from the image and classified separately. In doing so, two shape files were generated in a GIS by digitizing water bodies and commercial buildings. This implied careful demarcation of these features on the imagery. The high-spectral and spatial resolutions of the original aerial photography supplemented by detailed ground truth information facilitated the accurate delineation of the two classes. The resulting shape files were used to subset and produce two new images, one containing all water pixels and the other all commercial building pixels from the original imagery.

ORTHO-IMAGERY LULC CLASSIFICATION

The false-color and near-infrared image was imported into Leica Geosystems' Earth Resource Data Analysis System Image (ERDAS IMAGINE) 9.2 image analysis software. The main image was classified using the supervised classification. The accuracy of this mapping method depends heavily on the analyzer's ability to recognize conventional or significant classes in a scene from professional knowledge or familiarity with the investigated area. During the investigation, several on-site visits were conducted to facilitate increased confidence in the classifying process. Through supervising selection, discrete classes are chosen and assigned a category name (for example, forest or water). The resulting training sites are areas of known land cover category. Multiple training sites were delineated based on similarity in tone or color for each category. The final classification was achieved by statistical processing in which every pixel is compared to the various selected signatures and assigned to the closest spectral class. Water bodies and commercial subset images were imported and classified separately in ERDAS IMAGE. Unsupervised classification was performed on the two images. Given that these images were representing single classes, the output was simplified to one class per image corresponding to the open water and developed/commercial land use, respectively. Typically, through the unsupervised classification, pixels were grouped into multiple clusters that produced a large number of classes, which are difficult to interpret. The three output classified images were stacked together in ERDAS IMAGE to obtain the final LULC map. The following are the six most representative classes that resulted through the image classification scheme (plate 5).

1. *Open water*—includes all areas identified as water: lakes and ponds.

2. *Barren*—includes any land not covered by man-made structures, vegetation, or water; disturbed land; or accumulation of earthen material. Most of the barren ground in the recharge area consists of disturbed land or land cleared for development (plate 5).
3. *Developed/residential, roads, and parking spaces*—due to the high spectral similarity between residential, commercial parking spaces, and roads, these land covers were grouped in a single representative class. This class incorporates mostly impervious lands with very minimum vegetation cover. Any vegetation included in this class is due to spectral confusion.
4. *Developed/commercial*—includes only identified commercial buildings present within developed areas. These man-made structures were classified as a separate class in order to distinguish between residential and commercial buildings. Impervious surface accounts for almost 100% of the total cover with vegetation coverage absent.
5. *Mixed forest*—represents the land covered by multiple types of trees and high shrubs. In this category are included areas extensively covered by kudzu vegetation. Spectral signature and texture similarity makes it difficult to differentiate between the different types of vegetation.
6. *Grass/pasture*—spectral signatures are similar to the mixed forest class; however, the different texture characteristic to grasslands enabled the selection of these land uses as a singe class. An acceptable level of distinction between the farmlands or pasturelands and other types of land covered with grass such as landscaping could not be achieved. For this reason this class groups types of land covers such as plowed land, pasture, hay fields, rough grassland not used for pasture or landscaping, fallow fields overgrown with grasses and low brush, golf courses, residential lawns, and urban parks and landscape areas.

The most prevailing land cover in the recharge area is mixed forest (75.3%) followed by grass/pasture (13.0%) (plate 5, table 1). Forest and shrub vegetation covers most of the elevated and steep terrains whereas grass/pasture is mainly associated with very gentle slope to flat lands (plate 5, fig. 4).

The next pervasive class, accounting for approximately 7.4% of the total area, is the developed land cover (table 1). This class is divided between residential and commercial (table 1) and represents most of the impervious surface in the recharge area. Most of the developed

Table 1.—Land-use/land-cover coverage area and percentage in the Trussville Utilities recharge area

Classes	Area (mi^2)	Percentage
Open water	0.4	1.0
Barren	1.3	3.3
Developed/residential, roads, and parking spaces	2.6	6.4
Developed/commercial	0.4	1.0
Mixed forest	30.2	75.3
Grass/pasture	5.2	13.0
Total	40.0	100.0

land is situated in the low-lying or nearly flat areas (plate 5, fig. 4). Barren and open water exhibit the lowest percentage of LULC in the area (plate 5, table 1).

IMAGE CLASSIFICATION ACCURACY ASSESSMENT

Image classification accuracy is generally affected by a number of factors such as spectral and spatial resolution of the original data, ground reconnaissance (or ground truth), and brightness variation. The high-resolution color and near-infrared ortho-imagery offers the best platform for obtaining accurate estimates of development, and respectively, impervious surfaces. Even with limited knowledge of the investigated area, visual inspection of the aerial photography allows for the identification of a detailed list of land covers. Although more detail can be identified in the photography (for example, low, medium, and high intensity developed land cover), the identified categories (table 1) are of most importance to the proposed objectives. However, the advantage of using this type of imagery is that it allowed the most accurate identification of impervious surfaces. In low spatial and spectral resolution imagery (for example, Landsat imagery) mixed pixels containing two or more classes are very common. Consequently, the spectral signature of a mixed pixel may be misclassified. In this situation, ground truth is essential in improving the accuracy. Limitations associated with classifying the high-resolution ortho-imagery are generally related to shadowing effects that influence the color/tone causing spectral confusion. Nevertheless, by using the supervised classification, the accuracy of the classification was not significantly affected.

Accuracy assessment for the aquifer recharge area classification involved detailed on-site and imagery inspection of each LULC class. An attempt to evaluate the accuracy of each class was performed using randomly selected ground-through and the corresponding imagery geospatial-referenced points. One hundred three points were used in the accuracy assessment (table 2). The results were summarized by numbers of matching and mismatching points (table 2), translated to a classification accuracy of approximately 86.4%. It should be noted, however, that a limited number of reference points were selected from the forest class. Because this class has the largest ground cover extent (75.3%) (table 1, plate 5), it is obvious that increasing the number of reference points within this class would dramatically increase the classification accuracy assessment. Developed/residential is the most misclassified class, apparently due to parts of this ground cover that were attributed to the barren, developed/commercial, mixed forest, and grass/pasture classes (table 2). Consequently, to a small extent, the impervious surface area has been underestimated.

Table 2.--Reference Data

Classes	W	B	DR	DC	F	GP
Open water (W)	**20**					
Barren (B)		**10**	3			2
Developed/residential, roads, and parking spaces (DR)		3	**14**	2	2	2
Developed/ commercial (DC)			2	**10**		
Forest (F)			2		**20**	3
Grass/pasture (GP)		2	2		3	**15**
Ground truth classified total: 103; Number correct: 89; Number incorrect:14; Classification accuracy: 86.4 %						

POTENTIAL AQUIFER RECHARGE AREAS CLASSIFICATION

Factors such as soil hydrologic characteristics (e.g., conductivity and drainage properties), relief slopes, type and spatial distribution of land-use/land-cover, and aquifer hydrogeologic characteristics affect the amount of water recharging an aquifer (Mazari and Mackay, 1993; Walt and others, 2010; Troiano and others, 1998; Jiang and others, 2009). Groundwater recharge generally occurs in aquifer outcrops, where physiographic, morphologic, and LULC characteristics favor water percolation as opposed to runoff. Aquifer outcrop characteristics play a critical role in aquifer contaminant vulnerability since they control the amount of meteoric water and contaminant infiltration to the water table (Walt and others, 2010). For example, in areas where aquifer outcrops are characterized by soils exhibiting extremely low vertical conductivities and drainage rates and/or steep slopes and/or are overlain by impervious surfaces (extensive development covering most of an area), recharge will be drastically reduced or absent. Aquifers are most vulnerable in their outcrops, under water-table conditions, and therefore, contaminant inputs are controlled by the aforementioned parameters as well. Urbanization is most often accompanied by a rise in anthropogenic contaminants. Even though the high potential for runoff in developed areas may decrease surface contaminant percolation to groundwater, it substantially limits local aquifer replenishment. This problem becomes more severe in hilly and mountainous zones such as parts of the investigation area. Even though aquifer outcrops in this area are extensive, precipitation percolation to the water table and further to the aquifer is limited due to high runoff rates. Most of the recharge would presumably occur within the low-lying and flat areas. However, these areas are generally developed for commercial and residential use (plate 5). In such areas, land-use planning is critical to achieve high quality, sustainable groundwater resources.

Groundwater recharge is variable, dependent on a complex set of interactions between natural factors that result in highly variable recharge rates, temporally and spatially. As part of this investigation, the potential for aquifer recharge has been evaluated. The methodology employed is based on a conceptual understanding of phenomena influencing meteoric water and contaminants percolation from the aquifer outcrop to the water table.

Among several factors controlling recharge rates and potential recharge areas, soil moisture is directly related to the water table elevation, since it increases soil moisture not only within the saturated horizon but also within the capillary zone (above the water table). For instance, areas with a high water table have smaller storage capacity compared to areas with deeper water table (Mew and others, 2002). Therefore, during rainy periods, in flat areas, precipitation may pond on the surface and may be lost to evapotranspiration (ET). Conversely, in sloping and hilly areas, most precipitation is lost to runoff. However, the soil moisture parameter is integrated (among other parameters) in the soil drainage estimation (USDA-NRCS, 2010a) where it becomes part of the recharge area evaluation.

Soil conductivity and drainage characteristics also play important roles in the evaluation of aquifer recharge. Soil conductivity depends upon soil texture. For example, a sandy-textured soil will allow water percolation at faster rates compared to more clayey, low conductive soils. While both drainage and conductivity properties refer to the infiltration capacity of the soil, they are measured differently (plate 6). Soil and runoff properties incorporated into the recharge area classification are estimated by USGS-NRCS, based on actual field observations.

Land cover plays an equally important role in groundwater recharge (see LULC section). Imperious surfaces such as large parking spaces, shopping centers, and business complexes completely obstruct local aquifer recharge. Some types of vegetation and land cover may reduce the amount of infiltrating water. For instance, previous investigations indicate that the relative recharge rates of undisturbed forested areas are greater than those of a highly disturbed and compacted lawns or fallow farmlands.

Precipitation rates are an additional factor influencing aquifer recharge rates, which are addressed in a subsequent section of this report.

The aquifer outcrops/geology, runoff/slopes, soil conductivity, soil drainage, and land-use/land-cover spatial coverages were integrated in a GIS database for analyses and classification processes. These data were utilized to classify and spatially delineate potential recharge zones along aquifer outcrop areas based on their hydrological similarities. Data used in this process are the Geological Survey of Alabama aquifer outcrops (GSA, 1998), the 2009 aerial photography derived LULC, and the USDA-NRCS, **Soil Survey Geographic**-certified dataset (SSURGO) soil conductivity, runoff, and drainage layers (USDA-NRCS, 2006). The GIS display of these layers was based on the information required for the classification. For example, soil data was represented by three layers, displayed by runoff potential, drainage, and conductivity, respectively. Depending on the level of detail and spatial variance, spatial data were first classified based on similar or identical properties (plate 6). Consequently, data analyses and the first classification process resulted in five aquifer outcrop, six runoff, five soil drainage, four soil saturated hydraulic conductivity, and six LULC classes (plate 6). These layers were converted to raster files and reclassified into three hydrological classes (plate 6). Reclassification accounted for the potential of a particular area to retain and transmit rainfall water to depth, based on the particular property being evaluated (table 3). Thus, three hydrological classes were identified for each layer: class 0–low to extremely low potential for aquifer recharge, 1–medium potential for aquifer recharge, and 2–high potential for aquifer recharge (plate 6, table 3).

Table 3.—Criteria used to convert aquifer, soil units, runoff, and LULC into hydrological classes

Map layer	Classes	Hydrological class
Aquifer outcrops	Bangor aquifer	2
	Hartselle aquifer	
	Tuscumbia Limestone/Fort Payne aquifer	
	Valley and Ridge aquifer system	
	Confining unit	0
Runoff	Very high runoff	0
	High runoff	
	Medium runoff	1
	Low runoff	
	Very low runoff	2
	No runoff	
Drainage	Poorly drained	0
	Somewhat poorly drained	
	Moderately well drained	1
	Excessively drained	2
	Well drained	
Saturated hydraulic conductivity	No conductivity	0
	Extremely low conductivity	
	Moderate conductivity	1
	High conductivity	2
LULC	Mixed forest	2
	Open Water	0
	Developed/residential	
	Developed/roads and parking spaces	
	Barren	1
	Grass/pasture	

Potential recharge area classes were identified in GIS using the following equation 1:

$$RA=H*LULC*R*D*K_{SAT}, \qquad (1)$$

where RA, H, LULC, R, D, and K_{SAT} represent the potential aquifer recharge areas, aquifer outcrops, land-use/land-cover, runoff, soil drainage, and soil vertical conductivity hydrologic classes, respectively. Equal weight was assigned to each of the parameters since they can equally impede recharge to the aquifer (i.e. outcrop of a confining layer, impervious surface, low conductivity and drainage soil, and high runoff potential). It should be noted that hydrologic classes are randomly distributed within the recharge area. Since there are three hydrologic classes (table 3), the probability distribution factor of each data are six (three factorial). The exception to this is the aquifer outcrop layer with two hydrologic classes creating a probability distribution factor of four. Therefore, potential aquifer recharge areas distribution is a variable, dependent on the spatial distribution of the hydrologic classes. The calculation resulted in five classes, each being assigned a number. For example, the classes with lowest and highest potential for aquifer recharge were assigned 0 and 32, respectively. Through multiplication, any area exhibiting one hydrologic class coded with 0, will be assigned the lowest potential for aquifer recharge. Several scenarios are possible in such areas. One possible situation in this case is that four of the five input data layers are represented by the highest favorable class (2) and the fifth one is represented by the lowest favorable class (0). The outcome class will be 0, meaning extremely low potential for aquifer recharge. Although it may seem an extreme approach to spatially identifying areas of potential aquifer recharge, it is doubtlessly the most accurate way. For instance, an area overlying an aquifer outcrop characterized by a high percentage of development (impervious surface) exhibits an extremely low potential for aquifer recharge, regardless of what the soil properties or runoff rates are. Similarly, soil conductivity and drainage properties and runoff rates can, in turn, act as standalone factors that can impede precipitation infiltration and groundwater replenishment.

The calculation resulted in five classes of potential aquifer recharge areas: extremely high potential for aquifer recharge; high potential for aquifer recharge; moderate potential for aquifer recharge; moderately low potential for aquifer recharge; and extremely low potential for aquifer (plate 6). Spatially, there is limited area favorable to incident precipitation infiltration within the delineated recharge area (plate 6). The spatial extent of these areas is limited by the high runoff rates characteristic of the recharge area (plate 6). While some infiltration may take place during light rain events, runoff is presumably pervasive during the heavy episodes. Furthermore, recharge in hilly and mountainous settings occurs mainly from snow during the slow melting process. Therefore, given the humid subtropical climate (characterized by hot summers, mild winters, and abundant rainfall) of this area, it is most likely that recharge occurs “focused” along gentle-sloping and flat areas, disseminated within commercial and residential development (plate

6). This may adversely impact the quality of water recharging the underlying aquifers because of contamination derived from industrial, residential, and commercial land covers (for example, industrial and sewage effluents, fertilizers, and pesticides). Insight is thus gained into recharge and contamination source zones, openness of the investigated system, and spatial variability in recharge occurrence.

PHYSICAL PROPERTIES AND CHEMICAL AND ISOTOPIC COMPOSITION OF GROUNDWATER

Groundwater samples were collected during two site visits in 2010 during June (summer) and November (fall) to identify seasonal impacts on groundwater physical properties. Geochemical analyses were conducted on four selected samples collected from wells developed at variable depths within the Tuscumbia Limestone/Fort Payne Chert and Bangor Limestone aquifers (two Tuscumbia Utilities (TU) public supply wells (W-7, W-10), the TU unused flowing well (FW), and a private well (P-2)). During the summer sampling event, physical parameters were acquired from 10 wells (8 TU and 2 private wells) and during the fall event from eight wells (the TU wells) (table 4). Analyses for the stable isotopes of hydrogen ($\delta^{18}O$) and oxygen (δD) were performed from samples collected during both events while those for the carbon ($\delta^{13}C$) analysis were collected during the fall sampling event. Aqueous samples for chlorofluorocarbon (CFCs) and sulphur hexafluoride (SF_6) groundwater dating were collected from the eight TU wells and private well P-1 in June.

PHYSICAL PROPERTIES

Physical properties of groundwater that were assessed in situ included temperature (T), hydrogen ion activity (pH), specific conductivity (SC), oxydo-reduction potential (ORP) (table 4), and total dissolved solids (TDS). Hydrogen ion activity in an aqueous solution is controlled by interrelated chemical reactions that produce and consume hydrogen ions (Hem, 1985). The reaction of dissolved carbon dioxide with water is one of the most important mechanisms in establishing pH in natural water systems. Water collected during the summer sampling event typically had slightly acidic to neutral pH values (5.8-7.2), and moderate SC and TDS values (60 to 343 microsiemens per centimeter [µS/cm] and 39 to 223 milligrams per liter (mg/L), respectively). Physical property values recorded during the fall event were generally lower than

Table 4.—Selected physical properties of water samples collected from wells in the Trussville Utilities recharge area.

Sample sites*	**Aquifer**	**Depth**	June 2010					November 2010				
			T (°C)	**pH**	**ORP (mV)**	**SC (µS/cm)**	**Static water level (ft bls)**	**T* (°C)**	**pH***	**ORP* (mV)**	**SC* (µS/cm)**	**Static water level* (ft bls)**
W-12	Bangor Limestone	339	17.4	7.2	277	260	22	16.6	6.6	195	229	31.8
W-9	Bangor Limestone	300	18.7	6.9	229	340	30.3	17.1	6.8	142	230	39.3
W-10	Bangor Limestone	289	18.4	6.6	267	282	-	18.2	6.3	191	211	-
W-14	Bangor Limestone	355	17.9	7.2	307	278	66.5	17.5	6.6	189	235	83.5
Average	-	-	*18.1*	*7.0*	*270*	*290*	-	*17.4*	*6.6*	*179.3*	*226*	-
FW	Tuscumbia Limestone/ Fort Payne	155	16.4	6.8	256	133	-5	15.4	7.6	-264	98	-5
W-7	Tuscumbia Limestone/ Fort Payne	154	17.8	6.2	320	182	22.0	16.7	6.0	242	162	30.8
W-6	Tuscumbia Limestone/ Fort Payne	152	18.3	5.8	301	113	16.5	18.7	6.1	126	135	23.0
W-5	Tuscumbia Limestone/ Fort Payne	170	17.6	7.2	143	298	23.5	17.9	6.6	173	251	30.37
P-1	Tuscumbia Limestone/ Fort Payne?	80	17.8	5.8	189	60	29.1	-	-	-	-	-
Average	-	-	*17.5/ 17.6*	*6.5/6.4*	*255/ 242*	*182/157*	-	*17.2*	*6.6*	-	*162*	-
P-2	**-**	250	18.0	6.1	-	343	-	-	-	-	-	-
Average	-	-	**17.8**	**6.6**	**254**	**229**	**-**	**17.3**	**6.6**	**-**	**194**	**-**

*W=Tuscumbia Utilities public supply wells; FW= Tuscumbia Utilities unused flowing well; P=privately owned wells.

the summer ones (table 4) (figs. 5 through 11). An increase in pH was noted for the flowing welland well 6 (fig. 5). At well 6, the increase in pH was accompanied by an increase in SC and TDS (figs. 5-7). There is a good positive relationship between SC and pH (fig. 10). This suggests the presence of water-rock reactions and limestone dissolution that release Ca^{2+} (and some Mg) and HCO_3^{2-} ions in solution. This assumption is supported by a good correlation between pH, Ca^{2+}, HCO_3^{2}, and SC observed for the four selected wells (table 5).

ORP or the redox potential (Eh) is a numerical index indicating the tendency of system/solution to acquire electrons and thus be reduced (Hem, 1985). Oxidation is the loss of electrons by a substance undergoing a chemical reaction. Conversely, reduction is the gain of electrons by a substance undergoing a chemical reaction. The more positive the ORP of a solution is, the higher is its tendency to be reduced (for example, to be reduced by oxidizing a new introduced species). Redox potential evaluations are very important in estimating the solubility of metals in natural water systems. However, temperature, pH, irreversible reactions, and other factors limit ORP interpretations. These measurements have been previously used by Garrels and Christ (1990) to monitor changes in systems. All monitored wells except well W-5 had ORP values that decreased over the summer period (fig. 8). As the ORP intensity changes over time, the geochemical character of groundwater in the investigated aquifers may change as well. The decrease in ORP is also accompanied by a decrease in pH, SC, TDS, and static water levels for most of the sampling locations.

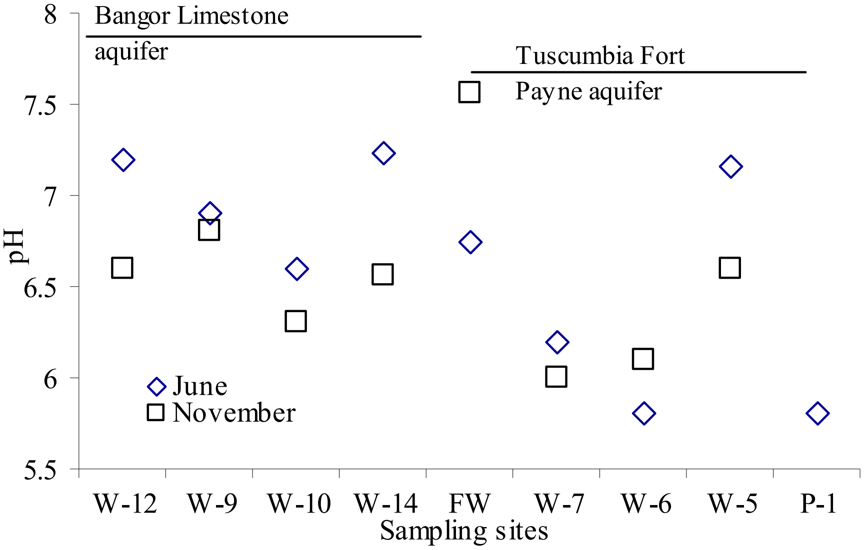


Figure 5.—Seasonal variation of pH values.

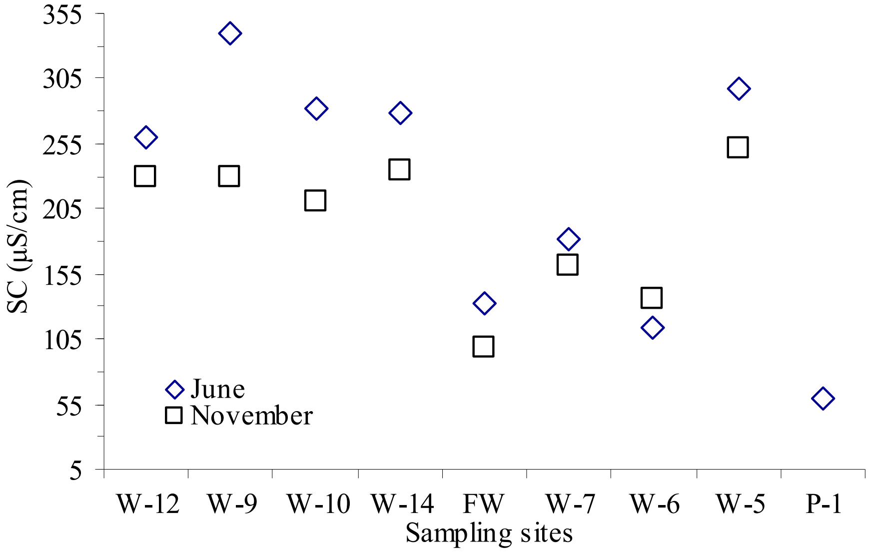


Figure 6.—Seasonal variation of SC concentrations.

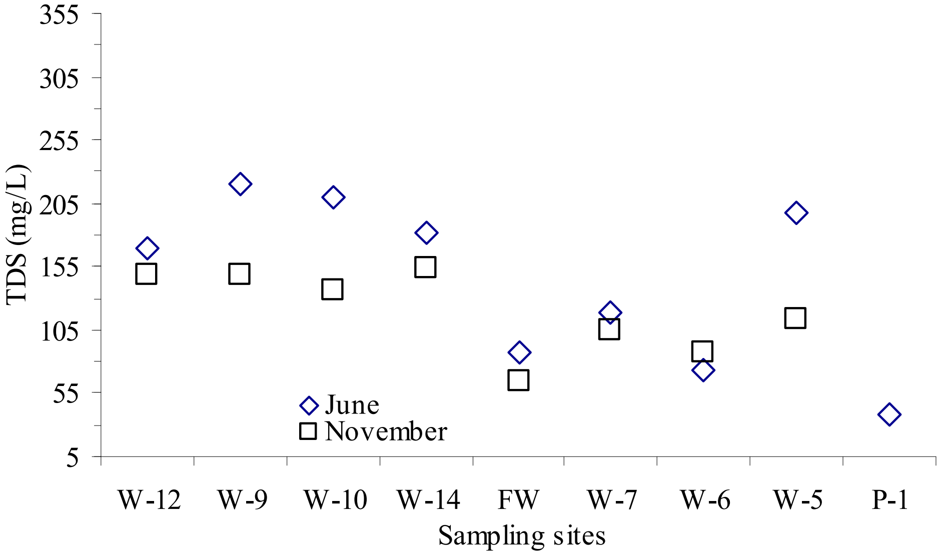


Figure 7.—Seasonal variation of TDS concentrations.

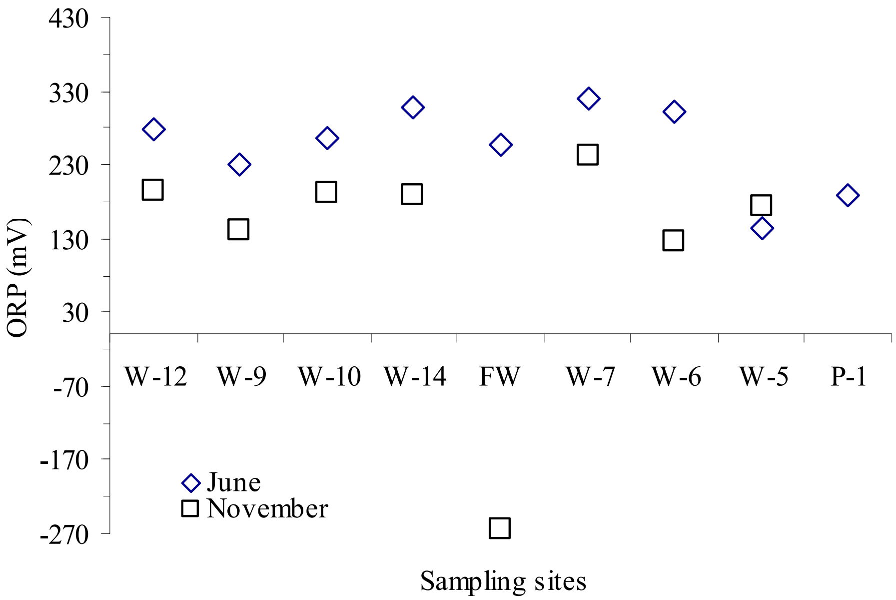


Figure 8.—Seasonal variation of ORP values.

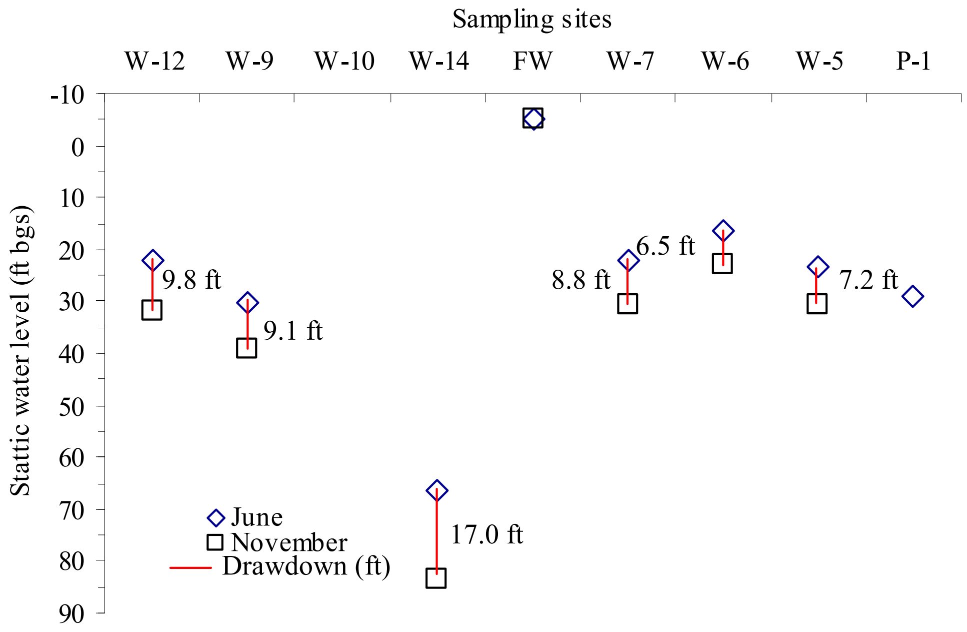


Figure 9.—Seasonal variation of static water levels. Drawdown values corresponding to each well are represented by lines connecting the two summer and fall values. Corresponding drawdown values are assigned to each well.

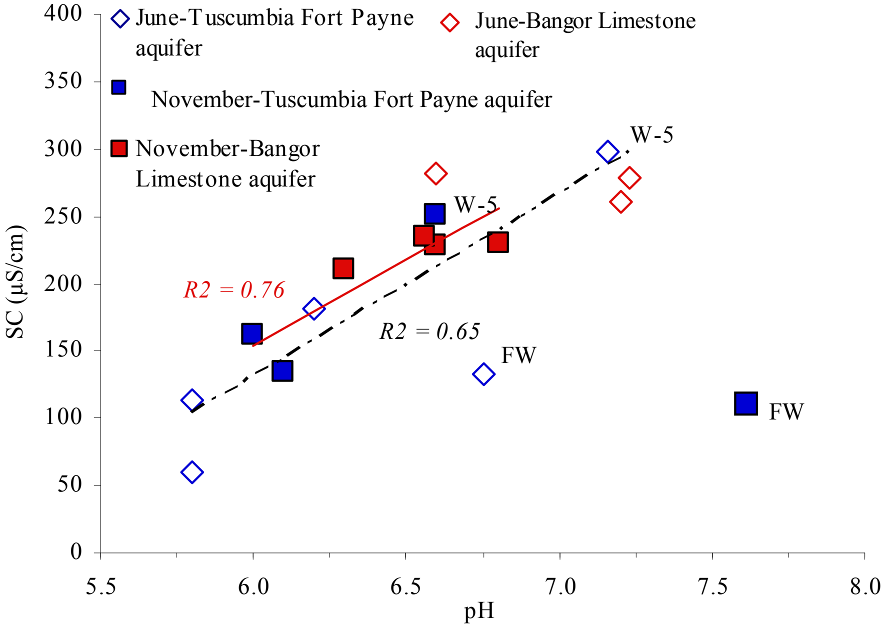


Figure 10.—Seasonal representation of the correlation between pH and SC. Note that linear regression for the November data has been estimated using all TU public supply wells except FW. This is the only location where there is no positive correlation between the two parameters.

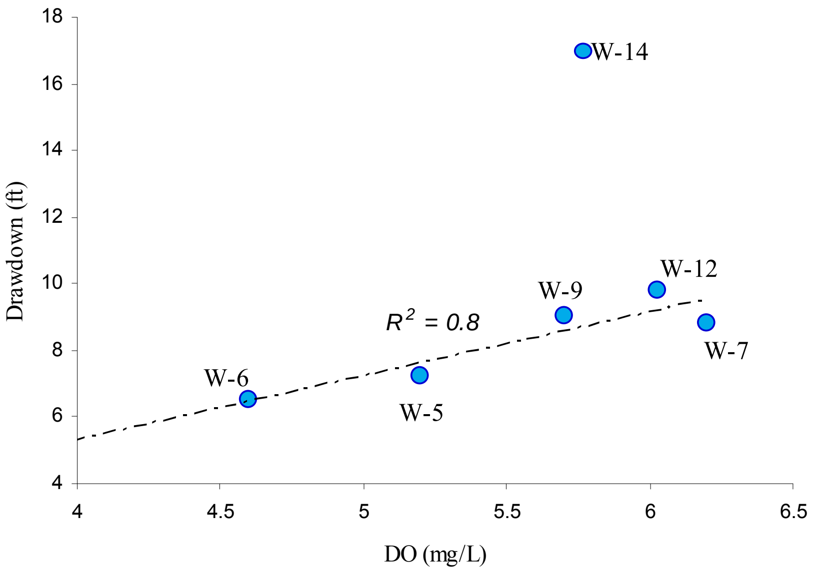


Figure 11.—Relationship between drawdown and DO for five selected TU wells. The linear regression between the two parameters was estimated excluding FW and W-14 wells. Water levels at the flowing well are assumed to be constant over the investigation period (drawdown is zero); Drawdown at W-14 is about 7 ft higher compared to all other wells, significantly decreasing the correlation coefficient. Static water levels were not available for W-10.

Table 5.—Major cations and anions (mg/L, except where indicated), alkalinity, conductivity, and pH of water samples collected from wells in the Trussville Utilities recharge area.

Sample site	**K^+**	**Na^+**	**Ca^{2+}**	**Mg^{2+}**	**Fe**	**Cl^-**	**HCO_3^-**	**Akalinity (mg $CaCO_3$/L)**	**SO_4^2**	**NO_3^-**	**SC (µS/cm)**	**pH**
Flowing well (FW)	0.7	1.6	29.4	1.8	0.6	1.7	100	82	3.9	0.6	176	5.3
Private well-2 (P-2)	1.1	9.8	52.1	3.6	4.4	28.2	124	102	5.2	21.9	343	6.1
W-7	0.5	1.8	35.6	2.8	0.02	2.6	117	96	5.9	3.4	182	6.2
W-10	0.2	2.9	60.0	4.3	0.03	3.4	199	163	16.5	3.2	340	6.6

*W=Tuscumbia Utilities public supply wells
FW=Tuscumbia Utilities unused flowing well
P=privately owned wells

For the summer and fall sampling events static water levels ranged from 22 to 66.5 ft below land surface (bls) and from 30.8 to 83.5 ft bls, respectively (table 4). The mean water level decline (excluding wells FW and P-1) is approximately 10 ft with the highest value occurring in well 14 (17 ft). The decrease in water level over the summer may be explained by an increase in groundwater withdrawals to satisfy increased water demands. Static water level drawdown occurs when the withdrawal rate in an aquifer exceeds natural recharge rates. This disrupts the natural equilibrium of the aquifer, enhancing mixing of multiple water members at the sampling location. In these conditions, source waters may belong to multiple or different environments. For instance, during increased aquifer withdrawals, induced downward and upward gradients may exist. Replenishing water usually travels at a faster rate towards the discharge location (in this case the pumping well). Groundwater chemical characterization is difficult under such conditions.

Changes in physical parameters in the investigated aquifers strongly suggest alteration of the natural recharge source water during the summer period. The observed decreases in TDS, SC, and PH at the investigated locations indicate that recharge waters during the summer period are less mineralized. It is likely that fresher, modern, and shallower waters are mixing with older, more mineralized ambient groundwaters at the sampled horizon. This hypothesis is further supported by the good positive correlation between drawdown values and DO concentrations (fig. 11). The exception from this general behavior is well 6, where a slight increase in pH, SC, and TDS and a decrease in DO concentrations are observed. Except for the flowing well, which does not experience a change in hydraulic pressure, W-6 exhibits the lowest drawdown (6.5 ft) and DO concentration (4.6 mg/L). Therefore, a limited degree of mixing with more modern waters and natural recharge disturbance can be assumed at this location. Increases in pH and SC suggest a steady increase of the groundwater age at this location. This may also suggest a different source of recharge at this location or the influence of other factors on groundwater evolution.

Generally, the Bangor Limestone exhibits slightly lower water levels and higher drawdown compared to the Tuscumbia Limestone/Fort Payne Chert aquifer in response to groundwater withdrawals (table 4, figs. 9, 11). Slower aquifer recharge and recovery rates may be associated with the Bangor Limestone aquifer. Furthermore, the drop in static water levels over the summer period indicates that production rates exceed aquifer replenishment rates and that recharge during the summer period is low. Higher runoff rates and lower amounts of meteoric water infiltration during high intensity summer precipitation events (see the topography section) may also explain lower recharge occurring over the investigated period. This may be related to the past years drought conditions that drastically limited the amount of recharge to the aquifer. With less groundwater flowing through the aquifer, excessive aquifer development may result in the occurrence of cones of depression and draining of rivers and lakes. During the fall field surveys, water levels in the Cahaba River dropped dramatically so that parts of the river channel were dry.

CHEMICAL COMPOSITION

More than 90 percent of the dissolved solids in groundwater can be attributed to eight ions: sodium (Na^{2+}), calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), chloride (Cl^{-}), bicarbonate (HCO_3^{-}), and carbonate (Co_3^{2-}) (Fetter, 1994). The quantity of major cations and anions determines water types, which are used to characterize groundwater quality in specified areas. The primary cations in the investigated aquifers are Ca^{2+}, Na^{2+}, and Mg^{2+} and the major anions are HCO_3^{-}, Cl^{-}, SO_4^{2-}, and nitrate (NO_3^{-}) (table 5). Additionally, iron (Fe) is present in all four samples that were analyzed for trace metals. K^{+} and Na^{2+} in these aquifers primarily originate from dissolution of minerals composing the aquifer matrix. Na^{2+} ions are retained on the surfaces of clay minerals and may be highly concentrated in clay layers. The highest K^{+}, Na^{2+}, Fe, Cl^{-}, and nitrate (NO_3^{-}) concentrations were recorded at the private well P-2. Therefore, the elevated specific conductivity value (343 µS/cm) measured at this location is the result of multiple dissolved ions present in solution. The presence of Cl^{-} and NO_3^{-} concentrations

(28.2 and 21.9 mg/L, respectively) higher than the baseline concentrations in these groundwaters (table 5), indicates the presence of anthropogenic contamination. Previous research indicated that groundwater in karst systems is highly vulnerable to surface contamination, particularly nitrate contamination from fertilizers (Coxon, 1999). In the investigated area, agricultural lands are mainly characterized by farm lands. However, this well is located within one of the largest residential areas in Trussville (plate 5). Sources of contamination at this location are probably associated with sewer breakthrough, confirmed by the Cl/NO_3^- ratio higher than one (1.3) (for example, higher chloride concentrations are generally associated with contamination originating from septic systems) (Alhajjar and others, 1990).

Iron naturally occurs in waters throughout Alabama, although concentrations generally are low due to the characteristic insolubility of iron under natural aquifer conditions. The drinking water standard for iron (0.3 mg/L) is commonly exceeded, especially in coastal plain aquifers where localized concentrations may exceed 10 mg/L. Iron is one of the most objectionable drinking water constituents of groundwater and, generally, when iron is encountered at concentrations near or above drinking water standards in a test well, the well is abandoned.

Iron primarily occurs in two forms, which are determined by the presence of iron-bearing minerals and reactions of these minerals with water under specific subsurface conditions of pH and ORP. However, consideration of ORP and pH alone in explaining iron concentrations is simplistic and may not be adequate in every situation. Most of the iron released from sediments near the surface is oxidized to form slightly soluble to insoluble ferric iron Fe^{3+} (ORP>0.20 and pH >5) (Hem, 1985). With increasing depth, oxygen is consumed, and as the environment becomes reducing (ORP 0.20 to –0.10), ferric iron is reduced and ferrous iron (Fe^{2+}) becomes the dominant form within the normal pH range of natural water (pH 5-9) (Hem, 1985).

Figure 12 shows the position of wells with measured values of ORP and pH on the iron phase diagram, which gives predicted concentrations of ferrous iron in water. The phase diagram indicates that iron concentrations are below the drinking water standard for all samples collected in May 2010 with the exception of the privately owned well P-1 that was contaminated with iron bacteria, which resulted in large concentrations of iron hydroxide. Predicted iron concentrations were generally higher for water samples collected from the same wells in November 2010 with concentrations in wells 6, 7, and 10 above the drinking water standard.

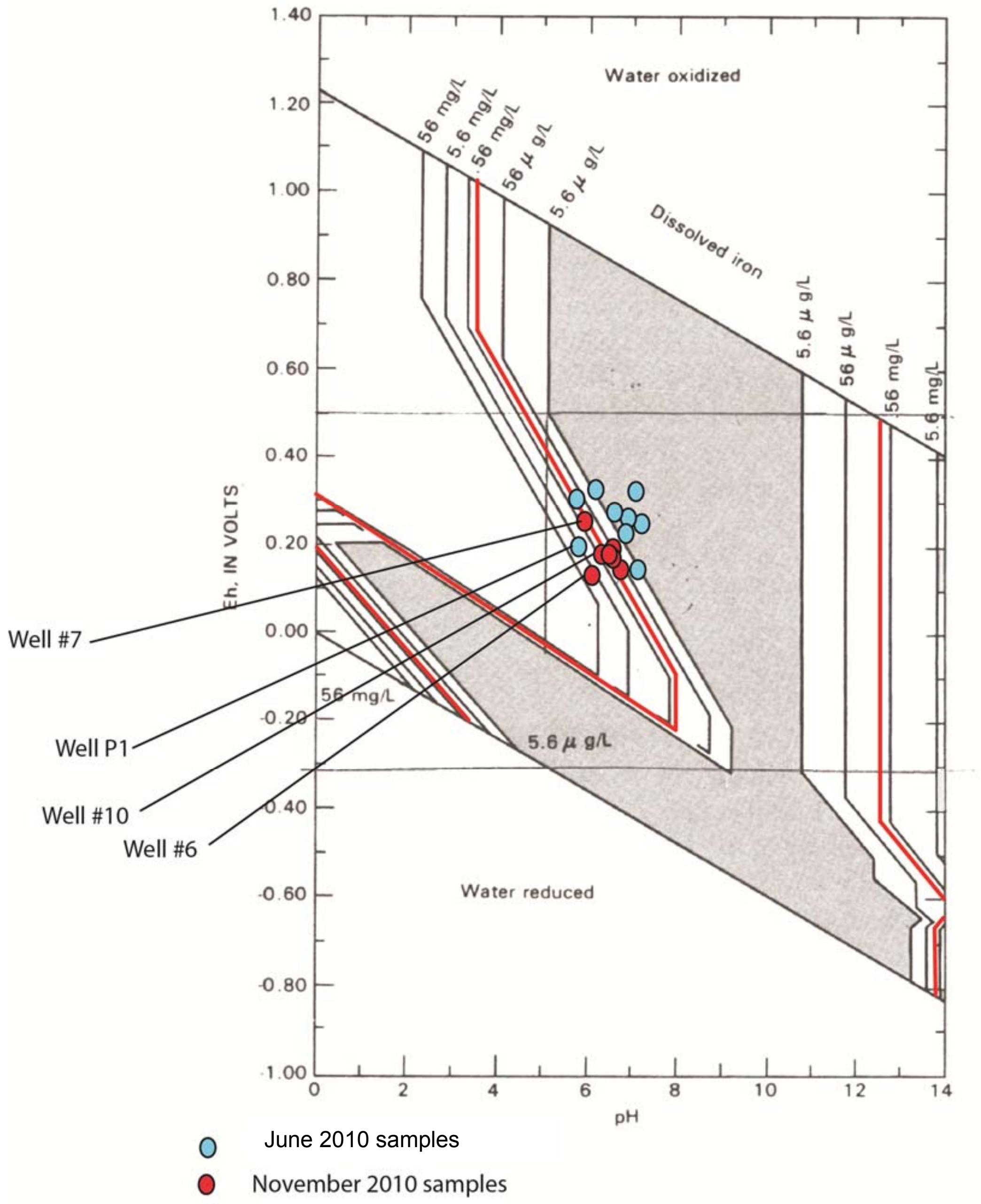


Figure 12.—Phase diagram for iron with values of ORP and pH from selected Trussville wells.

In the recharge area, iron exhibits very low concentrations in the TU public supply wells (W-7, W-10). However in the unused flowing well FW and the private well P-2, iron concentrations are as high as 0.6 and 4.4 mg/L, respectively (table 5).

Waters replenishing aquifers in close proximity to the ground surface are rich in CO_2 originating from the atmosphere and from the oxidation of organic matter by bacteria (Moss, 1989). As CO_2 dissolves in water, H_2CO_3 forms, giving rise to a more acidic character of recharge waters. Migration of these waters through the aquifer enhances carbonate dissolution resulting in an increase in HCO_3^- and Ca^{2+} concentrations in groundwater. Groundwater geochemical evolution can be assessed by evaluating the major anion and cation concentrations. The major ionic composition of water collected from wells FW, W-7, W-10, and P-2, as illustrated by the Piper and Stiff diagrams in figures 13 and 14, is dominated by calcium and bicarbonate ions. Similar to the Piper diagram, the Stiff diagram reveals Ca^{2+} and HCO_3^{2-} as the dominant ions that have roughly equal importance in the shape of the plot (fig. 14). However, the proportion in which each of these ions occurs is different for all samples. The higher concentrations of chloride measured in the well P-2 classifies this water as a Ca-HCO_3^--Cl type (). This reveals the impact of both natural and anthropogenic effects in the evolution of

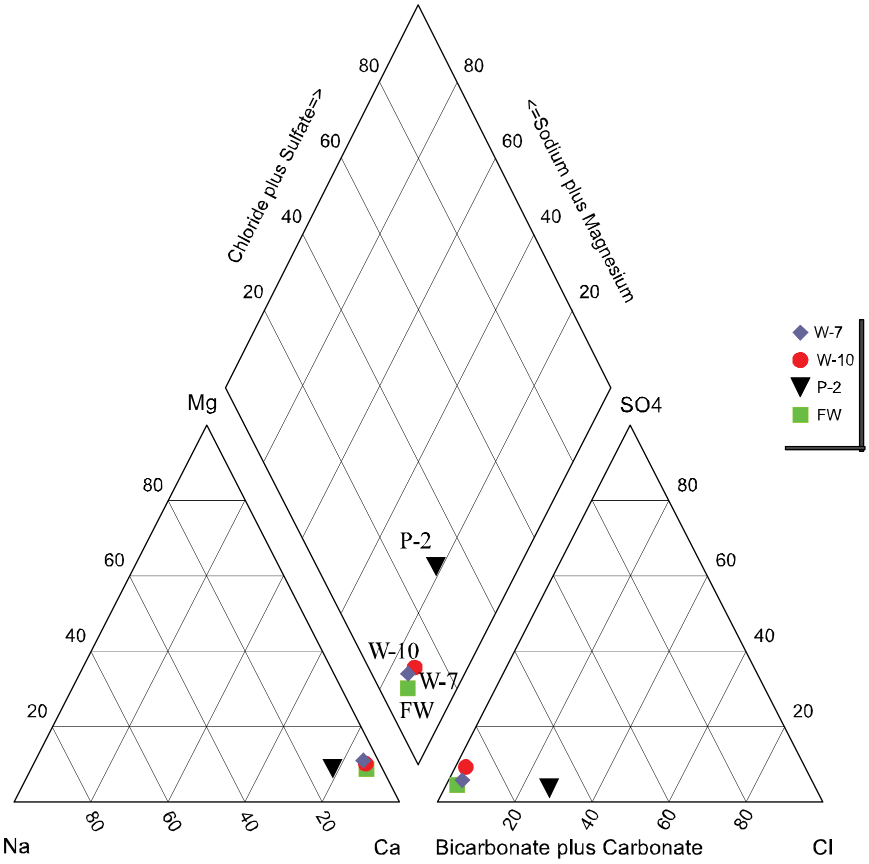


Figure 13.—Piper trilinear diagram showing major ion composition of water collected from TU wells FW, W-7, and W-10 and private well P-2.

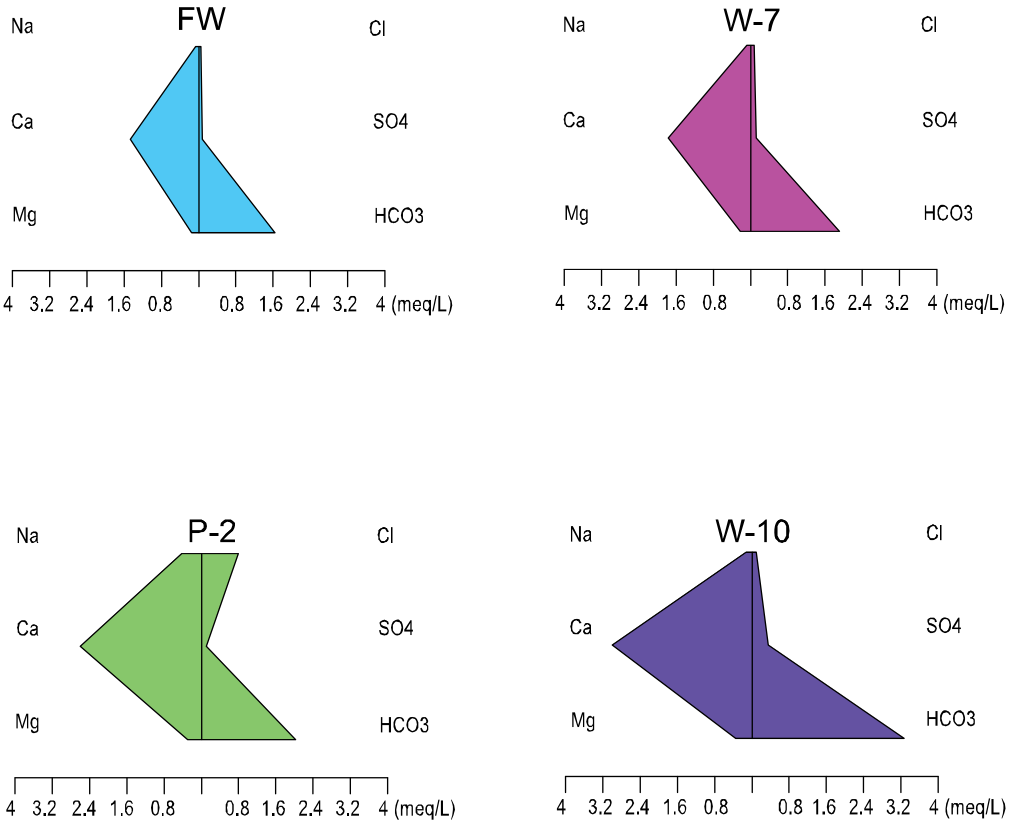


Figure 14.—Stiff diagrams for the selected wells sampled in the Trussville Utilities recharge area.

groundwater feeding this well. The observed elevated nitrate concentrations (21.9 mg/L) further supports the anthropogenic impact on groundwater chemistry at this location.

The form in which CO_2 exists in water is strongly dependent on pH. Carbonate evolution in natural environments is represented by three chemical reaction steps: the reaction of carbon dioxide (CO_2) and water to form carbonic acid (H_2CO_3), the conversion of carbonic acid to hydrogen ion and bicarbonate (HCO_3^-), and the conversion of bicarbonate to hydrogen ion and carbonate (CO_3^{2-}). The result of these reactions can be clearly observed by examining the pH and concentrations of carbon dioxide, bicarbonate, and carbonate in samples collected from the project wells. Furthermore, the different carbonate faces can be identified using pH information. For example, at pH 6.4, 50% of the carbon dioxide is in the form of HCO_3^- and the other 50% exists as H_2CO_3. The presence of carbonate in the system is associated with basic pH values. In groundwater samples collected from the Tuscumbia Limestone/Fort Payne Chert and Bangor Limestone aquifers, carbonate has not been detected but bicarbonate concentrations are in relatively high concentrations (100 to 199 mg/L). At the time of collection, pH values ranged from 5.3 to 6.6 (table 5). A good correlation has been observed between pH, HCO_3^-, Ca^{2+}, Mg^{2+}, and SC. Therefore, the investigated groundwater experienced dissociation of carbonic acid into CO_2 and HCO_3^-. Although a limited number of samples were available for data interpretation, a general evaluation of the geochemical character for the investigated groundwater can be obtained. The presence of Mg^{2+} in low concentrations compared to Ca^{2+} (table 5) indicates that limestone is pervasive in the aquifer matrix as opposed to dolomite.

The mean measured pH for the four aqueous samples is 6.1, indicating that carbonate dissolution in these groundwaters is an ongoing process due to the continuous addition of acid (H^+) in solution (Moss, 1989). The tendency of a particular water system to dissolve or precipitate carbonates can be determined by calculating the calcite saturation index. The Langelier index (LI) has been used to evaluate the degree of saturation of waters with respect to $CaCO_3^-$ based on the pH of the water and the pH at which the water becomes saturated (pHs) (equation 1).

$$\text{Equation 1: } LI = pH - pH_s$$

For the investigated groundwater, LI values range from -3.4 to -1.7 (table 6). The negative values indicate that groundwater is undersaturated with respect to calcite and tends to dissolve carbonate minerals from the host rock. The most negative indexes are estimated for the Tuscumbia Limestone/Fort Payne Chert aquifer. Groundwater collected from the flowing well

Table 6.—Classification of water hardness
(after Durfor and Becker (1964) and Langelier index (LI)).

Sample site	**Concentration (mg/L as $CaCO_3$)**	**Hardness Classification**	**LI**
Flowing well	81	Moderately Hard	-3.4
Private well-2	144	Hard	-2.2
W-7	100	Moderately Hard	-2.3
W-10	168	Hard	-1.7

*W=Tuscumbia Utilities public supply wells
FW= Tuscumbia Utilities unused flowing well
P=privately owned wells

developed in this aquifer exhibits the lowest LI (-3.4), pH, alkalinity, conductivity, and Na^{2+}, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, and nitrate NO_3^- values (tables 5, 6). Therefore, groundwater at this location belongs to a different geochemical type compared to all other investigated waters. A different source of recharge can likely be assumed for the Tuscumbia Limestone/Fort Payne Chert aquifer at this location. The least negative saturation index was estimated for well W-10 developed in the Bangor Limestone aquifer. These observations are in consent with the field parameters collected during two field visits (summer and fall, 2010).

Water hardness is defined as the content of metallic ions that react with sodium soaps to produce solid soaps or produce mineral scales when evaporated. Hardness is expressed as the total concentration of Ca^2+ and Mg^2+ as mg/L equivalent of $CaCO_3$ (Freeze and Cherry, 1979). Measured water hardness for the aquifers varies between 81 and 168 mg/L $CaCO_3$ (table 6). Waters in the Tuscumbia Limestone/Fort Payne Chert and Bangor Limestone aquifers are classified as moderately hard to hard (Durfor and Becker, 1964) (table 6).

ISOTOPE INVESTIGATIONS AND WATER AGE DATING

Groundwater in the investigated area has been increasingly targeted for the region's growing water needs. Expanding use of groundwater resources requires better knowledge of recharge and flow conditions. Groundwater evolution is a critical focus of the current hydrogeological assessment, directed to develop a better understanding of the local/regional flow system, with respect to recharge mechanisms and groundwater residence times. Recent advances in analytical techniques make it possible to accurately measure extremely small concentrations of isotopes of key elements that enable the relatively accurate age dating of water. When combined with other geochemical and hydrogeologic information, isotopic data can help evaluate migration history and geochemical evolution of groundwater in aquifers and predict future areas of possible water resources development. Isotopes can be used as tracers of water movement, since unique isotopic signatures are characteristic to particular recharge environments. As part of this investigation groundwater samples from public supply and private wells constructed at various depths were analyzed for anthropogenic and natural and stable isotopes such as chlorofluorocarbon (CFCs) and sulphur hexafluoride (SF_6) and carbon ($\delta^{13}C$), oxygen ($\delta^{18}O$), and hydrogen (δD), respectively. These analyses provide essential measurements to identify the environment from which groundwater originated and constrain the period of time during which recharge occurred.

Stable isotopes of hydrogen, oxygen, and carbon are ideal tracers of groundwater sources and evolution along flow paths. Hydrogen and oxygen isotopes are best used in tracing sources of groundwater since they integrally compose the water molecule (Cook and Herczeg, 1999). These measurements provide information about recharge and discharge processes and are successfully used in delineating recharge areas (Cook and Herczeg, 1999). Carbon occurs in all forms of organic life and is the basis of organic chemistry. Carbon stable isotopes have been used as tracers of carbonate evolution in groundwater, given their distinct range of values for specific reservoirs. Besides reflecting the water-rock interaction and any other additional geochemical reactions that may take place within the saturated zone and aquifers, $\delta^{13}C$ of groundwater dissolved inorganic carbon (DIC) is also a good indicator of the land-use/land-cover characteristics of the source area (Cook and Herczeg, 1999).

Groundwater originates primarily from precipitation that infiltrates soil layers to the saturated zone. Groundwater transports anthropogenic atmospheric trace gases such as CFCs and SF_6 that can provide a temporal characterization of groundwater recharge, essential in determining the geochemical evolution of water from the time it enters the recharge area to the time of discharge. When combined, the two isotopes of CFCs and SF_6 can provide information about mixing processes, groundwater ages, and residence times with maximum resolution of about 50 years (Kazemi and others, 2006). These dating techniques have been employed worldwide and utilize relatively rapid and simplistic analytical procedures and unsophisticated sampling equipment to characterize groundwater systems (Cook and others, 1995; Plummer and others, 2001; Oster and others, 1996; MacDonald and others, 2003; and others).

Results of such investigations can aid in the development of sustainable groundwater management strategies and improve risk assessments related to groundwater resource depletion and contaminant transport.

OXYGEN AND HYDROGEN STABLE ISOTOPES

Ocean derived atmospheric waters are depleted in heavy isotopes (^{18}O and ^{2}H) relative to the standard mean ocean water (SMOW). $\delta^{18}O$ and δD isotopic composition of precipitation depends on the fraction of water remaining in the air mass from which the rain or snowfall is derived (Ellis and Mahon, 1977). Depletion of $\delta^{18}O$ and δD isotope signature in precipitation has been correlated with seasonal change (changes in temperature and humidity), latitude, altitude, distance from the coast, and amount of precipitation (Dansgaard, 1964). An example of latitudinal effect occurs over the North American continent where the rate of depletion of ^{18}O is approximately 0.5 percent per degree of latitude (Fritz and Frape, 1982). The cumulative effect of these physical parameters forms the isotopic character of precipitation, which is the source of surface-water runoff and recharge for groundwater aquifer systems.

Abundances of oxygen and hydrogen isotopes are measured (with an uncertainty of 1‰ for δD and 0.1‰ for $\delta^{18}O$) relative to an accepted standard, which is the SMOW, or Vienna SMOW (VSMOW) (Craig, 1961). The isotopic composition of sampled water is expressed in terms of relative difference of the ratio of heavy to light isotopes in the sample, compared to that of SMOW. The resulting compositional values are stated as positive (enriched) or negative (depleted) percentages relative to VSMOW. The average isotopic variation of global precipitation is defined by a linear regression of δD as a function of $\delta^{18}O$. Craig and Gordon (1965) estimated the mean worldwide isotope composition of precipitation to be $\delta^{18}O = -4$ per mil (‰) and δD = -22 ‰. The worldwide average correlation between hydrogen and oxygen isotope ratios in precipitation is given by the equation $\delta D = 8\ \delta^{18}O + 10‰$, called the Global Meteoric Water Line (GMWL).

Groundwater samples for oxygen and hydrogen stable isotope analyses were collected during two sampling events in June and November 2010. During the summer event, samples were collected from seven of the TU public supply wells and an abandoned TU flowing well, two private wells, and from Thomas Spring (not in the investigated area). The fall sampling included only the TU wells (a total of eight samples).

The δD and $\delta^{18}O$ isotope signatures for groundwater samples collected during the summer event ranged between -25.0 to -30.6 ‰ and -5.1 to -5.7 ‰, respectively. Fall samples isotopic signature followed a narrower range for the δD data, -25.4 to -27.4 ‰, and a wider range for the $\delta^{18}O$ data, from -4.75 to -5.35 ‰ (table 7). Due to data availability, seasonal comparison includes only the TU wells. Summer groundwater $\delta^{18}O$ signature exhibits a homogeneous spatial distribution compared to the fall (fig. 15). While there is some variation in the δD data spatial distribution (with the exception of two wells), no significant differences were observed between the two seasons. Two exceptions were observed at TU wells 14 and 5 where groundwater becomes more enriched in heavier oxygen and hydrogen isotopes between the summer and fall sampling events (fig. 15).

Table 7.--$\delta^{18}O$ (‰ VSMOW), δD (‰ VSMOW), and $\delta^{13}C$ (‰ PDB) isotope signature in groundwater

			June 2010			November 2010				
Sample site	**Aquifer**	**Depth**	**δD**	**δ^{18}O**	**pH**	**δD**	**δ^{18}O**	**δ^{13}C**	**pH**	**DIC (mg/L)**
W-12	Bangor Limestone	339	-27.2	-5.2	7.2	-26.9	-5.01	-10.9	6.6	37.4
W-9	Bangor Limestone	300	-27.9	-5.3	6.9	-27.4	-5.0	-11.1	6.8	37.4
W-10	Bangor Limestone	289	-27.2	-5.4	6.6	-27.2	-5.4	-11.9	6.3	33.8
W-14	Bangor Limestone	355	-27.5	-5.3	7.2	-26.1	-4.9	-10.2	6.6	36.2
Average		-	*-27.5*	*-5.3*	*7.0*	*-26.9*	*-5.1*	*-11.0*	*6.6*	*36.2*
FW	Tuscumbia Limestone/Fort Payne	155	-26.6	-5.2	6.8	-27.3	-5.3	-12.2	7.6	14.4
W-7	Tuscumbia Limestone/Fort Payne	154	-25.0	-5.2	6.2	-25.7	-5.0	-11.5	6.0	28.3
W-6	Tuscumbia Limestone/Fort Payne	152	-26.8	-5.1	5.8	-26.6	-5.1	-13.4	6.1	24.1
W-5	Tuscumbia Limestone/Fort Payne	170	-28.0	-5.2	7.2	-25.4	-4.8	-10.2	6.6	39.5
Average		-	*-26.6*	*-5.2*	*6.5*	*-26.3*	*-5.1*	*-11.8*	*6.6*	*26.6*
P-1	Tuscumbia Limestone/Fort Payne?	80	-30.6	-5.7	5.8	-	-	-	-	-
P-2	Tuscumbia Limestone/Fort Payne?	250	-25.8	-5.1	6.1	-	-	-	-	-
General Average	-	-	**-27.3**	**-5.3**	**6.6**	**-26.6**	**-5.1**	**-11.4**	**6.6**	**31.4**

*W=Tuscumbia Utilities public supply wells
FW= Tuscumbia Utilities unused flowing well
P=privately owned wells

Lambert and Aharon (2009) developed a local Tuscaloosa meteoric water line (TLMWL) from precipitation collected from the rain-gage station at the University of Alabama in Tuscaloosa. The TLMWL was developed using an average of multiple δ^{18}O (a) and δD readings from precipitation samples collected during a 3-year period (2005-2008). The weighted annual (3-year) δ^{18}O and δD mean values are -4.7‰ and -24.3‰, respectively (Lambert and Aharaon,

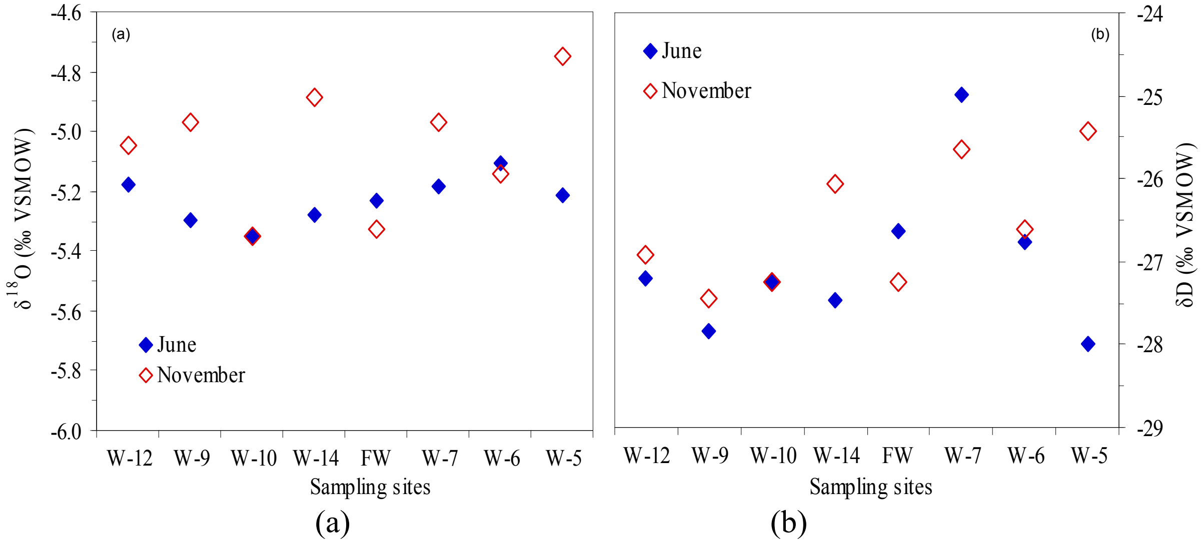


Figure 15.—Groundwater δ^{18}O (a) and δD (b) isotope signature seasonal variation.

2009). These values are more enriched in the heavy isotopes compared to the Trussville groundwater samples. This may be explained by the wide range of values incorporated in estimating the mean, which includes all four seasons and periods of drought and intense rain events. Although latitudinally, the difference between the two locations is insignificant (Trussville: 33°36’32”W; Tuscaloosa: 33°12’35”W), altitudinally, there is enough difference (Trussville average elevation: 787 ft; Tuscaloosa average elevation 223 ft) to explain the more depleted isotope signatures of groundwater collected in the recharge area.

Generally, precipitation becomes more depleted in heavy isotopes of oxygen and hydrogen with increasing elevation. Nevertheless, once precipitation infiltrates to the water table it mixes with the ambient groundwater, resulting in a distinctive isotopic signature. Drip water (seepage) and shallow groundwater samples collected at the Desoto Caverns in Childersburg (about 30 miles southeast of Trussville) exhibit average δ^{18}O and δD values of -5.1 and -25.98 ‰ and -5.0 and -25.3‰, respectively (Lambert and Aharaon, 2009). Trussville groundwater δ^{18}O average values (summer and fall: -5.3 and 5.1‰, respectively) closely match those recorded at Childersburg, Alabama. However, δD average values are more depleted in the heavy hydrogen isotope (summer and fall: -27.25 and -26.6 ‰, respectively). Slightly depleted δD values are likely caused by different rates of evaporation experienced by meteoric waters supplying the two types of groundwater (Childersburg and Trussville).

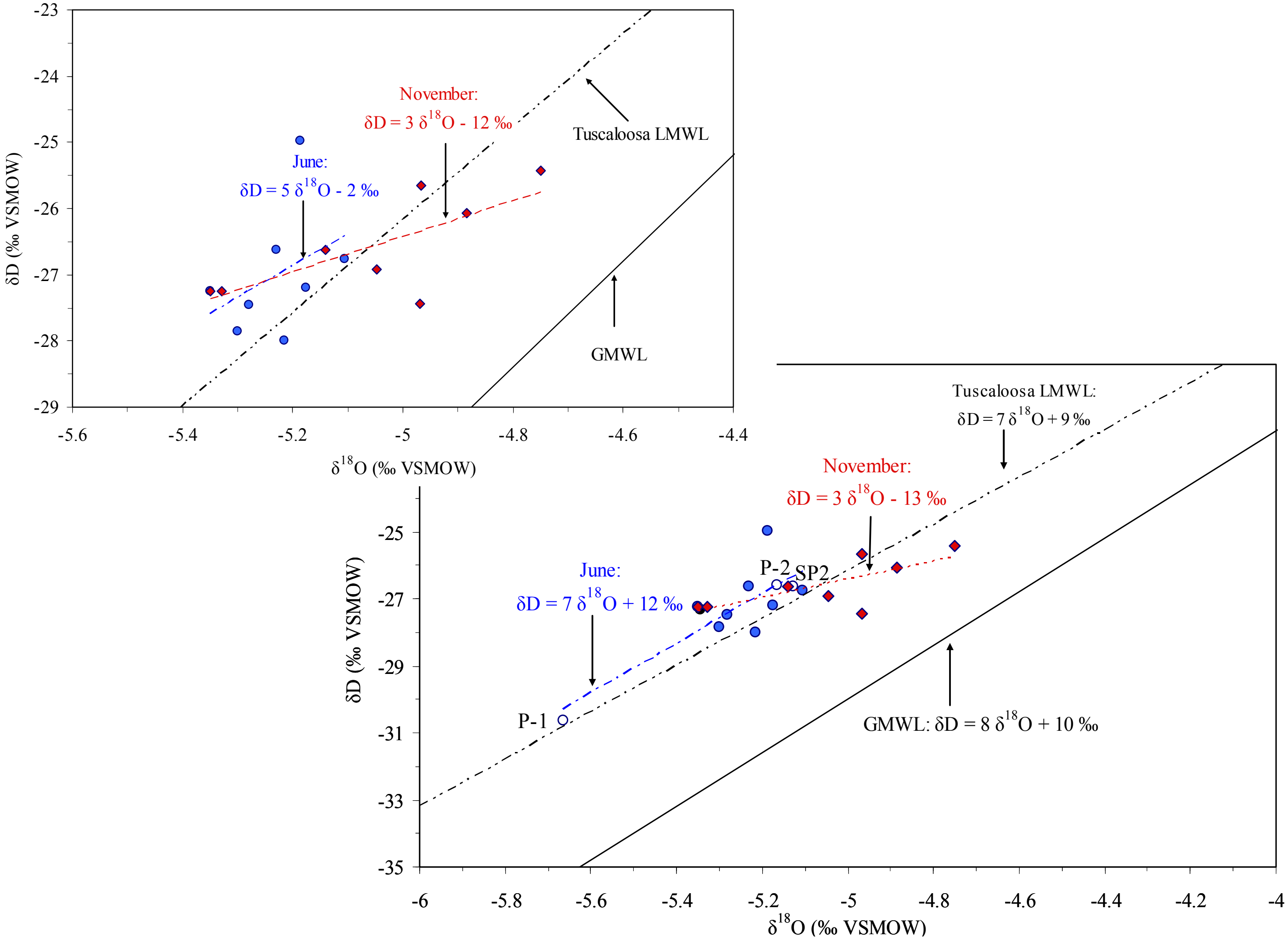


Figure 16.—Cross-plot of the $\delta^{18}O$ and δD groundwater data collected from the Trussville Utilities public supply, private (TP1 and TP2), and flowing wells and from Thomas Spring (Jefferson County, Alabama) (SP2). The insert is a cross-plot of the TU wells $\delta^{18}O$ and δD that is used for seasonal comparison.

Figure 16 represents a cross plot of the summer and fall isotope data relative to the GMWL and TLMWL. Summer isotope data plot above the GMWL and TLMWL (fig. 16). While all fall data plot above the GMWL, four out of eight of the data points plot below the TLMWL (fig. 16). Most of the data points below the TLMWL are associated with wells screened in the Bangor aquifer (for example, wells W-9, W-12, and W-14). The fourth data point below the TLMWL corresponds to TU well W-5, screened in the Tuscumbia Limestone/Fort Payne Chert aquifer. Summer groundwater isotopic signature corresponding to these wells plots above the TLMWL. Points below the TLMWL are related mainly to the $\delta^{18}O$ signature that becomes heavier between the two sampling events (fig. 15). Groundwater signature from samples collected at the four Bangor Limestone wells is also associated with an increase in δD (fig. 15). These observations are indicative of a different source of recharge during the summer period which may result from mixing of the ambient groundwater with more recent recharged groundwater.

The more homogeneous range of the summer data indicates a smaller degree of groundwater mixing in the investigated aquifers and the likelihood of common regional recharge for both Bangor and Tuscumbia Limestone/Fort Payne Chert aquifers (for example, recharge occurring within the recharge area). The narrow range of groundwater $\delta^{18}O$ and δD summer values suggests a short recharge period with low evaporation rates of infiltrating water. Therefore, most recharge likely takes place during colder seasons when evaporation is lowest to absent. This narrow variation may be also attributed to the smaller seasonal temperature fluctuations that occur in humid subtropical climates compared to much larger temperature ranges characteristic of temperate climates.

Generally, waters with lower $\delta^{18}O$ and higher δD values than the precipitation water from which the local meteoric water is derived, plot above the meteoric water line. Displacement of the fall data from the TLMWL may be due to factors such as evaporation, residence time, water-rock exchange reactions, and mixing with different signature waters (for example, newly infiltrated precipitation or groundwater of variable age and composition). During evaporation and mixing processes, $\delta^{18}O$ and δD composition changes and shifts away (below and to the right) from the MWL (global or local) as indicated by the linear-square regression of the isotope data (fig. 16). However, due to the characteristically low concentrations of hydrogen isotopes and relatively high concentrations of oxygen isotopes in rocks, exchange reactions between water and rocks are generally characterized by an oxygen shift from the MWL along the “x” axis of the regression. Commonly, $\delta^{18}O$ shifts are accompanied by slight shifts in δD compositions (Ellis and Mahon, 1977), as observed in the fall water signature (fig. 16). Waters experiencing depletion of ^{18}O (the heavy isotope) and a slight increase of D (the heavy isotope of hydrogen) may plot to the right and below the local meteoric water line (fig. 16). This generally is an indication that the investigated waters may have been part of silicate hydrolysis reactions (Coplen, 1993).

CARBON STABLE ISOTOPES

Carbon stable isotopes in groundwater DIC analysis offers information about the type of groundwater regarding the source of recharge and the existence of water-rock interaction processes. Unconfined, shallow aquifers have $\delta^{13}C$ signatures very similar to those of pore-water and source waters. Groundwater DIC content is dependent on the carbon dioxide (CO_2) content of the soil. In open systems, such as the vadose zone, the continuous supplement of CO_2 increases the DIC concentration. Dissolution of CO_2 and formation of $H_2CO_3^-$ increase the acidity of the infiltrating water, which facilitates limestone dissolution. Closed conditions arise however, in recharge areas characterized by fast infiltration rates to the aquifer. Similarly, soils with very little or no carbonates behave as closed systems. In these systems, the final DIC concentration is extremely low (Clark and Fritz, 1997). The $\delta^{13}C$ signature of deeper, semiconfined, and confined aquifers depends on groundwater residence times and geochemical processes that occur along flowpaths.

The type of vegetation present in recharge areas exerts significant influence on the $\delta^{13}C$ signature of the soil CO_2, and furthermore, $\delta^{13}C$ signature of groundwater. Three photosynthetic cycles influencing this signature are: the Calvin or C3, the Hatch-Slack or C4, and the Crassulacean acid metabolism (CAM) (Ehleringer and others, 1991). C3 plants are dominant in most terrestrial ecosystems and have an average $\delta^{13}C$ signature of -27‰ (Vogel, 1993). C4 plants are characteristic of hot, open environments (for example, tropical and temperate grasslands) (Ehleringer and others, 1991) and have an average $\delta^{13}C$ of -12.5‰ (Vogel, 1993). Crassulacean acid metabolism (CAM) plants are characteristic of desert environments and switch between C3 and C4 pathways of CO_2 fixation from day to night. Their characteristic $\delta^{13}C$ signature ranges between -13 to 27‰ (Clark and Fritz, 1997). Measurements of carbon stable isotope ratio ($^{13}C/^{12}C$) of groundwater DIC offer the possibility of estimating subsurface water transport rates (Mook, 2000). DIC concentrations are reported in parts per million per liter (ppm/L), whereas isotope ratios are reported in the conventional delta (δ) notation in per mil (‰). $\delta^{13}C$ data are reported relative to Vienna Pee Dee Belemnite (VPDB) and the standard deviation for the measurements is ±0.2 ‰ (1σ). Standard deviation of the measurements is based on sample replicates as well as internal and international standards. Uncertainties of the $\delta^{13}C$ measurements are 0.5‰ VPDB.

Distinctive $\delta^{13}C$ values for organic and inorganic carbon (-27‰ to -12.5‰ for plants, -2‰ to +2 ‰ for marine carbonates, and -12‰ to +2‰ for soil carbonates) have been used to identify sources of DIC in groundwater (Deines and others, 1974). The eight TU wells were sampled and analyzed for $\delta^{13}C$ of groundwater DIC. DIC and $\delta^{13}C$ values ranged from 14.1 to 39.5 ppm/L and from -13.4‰ (most depleted) to -10.2 ‰ (least depleted), respectively (table 7; fig. 17). Average DIC and $\delta^{13}C$ values are 31.4 ppm/L and -11.4‰, respectively (table 7). The most depleted $\delta^{13}C$ value (-13.4‰) is associated with the shallower well W-6 that produces fresh water from the Tuscumbia Limestone/Fort Payne Chert aquifer (fig. 17). Wells W-14 and W-5, developed in the same aquifer, exhibit the heavier values (-10.24 and -10.22‰, respectively) (fig. 17). No preferential distribution of $\delta^{13}C$ values by aquifers has been observed. DIC data variation is larger compared to $\delta^{13}C$ as it offers insight regarding the openness of the investigated system.

Generally, there is a good positive correlation between DIC and $\delta^{13}C$ values (fig. 18) indicating the input of DIC into the system from processes associated with carbonate dissolution along migration paths. Isotopic exchange between groundwater during carbonate dissolution shifts $\delta^{13}C_{DIC}$ towards more positive values. Enrichment in the heavier isotope of carbon (^{13}C) is also accompanied by an increase in alkalinity due to transfer in solution of Ca^{2+} and Mg^{2+} (fig. 18). Given the relatively low values of DIC and $\delta^{13}C$, it can be inferred that recharge occurs under closed conditions, with fast percolation rates of precipitation to the water table (for example karsts or fractured aquifer media) (Clark and Fritz, 1997). Under open conditions, $\delta^{13}C$ values would be closer to or lower than -14‰ due to the fractionation occurring between DIC ($HCO_3^- + H_2CO_3$) and soil CO_2 (Zhang and others, 1995).

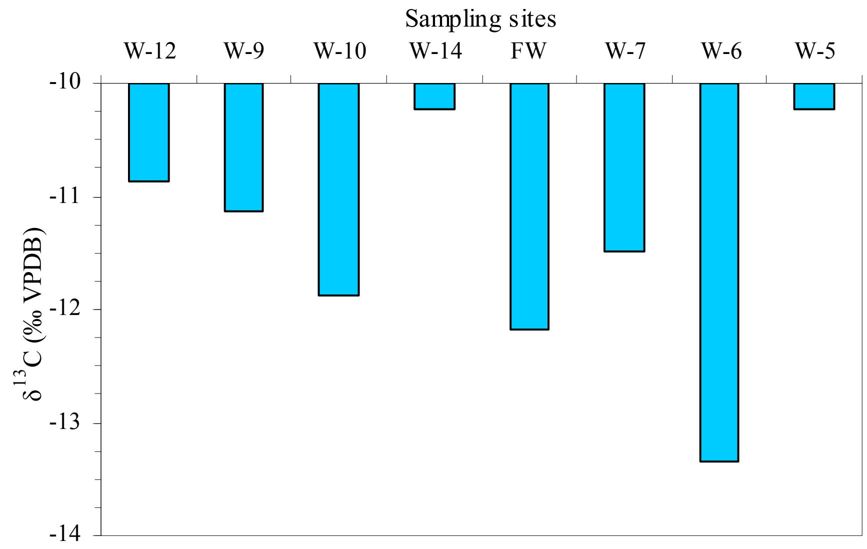


Figure 17.—δ^{13}C distribution by sampling site.

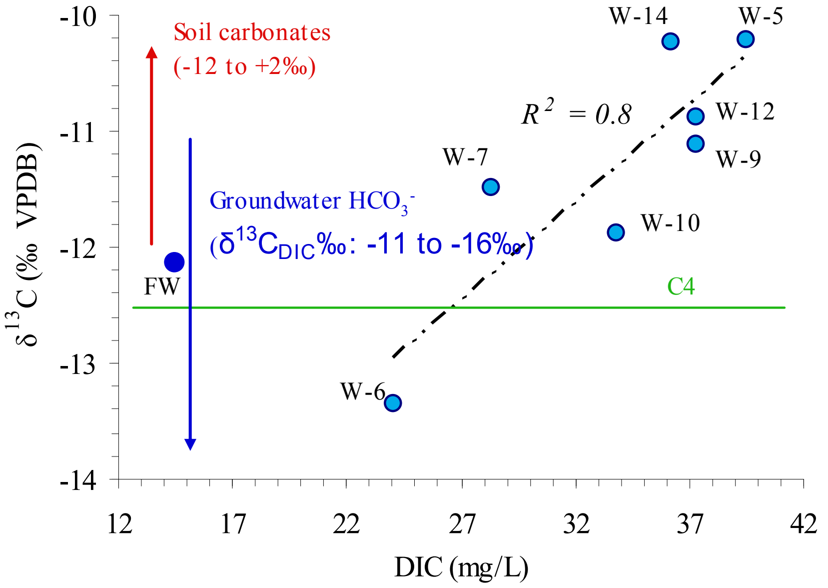


Figure 18.—Relationship between δ^{13}C and DIC in groundwater collected from Trussville Utilities wells. Note that the correlation between the two parameters is estimated excluding the FW data. When including FW data, the estimated correlation coefficient becomes 0.5.

Groundwater signature in the recharge area is affected by (1) soil CO_2 derived from the decay of terrestrial vegetation and respiration of plant roots and (2) carbonate bedrock dissolution by carbonic acid or sulfuric acid and organic acids enriched in the infiltrating water from the root zone. During the first process, $\delta^{13}C$ values of pore water are most likely to center around -25‰ (Mook, 2000). After meteoric water infiltrates to the water table (second process), water/rock reactions shift $\delta^{13}C$ signature towards more positive values (greater than -14‰). This shift in isotopic composition is dependent on the degree of dissolution of carbonate minerals, groundwater residence times, and mixing degree with different signature waters. The average $\delta^{13}C$ value (-11.4‰) lies near the combined average $\delta^{13}C$ values of soil CO_2 and carbonate dissolution. Therefore, groundwater $\delta^{13}C$ signature is mainly controlled by two factors: soil CO_2 and carbonate dissolution. Under these conditions, carbonate dissolution along flowpaths is the main reaction affecting the $\delta^{13}C$ signature after recharge water enters the aquifer system.

The lowest DIC concentration was measured in the flowing well (table 7; fig. 18). There is a gap between the DIC value recorded for the flowing well (14.1 mg/L) and the next lowest value (24.1 mg/L), resulting in a narrower range of DIC values when the flowing well is not considered: 24.1 to 39.5 mg/L. Therefore, this value was considered an outlier and eliminated from the data analysis. Furthermore, the highest pH value (measured at the time of sampling for the carbon isotope analysis) was recorded at this well (fig. 19). Compared to all other

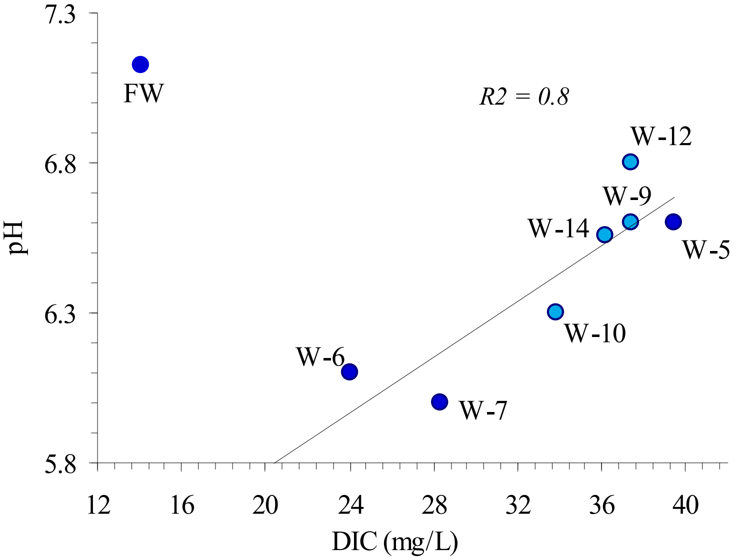


Figure 19.—Cross-plot of DIC and pH values. Note that the linear relationship between the two parameters is estimated excluding the FW data.

investigated wells, FW is set apart by the highest hydraulic pressure (water level is 5 ft above ground surface) and by the lowest temperature, ORP, SC, DO, and TDS values (table 4). These characteristics indicate that different recharge conditions are associated with this location within the Tuscumbia Limestone-Fort Payne Chert from which this well is producing.

The second lowest DIC (24.1 mg/L) and most depleted $\delta^{13}C$ (-13.4‰) values were recorded in samples collected from well 6 (fig. 18). The lowest SC (98 and 135 µS/cm at FW and W-6, respectively) and TDS (64 and 88 mg/L, FW and W-6, respectively) values were recorded at the FW and W-6 locations. The more depleted $\delta^{13}C$ signatures and the lowest SC and TDS values measured in these groundwater samples are an indication of a greater influence of soil DIC rather than carbonate dissolution. Furthermore, the most elevated static water levels were measured at these locations (5 ft above ground surface at FW and 23 ft below ground level (bgl) at W-6). Both wells produce water from the Tuscumbia Limestone/Fort Payne Chert aquifer that is generally characterized by more elevated water levels, compared to the Bangor aquifer (fig. 9). The more distinct character of these samples indicates the possibility that water recharging the two wells likely belongs to the same recharge area experiencing dilution along the flow path. Bangor Limestone groundwater samples are set apart by lower water levels and higher conductivities, DIC concentrations, and heavier $\delta^{13}C$ signatures, compared to those collected from Tuscumbia Limestone/Fort Payne Chert (figs. 6, 9, 17, 18, 20). Geochemical characteristics of groundwater extracted from well W-5 (W-5) are similar to those of groundwater extracted

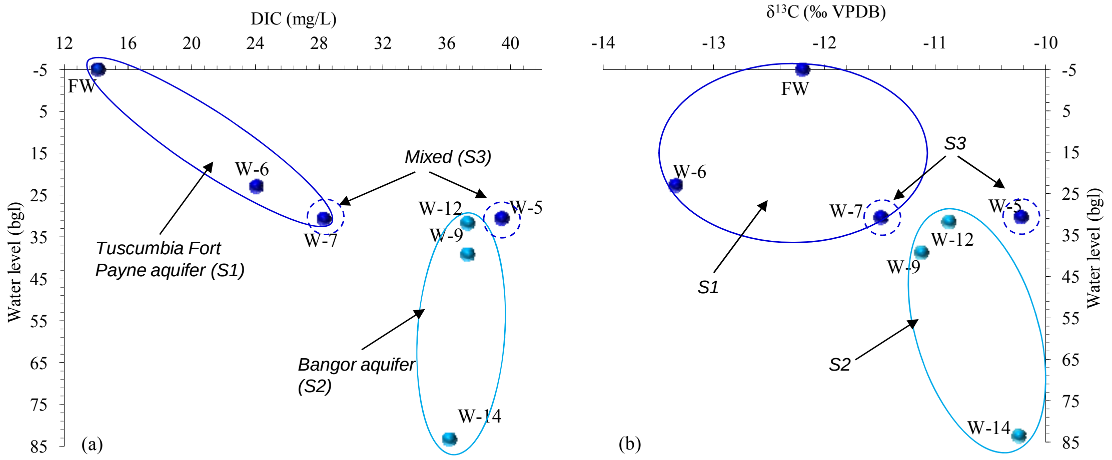


Figure 20.—Distribution of DIC (a) and $\delta^{13}C$ (b) values as a function of static water level. Circles represent fields of characteristic geochemical signature and water levels of the Tuscumbia Fort Payne (S1) and Bangor Limestone (S2) aquifers and of intermediate or mixed signatures (S3).

from the Bangor aquifer (W-9, W-12, W-14, W-10) (figs. 6, 19, 20).This suggests that at this location there is significant mixing of the Tuscumbia Limestone/Fort Payne Chert water with more mineralized waters such as those originating from the Bangor limestone aquifer (fig. 20). The sample from W-7 exhibits an intermediate behavior between the two fields (figs. 6, 19, 20) suggesting that some mixing may exist or recharge conditions may differ.

CHLOROFLUOROCARBON AND SULFUR HEXAFLUORIDE GROUNDWATER AGE DATING

Chlorofluorocarbons (CFCs), organic compounds containing C, Cl, and fluoride (F), commonly known as Freon, have been widely used as refrigerants, propellants, and solvents (Rossberg and others, 2006). Approximately 1 million tons of CFCs were produced worldwide by 1974. Due to their multiple applications, they are believed to be the most useful chemical compounds that have ever been produced and no natural source has been discovered (Lovelock, 1971). The atmospheric lifetime of trichlorofluoromethane (CFC-11), dichlorodifluoromethane (CFC-12), and trichlorotrifluoroethane (CFC-113), those species used to date relatively young groundwaters, is 40, 100, and 85 years, respectively (Badr and others, 1990). Industrial use of CFC-12 started in 1930s, CFC-11 in the 1950s, and CFC-113 in the 1970s (Plummer and Busenberg, 1999). These compounds dissolve in precipitation, becoming part of the hydrologic cycle and can be identified in groundwater that has been recharged in the past 50 years.

The usefulness of this dating technique has been only recently considered for use in characterizing regional patterns of shallow groundwater systems (Busenberg and Plummer, 1992). Using purge and trap, gas chromatographic techniques with electron-capture detector (GC-ECD), CFC-11, CFC-12, and CFC-13 concentrations in water can be determined with a detection limit of 0.3 picograms per kilogram of water (pg/kg-1) (Bullister, 1984; Bullister and Weiss, 1988; Busenberg and Plummer, 1992). This makes possible the use of CFC-12, CFC-11 and CFC-113 to identify groundwater recharged since approximately 1941, 1947, and 1955, respectively. This is a feasible dating technique because (1) the atmospheric mixing ratios of these compounds are known and/or have been reconstructed over the past 50 years, (2) the Henry's law solubilities in water are known, and (3) concentrations in air and young water are relatively high and can be measured (Cook and Herczeg, 1999).

The observed decreasing concentrations of CFCs in the atmosphere over the last decade or so resulted in ambiguity in CFC-based apparent age estimation. Therefore, sulfur hexafluoride

(SF_6) has been used as an alternative to CFCs for gas-solubility water dating (Busenberg and Plummer, 1997). Production of SF_6 began in the 1960s for use in high voltage electrical switches. SF_6 is extremely stable and has an estimated atmospheric lifetime of 800 (Morris and others, 1995) to 3,200 years (Ravishankara and others, 1993). SF_6 analyses can be conducted with a precision of 1-3% using GC-ECD techniques (Wanninkhof and others, 1991; Law and others, 1994). Therefore, although atmospheric mixing ratios are small (currently about 4 parts per trillion by volume (pptv)), dating using this method is possible from about 1970. SF_6 accumulation in the atmosphere is extremely rapid with an approximate current growth rate of approximately 6.9% per year (Geller and others, 1997). Records retrieved from previously dated groundwater, seawater concentrations (Law and others, 1994), production records, and atmospheric measurements (Ko and others, 1993; Elkins and others, 1996; Maiss and others, 1996; Geller and others, 1997; Levin and Hesshaimer, 1996) were used to reconstruct the historical atmospheric mixing ratio of SF_6.

Groundwater evaluations conducted by simultaneously using different tracers offer important information about ground-water travel times and age frequency distribution for mixed waters (Bőhlke, 2002). This information is invaluable for important resource-management decisions. If no biological or geochemical processes alter the CFCs and SF_6 concentrations in aquifers and their source is of atmospheric origin, apparent ages can be evaluated. The apparent groundwater age is determined by comparing the partial compounds in the sample, calculated from their measured concentrations, using solubility data for each compound, with the record of atmospheric partial pressures over North America at different times (fig. 21). Generally, four independent ages are generated from the three CFC compounds and SF_6 concentrations. These apparent ages can be used as a crosscheck on the sampling and analytical methods, and used to evaluate mixing processes.

Estimated apparent ages using both CFCs and SF_6 dating tools can be affected by factors such as excess air, recharge temperature, and degradation of CFCs. Excess air represents the air bubbles trapped in groundwater during the recharge process. This trapped air slowly dissolves in groundwater increasing the CFC concentration and underestimating the estimated age. This is not an issue for waters recharged prior to 1990 but affects dating of waters recharged after 1990 because of declining atmospheric CFC concentrations (Plummer and Busenberg, 2000). CFCs solubility is estimated based on the recharge temperature. Overestimation of the recharge

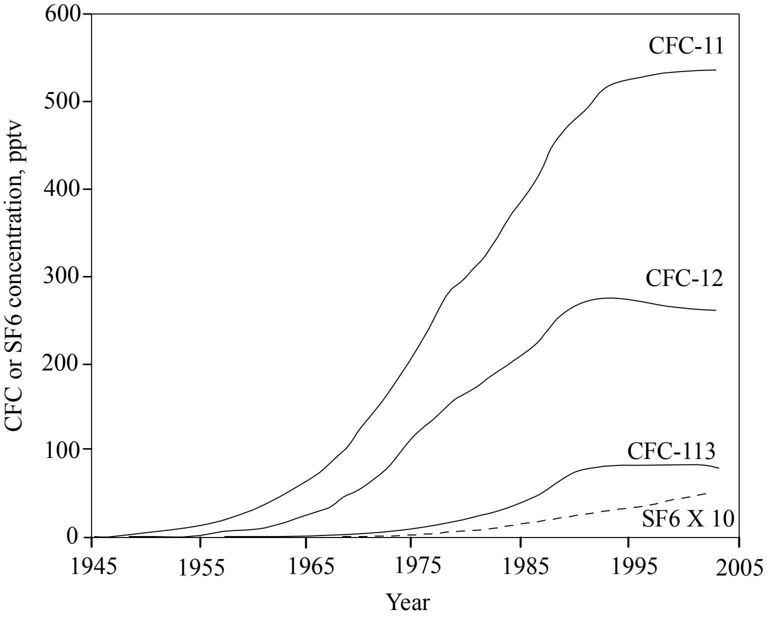


Figure 21.—Input history of CFCs and SF_6 atmospheric concentrations (Plummer and Busenberg, 1999: Busenberg and Plummer, 2000).

temperature will result in CFCs concentrations greater than actual values and overestimation of groundwater ages (Busenberg and Plummer, 1992). CFCs are degraded by microbial activity in soils with high organic content and in anoxic waters with sulfate-reduction or methanogenesis. CFC-11 is the most degraded CFC compound, which leads to a decrease in concentration and age overestimation (Kazemi and others, 2006).

Generally, CFC ages are considered reliable when all three compounds generate similar dates. If the three ages do not agree, CFC-12 is considered the most reliable, followed by CFC-113, and lastly CFC-11 (U.S. Geological Survey, CFC Laboratory, written commun, 2003). CFCs compounds, and especially CFC-11, degrade easily in poorly oxygenated waters. In contrast, FS_6 is stable in low-dissolved oxygen conditions (Robinson, 2004). Three samples collected for this assessment and submitted for CFCs and SF_6 analyses were degraded or contaminated (table 8), negating a valid age estimation. The contamination was probably caused by air introduced by the turbine pump during sampling. Only two samples have SF_6 concentrations within the range expected for air-saturated waters that are less than 40 years. At these two locations, one CFC age is also available (table 8). However, the apparent equilibration years for the two ages are different for the two compounds. No more than two samples exhibited two CFC ages and four samples had only one CFC age estimation available (table 8). Except for

Table 8.—Apparent groundwater ages from CFCs and SF_6 dating methods.

Sample site	Aquifer	Depth and screened interval (ft bls)	Apparent age and uncertainty (in years)				Final age (years)	Tracer used
			CFC-11	CFC-12	CFC-113	SF6		
W-12	Bangor Limestone	339 (311-339)	*Contam.*	*Contam.*	*Contam.*	*Contam.*	*Contam.*	*Contam.*
W-9	Bangor Limestone	300 (235-285)	30.5±2	19.5±2	*Contam.*	*Contam.*	19.5±2	CFC-12
W-10	Bangor Limestone	289 (156-268)	*Contam.*	18.5±2	*Contam.*	*Contam.*	18.5±2	CFC-12
W-14	Bangor Limestone	355 (324-355)	*Contam.*	*Contam.*	*Contam.*	*Contam.*	*Contam.*	*Contam.*
FW	Tuscumbia Limestone/ Fort Payne	155 (110-150)	29±2	*Contam.*	29±2	*Contam.*	29±2	CFC-11/ CFC-113
W-7	Tuscumbia Limestone/ Fort Payne	154 (101-154)	*Contam.*	*Contam.*	*Contam.*	*Contam.*	*Contam.*	*Contam.*
W-6	Tuscumbia Limestone/ Fort Payne	152 (85-152)	*Contam.*	*Contam.*	23±2	28±2	25.5±2	CFC-113/ SF_6
W-5	Tuscumbia Limestone/ Fort Payne	250 (79-170)	*Contam.*	*Contam.*	23±2	*Contam.*	23±2	CFC-113
P-1	Tuscumbia Limestone/ Fort Payne?	-80	*Contam.*	17.5±2	*Contam.*	1±2	17.5±2	SC/CFC-12

Contam.—Contaminated (not valid age determination due to supersaturation with additional non-atmospheric sources of CFC or SF_6).

the FW sample (sample could be collected without pumping), concentrations of CFC-11, CFC-12, and CFC-113 in groundwater samples did not yield concordant apparent ages based on the analytical methods. Concentrations higher than those possible for equilibrium with the modern air are considered “contaminated” (table 8).

Based on CFC analyses, apparent groundwater ages in the investigated aquifers ranged from 17.5±2 to 30.5±2 years (table 8). SF_6 based ages determined for wells W-6 and P-1 were 28±2 and 1±2 years, respectively. For this report an age estimate was considered reliable when more than one CFC species yielded a similar age or when CFC and SF_6 ages were concordant. Furthermore, if a CFC-12 age was available, but not in agreement with other age-dates, the former was considered the valid age. CFC-12 was the only compound that enabled age-dating of the sample collected from W-10 (18.5±2 years, table 8) and is considered reliable, since it is very similar to the one from sample W-9 (19.5±2 years). Wells W-9 and W-10 are about 100 ft away from each other (plate 4), are developed in the Bangor Limestone aquifer, and are screened in similar stratigraphic zones (235-285 ft and 156-268 ft, respectively, table 8). The CFC-11 estimated age of 30.5±2 for sample W-9 is considered unreliable, given the tendency of this compound to degrade at fast rates (Kazemi and others, 2006) and the close agreement of the CFC-12 ages for the W-9 and W-10 samples. Dissolved oxygen levels and reduction potentials at the investigated samples are relatively high, indicating the low potential for CFCs microbial degradation in these aquifers. CFC-12 derived ages for groundwater samples W-9 and W-10 are 18.5±2 and 19.5±2 years, respectively. The slight difference between the two concentrations is not relevant since the error of estimation (±2) is higher than the age difference. However, given the presence of nitrate (3.2 mg/L) in water sample W-10, a possible slight overestimation of the age may be possible.

The relatively high degree of CFCs and SF_6 contamination from sources other than atmospheric equilibration was not entirely unexpected given that samples were collected from high-capacity production wells and that some CFCs and SF_6 contamination was observed in previous studies in similar hydrogeologic settings in Calhoun County, Alabama (Robinson, 2004). One possible explanation is that low, but above atmospheric concentrations of CFCs and SF_6, were introduced into the Tuscumbia Limestone/Fort Payne Chert and Bangor Limestone aquifers with recent recharge that incorporated local sources of contamination (such as improper waste disposal of CFC refrigerants, electronic components, and other materials containing SF_6). This may be applicable, especially to the groundwater sample collected from the private well P-1, which is one of the shallowest investigated wells developed in the Tuscumbia Limestone/Fort Payne Chert aquifer.

SF_6 concentrations at equilibrium with the atmosphere were available in sample W-6 and P-1 (table 8). Since geochemical data were not available for these locations, no speculations could be made regarding the source of contamination besides the excess air introduced during pumping. While CFC-113 and SF_6 in sample W-6 are not identical, the two ages are relatively close, considering the error of estimation (±2 years). However, the very young SF_6 age (1±2 years) estimated for sample P-1 is not in agreement with the CFC-12 age estimate of 17.5 years (table 8). Well P-1 is located on the Tuscumbia Limestone/Fort Payne Chert outcrop (plate 2) and within one of the areas classified with moderate to high recharge potential (plate 6). Oxygen and hydrogen isotope signatures of this water sample lie in the more depleted range of values (table 7). In fact, the most depleted values are measured in this sample (table 7). δD and $\delta^{18}O$ measured in this sample are depleted with 4 and 0.5‰, respectively, compared to the Tuscumbia

Limestone/Fort Payne Chert aquifer average δD and $\delta^{18}O$ values (table 7). This well is also located the furthermost north in the recharge area and at the highest elevation compared with all other investigated wells (plate 1). The signature difference may be explained as precipitation becomes more depleted in the heavy isotopes of hydrogen and oxygen with increasing latitude and elevation. The different δD and $\delta^{18}O$ signature may also be explained by a smaller degree of mixing occurring at this depth in the aquifer.

The lowest SC, TDS, and pH values for the entire sampling period were recorded in sample P-1. When compared with all other values, this is an indication of a shorter groundwater residence time and less water-rock interaction compared to other samples collected from the Tuscumbia Limestone/Fort Payne Chert aquifer (for example, W-6, W-7, and FW). Regression models using calcium concentrations and available groundwater age data have been used to project groundwater ages for samples where age-dates were not available (Robinson, 2004). This method requires knowledge of the hydrologic settings from which samples were collected and comparative data from the same aquifer. Based on the physical and geochemical data available for this study, it was concluded that SC is mainly the result of limestone dissolution. Therefore, it is possible to use SC values for age estimations and evaluations.

The groundwater age and SC data recorded in sample FW can be used as a reference point, since the two available age-dates are identical (table 8), there are no fluctuations in water levels, and groundwater discharge occurs under natural conditions, eliminating the mixing effect. Based on SC and age values, groundwater age in sample W-6 was estimated to be 25 years. This estimate is in agreement with the one conducted using CFC-113 and SF_6 concentrations (table 8). This further offers confidence in the groundwater age estimate at well 6. Using the least-square linear regression between the FW and W-6 ($y = 0.18 x + 5.73$), groundwater age for sample P-1 is estimated to be 16.5 years. Based on this projection, there is a 1-year error of estimation using CFC-12 for this location. Since ORP values are highly positive, microbial degradation is assumed to be absent. Considering the above mentioned evaluations, and the higher reliability of the CFC-12 compound in dating groundwater, the final groundwater age in groundwater at the P-1 location is considered to be 17.5±2 years. Although it is ideal to include a large number of points in a regression model, the close match with the available groundwater ages at locations W-6 and P-1 offers some level of confidence to the estimation. Contrary to other regression models that get an estimate based solely on the closest values, the current evaluation aimed to gain confidence in the known values.

Two CFC compounds, CFC-11 and CFC-12 and the SF_6 tracer in sample W-5 likely originate from a non-atmospheric source making age dating impossible. Therefore, the age date for sample W-5 was estimated to be 23±2 years, using solely the CFC-113 concentration (table 8). The geochemical isotopic signature of groundwater at this location indicates a different source of recharge (presumably from the Bangor Limestone aquifer) compared to all other Tuscumbia Limestone/Fort Payne Chert samples (see the physical and chemical parameters section). Therefore, travel times and flowpaths may vary as well at this location. However, because a second age data is not available for well W-5, a relationship evaluation between this sample and other Tuscumbia Limestone/Fort Payne Chert or Bangor Limestone aquifer samples can only be established using the CFC-113 data. Furthermore, given its development in the Tuscumbia Limestone/Fort Payne Chert aquifer and the high geochemical similarity with water developed from the Bangor Limestone, considerable mixing of different end-member waters is likely at this location. Therefore, groundwater age validation using the regression model established for the Tuscumbia Limestone/Fort Payne Chert aquifer cannot be applied to this sample.

Generally, Bangor Limestone aquifer waters are associated with the youngest ages (table 8). The investigated wells developed in the Bangor Limestone aquifer are located in close proximity to the Cahaba River (plate 4). Although screens in these wells are set starting at 150 ft below land surface, it is probable that some modern water from the river infiltrates to the developed water-bearing horizon (especially during pumping rates higher than those of aquifer recharge). Analysis of groundwater age distribution with depth reveals two potential flowpaths in the Tuscumbia Limestone/Fort Payne Chert aquifer (fig. 22). Depth analysis was conducted using the mean average value of the screened interval from which water is being produced. For example, well W-10 is screened from 156 to 268 ft resulting in a mean average aquifer production depth of 212 ft. Due to limited water age data (only two wells), travel paths could not be identified for the Bangor Limestone aquifer.

Generally, most samples exhibited a high degree of CFCs and SF_6 contamination from sources other than atmospheric equilibration. Given the highly oxygenated and oxidizing nature of these aquifers, CFCs degradation is insignificant and the main source of contamination in

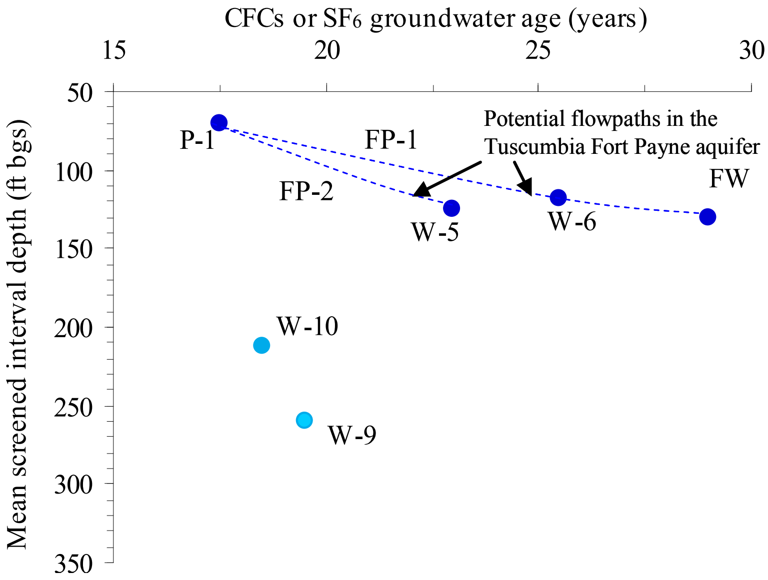


Figure 22.—CFCs and SF_6 groundwater age distribution with mean screened depth interval. Dark blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers and light-blue filled circles represent the Bangor Limestone aquifer.

these samples comes from the excess air introduced during pumping and/or from anthropogenic contamination (for example sample P-1) (Busenberg and Plummer 2000; Zoellmann and others 2001). Therefore, if all three CFC compounds are presumed to be stable in the aquifer system, then the lack of concordance could result from complex mixtures of groundwater from shallow and deep flow paths that converge near the sampling horizon. Apparent age dates estimated for this study are similar to those estimated for the Valley and Ridge aquifer in Calhoun County (Robinson, 2004). Therefore, although based on a limited number of points, an average groundwater travel time and residence times can be estimated for the investigated system. Average residence times in the Tuscumbia Limestone/Fort Payne Chert and Bangor Limestone aquifers are estimated to be 22.2±2 years. Estimation of recharge rates using groundwater data is not possible in this study given the limited information regarding the vertical and horizontal flow components at any investigated location within the aquifer.

GROUNDWATER RECHARGE

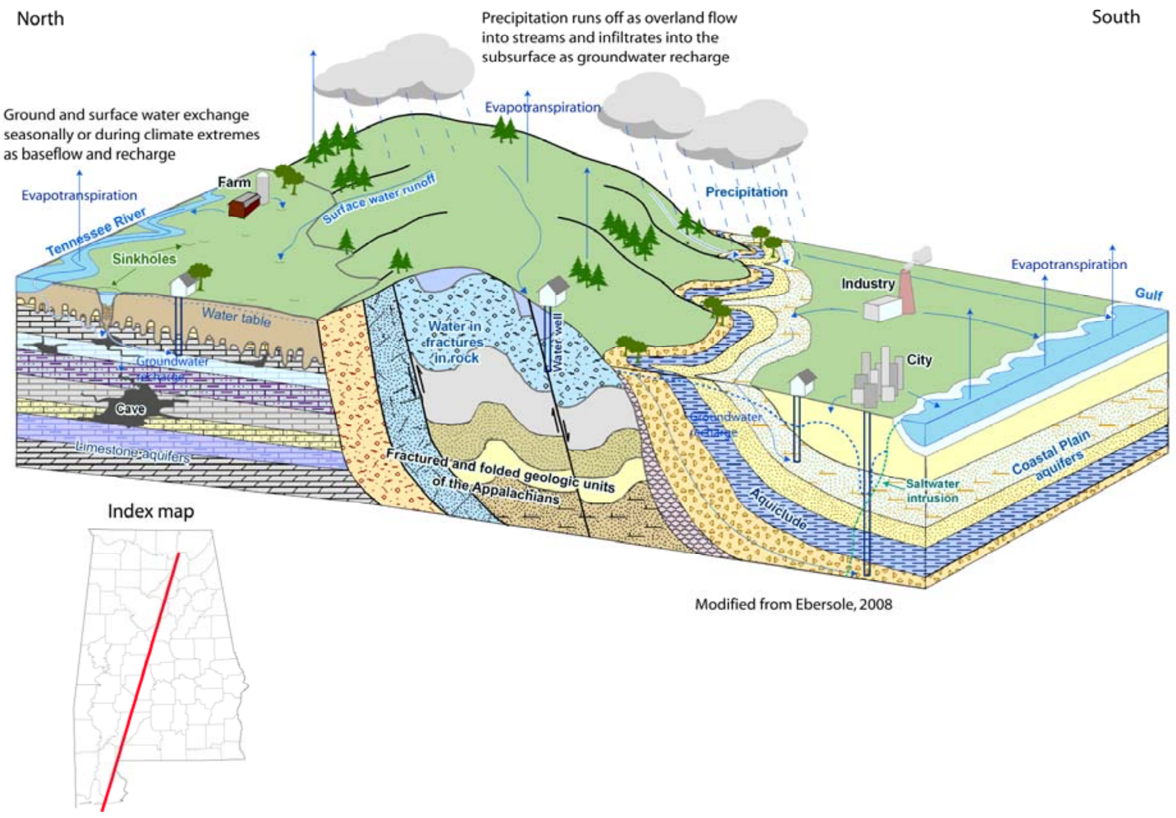
Unlike the Coastal Plain where groundwater recharge can move long distances in aquifers that exceed depths of 2,500 ft (Cook, 2004) or the Tennessee River watershed area where aquifers are relatively thin and shallow with local recharge (Cook and others, 2010), the Valley and Ridge is characterized by large, complex structures with faults and fractures that create local and long distance pathways for groundwater movement (Cook, 1997). Recharge rates are controlled by a number of factors including porosity, which in Paleozoic aquifers is primarily secondary and tertiary and is the result of leached fossils, bedding plane conduits, fractures, and solution cavity development and permeability, and relies on the magnitude of interconnectedness of pore spaces. Major aquifers in the Trussville area are composed of limestone, dolomite, and chert. Most carbonate rocks in the Valley and Ridge are indurated and thoroughly cemented, resulting in limited intergranular porosity. Rocks with significant chert development are brittle and have greater fracturing. Therefore, in much of the area of investigation, fractures provide much of the porosity and permeability for groundwater movement and storage. Fractures are characterized as stress-relief (vertical) and bedding-plane (horizontal) and are typically non-uniform and can vary significantly over short distances (Bossong and Harris, 1987).

Some rock units have significant karst development. The principal constituent of these rocks is calcium carbonate ($CaCO_3$), a compound which is readily soluble in several dilute acids that are normally present in precipitation and runoff. However, the most significant process affecting solution development in these carbonate rocks is the production of carbonic acid by percolating groundwater. As water moves downward through the regolith, it encounters carbon dioxide (CO_2), which is produced by decay of organic matter (Freeze and Cherry, 1979). Water and CO_2 combine to form carbonic acid, which dissolves limestone and aids in development of solution-enlarged fractures and cavities (Mann and others, 1996).

Recharge may also be influenced by drought, seasonal precipitation, land surface slope, surface drainage, and the conductive character of surface material. If the topography is relatively flat and surface materials are permeable, more surface water will infiltrate into local aquifers. Recharge may also be greater where faults and fractures are common, subjected to solution enhancement, and extend to the surface where they connect surface water and aquifers (Bossong, 1988; Baker and others, 2005).

Estimates of recharge can be useful in determining available groundwater, impacts of disturbances in recharge areas, and water budgets for water-resource development and protection. Numerous methods have been used for estimating recharge, including development of water budgets, measurement of seasonal changes in groundwater levels and flow velocities. However, equating average annual baseflow of streams to groundwater recharge is a widely accepted method (Risser and others, 2005). Although it is desirable to assess recharge in watersheds with unregulated streams that are not subject to surface-water withdrawals or discharges from wastewater treatment plants or industries, it is unrealistic to expect that no human impacts occur in any of the assessed watersheds.

Average precipitation in the Trussville area is 56 inches per year and is distributed as runoff, evapotranspiration, and groundwater recharge (fig. 23). Sellinger (1996) described the various pathways of precipitation movement that compose stream discharge and determine the shape of a stream hydrograph (fig. 24). However, for the purposes of this report, precipitation movement pathways shown in figure 24 are combined into two primary components, runoff and baseflow. Runoff is defined as the part of total stream discharge that enters the stream from the land surface. Kopaska-Merkel and Moore (2002) reported that runoff in the Trussville area varies



Modified from Ebersole, 2008

Figure 23.—Alabama hydrologic cycle.

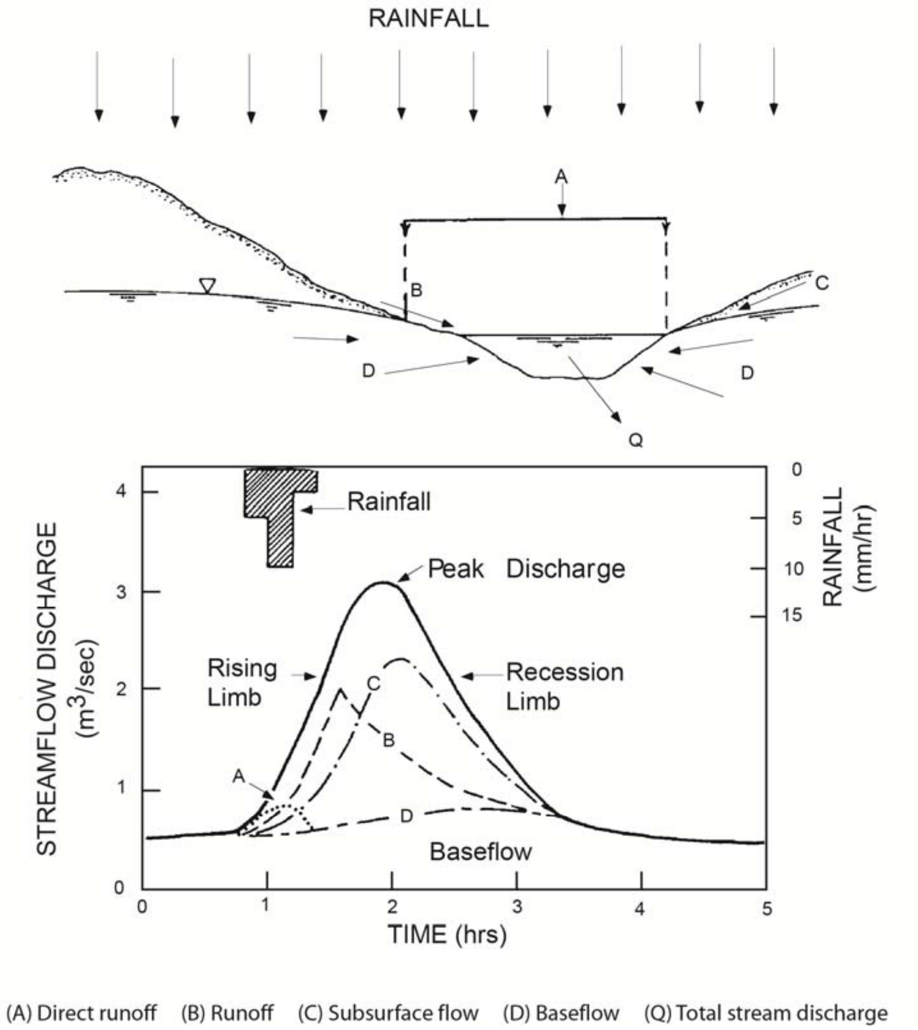


Figure 24.—Graphic and stormflow hydrograph illustrating pathways of movement of rainfall into streams (modified from Sellinger, 1996).

from 24 to 26 inches per year. However, local runoff in the Valley and Ridge is highly variable, depending on the location of the subject watershed with respect to topography, soils, and geology. Baseflow is the part of stream flow supplied by groundwater, an essential component that sustains stream discharge during periods of drought and is equated to groundwater recharge.

Separating runoff and baseflow from total stream discharge can be accomplished by several methods (Sellinger, 1996; Risser and others, 2005) including (1) recession analysis (Nathan and McMayhon, 1990), (2) graphical hydrograph separation (Meyboom, 1961), and (3) partitioning of stream flow using daily rainfall and stream flow (Shirmohammadi and others, 1984). More recently, a number of computer models have automated hydrograph separation techniques (Risser and others, 2005; Lim and others, 2005). The Meyboom method uses stream hydrograph data over two or more consecutive years. Baseflow is assumed to be entirely groundwater, discharged from unconfined aquifers. An annual recession is interpreted as the long-term decline during the dry season following the phase of rising stream flow during the wet season. The total potential groundwater discharge (V_{tp}) to the stream during this complete recession phase is derived as:

$$V_{tp} = \frac{Q_0 K}{2.3}$$

where Q_0 is the baseflow at the start of the recession and K is the recession index, the time for baseflow to decline from Q_0 to $0.1Q_0$.

Discharge data were analyzed using the Web Based Hydrograph Analysis Tool (WHAT) automated hydrograph separation program (Lim and others, 2005; Purdue University, 2004). This program was previously compared with the Meyboom graphical hydrograph separation method and other automated programs during the Tennessee River Watershed Recharge Assessment (Cook and others, 2010). A significantly better agreement was observed between runoff and base flow data resulting from the WHAT model and the Meyboom method compared to other automated programs. Based on this previous testing, the WHAT program was used to estimate recharge rates and to calculate volumes of groundwater recharge for the Trussville area.

Groundwater recharge for primary aquifers in the Trussville area was estimated using discharge data for the Cahaba River from the USGS discharge measurement station at U.S. Highway 11, which is located at the downstream boundary of the recharge area and manually measured discharge for the Cahaba River, which is near the upstream boundary of the recharge area (plate 7). Baseflow (groundwater recharge) was estimated for both stations. The recharge value for the Cahaba River watershed was determined by taking the difference in the upstream and downstream estimates. This value was normalized and used to calculate an estimated recharge for the entire recharge area. Results of groundwater recharge analyses are given in the “Groundwater Availability” section of this report.

SOURCES AND MOVEMENT OF GROUNDWATER DETERMINED FROM PHYSICAL, CHEMICAL, AND ISOTOPE COMPOSITION

The geochemical and isotope signatures provide information concerning the origin and migration pathways of groundwater that explains variations in the geochemical character of groundwater from one geographic location to the next. Specific conductance, an indirect measurement of dissolved solids such as chloride, nitrate, sulfate, phosphate, sodium, magnesium, calcium, and iron, is a good indicator of water pollution. In the recharge area, SC values follow a relatively narrow range for samples collected from the Bangor Limestone aquifer (table 4) indicating a relatively homogeneous lithology of water-bearing horizons (carbonate rocks) from which groundwater originates. SC values for water from the Bangor aquifer are slightly elevated compared to those recorded in samples collected from the Tuscumbia Limestone/Fort Payne Chert (fig. 6, table 8). This suggests that groundwater from the Bangor Limestone wells experiences more intense water-rock interactions as a result of longer travel times through carbonate rocks. In contrast, except for water recharging well W-5, groundwater in the Tuscumbia Limestone/Fort Payne Chert aquifer travels through more heterogeneous lithology, such as sandstone and carbonates, revealed by the lower SC values (fig. 6, table 8).

Hydrogen ion activities (pH) are within the acidic to neutral range, with more neutral values for samples collected from the Bangor Limestone aquifer and from well W-5. SC values positively correlate with pH for samples collected in June (fig. 25). There is no evident relationship between the two parameters for the fall event. Geochemical analyses indicate the presence of elevated calcium and bicarbonate concentrations. These ions are the major dissolved species influencing TDS and SC. For the four analyzed samples, calcium concentrations are linearly and positively correlated with pH values (correlation coefficient of 0.9). This is an indication of carbonate dissolution reactions along flowpaths. Based on these findings we assume that for all other locations where only physical parameters are available, dissolved calcium and bicarbonate are the major dissolved chemical components in water samples. Therefore, an increase in SC and TDS would result from carbonate dissolution. A slight decrease in pH and SC is observed over the summer period and is correlated with input of fresher recharge groundwater induced by lowering of groundwater levels (figs. 9, 26).

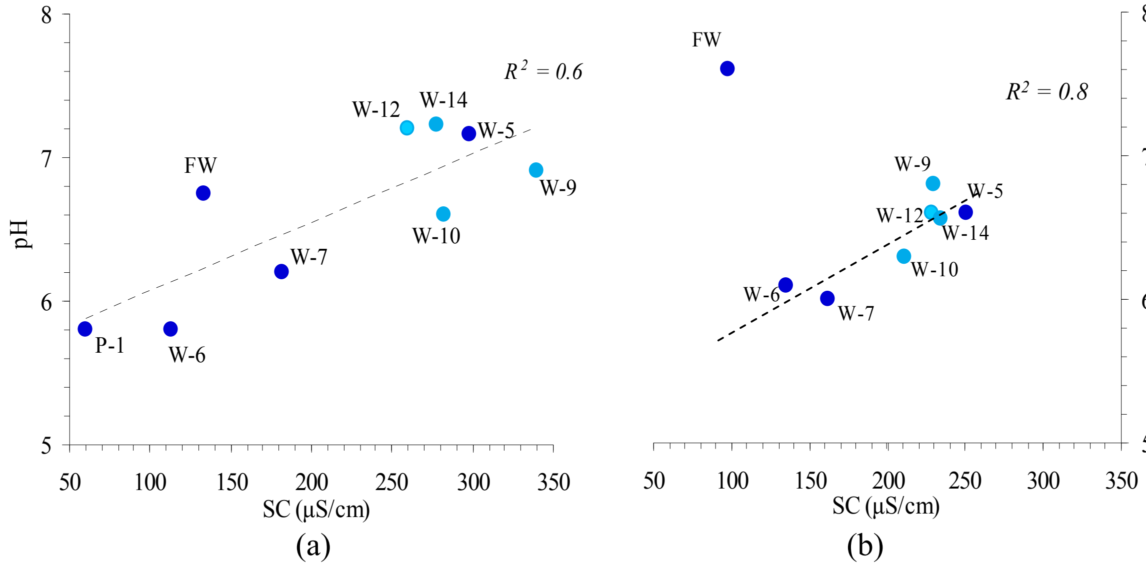


Figure 25.—Specific conductance and pH correlation for samples collected during the summer (a) and fall (b) sampling events. Note that the FW-pH and SC values exhibit an inverse correlation for the fall sample and, therefore, this sample is excluded from the regression correlation calculation. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

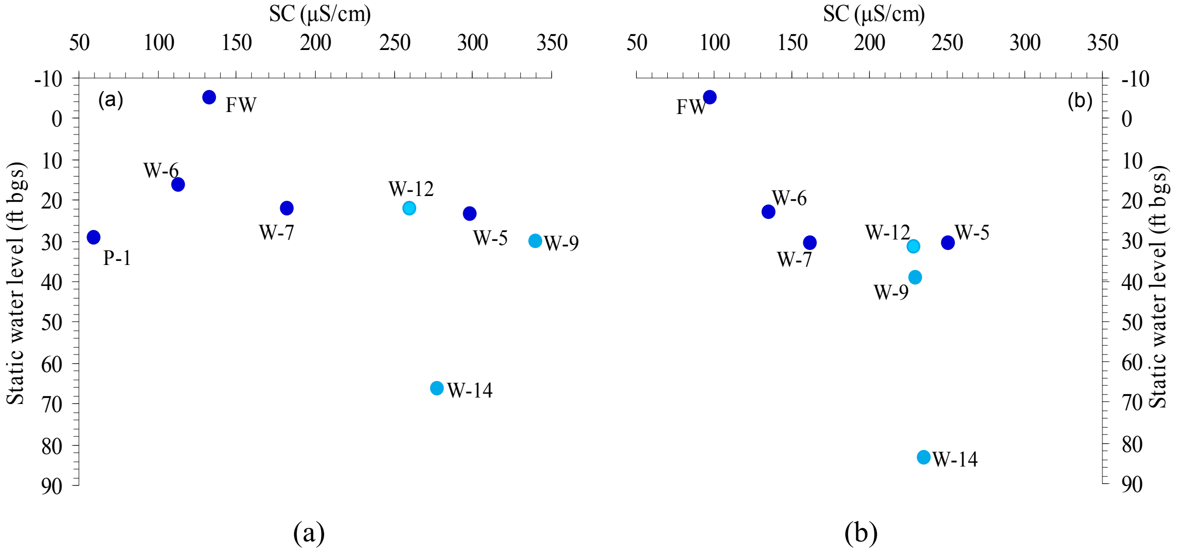
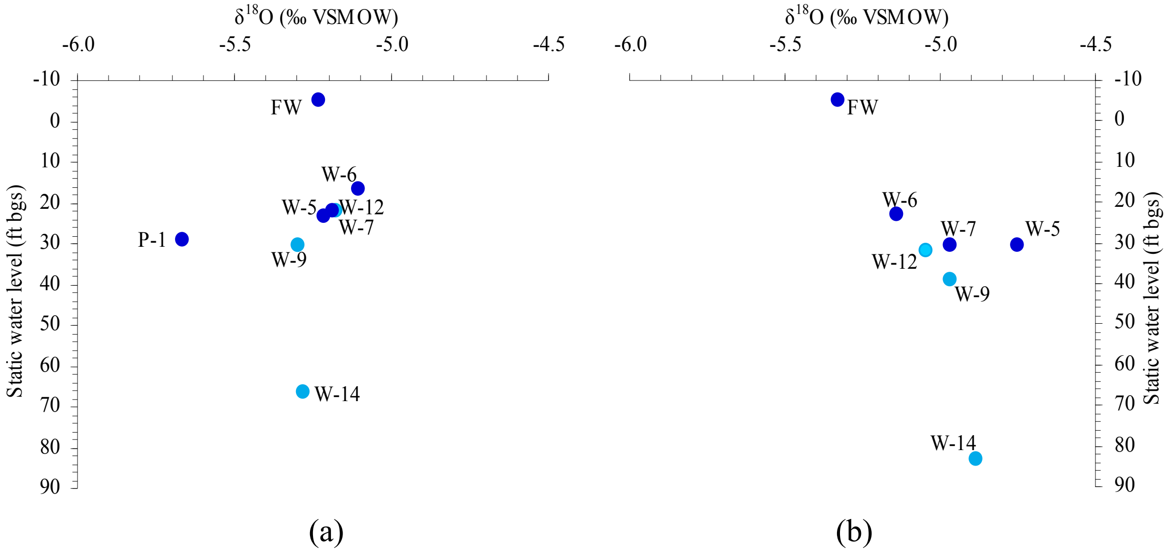


Figure 26.—Variation of specific conductance in response to static water levels for the summer (a) and fall (b) sampling events. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

Static water levels decreased from summer to fall in all production wells (fig. 9). Seasonal geochemical and isotope analyses offer insight into recharge sources and aquifer responses. Generally, from summer to fall, a shift towards less mineralized chemical composition of groundwater was observed (figs. 5, 26). Thus, as the summer season progresses, drought and increased water demand impacts cause declining groundwater levels, which leads to aquifer replenishment with fresher, less mineralized waters. One possible explanation to this behavior is that younger recharge water from shallower units is forced downward to discharge points at faster rates, limiting aquifer residence time and water-rock interaction. Groundwater velocities increase as hydraulic gradients steepen towards discharge points or wells. This results in lower TDS and SC, due to dilution of older, ambient, and more mineralized waters with younger, less mineralized, waters. Decreased TDS and SC are accompanied by more acidic pH (fig. 25). SC, TDS, and pH values recorded in sample W-6 shift slightly towards more mineralized groundwater (figs. 5, 26). The lowest drawdown was also observed at this location.

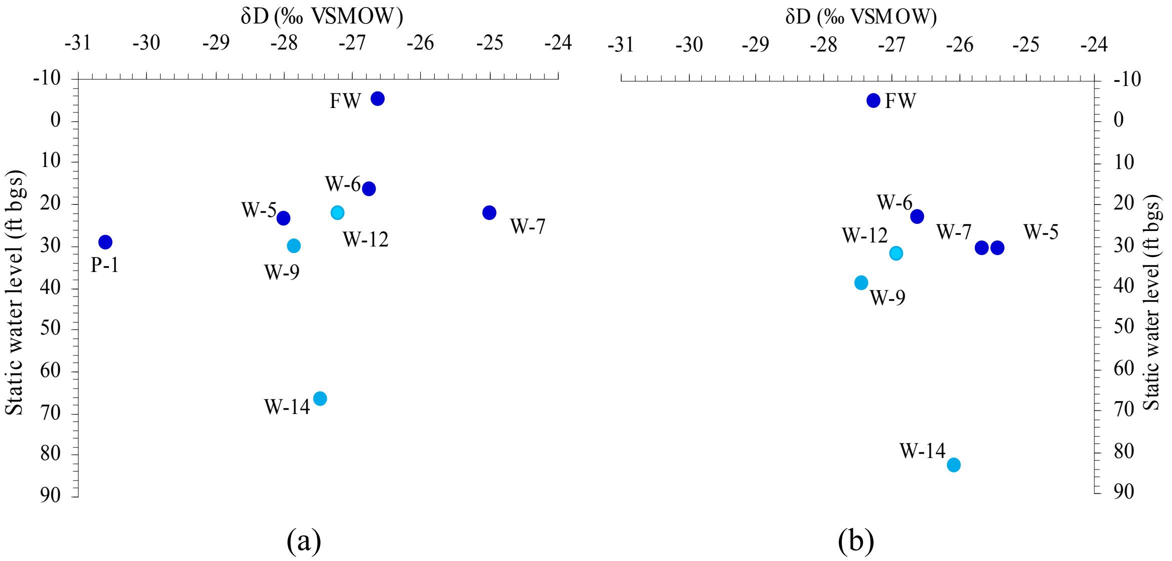
Changing water level impacts on recharge source analyses were also evaluated using the hydrogen and oxygen stable isotopes (figs. 27, 28). Although there is not much variation in $\delta^{18}O$ data, it is possible to observe the change in the range of values over the sampling period (fig. 10). Furthermore, while not much isotope signature variation is observed for the two investigated aquifers (figs. 27, 28), more heterogeneous values are associated with samples collected from the Tuscumbia Limestone/Fort Payne Chert aquifer (figs. 27, 28). Between the two sampling events, a slight shift of the $\delta^{18}O$ and δD values towards a more positive member is linked with the lowest water levels and higher drawdown. Hence, for that reason, fresher recharging groundwaters may be associated with slightly heavier $\delta^{18}O$ and δD values indicative of more modern member input during the summer (see $\delta^{18}O$ and δD composition for the youngest sample from well P-1) (fig. 29).

Groundwater age data is limited, due to unknown sources of contamination that result in sample supersaturation with respect to atmospheric equilibrium. However, correlation of these data with physical and stable isotope parameters helps place constraints on choosing the most accurate age date. Generally, higher TDS and SC characteristic to the Bangor Limestone aquifer are correlated with younger ages suggesting faster groundwater travel times compared to the Tuscumbia Limestone/Fort Payne Chert aquifer (fig. 30). Groundwater ages and SC values



(a) (b)

Figure 27.—Variation of $\delta^{18}O$ in response to static water levels for the summer (a) and fall (b) sampling events. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.



(a) (b)

Figure 28.—Variation of δD in response to static water levels for the summer (a) and fall (b) sampling events. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

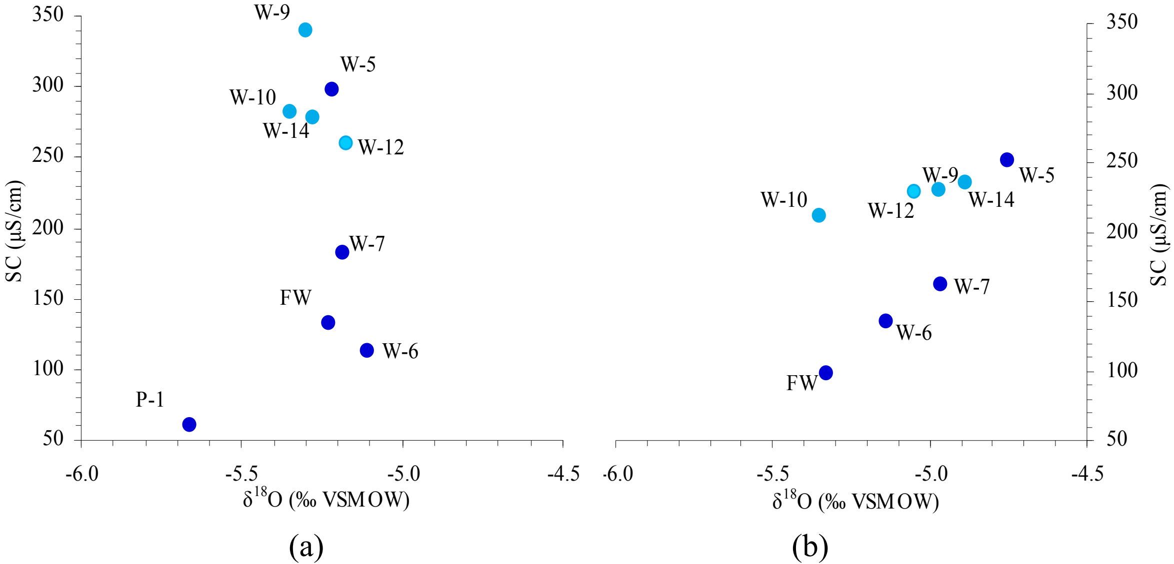


Figure 29.—Relationships between $\delta^{18}O$ and SC for the summer (a) and fall (b) sampling events. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

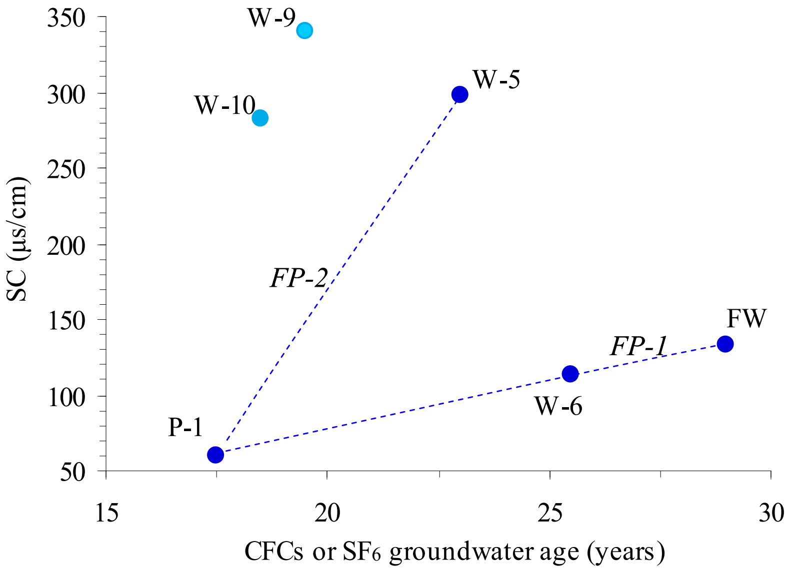


Figure 30.—CFCs and SF_6 groundwater age correlation with measured SC concentrations. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

suggest two possible flow paths: FP-1, flowing from P-1 to W-6 and to FW and FP-2, from P-1 to W-5 (figs. 22, 30, plate 7). Groundwater age, SC, and pH positively correlate along these potential flowpaths (figs. 25, 30). Furthermore, groundwater elevations decrease from P-1 along the flowpaths, except for FW, where isolated/local confining conditions may exist. A positive linear correlation is observed between static water levels and groundwater ages (fig. 31). Generally the highest water levels and oldest groundwater are characteristic of the Tuscumbia Limestone/Fort Payne Chert aquifer, which indicates that this groundwater experiences longer travel times and higher recharge rates. In contrast, the Bangor Limestone aquifer experiences shorter residence times, lower water levels and therefore, lower recharge rates. This hypothesis is further supported by larger drawdowns characteristic of this aquifer (fig. 9).

An additional investigation regarding groundwater age-data reliability was conducted using DIC concentrations. As groundwater DIC concentration decreases, the apparent age increases. Based on the five data points available for establishing this relationship, an inverse linear relationship (correlation coefficient of 0.7) exists between the two parameters (fig. 32). This is in agreement with the concept suggesting that DIC concentrations decrease with time along flowpaths. The oldest groundwaters (W-6 and FW) collected from the Tuscumbia

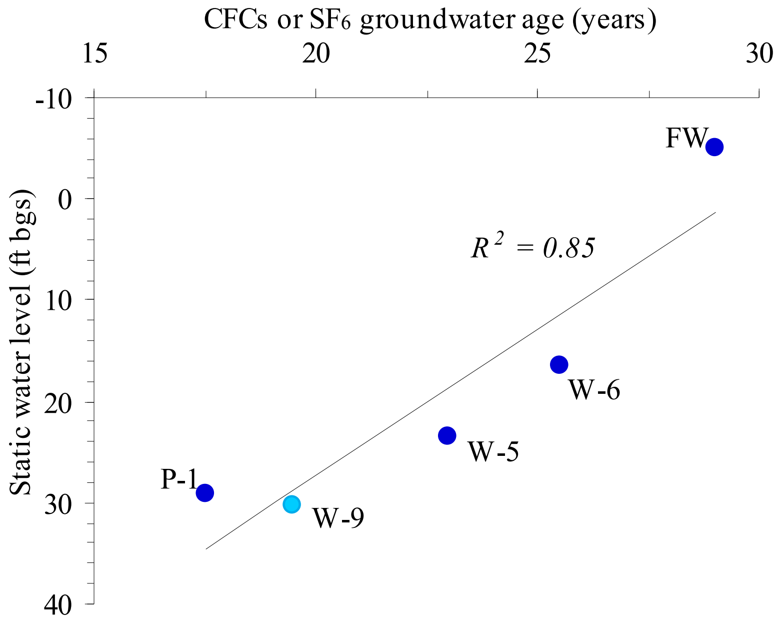


Figure 31.—CFCs and SF_6 groundwater age correlation with measured static water levels. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

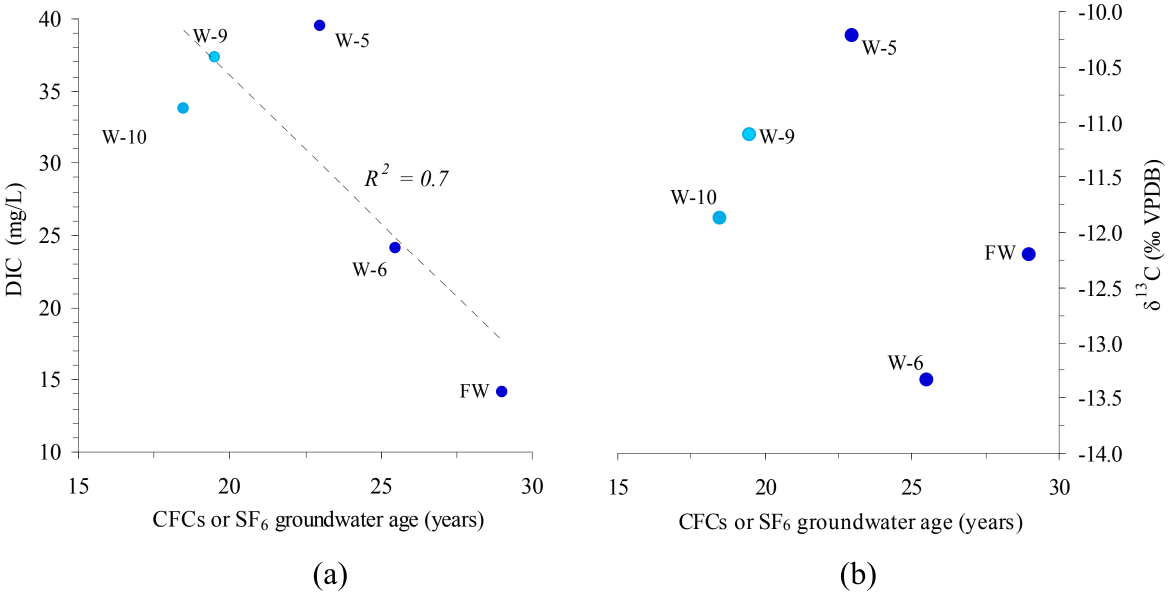
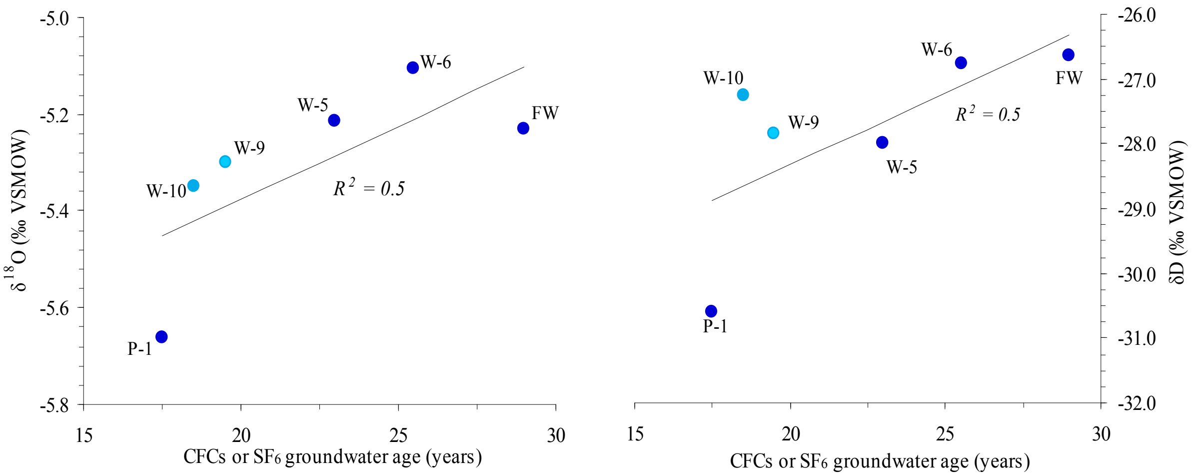


Figure 32.—CFCs and SF_6 groundwater age correlation with measured DIC concentrations (a) and $\delta^{13}C$ (b). Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

Limestone/Fort Payne Chert aquifer are associated with lighter $\delta^{13}C$ values, whereas younger groundwaters collected from the Bangor Limestone aquifer correlate with heavier $\delta^{13}C$ values (fig. 32). Exception is sample W-5 that exhibits a very similar behavior to samples collected from the Bangor Limestone aquifer (fig. 32). Therefore, younger groundwaters originating from wells developed in the Bangor Limestone aquifer and from well W-5, developed in the Tuscumbia Limestone/Fort Payne Chert aquifer, experience the highest influence of carbonate dissolution (also revealed by the higher SC, TDS, and pH values).

The oxygen and hydrogen isotopes indicate that recharge to the investigated aquifers originates mainly locally. A more distant source of recharge may be possible through preferentially longer flowpaths along connected fractures. However, if existent, mixing at the sampling horizon makes this evaluation impossible. A slight positive linear correlation (correlation coefficient of 0.5) is observed between the $\delta^{18}O$ and δD and the age data (fig. 33). Younger ages are associated with lighter isotope values (fig. 33) indicating that water recharging these locations (mainly the Bangor Limestone aquifer) may experience some evaporation as it would be expected during the summer period. If compared with the most depleted values measured in the shallowest and youngest water sample P-1, it is obvious that after entering the water table, meteoric water becomes slightly enriched in the heavier isotopes. Nevertheless, there



(a) (b)

Figure 33.—Relationships between $\delta^{18}O$ and SC for the summer (a) and fall (b) sampling events. Dark-blue filled circles represent the Tuscumbia Limestone/Fort Payne Chert aquifers, and light-blue filled circles represent the Bangor Limestone aquifer.

is a greater input of modern waters at these locations during the warmer seasons. This is in agreement with the GIS investigations that indicate that the Bangor Limestone wells are located within delineated areas of moderate and high potential of aquifer recharge (plate 6).

The physical parameters and isotope composition recorded for sample W-5 suggest that groundwater recharging the sampling horizon at well W-5 has a strong mineralized component that most likely originates from the nearby located Bangor Limestone aquifer (figs. 26, 29, 30, 32). Generally, in the stable isotope and age data correlation schemes, sample W-5 plots between the two water-members (for example, Tuscumbia Limestone/Fort Payne Chert and Bangor Limestone aquifers). This indicates that mixing of the more mineralized, Bangor Limestone and less mineralized, Tuscumbia Limestone/Fort Payne Chert groundwater members exists, with a higher influence of the more mineralized and younger groundwater member as revealed by the SC and TDS concentrations and groundwater age (figs. 29, 30).

Based on the recharge areas distribution and the geochemical investigations, it can be concluded that recharge originates mainly locally at wells P-1, W-9, and W-10. Extrapolating this to locations that exhibit similar geochemical behavior and location within the recharge classes, we conclude that most of the wells developed in the Bangor Limestone aquifer receive recharge locally, whereas wells developed in the Tuscumbia Limestone/Fort Payne Chert aquifer are replenished from longer flowpaths. Groundwater primarily recharges locally at well P-1 and flows south-west parallel to the Cahaba Mountain syncline axis, towards wells W-6, W-5, and FW (figs. 22, 30, plate 7). Although samples collected from the Bangor Limestone aquifer were acquired from greater depths (table 4), it is probably the nature of the host formation, the hydrogeologic heterogeneity of the transversed formations, the amount of recharge, and designated recharge area that have the greatest impact on groundwater travel times within the aquifer. The Bangor Limestone aquifer wells are located within the outcrop area and within the potential aquifer recharge areas (plate 7). Therefore, we presume that water recharging the aquifer at the investigated locations travels within one formation from the surface to the sampling point (the Bangor Limestone). Conversely, except for well P-1, all wells developed in the Tuscumbia Limestone/Fort Payne Chert aquifer are drilled through formations overlying the aquifer such as the Hartselle Sandstone and the Pride Mountain Formation. The Pride Mountain Formation, dark-gray shale containing minor intervals of sandstone, can locally play as confining layer. This may be the case at well FW that is drilled through Hartselle Sandstone and the Pride Mountain Formation and developed in the Tuscumbia aquifer (plate 7). The thickness and permeability of the overlying formations may create enough confinement to explain the higher pressure head at this location. It is well known that travel times through sandstone are longer compared to carbonate rocks. Therefore, the older ages and less mineralized chemistry of the Tuscumbia Limestone/Fort Payne Chert aquifer is explained by the geologic settings. The location of the Tuscumbia Limestone/Fort Payne Chert aquifer outcrop, northeast of the investigated wells explains the existence of longer travel paths such as those identified in this project. Recharge for the Tuscumbia Limestone/Fort Payne Chert aquifers most likely occurs within the delineated potential aquifer recharge areas determined for the purpose of this study.

GROUNDWATER AVAILABILITY

Groundwater availability is generally defined as the total amount of groundwater of adequate quality stored in the subsurface. However, due to the inability to accurately predict the amount of water in subsurface storage, volumes of groundwater recharge estimated for the Trussville recharge area were assumed to be the amount of available groundwater. Since aquifer recharge is a dynamic process, available groundwater is expressed in volume per unit time. Large quantities of groundwater, in excess of 1 mgd, can be obtained from wells constructed in the Tuscumbia/Fort Payne Chert aquifer if sufficient water-filled cavities are encountered

(McGregor and others, 1997). However, the non-uniform distribution of fractures and/or solution channels and cavities makes the prediction of groundwater movement and occurrence difficult.

Results from the WHAT automated hydrograph separation program indicate that baseflow was 19 percent of total discharge for the total period of record from October 1988 to October 2010. Results for hydrograph separation of data used for the recharge estimate (September 2009 to September 2010) indicate that baseflow was 17 percent of the total discharge. Recharge totals calculated for the Trussville recharge area (40 mi^2) are 8.7 mgd (217,500 gallons per square mile per day) or 4.6 inches of recharge per year. The estimated recharge rates are relatively small compared to current water demands or individual well production rates and help to explain significant summer season groundwater level drawdown, as much as 17 ft, in public water supply wells in the area. However, aquifer storage is significant, even when considering that the entire U.S. Highway 11 corridor has minimal stored groundwater in the Tuscumbia Limestone and Fort Payne Chert, based on recent test well drilling. The estimated volume of water stored in the Tuscumbia Limestone/Fort Payne Chert aquifer in the area along the Cahaba Mountain Syncline (14.2 mi^2) is about 90 million gallons.

GROUNDWATER EXPLORATION

One of the primary purposes of this investigation was to recommend sites for test well drilling in the Trussville Utilities service area. GSA GAP research resulting in possible test well locations included field assessments and evaluation of available published data. Published data included GSA quadrangle Series Map reports 23 (Osborne and Irvin, 2002), 25 (Raymond and others, 2003), and 26 (Rindsberg and others, 2003), Circular 162 (Osborne and Raymond, 1992), Monograph 16 (Thomas and Bayona, 2005) and a report prepared by Lowery (2009) titled *Irondale & Trussville Water Availability Report.* Numerous other miscellaneous data and documents were reviewed and used in the preparation of this report. GSA GAP field assessments consisted of groundwater sampling for inorganic and isotopic analyses and geologic sampling and mapping for stratigraphic characterizations, geologic maps, and structural and stratigraphic cross sections. Plate 8 shows the location of cross section A-A′ (plate 9). Plate 10 shows the location of six northwest-trending cross sections (B-B′ through F-F’′) constructed to show specific hydrogeologic regimes and proposed GSA test well sites (plates 11-15).

CONSULTANT PROPOSED TEST WELLS

After initiation of project tasks, GSA GAP was requested by Trussville Utilities to evaluate test well drilling sites recommended by Trussville Utilities consultants: Krebs Architecture & Engineering and Volkert, Inc., and a test well proposal from Graco Resources, Inc.

Graco Resources, Inc., transmitted a letter and map to the GSA GAP showing two proposed test well sites on the northwest and southeast flanks of Little Sand Mountain near the Pinnacle shopping center. Cross-section A-A′, constructed to evaluate the Graves proposal, is about 1 mile northeast of the Interstate 459-U.S. Highway 11 intersection and extends from near U.S. Highway 11 northwestward across Interstate 59 to the crest of Red Mountain (plates 8, 9). An assessment of the Graco Resources, Inc., proposal by GSA GAP indicated that the primary objective was the Tuscumbia Limestone/Fort Payne Chert aquifer. The proposed test well locations were adequate to penetrate the aquifer at an optimum depth. However, Interstate 59 and Pinchgut Creek lie in the recharge area immediately upgradient from the proposed test well locations. The highway and creek represent significant potential sources of groundwater contamination. Therefore, GSA GAP does not recommend drilling these proposed test wells.

Trussville Utilities transmitted documents from Krebs Architecture & Engineering to the GSA GAP dated January 22, 2009, consisting of five page-sized maps with test well locations, target formations, and drilling depths. Proposed test well sites 1 and 5 are about 5 miles northwest from the Trussville Utilities service area and were not evaluated due to the remoteness of the locations (plate 10).

Site 2 is on the Bangor Limestone outcrop in the SW¼NW¼ sec. 3, T. 16 S., R. 1 E., about 1 mile south from Argo (plate 10). The proposed test well will penetrate about 300 ft of Bangor Limestone, 200 ft of Hartselle Sandstone, and about 100 ft of Pride Mountain Formation before reaching the Tuscumbia Limestone/Fort Payne Chert at a depth of 600 ft (proposed depth by Krebs Architecture & Engineering). The GSA GAP evaluation indicates that the Bangor Limestone is not the primary objective for test well drilling. However, the location is suitable for a Tuscumbia Limestone/Fort Payne Chert test, although the total depth of a test well at this location is excessive (possibly 950 ft).

Site 3 is proposed to test the Tuscumbia Limestone/Fort Payne Chert near the axis of the Cahaba Mountain syncline in the SE¼SW¼ sec. 12, T. 16 S., R. 1 W., about 2,100 ft southwest from Trussville well W-7 (plate 10). The test well is proposed to penetrate the Hartselle Sandstone and Pride Mountain Formation prior to penetrating the Tuscumbia Limestone/Fort Payne Chert at a depth of 200 ft. An evaluation by GSA GAP indicates that the proposed well will penetrate erosional remnants of the Hartselle Sandstone and Pride Mountain Formation near the Tuscumbia Limestone/Fort Payne Chert contact about 1,000 ft from the Cahaba River. Based on GSA GAP data, a production well at this location may impact recharge and water levels in Trussville wells W-7 and W-5.

Site 4 is in the SW¼SW¼ sec. 4, T. 16 S., R. 1 E., and is proposed to penetrate 50 ft of Hartselle Sandstone and 250 ft of Pride Mountain Formation before penetrating the Tuscumbia Limestone/Fort Payne Chert (plate 10). A GSA GAP field evaluation of the site indicates that there are no adequate outcrops to obtain accurate dip measurements to guide the location of the well. Hartselle Sandstone dips recorded by Raymond and others (2003) along Little Cahaba Creek at Mary Munger Road were 8 and 11 degrees southeast. However, the measurements were made in a ridge gap where the structural character of the Hartselle Sandstone is most probably unlike that at site 4. Therefore, the total depth of a test well cannot be reliably predicted.

Trussville Utilities transmitted a single plate-sized map with no supporting text to the GSA GAP from Volkert, Inc., containing seven proposed test well locations with no designated depths or objectives. Sites 1, 3, 4, 5, 6, and 7 were outside the Trussville Utilities service area and were not evaluated. Site 2 consists of three possible locations (2A, 2B, and 2C). Site 2A is in the SW¼NW¼ sec. 34, T. 15 S., R. 1 E., between U.S. Highway 11 and Interstate 59 in the Argo community (plate 10). The proposed test well is on the hanging wall of the Argo fault, about 300 ft from the undifferentiated Knox Group-Red Mountain Formation contact. The proposed well will penetrate alluvium in the Clear Creek floodplain and the underlying undifferentiated Knox Group. Site 2B, similar to site 2A, is located in the SE¼SE¼ sec. 33, T. 15 S., R. 1 E., about 700 ft from the undifferentiated Knox Group-Red Mountain Formation contact (plate 10). Although the thickness of the undifferentiated Knox Group at proposed sites 2A and 2B is unknown, it is unlikely that a well of reasonable depth will penetrate the entire unit and therefore will not reach the Tuscumbia Limestone/Fort Payne Chert aquifer. Also, an on-site investigation by GSA GAP and Trussville Utilities personnel indicated that the test well sites will be subject to flooding by

Clear Creek. Site 2C is in the NW¼NW¼ sec. 3, T. 16 S., R. 1 E., about 700 ft east from U.S. Highway 11 near Argo (plate 10). This site is similar to Krebs site 2 and is located on the Bangor Limestone outcrop. The proposed well will penetrate about 300 ft of Bangor Limestone, 200 ft of Hartselle Sandstone, and 100 ft of Pride Mountain Formation before encountering the Tuscumbia Limestone/Fort Payne Chert at a depth of 600 ft. Therefore, the total depth of a test well at site 2C will be about 950 ft.

Since no supporting documentation was given with the proposed test well site map, the proposed total depth or primary targets of the test drilling proposed by Volkert, Inc., are unknown. However, it can be assumed that the primary objective for sites 2A and 2B is the undifferentiated Knox Group and site 2C is the Bangor Limestone.

GSA GAP PROPOSED TEST DRILLING

GSA GAP recommended seven test well locations in the Trussville Utilities service area. Test well site 1 is in the NE¼SW¼ sec. 18, T. 16 S., R. 1 E., near the intersection of Deerfoot Parkway and U.S. Highway 11 (plate 10). Cross section C-C′ shows test well 1 located on the crest of a small fold on the southeast flank of a northeast trending breeched anticline (plate 11). The well was predicted to encounter about 50 ft of Hartselle Sandstone, about 50 ft of Pride Mountain Formation, and about 120 ft of Tuscumbia Limestone/Fort Payne Chert (primary target formation) before reaching a total depth of 225 ft in the Red Mountain Formation.

The test well at site 1 was drilled on January 4, 2011, by Hand Service Company. The well encountered 2 ft of fill material, 30 ft of Hartselle Sandstone, and 363 ft of Pride Mountain Formation before penetrating the Tuscumbia Limestone at a depth of 393 ft (table 9). The explanation for the anomalously thick Pride Mountain Formation was that the dip of the beds unexpectedly increased to near vertical below 200 ft. Therefore, the Tuscumbia Limestone, which was expected to be encountered at about 100 ft, was not penetrated until 393 ft. Ninety-two feet of Tuscumbia Limestone was penetrated before drilling was halted at a depth of 485 ft. No economic quantities of water were found in the Tuscumbia Limestone. The primary objective (Fort Payne Chert) was not encountered, and GSA personnel at the drilling site recommended that drilling be suspended due to the excessive depth required to evaluate the Fort Payne Chert.

Site 2, SE¼NW¼ sec. 7, T. 16 S., R. 1 E., is about 2,000 ft southwest from the intersection of Happy Hollow Road and Deerfoot Parkway (plate 10). Cross section D-D′ indicates that the site is near the crest of a ridge capped by the Red Mountain Formation,

Table 9.—Drilling depths, formations, and drilling cutting descriptions for the test well at site 1.

Depth (feet)	Formation	Drill cutting description
0-2		Sandy fill material
2-10	Hartselle Sandstone	Well sorted, rounded, buff, fine to very fine sand
10-20	Hartselle Sandstone	Well sorted, rounded, dark buff, very fine sand
20-30	Hartselle Sandstone	Rounded, buff to dark yellow, fine to medium, sand with numerous dark brown limonite grains (1-3 mm)
30-40	Pride Mountain Formation	Dark gray clay with sparse sand grains
40-50	Pride Mountain Formation	Gray sandstone (60%) with dark gray clay (40%)
50-60	Pride Mountain Formation	Dark gray sandstone (60%) with dark gray clay (40%)
60-70	Pride Mountain Formation	Light gray sandstone (60%) with dark gray shale (40%)
70-80	Pride Mountain Formation	Dark gray sandstone with dark gray shale
80-90	Pride Mountain Formation	Dark gray, very fine sandstone with dark gray shale
90-100	Pride Mountain Formation	Dark gray-light gray, very fine sandstone with dark gray shale
100-110	Pride Mountain Formation	Dark gray clay with sparse sand grains
110-120	Pride Mountain Formation	Dark gray clay with gray sandstone and numerous limonite grains
120-130	Pride Mountain Formation	Light gray-dark gray-clear quartz grains, dark gray sandstone and limonite
130-140	Pride Mountain Formation	Light gray-dark gray-clear quartz grains, dark brown-yellow limonite, sparse light gray clay
140-150	Pride Mountain Formation	Light gray-dark gray-clear quartz grains, dark brown-yellow limonite, sparse light gray clay
150-160	Pride Mountain Formation	Dark gray clay with sparse sand grains
160-165	Pride Mountain Formation	Light brown-dark brown-red sandstone, red shale, gray clay
165-170	Pride Mountain Formation	Dark buff, fine sand with buff to clear pebbles and cobbles
170-180	Pride Mountain Formation	Buff, white, pink sandstone, dark gray to black shale, sparse limonite
180-190	Pride Mountain Formation	Buff, medium, well sorted, sand with sparse black shale
190-200	Pride Mountain Formation	Light gray, medium, sand with sparse dark gray shale and sparse limonite
200-210	Pride Mountain Formation	Light gray, fine to medium sand, sparse light gray clay
210-220	Pride Mountain Formation	Light gray, fine to medium sand, sparse light gray clay
220-230	Pride Mountain Formation	Light gray, fine to medium sand, sparse light gray clay
230-240	Pride Mountain Formation	Light gray, fine to medium sand, sparse light gray clay with sparse black shale
240-250	Pride Mountain Formation	Light gray, fine to medium sand, sparse light gray clay with sparse black shale
250-290	Pride Mountain Formation	Black, hard shale
290-320	Pride Mountain Formation	Black, hard shale, numerous dark gray sandstone fragments
320-393	Pride Mountain Formation	Black, hard shale, numerous dark gray and pink sandstone fragments
393-485	Tuscumbia Limestone	Dark gray limestone

translated over younger Mississippian rocks by the Happy Hollow fault (plate 12). Test well at site 2 would penetrate about 75 ft of Red Mountain Formation, a few feet of Hartselle Sandstone, and about 50 ft of Pride Mountain Formation before penetrating an undetermined thickness of the primary objective, the Tuscumbia Limestone/Fort Payne Chert. The well should terminate in the Red Mountain Formation at a depth of about 450 ft.

Site 2 was moved about 1,500 ft southwest due to property access issues. A test well at the adjusted location is projected to penetrate about 50 ft of Pride Mountain Formation and an undetermined thickness of the primary objective, the Tuscumbia Limestone/Fort Payne Chert. The well should terminate in the Red Mountain Formation at a depth of about 350 ft.

Drilling at the site was initiated on January 17, 2012, by Hand Service Company. The well encountered 59 ft of clay and sandstone in the Pride Mountain Formation before penetrating the Tuscumbia Limestone. The Tuscumbia Limestone was 32 ft thick and was deeply weathered with numerous clay-filled and open fractures and cavities. The Fort Payne Chert was encountered at a depth of 91 ft and was characterized as deeply weathered chert with about 10 percent clay. The chert was increasingly weathered and at a depth of 145 ft was described as 95 percent clay. No water was encountered in the Fort Payne Chert due to excessive weathering. Drilling was halted at 145 ft and the hole was abandoned on January 24, 2012. Table 10 provides drilling depths, formations encountered, and drill cutting descriptions for the site 2 test well.

Site 3, NW¼SW¼ sec. 34, T. 15 S., R. 1 E., is located along U.S. Highway 11 in the Argo community (plate 10). Cross section E-E′ indicates that the geologic section penetrated by a proposed test well at site 3 is in the footwall of the Argo fault and is overturned so that the units dip northwestward. The test well at site 3 will penetrate about 120 ft of Red Mountain Formation and 130 ft of Tuscumbia Limestone/Fort Payne Chert (primary objective) before termination of the well in the Pride Mountain Formation at about 260 ft (plate 13).

Drilling at the Argo test well site began on July 11, 2011. The well was drilled by Hand Service Company and encountered 190 ft of Red Mountain Formation and 200 ft of Fort Payne Chert prior to reaching a total depth of 555 ft in the Pride Mountain Formation. No economic quantities of water were encountered. Table 11 provides drilling depths, formations encountered, and drill cutting descriptions for the site 3 test well.

Table 10.—Drilling depths, formations, and drill cutting descriptions for the test well at site 2.

Depth (feet)	Formation	Drill cutting description
0-10	Pride Mountain Formation	Clay, light brown 5YR5/6, sparse sandstone, iron and manganese stained, very fine-grained
10-20	Pride Mountain Formation	Clay, grayish-orange 10YR7/4, sparse sandstone, iron and manganese stained, very fine-grained
20-30	Pride Mountain Formation	Clay, 70%, light brown 5RY5/6 to moderate reddish brown 10R4/6, sandstone 30%, fine-grained, iron and manganese stained
30-40	Pride Mountain Formation	Clay 40%, light brown 5YR5/6 to grayish brown 5YR3/2, sandstone, 20%, fine-grained, shale, 40%, medium gray N5
40-50	Pride Mountain Formation	Clay 70%, light brown 5YR5/6, clay, 20%, medium dark gray N4, sandstone 10%, fine- to medium-grained, iron stained
50-59	Pride Mountain Formation	Clay, 60%, medium dark gray N4, clay, 30%, light brown 5YR5/6, sandstone, 10%, fine- to medium-grained, iron stained
59-62	Tuscumbia Limestone	Limestone, 60% medium light gray N6, sandstone, 20%, fine- to medium-grained, iron stained, clay, light brown 5YR5/6
62-67	Tuscumbia Limestone	Limestone, 80%, very light gray N8, light gray N7, and medium gray N5, sparse calcite rhombs, clay 15%, light brown 5YR5/6, trace sandstone (as above)
67-77	Tuscumbia Limestone	Limestone, 75%, very light gray N8 to med gray N5, numerous calcite filled fractures and weathered surfaces, few calcite fragments, clay 25%, light brown 5YR5/6
77-87	Tuscumbia Limestone	Limestone 50%, very light gray N8 to medium gray N5, extremely weathered surfaces, iron stained, some calcite, clay 50%, light brown 5YR5/6 (likely clay filled fractures and cavities in limestone
87-91	Tuscumbia Limestone	Limestone 100%, numerous calcite filled fractures, weathered limestone surfaces (cavity walls)
91-95	Fort Payne Chert	Chert, 80%, very pale orange 10YR8/2 and medium gray N5, iron stained, vugular, calcite 10%, clay 10%, (well made water at limestone-chert contact
95-120	Fort Payne Chert	No samples
120-125	Fort Payne Chert	Chert, 50%, weathered with numerous weathered cavity-fracture surface, vugular, light brown 5YR5/6 to pale brown 5YR5/2, clay, 50%, light brown 5YR5/6, trace limestone medium gray N5
125-135	Fort Payne Chert	Clay, 80%, light brown 5YR5/6, chert, 10%, light brown 5YR5/6, vugular, limestone, 10%, very light gray N8
135-145	Fort Payne Chert	Clay, 95%, light brown 5YR5/6 with chert fragments, 5%

Table 11.—Drilling depths, formations, and drill cutting descriptions for the test well at Argo site 3.

Depth (feet)	Formation	Drill cutting description
0-15	Red Mountain Formation	Clay , pale yellowish orange 10YR8/6, trace sandstone, fine-grained
15-33	Red Mountain Formation	Sandstone, moderate reddish brown 10R4/6, fine- to medium-grained, hematite nodules, medium dark gray N4
33-40	Red Mountain Formation	Same as above
40-50	Red Mountain Formation	Clay, 5YR5/6, fine-grained sand and hematite, sparse pebbles moderate reddish brown 10R4/6
50-60	Red Mountain Formation	Clay, grayish orange 10YR7/4, sparse fine sand grains and hematite.
60-70	Red Mountain Formation	Same as above
70-80	Red Mountain Formation	Same as above
80-90	Red Mountain Formation	Same as above
90-100	Red Mountain Formation	Same as above
100-110	Red Mountain Formation	Same as above
110-120	Red Mountain Formation	Same as above
120-130	Red Mountain Formation	Same as above
130-140	Red Mountain Formation	Same as above
140-150	Red Mountain Formation	Same as above
150-160	Red Mountain Formation	Clay, dark yellowish orange 10YR6/6, sandstone, fine- to very fine-grained
160-170	Red Mountain Formation	Same as above
170-180	Red Mountain Formation	Same as above
180-190	Red Mountain Formation	Clay, moderate yellowish brown 10YR5/4, sparse sandstone, fine- to very fine-grained, pale yellowish brown 10YR6/2
190-200	Fort Payne Chert	Clay, moderate yellowish brown 10YR5/4, sandstone, pale yellowish brown 10YR6/2, fine- to very fine-grained, sparse chert, dark yellowish orange 10YR6/6
200-210	Fort Payne Chert	Clay, dark yellowish orange 10YR6/6, chert (as above), sparse sandstone, fine- to very fine grained
210-220	Fort Payne Chert	As above (increasing chert)
220-230	Fort Payne Chert	Chert, dark yellowish orange 10YR6/6 to moderate yellowish brown 10YR5/4, black staining on surfaces
230-240	Fort Payne Chert	Chert, very pale orange 10YR8/2, pale yellowish orange 10YR8/6, grayish orange 10YR7/4, and dark yellowish orange 10YR6/6
240-250	Fort Payne Chert	Chert, very pale orange 10YR8/2 to dark yellowish orange 10YR6/6, trace sandstone, fine-grained (caved from above)
250-260	Fort Payne Chert	Chert, dark yellowish orange 10YR6/6, chert, sparse sandstone, fine- to very fine- grained
260-270	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to very pale orange 10YR8/2, trace porosity but mostly dense, trace black stain, trace sandstone
270-280	Fort Payne Chert	Chert, very pale orange 10YR8/2 to dark yellowish orange 10YR6/6, trace sandstone, fine-grained (caved from above)
280-290	Fort Payne Chert	Same as above
290-300	Fort Payne Chert	Chert, very pale orange 10YR8/2 to dark yellowish orange 10YR6/6, trace sandstone, fine-grained (caved from above)
300-310	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to very pale orange 10 yr 8/2, trace porosity but mostly dense, trace black stain, trace sandstone

Table 11.—Drilling depths, formations, and drill cutting descriptions for the test well at Argo site 3—continued.

Depth (feet)	Formation	Drill cutting description
310-320	Fort Payne Chert	Same as above
320-330	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to dark yellowish orange 10YR6/6, no porosity, trace black stain
330-340	Fort Payne Chert	Chert as above with increase in dense porcellanic chert, pale yellowish brown 10YR6/2
340-350	Fort Payne Chert	Chert, very pale orange 10YR8/2 to dark yellowish orange 10YR6/6, rarely fossiliferous and porous, trace sandstone, fine-grained (caved from above)
350-360	Fort Payne Chert	Chert, very pale orange 10YR8/2 to dark yellowish orange 10YR6/6, rarely fossiliferous and porous, ,black and red staining, large conglomerate fragment (chert with black asphaltic matrix),trace sandstone, fine-grained (caved from above)
360-370	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to dark yellowish orange 10YR6/6
370-380	Fort Payne Chert	Same as above
380-390	Fort Payne Chert	Chert, very pale orange 10YR8/2 to dark yellowish orange 10YR6/6, rarely fossiliferous and porous, ,black and red staining, large conglomerate fragment (chert with black asphaltic matrix), trace sandstone, fine-grained (caved from above)
390-400	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to dark yellowish orange 10YR6/6, no porosity, trace black stain
400-410	Fort Payne Chert	Same as above with increased fractures
410-420	Fort Payne Chert	Same as above
420-430	Fort Payne Chert	Same as above
430-440	Fort Payne Chert	Same as above
440-450	Fort Payne Chert	Same as above
450-460	Fort Payne Chert	Same as above
460-470	Fort Payne Chert	Same as above but very fractured
470-480	Fort Payne Chert	Same as above
480-490	Fort Payne Chert	Same as above with increased clay
490-500	Fort Payne Chert	Same as above
500-510	Fort Payne Chert	Same as above with large siltstone fragments, light brownish gray 5YR6/1
510-520	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to dark yellowish orange 10YR6/6, no porosity, trace black stain, trace sandstone
520-530	Fort Payne Chert	Chert, grayish orange 10YR7/4 to dark yellowish orange 10YR6/6, to dark yellowish orange 10YR6/6, fossiliferous with porosity, trace black stain, trace sandstone
530-537	Fort Payne Chert	Same as above
537-540	Pride Mountain Formation	Siltstone, dusky yellow 5Y6/4 to lt. olive brown 5Y5/6
540-555	Pride Mountain Formation	Siltstone, dusky yellow 5Y6/4 to lt. olive brown 5Y5/6, chert as above (probably caved from above)

Site 4, NE¼NE¼ sec. 18, T. 16 S., R. 1 E., is approximately 1,100 ft north of U.S. Highway 11 and 1,300 ft southeast from the Argo fault (plate 10). Cross section D-D′ (plate 12) indicates that the test well at site 4 would penetrate about 80 ft of Hartselle Sandstone, about 30 ft of Pride Mountain Formation, about 240 ft of Tuscumbia Limestone/Fort Payne Chert (primary objective), and about 5 ft of Frog Mountain Sandstone, before terminating in the Red Mountain Formation. Raymond and others (2003) mapped a normal fault that extends southward about 1,500 ft from the Argo fault, SE¼ sec. 7, T. 16 S., R. 1 E. Possible surface expression of the fault indicates that there may be some lateral displacement. The proposed test well location is near the southern terminus of the fault. This fault may increase the likelihood of significant fracturing of the Tuscumbia Limestone and Ft. Payne Chert in the vicinity of the test well. Field mapping in the site 4 area indicates that the Hartselle Sandstone dips 59 degrees southeast and the Red Mountain Formation dips 64 degrees southeast. Based on these observations, the projected total depth of the test well would be 375 ft.

Site 5, NE¼SW¼ sec. 7, T. 16 S., R. 1 E., is situated about 700 ft west from Deerfoot Parkway, 3,000 ft south from Interstate 59, and 700 ft south from the Happy Hollow fault (plate 10). Cross section D-D′ indicates that the test well at site 5 would penetrate approximately 60 ft of Sequatchie Formation and Chickamauga Limestone and 300 ft of undifferentiated Knox Group before penetrating the Happy Hollow fault and a repeat section of about 150 ft of Sequatchie Formation and Chickamauga Limestone prior to reaching a total depth of 530 ft in the undifferentiated Knox Group (plate 12).

Site 6, NE¼NE¼ sec. 13, T. 16 S., R. 1 W., is about 800 ft east from Happy Hollow Road (plate 10). On-site investigations (cross section C-C′) indicate that the site lies on the northwest flank of a breeched subsurface anticline, near the crest of a ridge capped by the Hartselle Sandstone about 1,000 ft southeast from the Happy Hollow fault (plate 11). The Hartselle Sandstone was evaluated near site 6 by Raymond and others (2003) and found to strike about north 40 degrees east and dip 24 degrees northwest. Therefore, the test well at site 6 will penetrate about 80 ft of Hartselle Sandstone, and about 60 ft of Pride Mountain Formation before penetrating about 110 ft of the primary objective, the Tuscumbia Limestone/Fort Payne Chert. The well will terminate in the Red Mountain Formation at a depth of about 275 ft (plate 11).

Site 7, SE¼NE¼ sec. 13, T. 16 S., R. 1 W., is about 400 ft east from Houser Drive (plate 10). Cross section B-B′ indicates that the site resides on the crest of a breeched subsurface anticline, near the crest of a ridge capped by the Red Mountain Formation (plate 14). Mississippian aged sediments including the typical primary drilling objective (Tuscumbia Limestone/Fort Payne Chert) have been eroded at this site. Therefore, the test well at site 7 will evaluate potential Ordovician and Cambrian aquifers, including the Sequatchie Formation and Chickamauga Limestone and the undifferentiated Knox Group. The well will terminate in the undifferentiated Knox Group at a depth of about 600 ft.

HYDROGEOLOGIC EVALUATION OF THE TRUSSVILLE UTILITIES CAHABA RIVER PROPERTY

Trussville Utilities requested GSA GAP to evaluate the groundwater availability potential of 1,440 acres that it owns along and east of the Cahaba River, sec. 6, T. 16 S., R. 1 E., and sec. 31, T. 15 S., R. 1 E., north of Interstate 59 and east of Deerfoot Parkway. The property extends along the east flank of the Cahaba Mountain Syncline and is characterized by variable topography, with ridges capped by Tuscumbia Limestone/Fort Payne Chert and the Cahaba River valley where the Tuscumbia Limestone/Fort Payne Chert is eroded exposing Red Mountain Formation partially covered by alluvium adjacent to the Cahaba River channel (plate 10). The Red Mountain Formation is underlain by the Sequatchie Formation and Chickamauga Limestone and the undifferentiated Knox Group (Raymond and others, 2003).

The Tuscumbia Limestone/Fort Payne Chert aquifer underlying the subject property consists of relatively thin, erosional remnants that have limited water availability. Although the Sequatchie Formation and Chickamauga Limestone and undifferentiated Knox Group are unproven aquifers in the Trussville area, they may have significant water availability potential.

A test well was proposed and approved by the Trussville Utilities Board to evaluate the potential for economic quantities of water on the property. Since the Tuscumbia Limestone/Fort Payne Chert are thin and are not likely to contain adequate water, GSA proposed a test well sufficient to evaluate the most likely potential aquifer, the Sequatchie Formation and Chickamauga Limestone. Although this unit is not an aquifer in the Trussville area, it yields water for public supplies in some areas of the Alabama Valley and Ridge.

Drilling began at the test well site (NE¼NW¼ sec. 6, T. 16 S., R. 1 E.) on January 25, 2012. The well was drilled by Hand Service Company. The well penetrated 30 ft of Tuscumbia Limestone/Fort Payne Chert, 270 ft of Red Mountain Formation, and 236 ft of Sequatchie Formation and Chickamauga Limestone before reaching a total depth of 506 ft in silty limestone.

The well penetrated a number of soft limestone beds in the lower Red Mountain Formation and in the Sequatchie Formation and Chickamauga Limestone that yielded water. However, the quantities were not adequate for public water supply and production testing was not warranted. Table 12 provides drilling depths, formations encountered, and drill cutting descriptions for the Trussville Utilities Deerfoot Parkway property.

SUMMARY

Trussville is a growing community with increasing water demands. Providing adequate water supplies in the future will depend on hydrogeologic knowledge of current water sources and alternative sources that may be developed. Although current sources have been adequate, recent drought and increasing water demands caused the Trussville Utilities Board of Directors to become concerned about future water supplies. Therefore, the Board of Directors has commissioned multiple water resource assessments to provide information about groundwater sources in the Trussville area and to locate additional supplies. The GSA was tasked with providing comprehensive hydrogeologic data concerning stratigraphy, groundwater recharge and movement, and locations for test well drilling. The area of investigation covers about 450 mi^2 in north-central Alabama (northeastern Jefferson and southwestern St. Clair Counties, and includes the Trussville Utilities service area (approximately 44 mi^2), and the aquifer recharge areas for current and potential future aquifers (approximately 40 mi^2).

Trussville Utilities supplies water from relatively shallow groundwater sources developed near commercial and residential areas of the city. These shallow aquifers typically have relatively small recharge areas and may be susceptible to contamination originating from the land surface. Therefore, major tasks for the GSA assessment were to determine the extent of the recharge area, directions of groundwater movement, and identification of test well sites that would maximize groundwater production potential while minimizing the potential for contamination.

An evaluation of area stratigraphy and Trussville Utilities water production revealed that current supplies are sourced from two aquifers: the Mississippian aged Bangor Limestone and the Tuscumbia Limestone/Fort Payne Chert. Other potential aquifers in the area are currently undeveloped and include the Ordovician aged Sequatchie Formation and Chickamauga Limestone and the Ordovician and Cambrian aged Knox Group.

Table 12.—Drilling depths, formations, and drill cutting descriptions for the test well drilled on the Trussville Utilities Deerfoot property.

Depth (feet)	Formation	Drill cutting description
0-10	Tuscumbia Limestone/Fort Payne Chert	Chert, weathered
10-20	Tuscumbia Limestone/Fort Payne Chert	Clay, moderate yellowish grown 10YR5/4, sparse chert
20-30	Tuscumbia Limestone/Fort Payne Chert	Chert 50%, light brown 5YR5/6 to moderate reddish orange 10R6/6, sandstone 30%, dark yellowish brown 10YR2/2, fine- to very fine grained, clay 20%, light brown 5YR5/6
30-40	Red Mountain Formation	Sandstone 90% dark yellowish frown 10YR4/2, fine- to very fine grained, chert 10% (probably caved from above), trace clay, light brown 5YR5/6
40-50	Red Mountain Formation	As above
50-60	Red Mountain Formation	Sandstone (as above) 100%, trace chert (probably caved from above)
60-70	Red Mountain Formation	Sandstone 90%, moderate yellowish brown 10YR5/4 to dark yellowish brown 10YR4/2, fine- to very fine-grained, frequent black staining, chert 10% (as above)
70-80	Red Mountain Formation	Sandstone 100% (as above), trace chert (as above)
80-90	Red Mountain Formation	Sandstone 70%, moderate yellowish brown 10YR5/4 to dark yellowish brown 10YR4/2, fine- to very fine-grained, frequent black staining, sandstone 30% medium dark gray N4, soft, fine-grained, trace clay, yellowish gray 5YR7/2
90-100	Red Mountain Formation	Sandstone 100% (as above), mud stream moderate reddish brown at 98 ft (probable hematite layer)
100-110	Red Mountain Formation	Sandstone 100% (as above) mud stream as above
110-120	Red Mountain Formation	Same as above
120-130	Red Mountain Formation	Sandstone 100%, dark gray N3, fine- to very fine grained, mud stream moderate red 5R4/6
130-140	Red Mountain Formation	Sandstone 100% (as above), trace sandstone moderate red 5R4/6 (coarse-grained hematite)
140-150	Red Mountain Formation	Same as above
150-160	Red Mountain Formation	Same as above
160-170	Red Mountain Formation	Same as above
170-180	Red Mountain Formation	Sandstone 20% (as above), sand 80%, moderate red 5YR4/6, medium-grained
180-190	Red Mountain Formation	Sandstone 100%, sandstone 100% (as above), trace sandstone moderate red 5R4/6 (coarse-grained hematite)
190-200	Red Mountain Formation	Sandstone 100%, brownish gray 5YR4/1, fine-grained, mud stream slight red tint
200-210	Red Mountain Formation	Sandstone 100%, medium dark gray N4, very fine-grained, mud stream gray
210-220	Red Mountain Formation	Sandstone 100% (as above)
220-230	Red Mountain Formation	Limestone 90%, pale brown 5YR5/2, weathered, sandstone 10% (as above)
230-240	Red Mountain Formation	Sand and clay 70%, moderate red, limestone 30%, medium gray N5
240-250	Red Mountain Formation	Limestone 100%, medium dark gray N4, mud stream moderate red 5R4/6 (probable hematite stringers
250-260	Red Mountain Formation	Drilling dry, sample ground up to clay sized particles 90%, readily reacts to HCl, limestone fragments 10%, medium dark gray N4

Table 12.—Drilling depths, formations, and drill cutting descriptions for the test well drilled on the Trussville Utilities Deerfoot property—continued.

Depth (feet)	Formation	Drill cutting description
260-270	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, medium dark gray N4, mud stream pale yellowish brown 10YR5/4
270-280	Chickamauga Limestone and Sequatchie Formation	Drilling dry, ground up matrix, light gray N7
280-290	Chickamauga Limestone and Sequatchie Formation	Limestone 70%, medium dark gray N4, calcite, 30%, white N9 to very light. gray N8, mud stream red tinted
290-300	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, medium dark gray N4, trace calcite, mud stream gray
300-310	Chickamauga Limestone and Sequatchie Formation	Limestone as above with numerous calcite rhombs
310-320	Chickamauga Limestone and Sequatchie Formation	Limestone, 100%, medium light gray N6 to very light gray N8
320-330	Chickamauga Limestone and Sequatchie Formation	Limestone, 100% with numerous calcite rhombs, white to translucent
330-340	Chickamauga Limestone and Sequatchie Formation	Same as above
340-350	Chickamauga Limestone and Sequatchie Formation	Limestone as above 98%, sandstone, trace, light olive gray 5Y6/1, chert, trace, olive gray 5Y4/1
350-360	Chickamauga Limestone and Sequatchie Formation	Limestone as above 98%, abundant calcite, dolomite, 2%, medium bluish gray 5B5/1, trace sandstone, very fine-grained, light brown
360-370	Chickamauga Limestone and Sequatchie Formation	Same as above, limestone 95%, dolomite 5%
370-380	Chickamauga Limestone and Sequatchie Formation	Same as above, limestone 70%, dolomite 30%
380-390	Chickamauga Limestone and Sequatchie Formation	Limestone 99%, medium light gray N6, less calcite, trace dolomite, medium bluish gray 5B5/1, trace sandstone, very fine-grained, pale brown 5YR5/2
390-400	Chickamauga Limestone and Sequatchie Formation	Same as above, limestone 95%, dolomite 5%
400-410	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, medium dark gray N4 to medium light gray N6, abundant calcite, trace limestone dark gray N3, trace dolomite
410-420	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, dark gray N3, abundant calcite, white to translucent
420-430	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, dark gray N3, sparse calcite
430-440	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, dark gray N3 to medium light gray N6, abundant calcite
440-450	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, brownish gray 5YR4/1 to med gray N5, abundant calcite
450-460	Chickamauga Limestone and Sequatchie Formation	Limestone 100%, brownish gray 5YR4/1, silty, sparse calcite
460-470	Chickamauga Limestone and Sequatchie Formation	Silty limestone 100%, medium dark gray N4 to medium light gray N6 to brownish gray 5YR4/1
470-480	Chickamauga Limestone and Sequatchie Formation	Same as above
480-490	Chickamauga Limestone and Sequatchie Formation	Silty limestone 70%, crystalline limestone 30%, medium dark gray N4 to medium light gray N6 to brownish gray 5YR4/1

Table 12.—Drilling depths, formations, and drill cutting descriptions for the test well drilled on the Trussville Utilities Deerfoot property—continued.

Depth (feet)	Formation	Drill cutting description
490-500	Chickamauga Limestone and Sequatchie Formation	Same as above
500-506	Chickamauga Limestone and Sequatchie Formation	Same as above

The land-use/land-cover in the recharge area is dominated by mixed forest (75.3%) and grass/pasture (13.0%). However, much of this undeveloped land is in the central and northeastern parts of the recharge area. All of the current Trussville Utilities water production wells are in the southwestern part of the area, dominated by developed/residential, roads, and parking spaces and developed/commercial land-use classifications.

Groundwater samples were collected during two site visits in June (summer) and November (fall) 2010 to identify seasonal impacts on groundwater physical properties. Analyses for the stable isotopes of hydrogen ($\delta^{18}O$) and oxygen (δD) were performed from samples collected during both events while those for the carbon ($\delta^{13}C$) analysis were collected during the fall sampling event. Aqueous samples for chlorofluorocarbon (CFCs) and sulphur hexafluoride (SF_6) groundwater dating were collected from the eight TU wells and a private well (P-1) in June.

A more homogeneous range of summer $\delta^{18}O$ and δD data indicates a smaller degree of groundwater mixing in the investigated aquifers and the likelihood of common regional recharge for both Bangor and Tuscumbia Limestone/Fort Payne Chert aquifers. The narrow range of groundwater $\delta^{18}O$ and δD summer values suggests a short recharge period with low evaporation rates of infiltrating water. Therefore, most recharge likely takes place during colder seasons when evaporation is lowest to absent.

Groundwater levels, drawdown, and geochemical parameters were used to characterize groundwater movement and climate and production impacts. Based on CFC analyses, apparent groundwater ages in the investigated aquifers ranged from 17.5±2 to 30.5±2 years. SF_6 based ages determined for W-6 and P-1 were 28±2 and 1±2 years, respectively. Generally, Bangor Limestone aquifer waters are associated with the youngest ages. The investigated wells developed in the Bangor Limestone aquifer are located in close proximity to the Cahaba River. Although screens in these wells are set starting at 150 ft below land surface, it is probable that some modern water from the river infiltrates to the developed water-bearing horizon (especially during pumping rates higher than those of aquifer recharge). Generally, the highest water levels and oldest groundwater are characteristic of the Tuscumbia Limestone/Fort Payne Chert aquifer, which indicates that this groundwater experiences longer travel times and higher recharge rates. In contrast, the Bangor Limestone aquifer experiences shorter residence times, lower water levels and, therefore, lower recharge rates. This hypothesis is further supported by larger drawdowns characteristic of this aquifer. Analysis of groundwater age distribution with depth indicated that water in the Tuscumbia Limestone/Fort Payne Chert aquifer flows from northeast to southwest along the Cahaba Mountain Syncline at a rate of about 2.4 miles per year. Due to limited water age data (only two wells), travel paths could not be identified for the Bangor Limestone aquifer.

Unlike the Coastal Plain where groundwater recharge can move long distances in aquifers that exceed depths of 2,500 ft or the Tennessee River watershed area where aquifers are relatively thin and shallow with local recharge, the Valley and Ridge is characterized by large, complex structures with faults and fractures that create local and long distance pathways for groundwater movement. Recharge rates are controlled by a number of factors including porosity, which in Paleozoic aquifers is primarily secondary and tertiary and is the result of leached fossils, bedding plane conduits, fractures, and solution cavity development and permeability, and relies on the magnitude of interconnectedness of pore spaces.

Average precipitation in the Trussville area is 56 inches per year and is distributed as runoff, evapotranspiration, and groundwater recharge. Since most groundwater recharge is discharged to streams as baseflow in aquifer recharge areas, estimates of baseflow may be used to approximate groundwater recharge rates. This is accomplished by separating baseflow and runoff components of stream flow. GSA used the automated hydrograph separation program WHAT (Web Based Hydrograph Analysis Tool) to estimate baseflow and then calculated recharge rates and volumes using estimated baseflow values. The investigated area was divided into two recharge zones to evaluate the Tuscumbia Limestone/Fort Payne Chert aquifer along the Cahaba Mountain Syncline and the Bangor Limestone and Tuscumbia Limestone/Fort Payne Chert aquifers along and southeast of the Argo Fault.

Results from the WHAT automated hydrograph separation program indicate that baseflow was 19 percent of total discharge for the total period of record from October 1988 to October 2010. Results for hydrograph separation of data used for the recharge estimate

(September 2009 to September 2010) indicate that baseflow was 17 percent of the total discharge. Recharge totals calculated for the Trussville recharge area (40 mi^2) are 8.7 mgd (217,500 gallons per square mile per day) or 4.6 inches of recharge per year. The estimated recharge rates are relatively small compared to current water demands or individual well production rates. However, aquifer storage is significant with the estimated volume of water in the Tuscumbia Limestone/Fort Payne Chert aquifer about 50 billion gallons. This is supported by significant summer season groundwater level drawdown, as much as 17 ft, in public water supply wells in the area.

One of the primary purposes of this investigation was to recommend sites for test well drilling in the Trussville Utilities service area. GSA GAP research resulting in possible test well locations included field assessments and evaluation of available published data. GSA GAP recommended seven test well locations in the Trussville Utilities service area. Three of the recommended sites were drilled between January 2011 and January 2012. A fourth well was drilled to evaluate the potential for economic quantities of water on a tract of land owned by Trussville Utilities north of I-59 and east of Deerfoot Parkway along the Cahaba River. The primary objective for the first three wells was the Tuscumbia Limestone/Fort Payne Chert.

The first test well was drilled near the intersection of U.S. Highway 11 and Deerfoot Parkway. The well encountered 30 ft of Hartselle Sandstone underlain by 363 ft of Pride Mountain Formation before penetrating the Tuscumbia Limestone. The well was terminated in the Tuscumbia Limestone at a depth of 485 ft with no economic quantities of water encountered. An unexpected steepening of dips in the Pride Mountain Formation caused the Fort Payne Chert to be at excessive depth at the drilled location.

Test well 2 was drilled just north of the Happy Hollow Fault, 0.5 mile south of Happy Hollow Road and I-59 and 0.5 mile west of Deerfoot Parkway. The primary objective was the Tuscumbia Limestone/Fort Payne Chert. The well penetrated 59 ft of Pride Mountain Formation, 32 ft of extremely karstified Tuscumbia Limestone, and 54 ft of Fort Payne Chert. The well was terminated at a depth of 145 ft. The Tuscumbia Limestone contained water in several karst zones. However, it was too shallow to be considered for testing. The entire Fort Payne Chert section was deeply weathered and consisted of clay with thin, remnant chert beds.

The third test well was drilled in the Argo community near the intersection of U.S. Highway 11 and Micklewright Road. The well was drilled into an overturned section adjacent to the Argo Fault with the Fort Payne Chert as the primary objective. The well penetrated 190 ft of Red Mountain Formation underlain by 347 ft of Fort Payne Chert. No Tuscumbia Limestone was recognized and the well was terminated in the Pride Mountain Formation at a depth of 555 ft. The entire Fort Payne Chert section was deeply weathered to clay with remnant chert beds. There was no economic quantity of water encountered.

The fourth test well was drilled 1 mile north of I-59, just east of Deerfoot Parkway and the Cahaba River on a tract of land owned by Trussville Utilities. The Fort Payne Chert in this area consists of erosional remnants and was not considered a viable exploration target. Therefore, the primary objective was the Sequatchie Formation and Chickamauga Limestone. The well penetrated 30 ft of Fort Payne Chert, 230 ft of Red Mountain Formation, and 246 ft of Sequatchie Formation and Chickamauga Limestone. The well was terminated at a depth of 506 ft. The well encountered several carbonate water-bearing zones in the lower Red Mountain Formation and upper Sequatchie Formation and Chickamauga Limestone but quantities were considered inadequate for testing.

RECOMMENDATIONS

Land use is a major issue impacting current and future water supplies for the Trussville area. All of Trussville Utilities current groundwater production is in or near heavily developed areas. Although current water-quality impacts are minor, future water source development should occur in less developed areas where water quality can be more easily protected. The recharge area for aquifers in the Trussville Utilities Service area covers about 40 mi^2. Much of this area is undeveloped or has only sparse commercial and residential development, particularly northwest of the city. Due to the shallow, karst character of available aquifers, these areas must be protected in the future to insure high quality water sources. Protective measures may include land purchases, cooperative efforts with state and federal agencies to implement protective incentive programs, and legislation or ordinances to guide planning and development.

Based on recent strategic test well drilling, it appears that the U.S. Highway 11 corridor northeast of the city of Trussville has limited potential for future groundwater development for public water supplies. Although the Tuscumbia Limestone/Fort Payne Chert is a prolific aquifer in many areas of the Alabama Valley and Ridge, it is extremely weathered in outcrop and appears to be similar in the subsurface from Argo, southwestward to Deerfoot Parkway. The same situation exists in the Happy Hollow Road area. Therefore, other than high-risk test wells to evaluate the Knox Group or Bangor Limestone, the most viable area for test well drilling is along the Cahaba Mountain Syncline northeast of the city of Trussville to evaluate the Tuscumbia Limestone/Fort Payne Chert.

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