GEOLOGICAL SURVEY OF ALABAMA

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Characterization of Hydrogeology and Regional Groundwater Movement in Madison County and Redstone Arsenal, Alabama

By

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Tuscaloosa, Alabama
2015

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INTRODUCTION

Redstone Arsenal (RSA) was established in 1941 to support World War II military actions with chemical and munitions manufacturing. Later, Redstone Arsenal became a historically important site for the development of missile and rocket technology. However, it is also known in the environmental community for biological habitat and species including the endangered Alabama cave shrimp (*Palaemonias alabamae*) in Bobcat Cave and the Tuscumbia Darter (*Etheostaoma tuscumbia*), a species of High Conservation Concern, in Williams Spring (McGregor and others, 2004).

Redstone Arsenal is bounded on the south by the Tennessee River and on the west, north, and east by expanding urban areas of the cities of Madison and Huntsville. Activities on the arsenal and urbanization of areas hydrologically upgradient from the arsenal cause changes in runoff and impact water quality. Previous investigators (Rheams and others, 1992; McGregor and others, 1996-2008; McGregor and others, 2004; Campbell and others, 1977; Campbell, 1997) addressed effects of water quality and water movement on wildlife on the arsenal. This investigation incorporates geologic and hydrogeologic data off the arsenal with abundant data collected on the arsenal to characterize the stratigraphic composition of the area, potentiometric surfaces and water table maps, pathways of groundwater movement and confinement, and surface water and groundwater interactions that influence environmental conditions on Redstone Arsenal.

HYDROGEOLOGY

Much of the surface and shallow subsurface of Madison County is composed of the Fort Payne Chert and Tuscumbia Limestone. The geology of the topographically low areas of the Redstone Arsenal area are characterized by Tuscumbia Limestone at the surface, underlain by Fort Payne Chert. The formation has an average thickness of about 160 feet.

The Tuscumbia Limestone overlies the Fort Payne Chert although in some areas it is lithologically indistinct. Surface and near-surface parts of these units are weathered into clayey soils and karst terrains characterized by solution enhanced fractures. Well drilling in Madison County shows the local occurrence of fractures on multiple levels that store and transmit large amounts of water. Many of these karst features are connected to surface-water bodies so that water is readily exchanged between the surface and subsurface. Drilling also shows that in

many areas fractures do not occur or are so small that they are not detected during drilling. Therefore, transmission of large amounts of groundwater over long distances is uncommon.

DATA AVAILABILITY, METHODS, AND LIMITATIONS

Considerable data from a variety of sources are available for construction of structure and isopachous maps and for hydrogeologic characterization of aquifers in the study area, including water wells and test holes, stratigraphic test holes, oil and gas test wells, test holes and borings from Redstone Arsenal, and surface geologic maps. Challenges are presented in the utilization of much of the data for the purposes intended for this investigation, however, due to factors such as variations and inconsistencies in the types of data collected, variations in the quality of data collected, levels of detail of observations and measurements, and spatial variability of data across the area. Geologic interpretations presented in this report are based primarily on geophysical log measurements; visual appearance of rock from borehole optical - and acoustic televiewer data; sample logs from various geologists; drillers' logs; and correlation of subsurface data with surface geology. No examinations of outcrops, well cuttings, or cores from RSA wells were conducted by the authors in this investigation. The authors did rely, however, on experience and data from first-hand examination and description of rocks of coeval stratigraphic sections in both surface and subsurface settings outside the arsenal boundaries, including outcrops and wells in Alabama, Tennessee, Mississippi, and Kentucky.

To assist in assessment of the hydrogeology of the area of investigation, extensive hydrologic, geologic and geophysical data collected primarily by RSA contractors for environmental purposes were provided to GSA in March, 2014; these data are from more than 16 reports and numerous other compilations, tables, and illustrations representing more than 15 years of scientific investigations. Natural gamma logs (gamma ray) and other geophysical logs such as neutron, density, acoustic, and visual (optical) logs are available for many of the test holes drilled in the RSA area. References are made in this report to logs and data collected in RSA by COLOG, a division of Layne Christensen Company. The terms "RSA area" and "RSA" as used herein includes the area within the arsenal boundary (including the NASA Marshall Space Flight Center) as well as a portion of northern Morgan County, Alabama, where limited test well drilling and logging operations were conducted by RSA contractors to obtain data south of the Tennessee River. Extensive data regarding "ambient" (natural, non-

pumping) groundwater flow intervals as well as flow induced under “stressed” (pumping) conditions and geochemical data are available from RSA boreholes. The geological analyses and interpretations presented in this report rely primarily on data from wells that penetrate to the Devonian Chattanooga Shale, supplemented locally by data from shallower wells.

Outside the RSA area are relatively few available geophysical logs, especially of the types mentioned above. Geochemical data collected off post by various entities are restricted in most cases to water samples obtained from specific intervals from public supply wells and limited data from other test wells. Most of the geophysical logs run in boreholes outside RSA are spontaneous potential and resistivity (and/or single point resistance) logs recorded more than 40 years ago by GSA or USGS personnel. Geophysical logs are rarely run in water wells and test wells; drillers rely instead on observation of drill cuttings and drilling characteristics (e.g. penetration rate) and the presence or absence of groundwater entering the borehole to determine availability of potential intervals for further evaluation. There is a general lack of appreciation of the utility of geophysical logs in water well drilling applications, but cost is the major factor. In the RSA area, gamma ray logs are the principal and most consistently available logs to match with visual borehole logs to make interpretations of lithologies present in the subsurface. Variation in gamma ray log scales ranges from 50 counts per second (CPS) to 1,200 CPS in reports presented, with logs generally shown on page scale format. Gamma ray logs presented with scales above several hundred CPS are sufficient to recognize the contrast of the most radioactive interval, the Chattanooga Shale, with most other geologic intervals, but lack sufficient resolution to perform detailed stratigraphic analyses and correlations with other logs and data. The lack of consistency and resolution of many of the gamma ray logs run in RSA test wells is incongruous with findings reported in the Central Dye Trace Report (2004) by Shaw Environmental, Inc., which highlighted the usefulness of recognition of marker horizons within the stratigraphic section using natural gamma radiation. Neutron and density logs are available for many wells logged in the NASA Marshall Space Flight Center (MSFC).

Whereas the locations, ground level elevations, and other pertinent data of wells and boreholes in RSA have been determined to consistently high standards of precision, detail, and, presumably, accuracy, similar data from wells outside the arsenal are of widely variable precision and accuracy. Few well locations and elevations determined for wells outside RSA conform to the standards of those measured within the arsenal. However, the reliability –

accuracy and precision – of most well locations, elevations, water levels, and other pertinent data collected by GSA and USGS personnel over the years is considered suitable for purposes of this investigation. Hand-held GPS equipment was used by GSA personnel in this study to locate a number of wells outside RSA, and elevations were determined to the level of accuracy of USGS 7.5 minute topographic quadrangles. It was beyond the scope of this investigation, however, to attempt determination of locations and elevations of a large number of wells (especially those no longer in existence), and reliance on the accuracy of the well records on file with GSA was made on a case by case basis.

GEOLOGY

General Stratigraphy and Surface Geology

Geologic units cropping out in the study area range in age from Ordovician to Pennsylvanian, with older formations found at lower elevations in the northwestern part of the area and younger units comprising uplands and mountains (plate 1). Because regolith of weathered Paleozoic strata and alluvial deposits found along stream valleys cover the majority of the study area, bedrock geology is mapped from sparse outcrops and/or inferred from projection from the subsurface to the surface. In some wells, regolith comprises more than half of the total depth reached in drilling. These unconsolidated materials, though integral to the hydrologic regime, are not described and discussed herein; rather, the geology of the underlying Paleozoic rocks are the focus of this report. Mississippian Fort Payne Chert and overlying Tuscumbia Limestone make up the greatest portion of outcrop in the area of investigation and are the principal units containing aquifer intervals. Overlying the Tuscumbia Limestone are generally grain-rich limestone beds of the Monteagle Limestone; locally present shale and limestone of the Pride Mountain Formation; sandstone and shale beds of the Hartselle Sandstone; limestone of the Bangor Limestone; and sandstones and thin shale beds of the Pennsylvanian Pottsville Formation. Thin but widespread units, Mississippian Maury Formation and Devonian Chattanooga Shale underlie the Fort Payne Chert. Chattanooga Shale provides a useful unit for delineation of stratigraphy, correlation, and mapping geologic structure. The Chattanooga Shale is recognizable by its distinctive black color, commonly petroliferous and sulfurous content and odor, and high natural gamma radiation, resulting primarily from relatively high uranium content (Glover, 1959; Conant and Swanson, 1961). Though not cropping out in the primary area of investigation (plate 1), rocks of Silurian age

occur at the surface a few miles to the north and northeast and are present in the subsurface over a large portion of the study area. Malmberg and Sanford (1963) mapped limestone, shale, and thin sandstone beds cropping out beneath Chattanooga Shale in northern Madison County as part of the Silurian Red Mountain Formation and/or Ordovician Chickamauga Limestone. Later workers (Jewell, 1969; Chaffin and Szabo, 1975; Szabo and Chaffin, 1982) considered Silurian outcrops to be Brassfield Limestone and Ordovician outcrops to be part of the Sequatchie Formation.

A finding of this investigation is that the subsurface geology delineated herein is most consistent with and supportive of the surface geologic map of Kidd and others (1975). The principal difference of their map with other published geologic maps of the area is the contact of the Fort Payne Chert and the Tuscumbia Limestone, the elevation of which significantly affects the relative proportions of mapped outcrop of the two formations. Because of generally low topographic relief over most of the study area in which the Fort Payne and Tuscumbia crop out, especially in the immediate Hunstville and RSA areas, relatively small variation of the geologic contact elevation significantly affects each formation's area of outcrop. An interpretation of the Fort Payne-Tuscumbia contact from subsurface data collected during RSA hydrogeologic investigations in conjunction with data previously on file with GSA is presented here and is intended to provide a more consistent basis for delineation of these two units than previously available.

Geologic Structure

The study area lies on the southern flank of the Nashville dome, a major anti-form that is part of the generally north-south oriented Cincinnati arch. As demonstrated by a map of the top of Chattanooga Shale (plate 2), the south-plunging axis of the Nashville dome is located in the western part of the study area, just east of and approximately parallel to the Madison County line. East of the axis, the overall dip of the formations is generally to the south-southeast at about 30 feet per mile (approximate 0.33 degree dip) with a total elevation difference of about 600 feet across the area of investigation at the top of the Chattanooga Shale. As shown in plate 3, the top of the Fort Payne Chert also dips to the south-southeast at about 30 feet per mile. Geologic cross sections (plates 4, 5, and 6) also depict geologic structure in RSA and nearby areas. Note that no faults are shown on the structure maps and cross sections, interpretations consistent with previously published geologic and structure maps of the area.

Localized areas of comparatively higher dip rate are evident, however, such as in section 30, T. 5 S., R. 1 W. in the southern part of the study area, where an elevation difference of 58 feet at the top of the Chattanooga Shale occurs between test holes RSA 1155 and 1844, equivalent to a dip rate of approximately 134 feet per mile (1.45 degrees). Centered in the SE ¼, section 35, T. 4 S., R. 2 W. in the western part of RSA, a northwest-trending structural low is about 220 feet lower at the top of the Chattanooga Shale than a mapped structural nose located approximately 2.4 miles to the northwest (section 28, T. 4 S., R. 2 W.), indicating an overall dip rate of about 90 feet per mile. Whereas the overall dip of the strata across the study area and localized areas of comparatively high rates of dip are indicative of folding resulting from the development of the Nashville dome, well data do not appear to provide unequivocal evidence of faults in the area. Additional data illustrating structural features in RSA and interpretations of the relationships between geologic structure and stratigraphy will be presented in a following section of this report.

Silurian and Ordovician Stratigraphy

The base of the Chattanooga Shale defines a significant regional unconformity that marks the end of a long period of erosion prior to deposition of late Devonian and early Mississippian age rocks. Delineating this unconformity is important in understanding the geologic history of the region, especially the development of the Nashville dome (Reesman and Stearns, 1989), and in identifying the geologic units present beneath the Chattanooga Shale (subcrop) in the study area. Various interpretations of subcropping Silurian and Ordovician units in the area of investigation have been offered by previous workers. For example, data from petroleum test well B352 (Newman No. 1 Lam) drilled in 1945-46 in section 10, T. 4 S., R. 1 E. was interpreted by McGlamery (1955) to have penetrated 95 feet of Silurian rocks, whereas Jewell (1969) interpreted the same interval as Ordovician Leipers Limestone and Inman Formation. Similarly, unpublished sample logs and descriptions on file with GSA, document significant differences among workers in interpretations (and in some instances differences in descriptions of well cuttings of the same intervals in the same wells by different workers) of pre-Chattanooga Shale strata in the area. Though numerous test holes and wells have drilled into rocks lying below the Chattanooga Shale in the study area, sparse definitive data to identify pre-Chattanooga stratigraphic intervals penetrated by drilling have been presented to date,. A Silurian brachiopod, *Dolmonella elegantula,* was tentatively identified in

a sample log from a depth of 200 feet, author unknown, of USGS test well CT-2 drilled in February, 1951 in section 31, T. 3 S., R. 1 E.. The geologic sample log and electric logs (spontaneous potential and single point resistance) run in this borehole provide data useful for correlation with logs from other wells in the study area. In this investigation, Silurian units are interpreted to be present in the subsurface over much of the assessed area and include Brassfield Limestone and locally-occurring shale beds of the overlying Osgood Formation. In the RSA area, examination and interpretation of available data from wells drilled through the Chattanooga Shale suggest widespread subcrop of Silurian Brassfield Formation with localized occurrences of thin beds of Osgood Formation present in a few wells. For example, in well RS1773 (section 24, T. 5 S., R. 2 W.) 12.9 feet of grayish-green shale are interpreted to be beds of the Osgood Formation from drilled depths of 265.4 – 278.3 feet.

In northwestern Madison County and northern Limestone County, Silurian rocks are not present and locally the Chattanooga Shale is absent as well, indicating their removal or non-deposition along the crest of the Nashville dome. As will be discussed below, outcrops of Mississippian Maury Formation disconformably overlie Ordovician shale beds at the community of Gipsy in Limestone County. Small variations in thickness of the Devonian and Lower Mississippian units across the study area – generally showing slight thickening away from the axis of the Nashville dome – suggest no large variations in topography existed at the time of resumption of sediment deposition in the late Devonian period. These data appear to support the interpretation by Reesman and Stearns (1989) of regional smoothness of the pre-Chattanooga unconformity in Tennessee and northern Alabama.

Some wells and test holes in or near the study area penetrate Ordovician aged rocks, and a few have reached strata of the Knox Group of Cambrian and Ordovician age (McGlamery, 1955; Jewell, 1969). Carbonate rocks predominate the Ordovician and Cambrian sections, but some shale and thin sandstone beds are present locally. In addition to data from the aforementioned wells, borehole data from test holes MT-127 and P-68 (section 28, T. 4 S., R. 2 W.), P-79 (section 30, T. 4 S., R. 2 W.), MT-123 (section 3, T. 5 S., R. 2 W.), and petroleum tests P5893 (section 1, T. 6 S., R. 1 E.), P1630 (section 17, T. 5 S., R. 1 E.), and P11085 (section 20, T. 2 S., R. 1 E.) are useful in correlation of Silurian and Ordovician rocks in the area. At RSA, at least 9 wells are interpreted to have reached total depth in Ordovician rocks. In particular, test wells RS1773 (section 24, T. 5 S., R. 2 W) and RS1412 (section 14, T. 4 S., R. 2

W.) are interpreted here to have been drilled through Silurian rocks and as deep as the Upper Ordovician Inman Formation.

Maury Formation

Lying immediately above the Chattanooga Shale is the Lower Mississippian (Kinderhookian) Maury Formation, comprised primarily of green to olive-gray, commonly glauconitic and phosphatic shale beds. The Maury Formation is commonly about 1-3 feet thick across the study area. At RSA, optical televiewer logs show that very thin limestone beds occur locally above the Chattanooga Shale but generally below or, in some wells, interbedded with green shale beds typical of the Maury Formation. Conkin and Ciesielski (1973) reported thin limestone beds interbedded with shale in two measured outcrop sections of the Maury Formation at Gipsy, Limestone County, Alabama, located about 20 miles northwest of RSA. Based primarily on arenaceous foraminifera found at the Gipsy sections, they concluded an early to middle Kinderhookian age for the Maury Formation there. Furthermore, they indicated close resemblance of the Maury foraminiferal faunal assemblages to those of the Chouteau Limestone of western Illinois, the Rockford Limestone of southern Indiana, and the Compton Limestone of southwestern Missouri. Though additional study is necessary to firmly establish correlation of the Maury Formation at Gipsy with the subsurface sections of Maury logged in the study area, general resemblances and stratigraphic position suggest similar age and stratigraphy.

Fort Payne Chert

Fort Payne Chert is generally described in the geologic literature as very light gray to light-olive gray, thin- to thick-bedded, fossiliferous or bioclastic limestone, siliceous and dolomitic limestone, and dolomite with abundant nodules, lenses, and beds of light- to dark-gray chert, with some scattered beds of greenish-gray shale (Thomas, 1972; Copeland and others, 1975; Szabo and others, 1988; Raymond, 2003). Bedded chert is common throughout the unit but is more concentrated in the lower part of the formation. The percentage of chert in the Fort Payne is estimated to vary from 20 to 80 percent (Holler, 1975).

Thickness of the Fort Payne Chert in the area of investigation ranges from about 140 feet to more than 170 feet. Jewell (1969) gave a maximum thickness of 150 feet to the Fort Payne in Madison County. Thomas (1972) shows the Fort Payne Chert to be 195 feet thick in the Rohwer No. 1 Hough petroleum test well (OGB Permit 128) in section 2, T. 6 S., R. 1 W.,

Morgan County, Alabama, and he indicates that the formation thickness generally exceeds 150 feet throughout the East Warrior Platform of north Alabama. In the Fisk 7.5 minute quadrangle, which includes the northernmost part of the study area, an average thickness of about 160 feet was ascribed to the formation by Chaffin and Szabo (1975). Copeland and others (1975) indicate the formation is 155 to 185 feet in Madison County. Raymond (2003) states that the formation ranges in thickness from 115 to 130 feet in the Madison quadrangle but indicates a thickness as low as 75 feet in well P-35 at Betts Spring due to dissolution of limestone beds. Data from 61 RSA wells that penetrate the complete Fort Payne interval – including three wells in Morgan County – demonstrate a range in thickness of the formation from 143.4 feet to 165.1 feet with an average thickness of 156.1feet (median 157.4 feet). Because available data outside RSA generally do not permit distinction of the Maury Formation and the Fort Payne Chert, thicknesses of the two units are combined in the isopach map shown in plate 7. Minor thinning of the Fort Payne from southeast to northwest, likely reflecting subtle influence of the Nashville dome on early Mississippian sedimentation, is interpreted from the geologic map of the study area (plate 1) and structural mapping of the top of Chattanooga Shale and top of the Fort Payne Chert (plates 2 and 3).

Fort Payne Chert Lithofacies

Fort Payne Chert demonstrates vertical and lateral variations in geophysical log responses as well as variations in visual appearance recorded in optical televiewer logs in the RSA area. These variations are interpreted to result from changes in lithology, bedding, sedimentary structures, and/or rock properties such as porosity. The Fort Payne Chert is subdivided into four general lithofacies in RSA and nearby areas on the basis of the available data. No well cuttings or cores were examined in the course of this study to support the interpretations presented here, but outcrops of the Fort Payne and Tuscumbia (or their stratigraphic equivalents) as well as drill cuttings, cores, and geophysical logs have been examined by the authors elsewhere to provide some basis for forming tentative interpretations of lithologies present in RSA and nearby areas. Data from wells that penetrated to the top of the Chattanooga Shale or deeper are the primary data sources for these analyses and interpretations. Well control and data quality are sufficient in much of the southern part of RSA to map the extent and thicknesses of the various lithofacies (plates 8-11) and illustrate in cross sectional view as well (plates 4-6). Each lithofacies is the product of primary depositional environments

as well as later diagenetic processes. Lithofacies variations probably resulted from factors such as changes in ancient sea floor topography, water depth, currents, sediment sources, and fauna (fossils) across the study area.

Lying immediately above the Maury Formation in many of the wells, is an interval of light-gray to tan or buff colored limestone that ranges in thickness to a maximum of about 25 feet. Though not present in all wells at RSA, this facies is generally widespread across the southern half of the arsenal area and is distinctive on geophysical and optical televiewer logs. There is a general lack of clay in this relatively thin limestone interval as indicated by the very low gamma ray response and interpreted from visual appearance. The interpreted lithology of this interval suggests conditions conducive to calcium carbonate deposition, presumably relatively clear marine water free from significant clastic influx. In many wells the limestone appears to be boundstone, locally displaying some stromatactis-like features (cavities?) with irregular boundaries and suggesting deposition as bioherms, though no identification of faunal elements can be made from the available data. Irregular masses of dark chert occur in the limestone, suggests association with siliceous sponges. Low porosity in the limestone is indicated by neutron and density logs run in wells in the MSFC area, indicating likely occlusion of original pore space due to compaction, cementation, and growth of chert nodules and masses.

Deposition of the lower Fort Payne limestone lithofacies as bioherms is also suggested by an isopach map (plate 8), showing the thickest areas trending in a general northwesterly direction across the central part of RSA. This area of relatively thick limestone abruptly pinches out to the north; in the southern part of the arsenal the unit maintains a relatively consistent thickness of about 4-5 feet except for a small area of greater variation south of MSFC in the Wheeler Lake area. North of the limit of the facies shown in plate 8, very thin beds (generally less than a foot thick) of shaly limestone in the lowermost Fort Payne possibly constitute coeval sediments but are not mapped as part of the facies in the interpretation presented in this report. Buildups of carbonate sediments along subtle sea floor topographic features such as high areas or shelf breaks, interpretations well-documented in geologic literature for similar limestone deposits, is suggested by the overall thickness trend of the Fort Payne Chert and Maury Formation (plate 7). In particular, the area demonstrating the thickest lower Fort Payne limestone facies development at RSA roughly coincides with the area of

relatively thin (150 feet or less) Fort Payne-Maury, perhaps indicating the area was once a low-relief sea floor platform. There does not, however, appear to be any well-defined structural feature on the present-day configurations of the top of the Chattanooga Shale (plate 2) or top of the Fort Payne Chert (plate 3) supporting this interpretation. Uplift of the Nashville dome likely significantly altered paleo structural features, rendering detection difficult. Additional work, especially regarding petrology and paleontology, is necessary to better define and delineate the hypothesis offered here.

Above the basal Fort Payne limestone facies is a cherty carbonate interval of generally higher shale content, including some beds that appear to grade to calcareous and/or cherty shale. This shaly carbonate lithofacies forms the bulk of the interval described by early workers as comprising the typical cherty carbonate rocks of the Fort Payne, especially in those interpretations favoring a relatively thin Fort Payne Chert. Ranging to about 70 feet thick (plate 9), the shaly carbonate facies is commonly medium to dark greenish-gray but can appear irregularly banded due to lighter colored, slightly purer carbonate strata interbedded with darker, shale and/or dark colored chert. Rocks in this facies are commonly thin bedded, with some intervals having a laminated appearance on optical televiewer logs. As seen in optical logs, most of the impure limestone beds are wackestones with crinoid stems and plates and other fossil particles scattered in a matrix of finer lime mud and clay. Chert content of this facies is highly variable, and chert can occur in nodular form and as irregular beds, suggesting a biogenic origin. Due to higher shale content, increased natural gamma radiation is evident in this facies, compared to the basal Fort Payne limestone beds. Some wells, however, display relatively high gamma ray response in the lower part of the unit but show gradual decline in natural gamma radiation in the overlying portion of this facies, indicating overall decrease in clay content upward and increase in proportion of carbonate and/or chert. Many beds of this lithofacies are probably dolomitic, as indicated by slightly higher average density log measurements made in MSFC wells compared to carbonate beds of the middle to upper Fort Payne Chert and Tuscumbia Limestone.

The shaly carbonate facies is thickest across the southern part of RSA and thins to less than 10 feet in the northern part of the arsenal. The area with high rates of thinning to the north, shown on plate 9, is roughly coincident but somewhat north of the limit of the underlying limestone facies (plate 8). There is also significant thinning of the shaly carbonate facies in the

southeastern part of RSA, occurring in approximately the same area as the thinner Fort Payne-Maury interval. Also notable for the southeastern part of RSA is a general inverse relationship of thickness patterns of the shaly carbonate facies and the underlying limestone facies. Furthermore, as will be shown and discussed later, in many wells there is also an inverse thickness relationship of the shaly carbonate facies with the overlying facies. Also evident, is an area of thick shaly carbonate facies that appears to trend northwesterly along the axis of the topographic trend of Madkin Mountain. In a very general sense, this area of RSA displays structural nosing on top of the Chattanooga Shale surface. The significance of these trends is not well understood but suggests relationships among geologic structure, sedimentary depositional environments, and/or sources of sediments.

Following probable conditions of relatively high turbidity during the initial phase of deposition of the shaly carbonate lithofacies, there was a general decrease in influx of terrigenous clastic material. A likely silica source for development of abundant chert in these strata are abundant siliceous sponges that inhabited early Mississippian seas of the region. In a few wells, thin, discontinuous limestone beds similar in appearance to the lower Fort Payne "boundstone" facies described previously occur in the middle to upper part of this facies, suggesting relatively brief or localized return to periods and conditions conducive to bioherm development.

Lying above the shaly carbonate facies is a carbonate interval in the middle to upper part of the Fort Payne Chert, here termed the "middle carbonate facies", comprised primarily of a gradational sequence of limestone and dolomite beds that demonstrate general progressively upward decreasing shale and chert content and generally upward increasing grain-size sorting. The interval is for the most part lighter colored than the underlying shaly carbonate facies, though some dark colored beds are interbedded with light colored limestone and dolomite beds, especially in the lower part of the sequence. Beds in the lower part of the facies are commonly greenish-gray to medium brownish-gray whereas strata in the upper part are more commonly light gray to light brownish-gray.

Bedding in the lower part of the sequence is commonly very irregular, locally displaying sharp contacts of individual beds and cross cutting relationships suggestive of action by currents or soft sediment deformation. Furthermore, variability of dip within the facies shown on televiewer logs suggests deposition in higher energy marine environments than those

of the underlying facies; some dip patterns in the upper part of the facies indicate possible crossbedding.

Chert content is variable within the facies, but there is an overall decrease in silica content compared to the underlying facies and a general decrease in chert content upward within the sequence. Some of the “cleaner” (typically light colored, low gamma ray response) limestone beds display numerous stylolites, especially in the upper part of the facies. These lighter colored limestone beds are similar in appearance to some intervals in the Tuscumbia Limestone, except for overall higher chert content in the Fort Payne beds.

The middle carbonate lithofacies generally contains a higher percentage of coarser grained material than the underlying shaly carbonate facies. Disarticulated crinoids, sponges (?), shells – brachiopods and bivalves (?), and other unidentified calcareous and/or cherty bioclastic material are common in the facies. Fossil fragments are commonly more distinctive in the lower part of the facies due to the overall darker color of the matrix and generally larger size of the fossil material in the lower beds, likely owing to greater preservation in lower energy depositional environments and thus less disarticulation and abrasion. Though grain size cannot be determined from available data, limestone beds in the upper part of the facies appear to be bioclastic packstones to grainstones, comprised principally of sand-sized carbonate grains. In many wells and especially in the lower part of the sequence, bioclastic material appears vaguely thrombolitic, suggesting algae and/or cyanobacteria may have aided in early sediment binding or that some grains may be intraclasts reworked from previously deposited or nearby biostrome areas. Some of the larger “grains” seen on optical televiewer logs are likely small chert nodules.

The middle carbonate facies comprises the thickest lithofacies of the Fort Payne Chert in most of the wells at RSA. Thickness ranges from greater than 130 feet in the west-central part of RSA to less than 70 feet in localized areas in the eastern and southern part of the area (plate 10). In the northern part of RSA, this facies constitutes nearly the entire formation present, though thickness values in that area are not displayed on the isopach map because the upper part of the facies has been removed by erosion except for well RS1486 (sec 8, T. 4 S, R. 1 W.). Thickness of the middle carbonate facies is generally inversely related to the thickness of the underlying shaly carbonate facies similar to that mentioned previously for the shaly carbonate facies and underlying lower limestone. In some wells, especially in the southern part

of RSA, the contact of the middle carbonate interval with the underlying facies appears sharp, whereas data from most wells show a gradational contact.

Natural gamma response in the middle carbonate facies is commonly low, especially in uppermost beds indicating overall low clay content, though there are some distinct thin shale beds locally. The Central Dye Trace Report (2004) described a locally persistent marker bed (termed the “A” marker) with distinctive low gamma ray response at or near the top of this facies, and this horizon was tentatively utilized as the top of the Fort Payne Chert by the authors of the report. Correlation of this interval of light colored limestone beds across much of RSA is made herein through the use of gamma ray logs (where log scales permit) and/or using televiewer logs and local use of density and neutron logs. It is considered here to mark the top of the middle carbonate facies of the Fort Payne.

The uppermost lithofacies of the Fort Payne Chert in the RSA area is comprised principally of cherty, slightly argillaceous limestone and some thin shale beds. This interval is transitional with the overlying Tuscumbia Limestone. The contact with the underlying middle carbonate facies described above is, in most wells, fairly distinct due to overall darker color of the upper carbonate facies, darker and more abundant chert than contained in the immediately underlying beds, and more distinct shale beds. Some limestone beds of this facies are similar in appearance to the carbonate grainstones prevalent in the Tuscumbia Limestone, but the Fort Payne beds are commonly darker colored and contain more chert than limestone beds of the overlying Tuscumbia. Large chert nodules are present in this Fort Payne facies; some nodules appear to be coalesced into irregular strata or “beds” of chert. Suspected origin of the silica is biogenic (large individual and/or colonies of siliceous sponges). Gamma ray log response in this interval is generally higher than the upper part of the underlying middle carbonate facies due to numerous thin shale partings and beds and overall higher clay content, but locally some limestone beds of this facies are very “clean”, suggestive of well-washed and well-sorted grainstones.

Thickness of the upper carbonate facies ranges from 9 to 38 feet at RSA (plate 11). The facies reaches its maximum thickness in the southeastern part of RSA, and in that area thickness appears to follow the familiar inverse relation with thickness of the underlying facies. Elsewhere, however, that relation does not appear valid, and thickness, for the most part, is relatively uniform across much of RSA. Some of the minor thickness variations are likely due

to the generally gradational and somewhat arbitrary nature of the upper contact with the Tuscumbia Limestone. The facies is absent in most of the northern part of RSA due to removal by erosion; however, well RS1486, located in the northeastern part of the arsenal, on the northern slope of Madkin Mountain, is interpreted to have penetrated a complete section of the upper carbonate facies.

Porosity and lithology interpretations from density and neutron logs

Density and neutron logs, available for wells in the MSFC area of RSA, are used to facilitate more accurate lithologic determinations and stratigraphic correlations, especially where utilized in conjunction with optical televiewer and gamma ray logs. In addition, density log measurements are commonly used to estimate porosity from calculations using known or assumed density values for matrix density where porosity is zero, assumed or known density of formation water, and geophysical log values in the intervals of interest. Where calibrated against rock of known porosity, lithology, and water content, neutron logs can also provide estimates of formation porosity as well. Deriving reasonable estimates of lithology and porosity are important not only in understanding the relationships of these parameters but also in providing useful means of estimating aquifer storage and supporting estimates of groundwater flow. Available neutron and density log data from MSFC test wells suggest the presence of intervals of porous rock and/or strata of similar lithologic characteristics. In particular, and as mentioned by COLOG in descriptions of geophysical logs run in MSFC, a potentially porous interval of relatively low neutron counts and somewhat lower density occurs within the middle Fort Payne carbonate lithofacies described above.

Unavailable, however, are independent petrophysical measurements of porosity or bulk mineralogy, commonly measured from rock core samples, necessary to calibrate the available geophysical well log data and visual observations. Moreover, because the resolution (scale) of the gamma ray logs run in conjunction with neutron and/or density logs in the MSFC wells is very low, the usefulness of the suite of logs for lithology and porosity determination is diminished. Neutron logs run in the MSFC wells provide only a qualitative indicator of porosity, due to the absence of calibration. Despite these limitations, ranges of reasonable estimates of lithologic composition and porosity for the Fort Payne Chert are herein determined and discussed below, especially for the “porous” interval mentioned above.

Porosity estimates from density log data are dependent not only upon the bulk density measured by the logging tool, but also on matrix density, whether measured or assumed. Matrix density is dependent on the mineral content of the rock and cementation considerations. Common usage of density logs to estimate porosity are based on assumption of 2.71 grams per cubic centimeter (g/cc) matrix density for limestone or 2.65 g/cc matrix density for sandstone if actual matrix density is unknown. While the bulk density of pure, nonporous limestone is commonly assumed to be that of calcite, 2.71-2.72 g/cc, the mineralogical composition of the Fort Payne Chert and Tuscumbia Limestone, presently poorly known, can significantly affect actual bulk density of particular strata. With addition of minerals commonly found in the Fort Payne Chert, such as quartz (density 2.65-2.66 g/cc), dolomite (density 2.80-2.99 g/cc), pyrite (density 4.95-5.17 g/cc), anhydrite (density 2.89-3.05 g/cc) and clays, such as illite (density 2.60-3.0), chlorite (density 2.60-3.22), and glauconite (density 2.20-2.80 g/cc) the matrix density of rocks comprising geologic formations can vary significantly. Density of fresh formation water is commonly assumed to be 1.0 g/cc, and salinities must be considerably higher than those present in formation waters generally encountered at the relatively shallow depths in the study area in order to use a higher water density in porosity calculations.

Gamma ray, neutron, and density logs from well MW00-101D, for example, in MSFC provide data useful in identification of potentially porous intervals and derivation of estimates of bedrock porosity in proximity to the borehole (plate 12). Coupled with the optical televiewer log, these logs also aid in lithology interpretation. The interval from 94.3 to 99.9 feet, here designated “interval A”, demonstrates relatively low neutron log counts, comparatively low bulk density, and low natural gamma radiation, characteristics indicative of comparatively porous rock with low shale or clay content. Porosity estimates from several depths in the zone of interest and assumed matrix densities used in the calculations are shown in plate 12 and table 1; standard limestone matrix density of 2.71 g/cc and dolomite matrix density of 2.87 g/cc are used in calculations for comparative purposes. Assumption of a matrix density of 2.80 g/cc or greater seems warranted based on the overall density measurements of the Fort Payne Chert shown on the long-spaced density curve. Short-spaced density measurements are used to correct for possible inaccuracies inherent in borehole rugosity, and the display of the long-spaced density curve reflects any correction needed. Optical televiewer and well site core descriptions available for this well suggest interval A is comprised primarily of cherty

dolomitic limestone that is somewhat porous. Calculated porosity values using 2.80 g/cc matrix density range from approximately 4 percent to more than 13 percent (table 1).

Depth	ϱma	ϱbulk	ϱma-ϱbulk	ϱf	ϱma-ϱf	Porosity
95	2.71	2.60	0.11	1.00	1.71	0.0643
96	2.71	2.64	0.07	1.00	1.71	0.0409
97	2.71	2.72	-0.01	1.00	1.71	-0.0058
98	2.71	2.55	0.16	1.00	1.71	0.0936
99	2.71	2.80	-0.09	1.00	1.71	-0.0526
Depth	ϱma	ϱbulk	ϱma-ϱbulk	ϱf	ϱma-ϱf	Porosity
95	2.87	2.60	0.27	1.00	1.87	0.1444
96	2.87	2.64	0.23	1.00	1.87	0.1230
97	2.87	2.72	0.15	1.00	1.87	0.0802
98	2.87	2.55	0.32	1.00	1.87	0.1711
99	2.87	2.80	0.07	1.00	1.87	0.0374
Depth	ϱma	ϱbulk	ϱma-ϱbulk	ϱf	ϱma-ϱf	Porosity
95	2.80	2.60	0.20	1.00	1.80	0.1111
96	2.80	2.64	0.16	1.00	1.80	0.0889
97	2.80	2.72	0.08	1.00	1.80	0.0444
98	2.80	2.55	0.25	1.00	1.80	0.1389
99	2.80	2.80	0.00	1.00	1.80	0.0000

Table 1.—Comparison of porosity calculations of Fort Payne Chert at selected depths, well MW00-101D, using various matrix density values. Assumed matrix densities of 2.71 g/cc, 2.87 g/cc, and 2.80 g/cc (ϱma, matrix density; ϱbulk, bulk density from geophysical log; ϱf, fluid density).

Density logs from nearby wells, however, display significant difference in overall densities of the logged Fort Payne sections and serve to illustrate the need for caution in accepting log measurements without accurate petrophysical data or knowledge of conditions that can affect log readings. Wells MW00-102D and MW00-202D (plate 13), located approximately 2,850 feet apart and both less than one mile southeast of MW00-101D, show a very approximate but significant difference in average overall bulk density of 0.4 g/cc in the logged Fort Payne Chert sections (average density about 2.45 g/cc in MW00-102D and average density about 2.85 g/cc in MW00-202D). It is unknown whether this large density difference is

the result of difference in lithology at the two locations, difference in porosity, difference in borehole conditions, or due to log calibration issues. Assuming no major overall differences in lithology, borehole conditions, or log calibration, average porosity calculated in the lower density (2.45 g/cc) Fort Payne section logged in well MW00-102D is about 19%, while calculated average porosity for well MW00-202D (average density 2.85 g/cc) is less than zero (assuming matrix density of 2.80 for both wells). A difference in porosity of this magnitude is unlikely and probably indicates the necessity to assume significantly different matrix densities in calculations for each well if the logs are to be utilized for estimating porosity. Moreover, possible difference in porosity between the two wells indicated above by density logs appears to be contradicted by neutron log measurements from the two wells in correlative water-saturated intervals. For example, neutron log measurement for the upper 15 feet of the middle carbonate facies, shown on plate 13 as interval B, is about 5,700 counts per second (cps) in well MW00-102D, whereas the correlative interval in well MW00-202D displays a neutron -measurement of about 5,000 cps. Assuming similar shale content and borehole conditions, this difference appears to indicate higher porosity in well MW00-202D, the opposite of possible porosity difference calculated from density measurements. Interval A is also shown on the logs for comparison with the same interval on well MW00-101D discussed previously.

Also shown in plate 13 are density and neutron logs (along with gamma ray, caliper, drill bit size, and photoelectric absorption (PEF) measurements) run by Schlumberger Well Services through the Fort Payne Chert in petroleum test well P5893, located in the southeastern corner of the study area about 12 miles southeast of the MSFC wells. Photoelectric cross section measurements are used as indicators of lithology, especially where used in conjunction with other geophysical log parameters and/or rock samples. While porosity estimates shown by the logging company for well P5893 are dependent on the assumed matrix density (2.71 g/cc used by Schlumberger), it appears reasonable that porosity in the interval 300-330 feet is about 2-3 %, whereas porosity in the interval 330-350 is about 5-7%. Neutron measurements, commonly calibrated in petroleum logging applications and in this log, aid in porosity estimation as well as lithology determination. Also marked on the log for comparison is a matrix density of 2.87 g/cc (dolomite) which would result in higher porosity estimates from the density log. A higher matrix density may be appropriate for the interval 330-370 feet due to the neutron porosity curve reading to the left (higher) of the density porosity in that interval and

PEF measurements of approximately 2.5-3.0 barns/electron, both indicative of dolomite (Schlumberger, 1986). Limestone is interpreted in the interval 300-330 as indicated by higher PEF measurements than below and the closer tracking of porosity curves, but there are also some indications of the presence of quartz (presumably chert) where the neutron log tracks to the right of the density curve. Moreover, this well log likely represents a Fort Payne stratigraphic sequence similar to that found in the MSFC and southern RSA area – a thin lower interval of limestone (420-424 feet) overlain by shaly carbonate rocks (390-420 feet), which grades upward (370-390 feet) to clean carbonates (297-370 feet) that are in turn overlain by an interbedded shale and carbonate interval (252-297 feet). Thus well P5893 serves as independent calibration for geophysical log parameters estimated and/or interpreted from logs within RSA and lithofacies interpretations presented for the RSA area.

In summary, though different apparent porosity estimates can be made from density logs run in each well, depending on assumptions for matrix densities, it appears reasonable that porosity of the zone of interest in well MW00-101D is in the range of 2-5%. Assuming an average porosity of 2% for the approximate 160 foot thick Fort Payne Chert interval implies that more than one million gallons per acre may be stored in the aquifer. While the identification of flow zones and determination of flow estimates from hydrophysical logs and testing are critical for understanding groundwater flow, data from density, neutron, and other logs can aid in understanding aquifer storage.

Tuscumbia Limestone

The Tuscumbia Limestone is generally composed of a sequence of light-gray to light-brownish-gray coarse- to medium-grained bioclastic lime wackestones to grainstones, light-brownish-gray granular cherty calcareous dolomite, and randomly distributed light-gray and white nodular chert (Holler, 1975; Raymond and others, 1988). Tuscumbia Limestone ranges in thickness from about 140 to 180 feet in the study area; the formation is about 170 feet thick in wells in the southern part of RSA. In most of the study area the Tuscumbia Limestone has been partially or completely removed by erosion. Data from 7 wells that penetrated the complete Tuscumbia stratigraphic section, all located in the southern part of the study area, are the primary sources used in this investigation to characterize the overall aspects of the formation in the subsurface. Numerous other wells provide data relevant to the lower part of the Tuscumbia,

especially regarding the geologic contact of the formation with the underlying Fort Payne Chert.

The contact of the Fort Payne Chert with the Tuscumbia Limestone is considered conformable and gradational (Thomas, 1972; Raymond, 2003). In some wells the two formations appear to interfinger, commonly resulting in somewhat arbitrary determinations of the Fort Payne-Tuscumbia contact. Many of the criteria used by Raymond (2003) to distinguish the Fort Payne from the Tuscumbia in outcrops in the Madison quadrangle are difficult to apply in this investigation of subsurface geology, though some features observed in optical televiewer and other logs are consistent with Raymond's observations and interpretations. The widely used field criteria of Thomas (1972) used to distinguish the two formations, including rock color; chert content, color, and type (bedded vs. nodular), are applied where possible in this study. From the available subsurface data, Tuscumbia Limestone is distinguished from the Fort Payne Chert (taken as whole) by the general decrease in the amount of chert, especially dark colored, bedded chert; an overall decrease in shale in the Tuscumbia; and a greater proportion of lighter colored bioclastic limestone (as interpreted from borehole optical televiewer logs). The general appearance of Tuscumbia Limestone is more uniform and consistent than the more heterogeneous and complex Fort Payne Chert. Tuscumbia Limestone displays apparent overall increased grain sorting, though limestone intervals are separated by generally thin but discreet shale beds in the Tuscumbia stratigraphic sequence, especially in the lower half of the formation. Lighter color of chert and limestone comprising the Tuscumbia as compared to the Fort Payne is consistent with descriptions by Thomas (1972) and Holler (1975). Other observations of herein identified Fort Payne Chert consistent with distinguishing criteria listed by previous authors are the occurrence of large crinoid columnals and plates; very light colored, rounded features that are likely quartz geodes or chert nodules; and bedded chert. Stylolites are common in Tuscumbia Limestone seen in optical televiewer logs and less common in Fort Payne lithologies, except, as noted previously, for limestone beds in the upper part of the Fort Payne middle carbonate facies and in other relatively thin intervals within other Fort Payne facies.

Tuscumbia outcrops locally display lenticular bedding and/or crossbedding, and some features visible in optical logs in RSA wells are suggestive of crossbedding in some Tuscumbia intervals. Moreover, dip angle and direction data shown on optical and acoustic televiewer logs

from Tuscumbia beds are consistent with interpretation of crossbedding. Indications of crossbedding are far less common in the Fort Payne Chert.

Tuscumbia Limestone penetrated by wells in the southern part of RSA consists of a general sequence of limestone and shale beds that display characteristics of a shoaling-upward carbonate sequence, accompanied by sporadic influxes of terrigenous clastic sediments, primarily clay. The lower part of the sequence consists of limestone with a significant number of shale beds and overall higher clay content as evidenced by the overall higher natural gamma radiation than the upper part of the formation. While influx of terrigenous clastic sediments was introduced into the area during deposition of the upper part of the Tuscumbia, the influx of these sediments generally decreased, though the uppermost part of the sequence displays an increase in shale beds. Overlying the Tuscumbia is the Monteagle Limestone, comprised largely of oolitic carbonate sand beds, indicating definite shoaling conditions in Mississippian seas in the region.

FLOW INTERVALS FROM RSA WELL DATA

Data regarding groundwater flow in the study area have been collected for many years by government research agencies such as GSA and USGS; regional, municipal, and local water supply entities; companies contracted by RSA; and other workers. These data document both regional and localized patterns of groundwater flow. Data collected for RSA primarily by various contractors have recently been made available to GSA for analyses. These data, including water level, dye trace, geophysical and hydrophysical well logs, and pumping test data, document complex groundwater flow regimes in RSA and surrounding areas. For purposes of analysis, a subset of some of these data, primarily from geophysical and hydrophysical logs recorded by COLOG, are discussed in this section of the report.

Groundwater flow intervals from wells representing 77 well locations in the RSA area are herein chosen for analyses by GSA. One location, RS1155, includes data from a shallow well drilled nearby, (RS1154), that provides shallow bedrock data not available in RS1155, and together these boreholes are treated herein as one well. In addition, 3 “off post” test wells in northern Morgan County are included. In each borehole a number of geophysical and hydrophysical measurements were made by RSA contractors, and details regarding construction, measurements, analyses, and methodologies are documented in their reports. Reliance is made on the work performed by RSA contractors for the analyses presented in this

investigation. Primary criteria for choosing wells were: penetration of the stratigraphic section to the Chattanooga Shale or older rocks (to insure penetration of the entire Mississippian section), availability of geophysical logs or other data to define the stratigraphy penetrated by each well, and availability of groundwater flow data. Following stratigraphic analyses to determine formation contacts and lithofacies boundaries in each well, each flow interval was assigned to a stratigraphic interval, or in some cases multiple stratigraphic intervals. Data were compiled into spreadsheets, and summaries of the data are presented and discussed here. Only one well, RS1413, is a “dry hole” with no flow intervals identified, but that well is included in some analyses for statistical purposes.

In the 77 test wells utilized, a total of 436 groundwater flow intervals were identified, tested, and analyzed by RSA contractors. All of the flow intervals identified are in the Paleozoic rock stratigraphic section. Groundwater flow was measured from hydrophysical logs as flow occurring under natural (non pumping) conditions, reported by COLOG as “ambient” flow, and as flow under stressed (pumping) conditions, reported as “interval specific flow rate during pumping”. Of the 436 groundwater flow intervals identified, only 27 intervals had ambient flow greater than or equal to 1.0 gallon per minute (gpm) with 25.1 gpm maximum (included are flows designated by COLOG as negative, i.e. flow from the fluid-filled borehole into the aquifer). For many intervals, ambient flow was determined to be less than 0.1 gpm, including a significant number with flow insufficient to be measured over the testing periods. Depths of the 27 larger flow intervals range from 39.5 feet to 314.4 feet.

The number of flow intervals per well ranges from 0 to 12, with a median of 5 intervals, and a mean of 5.66. Data regarding the number of flow intervals with depth below ground level are displayed graphically in fig. 1. It should be noted that for each borehole, hundreds of “features” (in some wells more than 1,000) were commonly identified by RSA contractors on geophysical, optical televiewer, and acoustic televiewer logs, but only a small number of the features were typically found to have measureable groundwater flow. Features identified as flow conduits include bedding planes exhibiting a wide range of width; small cavities to large cavernous features; and fractures, mostly at high angles relative to bedding. Enlargement of bedding plane conduits has likely occurred due to dissolution of carbonate rocks (limestone and dolomite) and in some instances by removal of clay along and within shale beds and partings.

Many flow intervals display some combination of the above features, probably indicating complex relationships and long histories of development.

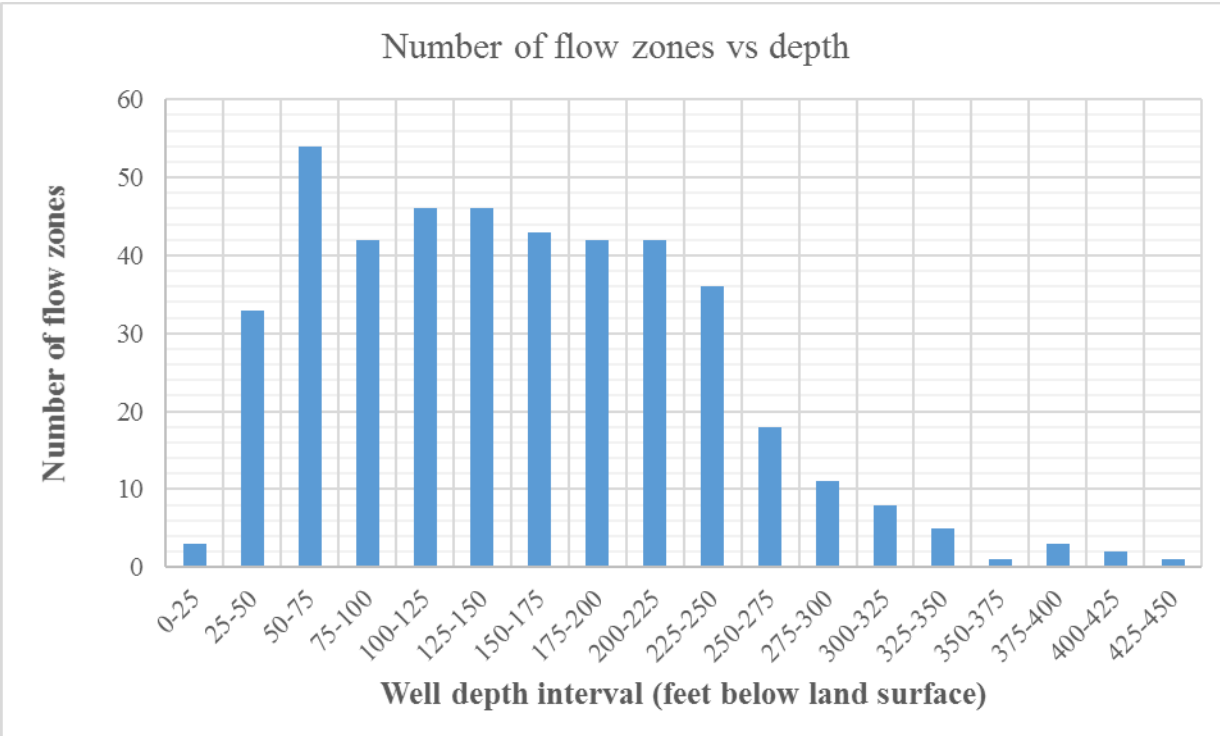

Figure 1.—Number of flow intervals vs. depth below ground surface for 77 test wells in RSA.

Expressed as a percentage of total well depth, the depth of flow intervals range from slightly less than one quarter (23.9%) to total depth (100%). Forty-eight (48) of the 77 wells (62.3%) exhibit flow intervals occurring over more than 90 percent of total drilled depth, while only 16 wells have flow intervals over less than 75 percent of the total depth, i.e. relatively shallow flow zones.

Groundwater flow intervals were recorded in every stratigraphic interval penetrated (table 2), but the numbers are heavily skewed toward the Fort Payne Chert and secondarily, the Tuscumbia Limestone, probably because those are the two main stratigraphic intervals penetrated by the RSA boreholes. Obviously where the Tuscumbia has been removed by erosion (or compose remnants as regolith materials), primarily in the northern part of RSA, there are no recorded flow intervals for that formation. Conversely, flow intervals that occur in

the younger Monteagle Limestone are in areas of higher elevation, primarily in the southern part of RSA, where that formation is present. Somewhat surprising are the number of flow intervals that occur in rocks below the Fort Payne Chert – 60 (not counting 6 flow zones shown in table 2 that are primarily in units below the Fort Payne but which include some lowermost Fort Payne beds). Of the 27 flow zones with higher ambient flow discussed previously, 14 are in the Tuscumbia Limestone, 11 in the Fort Payne Chert, 1 in the Fort Payne Chert and Maury Formation, and 1 in the Chattanooga Shale.

Stratigraphic interval	Number of flow intervals
Mm	8
Mm/Mt	1
Mt	119
Mt/Mfp	1
Mfp	241
Mfp/Maury	1
Maury	2
Mfp/Maury/Dc	3
Mfp/Maury/Dc/Sb	2
Maury/Dc	4
Maury/Dc/Sb	2
Dc	12
Dc/Sb	9
Sb	27
Sb/Os	1
Os	3
Total	436

Table 2.—Number of flow intervals in stratigraphic intervals penetrated by 77 boreholes in RSA area (Mm: Monteagle Limestone; Mt: Tuscumbia Limestone; Mfp: Fort Payne Chert; Maury: Maury Formation; Dc: Chattanooga Shale; Sb: Brassfield Limestone; Os: Sequatchie Formation).

Because past researchers have concluded that regolith (overburden) thickness and the occurrence of large-capacity groundwater flow zones in Madison County are related (Christensen and others, 1975), flow interval data from the 77 wells used in this study were

analyzed for possible relationships to regolith thickness. This research, however, shows that for a given well location there appears to be no clear relation between the number of flow zones and thickness of regolith in each well (fig. 2) nor is there an unambiguous relationship between depth of the deepest flow interval in a well vs thickness of regolith (fig. 3). However, large bedrock cavities are more common at shallow depths, likely due to increased karst development, probably concomitant with regolith development. In addition, the 27 zones of higher ambient flow discussed previously are more likely to be found at shallow depths (fig. 4), but thickness of regolith is not necessarily a factor with respect to flow magnitude of these zones (fig. 5). It may be possible, however, that a positive relationship exists between thickness of regolith and development of flow zones along bedding surfaces in bedrock areas adjacent to thick areas of overburden. Most of the flow intervals identified and tested in RSA are features that can be characterized as “bedding plane conduits” or “bedding plane fractures”, substantiating the well-known dominance of horizontal groundwater flow versus vertical flow in hydrogeologic flow regimes in sedimentary rocks. Development of karst such as exists in much of the study area with accompanying development of localized areas of thick regolith may provide groundwater flow pathways such as where poorly consolidated regolith lies lateral to or near bedding planes in bedrock or adjacent to stratigraphic intervals with remnant primary porosity or porosity developed during some phase of the strata’s diagenetic history (e.g. partial dissolution of early calcite cements). Not discounted, however, are the contributions of high angle fractures to groundwater flow and development of karst in the study area. Fractures and other high angle features are identified by COLOG for most of the RSA test wells, and the relative contributions of vertical and horizontal flow regimes discussed for each well.

Data from 59 wells in the RSA area for which identifications and thicknesses of the lithofacies of the Fort Payne Chert could be made were analyzed for possible relationships between the number of flow zones and facies. (Two additional wells, RS1803 and MWOO-505D, penetrate the entire Fort Payne Chert but groundwater flow data were unable to be collected due to borehole conditions). These data, shown in table 3, provide no clear indication of preferred distribution of flow zones within a particular facies, though flow intervals in the upper carbonate facies and shaly carbonate facies are slightly more prevalent than would be expected by comparison to average thicknesses; conversely, flow zones in the middle carbonate facies and lower limestone facies are somewhat underrepresented, based on average

thicknesses. Examples of depth intervals of flow zones in relation to facies are illustrated in the stratigraphic cross sections (plates 4, 5, and 6). Although there are significant flow intervals in the Tuscumbia Limestone, the small number of RSA area wells (7) that penetrate the entire formation preclude meaningful analysis of the data.

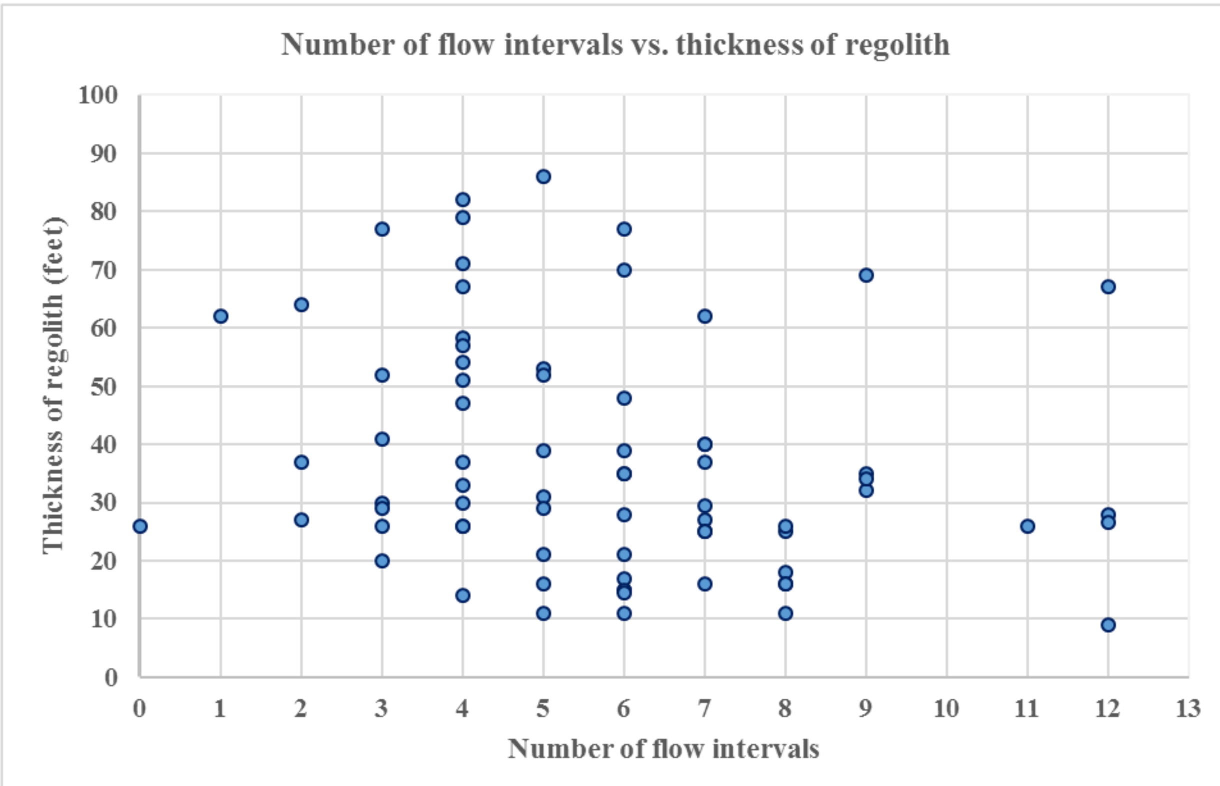

Figure 2.—Number of flow intervals per well relative to thickness of regolith at each location (each data point represents 1 of 73 RSA wells).

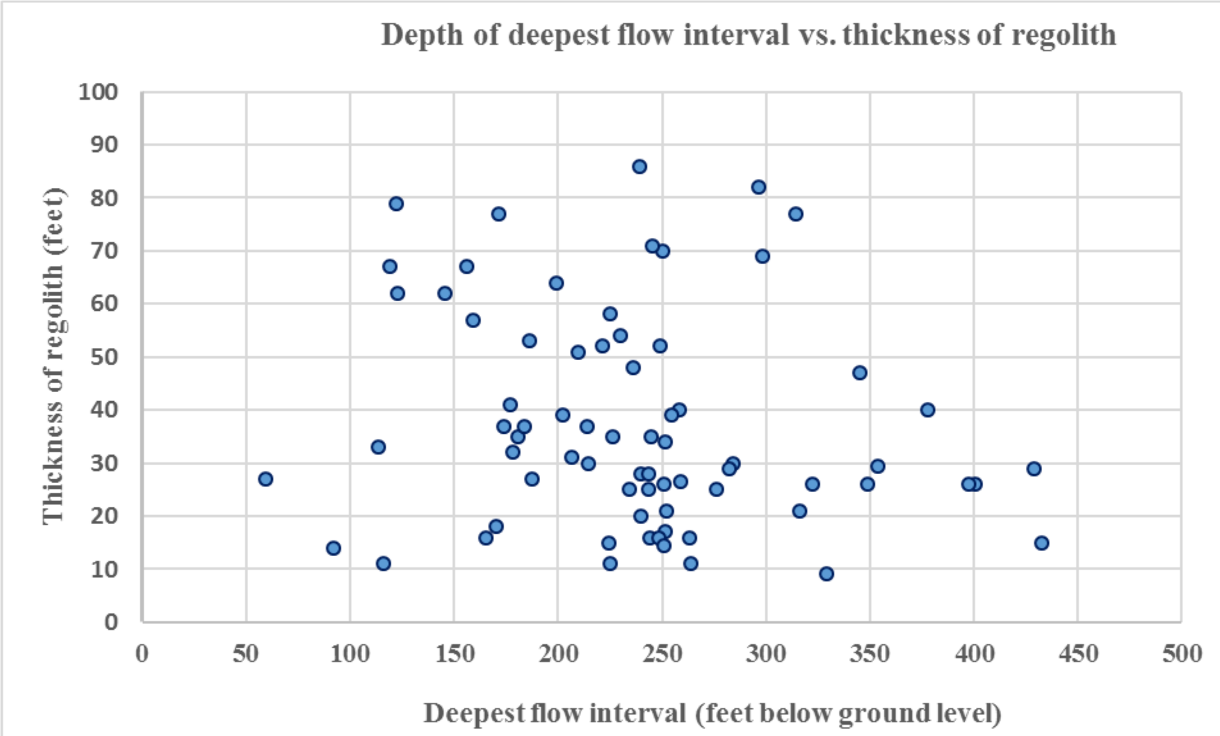

Figure 3.—Depth of deepest flow interval per well relative to thickness of regolith at each location (each data point 1 of 72 wells in RSA area).

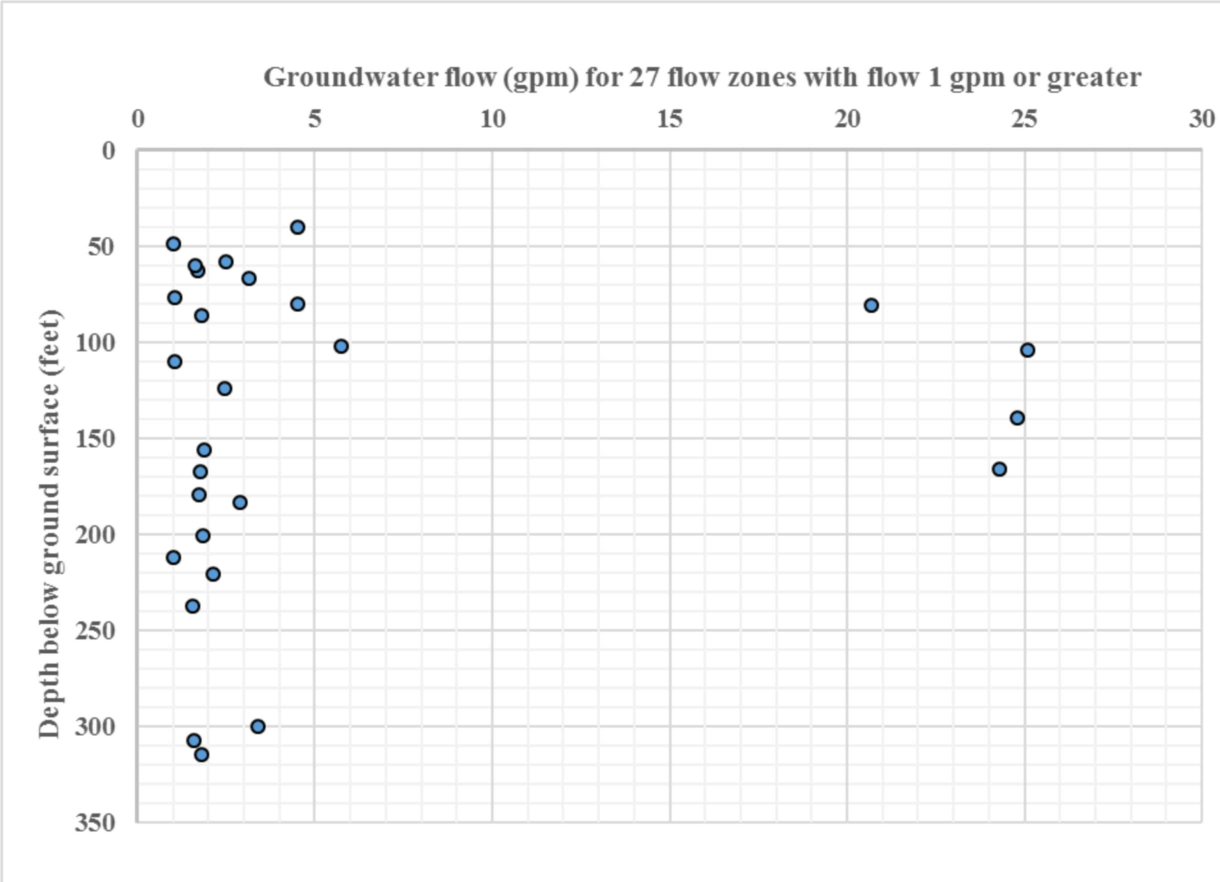

Figure 4.—Relationship of magnitude of groundwater flow (ambient) to depth below ground surface for 27 largest flows of 436 flow zones in RSA wells.

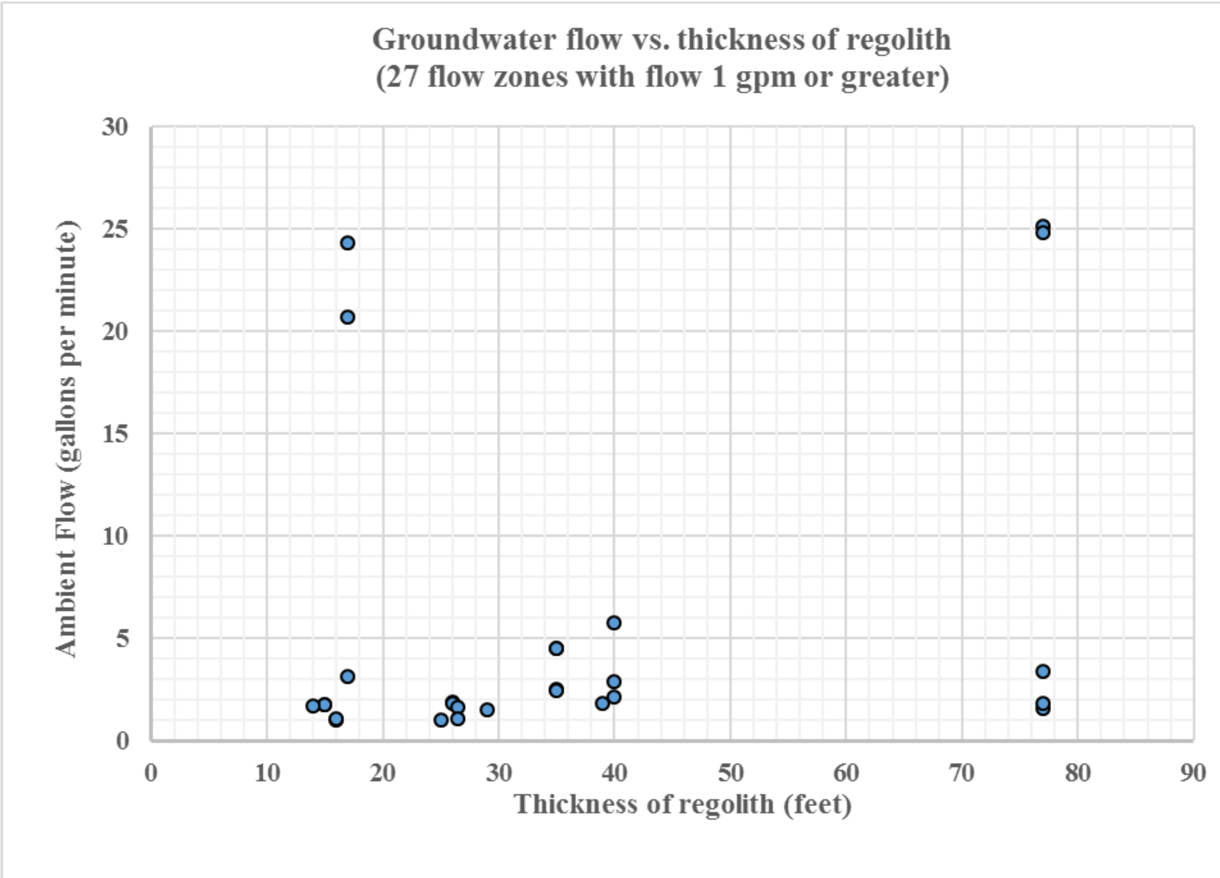

Figure 5.—Relationship of magnitude of groundwater flow (ambient) to thickness of regolith for 27 largest flows of 436 flow zones in RSA wells.

Table 3.—Relationship of Fort Payne Chert facies thickness (feet) and number of flow zones.

Well (RSA well number)	Thickness of facies and number of flow zones ( )				Thickness of Fort Payne Chert (Mfp)
	Upper carbonate facies	Middle carbonate facies	Shaly carbonate facies	Lower limestone facies	
RS1802	15.7 (0)	71.1 (0)	67.0 (0)	5.4 (0)	159.2
MWOO-202D	17.7 (0)	97.6 (2)	43.7 (0)	5.2 (0)	164.2
MWOO-507D	11.6 (0)	93.2 (0)	41.2 (0)	11.4 (0)	157.4
RS1678	20.9 (0)	70.0 (0)	55.0 (0)	11.3 (0)	157.2
RS1183	18.0 (0)	84.0 (3)	30.8 (0)	10.6 (0)	143.4
RS1164	38.0 (1)	65.7 (0)	57.4 (1)	4.0 (0)	165.1
RS1844	15.0 (0)	77.2 (0)	57.5 (0)	5.3 (1)	155.0
RS1846	14.2 (0)	90.0 (0)	48.0 (0)	5.2 (0)	157.4
MWBK-103D	17.1 (0)	123.7 (3)	18.9 (0)	0 (0)	159.7
MWOO-103D	13.2 (0)	100.8 (1)	36.7 (1)	10.6 (0)	161.3
MWOO-402D	15.8 (0)	121.7 (4)	22.7 (0)	0 (0)	160.2
MWOO-502D	17.0 (1)	99.1 (1)	35.5 (0)	10.1 (0)	161.7
RS1966	14.9 (0)	98.9 (0)	36.6 (0)	9.4 (0)	159.8
RS1967	15.9 (1)	100.6 (1)	35.3 (0)	10.8 (1)	162.6
RS1486	17.0 (0)	127.9 (2)	4.3 (0)	0 (0)	149.2
RS1806	13.6 (0)	93.1 (2)	39.5 (1)	4.5 (0)	150.7
RS1773	14.7 (0)	93.2 (2)	43.2 (0)	4.9 (0)	156.0
RS1184	23.0 (1)	75.3 (1)	36.5 (1)	11.6 (0)	146.4
RS1158	28.3 (0)	83.7 (1)	48.0 (1)	4.0 (0)	164.0
RS1845	14.1 (0)	96.6 (1)	41.1 (0)	5.4 (0)	157.2
RS1809	27.3 (0)	83.2 (0)	44.2 (0)	4.0 (0)	158.7
MWOO-203D	16.7 (1)	96.0 (3)	40.0 (1)	6.6 (0)	159.3
MWOO-204D	16.8 (1)	95.6 (2)	35.6 (0)	9.6 (0)	157.6
MWOO-602D	18.2 (0)	90.4 (1)	43.5 (3)	10.1 (0)	162.2
RS1718	31.8 (1)	82.2 (1)	42.3 (0)	4.5 (0)	160.8
RS1676	21.3 (0)	82.8 (1)	39.3 (2)	15.4 (0)	158.8
RS1185	27.3 (1)	85.2 (2)	42.6 (2)	3.0 (0)	158.1
RS1195	14.0 (0)	87.0 (0)	27.3 (3)	25.0 (1)	153.3
MWOO-101D	15.8 (1)	92.2 (1)	42.8 (1)	9.6 (0)	160.4
MWOO-102D	16.5 (0)	93.7 (2)	40.8 (1)	7.9 (0)	158.9
MWOO-205D	14.1 (1)	85.4 (1)	56.7 (2)	4.7 (0)	160.9
MWOO-212D	12.9 (0)	89.9 (1)	45.1 (4)	7.1 (0)	155.0
MWOO-506D	18.1 (1)	88.1 (3)	43.8 (0)	10.3 (0)	160.3
RS1742	21.9 (0)	81.7 (4)	45.5 (0)	10.7 (0)	159.8
RS1741	19.7 (1)	91.7 (0)	28.1 (0)	8.0 (0)	147.5

Table 3. (continued)—Relationship of Fort Payne Chert facies thickness (feet) and number of flow zones

Well (RSA well number)	Thickness of facies and number of flow zones ( )				Thickness of Fort Payne Chert (Mfp)
	Upper carbonate facies	Middle carbonate facies	Shaly carbonate facies	Lower limestone facies	
RS1521	20.4 (0)	79.3 (1)	39.9 (1)	12.1 (0)	151.7
RS1512	20.6 (1)	80.6 (2)	42.9 (1)	9.7 (0)	153.8
RS1807	21.5 (0)	84.1 (1)	47.0 (0)	4.9 (0)	157.5
RS1186	19.6 (1)	88.0 (3)	37.3 (1)	1.1 (0)	146.0
RS1187	16.6 (1)	85.9 (2)	31.1 (2)	12.0 (0)	145.6
RS2239	21.8 (0)	91.8 (1)	40.4 (1)	4.9 (0)	158.9
RS1155 and 1154	15.7 (0)	69.1 (2)	65.2 (1)	5.4 (0)	155.4
MWOO-104D	14.8 (0)	98.4 (2)	43.2 (1)	0.4 (0)	156.8
RS1804	15.7 (1)	82.2 (2)	51.2 (0)	5.0 (0)	154.1
RS1513	18.5 (1)	94.1 (3)	34.6 (0)	2.8 (0)	150.0
RS1534	23.3 (1)	74.7 (1)	52.1 (4)	4.0 (0)	154.1
RS1847	15.5 (0)	88.8 (0)	42.8 (1)	5.2 (0)	152.3
RS1161	31.1 (0)	79.3 (1)	47.1 (2)	4.3 (0)	161.8
RS1519	17.5 (1)	75.2 (0)	51.7 (2)	2.5 (0)	146.9
RS1520	18.1 (1)	84.1 (3)	39.2 (1)	7.7 (0)	149.1
RS1522	16.6 (0)	80.3 (1)	43.3 (2)	9.0 (0)	149.2
RS1808	20.4 (0)	87.6 (1)	44.2 (1)	5.0 (0)	157.2
RS1182	18.4 (1)	102.1 (4)	33.1 (2)	2.0 (0)	155.6
RS1166	24.1 (1)	77.3 (4)	42.0 (2)	20.2 (1)	163.6
RS1152	17.3 (0)	79.1 (2)	59.0 (4)	4.7 (0)	160.1
RS1805	9.0 (0)	84.2 (0)	52.0 (1)	4.5 (0)	149.7
RS1739	21.9 (1)	71.0 (2)	62.1 (2)	4.6 (0)	159.6
RS2241	22.5 (1)	73.8 (1)	50.9 (1)	5.0 (0)	152.2
RS1149	14.1 (0)	97.1 (4)	41.6 (1)	5.0 (0)	157.8
Average facies thickness (feet)	18.7	88.1	42.5	6.9	156.2
Percent of average Mfp thickness	11.97	56.37	27.23	4.43	100.0
Total flow zones (Mfp facies)	24	89	58	4	175
Percent of Mfp zones (175)	13.71	50.86	33.14	2.29	100.0

SEISMIC DATA EVALUATION

High resolution seismic data were acquired by geophysical consultants on RSA, consisting of 47.7 miles of land and 43.9 miles of water borne data. The initial 13.56 miles of data were processed using shear waves and compressional waves. The remainder were processed using compressional wave data only. Interpretations of the data included identification of a limited number of karst features and a large number of north-south trending normal faults, which form a dense pattern of horsts and grabens across the entire RSA. Review of these data and interpretations by GSA personnel indicate a number of concerns regarding the interpretation of the data. A dense pattern of relatively deep, large throw normal faults in the geologic environment of north Alabama is questionable. Existing geologic literature and structural mapping done by GSA during this investigation indicates that geologic structure is subtle, related to gentle slopes on the south flank of the Nashville Dome. The interpretation of seismic data acquired on RSA indicates a much less passive geologic environment. Although fracturing and associated karst development in north Alabama is well documented, relatively large throw faulting is doubtful. GSA recognized a number of seismic pitfalls that may cause misinterpretations including, karst features and fracture zones misinterpreted as faults, multiples, probably related to near surface karst features, changes in directions of lines along roads from strike to dip that create false structural features, if not accounted for in processing, too few tie lines that would confirm interpretations, and omission of critical well data that would add subsurface control. Reinterpretation of seismic was beyond the scope of the GSA investigation, however, a cursory evaluation indicates that seismic reprocessing and interpretation may be warranted.

GROUNDWATER MOVEMENT

Aquifers in the Redstone Arsenal area are semi-confined or unconfined due to shallow depths and absence of confining layers that isolate groundwater from the water table and the land surface. Therefore, groundwater movement is controlled by gravity as water moves from topographic highs to topographic lows where it discharges as springs or to surface-water bodies as base flow. Groundwater movement in the Tuscumbia Limestone and Fort Payne Chert is preferential with respect to direction and velocity, related to the geometry and connectivity of fracture systems. Previous investigations by the GSA in similar hydrogeologic settings in the Tennessee Valley found that groundwater flow velocities in the Tuscumbia Limestone/Fort

Payne Chert aquifer in the Muscle Shoals area of Colbert County varied from 65 to 1,800 feet per hour (Chandler and Moore, 1991) and in the Huntsville area from 50 to 142 feet per hour (Baker, 2002).

Groundwater movement in karst terrains is primarily determined by two techniques; tracer surveys and water surface mapping using water levels from wells, springs, and streams. Campbell (1997) reported that at least 10 dye trace surveys were performed by the Geological Survey of Alabama in the Redstone Arsenal area. Seven tracer surveys using dyes and optical brightener were performed by Rheams and others (1992) in the southern Madison County area. Detections of dye in this area indicate water movement from 2,000 feet to 4.7 miles to the south and southwest. Five of these surveys were performed in the Matthews and Bobcat Caves areas. However, no dye was detected in the caves. Campbell (1997) reported other surveys where dye was detected in Bobcat Cave after introduction into the subsurface less than 300 meters south from the cave, indicating local recharge and northward water movement.

Two previous water level maps (Rheams and others, 1992 and Mann and others, 1997) indicate water movement generally southward to the Tennessee River with local westward water movement in areas of relatively high elevation near the eastern boundary of the arsenal. Water level mapping for this investigation indicates that Redstone Arsenal is located in a ground-water sink with the Tennessee River as the downgradient boundary.

GROUNDWATER LEVELS

The Tuscumbia Limestone and Fort Payne Chert aquifer in the project area is primarily unconfined or partially confined due to shallow depths and absence of confining layers that isolate groundwater from the water table and the land surface. Therefore, groundwater movement in these aquifers is controlled by gravity as water moves from topographic highs to topographic lows where it discharges as springs or to surface-water bodies. However, wells constructed in deeper strata may be confined and under hydraulic pressure.

Groundwater movement in Paleozoic aquifers is preferential with respect to direction and velocity, related to the geometry and connectivity of fracture systems. Directions of groundwater movement can be determined from contour maps of water level elevations. There are three types of water level maps: Water table maps, potentiometric maps, and hybrid water table-potentiometric maps. Water table maps show the configuration of groundwater under water table conditions (unconfined). These water levels generally mimic land surface

topography. Water levels used in the preparation of these maps can be from shallow wells, streams, springs, sink holes, and caves. Potentiometric maps represent groundwater levels in confined aquifers. Since confined groundwater is under hydraulic pressure, the elevation of the potentiometric surface is defined as the level that water rises in properly cased wells. The third type of water level map, common in the Tennessee River watershed, is a hybrid, composed of a mixture of water table, semi-confined, and/or confined water levels (Cook and others, 2009). Additionally, the process of developing water level maps will aid in determining the presence of multiple aquifers, degrees of confinement, and separate ground water flow paths within karst aquifers. For the purpose of this project, focus has been on establishing local groundwater flow directions and determining if groundwater levels indicate the presence of multiple aquifers or disconnected flow paths within the aquifer.

A water table map was prepared using groundwater level data collected by GSA from all available wells (approximately 88 wells) in the project area surrounding the Redstone Arsenal and using a portion of the groundwater level data provided by RSA (approximately 145 RSA wells) measured within and along the RSA boundary. Wells outside of the RSA were identified from GSA well records and public water supply (PWS) utility records. The groundwater levels measured by GSA were collected during the first quarter of 2014. These measurements were collected using standard steel measuring tapes or pressurized airline measurement devices. The PWS wells were measured by PWS personnel using automated measuring equipment or pressurized airline measurement devices. The water levels were adjusted for mean sea level elevation, plotted according to location, and contoured to delineate lines of equal groundwater level (plate 14).

GSA analyzed all groundwater level data provided by Redstone Arsenal, this included multiple years of data collected at various times of the calendar year. Due to natural seasonal fluctuations in groundwater levels only the RSA groundwater level data from the first quarter of each year could be used to compare with the data collected by GSA. To further ensure 2014 groundwater levels could be compared and mapped with groundwater data from previous years, precipitation data were collected from 62 weather observation stations in Madison, Limestone, and Morgan Counties for the first quarter of 2011, 2012, 2013, and 2014. It was determined that RSA groundwater data from the first quarter of 2012 is the best data set to use with the 2014 groundwater data collected by GSA. The 2012 RSA data has the highest number of wells

measured with the greatest spatial distribution, with precipitation rates relatively similar to the first quarter of 2014. The project area received approximately 16.95 inches of precipitation during the first quarter of 2012 compared to approximately 12.26 inches of precipitation for the first quarter of 2014. Once the data set was chosen, groundwater levels were adjusted for mean sea level elevation, plotted according to location along with the GSA wells, and contoured to create a groundwater level map. Fifty foot contour intervals were used to contour a majority of the project area and are represented by solid black lines on the water table map (plate 14). To determine groundwater flow direction in areas with lower relief 25 foot contour intervals were used and are represented by dashed black lines. Within the RSA boundary 5 foot contour intervals were needed north of Wheeler Lake due to the relatively flat terrain and low hydraulic gradient, these contour intervals are represented by solid blue lines on the USGS quadrangle base map (plate 14) and by solid *orange* lines on the elevation map base map (plate 14).

The project area boundary is the surface-water drainage boundary for Indian Creek. The boundary was selected because it includes all of RSA and is also a regional groundwater divide. Groundwater level mapping within the project boundary indicates that the general flow of groundwater in the Tuscumbia and Fort Payne aquifers is in a southerly direction eventually discharging to the Tennessee River (plate 14). However, intricate groundwater flow patterns occur throughout the area where complex surface and groundwater drainage patterns are influenced by highly variable topographical relief (plate 14). The primary groundwater flow direction is southward to the Tennessee River; however, groundwater may flow any direction depending on topography.

Along the northwestern boundary of the project area, which is the northern boundary of the surface water drainage basin, groundwater flows to the north and northwest and eventually discharges to Buffalo Branch and Limestone Creek. It should be noted that the water does not continue along its northern trajectory once it discharges to the surface streams, and the surface streams eventually turn southward and discharge to the Tennessee River. Along the northeastern boundary of the project area, groundwater flows to the north and northeast and eventually discharges to Beaverdam Creek. Again, the water does not continue its northern trajectory once it discharges to the surface streams, and the surface streams eventually turn southward and discharge to the Tennessee River. As indicated earlier, topography has strong local influence on directions of both groundwater and surface water flow. This is exhibited in

the northern part of (plate 14), where groundwater levels and topography delineate the project area boundary and drainage divide for Indian Creek. Elevation changes of 300 to 400 feet are common with relief of nearly 700 feet in some areas. Hills are often conical in shape, with steep gradients that force groundwater to migrate locally in all directions over relatively short distances (plate 14). Regional groundwater flow is southward in the project area and is controlled by topography related to the Tennessee River Valley and structural geologic dip related to the Nashville Dome (plate 14).

The central portion of the project area is relatively flat; groundwater and surface water flow is southward across the Redstone Arsenal northern boundary (plate 14). One exception, an area of high relief located on the north border of RSA, has a local influence on the ground water flow (plate 14). Water-level data indicates the presence of an area of low hydraulic gradient the south-central portion of the project near the center of Redstone Arsenal, immediately south of Wheeler Lake. Groundwater levels stabilize at around 560-570 feet of elevation. Average groundwater levels continue to be found in the 560-570 feet range across the Wheeler Lake area and into the southern part of the Redstone Arsenal. As mentioned previously, contour intervals of 5 feet were used to delineate lines of equal groundwater levels in the areas with low relief and low hydraulic gradient within RSA. This has exposed a local groundwater low that is associated with the structural low discovered while mapping the top of the Chattanooga Shale (plate 2). The structural and groundwater low are located in the west-central part of RSA southeast of Bobcat Cave. GSA recommends additional exploration and research in this area of RSA. The groundwater levels in the southeast and south-central portion of the Redstone Arsenal increase to over 600 feet near the southern border of the project area, creating a reversal in the hydraulic gradient. This anomalous northward flow in most likely the result of an ancient natural levee in the northern flood plain of the Tennessee River (plate 14). Groundwater and surface water on the north side of the ancient natural levee flow north and discharge to Wheeler Lake or one of its tributaries and ultimately discharge into the Tennessee River (plate 14).

As stated earlier in the report, another important aspect of the RSA groundwater project was to characterize areas with multiple aquifers and areas with vertical hydraulic connectivity of multiple stratigraphic intervals. The occurrence of multiple aquifers indicates confinement that influences groundwater flow paths, movement and distribution of

contaminants, and the hydrologic character of base flow that impacts stream flows and habitats. Hydraulic connectivity of multiple stratigraphic intervals indicates connected fracture zones and karst intervals that also influence groundwater flow paths, groundwater quality, and stream base flow.

GSA analyzed RSA groundwater level data collected in 2012, to compare groundwater levels from wells with varying screen elevations. GSA compared groundwater level data from wells in close proximity with similar surface elevations and utilized groundwater level data that was collected by RSA on the same day or within no more than one week between sample dates and with no significant precipitation events during the collection dates. GSA analysis revealed a number of areas on the RSA where groundwater levels indicate additional aquifers shallower and deeper than the Tuscumbia Limestone and Fort Payne Chert. The analysis also identified areas where deep wells have similar groundwater levels to shallow wells. The following includes examples of areas on the RSA with multiple aquifers and areas with possible confinement.

Wells Z-RS1413D and Z-RS1415 are located 10 feet apart, near the northeast RSA boundary (plate 15 and fig. 6). Well Z-RS1413D is screened in the Brassfield Limestone from 155 to175 feet below land surface (bls) (457.2 to 437.2 feet mean sea level elevation (MSL)) and well Z-RS1415 is screened in the Fort Payne Chert from 68 to 78 feet bls (541.6 to 531.6 feet MSL). The groundwater level measured by RSA personnel on 1/26/2012 in well Z-RS1413D was 129 feet bls (483 MSL) and in well Z-RS1415 was 3.7 feet bls (605.7 MSL). This indicates that local confinement in the deep Brassfield Limestone and shallower Fort Payne Chert effectively segregate groundwater levels in these stratigraphic intervals.

Wells N115-RS432, N115-RS419, and N115-RS468 are located approximately 110 feet apart in the south-central part of RSA, near the Tennessee River (plate 15 and fig. 7). Well N115-RS432 is screened in the Tuscumbia Limestone from 197.5 to 207.5 feet bls (457.2 to 427.2 feet MSL). Well N115-RS419 is screened from 58.6 to 74.8 feet bls (697.7 to 681.5 feet MSL) and well N115-RS468 is screened from 42.5 to 52.5 feet bls (720.7 to 710.7 feet MSL), both in the regolith or alluvium. The groundwater level measured by RSA personnel on 1/27/2012 in well N115-RS432 was 169.9 feet bls (584.6 feet MSL). Water levels in wells N115-RS419 and N115-RS468 were 42.5 feet bls (713.8 ft MSL) 53.7 feet bls (710 feet MSL),

respectively. In this part of RSA, groundwater in the shallow regolith or alluvium is separated from the deeper Tuscumbia Limestone.

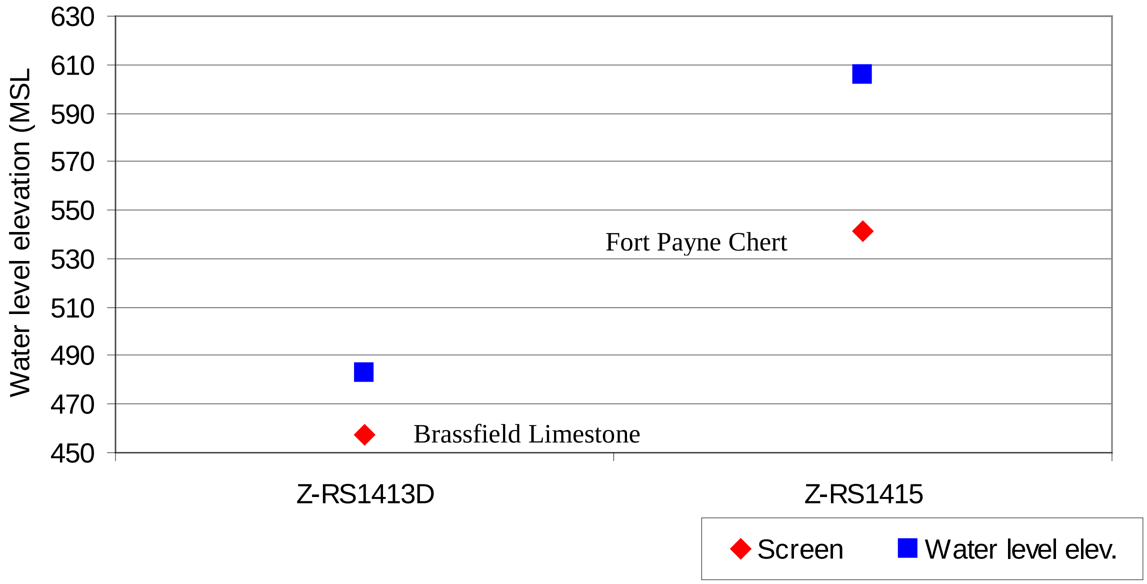

Figure 6.—Wells in close proximity in separate stratigraphic units with isolated water levels.

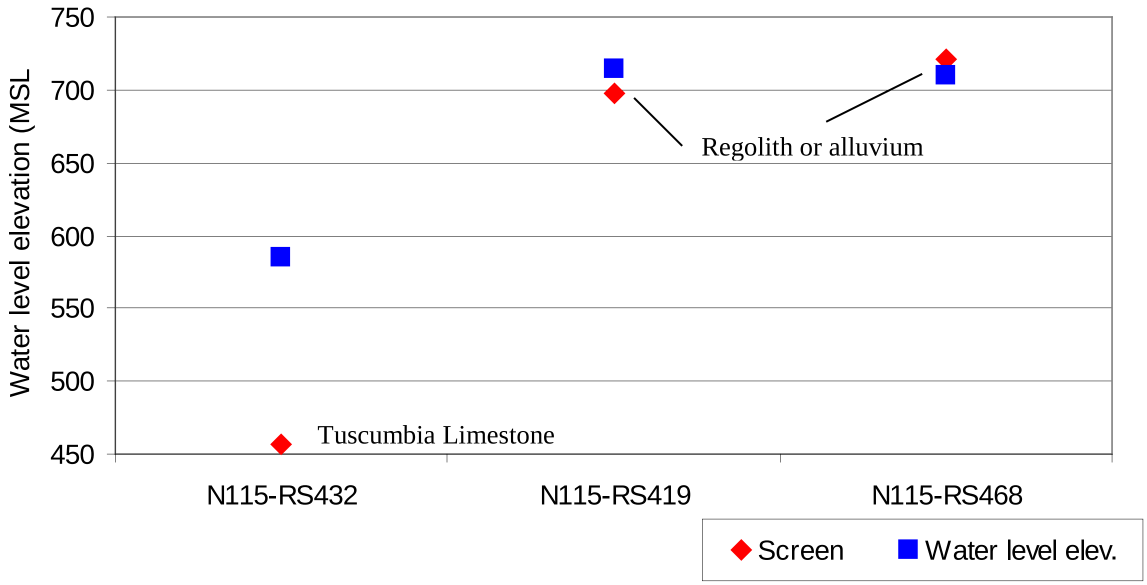

Figure 7.—Wells in close proximity in separate stratigraphic units with isolated water levels.

Wells Z-RS1487a, Z-RS1416, and Z-RS1418 are located about 1800 feet apart in the north-central area of the RSA (plate 15 and fig. 8). Well Z-RS1487a is screened in the Fort Payne Chert from 68 to 78 feet below land surface (bls) (569.4 to 559.4 feet MSL), Well Z-RS1416 is screened in the Fort Payne Chert from 36 to 56 feet bls (602.7 to 582.7 feet MSL), and well Z-RS1418 is screened in the Fort Payne Chert from 82 to 92 feet bls (547.1 to 537.1 feet MSL). Groundwater level measurements by RSA personnel were as follows: on 1/28/2012 in well Z-RS1487a, water level 100.2 feet bls (537.2 feet MSL); in well Z-RS1416, measured 1/31/2012, water level 44.5 feet bls (639.2 feet MSL); and in well Z-RS1418, measured 1/31/2012, water level 35.5 feet bls (593.6 feet MSL). Although the wells are in close proximity and constructed in the same stratigraphic interval, water levels are highly variable, indicating that water bearing zones are isolated. This indicates that the geographic extent of fracture zones and karst development in the Fort Payne Chert in this area is relatively small.

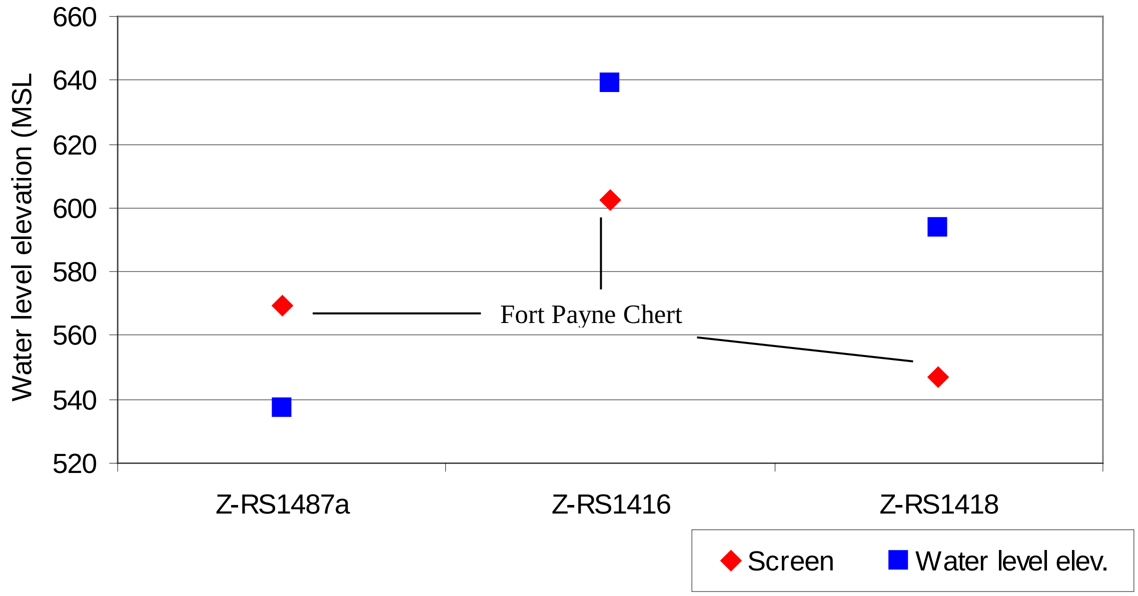

Figure 8.—Wells in close proximity constructed in the same stratigraphic unit with isolated water levels.

The designation given to a nest of two wells located in the south-central portion of the RSA project area south of Buxton Road is 152-RS1804 (plate 15). Individual wells are designated as D and S. Well 152-RS1804D is screened in the Fort Payne Chert from 178 to 188 feet below land surface (bls) (399.3 to 389.3 feet MSL). Well 152-RS1804S is screened in the Tuscumbia Limestone from 98.5 to 103.5 feet bls (478.8 to 473.5 feet MSL). Groundwater levels measured by RSA personnel on 1/31/2012 were 19.1 feet bls (558.2 feet MSL) for well 152-RS1804D and 64.2 feet bls (513.1 feet MSL) for well 152-RS1804S. The difference in water levels in the two wells is 45.1 feet, indicating that local confinement in the deeper Fort Payne Chert and shallower Tuscumbia Limestone effectively segregate groundwater levels in these stratigraphic intervals.

The following are examples of areas on RSA where stratigraphy and water levels indicate a lack of confinement and possible connection of fractures and karst features. Z-RS1232 is the designation given to a nest of three wells located in the central part of the RSA project area (plate 15 and fig. 9). Individual wells are designated as D, I, and S. Well Z-RS1232D is screened in the Fort Payne Chert at 130 to 150 feet bls (449 to 429 feet MSL). Well Z-RS1232I is screened at the contact between the Tuscumbia Limestone and Fort Payne Chert at 92 to 112 feet bls (478 to 458 feet MSL). Well Z-RS1232S is screened at the contact between the Monteagle Limestone and the regolith at 36 to 46 feet bls (543 to 533 feet MSL) and in the Monteagle Limestone at 61’ to 71 feet bls (518 to 508 feet MSL). Groundwater levels measured by RSA personnel on 1/29/2012 were: 10.5 feet bls (568.5 feet MSL) in well Z-RS1232D; 10.7 feet bls (568.3 feet MSL) in well Z-RS1232I; and 11.8 feet bls (567.2 feet MSL) in well Z-RS1232S. The change in groundwater elevation from the deepest screen setting Z-RS1232D to the shallowest Z-RS1232S is 1.3 feet, which indicates that in this area there is hydraulic connection between four stratigraphic units from near land surface to at least 150 feet bls. This has significant implications for base flow and movement of contaminants in the subsurface.

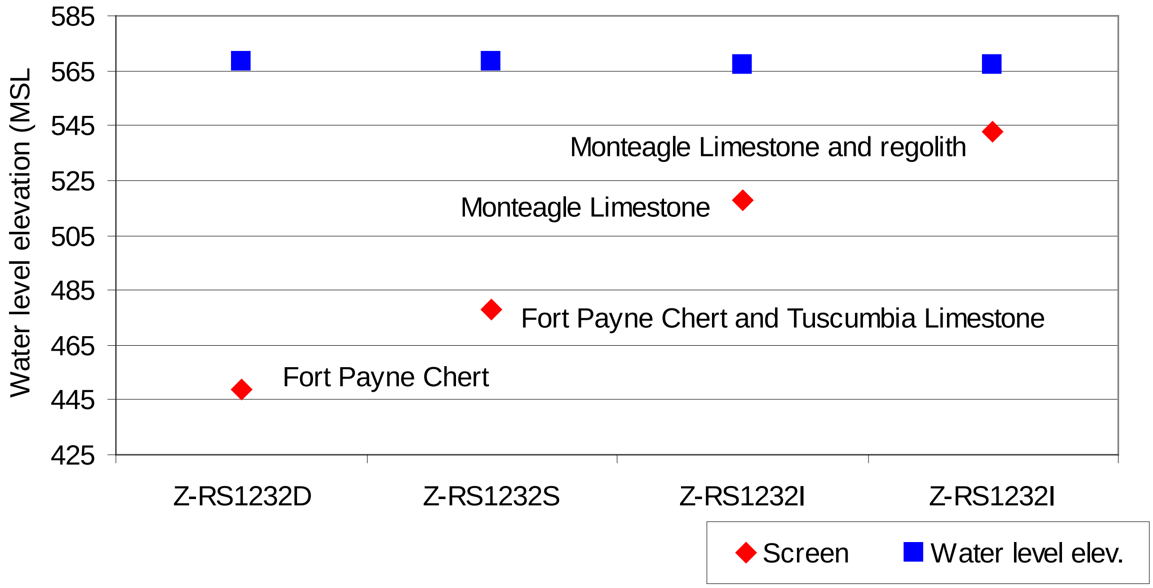

Figure 9.—Groundwater levels in wells constructed in four stratigraphic units indicating hydraulic connection.

Z-RS1231 is the designation given to a nest of three wells located in the east-central portion of the RSA project area east of Patton Road (plate 15 and fig. 10). Individual wells are designated as D, I, and S. Well Z-RS1231D is screened in the Fort Payne Chert from 126.5 to 146.5 feet below land surface (bls) (435.1 to 425.1 feet MSL). Well Z-RS1231I is screened at the contact between the Tuscumbia Limestone and Fort Payne Chert from 85 to 100 feet bls (476.6 to 461.6 feet MSL). Well Z-RS1231S is screened in the Tuscumbia Limestone from 29 to 39 feet bls (532.6 to 522.6 feet MSL) and at 56 to 66 feet bls (505.6 to 495.6 feet MSL) also in the Tuscumbia Limestone. Groundwater levels measured by RSA personnel on 1/28/2012 were 2.2 feet bls (559.4 feet MSL) for well Z-RS1231D, 1.7 feet bls (559.9 feet MSL) for well Z-RS1231I, and 2.6 feet bls (559 feet MSL) for well Z-RS1231S. The difference in water levels in the three wells is 0.9 feet, indicating that all three stratigraphic units penetrated in the wells are hydraulically connected.

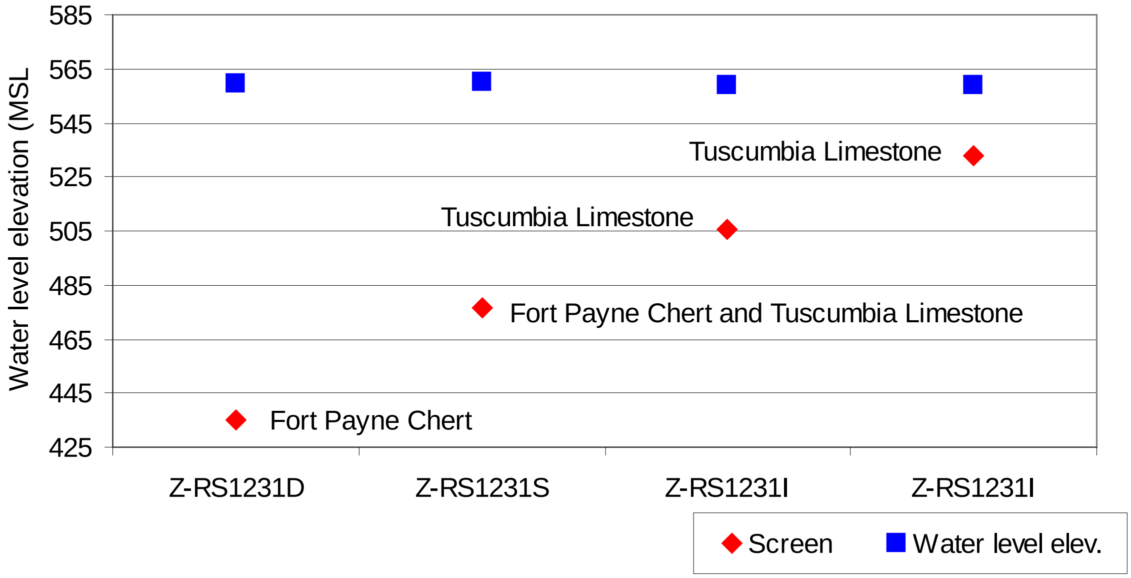

Figure 10.—Groundwater levels in wells constructed in four stratigraphic units indicating hydraulic connection.

Wells K-RS1182 and K94-RS574 are located 4000 feet apart on the eastern side of the RSA project area east of Bluejay Road (plate 15 and fig. 11). Well K-RS1182 is screened in the Brassfield Limestone from 248 to 258 feet bls (318.4 to 308.4 feet MSL) Well K94-RS574 is screened in the Tuscumbia Limestone from 40.3 to 50.3 feet bls (536.3 to 526.3 feet MSL). Groundwater levels measured by RSA personnel on 1/28/2012 were 3.3 feet bls (563.1 MSL) in well K-RS1182 and 19.8 feet bls (556.8 MSL) in well K94-RS574. Similar water levels in these wells indicate that hydraulic connection is likely.

The complexity of groundwater flow paths becomes apparent when the spatial distribution of wells, stratigraphic characteristics at well sites, and resulting groundwater levels are evaluated (plate 15). This evaluation identified local areas of hydraulic confinement and other areas where unconfined water levels occur to depths of at least 300 feet MSL, although a well-defined geographic pattern was not observed. One problematic issue is attempting to compare groundwater levels collected at time periods separated by weeks, months, or even years. Shallow karst aquifer systems, such as the Tuscumbia Limestone and Fort Payne Chert react quickly to precipitation and display widely variable levels. GSA recommends the installation of automated groundwater level and precipitation monitoring equipment in selected wells that displays and records groundwater level data in near real time.

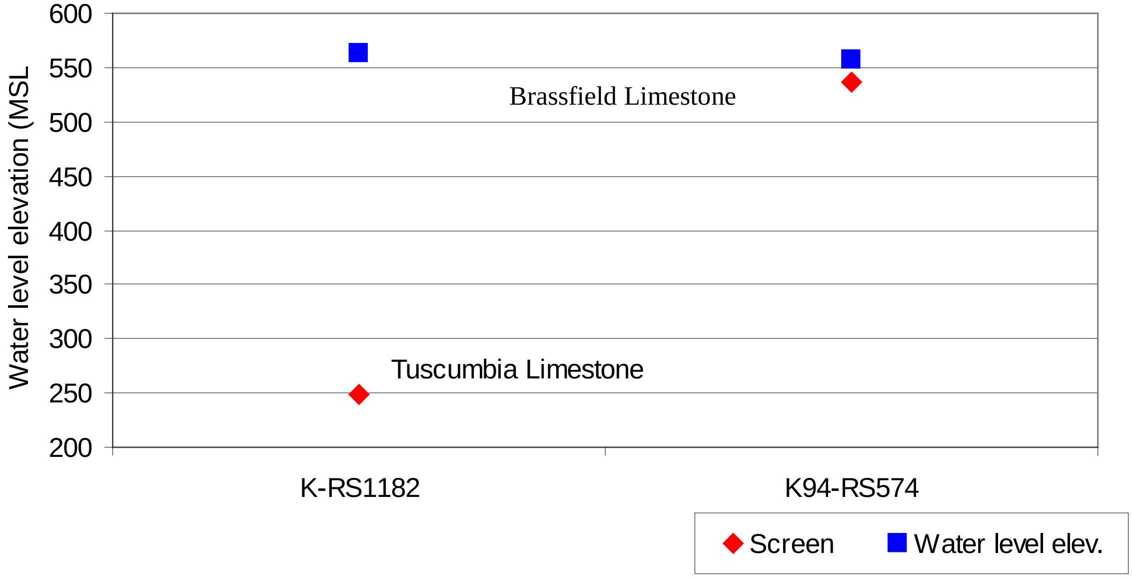

Figure 11.—Similar groundwater level elevations in wells constructed in different stratigraphic units indicating hydraulic connection.

GROUNDWATER RECHARGE AND SURFACE-WATER/GROUNDWATER INTERACTION

Unlike the Coastal Plain where groundwater can move long distances from recharge areas in aquifers that exceed depths of 2,500 feet (Cook, 2004) or the Valley and Ridge and Piedmont where large, complex faults create pathways for movement of recharge over long distances (Cook, 1997), groundwater recharge in much of the Tennessee River watershed is local. Recharge rates are controlled by a number of factors including porosity and permeability, which in Paleozoic aquifers are mainly secondary and characterized by leached fossils, fractures, and solution development. Most carbonate rocks in the Tennessee River watershed are indurated and thoroughly cemented, resulting in limited intergranular porosity. Therefore, 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). Recharge, originating from precipitation, may also be influenced by drought, seasonal precipitation, land surface slope, surface drainage, and the 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 developed for estimating recharge, including development of water budgets, measurement of seasonal changes in groundwater levels and flow velocities. However, equating average annual base flow of streams to groundwater recharge is the most widely accepted method (Risser and others, 2005) for estimating groundwater flow in and near aquifer recharge areas. 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 Tennessee Valley is about 54 inches per year (in/yr) (Southeast Regional Climate Center, 2012). Precipitation is distributed as runoff, evapotranspiration, and groundwater recharge. Sellinger (1996) described the various pathways of precipitation movement that compose stream discharge and determine the shape of a stream hydrograph (fig. 12). However, for the purposes of this report, the pathways of precipitation movement shown in figure 15 are combined into two primary components: runoff and base flow. Runoff is defined as the part of total stream discharge that enters the stream from the land surface. Kopaska-Merkel and Moore (2000) reported that average annual runoff in southeast Alabama varies from 18 to 22 in/yr, depending on the location of the subject watershed with respect to topography and geology. Base flow 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.

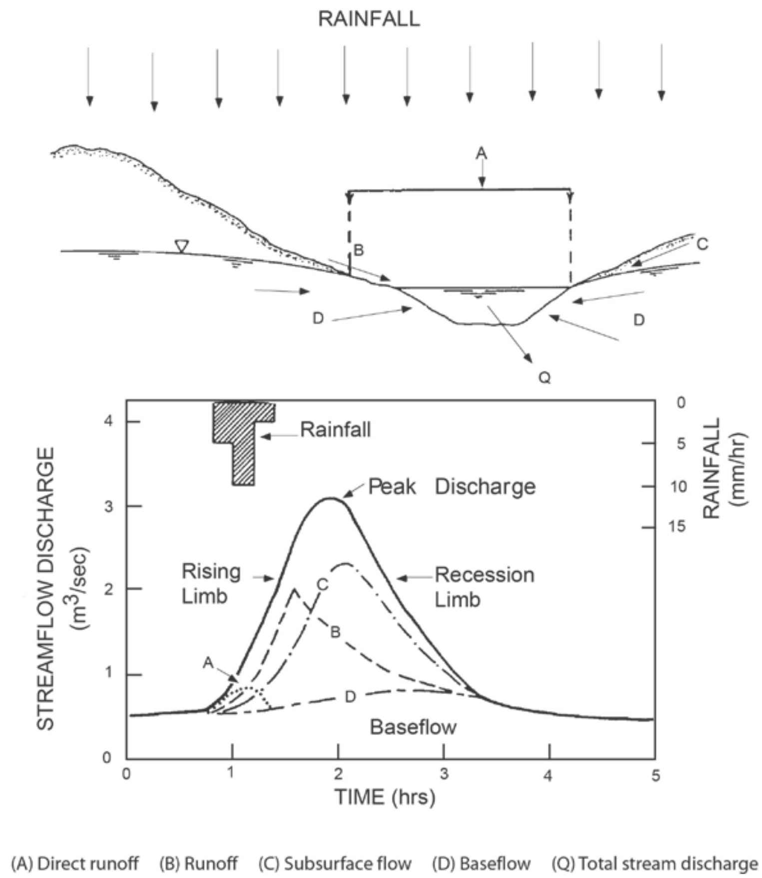

Figure 12.—Diagram and stormflow hydrograph illustrating pathways of movement of rainfall into stream (modified from Sellinger, 1996).

Separating runoff and base flow 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 requires stream hydrograph data over two or more consecutive years. Base flow 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 $0.1Q_0$.

Previous comparisons of automated hydrograph separation programs with the Meyboom graphical method indicated that the Web-based Hydrograph Analysis Tool (WHAT) automated hydrograph separation program (Purdue University, 2004; Lim and others, 2005) produced the most equitable results. Based on the general agreement between the Meyboom method and the WHAT program, input values were determined and base flow was estimated by the WHAT program. Baseflow output from the WHAT program was used to calculate recharge rates and volumes of groundwater recharge for unconfined and partially confined aquifers.

An estimate of recharge was determined for the RSA area using two hydrograph separation techniques on discharge data from Indian Creek. Discharge data for Indian Creek near Madison (USGS site 03575830) was used in the recharge evaluation. The period of record for Indian Creek began on December 10, 2008. Results indicate that groundwater recharge is about 6.9 inches per year (Cook and others, 2009). This equates to about 94 million gallons of groundwater per year being recharged to the aquifer system on RSA. Since the Fort Payne Chert and Tuscumbia Limestone aquifers that underlie the arsenal are mostly unconfined, this groundwater discharges locally to streams and forms the base flow component of discharge that provides stream flow and supports aquatic habitats during times of drought. Base flow for Indian Creek at Redstone Arsenal is on average, about 258,000 gallons per day or about 24 cubic feet per second.

LAND USE

Land use is directly correlated with water quality, hydrologic function, ecosystem health, biodiversity, and the integrity of streams and wetlands. When natural landscapes are subjected to urbanization, impervious surfaces such as roads, sidewalks, parking lots, and buildings cover previously porous soils and replace vegetation. Increases in imperviousness lead to higher rates and volumes of storm water runoff which can have devastating effects on local hydrology and biology including: increased flooding and streambank erosion, degraded aquatic habitat, reduced groundwater recharge, and increased surface-water pollution.

Watersheds within the Redstone Arsenal recharge area are dominated by urban development, including large areas covered by impervious surfaces.

Land use classification within the Redstone study area was calculated using the Multi-Resolution Land Characteristics (MRLC) National Land Cover Database (NLCD) raster datasets from 1992, 2001, and 2011. This tri-decade land-use characterization approach was employed to show land-use changes that have direct impacts on water quality in the area. The 1992 NLCD is a 21-class land cover classification system that has been applied consistently across the coterminous United States at a spatial resolution of 30 meters and is based on the unsupervised classification of Landsat Thematic Mapper (TM) circa 1992 satellite data (Vogelmann and others, 2001). The 2001 NLCD is a 16-class land cover classification scheme with a spatial resolution of 30 meters and is based primarily on a decision-tree classification of circa 2001 Landsat satellite data (Homer and others, 2007). The 2011 NLCD is the most recent national land cover product created by the MRLC. It provides the capability to assess wall-to-wall, spatially explicit, national land cover changes and trends across the United States from 2001 to 2011. It has the same classification scheme and resolution as the 2001 NLCD and is based primarily on a decision-tree classification of circa 2011 Landsat satellite data (Jin and others, 2013). Land use in the project area was subdivided into six classified groups defined as developed (urbanized), forested, agricultural, grassland/shrub/pasture, wetlands, and open water. Land use for all three vintages of data are shown on plates 16, 17, and 18.

Land-use changes in the study area were evaluated from 1992 to 2001. The average percentage for each class category for both NLCD 1992 and 2001 datasets were calculated for the entire project area then compared by percentage of class change (fig. 13). Class change percentages are as follows: open water decreased by 23.8 percent, developed land (urbanized) increased by 53.4 percent, forested land decreased by 39.4 percent, grassland/shrub/pasture increased by 49.7 percent, agriculture decreased by 55.7 percent, and wetlands decreased by 89.8 percent. These changes in land use are substantial and are indicative of widespread urbanization in the Indian Creek watershed.

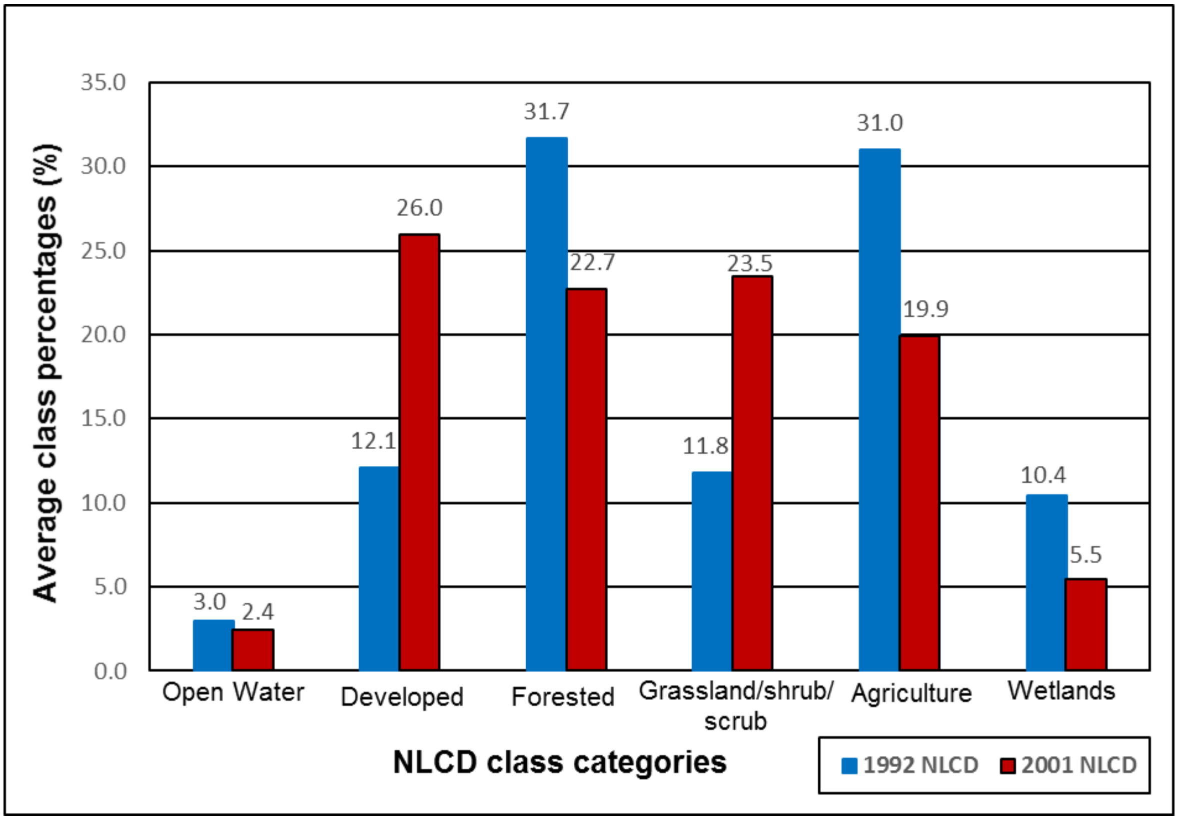

Figure 13. —Land use class comparison for NLCD 1992 and 2001 datasets.

Land use in the study area continued to change from 2001 to 2011, although the rate of urbanization slowed, most likely due to the economic downturn, which began in 2008. The average percentage for each class category for both NLCD 2001 and 2011 datasets were calculated for the entire project area then compared by percentage of class change (fig. 14). Class change percentages are as follows: open water decreased by 3.6 percent, developed land increased by 21.1 percent, forested land decreased by 1.8 percent, grassland/shrub/pasture decreased by 16.7 percent, agriculture decreased by 19.4 percent, and wetlands remained the same.

The largest land use category increase occurred within the developed land class in both vintage comparisons (53.4 percent increase from 1992 to 2001 and 21.1 percent increase from 2001 to 2011). This is likely due to the transition of agricultural land to urban areas for the support of population growth and urban sprawl. The NLCD “developed” land use classification

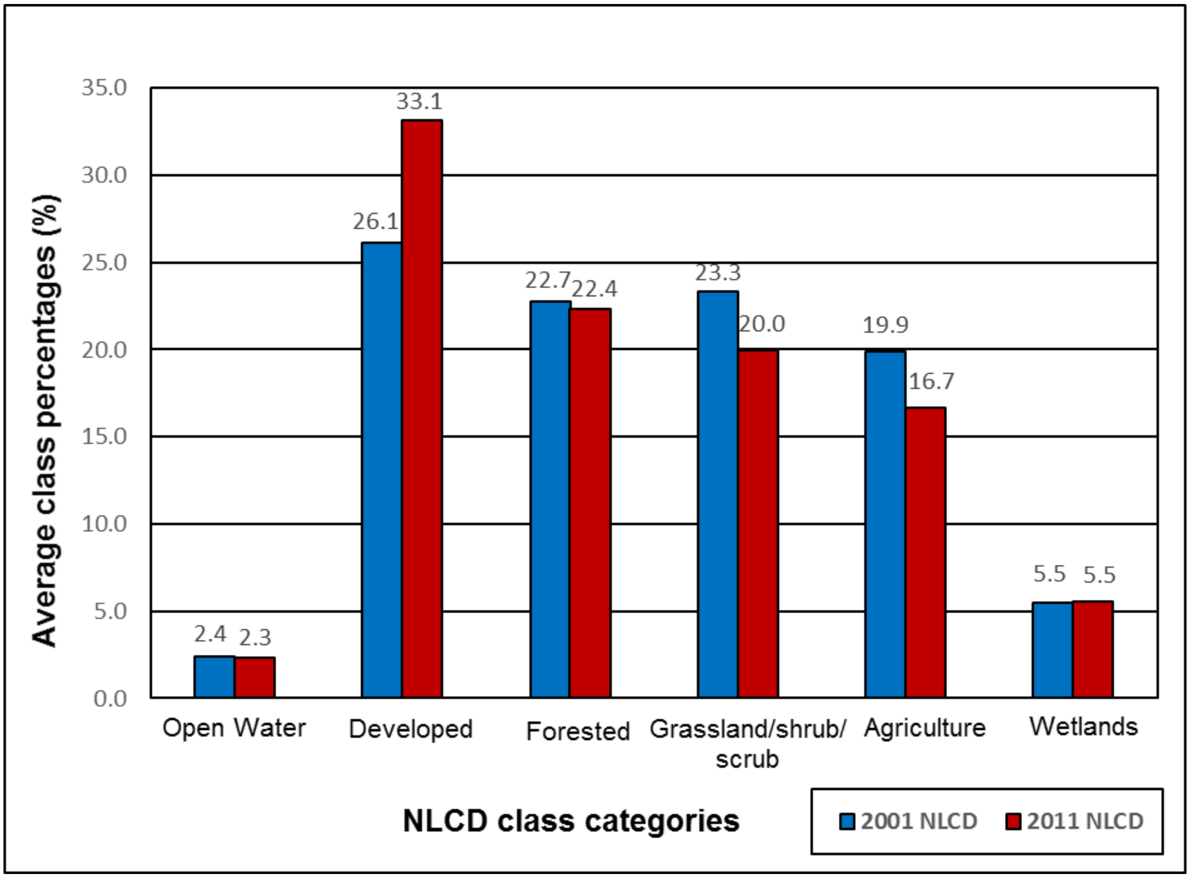

Figure 14. —Land use class comparison for NLCD 2001 and 2011 datasets.

commonly includes single family housing units, apartment complexes, row houses, and commercial and/or industrial facilities where people reside and work in large numbers (table _4). USEPA defines developed areas as having a high percentage (30 percent or greater) of constructed materials (i.e. asphalt, concrete, buildings, etc.), which are characterized by

Table 4. —Summary of land use data for the Redstone study area.

Class	**NLCD 1992 (%)**	**NLCD 2001 (%)**	**NLCD 2011 (%)**
Open Water	3.0	2.4	2.3
Developed	12.1	26.0	33.1
Forested	31.7	22.7	22.4
Grassland/shrub/pasture	11.8	23.5	20.0
Agriculture	31.0	19.9	16.7
Wetlands	10.4	5.5	5.5

impervious surfaces. From 1992 to 2011, development increased rapidly to the northwest of Redstone Arsenal while residential and commercial areas to the east, which existed prior to 1992 continued to urbanize, with many areas obtaining total build out (plates 16, 17, and 18).

WATER QUALITY

Water quality monitoring in Bobcat and Matthews Caves was initiated by the Geological Survey of Alabama in 1990. Since that time, a large amount of hydrologic and geochemical data has been collected that indicates that water in Bobcat Cave has relatively low concentrations of nutrients (phosphorus, nitrate, and ammonia) and periodic elevated concentrations of cadmium, chromium, and lead (McGregor and O'Neil, 2006). Water in Matthews Cave is characterized by relatively high concentrations of nitrate, low concentrations of phosphorus and ammonia, and periodic elevated concentrations of cadmium, chromium, and lead (McGregor and O'Neil, 2006).

Continued urbanization and associated runoff containing nonpoint source contaminants in areas adjacent to the arsenal will have increasing deleterious impacts on water quality on the arsenal, especially the eastern part including Matthews Cave. This is especially true in the northern part of RSA, where factors such as urban runoff, shallow aquifers with continuous surface- water and groundwater interaction, and southward surface-water and groundwater flow directions from urban areas to RSA profoundly influences water quality. Hydrologic and geochemical data indicate that Bobcat Cave may be isolated from much of the urban runoff that flows through the arsenal to the Tennessee River. Probable groundwater divides formed by Betts and Rainbow Mountains, interception of overland runoff and groundwater by Indian Creek, and a local northward hydraulic gradient protect the cave from regional urban influences, particularly elevated concentrations of nutrients and bacteria. GSA recommends regular regional evaluations of surface-water and groundwater quality to identify changes in geochemical trends or acute impacts.

SUMMARY AND CONCLUSIONS

The geology of the Redstone Arsenal area is characterized by Tuscumbia Limestone at the surface, underlain by Fort Payne Chert. Well drilling in Madison County shows the local occurrence of fractures on multiple levels that store and transmit large amounts of water. Many of these karst features are connected to surface-water bodies so that water is readily exchanged between the surface and subsurface. Groundwater recharge is about 6.9 inches per year. This

equates to about 94 million gallons of groundwater per year being recharged to the aquifer system on Redstone Arsenal. Groundwater movement in the Redstone Arsenal area of Madison County, Alabama is controlled by topography, surface-water features and by cavities and fractures that are difficult to map. Water quality on the arsenal will continue to be impacted by runoff originating from urban areas in close proximity to the arsenal. Interaction and exchange of groundwater and surface-water create pathways of movement for contaminants to move on the Arsenal and to eventually move to the Tennessee River. However, more comprehensive investigations of both ground water and surface-water systems will be required to determine specific sources and pathways of potential contaminants.

Redstone Arsenal lies east of the axis of the south-plunging Nashville dome. Paleozoic rocks cropping out in the area of investigation and/or penetrated by boreholes range from Pennsylvanian to Ordovician in age. Mississippian Fort Payne Chert and overlying Tuscumbia Limestone are the principal geologic units at the surface and relatively shallow subsurface in RSA. Devonian Chattanooga Shale provides the principal datum for structural and stratigraphic datum mapping the subsurface. The Silurian Brassfield Limestone is interpreted to underlie the Chattanooga Shale over most of the area of investigation, though this conclusion is based on sparse data. Rocks of the Ordovician Sequatchie Formation have been penetrated by some wells in RSA, and rocks of the Cambro-Ordovician Knox Group have been tested by a few oil and gas test wells in the surrounding area. A small number of wells in RSA penetrate the Monteagle Limestone, which overlies the Tuscumbia Limestone.

The Fort Payne Chert and Tuscumbia Limestone are the primary fresh-water bearing units in the area, but a study of 77 wells in the RSA area show that all stratigraphic units penetrated by test wells in RSA contain groundwater flow zones. Flow intervals are found as deep as 432 feet. The majority of flow zones are bedding plane conduits (“factures”), many of which have been solutionally enlarged. High-angle fractures also probably play a major role in the development of pathways for groundwater flow. Thickness of the regolith overlying Paleozoic rock aquifers appears to have little or no influence on the number of flow zones in a given well in RSA or on the depth of the deepest flow zone. Intervals with the highest ambient flow, however, occur at relatively shallow depths.

The average thickness of the Fort Payne Chert is approximately 156 feet in the Redstone Arsenal area; however, the upper part of the formation has been removed by erosion

or reduced to a deeply weathered residuum in most of the northern part of the area. Fort Payne Chert is distinguishable from the underlying Maury Formation, which is considered the basal Mississippian geologic unit. Very thin limestone beds are evident in Maury Formation, locally underlying or interbedded with the more typical green shale of the formation; the sequence appears correlative with Maury outcrops described by Conkin and Ciesieski (1973) in Limestone County. The Fort Payne Chert is conformably overlain by the Tuscumbia Limestone; the contact is somewhat arbitrarily picked in the subsurface based on chert amount, bedding characteristics, and color; overall rock color and bedding characteristics; gamma ray log characteristics; and stratigraphic position.

The Fort Payne can be subdivided into four lithofacies: a thin lower limestone interval which occurs across the southern half of the arsenal; a shaly carbonate facies that occurs across RSA but is thickest in the southern part of the area; a middle carbonate facies that occurs across the arsenal, reaches a maximum thickness of more than 130 feet, and comprises the majority of the formation in the northern part of RSA; and an upper carbonate facies that is relatively thin and forms a transitional unit with the overlying Tuscumbia Limestone.

All of the Fort Payne lithofacies have groundwater flow intervals. From a study of 59 test wells in RSA that penetrated the entire Fort Payne Chert interval there is slight bias of the upper carbonate facies and the shaly carbonate facies to contain flow zones as compared to their average thickness representation of the formation.

Analyses of density and neutron logs for wells drilled in the MSFC area through the Fort Payne Chert indicate the presence of porous intervals; optical televiewer logs also provide visual evidence of possible intergranular, fossil moldic, and vuggy porosity along with cavities developed along bedding planes and fractures. Quantifying porosity from available neutron logs in MSFC wells is not possible, however, due to lack of calibration. Calculation of porosity of Fort Payne Chert in the MSFC from density logs, though problematic due to lack of data regarding matrix densities, can be reasonably estimated for a few wells. The more porous intervals probably exceed 10 percent porosity, but porosity probably averages less than 5 percent. Moreover, judging from optical logs, significant amount of that porosity may be in the form of vugs and therefore not considered “effective” porosity. Porosity calculations from calibrated neutron and density logs from an oil and gas well east of the principal area of investigation show the Fort Payne Chert to have 2-7 percent porosity, a range that appears to

confirm the data and analyses for MSFC wells. These porosity estimates indicate that the cherty carbonate rocks of the Fort Payne have aquifer storage in addition to that provided by bedding plane conduits, cavities, and fractures.

High resolution seismic data were acquired by geophysical consultants on RSA, consisting of 47.7 miles of land and 43.9 miles of water borne data. Review of these data and interpretations by GSA personnel indicate a number of concerns regarding the interpretation of the data. A dense pattern of relatively deep, large throw normal faults in the geologic environment of north Alabama is questionable. GSA recognized a number of seismic pitfalls that may cause misinterpretations including, karst features and fracture zones misinterpreted as faults, multiples, probably related to near surface karst features, changes in directions of lines along roads from strike to dip that create false structural features. Seismic velocity contrasts in the region lead to collection of potentially important data for groundwater occurrence and movement. However, GSA recommends reprocessing and reinterpretation to capture the full utility of the data.

The Tuscumbia Limestone and Fort Payne Chert aquifers in the project area are primarily unconfined or partially confined, due to shallow depths and absence of confining layers that isolate groundwater from the water table and the land surface. Groundwater movement in Paleozoic aquifers is preferential with respect to direction and velocity, related to the geometry and connectivity of fracture systems. Directions of groundwater movement can be determined from contour maps of water level elevations.

A water table map was prepared using groundwater level data collected by GSA from all available wells (approximately 88 wells) in the project area surrounding the Redstone Arsenal (RSA) and using a portion of the groundwater level data provided by RSA (approximately 145 RSA wells) measured within and along the RSA boundary. Groundwater level mapping within the project boundary indicates that the general flow of groundwater in the Tuscumbia and Fort Payne aquifers is southerly, eventually discharging to the Tennessee River. However, intricate groundwater flow patterns occur throughout the area where complex surface and groundwater drainage patterns are influenced by highly variable topographic relief.

The central portion of the project area is relatively flat, where groundwater and surface-water flow is southward across the northern boundary of RSA. One exception, an area of high relief located on the northern RSA border, has a local influence on groundwater flow. Water-

level data indicates an area of low hydraulic gradient in the south-central portion of the project, immediately south of Wheeler Lake. A structural and groundwater low located in the west-central part of RSA, in the vicinity of Bobcat Cave influences groundwater flow and may also be a contributing factor in the formation of karst, including Bobcat Cave. GSA recommends additional exploration and research in this area of RSA.

Multiple aquifers separated by interbedded confining layers have significant implications for base flow and movement of contaminants on RSA. The evaluation of water levels and stratigraphy penetrated by monitoring wells on RSA lead to the identification of areas with multiple aquifers, characterized by isolated water levels and local and subregional confinement. Monitoring wells in three areas (northwest, south-central, north-central) of RSA exhibit multiple water-bearing zones with significantly different water levels. Monitoring wells in 2 areas in the east and east-central part of RSA exhibit similar water levels although the wells were constructed in different stratigraphic units, indicating hydraulic connections between fractures and karst features.

Groundwater recharge in much of the Tennessee River watershed is local. Recharge rates are controlled by a number of factors including porosity and permeability, which in Paleozoic aquifers are mainly secondary and characterized by leached fossils, fractures, and solution development. Recharge, originating from precipitation, may also be influenced by drought, seasonal precipitation, land surface slope, surface drainage, and the character of surface material. If the topography is relatively flat and surface materials are permeable, more surface water will infiltrate into local aquifers.

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Land-use class changes in the study area were evaluated for the Indian Creek watershed from 1992 to 2011, using land-use data for 1992, 2001, and 2011. From 1992 to 2001, class change percentages are as follows: open water decreased by 23.8 percent, developed land (urbanized) increased by 53.4 percent, forested land decreased by 39.4 percent, grassland/shrub/pasture increased by 49.7 percent, agriculture decreased by 55.7 percent, and wetlands decreased by 89.8 percent. These changes in land use are substantial and are indicative of widespread urbanization in the Indian Creek watershed.

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For many years RSA has spent significant resources to monitor and remediate contaminant problems and to characterize and protect wildlife that inhabits the area. The preceding report represents efforts by the GSA Groundwater Assessment Program to provide additional insights into the hydrogeology of the area by evaluation of existing data.

REFERENCES CITED

Baker, R. M., 2002, Dye trace investigations in the vicinity of Chapman Mountain, city of Huntsville, Alabama: Alabama Geological Survey open file report, 35 p.

Baker, R. M., Cook, M. R., Moss, N. E., Henderson, W. P., 2005, Discharge and water withdrawal assessment, Mountain Fork watershed, Madison County, Alabama: Geological Survey of Alabama Open-File Report 0527, 27 p.

Bossong, C. R., 1988, Geohydrology and susceptibility of major aquifers to surface contamination in Alabama: Area 2: U.S. Geological Survey Water Investigations Report 88-4177, 16 p.

Bossong, C. R., and Harris, W. F., 1987, Geohydrology and susceptibility of major aquifers to surface contamination in Alabama; Area 1: U.S. Geological Survey Water Investigations Report 87-4068, 23 p.

Campbell, C. W., Sullivan, S. M., Roberts, L. R., Booher, E., Cochran, B., Frank, M., Samples, J., Wood, T., 1977, Protection of the Alabama cave shrimp field work and modeling, Department of Civil Engineering, The Universeity of Alabama in Huntsville, 37 p.

Campbell, C. W., 1997, Contaminant transport model for the Bobcat Cave watershed, The University of Alabama in Huntsville Research Institute, 24 p.

Chaffin, H. S., Jr., and Szabo, M. W., 1975 Geology and mineral resources of the Fisk quadrangle, Alabama: Geological Survey of Alabama Quadrangle Series Map 5, 21 p.

Chandler, R. V., and Moore, J. D., 1991, Fluorescent dye trace tests for storm water drainage wells in the Muscle Shoals area, Alabama, Final report: Alabama Geological Survey open file report, 305 p.

Christensen, R. C., Faust, R. J., and Harris, W. F., Jr., 1975, Water resources, *in* Environmental geology and hydrology, Huntsville and Madison County: Alabama, Alabama Geological Survey Atlas Series 8, 118 p.

Conant, L. C., and Swanson, R. P. 1961, Chattanooga Shale and related rocks of central Tennessee and nearby areas: U. S. Geological Survey Professional Paper 357, 91 p.

Conkin, J. E., and Ciesielski, P. F., 1973, Lower Mississippian (Kinderhookian) arenaceous foraminifera from the Maury Formation at Gipsy, Limestone County, Alabama: Geological Survey of Alabama, Bulletin 103, 55 p.

Cook, M. R., 1997, Origin and evolution of anomalous hydrogeochemical character of the Tuscaloosa aquifer system of west-central Alabama: University of Alabama unpublished Masters Thesis, 94 p.

Cook, M. R., 2004, Alternative water source assessment: An investigation of deep Cretaceous aquifers in southeast and south-central Alabama: Geological Survey of Alabama open file report, 43 p.

Cook, M. R., Moss, N. E., Jennings, S. P., 2009, Groundwater hydrogeology, recharge, and water availability in the Tennessee River watershed of Alabama: Geological Survey of Alabama open file report 0910, 44 p.

Copeland, C. W., Bolin, D. E., Doyle, F. L., Holler, D. P., Kidd, J. T., and Moser, P. H., 1975, Geology [of Huntsville and Madison County, Alabama], *in* Geological Survey of Alabama, Environmental geology and hydrology, Huntsville and Madison County: Alabama, Alabama Geological Survey Atlas Series 8, 118 p.

Glover, L., 1959, Stratigraphy and uranium content of the Chattanooga Shale in northeastern Alabama, northwestern Georgia and eastern Tennessee: U. S. Geological Survey Bulletin 1087-E, p.133-168.

Holler, D. P., 1975, Recognition and projection of the contact between the Mississippian Fort Payne Chert and Tuscumbia Limestone in Madison County, Alabama: University of Alabama, M.S. thesis, 76 p.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. 2007. Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Jewell, J. W., 1969, An oil and gas evaluation of north Alabama: Geological Survey of Alabama Bulletin 93, 65 p.

Jin, S., Yang, L., Danielson, P., Homer, C., Fry, J., and Xian, G. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment*, 132: 159 – 175.

Kidd, J. T., Holler, D. P., Chaffin, H. S., Jr., Copeland, C. W., Smith, W. E., Drahovzal, J. A., 1975, Surface Geology, *in* Environmental geology and hydrology, Huntsville and Madison County: Alabama, Alabama Geological Survey Atlas Series 8, 118 p.

Kopaska-Merkel, D. C., and Moore, J. D., 2000, Water in Alabama: Geological Survey of Alabama Circular 122N, p. 4.

Lim, J. K., Engle, B. A., Tang, Z., Choi, J., Kim, K., Muthucrishnan, S., and Tripathy, D., 2005, Automated web GIS based hydrograph analysis tool, WHAT: Journal of the American Water Resources Association, December edition, p. 1407-1416.

Malmberg, G. T., and Sanford, T. H., 1963, Geologic map of Madison County, Alabama; Geological Survey of Alabama Special Map 25.

Mann, S. D., Baker, R. M., Raymond, D. E., 1997, Documentation for a wellhead protection program: Madison County water Department, Madison County, Alabama, Geological Survey of Alabama Open File Report, 56 p.

McGlamery, Winnie, 1955, Subsurface stratigraphy of northwest Alabama: Geological Survey of Alabama Bulletin 64, 503 p.

McGregor, S. W., O'Neil, P. E., 1996-2008, Water quality and biological monitoring in Bobcat and Matthews Caves, Redstone Arsenal, Alabama, Alabama, Annual Geological Survey of Alabama Open File Reports.

McGregor, S. W., O'Neil, P. E., Shepard, T. E., Henderson, P. W., 2004, Monitoring of Tuscumbia Darter (*Etheostoma tuscumbia*) populations on Redstone Arsenal, Alabama, 2000-2004, Geological Survey of Alabama Annual Open File Report, 6 p.

McGregor, S. W., O'Neil, P. E., 2006, Water quality and biological monitoring in Bobcat and Matthews Caves, Redstone Arsenal, Alabama 1990-2006 open file report 0620, Alabama, Annual Geological Survey of Alabama Open File Report, 33 p.

Meyboom, P., 1961, Estimating groundwater recharge from stream hydrographs: Journal of Geophysical Research, v. 66, no. 4, p. 1203-1214.

Nathan, R. J., and McMahan, T. A., 1990, Evaluation of automated techniques for baseflow and recession analysis: Water Resources Research, v. 26, no. 7, p. 1465-1473.

Purdue University, 2004, WHAT-web-based hydrograph analysis tool, URL http://cobweb.ecn.purdue.edu/~what/ .

Raymond, D. E., 2003, Geology of the Madison 7.5 minute quadrangle, Madison County, Alabama: Geological Survey of Alabama Quadrangle Series Map 29, 29 p.

Raymond, D. E., Osborne, W. E., Copeland, C. W., and Neathery, T. L., 1988, Alabama stratigraphy: Geological Survey of Alabama Circular 140, 97 p.

Reesman, A. L., and Stearns, R. G., 1989, The Nashville Dome – an isostatically induced erosion structure – and the Cumberland Plateau Dome – an isostatically suppressed late Paleozoic extension of the Jessamine Dome: Southeastern Geology, v.30, no. 3, p.147-174.

Rheams, K. F., Moser, P. H., McGregor, S. W., 1992, Geologic, Hydrologic, and biologic investigations in Arrowood, Bobcat, Matthews, and Shelta caves and selected caves, Madison County, Alabama, Geological Survey of Alabama Open File Report, 262 p.

Risser, D. W., Gburek, W. J., and Folmar, G. J., 2005, Comparison of methods for estimating ground-water recharge and baseflow at a small watershed underlain by fractured bedrock in the eastern United States: U.S. Geological Survey Water Scientific Investigations Report 2005-5038, 31 p.

Schlumberger Well Services, 1986, Schlumberger log interpretation charts: Schlumberger Well Services, 122 p.

Sellinger, C. E., 1996, Computer program for performing hydrograph separation using the rating curve method: National Oceanic and Atmospheric Administration Technical Memorandum ERL GLERL-100, 11 p.

Shirmohammadi, A., Knisel, W. G., and Sheridan, J. W., 1984, An approximate method for partitioning daily streamflow data: Journal of Hydrology, p. 335-354

Southeast Regional Climate Center, 2012, Historical Climate Summaries for Alabama, URL http://www.sercc.net/climateinfo/historical/historical_al.html.

Szabo, M. W., and Chaffin, H. S., Jr., 1982, Geology and mineral resources of the New Market quadrangle, Alabama: Geological Survey of Alabama Quadrangle Series Map 8, 29 p.

Szabo, M. W., Osborne, W. E., Neathery, T. L., and Copeland, C. W., Jr., 1988, Geologic map of Alabama, (1:250,000): Alabama Geological Survey Special Map 220.

Thomas, W. A., 1972, Mississippian stratigraphy of Alabama: Geological Survey of Alabama Monograph 12, 121 p., 13 pls.

Vogelmann, J.E., S.M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and J. N. Van Driel, 2001. Completion of the 1990's National Land Cover Data Set for the conterminous United States, *Photogrammetric Engineering and Remote Sensing* 67:650-662.

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