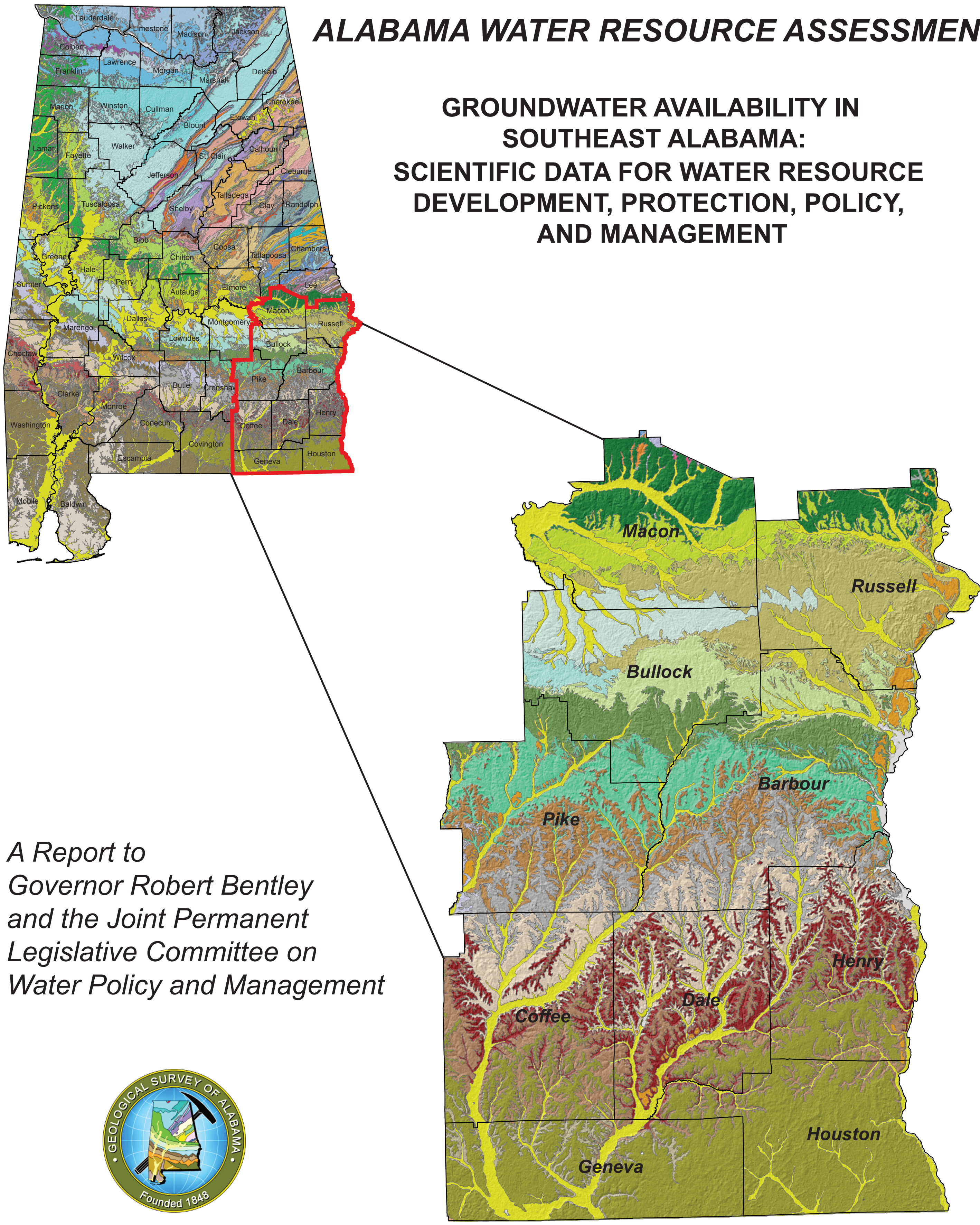
ALABAMA WATER RESOURCE ASSESSMENT

GROUNDWATER AVAILABILITY IN SOUTHEAST ALABAMA: SCIENTIFIC DATA FOR WATER RESOURCE DEVELOPMENT, PROTECTION, POLICY, AND MANAGEMENT



A Report to
Governor Robert Bentley
and the Joint Permanent
Legislative Committee on
Water Policy and Management

GEOLOGICAL SURVEY OF ALABAMA
Founded 1848

GEOLOGICAL SURVEY OF ALABAMA

Berry H. (Nick) Tew, Jr.

State Geologist

GROUNDWATER AVAILABILITY IN SOUTHEAST ALABAMA: SCIENTIFIC DATA FOR WATER RESOURCE DEVELOPMENT, PROTECTION, POLICY, AND MANAGEMENT

FOR
GOVERNOR ROBERT BENTLEY
AND THE
PERMANENT JOINT LEGISLATIVE COMMITTEE
ON WATER POLICY AND MANAGEMENT

OPEN FILE REPORT 1406

By

Marlon R. Cook, Neil E. Moss, Steven P. Jennings,
Mac McKinney, Alana L. Rogers, Kenneth M. Smith, Amye S. Hinson, and Ralph Norman

Funding for this project provided through the State of Alabama General Fund as appropriated in the 2013 and 2014 budgets of Governor Robert Bentley and the Alabama State Legislature

Tuscaloosa, Alabama

2014

Contents

Illustrations

Tables

Plates

Gordo and Eutaw Formations

Ripley Formation and Cusseta Sand Member

GROUNDWATER AVAILABILITY IN SOUTHEAST ALABAMA: SCIENTIFIC DATA FOR WATER RESOURCE DEVELOPMENT, PROTECTION, POLICY, AND MANAGEMENT

**FOR
GOVERNOR ROBERT BENTLEY
AND THE
PERMANENT JOINT LEGISLATIVE COMMITTEE
ON WATER POLICY AND MANAGEMENT**

EXECUTIVE SUMMARY

The economic future and quality of life for Alabamians is dependent upon the availability and protection of the state's natural resources. The most basic and essential of these are water resources. Planning for prudent development and protection of Alabama's water resources requires comprehensive knowledge of factors such as location and volume of available water, current water use, and projected future water demand. The following report is an initial regional assessment of groundwater resources in southeast Alabama and is part of an ongoing statewide assessment. This assessment, along with an assessment of surface-water availability being performed by the Alabama Department of Economic and Community Affairs Office of Water Resources, was mandated as part of an initiative by Governor Robert Bentley and the Permanent Joint Legislative Committee on Water Policy and Management to develop a statewide water resource management plan and future water policy legislation.

This groundwater assessment includes data concerning stratigraphy, hydrogeologic characteristics, current groundwater development and future groundwater development potential, production impacts, and groundwater availability and recharge. These data provide comprehensive knowledge of this critical water resource that will provide a foundation in support of prudent, future water management and policy decisions. Assessments of current and future projected aquifer conditions include drawdown, long-term rates of water level decline in wells, comparisons of current hydraulic head levels to tops of screened intervals in wells, and quantities of water in subsurface storage for each aquifer. Additional insights may be acquired by comparisons of current aquifer

conditions with current water use and future projected water demand. However, current water use and future demand data are not available at this time.

Sixteen geologic units in the Cretaceous and Tertiary Systems, varying in age from about 135 to 36 million years, underlie the project area. However, only 12 of these have hydrogeologic characteristics that define them as aquifers and, of these, 8 are major aquifers capable of producing adequate quantities of water for sustainable public, industrial, or irrigation water supply. Major aquifers include the Gordo Formation (including the hydraulically connected Eutaw Formation), Ripley Formation (including the Cusseta Sand Member), Clayton Formation (including the hydraulically connected Salt Mountain Limestone (in subcrop only)), Nanafalia, Lisbon, and Crystal River Formations. The Tallahatta Formation, Tuscahoma Sand, and Providence Formation are minor aquifers and are primarily developed for domestic or livestock supplies. The Coker Formation has limited geographic extent due to unsuitable water quality (excessive chlorides). The undifferentiated Lower Cretaceous (in subcrop only) was also evaluated and may be a future source of groundwater.

One purpose of the groundwater assessment is to generate spatial data based on hydrogeologic and well characteristics that may be used for future groundwater source development. Parameters for this purpose for each identified aquifer in the assessed area include well depths, depth to water, pumping rates, specific capacities, and net potential productive intervals. These data may be used by public water systems, citizens, industries, and agricultural interests to determine locations and specifications for water well construction. To observe specific information related to groundwater source development, see text in the body of the report.

Another purpose of the assessment is to evaluate historic and current groundwater levels to determine hydraulic characteristics and to observe climatic and water production impacts for selected aquifers in the assessed area. This is accomplished by construction of potentiometric surface maps. A potentiometric water level is the elevation to which water rises in a properly constructed well that penetrates a confined aquifer. The potentiometric surface is an imaginary surface representing the confined pressure (hydrostatic head) throughout all or part of a confined aquifer. This surface is helpful in determining directions of groundwater movement, hydraulic gradients, and depths from which water can be pumped at particular locations. When water is removed from an aquifer by pumping or by reductions in recharge, the potentiometric surface will fluctuate accordingly (drawdown/production or climatic impact). The difference between pre-pumping static water levels and partially recovered water levels affected by pumping is termed residual drawdown. Areas with closely spaced wells create “cones of depression” where individual well impact areas coalesce to form relatively large potentiometric surface impacts that may cover tens of square miles. It is important to note that as long as the potentiometric surface remains above the stratigraphic top of the aquifer, the aquifer media remains saturated so the declining surface only represents a decline in hydrostatic pressure. If the water level declines below the stratigraphic top of the aquifer, it becomes unconfined, possibly causing irreversible formation damage. Presently, no known water levels in southeast Alabama are in danger of declining below the stratigraphic top of any aquifer. Therefore, potentiometric surfaces and residual drawdown values provide important information to determine the affects of water production, strategies for water source protection, and future water availability.

Multiple disruptions in the Eutaw-Gordo aquifer potentiometric surface occurred near producing wells in the assessment area. The largest drawdown in the Gordo aquifer (more than 150 feet (ft)) occurs in the city of Eufaula in eastern Barbour County and the city of Union Springs in central Bullock County. The area of potentiometric impact at Union Springs is about 50 square miles (mi^2). Bullock County well F-1 is in close proximity to city of Union Springs public supply wells and effectively serves as a monitoring well for impacts from city of Union Springs groundwater production from the Gordo aquifer. Well F-1 had a water level decline rate of 3.3 ft/year between 1961 and 2010.

The down gradient extent of fresh water in the Gordo aquifer has not yet been established, with southernmost wells in northern Henry and Dale, central Pike, and northern Crenshaw Counties. Well F-23 (Ozark Utilities well no. 9) constructed in the Gordo aquifer in north-central Dale County is the deepest public water supply well in Alabama. The top of the screened interval is 2,260 ft below land surface (bls) and, as of the last water level measurement on July 1, 2013 (383 ft bls), there was 1,877 ft of water above the screens in well F-23.

Potentiometric surface mapping also indicates the presence of a regional groundwater level decline in the Eutaw and Gordo aquifers from 60 to 80 ft in much of Bullock County. A potentiometric surface constructed by Cook in 1993, from water levels measured in 1991 shows that the potentiometric surface for the Eutaw aquifer was about 30 feet higher in 1991 than in 2013 in this area of regional decline. Water level measurement dates indicate that most of this regional decline occurred after 1980 and is not related to excessive groundwater production, but is most likely the result of less precipitation and groundwater recharge on average since 1980.

Disruptions in the potentiometric surface for the Ripley aquifer occur in Ozark (north-central Dale County) where groundwater levels declined 30 ft in well F-04 and 56 ft in well F-17. Coalesced well impact areas cover about 5 mi^2 in the city of Ozark. The Ozark area has the largest cone of depression of the Ripley aquifer in southeast Alabama, with currently more than 100 ft of drawdown. Groundwater levels have also declined 82 ft in well L-5 and 142 ft in K-08 in Luverne and Rutledge, respectively (central Crenshaw County), 66 ft in well I-3 and 53 ft in well Q-8 in Troy (central Pike County), and 42 ft in well O-01 in central Henry County.

Due to the hydraulic connection between the Clayton and Salt Mountain aquifers, potentiometric surface maps prepared for this project represent water levels in both aquifers. Therefore, references to the Clayton aquifer include the Salt Mountain aquifer also. The largest area of depressed potentiometric surfaces in Alabama is in the Dothan area in the Nanafalia and Clayton aquifers. Water levels for five public supply wells operated by Dothan Utilities and screened solely in the Clayton aquifer were evaluated. All five wells are located north of downtown Dothan in northwestern Houston County and are in close proximity, most likely with overlapping zones of pumping influence. Additional major depressed potentiometric surfaces occur in the Elba, Enterprise, and Ozark areas. However, recent data obtained from public water supply systems show that water levels in these areas have stabilized and are increasing due to construction of additional wells and reduction of pumping related to water rate increases and increased precipitation. Isolated disruptions in the Clayton aquifer potentiometric surface occur in the Dothan area (northwestern Houston and southeastern Dale Counties) where groundwater levels have declined from 47 ft in well I-04 and 90 ft in well 25. The area of coalesced impacted water levels covers about 18 mi^2 north and west from downtown Dothan. Groundwater levels declined 36 ft in well P-3 and 90 ft in well P-5 (Salt Mountain) in the Enterprise area of southeastern Coffee County, where two areas of coalesced impacted water levels covers about 18 mi^2 in and north of the downtown area and 9 mi^2 north and west of the city.

Isolated disruptions in the Nanafalia aquifer potentiometric surface occur in numerous individual wells across the project area. However, the largest disruption occurs in the Dothan area (northwestern Houston and southeastern Dale Counties) where groundwater levels declined as much as 248 ft (well I-08). Impacted production areas from a number of wells have coalesced to form an area of disruption in the potentiometric surface of about 15 mi^2 along with several additional individual well disrupted areas.

The Lisbon Formation is a minor aquifer and is only available in the southern part of the project area. Declining water levels in the Lisbon aquifer are isolated and only observed in individual wells. Isolated disruptions in the potentiometric surface occur near producing wells at Geneva (southern Geneva County) where the groundwater level has declined 75 ft in well S-8 and a minor disruption at Sanford (northeastern Covington County) where the groundwater level has declined 22 ft in well M-5.

Water use from the Crystal River aquifer includes public water supply at Florala (southeastern Covington County) and private water supply throughout the aquifer area, although the primary use of water is agricultural irrigation from a number of high capacity wells in southern Houston County. However, only minor disruptions in the potentiometric surface were observed and all occur from individual wells.

An additional purpose of the assessment is to evaluate long-term rates of groundwater level fluctuation in specific wells, in particular locations. Groundwater levels fluctuate almost continuously in response to recharge to and discharge from aquifers by natural and artificial processes, which can include pumpage from wells, natural groundwater discharge, recharge from changing rates of precipitation, and evapotranspiration. GSA maintains water level files for about 450 wells and springs throughout Alabama, including wells and springs in the GSA real-time monitoring system that can be accessed on the GSA website at http//www.gsa.state.al.us/. Water levels in most of these wells have been measured semiannually or annually for more than 15 years with many having records of more than 30 years. Groundwater levels in a select group of these wells were used to construct hydrographs (graphical illustrations of water level fluctuations over a specified time period). Wells were selected to illustrate various aquifer drawdown trends and to document temporal and spatial characteristics of declining groundwater levels in major pumpage centers in southeast Alabama.

Hydrographs can be used to explain impacts of aquifer confinement, drought, pumpage, and well efficiency. Regression lines constructed from individual water level measurements collected over many years describe long-term trends of groundwater fluctuation. In areas where water levels indicate long-term declines, regression lines are termed “decline curves.” Multiple hydrographs and decline curves in specific areas and aquifers can be used to evaluate groundwater production impacts and depressions in potentiometric surfaces, commonly known as “cones of depression,” to estimate changes in groundwater storage, and to predict future groundwater availability.

Generally, water levels in all selected Gordo wells exhibit at least one period of decline. The largest drawdown in the Gordo aquifer (more than 150 ft) occurs in the city of Eufaula in eastern Barbour County and the city of Union Springs in central Bullock County. City of Eufaula well K-02 has two periods of water level decline. The first, from 1961 to 1987, was at a rate of 3.6 feet per year (ft/yr). The second, from 1987 to 1995, was 6.0 ft/yr. From 1995 to 2002, water level stabilized and was recovering from 2002 to 2004. The top of the screened interval is 1,278 ft bls and, as of the last water level measurement on November 10, 2004 (199.1 ft bls), there was 1,078.9 ft of water above the screens in well K-02.

Water levels in well F-17 constructed in the Ripley aquifer at Ozark decreased from the initial static water level measured in 1954 (210 ft bls), to the lowest water level, measured during the 2000 drought (368 ft bls). However, since 2000 the water level has risen at a rate of 1.9 ft/yr due to construction of additional wells and reduction of pumping from the Ripley aquifer. The top of the screened interval is 753 ft bls and, as of the last water level measurement on July 1, 2013 (291 ft bls), there was 462 ft of water above the screens in well F-17.

Clayton well P-7 (Dothan Utilities well no. 4) has a long-term declining water level at a rate of 3.0 ft/yr from 1982 through 2004, and an increasing water level at a rate of 1.4 ft/yr from 2004 to the first quarter 2013. Water level recovery in well P-7 is due to additional wells constructed by Dothan Utilities and a reduction in water demand for the city of Dothan. The top of the screened interval is 570 ft bls and, as of the last water level measurement on January 1, 2013 (303.4 ft bls), there was 266.6 ft of water above the screens in well P-7.

Public supply wells in the Daleville area of Dale County and the Dothan area of Houston County were selected to illustrate conditions in two of the largest depressions of potentiometric surfaces in the Nanafalia aquifer. Three public supply wells in Daleville (southwestern Dale County) are located in close proximity to one another and all have similar water level histories. Well M-11 (Daleville Water and Sewer Board well no. 1) is screened in the Tuscahoma and Nanafalia aquifers and had a 178-ft decline from the initial static water level of 68 ft bls in 1961 to 246 ft bls in 2003 (4.3 ft/yr). The water level continued to decline at 1.5 ft/yr until 2007. Since 2007 the water level in well M-11 has risen at 1.7 ft/yr. The top of the screened interval is 355 ft bls and, as of the last water level measurement on July 1, 2013 (242 ft bls), there was 113 ft of water above the screens in well M-11.

Well I-11 (Dothan Utilities well no. 11) is screened in the Tuscahoma and Nanafalia aquifers. The water level declined from the initial static measurement in 1954 to 1985 at 4.3 ft/yr. From 1985 to 2013 the water level decline slowed to 1.6 ft/yr. The top of the screened interval is 635 ft bls and, as of the last water level measurement on January 1, 2013 (335.2 ft bls), there was 299.8 ft of water above the screens in well I-11.

The Crystal River Formation is a minor aquifer but is the primary groundwater source in the southern part of the project area along the Florida state line. All selected wells are observation wells in the GSA groundwater level monitoring program. Declining water levels in the Crystal River aquifer are isolated to individual wells. Generally, water levels in all monitored Crystal River wells are relatively stable with only minimal rates of water level change.

Subsurface water movement occurs in two primary environments. The first is in and near the recharge area, where aquifers are unconfined or partially confined, groundwater movement is under water table conditions, and groundwater/surface-water interaction is common. Groundwater discharge to streams forms the base flow component of stream discharge, forms the sustainable flow of contact springs and wetlands, and supports habitat and biota. Subsurface water movement in this environment is generally less than 15 miles and occurs from the updip limit of an aquifer down gradient to the point where the aquifer is sufficiently covered by relatively impermeable sediments and becomes confined in the subsurface.

The second environment is characterized by subsurface water that underflows streams and areas of low topography down gradient to deeper parts of the aquifer. Groundwater in this environment is separated from the land surface by relatively impermeable sediments that form confining layers.

Volumes of groundwater recharge and distances of groundwater movement in Alabama coastal plain aquifers are highly variable and are influenced by a number of factors including precipitation, permeability of recharge areas, hydraulic connection and exchange of groundwater between aquifers, and aquifer confinement and hydraulic gradient. 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 for estimating groundwater flow in and near aquifer recharge areas. Base flow estimates were made using manual and automated hydrograph separation methods. Discharge data for 12 ungauged stream sites (nodes) in the southeast Alabama pilot project area were used in the recharge evaluation. Selected sites were on main stems or tributaries of the Choctawhatchee, Pea, Yellow, and Conecuh Rivers. Nodes were selected in strategic locations relative to critical aquifer recharge area boundaries.

Estimates of base flow contributions of individual aquifers or related aquifer groups (unconfined and partially confined aquifer recharge) indicate that the largest recharge rate occurs in the Crystal River aquifer (408.4 million gallons per day (mgd)). This was expected, due to the size of the recharge area, stratigraphic composition of the formation (sandy residuum and karst limestone) that maximizes infiltration of precipitation into the subsurface, and relatively low topographic relief that minimizes runoff. Recharge for the Lisbon and Tallahatta aquifers was estimated together due to the proximity of the recharge areas and had the second largest recharge rate (269.9 mgd). The Nanafalia aquifer had the third largest rate (133.9 mgd). When recharge data were normalized relative to recharge area size, the Eutaw aquifer had the largest rate (273,900 gallons per day per square mile (g/d/mi^2)), followed by the Crystal River (242,700 g/d/mi^2), Lisbon and Tallahatta (239,100 g/d/mi^2), and Nanafalia (237,800 g/d/mi^2) aquifers.

Aquifers in the southeast Alabama pilot project area generally dip to the south-southeast into the subsurface at rates of 20 to 40 ft/mi. As the distance from the recharge area (outcrop) increases, aquifers are overlain by an increasing thickness of sediments, some of which are relatively impermeable. At some point, down gradient aquifers become fully confined and have no hydraulic connection with the land surface. Volumes of groundwater flow were determined for confined areas of major aquifers in the pilot project area using a modification of Darcy’s Law with recently measured water levels, aquifer thicknesses, and hydraulic gradients, and published estimates of transmissivity from wells in the project area. Confined aquifer recharge was estimated for a limited number of aquifers due to hydraulic connection of the Gordo and Eutaw Formations, lack of adequate hydraulic data for the Cusseta Member and Providence, Tallahatta, and Lisbon Formations, and absence of confinement in the Crystal River Formation. Confined aquifer recharge rates include the Gordo (6.5 mgd), Ripley (37.8 mgd), Clayton (48.1 mgd), and Nanafalia (24.6 mgd) aquifers.

Comparisons of estimated recharge rates reveal that confined rates are about 6 percent (%) of unconfined or partially confined rates for the Gordo aquifer, 61% for the Ripley and Clayton aquifers, and 18% for the Nanafalia aquifer, illustrating the importance of subsurface groundwater storage for future groundwater supplies.

Available groundwater is the total amount of groundwater of adequate quality stored in the subsurface. However, this simple definition is not adequate to describe the complexities of groundwater occurrence and use, particularly in Alabama where complex geologic/hydrologic relationships are common. Groundwater sustainability may be defined as the development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. The term safe yield should be used with respect to specific effects of pumping, such as water level declines or reduced stream flow. Thus, safe yield is the maximum pumpage for which the consequences are considered acceptable.

Groundwater sustainability is based on the rate of water removal, volume of water available (water in storage and rate of replenishment), and the ability of an aquifer to yield water (effective porosity). In confined aquifers with acceptable rates of groundwater production, water is removed and hydraulic head declines, yet aquifers remain fully saturated and potentiometric surfaces remain above the stratigraphic tops of geologic units. Therefore, useable aquifer storage is the volume of water that can be removed while maintaining head above the stratigraphic top of the aquifer.

Volumes of available groundwater in storage for major confined aquifers in the project area were estimated by multiplying values of storativity (volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head) by the average hydraulic head above the stratigraphic top of the aquifer and the confined aquifer area. Estimated values of groundwater in storage include fresh water only (less than 250 milligrams per liter chloride). Groundwater in storage for the Lower Cretaceous undifferentiated is about 2.2 billion gallons. Currently, Lower Cretaceous sediments are not developed as water sources in Alabama. However, evaluations of electric and geophysical logs and drill cutting descriptions in oil and gas test wells in the project area indicate that Lower Cretaceous sediments may have future potential as sources of fresh water. Groundwater in storage in the Coker aquifer is about 2.2 billion gallons; Gordo and Eutaw, 2.1 billion gallons; Ripley, 437 million gallons; Clayton and Salt Mountain, 931 million gallons; and Nanafalia, 117 million gallons.

A capture zone is the area of groundwater contribution to a water well. Knowledge of capture zones is used to construct wells with proper spacing and production rates to avoid over production and excessive aquifer drawdown. Also, it is important to know the area of groundwater contribution to a well so that contaminant sources may be monitored and controlled. Capture zone analysis provides critical information for groundwater source development and infrastructure planning.

Optimum well spacing, based on capture zone analysis, for selected aquifers in southeast Alabama along strike (east-west) are 1.5 miles for the Gordo and Tuscahoma aquifers and 1.0 mile for the Ripley, Clayton, Nanafalia, Tallahatta, Lisbon, and Crystal River aquifers. Optimum spacing in the up or down gradient direction (north-south) are 2.5 miles for the Ripley and Tuscahoma aquifers, 2.0 miles for the Gordo, Clayton, and Nanafalia aquifers, 1.5 miles for the Tallahatta aquifer, and 1.0 mile for the Lisbon and Crystal River aquifers.

Sustainable groundwater yield may be defined as: “The groundwater extraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social, and environmental values.” The groundwater extraction regime consists of wells in a specified area, producing at specified rates, for specified periods of time, in a specified aquifer or group of aquifers, and the impacts of these wells on groundwater levels, and/or surface water bodies. Sustainable yields may include groundwater extraction rates greater than recharge rates, depending on groundwater levels, rates of groundwater level drawdown, available groundwater in storage, impacts of groundwater extraction from unconfined or partially confined aquifers on surface-water levels or flows, and an extraction period that allows for reduced pumping or down time that provides time for aquifers to replenish. Levels of acceptable stress must be determined that provide balance between economic, social, and environmental needs. Generally, groundwater extraction regimes characterized by wells with adequate spacing, wells constructed in multiple aquifers, if available, and extraction rates that prevent excessive water level drawdown, will acquire acceptable levels of aquifer stress and will be sustainable for the long term. Aquifer stress areas in southeast Alabama are generally in and near population centers where water demand is high and where relatively large numbers of high capacity wells are extracting groundwater in close proximity. Based on these evaluations, a number of areas in southeast Alabama have readily identifiable aquifer stress, yet no well or group of wells in southeast Alabama currently has an unacceptable level of stress.

In order to ascertain the sustainability of groundwater resources in a specified area, available volumes of groundwater of adequate quality must be compared to current groundwater use. As mentioned previously, current water use values are not available. Therefore, total volumes of available groundwater in subsurface storage and confined aquifer recharge were compared to 2005 water use values in the assessment area. An exact comparison is not possible, since groundwater use data are compiled for geographic areas and are not available for specific aquifers. However, improved insights into groundwater availability and current groundwater production impacts can be developed by comparing available information. Unconfined or partially confined recharge was not included in the comparison, since water use from unconfined aquifers in southeast Alabama is relatively minimal. Also, groundwater use data includes all aquifers, which are compared to groundwater availability values for selected aquifers.

Total available groundwater in subsurface storage for all assessed confined aquifers (Lower Cretaceous, Coker, Eutaw/Gordo, Ripley, Clayton/Salt Mountain, and Nanafalia) is about 8.0 billion gallons and the Gordo, Ripley, Clayton, and Nanafalia aquifers are being replenished at a rate of 117.0 mgd. This is compared with total 2005 groundwater use for 13 counties in the assessment area, which is about 123 mgd. Therefore, when confined recharge rates for minor aquifers are considered, 2005 groundwater use is equivalent to confined recharge.

GROUNDWATER AVAILABILITY IN SOUTHEAST ALABAMA: SCIENTIFIC DATA FOR WATER RESOURCE DEVELOPMENT, PROTECTION, POLICY, AND MANAGEMENT

A DEMONSTRATION ASSESSMENT

FOR GOVERNOR ROBERT BENTLEY AND THE PERMANENT JOINT LEGISLATIVE COMMITTEE ON WATER POLICY AND MANAGEMENT

INTRODUCTION

The economic future and quality of life for Alabamians is dependent upon the availability and protection of the state's natural resources. The most basic and essential of these are water resources. Planning for prudent development and protection of Alabama's water resources requires comprehensive knowledge of factors such as location and volume of available water, current water use, and projected future water demand. The following report is an initial regional assessment of groundwater resources in southeast Alabama and is part of an ongoing statewide assessment. This assessment, along with an assessment of surface-water availability being performed by the Alabama Department of Economic and Community Affairs Office of Water Resources, was mandated as part of an initiative by Governor Robert Bentley and the Permanent Joint Legislative Committee on Water Policy and Management to develop a statewide water resource management plan and future water policy legislation.

Groundwater is an essential resource in Alabama, especially for public water supplies, where about 40 percent (%) (by volume) and about 70% (by geographic area) originates from groundwater sources. Groundwater is well suited as potable water sources for much of the state due to its minimal treatment requirements, relatively small development and production costs, and insusceptibility to drought and surface contamination. Alabama has 25 major aquifers that receive replenishment from recharge areas that cover most of the land surface of the state. Recharge areas are the basis for groundwater/surface-water interaction and serve to provide surface-water base flow that supports stream discharge and reservoir levels, wetlands, and biological habitats and species throughout Alabama.

This assessment of groundwater in southeast Alabama includes data concerning stratigraphy, hydrogeologic characteristics, current groundwater development and future groundwater development potential, production impacts, and groundwater availability and recharge. These data provide comprehensive knowledge of this critical water resource that will provide a foundation in support of prudent future water management and policy decisions. Capture zones were modeled for 120 wells constructed in eight major aquifers in southeast Alabama. Hydrologic data were collected from GSA well files, open-file reports, and field assessments. Input data to the model included well location, aquifer confinability, transmissivity, hydraulic gradient, flow direction, the quantity of water production, production time, and aquifer thickness.

ACKNOWLEDGMENTS

The Geological Survey of Alabama Groundwater Assessment Program acknowledges those individuals and entities that made this work possible. Governor Robert Bentley and the Permanent Joint Legislative Committee on Water Policy and Management (Senator Arthur Orr and Representative Alan Booth, Co-Chairs) provided the impetus and vision for this work in addition to making funds available for its completion. Dr. Berry H. (Nick) Tew, Alabama State Geologist, provided leadership and guidance. The Choctawhatchee, Pea and Yellow Rivers Watershed Management Authority (Ms. Barbara Gibson, Executive Director) is a long-time partner in the collection of water-related scientific data in southeast Alabama. Other contributors include Mr. Brian Atkins, Mr. Tom Littlepage, and Mr. Dow Johnston with the Alabama Department of Economic and Community Affairs Office of Water Resources and numerous local government officials, water system personnel, and citizens who provided data and assistance.

PURPOSE AND SCOPE

The assessment area for this project includes all or parts of 19 counties in southeast Alabama and includes over 400 wells. The primary source of water supplies in this area is groundwater, originating from 11 major and minor aquifers consisting of sand, limestone, and interbedded clay of Tertiary and Cretaceous age. Major aquifers in the region include the Gordo, Ripley, Clayton and Nanafalia Formations, and the Salt Mountain Limestone (fig. 1).

The purpose of this report and the scientific research on which it is founded is to provide hydrogeologic data for stakeholders and decision makers to formulate policy and management strategies for Alabama's water future. Utilization of scientific data as a basis for water resource management is a prudent approach that can prevent needless, costly, and inappropriate management decisions that may damage the future availability of this critical resource. Conclusions and recommendations drawn from this research include current groundwater availability, development, and production impacts and future groundwater development potential and strategies.

Assessments of current and future projected aquifer conditions include drawdown, long-term rates of water level decline in wells, comparisons of current hydraulic head levels to tops of screened intervals in wells, and quantities of water in subsurface storage for each aquifer. Additional insights may be acquired by comparisons of current aquifer conditions with current water use and future projected water demand. Current groundwater production impacts in southeast Alabama occur in areas of hydraulic head drawdown consisting of multiple wells in population centers related to public water supply and in single wells in rural areas related to public water supply, agricultural or industrial water use. Development of strategies for future groundwater source development rely on spatial interpretations of current and future projected aquifer characteristics including hydraulic conditions, stratigraphic characteristics, and groundwater availability.

One purpose of the groundwater assessment is to generate spatial data based on hydrogeologic and well characteristics that may be used for future groundwater source development. Parameters for this purpose for each identified aquifer in the assessed area include well depths, depth to water, pumping rates, specific capacities, and net potential productive intervals. These data may be used by public water systems, citizens, industries, and agricultural interests to determine locations and specifications for water well construction. To observe specific information related to groundwater source development, see text in the body of the report.

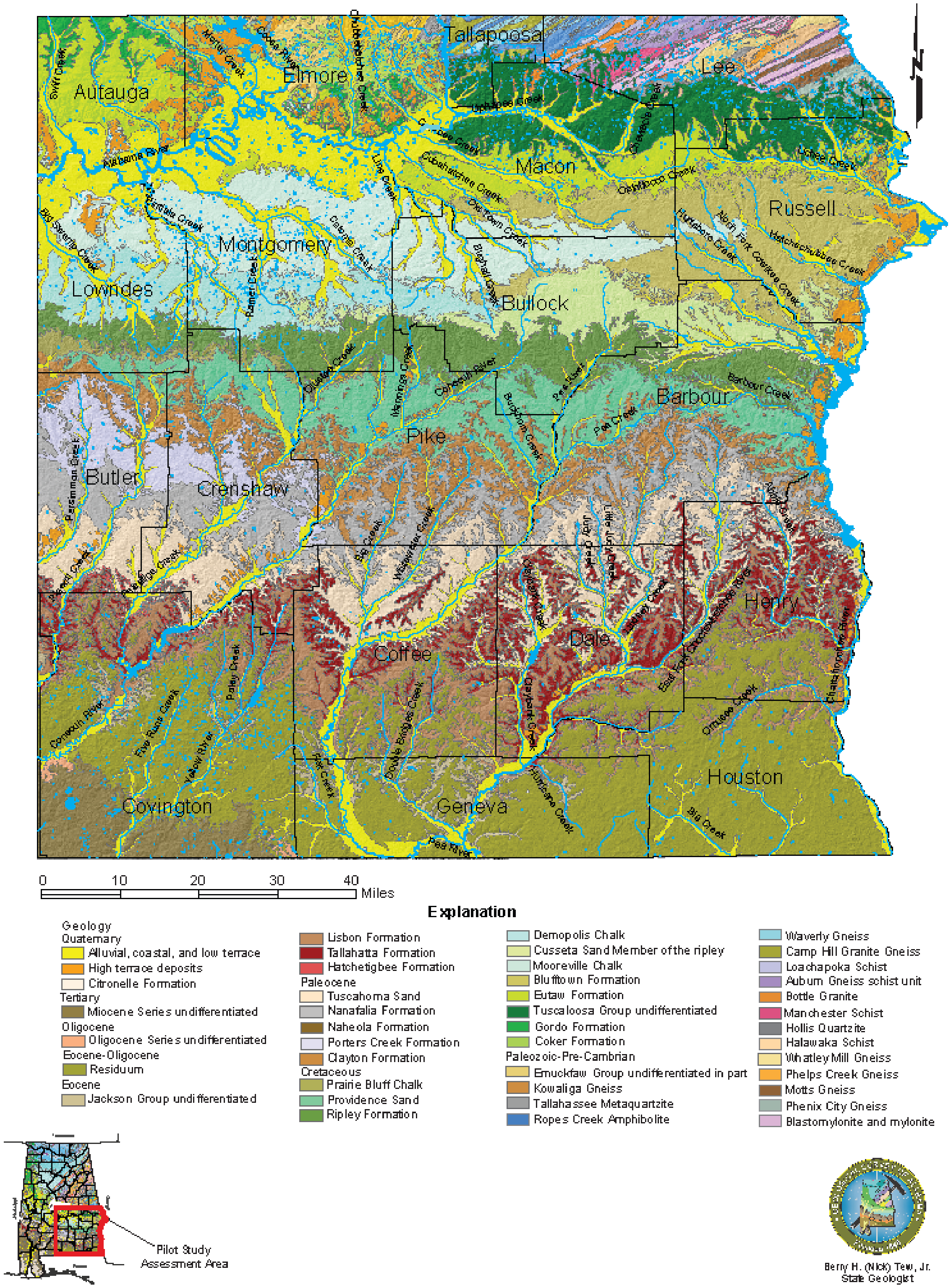


Figure 1.—Study area in the southeast Alabama project area.

Another purpose of the assessment is to evaluate historic and current groundwater levels to determine hydraulic characteristics and to observe climatic and water production impacts for selected aquifers in the assessed area. This is accomplished by construction of potentiometric surface maps. A potentiometric water level is the elevation to which water rises in a properly constructed well that penetrates a confined aquifer. The potentiometric surface is an imaginary surface representing the confined pressure (hydrostatic head) throughout all or part of a confined aquifer. This surface is helpful in determining directions of groundwater movement, hydraulic gradients, and depths from which water can be pumped at particular locations. When water is removed from an aquifer by pumping or by reductions in recharge, the potentiometric surface will fluctuate accordingly (drawdown/production or climatic impact). The difference between pre-pumping static water levels and partially recovered water levels affected by pumping is termed residual drawdown. Areas with closely spaced wells create “cones of depression” where individual well impact areas coalesce to form relatively large potentiometric surface impacts that may cover tens of square miles. It is important to note that as long as the potentiometric surface remains above the stratigraphic top of the aquifer, the aquifer media remains saturated so the declining surface only represents a decline in hydrostatic pressure. If the water level declines below the stratigraphic top of the aquifer, it becomes unconfined, possibly causing irreversible formation damage. Presently, no known water levels in southeast Alabama are in danger of declining below the stratigraphic top of any aquifer. Therefore, potentiometric surfaces and residual drawdown values provide important information to determine the affects of water production, strategies for water source protection, and future water availability.

An additional purpose of the assessment is to evaluate long-term rates of groundwater level fluctuation in specific wells, in particular locations. Groundwater levels fluctuate almost continuously in response to recharge to and discharge from aquifers by natural and artificial processes, which can include pumpage from wells, natural groundwater discharge, recharge from changing rates of precipitation, and evapotranspiration. GSA maintains water level files for about 450 wells and springs throughout Alabama, including wells and springs in the GSA real-time monitoring system that can be accessed on the GSA website at http//www.gsa.state.al.us/. Water levels in most of these wells have been measured semiannually or annually for more than 15 years with many having records of more than 30 years. Groundwater levels in a select group of these wells were used to construct hydrographs (graphical illustrations of water level fluctuations over a specified time period). Wells were selected to illustrate various aquifer drawdown trends and to document temporal and spatial characteristics of declining groundwater levels in major pumpage centers in southeast Alabama.

AQUIFER AND WATER WELL CHARACTERIZATION METHODOLOGY

HYDROGEOLOGY

Geologic strata or beds in the subsurface that contain the highest percentages of sand and/or limestone and conversely the lowest percentages of silt and clay are most likely to contain economic quantities of water. Groundwater in these strata is contained in intergranular pore spaces (storage) and has the critically important property of interconnectedness of the porosity (permeability) to allow water to flow through the sediments to wellbores (transmissivity). Thus, locating porous and permeable sand and limestone beds within geologic formations and determining where they are thickest are important factors in predicting which geographic areas and geologic units have the greatest potential for containing and subsequently producing economic quantities of groundwater.

Sixteen geologic units in the Cretaceous and Tertiary Systems, varying in age from about 135 to 36 million years, underlie the project area (figs.2, 3). However, only 12 of these have hydrogeologic characteristics that define them as aquifers and, of these, 8 are major aquifers capable of producing adequate quantities of water for sustainable public, industrial, or irrigation water supply. Major aquifers include the Gordo Formation (including the hydraulically connected Eutaw Formation), Ripley Formation (including the Cusseta Sand Member), Clayton Formation (including the hydraulically connected Salt Mountain Limestone (in subcrop only)), Nanafalia, Lisbon, and Crystal River Formations (figs. 2, 3). The Tallahatta Formation, Tuscahoma Sand, and Providence Formation are minor aquifers and are primarily developed for domestic or livestock supplies (figs. 2, 3). The Coker Formation has limited geographic extent due to

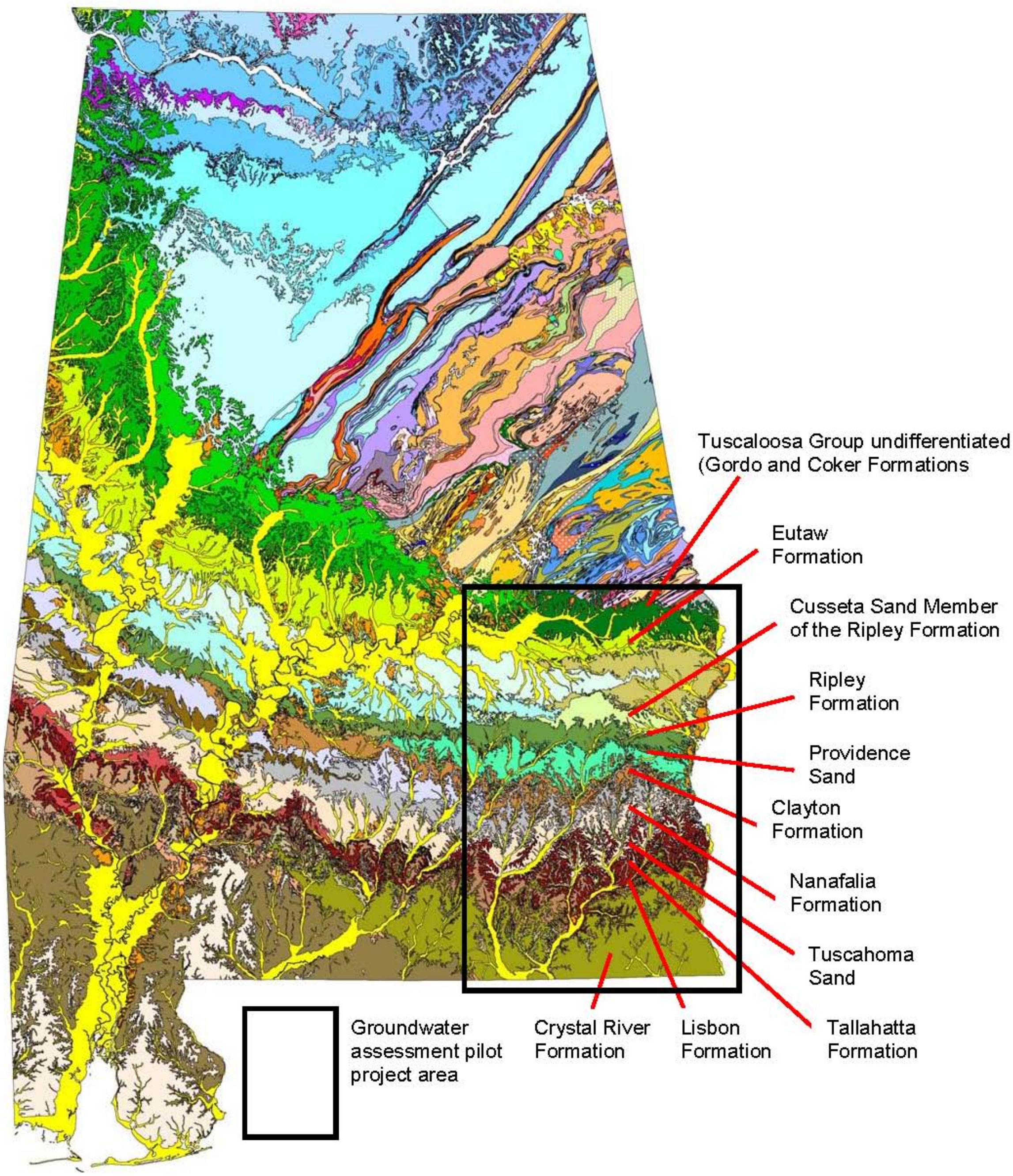


Figure 2.—Recharge areas for aquifers in the southeast Alabama project area (modified from Szabo and others, 1988).

unsuitable water quality (excessive chlorides). The undifferentiated Lower Cretaceous (in subcrop only) was also evaluated and may be a future source of groundwater (figs. 2, 3).

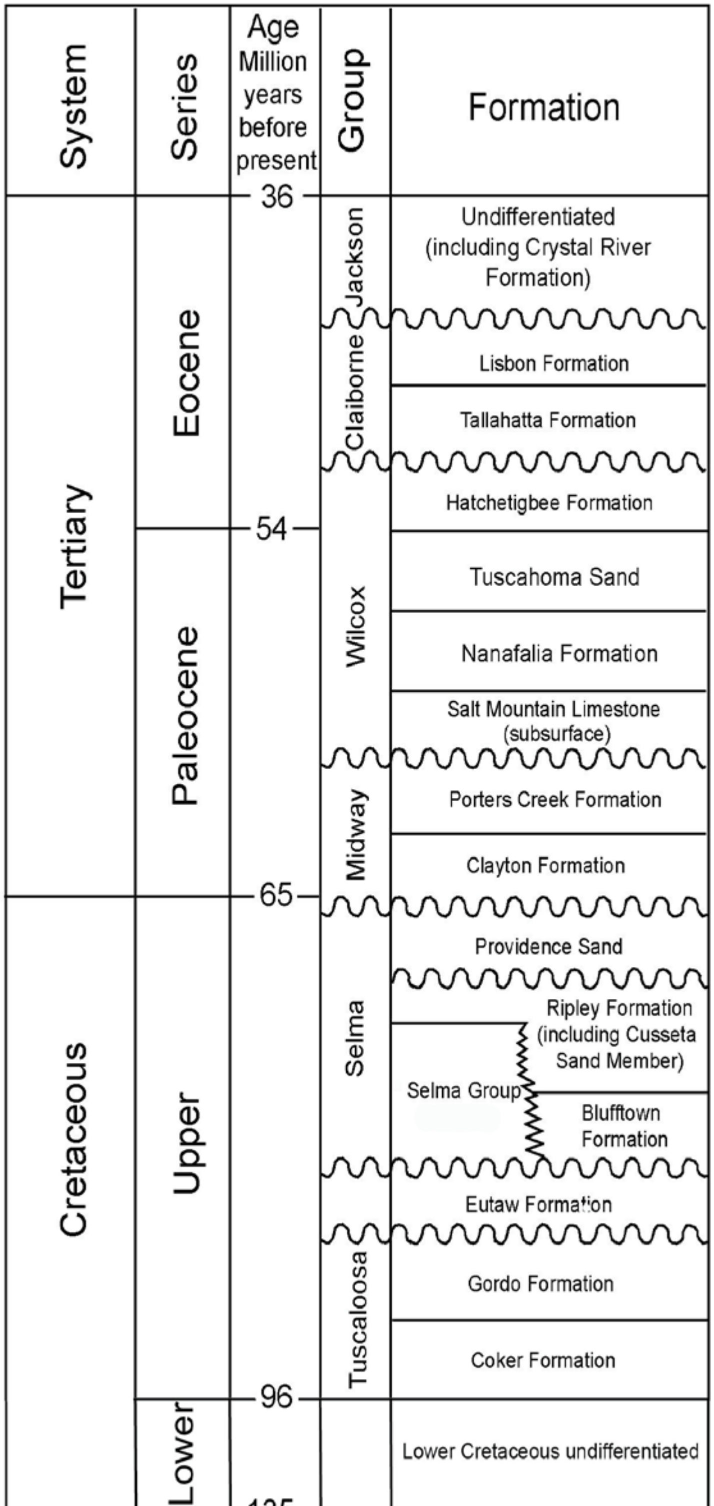


Figure 3.—Generalized stratigraphy of southeast Alabama.

WELL DEPTH

Well depth is generally constrained by limiting factors such as the cost associated with drilling wells and the quantity and quality of water required by the well supply. Well construction costs are directly related to well depth. Therefore, knowledge of well depths in particular areas can help reduce unnecessary construction costs. Depths of wells constructed in a particular aquifer generally correlate with the dip of the geologic formation, so that depths increase as the distance from the formation outcrop increases. The depth of a well is also important as related to the quantity and quality of water. Wells may need to be constructed at depths sufficient to provide adequate water quantity and quality, which relates to the intended use of the well.

Across the project area, identified well depths vary from 21 to 2,736 feet (ft), depending on location and aquifer. The majority of identified wells in the project area are located in the Gordo aquifer, which extends from Lee, along the northern margin of the study area, to northern Dale, and Henry Counties. The smallest number of identified wells are located in the Tallahatta aquifer, which outcrops in northern Covington, central Coffee, central and northern Dale, and central and northern Henry Counties.

DEPTH TO WATER

Depth to water data are necessary to produce potentiometric surface maps from which aquifer dynamics such as hydraulic head and gradient can be determined. When subtracted from the well head elevation, depth to water yields a water level elevation (hydraulic head). The surface created by mapping the hydraulic head is the potentiometric surface (discussed separately). Depth to water measured in wells constructed in aquifers of interest supplies valuable information to guide plans for construction of future wells. Pump size, pump setting depths, and cost to lift water to the land surface are important issues that depend on depth to water. With these data, important decisions can be made on economic feasibility and practicality of a future well.

Depth to water values were collected from wells with a chalked steel tape, or in some cases, retrieved from the original driller’s log. Water levels and well head elevations were recorded along with GPS coordinates to accurately place well locations on project plates. The water levels were then added to the plates and contoured where possible to show known and interpolated depth to water within the study area.

PUMPING RATES

Pumping rates are influenced by well performance characteristics and aquifer hydraulic properties such as permeability and transmissivity. Specific yield (discussed separately) can be determined by dividing the pumping rate by the amount of drawdown. Pumping rates and yields are useful in determining the capability of an aquifer to produce a sustained quantity of water and avoiding excessive pumping. Effects of excessive pumping (depletion) include well failure, increased pumping costs, land subsidence and possibly reduction of water in lakes and streams.

Well pumping rates were collected from original drillers log records and pumping tests. Pumping rates were contoured where possible to indicate known and interpolated rates in the study area.

SPECIFIC CAPACITY

Well discharge is largely related to aquifer characteristics, but it is also a function of the mechanical aspects of wells and the required flow rate to meet the needs of the users. Pumping rates therefore should not be considered the maximum yield of an aquifer at a given location. Water level and pumping rate data commonly are recorded as drawdown measured during a few hours of pumping at a specific rate or in some stepped progression of rates during a pumping test. From these data specific capacity can be calculated and is expressed as gallons per minute per foot of drawdown (gpm/ft).

Specific capacity data along with estimates of total dynamic head are useful in well design, wherein pump head-capacity curves can be combined with specific capacity curves to determine scenarios for well discharge rates (Driscoll, 1986). Specific capacity, though related in part to well construction and pump test factors, is also a general indicator of aquifer transmissivity, and empirical mathematical relationships and statistical measures have been developed for aquifers elsewhere to assist in groundwater development programs and well design (Robertson, 1963; Theis, 1963; Walton and Neill, 1963; Bradbury and Rothschild, 1985; Driscoll, 1986; Mace, 1997).

Larger populations in urban areas require more water than rural areas, which is shown in specific capacity data where high capacity wells are concentrated around population centers. Fewer, more widely spaced, high capacity wells are constructed in rural areas and are used for rural water utilities, agriculture, and industry. In these cases, specific capacity maps may provide inaccurate regional depictions of aquifer quality and therefore should be evaluated with other aquifer data to make accurate judgments of aquifer producibility.

Specific capacities were calculated for selected wells in the project area for each aquifer and mapped to depict the geographic distribution and magnitude of specific capacity values.

NET POTENTIAL PRODUCTIVE INTERVALS

Delineation of sand and limestone beds and determination of their thicknesses in the project area relied upon the use of geophysical well logs with the aid of drillers' logs and sample descriptions (Smith, 2001). Because geophysical well logs were acquired in a relatively small portion of the water wells and test holes drilled in the area, the analyses and interpretations presented here do not constitute a comprehensive study of all wells. Continuous recordings of measurements of the natural gamma radiation (gamma ray logs) in subsurface sediments, coupled with resistivity and spontaneous potential (SP) logs, were the principal means of determining the likely presence and thicknesses of quartz sand and limestone intervals in formations penetrated by boreholes. Gamma ray logs are not affected by formation water salinity, whereas resistivity and spontaneous potential logs are electrical measurements of the formation sediments and their contained water. Porosity measuring logging devices, typically deployed in oil and gas test wells, are rarely used in water well test holes due to costs and other considerations. These devices, as well as numerous other types of logs, have been utilized for many years in oil and gas exploration to help determine porous and permeable beds. This study presents results of a commonly used method whereby each gamma ray log is calibrated as a measure of the percent sand and/or limestone (sand and/or limestone denoted hereafter as "sand/limestone") (fig. 4). A summation of sand/limestone thickness, recorded as "net feet of sand/limestone" was determined for

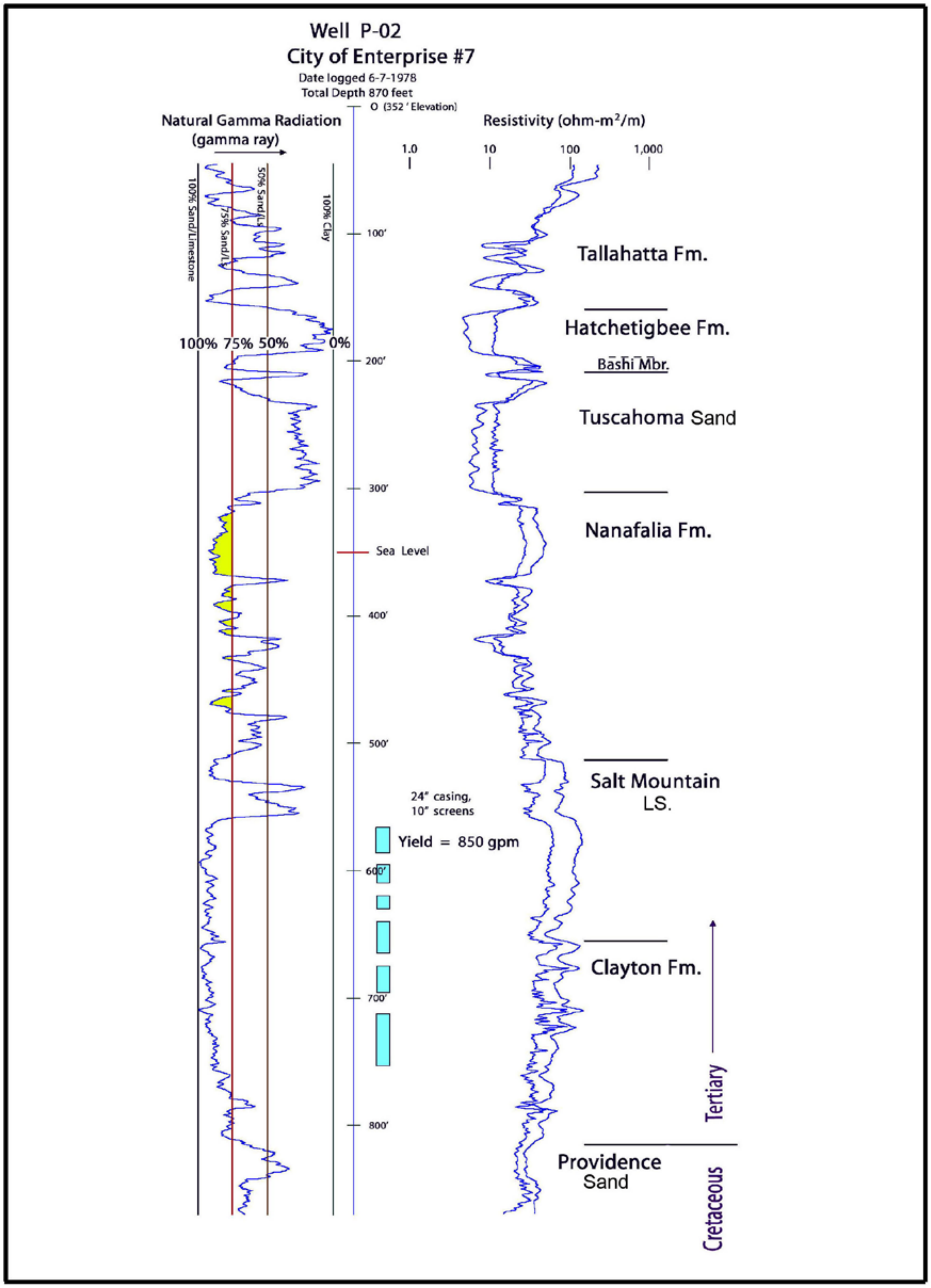


Figure 4.--Geophysical well logs illustrating method for determining net sand thickness (75% sand intervals highlighted in yellow for Nanafalia aquifer).

each well that penetrated and logged each of the major aquifers. Net feet of sand/limestone was plotted on a map and the values contoured. Net thickness of sand/limestone used for this assessment is greater than 75% for the logged interval. Limiting the net thicknesses to this high percentage of “clean” (less than 25% clay or silt-sized materials) sand/lime sediments provide indications of intervals of potential optimum aquifer quality, which are designated “net potential productive intervals” (NPPIs).

It should be noted that maps depicting NPPIs do not always coincide with thicknesses of the geologic formations. For example, it is not uncommon for a geologic formation to thicken southward in the study area, while the NPPI thins. Depositional environments, sediment supply, and post-depositional geologic events determine thickness of the geologic units and affect other characteristics such as porosity and permeability. It should also be stressed that locating areas of thick NPPI increases the probability of finding usable aquifers, but does not guarantee that desired quantities of groundwater of desired quality can be obtained.

As can be seen in figure 4, resistivity logs generally show higher resistivity values in cleaner sand intervals where fresh water is present. Although not shown in figure 4, spontaneous potential logs can be helpful as well, especially in determining bed boundaries. Use of resistivity and SP logs complement NPPI determinations, and, though less definitive, they can be used to evaluate wells in which gamma ray logs were not acquired to give a general estimate of net sand/limestone thickness. Data presented on NPPI maps (plates) in this report suggest downdip limits of water production in the aquifers are commonly a combination of NPPI thickness and water-quality (salinity) estimation from geophysical logs and limited water quality analyses.

POTENTIOMETRIC SURFACES AND GROUNDWATER LEVEL IMPACTS

A potentiometric water level is the elevation to which water rises in a properly constructed well that penetrates a confined aquifer. The potentiometric surface is an imaginary surface representing the confined pressure (hydrostatic head) throughout all or part of a confined aquifer. This surface is helpful in determining directions of groundwater movement, hydraulic gradients, and depths from which water can be pumped at particular locations (Cook and others, 2013). When water is removed from the aquifer by pumping or by reductions in recharge, the potentiometric surface will fluctuate accordingly (drawdown/production or climatic impact) (fig. 5). The difference between pre-pumping static water levels and partially recovered water levels affected by pumping is termed residual drawdown (Driscoll, 1986). It is important to note that as long as the potentiometric surface remains above the stratigraphic top of the aquifer, the aquifer media remains saturated so the declining surface only represents a decline in hydrostatic pressure. If the water level declines below the stratigraphic top of the aquifer, it becomes unconfined, possibly causing irreversible formation damage. Presently, no known water levels in southeast Alabama are in danger of declining below the stratigraphic top of any aquifer. Therefore, potentiometric surfaces and residual drawdown values provide important information to determine the affects of water production, strategies for water source protection, and future water availability (Cook and others, 2013).

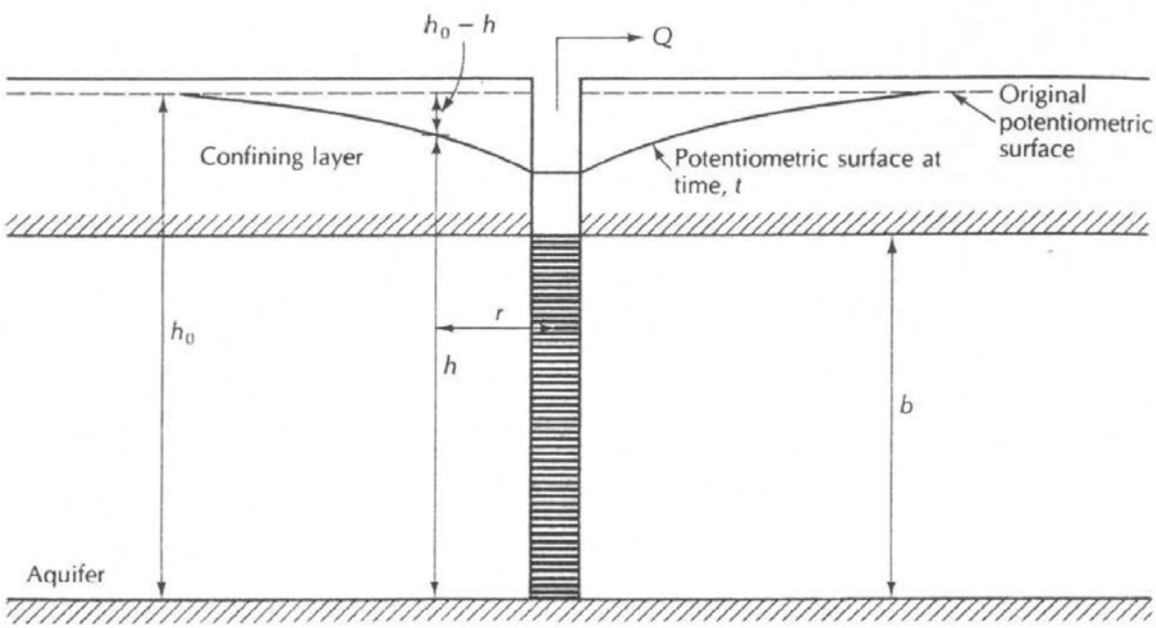


Figure 5.—Diagram depicting drawdown and potentiometric surfaces prior to and after pumping in a confined aquifer (modified from Fetter, 1994).

Groundwater levels and production impacts were evaluated using three maps prepared for each aquifer. Initial static water levels (depth to groundwater at or near the time of well construction) were obtained from over 427 well reports and drill logs. Water levels were adjusted for mean sea level elevation, plotted according to location, and contoured to create an initial static potentiometric surface map. Evaluation of initial static groundwater levels enables understanding of groundwater conditions prior to or in early stages of pumping.

A current potentiometric surface map was prepared using current water levels from all available wells in the project area for each aquifer. Wells were identified from GSA well files and Alabama Department of Environmental Management (ADEM) list of public water supply systems. Current depth to groundwater measurements were made using steel tape or air line measurement devices, the water levels were adjusted for mean sea level elevation, plotted according to location, and contoured to create a current potentiometric surface map. Evaluation of current groundwater levels enables understanding of current groundwater conditions and calculations of current groundwater storage volumes.

Comparing initial static groundwater levels with current levels enables the calculation of aquifer drawdown, and characterization of production and/or climactic impacts and changes in groundwater yield. Impacted areas with adequately spaced wells have isolated water level impacts related to individual wells. Areas with closely spaced wells create “cones of depression” where individual well impact areas coalesce to form relatively large potentiometric surface impacts that may cover tens of square miles. Impact assessments are essential to understand the geographic extent of impact areas and the potential for additional, future development of groundwater from specific aquifers and locales.

HYDROGRAPHS AND AQUIFER DECLINE CURVES

Groundwater levels fluctuate almost continuously in response to recharge to and discharge from aquifers by natural and artificial processes, which can include pumpage from wells, natural groundwater discharge, recharge from changing rates of precipitation, and evapotranspiration (DeJarnette and others, 2002). GSA maintains water level files for about 450 wells and springs throughout Alabama. Water levels in most of these wells have been measured semiannually or annually for more than 15 years with many having water level records of more than 30 years. Groundwater levels in a select group of these wells were used to construct hydrographs (graphical illustrations of water level fluctuations over a specified time period). Wells were selected to illustrate various aquifer drawdown trends and to document temporal and spatial characteristics of declining groundwater levels in major pumpage centers in southeast Alabama.

Generally, all wells with significant pumping rates will exhibit water level declines due to the fact that water can be pumped faster than it can move through aquifer material to the well bore (fig. 5). Most hydrographs will have two regression line frequency signatures. One is a long wave length related to pumpage or long-term drought. The other is an overprinted short wave length related to seasonal changes in recharge.

Groundwater levels, measured and recorded throughout the life of a well, can be displayed on a hydrograph that shows the history of groundwater level fluctuation. Hydrographs can be used to explain impacts of aquifer confinement, drought, pumpage, and well efficiency. Regression lines constructed from individual water level measurements collected over many years describe long-term trends of groundwater fluctuation. In areas where water levels indicate long-term declines, regression lines are termed “decline curves.” Multiple hydrographs and decline curves in specific areas and aquifers can be used to evaluate groundwater production impacts and depressions in potentiometric surfaces, commonly known as “cones of depression,” to estimate changes in groundwater storage, and to predict future groundwater availability.

AQUIFER AND WATER WELL CHARACTERISTICS

LOWER CRETACEOUS UNDIFFERENTIATED

HYDROGEOLOGY

Lower Cretaceous sediments overlie metamorphic and igneous crystalline rocks in southeast Alabama. Pink nodular limestone fragments and red and green clay near the top of the unit distinguish it from the massive sands of the overlying upper Cretaceous

Coker Formation of the Tuscaloosa Group (Davis, 1987). The total thickness of Lower Cretaceous sediments is known to reach more than 7,000 ft in Mobile Bay (Maher and Applin, 1968). Sediments of Early Cretaceous age do not crop out in Alabama, but thin northward and pinch out in the subsurface south of the Fall Line. The thickness of Lower Cretaceous sediments was documented in the following wells:

- the Scientific Resources Schuessler 18-7 well (Alabama Oil and Gas Board permit number 4903) in southwestern Bullock County, which penetrated about 650 ft before reaching total depth in crystalline rocks at 2,678 ft (-2,158 ft relative to mean sea level (MSL)),
- the Capitol Oil and Gas Company Gholson #1 well (Alabama Oil and Gas Board permit number 86) in northwestern Bullock County, which encountered about 430 ft before reaching total depth in crystalline rocks at a depth of 1,712 ft (-1,452 MSL), and
- the #1 Earl Capps 15-6 well (Alabama Oil and Gas Board permit number 3659) in central Henry County, which encountered Lower Cretaceous sediments at 3,260 ft (-2,837 MSL) and penetrated the entire unit (2,500 ft) before encountering crystalline granite.

Descriptions of drill cuttings by Alabama State Oil and Gas Board personnel indicate that Lower Cretaceous sediments are composed of alternating sand, gravel and clay layers. Sands are described as medium to very coarse grained with abundant gravel and large pink feldspar crystals. Clays are purple, red, brown, and green and are micaceous.

Although there is currently no water production from the Lower Cretaceous in Alabama, the geophysical log in the Schuessler 18-7 well indicates that the Lower Cretaceous sediments contain numerous sand layers with relatively high resistivities that may be capable of yielding economic quantities of fresh water. The Lower Cretaceous may be considered as a water exploration target for future water source development. Since there is currently no water production from the Lower Cretaceous and it has no recharge area in Alabama, the only aquifer characteristic that was evaluated for this project was an estimation of available fresh water in subsurface storage.

TUSCALOOSA GROUP

COKER FORMATION

HYDROGEOLOGY

The Coker Formation typically composes the lower part of the Tuscaloosa Group in most of Alabama. However, Tuscaloosa sediments exposed in Macon, Lee, and Russell Counties are undifferentiated and are mapped as Tuscaloosa Group undifferentiated (Szabo and others, 1988) (fig. 2). Smith (2001) recognized a threefold subdivision of Tuscaloosa sediments in southeast Alabama that included the lower Tuscaloosa Coker Formation and overlying upper Tuscaloosa Gordo Formation separated by the "middle marine shale." This well-defined stratigraphic separation was observed throughout southeast Alabama in oil and gas exploratory wells and water wells and was adopted for this research. Smith (2001) stated that the maximum thickness of the Coker Formation in southeast Alabama is about 400 to 450 ft. Descriptions of drill cuttings from the Capitol Oil and Gas Company Gholson #1 well in northwest Bullock County combined with geophysical log correlations indicate that the top of the Coker Formation was encountered at a depth of about 1,100 ft (-840 ft MSL) and the unit is about 220 ft thick, which indicates that the unit is thinning significantly northward toward the outcrop. Correlations from geophysical log data in the Schuessler 18-7 well in southwest Bullock County indicated that the top of the Coker Formation is at 1,780 ft (-1,260 ft MSL) and the unit is about 250 ft thick. Smith (2001) stated that the average rate of dip for the Coker Formation in southeast Alabama is about 42 feet per mile (ft/mi). However, data from Bullock County shows that the rate of dip is about 59 ft/mi, which indicates that the rate of dip increases northward as the formation nears the outcrop.

Smith (2001) described Coker sediments as light-gray to reddish-orange, ferruginous-stained, poorly sorted, invariably etched sand with trace amounts of coarse muscovite mica, igneous and/or metamorphic rock fragments, and coarse grains of orthoclase feldspar with grain size from fine to very coarse (0.03 to 2.0 millimeters (mm)), and gravel that is generally pale-pink to grayish-orange, usually somewhat rounded, and granular (2 to 4 mm) to rarely pebble (4 to 32 mm) in size. Interbedded clays are finely muscovitic, noncalcareous, silty, and varicolored yellow, orange, red and purple. The formation is described by Alabama Oil and Gas Board personnel from Bullock County well cuttings as alternating sand, gravel, sandy clay, and clay layers. Sands are fine to very coarse grained and micaceous. Clays are green, reddish brown, purple, and gray, micaceous, and carbonaceous. The Coker Formation is a minor aquifer in southeast Alabama and is limited to the northern part of the project area due to saline water in the formation in the southern part of the area. Due to the limited extent of the aquifer and its undifferentiated designation in outcrop, the only aquifer characteristic that was evaluated for this project is an estimate of fresh water in subsurface storage.

GORDO FORMATION

HYDROGEOLOGY

The Gordo Formation is the upper unit of the Tuscaloosa Group and, although it is undifferentiated in outcrop in east Alabama, it is well defined from drill cuttings and geophysical log character in the subsurface. The base of the unit is defined as the contact with the "middle marine shale." The upper contact with the Eutaw Formation is mainly defined by sediment color and relatively massive clay layers in the Gordo related to the different environments of deposition of the two units. However, identification of the contact between the Eutaw and underlying Gordo is more problematic in east Alabama than further west. The origin of the Eutaw Formation is primarily marginal marine whereas the Gordo originates from fluvial deposition (Cook, 1993). The basal Eutaw is composed of a regionally persistent massive sand layer with marine material including shell fragments, aragonite, and glauconite and colors from gray to buff. The top of the Gordo is nonfossiliferous and is characterized by relatively massive, varicolored (orange, brown, red, pink, and purple) clays, coarse-grained sand, and gravel. The Gordo Formation was encountered in the Ozark Utilities well in northern Dale County at a depth of 2,340 ft (-1,815 ft MSL) where it is 430 ft thick. In contrast, the Gordo in southwest Bullock County in the Schuessler 18-7 well was penetrated at 1,180 ft (-660 ft MSL) and was 500 ft thick and in the Gholson #1 well in northeast Bullock County at 525 ft (-265 ft MSL) where it was 475 ft thick. Smith (2001) reported that the dip of the Gordo Formation in Coffee, Dale, and Henry Counties is to the south-

southwest at about 35 ft/mi. The Gordo dips south-southwest at about 40 ft/mi in southern Bullock County but increases to about 48 ft/mi in the northern part of the county as it nears the outcrop. The undifferentiated Tuscaloosa Group, including Gordo sediments is exposed on the surface (recharge area) in east Alabama from northern Russell and southern Lee Counties westward through northern Macon County. The Gordo Formation is a major aquifer in southeast Alabama. Although individual water-producing sands are relatively thin, the accumulated contribution from the entire formation yields large quantities of excellent quality water. The downdip (southerly) limit of water production in the Gordo aquifer is due primarily to higher salinity of the formation waters downdip rather than a lack of sand and gravel to the south. However, the limit shown is currently poorly defined, with well F-07, located approximately 4 miles north of downtown Ozark, the most southerly freshwater production established to date from the aquifer at a screened depth of 2,750 ft (-2,250 ft MSL). Additional drilling and testing is needed to verify preliminary indications from geophysical well logs taken from oil and gas test holes that fresh water may exist in the Gordo farther to the south.

WELL DEPTH

Depths of identified wells constructed in the Gordo aquifer vary from less than 300 ft, southward to more than 2,700 ft (plate 1). The shallowest identified well is in northwestern Bullock County at a depth of 290 ft. The deepest identified well aquifer is in north-central Dale County at a depth of 2,736 ft. Deeper wells constructed in the Gordo aquifer may encounter water with chloride concentrations in excess of drinking water standards.

DEPTH TO WATER

Depth to water in the Gordo aquifer in the investigated area varies from 0 to more than 500 ft below land surface (bls) (plate 2). Depth to water generally increases down gradient from north to south at a rate of about 5 ft/mi. The deepest water levels are in northeast Bullock County near Peachburg and in southern Barbour County near Texasville (plate 2).

PUMPING RATES

Pumping rates were examined from area public supply wells as well as private supply and irrigation wells. Pumping rates range from 5 to over 1,000 gpm with 7 of 37 wells having pumping rates of 500 gpm or higher (plate 3). Higher capacity wells correlate with larger diameter public supply wells in Pike County and central Bullock and northern Dale Counties. There is also a higher rate well (900 gpm) just north of Baker Hill in southeastern Barbour County. The majority of the smaller capacity wells in the Gordo aquifer are in western Bullock County.

SPECIFIC CAPACITY

Plate 4 shows the specific capacities for wells constructed in the Gordo aquifer. Overall specific capacities vary from less than 1 gpm/ft in eastern Bullock County to over 13 gpm/ft in northern Dale County. Specific capacities of private wells for domestic use varied the least with most being between 1 to 3 gpm/ft. Specific capacities of public supply wells had the greatest variability ranging from less than 1 gpm/ft to just over 4 gpm/ft in Bullock County. The City of Ozark's public supply well in northern Dale County, which is the most down gradient well in the Gordo aquifer, had the highest specific capacity well at 13.1 gpm/ft.

NET POTENTIAL PRODUCTIVE INTERVALS

Net potential production intervals mapping for the Gordo aquifer in southeast Alabama indicates the thickest NPPI (about 200 ft) occurs across southern Barbour, northern Henry, Dale and Coffee, southwestern Pike, and central Crenshaw Counties (plate 5). A secondary thick NPPI trend extends south to north from northeastern Pike County (about 150 ft), through Union Springs to Fort Davis in south-central Macon County (about 100 ft) (plate 5).

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 56 private, state owned, and public water supply wells constructed in the Gordo/Eutaw aquifer. Potentiometric surface mapping indicates that the most complex groundwater flow patterns in the project area occur in the Gordo and Eutaw aquifers. From the updip limit of the Gordo aquifer in northern Macon County to central Bullock County groundwater flows in two primary directions. In western Macon County, initial static water level elevations for the Gordo-Eutaw aquifer decrease from 332.6 ft MSL at Tuskegee near the updip limit of the Gordo Formation in central Macon County to 181 ft MSL near Milstead in west-central Macon County. The hydraulic gradient for this area is 0.0027 (14.4 ft/mi) and groundwater flow is westerly into Elmore and Montgomery Counties (plate 6). This westerly flow is most likely influenced by low topography in the Tallapoosa River valley in the northwest part of the project area (plate 6). Initial static water level elevations decrease from 332.6 ft MSL at Tuskegee in central Macon County to 217 ft MSL just east of Union Springs in central Bullock County. The hydraulic gradient for this area of southern Macon and northern Bullock Counties is 0.0011 (5.8 ft/mi) and the groundwater flow is southerly. It should be noted that the potentiometric surface was depressed at Union Springs prior to the earliest initial static water levels obtained for the area (plate 6).The initial potentiometric surface map indicates that prior to 1960 Gordo and Eutaw aquifer water levels were drawn down about 40 ft and the depressed potentiometric surface area covered more than 5 mi^2.

Further south, initial static water level elevations increase from 217 ft MSL at Union Springs in central Bullock County to 230.14 ft MSL near Mount Andrew in northwestern Barbour County. The hydraulic gradient for this area is 0.0014 (7.4 ft/mi) and groundwater flow is northerly. Northerly flow is contrary to regional gradient and forms an east-west trending trough in the potentiometric surface that extends across Bullock County into Barbour County on the east and Montgomery County on the west (plate 6). This anomalous part of the potentiometric surface is positioned along the surface-water drainage divide for the Conecuh, Pea, Chattahoochee, and Alabama River watersheds and is probably a result of topographic relief (greater than 100 ft) of the east-trending escarpment that forms the drainage divide in Bullock County. Additional data and investigation will be required to document the regional extent of the anomaly.

The southern extent of anomalous northerly flow is marked by a groundwater ridge that extends through northwestern Barbour, southern Bullock, and northern Pike Counties. Southward from this “ridge,” through Pike and Barbour Counties, initial static water levels in the Gordo aquifer decrease from 230.14 ft MSL near Mount Andrew in northwestern Barbour County to 164 ft MSL in southeastern Pike County, indicating a continuation of southerly groundwater flow (plate 6). The hydraulic gradient for this area is 0.0008 (4.1 ft/mi).

The hydraulic gradient of the initial potentiometric surface decreases significantly southward from southern Pike and southern Barbour Counties. The hydraulic gradient of the aquifer in this area is 0.00002 (4.1 ft/mi) and groundwater flow continues in a southerly direction (plate 6).

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 36 private, state owned, and public water supply wells constructed in the Gordo/Eutaw aquifer. Each public water supply well had an average water-level recovery time of 12 hours prior to measurement to obtain a reasonable static water level. Many of the private wells were not in use. Private wells with operational pumps were measured without planned recovery time due to minimal pumping time and rates.

Current groundwater levels indicate significant hydrologic changes have occurred within the Gordo-Eutaw aquifer in Bullock County. The current potentiometric surface for the Gordo and Eutaw aquifers indicates that flow directions in the updip part of the aquifers are unchanged from the initial potentiometric surface. However, the hydraulic gradient for the westerly flow component has increased about 8% over the initial hydraulic gradient. The southerly flow component through Macon County is similar to the initial potentiometric surface. However, increased water production has expanded depressed potentiometric surface at Union Springs to about 160 ft of drawdown and an area of more than 50 mi^2 (plate 7).

The initial potentiometric surface for southern Bullock County indicated northerly flow. This anomalous flow pattern continues to be observed on the current potentiometric surface, although it is much less pronounced with average water levels in central Bullock County averaging about 120 ft MSL and rising to 164 ft MSL in southeastern Pike County and 180 ft MSL in central Barbour County. The hydraulic gradient for the southern part of the project area is approximately 0.0003 (1.7 ft/mi) and indicates a relatively flat potentiometric surface with very slow groundwater flow southward, similar to the initial static water levels, although well control in this part of the project area was too sparse to contour (plate 7).

GROUNDWATER LEVEL IMPACTS

Groundwater production and regional impact levels were determined from a total of 29 private, state owned, and public water supply wells constructed in the Gordo/Eutaw aquifer. Multiple disruptions in the Eutaw-Gordo aquifer potentiometric surface occurred near producing wells in the assessment area. Groundwater levels in the Union Springs area declined 115 ft in well L-5 and 164 ft in well F-1. As discussed above, the area of potentiometric impact at Union Springs is about 50 mi^2. Eufaula (eastern Barbour County) groundwater levels declined 125 ft in well K-02 and 154 ft in well V-02. Groundwater levels in well F-6 declined 86 ft in northwestern Barbour County at the State of Alabama Forestry Commission, 55 ft in well BB-02 at Clio (southwestern Barbour County), and 58 ft in well Q-19 and 54 ft in well R-01 at Troy (central Pike County), where the potentiometric surface impact area is about 18 mi^2 (plate 8).

Although declining water levels indicate water production in excess of recharge, these declines are occurring in deep, confined aquifers with high hydraulic heads, which allow adequate remaining head above the well screens, provided that water level decline rates are controlled in the future. Plate 8 also indicates the presence of a regional groundwater level decline in the Eutaw and Gordo aquifers from 60 to 80 ft in much of Bullock County. A potentiometric surface constructed by Cook (1993) from water levels measured in 1991, when compared to plate 7 shows that the potentiometric surface for the Eutaw aquifer was about 30 ft higher in 1991 than in 2013 in this area of regional decline. Water level measurement dates indicate that most of this regional decline occurred after 1980 and is not related to excessive groundwater production, but is most likely the result of less precipitation and groundwater recharge on average since 1980 (Cook and others, 2013). Figure 6 is a hydrograph for well N-7 located in rural west-central Bullock County. This well is constructed in the Eutaw aquifer, has been monitored by GSA since 1967, and illustrates the regional groundwater level decline and pre- and post-1980 annual water level decline rates. The water level in well N-7

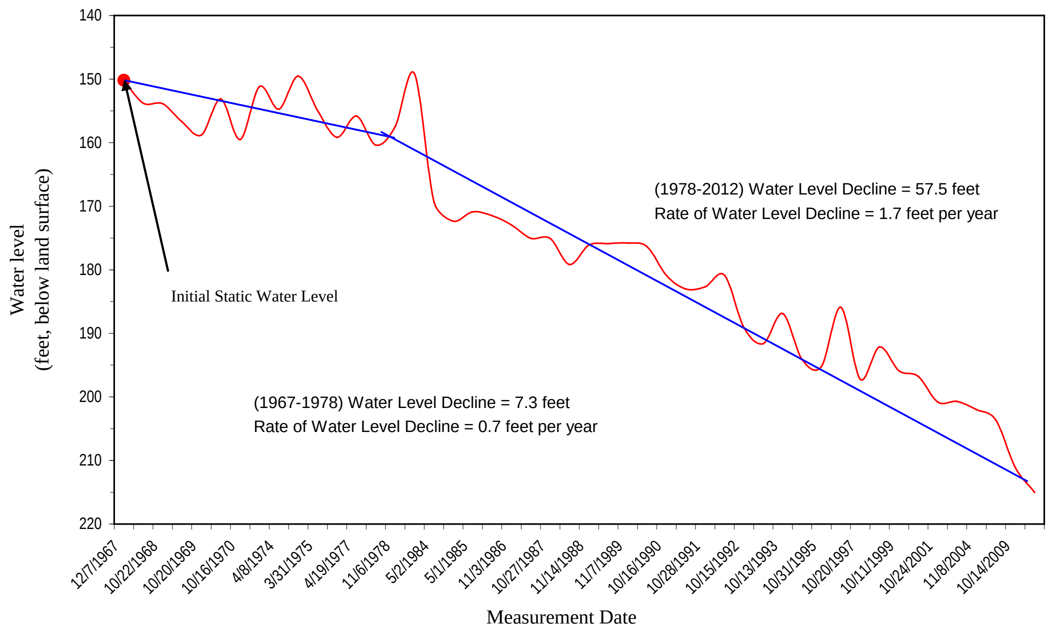


Figure 6.—Hydrograph of Bullock County well N-7, a domestic supply well constructed in the Gordo aquifer to a depth of 925 ft and open-ended.

declined 65 ft since 1967. However, the water level decline rate was 0.7 ft/yr between 1967 and 1978 but increased to 1.7 ft/yr between 1978 and 2012. An evaluation of hydrographs for more than 55 wells constructed in the Eutaw aquifer by Cook (1993) showed that water levels declined at an average annual rate 0.64 ft/year. Most of these wells were in rural areas with no production impacts.

HYDROGRAPHS AND AQUIFER DECLINE CURVES

The Gordo Formation is the major groundwater supply source for the northern part of the project area and the deepest aquifer in Alabama. The down gradient extent of fresh water in the aquifer has not yet been established, with southernmost wells in northern Henry and Dale, central Pike, and northern Crenshaw Counties. Wells constructed in the Gordo aquifer were selected from Barbour, Bullock, Dale, and Pike Counties to illustrate magnitudes of groundwater level drawdowns and rates of groundwater level declines in areas with the largest production impacts in southeast Alabama and in the deepest public water supply well in Alabama. Generally, water levels in all selected wells exhibit at least one period of decline. The largest drawdowns in the Gordo aquifer (more than 150 ft) occur in the city of Eufaula in eastern Barbour County and in the city of Union Springs in central Bullock County. City of Eufaula well K-02 has two periods of water level decline (fig. 7). The first, from 1961 to 1987, was at a rate of 3.6 ft per year (ft/yr) (fig. 7). The second, from 1987 to 1995, was 6.0 ft/yr (fig. 7). From 1995 to 2002 water level stabilized and was recovering from 2002 to 2004 (fig. 7). The top of the screened interval is 1,278 ft bls and, as of the last water level measurement on November 10, 2004 (199.1 ft bls), there was 1,078.9 ft of water above the screens in well K-02. Current water levels for this well were not available and therefore water level conditions since 2004 are not included in this assessment. It is likely that water levels in Eufaula have not recovered since 2004. However, missing water levels will be obtained and included as soon as possible.

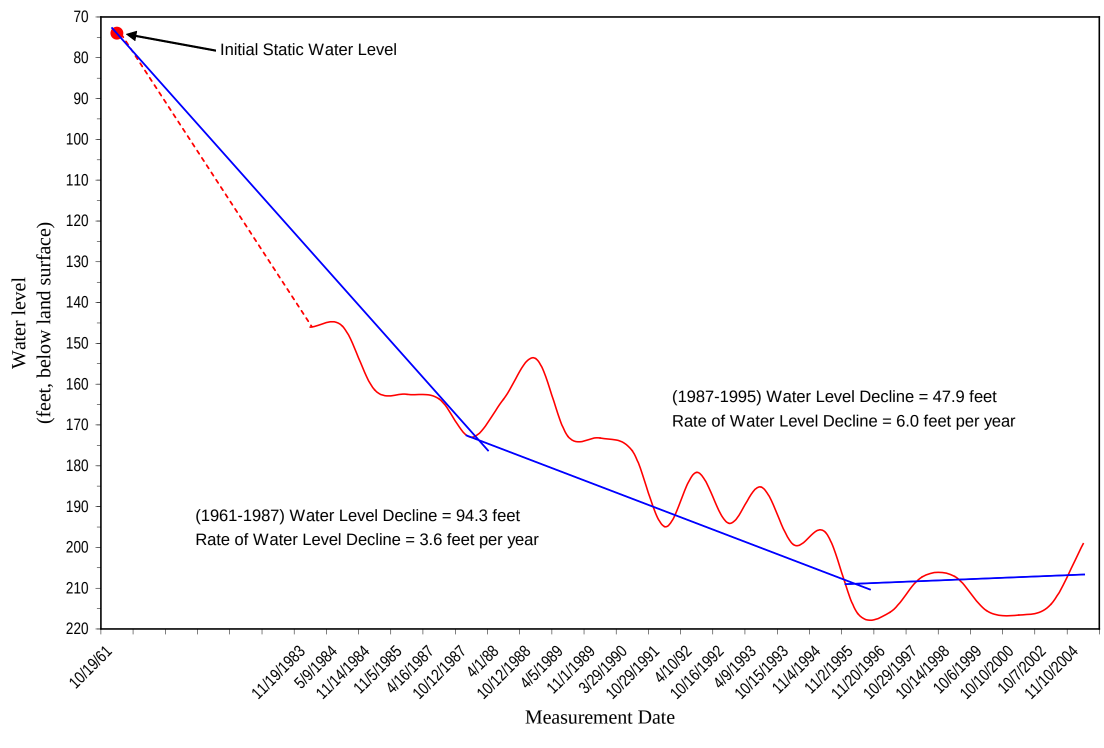


Figure 7.—Hydrograph of Barbour County well K-02, a public supply well constructed in the Gordo aquifer to a depth of 1,752 ft, with the top of the screen 1,278 ft bls.

Well N-7 in Bullock County is a domestic supply well with a water level decline of 65 ft and decline rate of 1.44 ft/yr since 1967 (fig. 6). However, unlike well F-1, well N-7 is in a large regional drawdown area that appears to be unrelated to groundwater production and is most likely a result of recurring drought and reduced recharge, as discussed previously. Well N-7 is not screened; however, the bottom of the well is 925 ft bls and, as of the last water level measurement on December 7, 2012 (215 ft bls), there was 710 ft of water in well N-7.

Bullock County well F-1 is in close proximity to city of Union Springs public supply wells and effectively serves as a monitoring well for impacts from city of Union Springs groundwater production from the Gordo aquifer. Well F-1 had a water level decline rate of 3.3 ft/year between 1961 and 2010 (fig. 8). Well F-1 is not screened; however, the bottom of the well is 882 ft bls and, as of the last water level measurement on October 19, 2010 (487.5 ft bls), there was 394.5 ft of water in well F-1.

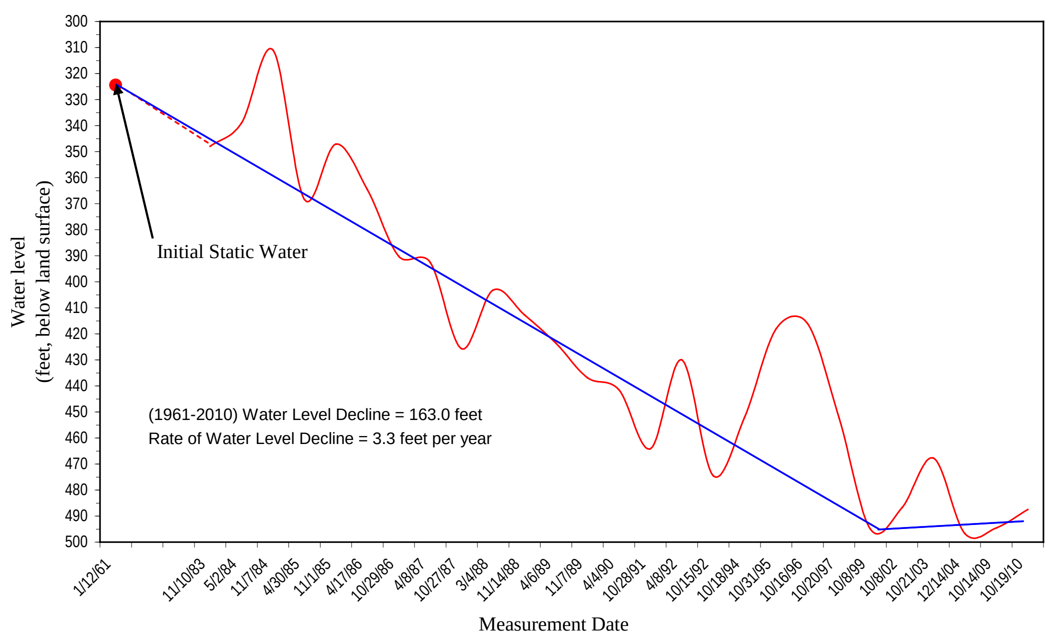


Figure 8.—Hydrograph of Bullock County well F-1, an unused well constructed in the Gordo aquifer to a depth of 882 ft and open-ended.

Well F-23 (Ozark Utilities well no. 9) in north-central Dale County is the deepest public water supply well in Alabama. The hydrograph for Well F-23 was generated from water levels provided by Ozark Utilities for the time period 2007 through July 2013 and the initial water level measured when the well was constructed in 2005. The hydrograph, from 2005 to 2007 declined at a rate of 5.3 ft/yr (fig. 9). This is due to a relatively high pumping rate during the first two years of production and severe drought conditions in 2006 and 2007, which significantly increased water demand. Since 2007 water levels fluctuated from 374 to 385 ft bls and the decline rate dropped to 0.8 ft/yr (fig. 9). The top of the screened interval is 2,260 ft bls and, as of the last water level measurement on July 1, 2013 (383 ft bls), there was 1,877 ft of water above the screens in well F-23.

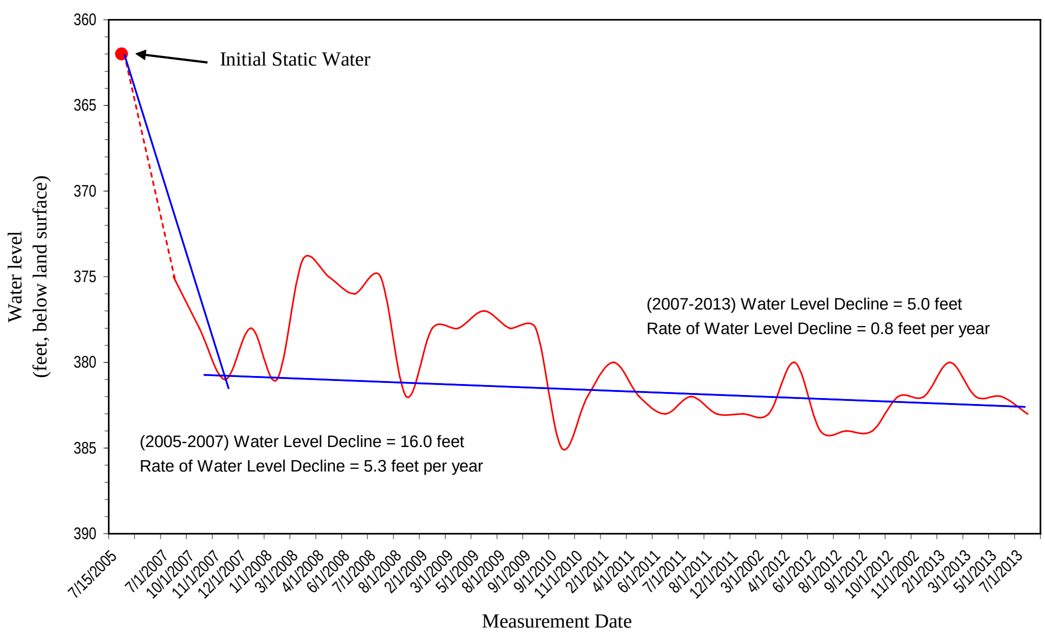


Figure 9.—Hydrograph of Dale County well F-23, a public supply well constructed in the Gordo aquifer to a depth of 2,736 ft, with the top of the screen 2,260 ft bls.

Well R-01 (City of Troy well no. 6) in Pike County is a public water supply well with three water level trends. The water level declined at a rate of 2.0 ft/yr from 1981 to 1992. The rate of decline increased to 5.0 ft/yr from 1992 to 2002. The declining trend reversed in 2002 when the water level increased at a rate of 1.7 ft/yr by 2007 (fig. 10). The water level in well R-01 declined a total of 58 ft from the initial static water level of 352 ft bls in 1981 to 410 ft bls in 2007 (fig. 10). The top of the screened interval is 1,802 ft bls and, as of the last water level measurement on October 17, 2007 (409.90 ft bls), there was 1,392.10 ft of water above the screens in well R-01.

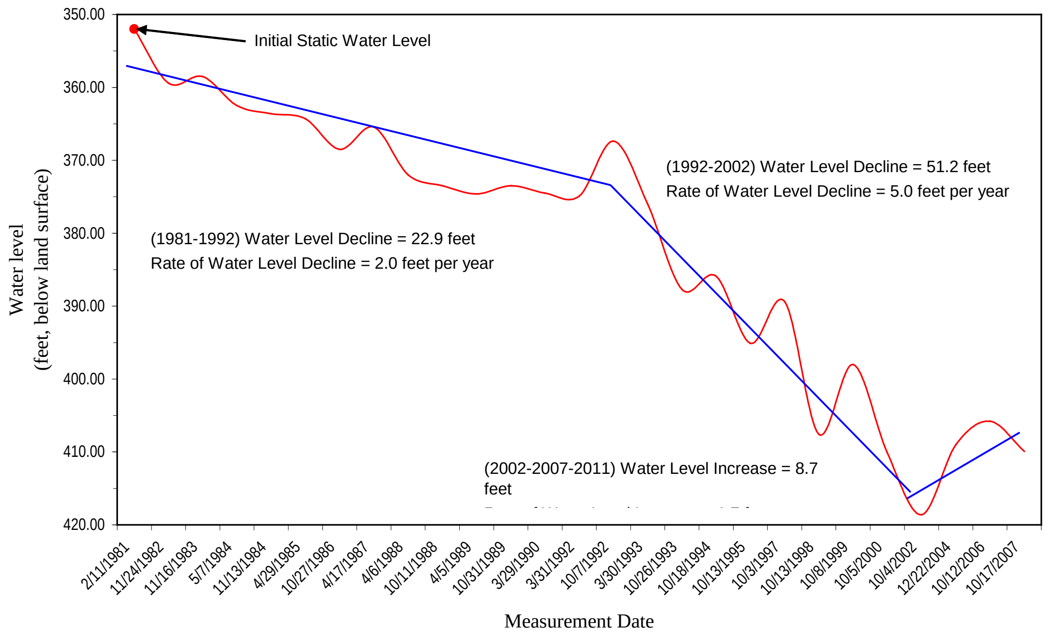


Figure 10.—Hydrograph of Pike County well R-01, a public supply well constructed in the Gordo aquifer to a depth of 2,240 ft, with the top of the screen 1,802 ft bls.

EUTAW FORMATION

HYDROGEOLOGY

The Eutaw Formation extends from west and central Alabama, where it is about 350 to 400 ft thick, to eastern Alabama where the formation thins to less than 300 ft. The formation outcrops just north of the Bullock/Macon County line (fig. 1). The Eutaw Formation is about 230 ft thick in both the Capitol Oil and Gas Company Gholson #1 well (Alabama Oil and Gas Board permit number 86) in northwestern Bullock County where the top of the Eutaw was penetrated at 30 ft MSL and the Scientific Resources

Schuessler 18-7 well (Alabama Oil and Gas Board permit number 4903) in southwestern Bullock County where the top of the Eutaw was penetrated at 420 ft MSL. The formation dips to the south-southwest at about 39 ft/mi.

Smith (2001) describes the Eutaw Formation in outcrop in east Alabama as light-gray to light-greenish-gray, glauconitic, muscovitic, fossiliferous, well-sorted, fine- to medium-grained quartzose sand with subordinate beds of thinly laminated to massive dark-gray, micaceous, lignitic and carbonaceous silty clay and clay. Smith (2001) described the subsurface Eutaw in Bullock, Pike, and Barbour Counties as very fine quartzose sandy clay and calcareous shale containing traces of glauconite and phosphatic grains with very rare pelecypod shell fragments. Clays and shales are interbedded with lenses and thin beds of indurated very fine- to fine-grained quartzose sandstone, sandy limestone, and thin beds of sand. The Eutaw is described from drill cuttings from the Capitol Oil and Gas Company Gholson #1 well in northwest Bullock County as fine-grained, micaceous sand with ostracod shell fragments, coarse-grained glauconite, and aragonite prisms and gray to greenish-gray, fossiliferous, chalky shale.

The Eutaw Formation in west and central Alabama can be divided into three distinctive lithologic layers: the lower basal sand unit, the middle Eutaw unit, and the upper Tombigbee Sand Member (Cook, 1993). In east Alabama the upper contact of the Eutaw with the overlying Blufftown Formation is not well defined and forms a gradational transition from carbonate to clastic sediment deposition. The basal sand unit is persistent and is recognized in geophysical log character across the state, including east Alabama and in Bullock County. Geophysical log character and net sand mapping suggests that the basal sand unit was deposited as a barrier island complex that extended from northeast Mississippi across much of Alabama (Cook, 1993). Potentiometric surface mapping indicates that the Eutaw Formation is hydraulically connected to the Gordo Formation. The basal sand supplies water for public water supplies throughout west and central Alabama but may only be an objective for water well drilling in southeast Alabama as an additional screened interval as part of a Gordo Formation primary objective. The Eutaw Formation is hydraulically connected to the underlying Gordo Formation in southeast Alabama. Although it is evaluated separately stratigraphically, all hydraulic evaluations are included with the Gordo aquifer.

RIPLEY FORMATION CUSSETA SAND MEMBER

HYDROGEOLOGY

Outcrop exposures of the Cusseta Sand Member of the Ripley Formation in Alabama extend from the Chattahoochee River in northeastern Barbour County and southeastern Russell County westward through central Bullock County into southern Montgomery County (Smith, 2001). Along the Chattahoochee River, the Cusseta averages about 200 ft in thickness. Westward, the Cusseta gradually thins to about 125 ft in eastern and central Montgomery County and merges with the Demopolis Chalk in southwestern Montgomery County. In outcrop, the Cusseta consists predominantly of cross-bedded coarse quartzose sand and granular gravel with subordinate beds of dark-gray to black carbonaceous clay (Smith, 2001). The Cusseta surface exposure (recharge area) in Bullock County varies from 5 to 10 miles wide from the Barbour County line westward to Union Springs and thins to less than 2 miles wide into Montgomery County.

Smith (2001) described the Cusseta Sand in the subsurface as a distinct unit in Crenshaw, northeastern Coffee, Dale, and Henry Counties; but further westward, the Cusseta quartzose sands are replaced with clays, marls, and thin beds of limestone so it can no longer be distinguished from the Ripley Formation or the underlying Blufftown Formation. The Cusseta Sand in Bullock County is described by Smith (2001) in the R. W. Williams Sorrell #1 well (Alabama Oil and Gas Board permit number 1401) in southwest Bullock County as clear to very light gray, ferruginous-stained, quartzose, moderately well sorted, medium to very coarse sand with black, heavy minerals. Sands may include feldspar; and they are finely fossiliferous with phosphatic fish tooth and bone fragments, rare oyster shell fragments, ostracods, and calcareous benthonic foraminifera; and they contain traces of light-olive-gray, noncalcareous, and micaceous clay. Although little subsurface control exists in Bullock County, the R. W. Williams Sorrell #1 well was spud in the Cusseta Sand where Smith (2001) described about 50 ft of the unit. The Cusseta Sand is historically a major water producer in northern Dale and southern Pike Counties.

RIPLEY FORMATION UNNAMED UPPER MEMBER

HYDROGEOLOGY

The unnamed upper member of the Ripley Formation extends in outcrop across the entire state of Alabama with the up gradient terminus in Bullock County extending from the town of Midway in the southeastern part of the county to High Ridge in the southwestern part of the county. Smith (2001) described the surface exposed Ripley as massive-bedded to cross-bedded, glauconitic fine sands and sandy clay with thin indurated beds of fossiliferous sandstone having a total thickness of about 135 ft. Smith (2001) stated that the Ripley consists of predominantly fine-grained lithologies and serves as an aquiclude. The Cusseta and unnamed upper members of the Ripley Formation serve as major aquifers in Barbour, Pike and Dale Counties. Aquifer characteristics described below are representative of the Cusseta and upper unnamed members of the Ripley Formation combined.

WELL DEPTH

Depths of identified wells constructed in the Ripley aquifer vary from less than 100 ft, southward to more than 900 ft (plate 9). The shallowest identified well is 30 ft, near the updip limit in central and northern Bullock County, and the deepest is 1,029 ft near the downdip limit of adequate water quality in southern Dale, southern Henry, and southern Crenshaw Counties (plate 9).

DEPTH TO WATER

Depth to water increases gradationally downgradient at about 15 ft/mi from less than 30 ft in the recharge area in central Barbour and southern Bullock Counties to more than 300 ft in central Pike and central Dale Counties (plate 10). Depth to water is affected by drawdown in four locations within the study area (plates 10, 16). These areas are in Pike and Barbour Counties and are associated with large capacity public supply wells. The Chattahoochee River also profoundly affects the depth to water, with a measured water level in well A-3 in northern Henry County of 55 ft (plate 10).

PUMPING RATES

Pumping rates were examined from selected area public supply wells as well as private supply and irrigation wells. Pumping rates vary from 10 to 1,200 gpm with 7 of 20 wells having pumping rates of 500 gpm or higher (plate 11). Higher pumping rates correlate well with areas of thick NPPIs in central Crenshaw, southern Pike, northwestern Coffee, and southern Dale Counties.

SPECIFIC CAPACITY

Plate 12 shows specific capacities for wells constructed in the Ripley/Cusseta aquifer in southeast Alabama. Specific capacities of private wells for domestic use were low, generally less than 1 gpm/ft. Specific capacities of public supply wells varied from less than 2 gpm/ft to greater than 15 gpm/ft. Most of the higher capacity public supply wells were close to the downdip limit of production for the Ripley/Cusseta aquifer.

NET POTENTIAL PRODUCTIVE INTERVALS

Sand beds of the Cretaceous Ripley Formation and its locally present Cusseta Sand Member comprise a significant aquifer across a portion of the study area. The thickest NPPI (100-175 ft) area of the Ripley/Cusseta aquifer (plate 13) extends from southeastern Crenshaw County across southern Pike County and connects to a thick (175 ft) area in south-central Henry County. Another thick NPPI area is in southern Dale County, but the sands there likely contain brackish water. The downdip limit of freshwater occurrence extends from southernmost Crenshaw County southeastward through Coffee County and thence in an easterly direction across southern Dale and Henry Counties.

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 40 private, state owned, and public water supply wells constructed in the Ripley aquifer. Initial static groundwater level elevations in the Ripley aquifer vary from 520 ft MSL near the recharge area in southern Bullock County to 123 ft MSL at Daleville in southwestern Dale County. The hydraulic gradient is approximately 0.0013 (6.8 ft/mi). Groundwater flow is southward across Crenshaw, Coffee, Pike, Dale, and western Barbour Counties, approximately south 50º east in Henry County, and south 70º east in eastern Barbour County where the Chattahoochee River has a major influence on the direction of groundwater flow in the aquifer (plate 14).

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 36 private, state owned, and public water supply wells constructed in the Ripley aquifer. Current static water levels indicate only slight expansion of existing disturbances to the Ripley aquifer potentiometric surface at Rutledge and Luverne (central Crenshaw County) and at Ozark (central Dale County) and one additional disturbance at Brundidge (southeastern Pike County) occurred since the initial static water level measurement period. Current potentiometric groundwater level elevations in the Ripley aquifer vary from 524 ft MSL near the recharge area in southern Bullock County to 95 ft MSL at Daleville in southwestern Dale County (plate 15). The hydraulic gradient is approximately 0.0014 (7 ft/mi). Groundwater flow is southward in Crenshaw, Coffee, Pike, Dale, and western Barbour Counties, approximately south 35º east in Henry County, and south 70º east in eastern Barbour County where the Chattahoochee River continues to influence the direction of groundwater flow in the aquifer (plate 15).

GROUNDWATER LEVEL IMPACTS

Groundwater production impact levels were determined from a total of 32 private, state owned, and public water supply wells constructed in the Ripley aquifer. Disruptions in the potentiometric surface for the Ripley aquifer occur in Ozark (north-central Dale County) where groundwater levels declined 30 ft in well F-04 and 56 ft in well F-17. Coalesced well impact areas cover about 5 mi^2 in the city of Ozark. Groundwater levels have also declined 82 ft in well L-5 and 142 ft in K-08 in Luverne and Rutledge, respectively (central Crenshaw County), 66 ft in well I-3 and 53 ft in well Q-8 in Troy (central Pike County), and 42 ft in well O-01 in central Henry County (plate 16).

The Ripley Formation is a major aquifer in specific locales in the central part of the project area. Wells constructed in the Ripley aquifer were selected from Barbour, Dale, Henry and Pike Counties based on the quantity and quality of information available to generate long-term hydrographs that show varying conditions related to groundwater production, drought, and seasonal fluctuations that impact the Ripley aquifer. Wells selected include public, unused, and domestic supply wells.

Dale County wells F-16 (Ozark Utilities well no. 1) and F-17 (Ozark Utilities well no. 2) are public supply wells constructed within close proximity to one another. Similar water level trends in both wells indicate that water levels in well F-16 (fig. 11) are influenced by pumpage at nearby well F-17. Well F-16 has been unused for decades, but exhibited a declining water level at the rate of 1.9 ft/yr from 1981 to 2000 and a rising water level from 2000 to 2007 (2007 is the last available measured water level). The top of the screened interval is 805 ft bls and, as of the last water level

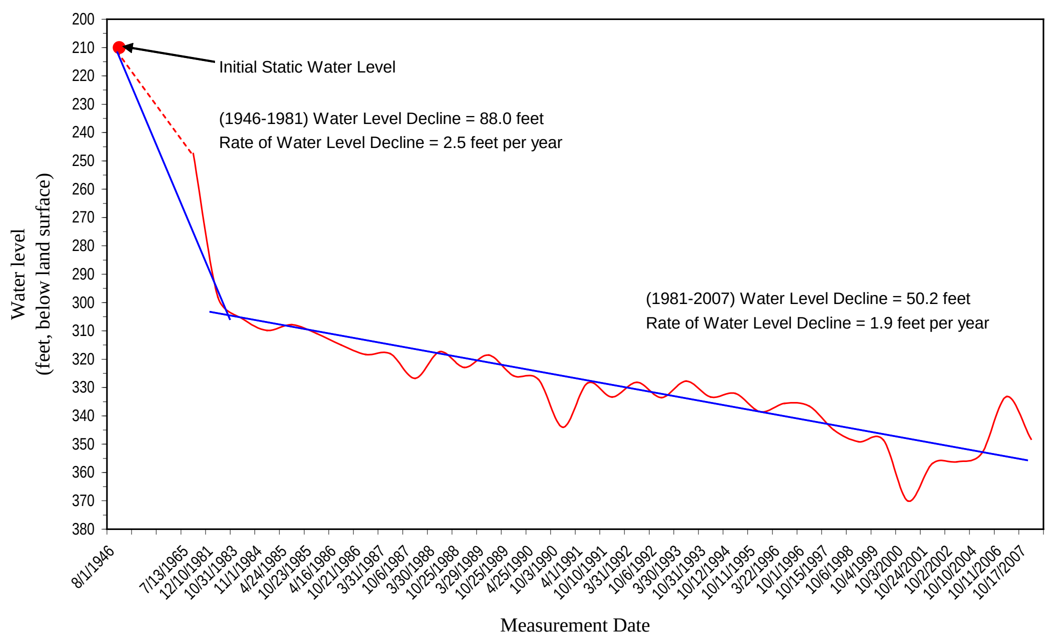


Figure 11.—Hydrograph of Dale County well F-16, an unused public supply well constructed in the Ripley aquifer to a depth of 845 ft, with the top of the screen 805 ft bls.

measurement on October 17, 2007 (348.23 ft bls), there was 456.77 ft of water above the screens in well F-16. Water levels in well F-17 decreased from the initial static water level measured in 1954, to the lowest water level, measured during the 2000 drought. Well F-17 illustrates Ripley aquifer drawdown in the Ozark area, which has the largest cone of depression in the Ripley aquifer in southeast Alabama, with currently more than 100 ft of drawdown (fig. 12). However, since 2000 water levels have risen at a rate of 1.9 ft/yr due to construction of additional wells and reduction of pumping from the Ripley aquifer. The top of the screened interval is 753 ft bls and, as of the last water level measurement on July 1, 2013 (291 ft bls), there was 462 ft of water above the screens in well F-17.

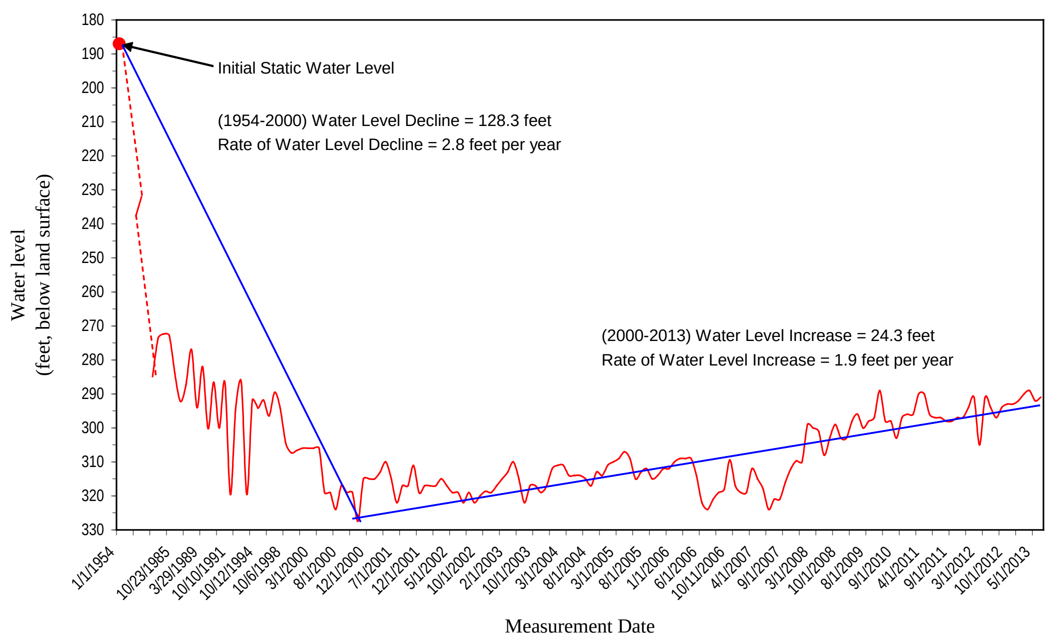


Figure 12.—Hydrograph of Dale County well F-17, a public supply well constructed in the Ripley aquifer to a depth of 813 ft, with the top of the screen 753 ft bls.

Well P-2, a domestic supply well located in Barbour County, has been monitored by GSA since 1967 and has an average water level increase of 0.1 ft/yr that cannot be explained with available information. Water levels in well P-2 exhibit major seasonal fluctuations and drought impacts in 1978, 1980, 2000, and 2007 (fig. 13) due to the fact

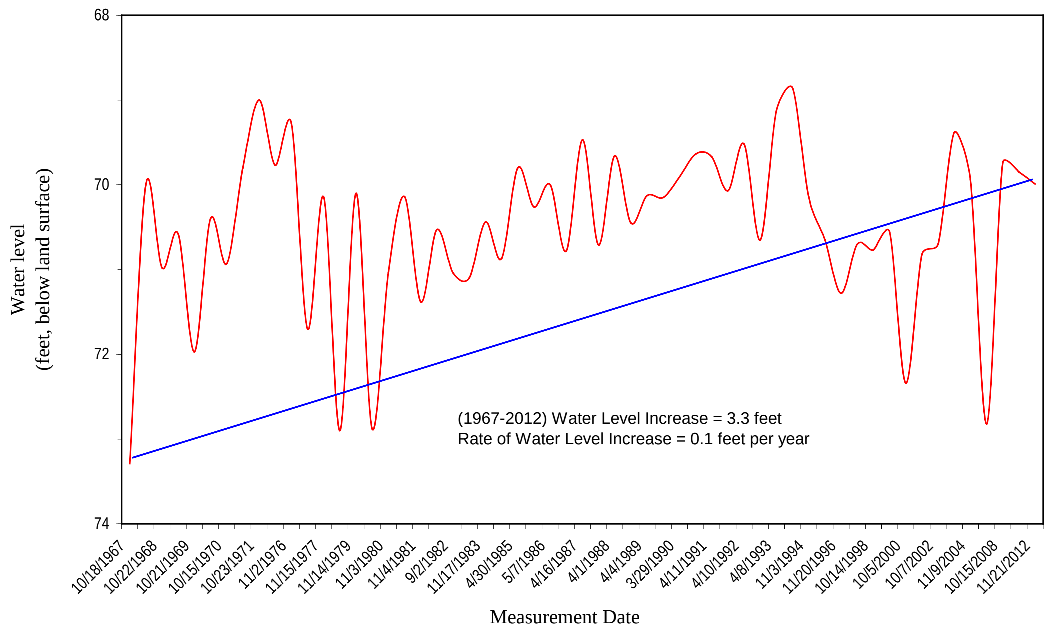


Figure 13.—Hydrograph of Barbour County well P-2, a domestic supply well constructed in the Ripley aquifer to a depth of 181 ft and open-ended.

that this well is shallower and has less confinement than wells that are less impacted by land-surface conditions. Well P-2 is not screened; however, the bottom of the well is 181 ft bls and, as of the last water level measurement on November 21, 2012 (69.99 ft bls), there was 111.01 ft of water in well P-2.

Water levels in well O-01 (Henry County Water System well no. 2), a public supply well in south-central Henry County, declined from the initial static water level of 43 ft bls in 1983 to 85 ft bls in the first quarter 2010. The addition of new groundwater sources and the end of severe drought conditions prompted increasing water levels at a rate of 0.7 ft/yr since 2010 (fig. 14). The top of the screened interval is 630 ft bls and as of the last water level measurement on March 1, 2013 (85 ft bls), there was 545 ft of water above the screens in well O-01.

Well L-01 (Pike County Water Authority well no. 3) is a public water supply well that has been in use since 1978. Water levels declined 36 ft from the initial static water level of 152 ft bls in 1978 to 2003. Since 2003, water levels have increased at a rate of 1.6 ft/yr (fig. 15). This is most likely due to Pike County Water Authority's increased reliance

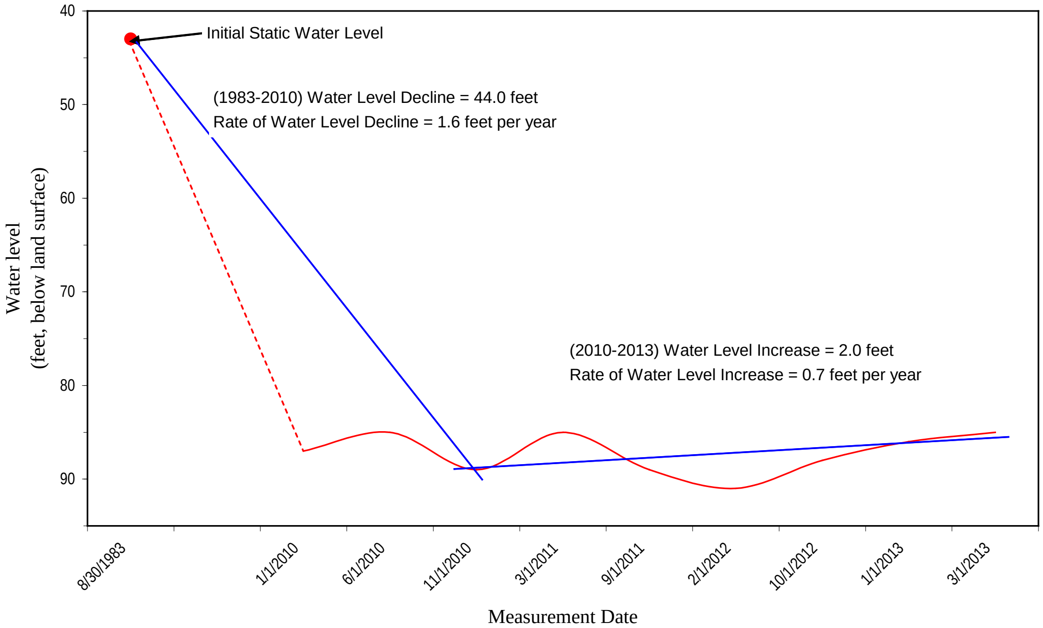


Figure 14.—Hydrograph of Henry County well O-01, a public supply well constructed in the Ripley aquifer to a depth of 818 ft, with the top of the screen 630 ft bls.

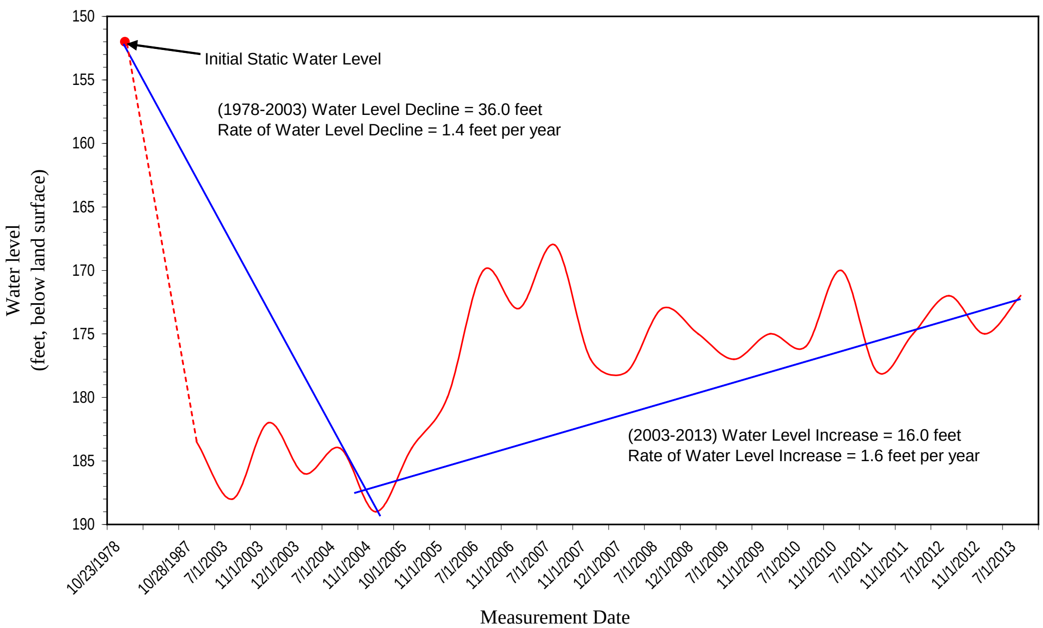


Figure 15.—Hydrograph of Pike County well L-01, a public supply well constructed in the Ripley aquifer to a depth of 544 ft, with the top of the screen 526 ft bls.

on their deeper Gordo well for water supply. The top of the screened interval is 526 ft bls and, as of the last water level measurement on July 1, 2013 (172 ft bls), there was 354 ft of water above the screens in well L-01.

PROVIDENCE SAND

HYDROGEOLOGY

The Providence Sand is the uppermost unit within the Cretaceous System in eastern Alabama. In outcrop, the Providence extends from the Georgia state line through northern Barbour, southern Bullock and Montgomery Counties and terminates in south-central Lowndes County, Alabama (Szabo and others, 1988). The Providence is subdivided into a lower Perote member and an upper unnamed member. The Perote member ranges from less than 10 to about 150 ft in thickness and consists of dark-gray, highly micaceous and carbonaceous, laminated to thin-bedded, silty clay and fine quartzose sand. The upper unnamed member ranges from 80 to 150 ft in thickness and consists of thinly laminated sand and clayey silt that is in part marine and abundantly fossiliferous, overlain by thick-bedded to cross-bedded sand (Smith, 2001). The Providence Sand is a relatively minor aquifer in southeast Alabama. Adequate data was unavailable to evaluate well and aquifer characteristics.

CLAYTON FORMATION

HYDROGEOLOGY

The oldest Tertiary sediments in eastern Alabama rest unconformably upon sediments assignable to the Upper Cretaceous Providence Sand (Smith, 2001). In Alabama, these beds are assigned to the Clayton Formation, which is named from typical exposures near the town of Clayton in west-central Barbour County (Langdon, 1891). In outcrop, a geographically widespread basal transgressive sand of the Clayton consists of 5 to 10 ft of gravelly medium to coarse quartzose sand and clay pebbles. The overlying beds generally consist of 10 to 25 ft of highly fossiliferous sandy limestone, usually represented by deeply weathered exposures of ferruginous sand containing chert fragments (Smith, 2001). This limestone is normally overlain by massive-bedded silty clay and clayey very fine sand. In many exposures, the top of the formation is marked by a very glauconitic clayey sand, which is usually deeply weathered, resulting in reddish or reddish-brown residual ferruginous sandy clay containing thin lenses and seams of the dehydrated iron oxide goethite, commonly known as brown iron ore (Smith, 2001).

In the subsurface, the Clayton Formation extends from central Barbour and Pike Counties southward to the Florida State Line, thus underlying most of the project area. Drillers' logs from many wells in the area note that the unit predominantly consists of "rock" or "lime rock" interbedded with "sand," "shale," "clay," or "marl" (Smith, 2001). Smith (2001) described limestones in the unit from drill cuttings as yellowish-gray, massive, indurated, or invariably quartzose silty to medium quartzose sandy, sparingly glauconitic and phosphatic, and are very highly calcareous.

Potentiometric surface mapping indicates hydraulic interconnection of the Salt Mountain Limestone and Clayton aquifers over most of the project area. The presence locally in the study area of clay beds occurring between the Clayton Formation and the overlying Salt Mountain Limestone, assigned to the Porters Creek Formation by Smith (2001), indicates possible local hydraulic separation of the two units in the extreme western part of the project area. Therefore, hydraulically the units are evaluated as one. However, NPPIs for the Salt Mountain Limestone aquifer were mapped separately due to its distinctive lithologic character of fossiliferous limestone with quartz sand interbeds and its classification as a major aquifer in southeast Alabama.

WELL DEPTH

Depths of identified wells constructed in the Clayton aquifer vary from less than 200 ft to more than 900 ft southward (plate 17). The shallowest identified well is in northern Crenshaw County at a depth of 170 ft and the deepest is in northern Houston County at a depth of 1,015 ft.

DEPTH TO WATER

Depth to water in the Clayton aquifer in the project area varies from 0 to approximately 300 ft bls (plate 18). The shallowest water levels in the confined part of the aquifer occur in the major river valleys in Crenshaw, Dale, and Coffee Counties. The deepest water levels occur in the Ozark area of central Dale County and in northwestern Houston County near Dothan, where impacts of water production for public water supply are observed (plate 18). Water levels in southeast Coffee County around Enterprise also indicate impacts from public water supply production.

PUMPING RATES

Pumping rates were examined from area public supply wells as well as private supply and irrigation wells. Pumping rates vary from less than 100 gpm in southern Barbour County to more than 1,500 gpm in southern Dale and northwestern Houston Counties (plate 19). Twenty of 34 wells have pumping rates of 500 gpm or higher. Larger pumping rates correlate well with areas of thick NPPIs in southern Coffee, Dale, and Henry Counties and northwestern Houston County.

SPECIFIC CAPACITY

Plate 20 shows specific capacities for wells constructed in the Clayton and Salt Mountain aquifers. Specific capacities of private wells for domestic use varied from less than 1 gpm/ft to over 7 gpm/ft. The majority of wells with specific capacity data in the Clayton and Salt Mountain aquifers are public supply wells and their values vary from less than 2 gpm/ft to over 66 gpm/ft. Most of the public supply wells are near the cities of Dothan, Enterprise and Ozark. Several wells used for agriculture and industry are spread throughout the project area and specific capacity for those wells vary from less than 7 gpm/ft to 16 gpm/ft.

NET POTENTIAL PRODUCTIVE INTERVALS

The Tertiary Clayton Formation is composed of limestone and sand beds that comprise one of the most important aquifers in southeastern Alabama. As shown in plate 21, a thick area of NPPI extends from the Dothan area of northwestern Houston County, where the NPPI is more than 250 ft thick, across southern Dale County and south-central Coffee County, where the NPPI varies from 125 to 175 ft thick. The Clayton appears to thin away from this thick “fairway,” though this thinning is poorly defined due to more sparse well control. The probable downdip limit of water production in the Clayton aquifer extends across central Covington County to Geneva County and continues eastward across the southern part of the study area. This limit is due to both thinning of the NPPI and to an increase in salinity of the groundwater.

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 40 private, state owned, and public water supply wells constructed in the Clayton and Salt Mountain aquifers. Due to the hydraulic connection between the Clayton and Salt Mountain aquifers, potentiometric surface maps prepared for this project represent water levels in both aquifers. Therefore, references to the Clayton aquifer include the Salt Mountain aquifer also. Initial static water level elevations in the Clayton aquifer vary from 410 ft MSL near the recharge area at Honoraville in northern Crenshaw County to 150 ft MSL at the city of Enterprise in southeastern Coffee County. The hydraulic gradient is approximately 0.0013 (7.0 ft/mi). Groundwater flow is southward in Crenshaw, Coffee, Pike, Dale, Covington, Geneva, and western Barbour Counties, approximately south 25º east in Houston County, and south 70º east in Henry County and eastern Barbour County where the Chattahoochee River influences directions of groundwater flow in the aquifer (plate 22).

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 52 private, state owned, and public water supply wells constructed in the Clayton and Salt Mountain aquifers. Current static water levels indicate that major disruptions of the Clayton-Salt Mountain aquifer potentiometric surface have occurred since the initial static water level measurement period at Dozier in southern Crenshaw County, Elba (east-central Coffee County), Enterprise (southeastern Coffee County), Ozark (central Dale County), and the Dothan area of southeastern Dale and northwestern Houston Counties. Current static water level elevations in the Clayton aquifer vary from 406 ft MSL near the recharge area at Honoraville in northern Crenshaw County to 156 ft MSL at the city of Enterprise in southeastern Coffee County. The hydraulic gradient is approximately 0.0013 (6.77 ft/mi). Groundwater flow is southward in Crenshaw, Coffee, Pike, Dale, Covington, Geneva, and western Barbour Counties, approximately south 25º east in Houston County, and south 60º east in Henry County and eastern Barbour County where the Chattahoochee River influences directions of groundwater flow in the aquifer (plate 23).

GROUNDWATER LEVEL IMPACTS

Groundwater production impact levels were determined from a total of 27 private, state owned, and public water supply wells constructed in the Clayton and Salt Mountain aquifers. Isolated disruptions in the Clayton aquifer potentiometric surface occur in the Dothan area (northwestern Houston and southeastern Dale Counties) where groundwater levels have declined from 47 ft in well I-04 and 90 ft in well 25. The area of coalesced impacted water levels covers about 18 mi^2 north and west from downtown Dothan. Groundwater levels declined 36 ft in well P-3 and 90 ft in well P-5 (Salt Mountain) in the Enterprise area of southeastern Coffee County, where two areas of coalesced impacted water levels covers about 18 mi^2 in and north of the downtown area and 9 mi^2 north and west of the city. Groundwater levels have declined 50 ft in well J-6 at New Brockton (central Coffee County), 51 ft in well K-01 at Elba (western Coffee County), 157 ft in well T-6 (Salt Mountain) and 204 ft in well W-1 at Dozier and Brantley, respectively (southern Crenshaw County), 54 ft in both N-8 and V-3 wells at Newville and Headland, respectively (southwestern Henry County), 32 ft in well J-7 and 33 ft in well F-4 at Abbeville (central Henry County), and 75 ft in well O-4 at Midland City (southeastern Dale County). Water levels declined 30 ft in well F-04 to 114 ft in well K-1 at Ozark (central Dale County) where the coalesced water level impact area is about 6 mi^2 west and southwest from downtown. Water levels declined 87 ft in well DLE-1 (central Dale County at the Fort Rucker Cairns Landing Field). Well DLE-1 is an unused well in the Clayton aquifer and is included in the GSA real-time groundwater monitoring system. Although unused, this well is probably influenced by pumpage from the nearby Newton public water supply system (plate 24).

HYDROGRAPHS AND AQUIFER DECLINE CURVES

The Clayton Formation is a major water source for the southern and central parts of the project area. The Salt Mountain Limestone is hydraulically connected to the Clayton Formation and is a major aquifer in south-central and west-central parts of the project area where limestone porosity is well developed. Public and domestic supply wells constructed in the Clayton and Salt Mountain aquifers in Coffee, Crenshaw, Dale, Henry and Houston Counties were selected to illustrate varying conditions in the Clayton aquifer throughout the project area.

Mapping of water levels in wells constructed in the Clayton aquifer indicates major depressed potentiometric surfaces in the Elba, Enterprise, Ozark, and Dothan areas. However, recent data obtained from public water supply systems show that water levels in these areas have stabilized and are increasing due to construction of additional wells and reduction of pumping related to water rate increases and increased precipitation.

The water level in well K-01 (City of Elba well no. 3) declined 63.3 ft (2.3 ft/yr) from 1973, when the initial static water was 105.7 ft bls, to the drought of 2000, when the lowest water level was measured (169 ft bls). Since 2000, the well has been increasing in water level at a rate of 0.5 ft/yr (fig. 16). The top of the screened interval is 349 ft bls and, as of the last water level measurement on August 21, 2013 (157 ft bls), there was

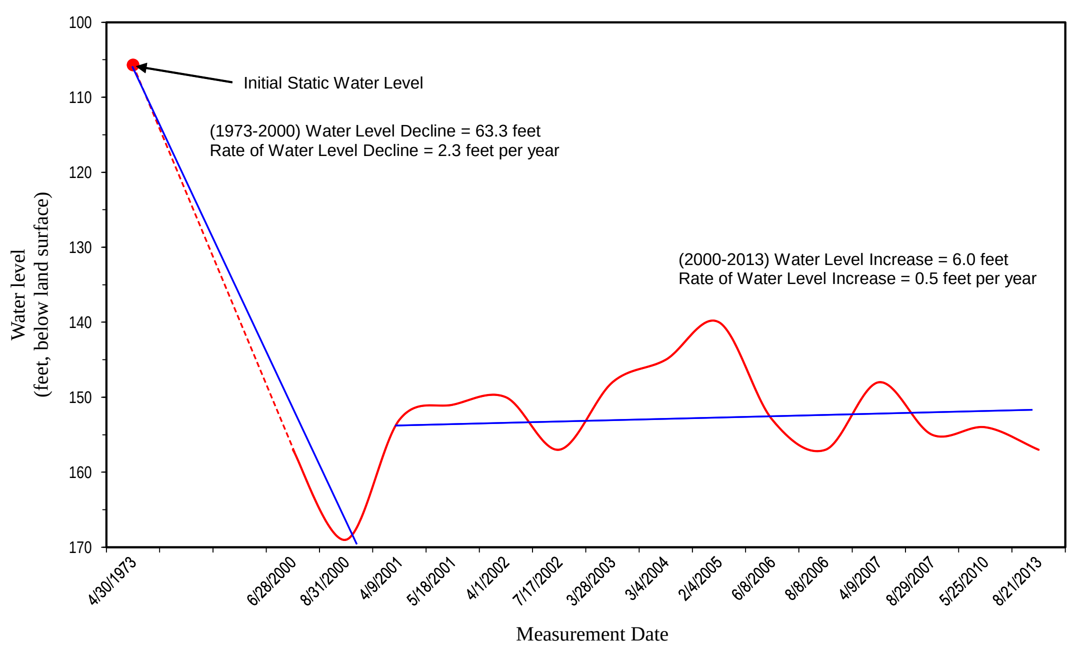


Figure 16.—Hydrograph of Coffee County well K-01, a public supply well constructed in the Clayton aquifer to a depth of 462 ft, with the top of the screen 349 ft bls.

192 ft of water above the screens in well K-01.

The hydrograph for well L-04 (City of Elba well no. 5) shows a declining water level trend from the initial level of 106 ft bls in 1973 to the lowest level measured during the 2007 drought (163 ft bls). However, the trend is increasing since 2007 at a rate of 1.8 ft/yr (fig. 17). The top of the screened interval is 440 ft bls and, as of the last water level measurement on August 22, 2013 (152 ft bls), there was 288 ft of water above the screens in well L-04.

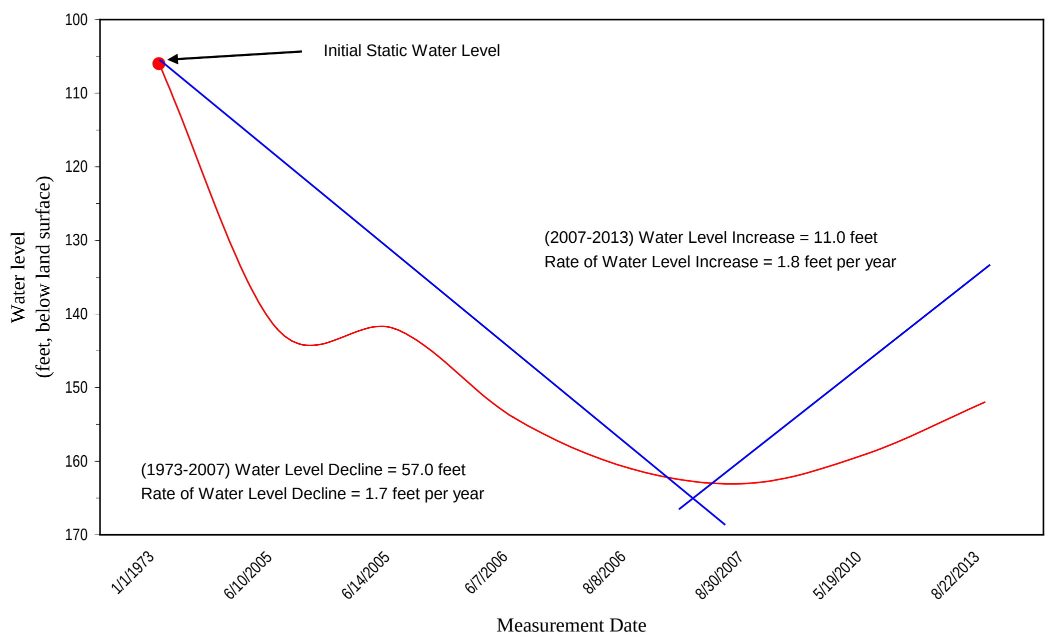


Figure 17.—Hydrograph of Coffee County well L-04, a public supply well constructed in the Clayton aquifer to a depth of 570 ft, with the top of the screen 440 ft bls.

Well I-2 in northwestern Crenshaw County is near the updip limit of the Clayton aquifer and has water levels that are influenced by surface conditions. Seasonal fluctuations and severe drought impacts of as much as 9 ft are observed in the hydrograph for this domestic supply well, which has an overall water level decline of 0.1 ft/yr since 1982 (fig. 18). Well I-2 is not screened; however, the bottom of the well is 170 ft bls and, as of the last water level measurement on November 8, 2012 (109.13 ft bls),there was 60.87 ft of water in well I-2.

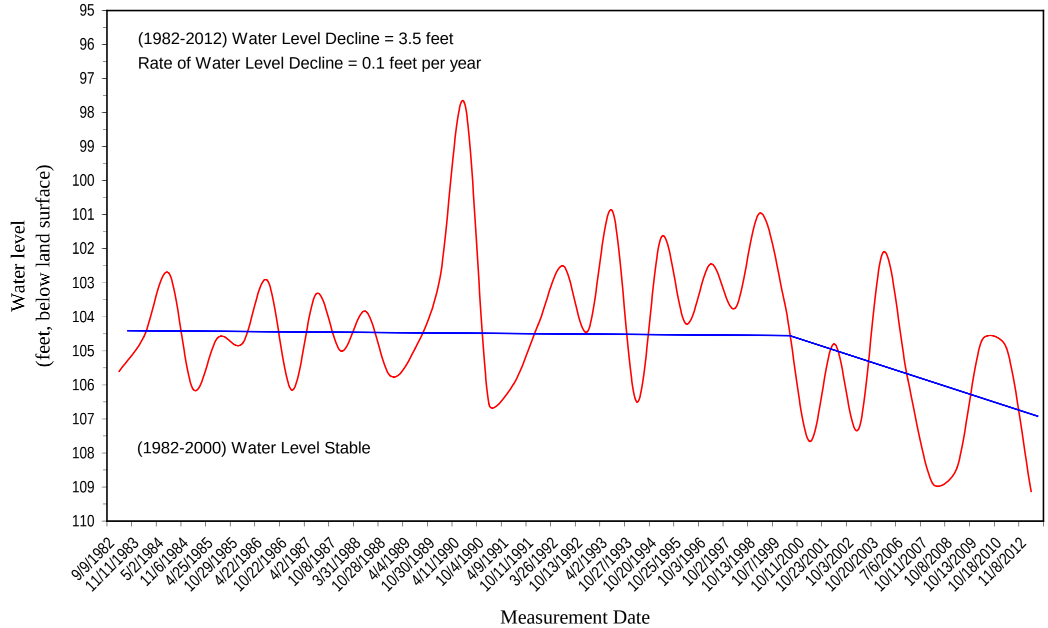


Figure 18.—Hydrograph of Crenshaw County well I-2, a domestic supply well constructed in the Clayton aquifer to a depth of 170 ft and open-ended.

Well DLE-1 (GSA real-time observation well) has a long history of declining levels at a rate of 1.0 ft/yr from 1980 through 2010, most likely a result of influence by nearby public water production by the town of Newton. However, since August 2012, the water level has risen about 6.4 ft, which indicates probable reduction in pumping in nearby wells (fig. 19). The top of the screened interval is 433 ft bls and, as of the last water level measurement on October 7, 2013 (123.14 ft bls), there was 309.86 ft of water above the screens in well DLE-1.

Hydrographs for three public supply wells selected in Dale County indicate that only well F-01 (Ozark Utilities well no. 5) has a continuously declining water level (1.5 ft/yr from 1981 to 2000 and 0.8 ft/yr since 2000) (fig. 20). The top of the screened interval is 655 ft bls and, as of the last water level measurement on July 1, 2013 (344 ft bls), there was 311 ft of water above the screens in well F-01. The water level in well F-04 (Ozark Utilities well no. 7) declined at rate of 1.2 ft/yr from 1989 to 2000 but was stable from 2000 to 2003 when a major pumping increase caused the water level to drop 22 ft from November 1, 2003, to January 1, 2004. Between January 1, 2004, and January 1, 2008, the water level has increased at a rate of 1.0 ft/yr (fig. 21). The top of the screened interval is 712 ft bls and, as of the last water level measurement on January 1, 2008 (319 ft bls), there was 393 ft of water above the screens in well F-04. Information from

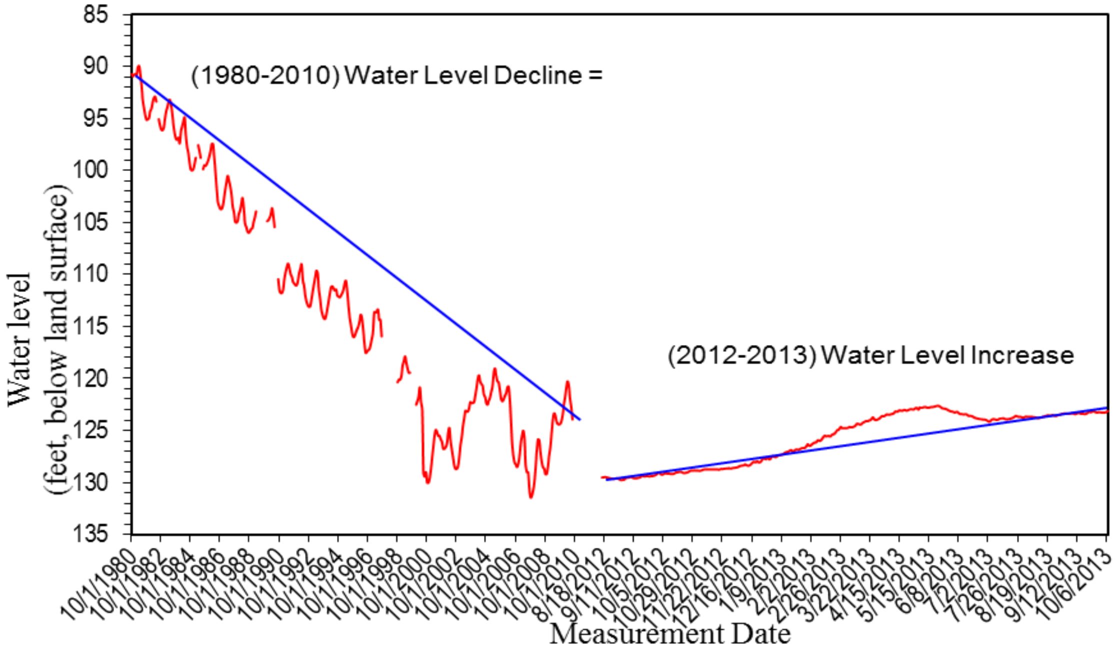


Figure 19.—Hydrograph of Dale County well DLE-1, an observation well constructed in the Clayton aquifer to a depth of 453 ft, with the top of the screen 433 ft bls.

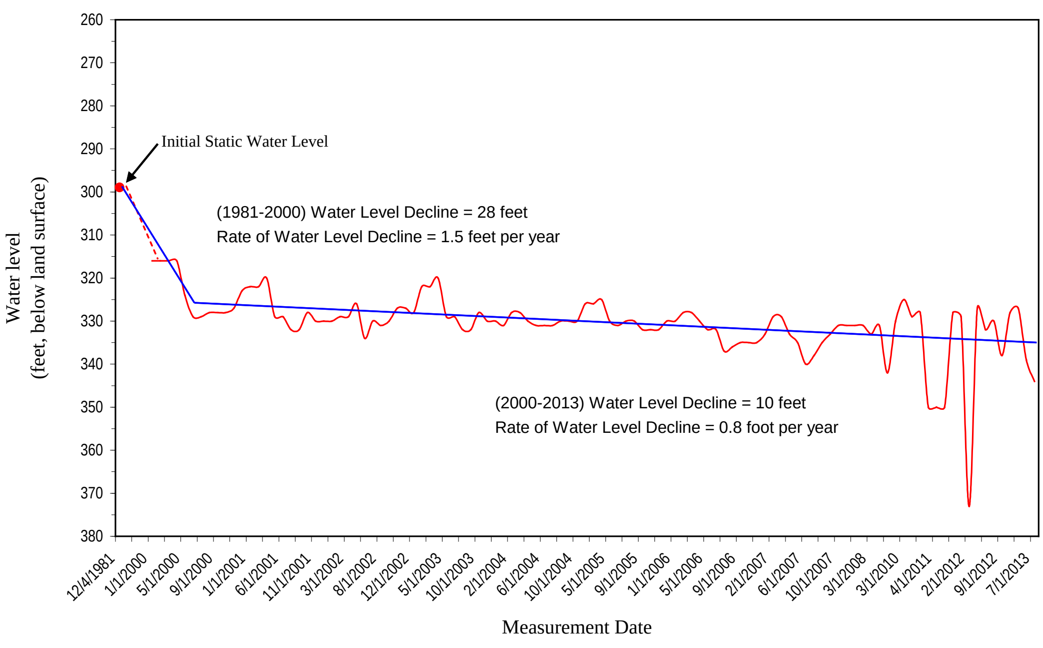


Figure 20.—Hydrograph of Dale County well F-01, a public supply well constructed in the Clayton aquifer to a depth of 908 ft, with the top of the screen 655 ft bls.

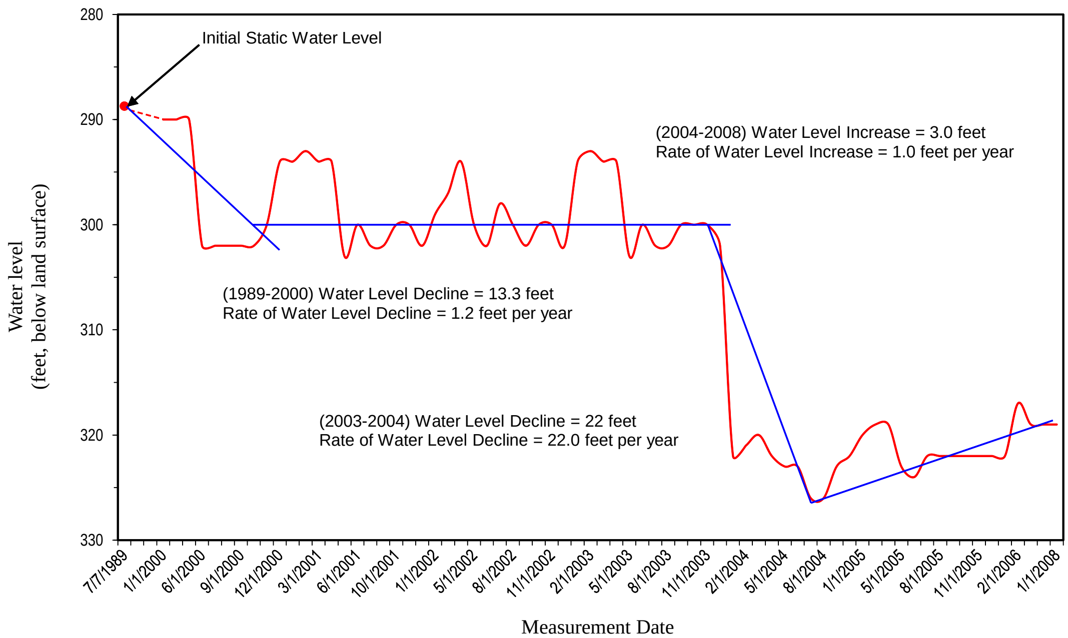


Figure 21.—Hydrograph of Dale County well F-04, a public supply well constructed in the Clayton aquifer to a depth of 870 ft, with the top of the screen 712 ft bls.

Ozark Utilities indicates that well F-04 has not been used since January 2008. Well P-7 (Dothan Utilities well no. 4) has a long-term declining water level at a rate of 3.0 ft/yr from 1982 through 2004, and an increasing water level at a rate of 1.4 ft/yr from 2004 to the first quarter 2013 (fig. 22). Water level recovery in well P-7 is due to additional wells constructed by Dothan Utilities and a reduction in water demand for the city of Dothan. The top of the screened interval is 570 ft bls and, as of the last water level measurement on January 1, 2013 (303.4 ft bls), there was 266.6 ft of water above the screens in well P-7.

Four public supply wells were selected in Henry County. Three of the four wells had increasing water levels, and one well has a stable water level. Well F-4 (Henry County Water Authority well no. 1) has a long period of declining water levels from 1982 through 2010 at a rate of 1.7 ft/yr, followed by a period of increasing water levels from 2010 through March 2013 at a rate of 3.2 ft/yr (fig. 23). The top of the screened interval is 588 ft bls and, as of the last water level measurement on March 1, 2013 (362 ft bls), there was 226 ft of water above the screens in well F-4. After an initial water level

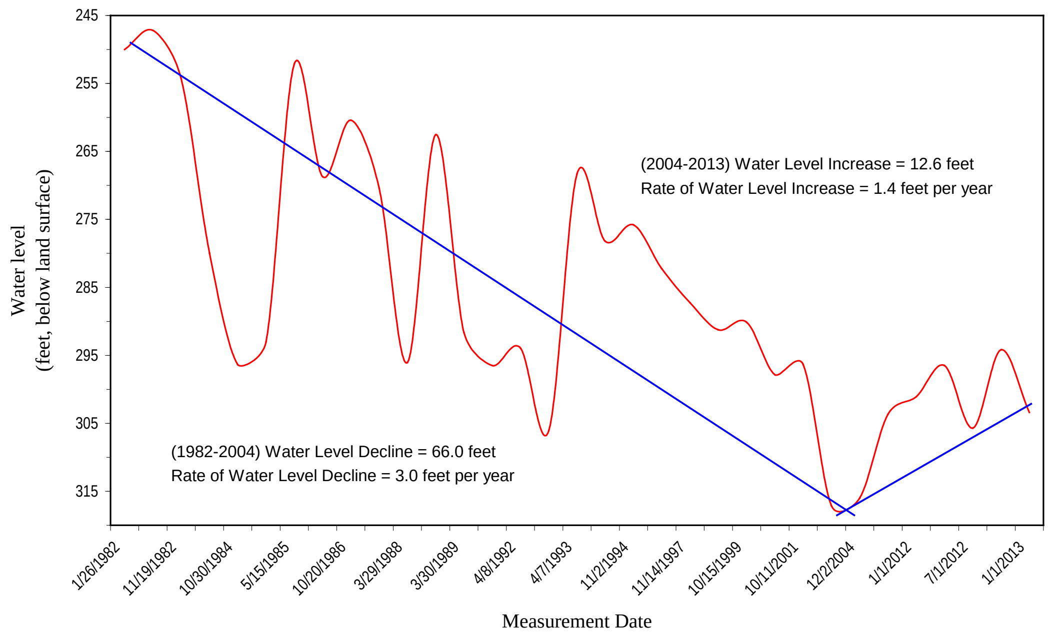


Figure 22.—Hydrograph of Dale County well P-7, a public supply well constructed in the Clayton aquifer to a depth of 704 ft, with the top of the screen 570 ft bls.

decline of 65 ft between 1985 and 1999, well U-03 (City of Headland well no.3) has a relatively stable water level with the exception of periodic fluctuations of as much as 60 ft, indicative of infrequent use (fig. 24). The top of the screened interval is 615 ft bls and, as of the last water level measurement on August 20, 2013 (335 ft bls), there was 335 ft of water above the screens in well U-03. Well X-1 (City of Headland well no.1) was abandoned in 2010 and had not been used since 2000. This well is characterized by a long period of declining water levels at a rate of 2.2 ft/yr from 1946 to 1982, and 3.4 ft/yr from 1982 to 2000. After the well ceased pumping, water levels increased at a rate of 0.8 ft/yr from 2000 to 2006 (fig. 25). The top of the screened interval is 590 ft bls and, as of the last water level measurement on October 5, 2006 (303.88 ft bls), there was 286.12 ft of water above the screens in well X-1. The water level in well X-2 (City of Headland well no. 2) declined at a rate of 2.9 ft/yr from 1964 to 1999 (fig. 26), but has somewhat stabilized since 1999. The top of the screened interval is 600 ft bls and, as of

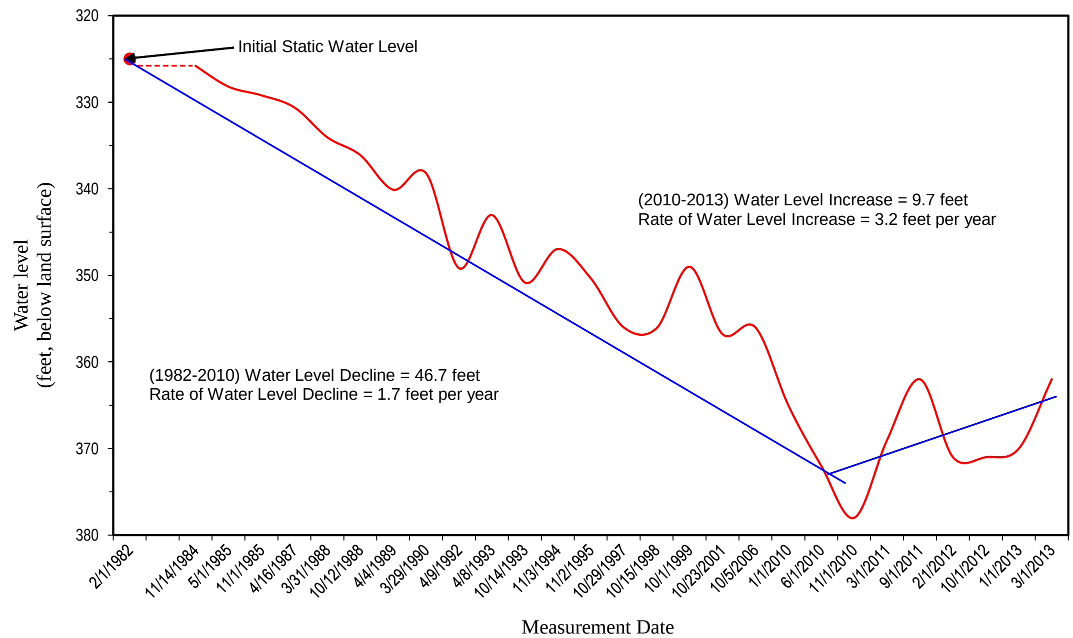


Figure 23.—Hydrograph of Henry County well F-4, a public supply well constructed in the Clayton aquifer to a depth of 690 ft, with the top of the screen 588 ft bls.

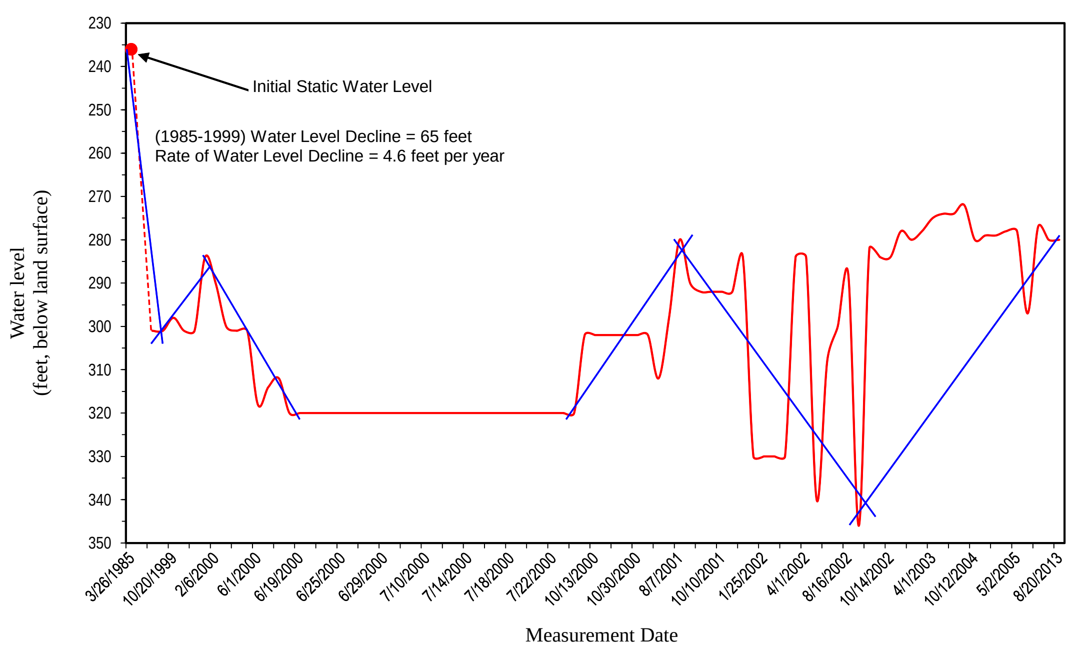


Figure 24.—Hydrograph of Henry County well U-03, a public supply well constructed in the Clayton aquifer to a depth of 718 ft, with the top of the screen 615 ft bls.

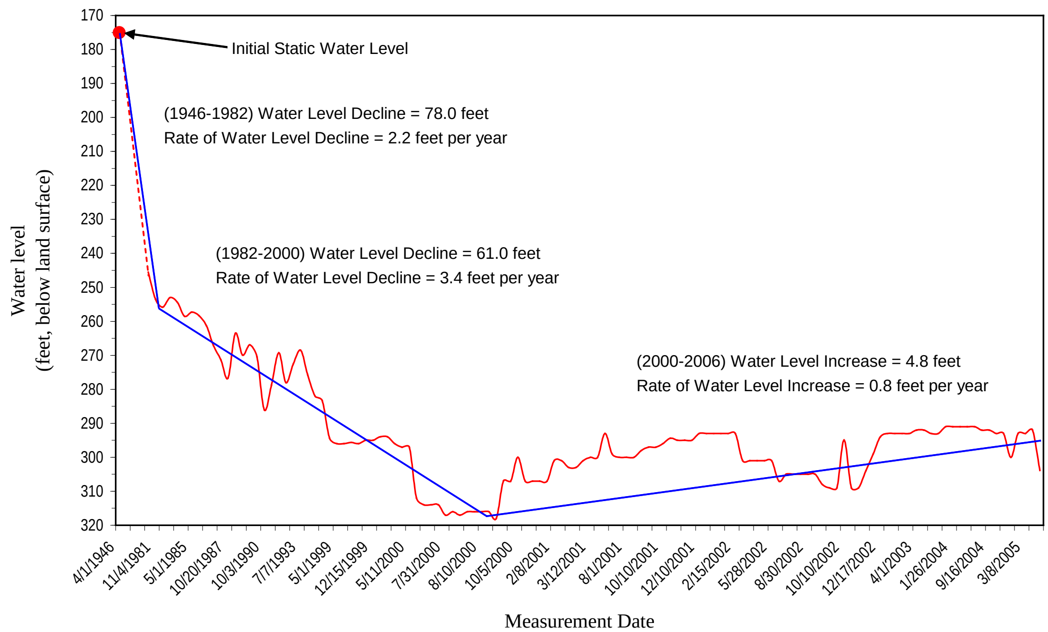


Figure 25.—Hydrograph of Henry County well X-1, a public supply well constructed in the Clayton aquifer to a depth of 659 ft, with the top of the screen 590 ft bls.

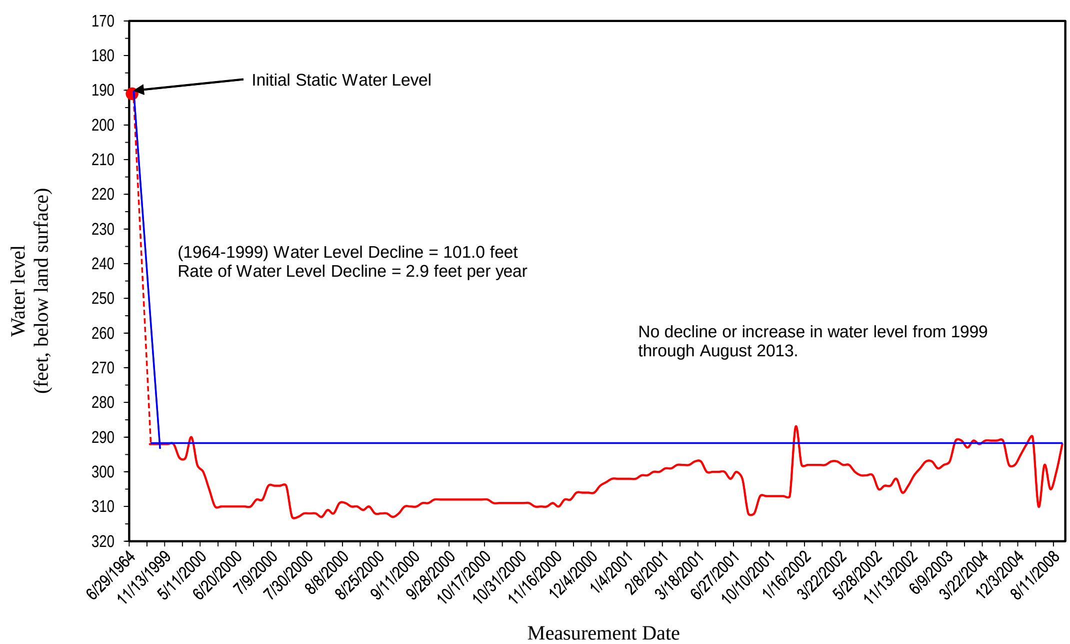


Figure 26—Hydrograph of Henry County well X-2, a public supply well constructed in the Clayton aquifer to a depth of 697 ft, with the top of the screen 600 ft bls.

the last water level measurement on August 20, 2013 (292 ft bls), there was 308 ft of water above the screens in well X-2.

The largest area of depressed potentiometric surfaces in Alabama is in the Dothan area in the Nanafalia and Clayton aquifers. Water levels for five public supply wells operated by Dothan Utilities and screened solely in the Clayton aquifer were evaluated. All five wells are located north of downtown Dothan in northwestern Houston County and are in close proximity, most likely with overlapping zones of pumping influence.

Well C-02 (Dothan Utilities well no. 29) had a declining water level at 2.0 ft/yr from the initial static water level measurement in 1994 to early 2012 (fig. 27). However, the water level stabilized during 2012 (fig. 27). The top of the screened interval is 850 ft bls and, as of the last water level measurement on January 1, 2013 (237.5 ft bls), there was 612.5 ft of water above the screens in well C-02.

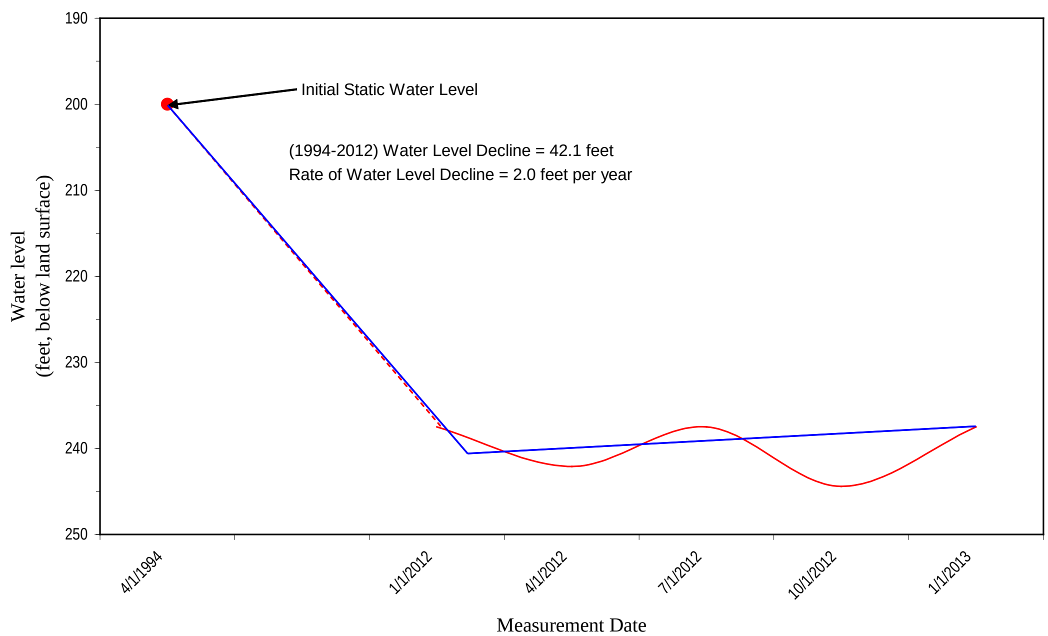


Figure 27.—Hydrograph of Houston County well C-02, a public supply well constructed in the Clayton aquifer to a depth of 1,015 ft, with the top of the screen 850 ft bls.

Well D-02 (Dothan Utilities well no. 23) had a declining water level at 2.2 ft/yr from the initial static water level measurement in 1974 to early 2012. However, the water level stabilized and rose slightly during 2012 (fig. 28). The top of the screened interval is 715 ft bls and, as of the last water level measurement on October 1, 2012 (269.2 ft bls), there was 445.8 ft of water above the screens in well D-02.

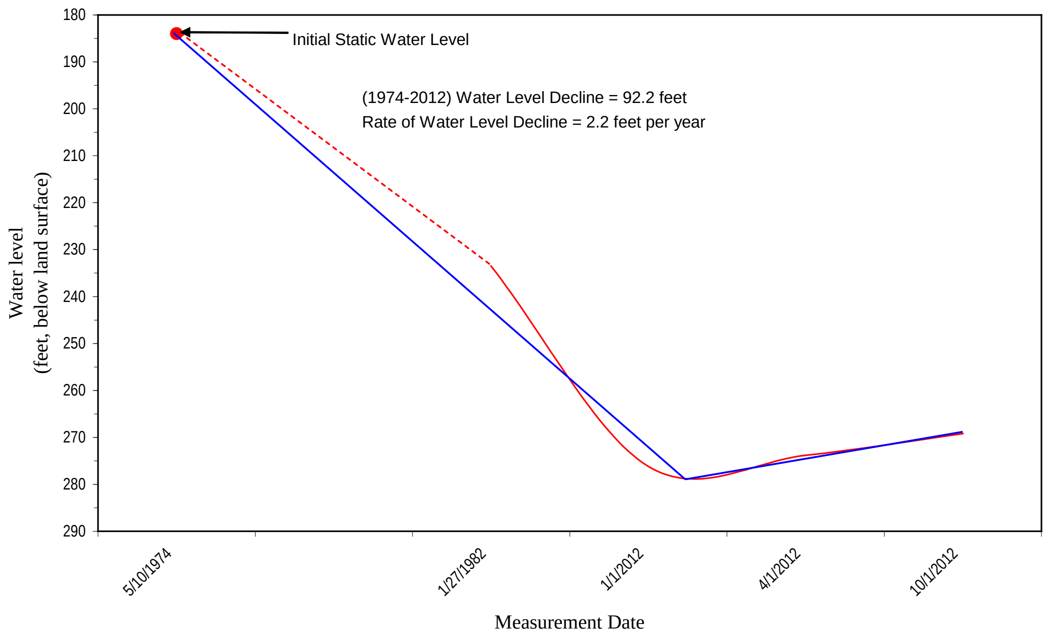


Figure 28.—Hydrograph of Houston County well D-02, a public supply well constructed in the Clayton aquifer to a depth of 875 ft, with the top of the screen 715 ft bls.

Well D-03 (Dothan Utilities well no. 22) had a declining water level at 1.7 ft/yr from the initial static water level measurement in 1973 (fig. 29). However, the water level stabilized and rose slightly during 2012. The top of the screened interval is 739 ft bls and, as of the last water level measurement on January 1, 2013 (256.8 ft bls), there was 482.2 ft of water above the screens in well D-03.

Well D-05 (Dothan Utilities well no. 31) had a declining water level at 2.4 ft/yr from the initial static water level measurement in 1996 to mid-2012 (fig. 30). However, the water level stabilized and rose 16 ft during the last half of 2012. The top of the screened interval is 710 ft bls and, as of the last water level measurement on January 1, 2013 (266.4 ft bls), there was 443.6 ft of water above the screens in well D-05.

Well I-01 (Dothan Utilities well no. 24) had a declining water level at 2 ft/yr from 1979 to 1982 but the water level has remained relatively stable from 1982 to 2013 (fig.

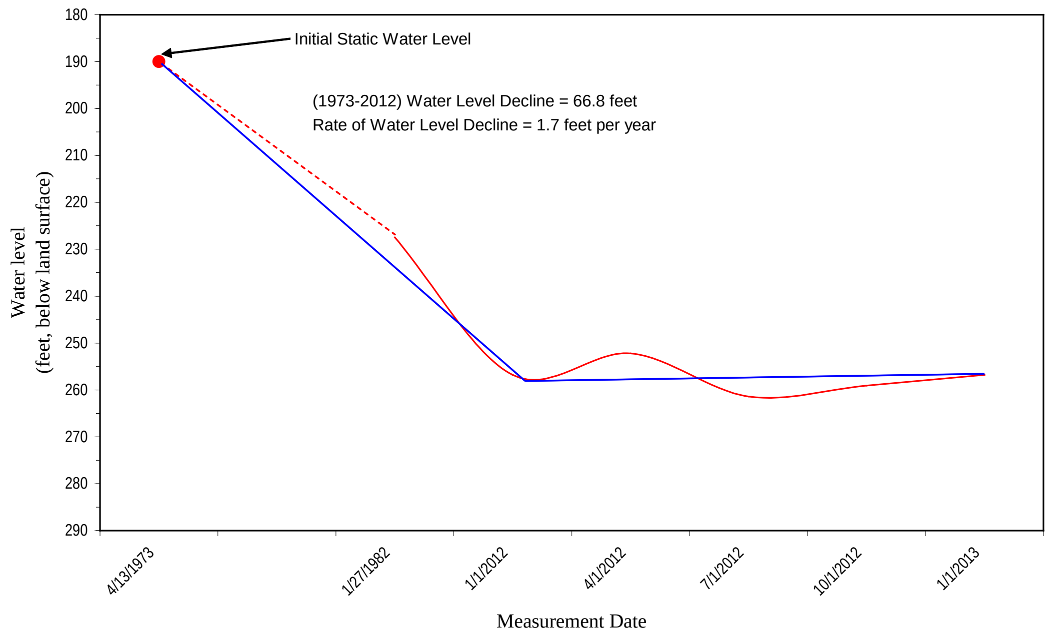


Figure 29.—Hydrograph of Houston County well D-03, a public supply well constructed in the Clayton aquifer to a depth of 850 ft, with the top of the screen 739 ft bls.

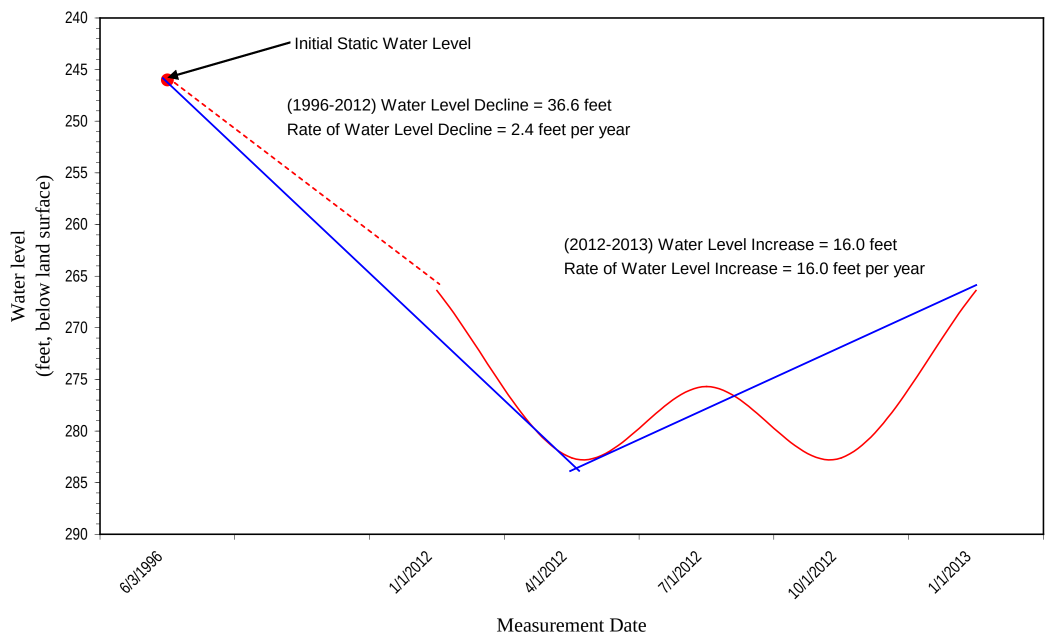


Figure 30.—Hydrograph of Houston County well D-05, a public supply well constructed in the Clayton aquifer to a depth of 975 ft, with the top of the screen 710 ft bls.

31). The top of the screened interval is 651 ft bls and, as of the last water level measurement on January 1, 2013 (237.5 ft bls), there was 413.5 ft of water above the screens in well I-01.

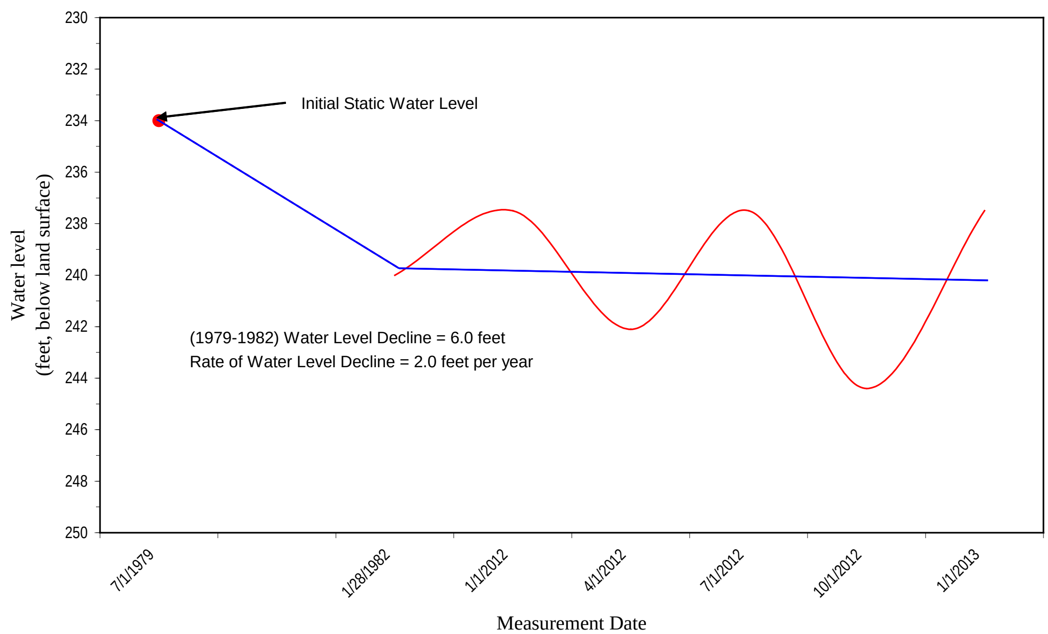


Figure 31.—Hydrograph of Houston County well I-01, a public supply well constructed in the Clayton aquifer to a depth of 990 ft, with the top of the screen 651 ft bls.

Water levels in three public supply wells (D-01, I-6, I-04) operated by Dothan Utilities and screened in multiple aquifers were evaluated. However, it was determined that the Clayton aquifer is the dominant water source in these wells so they are included with wells screened solely in the Clayton.

Well D-01 (Dothan Utilities well no. 26) is screened in the Clayton and Ripley aquifers. Well D-01 had declining water levels from the initial static measurement in 1981 through the third quarter of 2012 at 2.6 ft/yr (fig. 32). However, the water level stabilized and rose about 15 ft by January 2013. The top of the screened interval is 740 ft bls and, as of the last water level measurement on January 1, 2013 (255.2 ft bls), there was 484.8 ft of water above the screens in well D-01.

Well I-6 (Dothan Utilities well no. 10) is screened in the Tuscahoma and Clayton aquifers. Water levels have declined since 1951 through early 2012 at a rate of 2.7 ft/yr

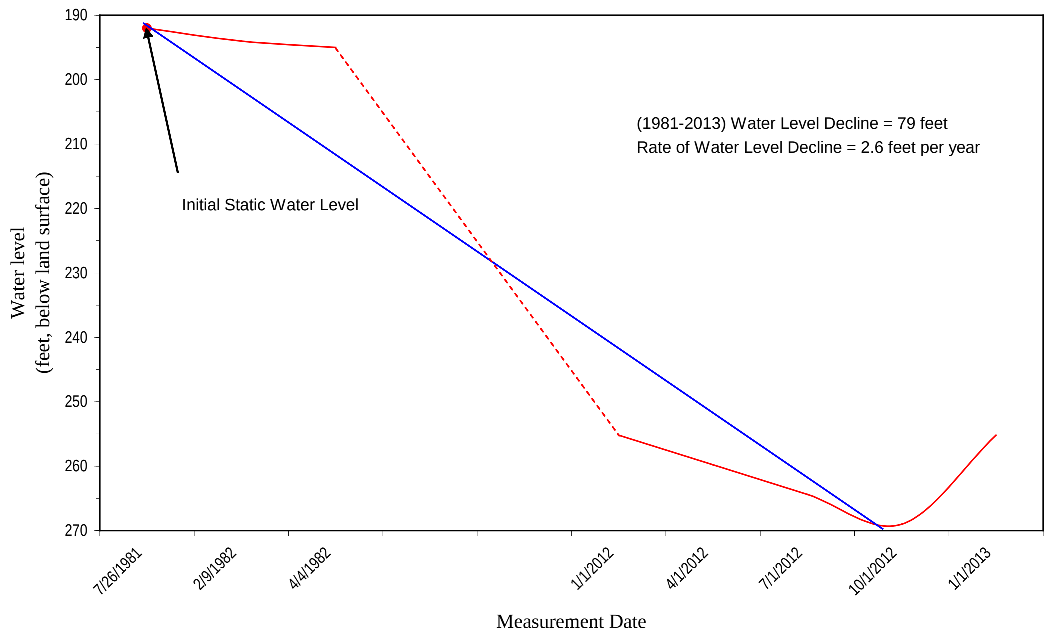


Figure 32.—Hydrograph of Houston County well D-01, a public supply well constructed in the Clayton and Ripley aquifers to a depth of 1,105 ft, with the top of the screen 740 ft bls.

(fig. 33). However, the water level has been relatively stable through early 2013. The top of the screened interval is 563 ft bls and, as of the last water level measurement on January 1, 2013 (305.3 ft bls), there was 257.7 ft of water above the screens in well I-6.

Well I-04 (Dothan Utilities well no. 20) is screened in the Nanafalia and Clayton aquifers. Water levels have declined since 1971 through the first quarter of 2013 at a rate of 1.1 ft/yr (fig. 34). The top of the screened interval is 545 ft bls and, as of the last water level measurement on January 1, 2013 (221.4 ft bls), there was 323.6 ft of water above the screens in well I-04.

SALT MOUNTAIN LIMESTONE

HYDROGEOLOGY

Potentiometric surface mapping indicates a likely hydraulic interconnection of the Salt Mountain Limestone and Clayton aquifers over most of the project area. However, the Salt Mountain Limestone aquifer NPPI was mapped separately due primarily to its

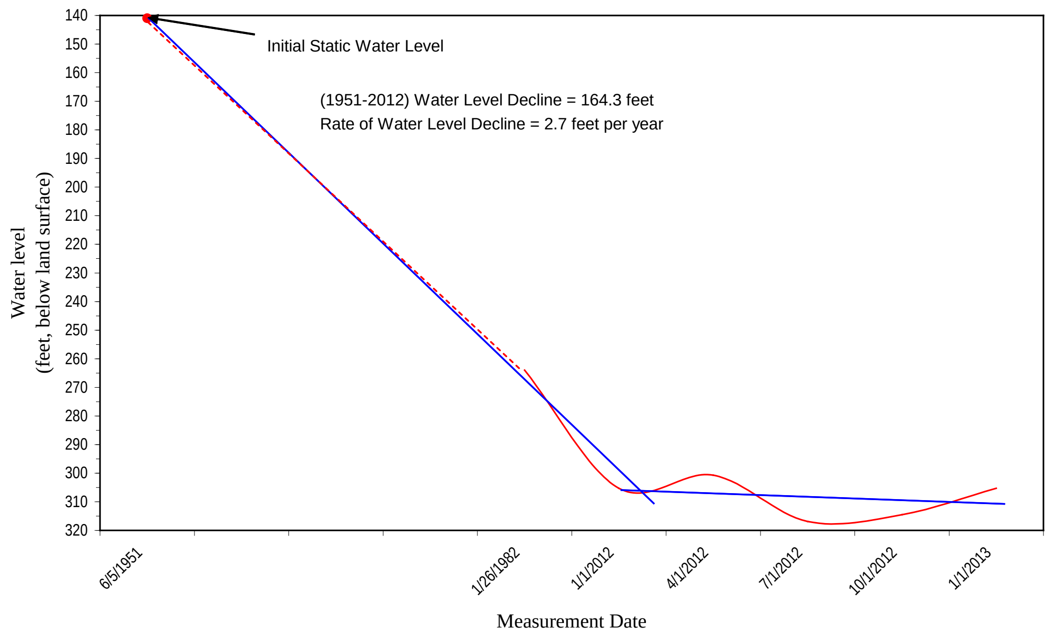


Figure 33.—Hydrograph of Houston County well I-6, a public supply well constructed in the Clayton and Tuscahoma aquifers to a depth of 754 ft, with the top of the screen 563 ft bls.

distinctive lithologic character of fossiliferous limestone with quartz sand interbeds (Smith, 2001). The presence locally in the study area of clay beds occurring between the Clayton Formation and the overlying Salt Mountain Limestone, assigned to the Porters Creek Formation by Smith (2001), indicates possible local hydraulic separation of the two units in the extreme western part of the project area.

As with the underlying Clayton Formation, the Salt Mountain Limestone within the project area consists predominantly of limestone and sand. Drillers' logs describe the unit as consisting of "hard limestone" and "soft limestone" or simply "limestone" or "lime" or "rock and sand." Smith (2001) reported that a microscopic examination of drill cuttings from wells in the project area revealed that the Salt Mountain Limestone consists of white to very light-gray, massive, highly porous and permeable, more rarely dense and indurated, rarely fine to medium quartzose sandy, highly fossiliferous limestone. These limestones vary from highly fossiliferous and porous to massive, dense, very fine-grained carbonates and contain exceptionally abundant algal, oyster,

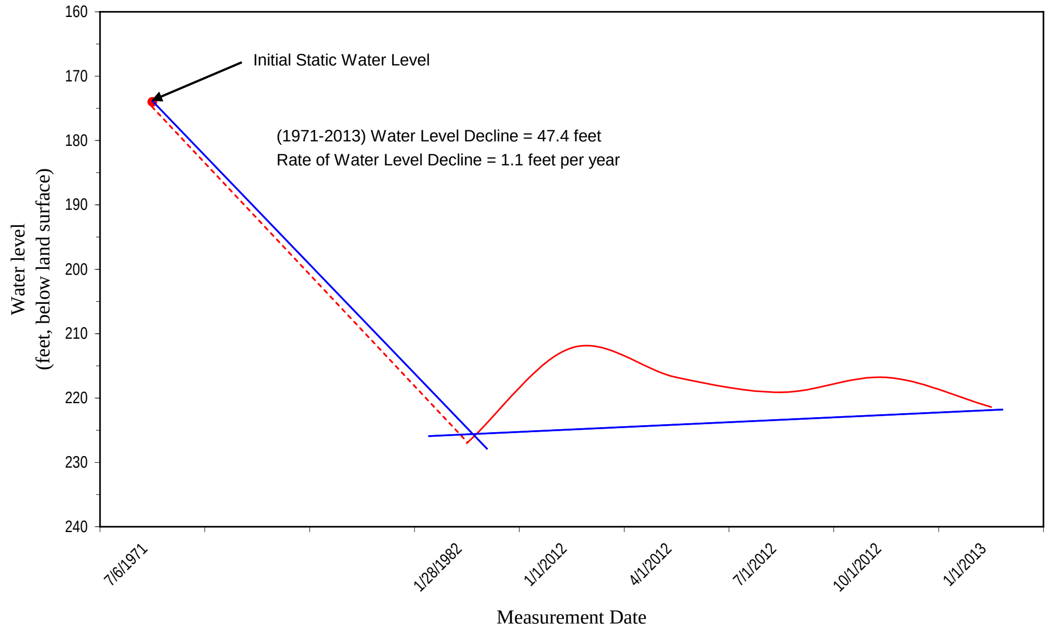


Figure 34.—Hydrograph of Houston County well I-04, a public supply well constructed in the Clayton and Nanafalia aquifers to a depth of 800 ft, with the top of the screen 545 ft bls.

pelecypod, gastropod, bryozoan, and echinoderm spine and plate fragments, as well as abundant larger foraminifera.

Smith (2001) noted the presence of visible porosity in well cuttings of some wells that penetrated the Salt Mountain Limestone, the presence in some wells of sand interbeds, and the general absence of clay. The thickest portion of the NPPI (150-250 ft) extends from northern Covington County southeast into southwestern Coffee County, north-central Geneva County, and southwestern Dale County (plate 25). The Salt Mountain is not present (or, on logs, not distinguishable from the Clayton) north of a line across northern Coffee and Dale Counties. The downdip limit of fresh water probably extends across south-central Covington and southwestern Geneva Counties.

WELL DEPTH

Depths of identified wells constructed in the Salt Mountain aquifer vary from less than 300 ft near the updip limit of the aquifer, southward to more than 800 ft (plate 26).

The shallowest identified well is in southeastern Crenshaw County at a depth of 258 ft and the deepest is in southeastern Coffee County at a depth of 868 ft.

DEPTH TO WATER

Potentiometric surface mapping indicates hydraulic interconnection of the Salt Mountain Limestone and Clayton aquifers over most of the project area. Therefore, depth to water in wells constructed in the Salt Mountain Limestone is similar to those in the Clayton Formation (see Clayton Formation depth to water discussion).

PUMPING RATES

Limited pumping rate data are available for the Salt Mountain aquifer due to the relatively small number of wells constructed solely in the Salt Mountain Limestone. However, from limited data, pumping rates vary from 600 to 850 gpm. Pumping rate data available for the Salt Mountain are not adequate to map separately, thus they are included with the Clayton aquifer (plate 19).

SPECIFIC CAPACITY

See Clayton Formation specific capacity discussion.

NET POTENTIAL PRODUCTIVE INTERVALS

Smith (2001) noted the presence of visible porosity in well cuttings of some wells that penetrated the Salt Mountain Limestone, the presence in some wells of sand interbeds, and the general absence of clay. The thickest portion of the net “clean” portion of the limestone and sand extends from northern Covington County southeastward across southwestern Coffee County into north-central Geneva County, where the NPPI is more than 250 ft thick. The Salt Mountain NPPI thins north and south away from this thick “fairway,” and to the east into Houston County. The Salt Mountain is not present (or, on logs, not distinguishable from the Clayton) north of a line across northern Coffee and Dale Counties. The downdip limit of fresh water probably extends across south-central Covington and southwestern Geneva Counties (plate 25).

NANAFALIA FORMATION

HYDROGEOLOGY

Where the Nanafalia Formation outcrops in southern Barbour and Pike and central Crenshaw Counties it is about 125 ft in thickness and consists of massive cross-bedded sand and glauconitic and fossiliferous fine sands (Smith, 2001). The recharge area extends from the Chattahoochee River in southern Barbour County westward through southern Pike and central Crenshaw Counties (Szabo and others, 1988). The Nanafalia Formation in the subsurface consists of greenish-colored and glauconitic-stained coarse to very coarse quartzose sand, fragments of marine fossils, and abundant medium to coarse glauconite. Some usually dense, indurated, frequently sandy limestone beds occur. (Smith, 2001). The thickness of the Nanafalia Formation is about 200 ft in western Houston, southern Dale, and Coffee Counties and increases to more than 300 ft in central Covington County.

WELL DEPTH

Depths of wells constructed in the Nanafalia aquifer vary from less than 200 to more than 1,000 ft (plate 27). The shallowest identified well is in central Barbour County at a depth of 21 ft, near the updip limits of the Nanafalia aquifer. The deepest identified well is in southern Geneva County at a depth of 1,180 ft, near the suggested downdip limit of adequate water quality.

DEPTH TO WATER

Depth to water in the Nanafalia aquifer in the investigated area varies from 0 to more than 280 ft bls (plate 28). The shallowest water levels in the confined part of the aquifer occur in the major river valleys in Dale and Coffee Counties. The deepest water levels (more than 250 ft bls) occur in eastern Coffee and central Houston Counties and indicate impacts from pumpage of large capacity public supply wells.

PUMPING RATES

Pumping rate data were examined for area public supply, private supply, and irrigation wells. Pumping rates range from 10 gpm in the northern part of the project area to more than 800 gpm near Dothan. Pumping rates generally increase from north to south but highest rates are in the Daleville-Ft. Rucker and Dothan areas where high capacity wells were constructed in the Nanafalia aquifer to provide public water supplies (plate 29).

SPECIFIC CAPACITY

Plate 30 shows specific capacities for wells constructed in the Nanafalia aquifer. Specific capacities of private wells for domestic use varied from less than 1 gpm/ft to 4 gpm/ft and most were located in the updip part of the project area. Specific capacities of public supply wells varied from less than 3 gpm/ft to greater than 30 gpm/ft with the highest values in the downdip part of the project area and in the Daleville-Ft. Rucker and Dothan areas where high capacity wells were constructed in the Nanafalia aquifer to provide public water supplies (plate 30).

NET POTENTIAL PRODUCTIVE INTERVALS

The Nanafalia Formation contains thick sand intervals along with some limestone beds. The thickest net “clean” sand and limestone occurs in a “fairway” from northern Covington County across southern Coffee and Dale Counties into western Houston County where the thickest NPPIs vary from 75 to 125 ft (plate 31). The thickest NPPIs occur in two main areas: one centered in the northwestern Houston County “panhandle” and southern Dale County and the other centered in Coffee County west of Enterprise (plate 31). Like other aquifers in this study, thinning of the formation and its NPPIs is evident in the updip direction (plate 31). The interpreted downdip limit of Nanafalia aquifer water production extends in a general northwest to southeast line across southern Covington County and southwestern Geneva County. This limit is the result of a general decrease in the net sand/limestone content and greater salinity to the southwest (plate 31).

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 47 private, state owned, and public water supply wells constructed in the Nanafalia aquifer. Initial potentiometric groundwater level elevations vary from 479 ft MSL near the recharge area at Baker Hill in northeastern Barbour County to 127 ft MSL at Slocomb in eastern Geneva County. The hydraulic gradient is 0.0016 (8.5 ft/mi). Groundwater flow is southward in Crenshaw, Coffee, Pike, Dale, Covington, Geneva, and Houston Counties and south 45° east in Henry County where the Chattahoochee River influences the direction of groundwater flow (plate 32). The initial potentiometric surface is undisturbed except for minor individual well drawdowns in northwestern Houston County (plate 32).

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 39 private, state owned, and public water supply wells constructed in the Nanafalia aquifer. Comparison of initial and current potentiometric surfaces indicate that only minor changes to the potentiometric surface occurred except for the Dothan area of northwestern Houston County where increased public water supply production from the Nanafalia aquifer caused a major expansion of the disturbed potentiometric surface area (plate 33). Current groundwater levels in the Nanafalia aquifer vary from 331 ft MSL in northeastern Dale County to 51 ft MSL at Slocomb in eastern Geneva County. The hydraulic gradient is 0.0010 (5.3 ft/mi) and groundwater flow is southward in Crenshaw, Coffee, Pike, Dale, Covington, Geneva, and Houston Counties and south 35° east in Henry County where the Chattahoochee River influences the direction of groundwater flow (plate 33).

GROUNDWATER LEVEL IMPACTS

Groundwater production impact levels were determined from a total of 33 private, state owned, and public water supply wells constructed in the Nanafalia aquifer. Isolated disruptions in the Nanafalia aquifer potentiometric surface occur in numerous individual wells across the project area. However, the largest disruption occurs in the Dothan area (northwestern Houston and southeastern Dale Counties) where groundwater levels declined as much as 248 ft (well I-08). Impacted production areas from a number of wells have coalesced to form an area of disruption in the potentiometric surface of about 15 mi^2 along with several additional individual well disrupted areas (plate 34). Other smaller disrupted areas include Pinckard (south-central Dale County) where the groundwater level has declined 71 ft in well N-05, 76 ft in well M-02 at Slocomb (eastern

Geneva County), 74 ft in well D-28 near Ariton (northwestern Dale County), 31 ft in well O-04 and 47 ft in well I-30 at Enterprise (southeastern Coffee County), and 62 ft in well M-8 at Andalusia (northern Covington County) (plate 34).

HYDROGRAPHS AND AQUIFER DECLINE CURVES

The Nanafalia Formation is a major source of groundwater in the south-central and southeastern parts of the project area. Public supply wells in Geneva, Dale, and Houston Counties and a domestic supply well in Henry County were selected for construction of hydrographs. Public supply wells in the Daleville area of Dale County and the Dothan area of Houston County were selected to illustrate conditions in two of the largest depressions of potentiometric surfaces in the Nanafalia aquifer. These wells have screened intervals that include part of the overlying Tuscahoma aquifer. However, the Tuscahoma screened intervals most likely have minimal influence on impacts observed in the Nanafalia aquifer.

Well R-04 (Geneva Water Works well no. 7) has a relatively stable water level with a slight decrease of 0.4 ft/yr from August 2011 through February 2013 based on measurements provided by the public supplier (fig. 35). The hydrograph indicates regular water level fluctuations of about 10 ft based on pumping and major recovery of more than 50 ft on four occasions in August 2011 and February 2013 when the pump was shut off for more than two days. Well R-04 is most likely screened, but the screened interval is not known. However, the bottom of the well is 1,180 ft bls and, as of the last water level measurement on February 15, 2013 (110 ft bls), there was 1,070 ft of water in well R-04.

Well J-1, a domestic supply well in Henry County, has a declining water level since the well was constructed in 1965. The hydrograph shows seasonal fluctuations of 2 to 5 ft and drought impacts of 7 to 10 ft in 1977, 1980, and 1983. From 1965 to 2012, the water level declined 12 ft or about 0.3 ft/yr (fig. 36). Well J-1 is not screened; however, the bottom of the well is 302 ft bls and, as of the last water level measurement on November 21, 2012 (142.14 ft bls), there was 159.86 ft of water in well J-1.

Three public supply wells in Daleville (southwestern Dale County) are located in close proximity to one another and all have similar water level histories. Well M-11

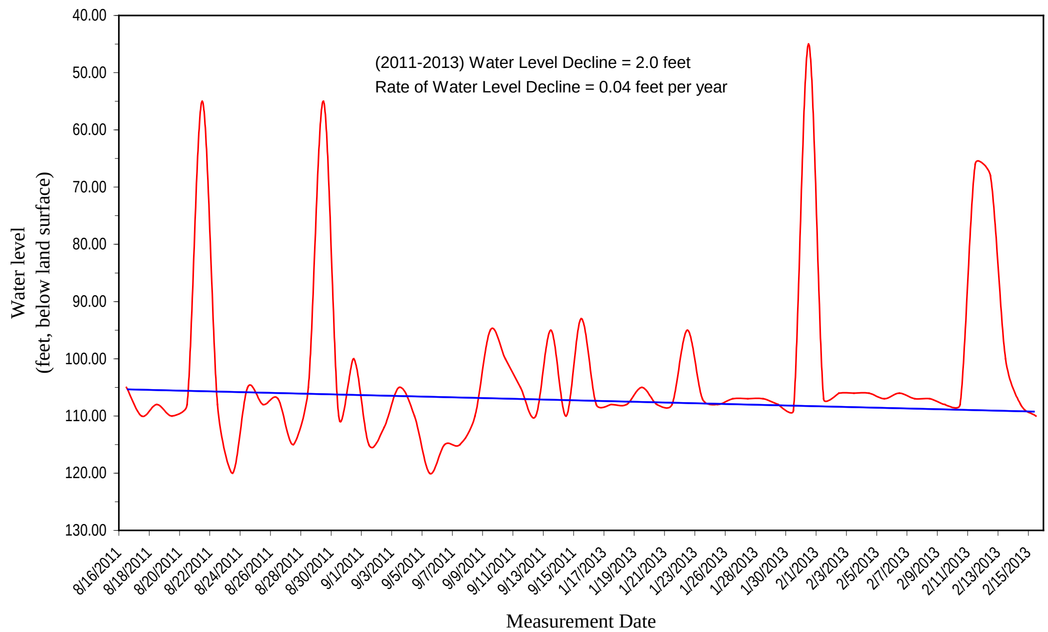


Figure 35.—Hydrograph of Geneva County well R-04, a public supply well constructed in the Nanafalia aquifer to a depth of 1,180 ft.

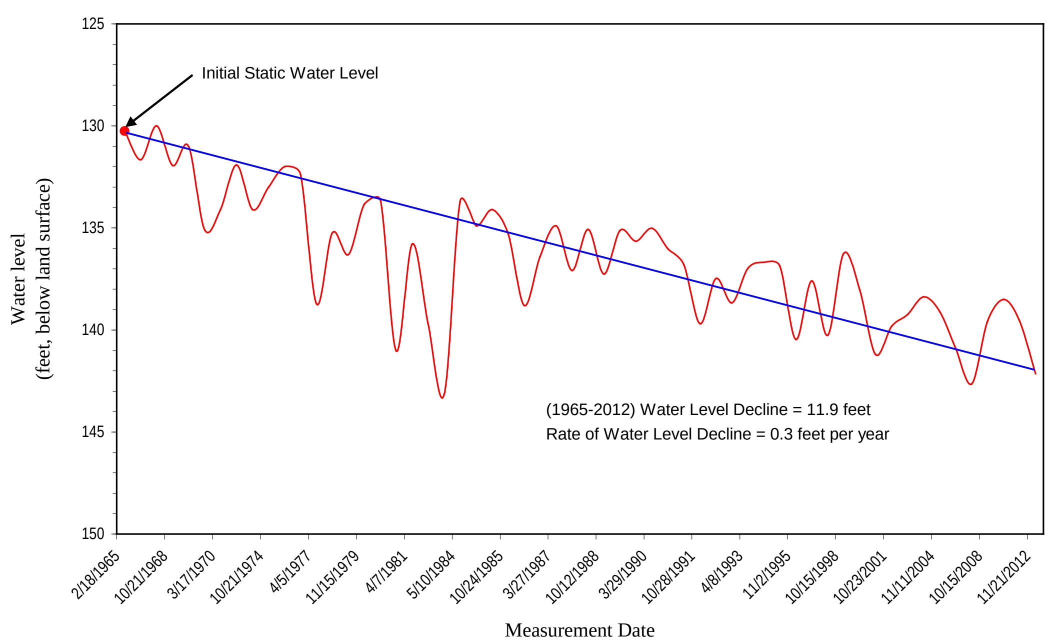


Figure 36.—Hydrograph of Henry County well J-1, a public supply well constructed in the Nanafalia aquifer to a depth of 302 ft and open-ended.

(Daleville Water and Sewer Board well no. 1) is screened in the Tuscahoma and Nanafalia aquifers and had a 178-ft decline from the initial static water level of 68 ft bls in 1961 to 246 ft bls in 2003 (4.3 ft/yr) (fig. 37). The water level continued to decline at 1.5 ft/yr until 2007. Since 2007 the water level in well M-11 has risen at 1.7 ft/yr (fig. 37). The top of the screened interval is 355 ft bls and, as of the last water level measurement on July 1, 2013 (242 ft bls), there was 113 ft of water above the screens in well M-11.

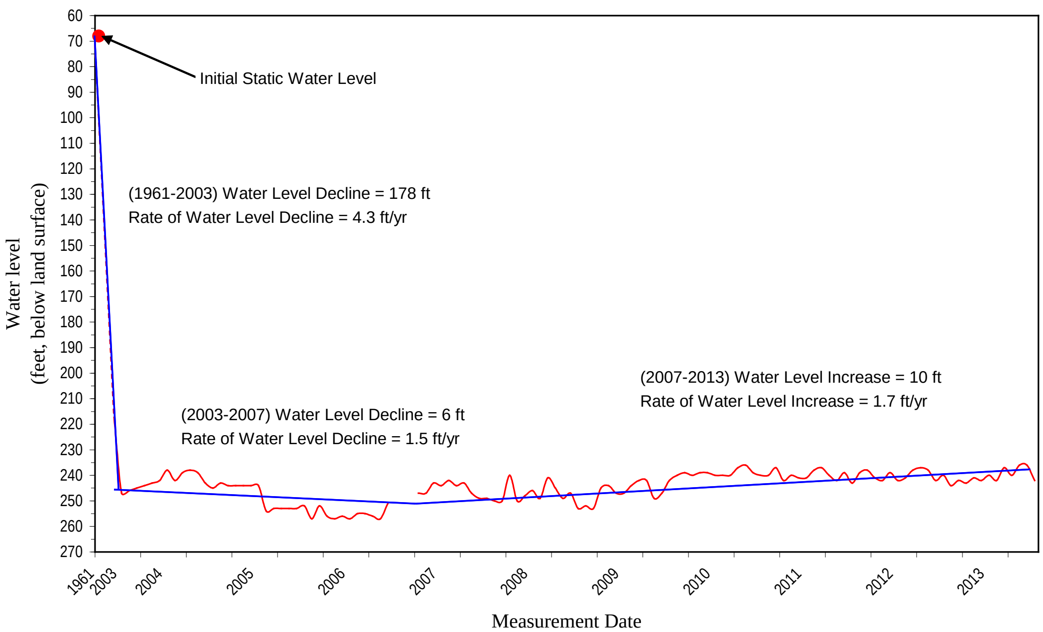


Figure 37.—Hydrograph of Dale County well M-11, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 700 ft, with the top of the screen 355 ft bls.

Well M-02 (Daleville Water and Sewer Board well no. 3) is screened in the Tuscahoma and Nanafalia aquifers and had a 65-ft decline from the initial static water level of 178 ft bls in 1961 to 243 ft bls in 2003 (1.6 ft/yr) (fig. 38). The water level continued to decline at 1.8 ft/yr until 2007. Since 2007, the water level in well M-02 has risen at 2.2 ft/yr (fig. 38). The top of the screened interval is 355 ft bls and, as of the last water level measurement on July 1, 2013 (237 ft bls), there was 118 ft of water above the screens in well M-02.

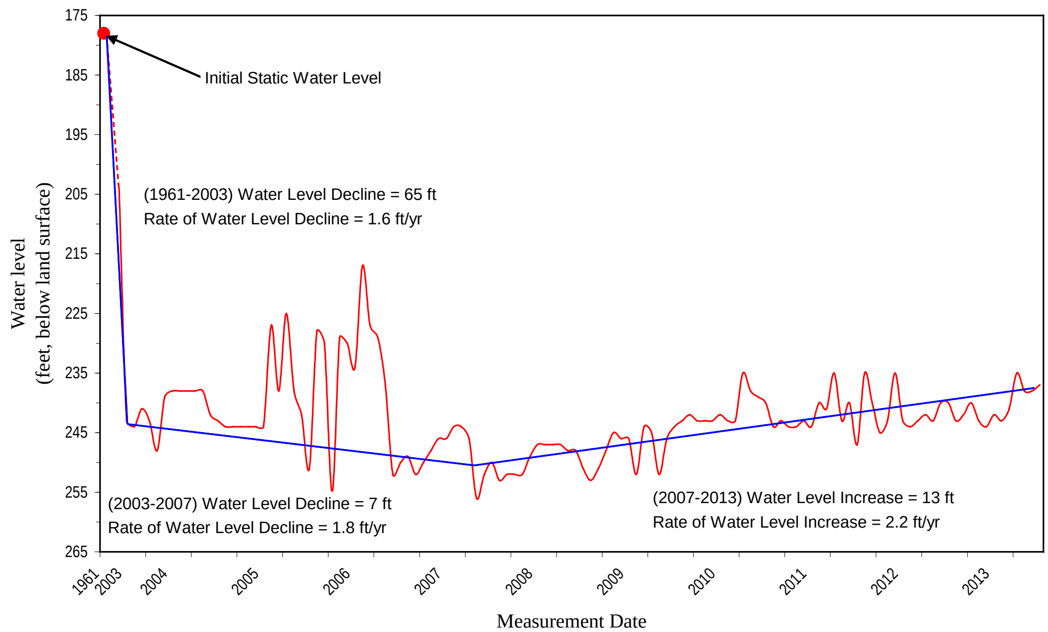


Figure 38.—Hydrograph of Dale County well M-02, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 707 ft, with the top of the screen 355 ft bls.

Well M-010 (Daleville Water and Sewer Board well no. 3) is screened in the Tuscahoma and Nanafalia aquifers and had a 29-ft decline from the initial static water level of 196 ft bls in 1986 to 225 ft bls in 2003 (1.7 ft/yr) (fig. 39). During this period, three large water level declines occurred in mid-2004 and 2005 and late 2007 (53, 43, and 36 ft, respectively), probably related to increased production due to drought demands. The water level continued to decline at 2.5 ft/yr until 2007. Since 2007, the water level in well M-010 has risen at 3.7 ft/yr (fig. 39). The top of the screen is 620 ft bls and, as of the last water level measurement on July 1, 2013 (212 ft bls), there was 408 ft of water above the screens in well M-010.

Water levels in all three wells have recovered since 2007, when the Daleville Water and Sewer Board constructed an additional high capacity well in the underlying Clayton aquifer about 4 miles east of the older wells.

Water levels in nine public supply wells operated by Dothan Utilities and screened in multiple aquifers were evaluated. However, it was determined that the Nanafalia aquifer

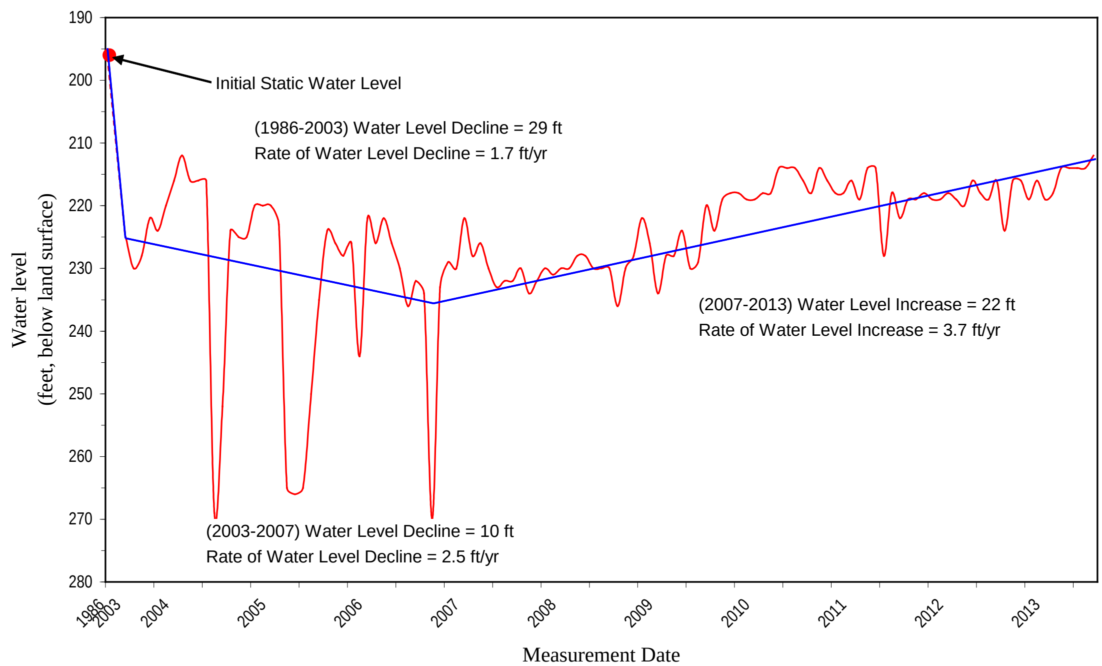


Figure 39.—Hydrograph of Dale County well M-010, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 773 ft, with the top of the screen 620 ft bls.

is the dominant water source in these wells, so they are included with wells screened solely in the Nanafalia.

Well I-05 (Dothan Utilities well no. 19) is screened in the Nanafalia and Clayton aquifers. The water levels declined from 1971 through the first quarter 2013 at 3.7 ft/yr (fig. 40). The top of the screened interval is 560 ft bls and, as of the last water level measurement on January 1, 2013 (324.9 ft bls), there was 235.1 ft of water above the screens in well I-05.

Well I-2 (Dothan Utilities well no. 4) is screened in the Tuscahoma and Nanafalia aquifers. The water level declined from the initial static measurement in 1946 to early 2012 at a rate of 2.7 ft/yr and has been stable from early 2012 to early 2013 (fig. 41). The top of the screened interval is 571 ft bls and, as of the last water level measurement on January 1, 2013 (325.5 ft bls), there was 245.5 ft of water above the screens in well I-2.

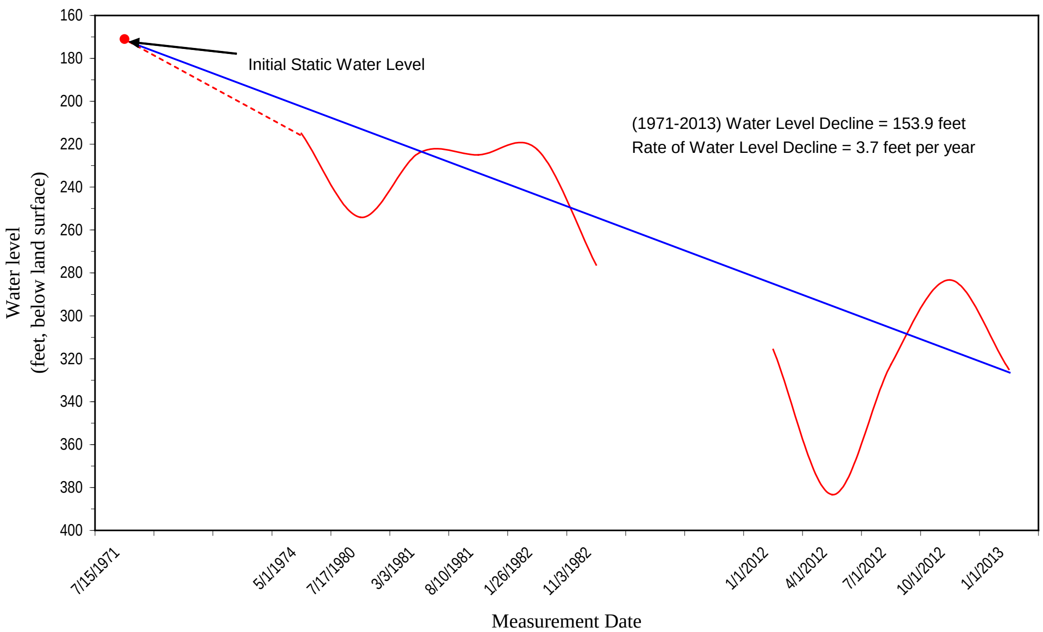


Figure 40.—Hydrograph of Houston County well I-05, a public supply well constructed in the Nanafalia and Clayton aquifers to a depth of 715 ft, with the top of the screen 560 ft bls.

Well I-11 (Dothan Utilities well no. 11) is screened in the Tuscahoma and Nanafalia aquifers. The water level declined from the initial static measurement in 1954 to 1985 at 4.3 ft/yr (fig. 42). From 1985 to 2013 the water level decline slowed to 1.6 ft/yr (fig. 42).The top of the screened interval is 635 ft bls and, as of the last water level measurement on January 1, 2013 (335.2 ft bls), there was 299.8 ft of water above the screens in well I-11.

Well J-3 (Dothan Utilities well no. 13) is screened in the Tuscahoma and Nanafalia aquifers. The water level declined from the initial static measurement in 1956 to 1985 at 5.4 ft/yr and slowed to 1.8 ft/yr from 1985 to 2013 (fig. 43). The top of the screened interval is 580 ft bls and, as of the last water level measurement on January 1, 2013 (324.9 ft bls), there was 255.1 ft of water above the screens in well J-3.

Well J-6 (Dothan Utilities well no. 14) is screened in the Tuscahoma and Nanafalia aquifers. The water levels declined from the initial static measurement in 1961 to early 2012 at 3.8 ft/yr but rose 13 ft from early 2012 to 2013 (fig. 44). The top of the screened

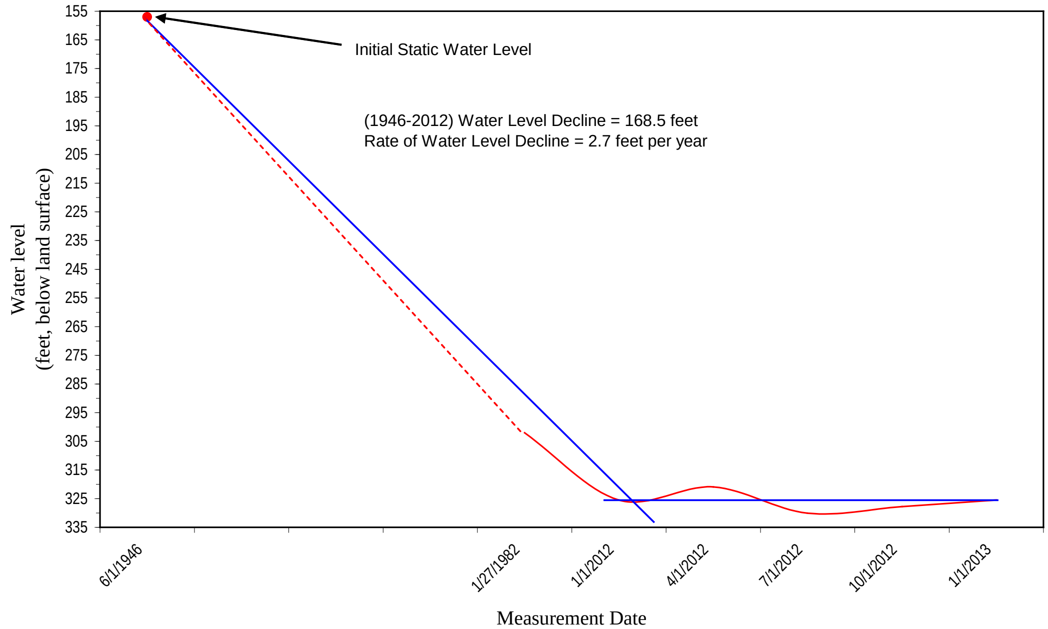


Figure 41.—Hydrograph of Houston County well I-2, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 786 ft, with the top of the screen 571 ft bls.

interval is 704 ft bls and, as of the last water level measurement on January 1, 2013 (386.5 ft bls), there was 317.5 ft of water above the screens in well J-6.

Well I-1 (Dothan Utilities well no. 15) is screened in the Tuscahoma and Nanafalia aquifers. The water level declined from the initial static measurement in 1961 to mid-2012 at 2.8 ft/yr (fig. 45). During the last part of 2012 the water level recovered about 32 ft (fig. 45). The top of the screened interval is 539 ft bls and, as of the last water level measurement on January 1, 2013 (300.6 ft bls), there was 238.4 ft of water above the screens in well I-1.

Well I-12 (Dothan Utilities well no. 16) is screened in the Tuscahoma and Nanafalia aquifers. The water level declined from the initial static measurement in 1963 to the third quarter of 2012 at 3.4 ft/yr but recovered about 25 ft during the last part of 2012 (fig. 46). The top of the screened interval is 595 ft bls and, as of the last water level measurement on January 1, 2013 (304.9 ft bls), there was 290.1 ft of water above the screens in well I-12.

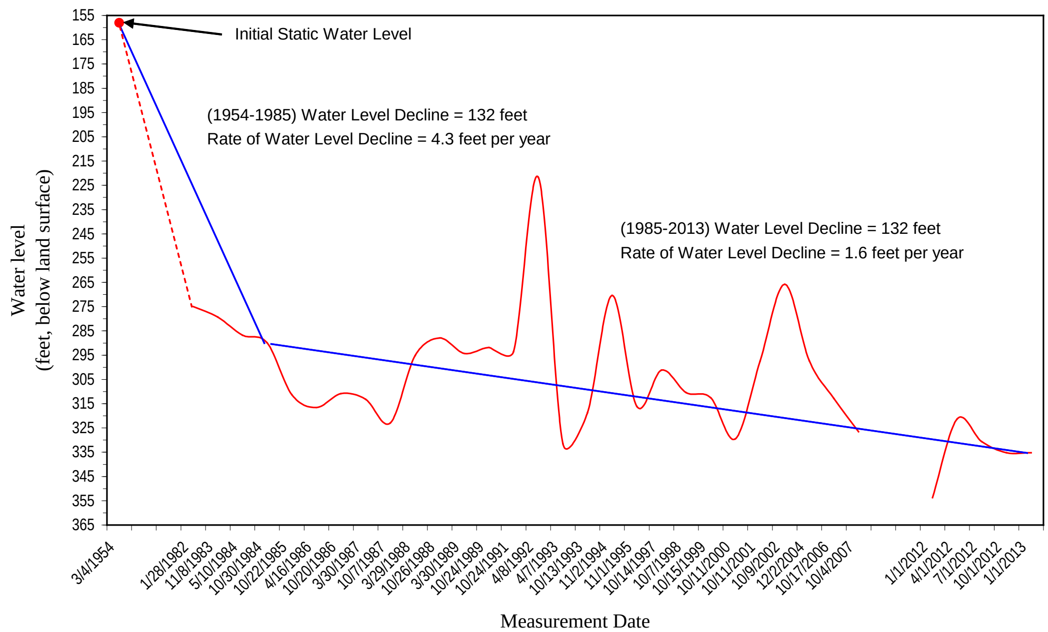


Figure 42.—Hydrograph of Houston County well I-11, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 835 ft, with the top of the screen 635 ft bls.

Well I-18 (Dothan Utilities well no. 17) is screened in the Tuscahoma and Nanafalia aquifers. The water levels declined from the initial static measurement in 1966 to 1986 at 6.0 ft/yr but recovered about 22 ft from 1986 to early 2013 (fig. 47). The top of the screened interval is 560 ft bls and, as of the last water level measurement on January 1, 2013 (304.9 ft bls), there was 255.1 ft of water above the screens in well I-18.

Well I-19 (Dothan Utilities well no. 21) is screened in the Tuscahoma and Nanafalia aquifers. The water levels declined from the initial static measurement in 1973 to mid-2012 at 3.7 ft/yr but recovered about 11 ft during the last part of 2012 (fig. 48). The top of the screened interval is 651 ft bls and, as of the last water level measurement on January 1, 2013 (349.9 ft bls), there was 301.1 ft of water above the screens in well I-19.

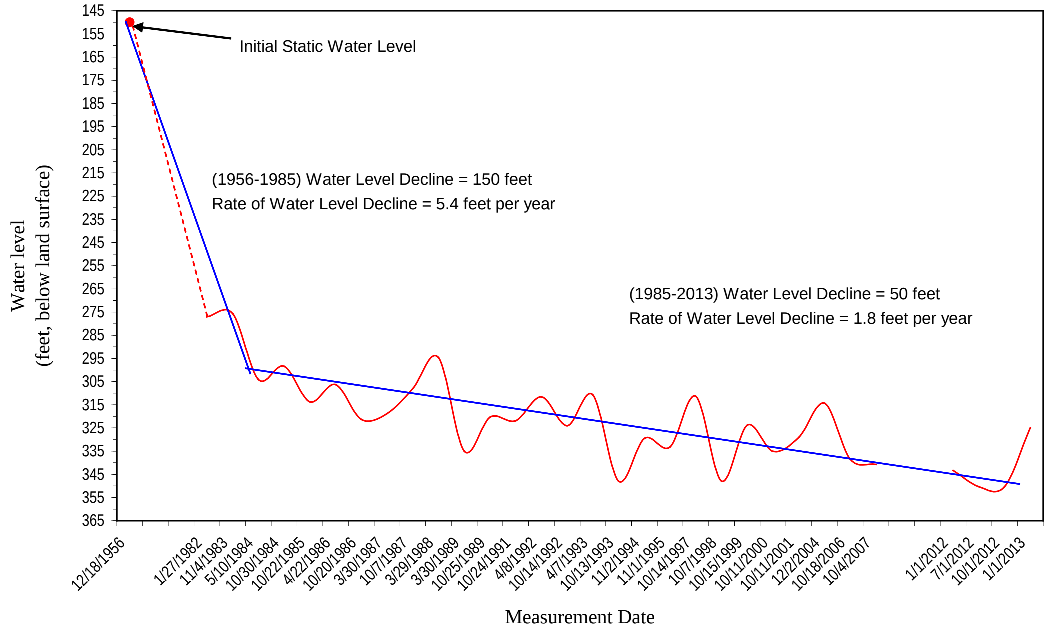


Figure 43.—Hydrograph of Houston County well J-3, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 720 ft, with the top of the screen 580 ft bls.

TUSCAHOMA SAND

HYDROGEOLOGY

The Tuscahoma Sand is about 80-125 ft thick in outcrop in eastern Alabama and generally consists of a thin basal glauconitic sand overlain by dark-gray to black, thinly laminated, micaceous and carbonaceous, nonfossiliferous clay and silty clay (Smith, 2001). Examination of drill cuttings from wells in the project area reveals that the Tuscahoma Sand consists primarily of dark-gray to olive-black or black, massive and structureless to somewhat fissile, quartzose silty, noncalcareous, carbonaceous clay and shale containing carbonized woody fragments with rare pyrite and/or marcasite (Smith, 2001). Within the project area, the Tuscahoma Sand consists predominantly of fine-grained clay/shale lithologies and generally serves as an effective aquiclude between the underlying Nanafalia and overlying Tallahatta Formation aquifers.

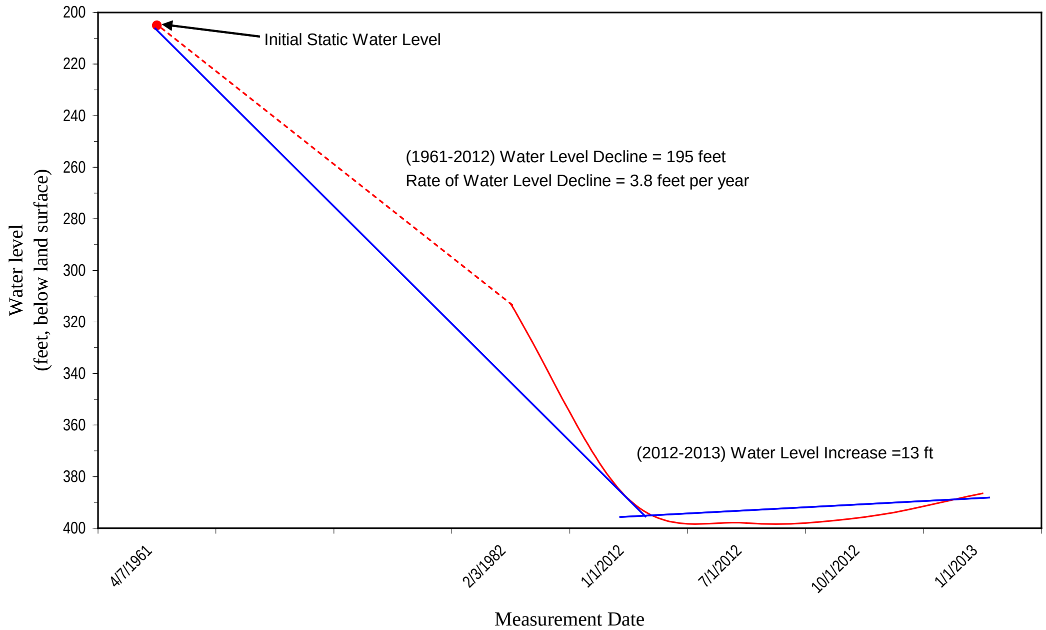


Figure 44.—Hydrograph of Houston County well J-6, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 804 ft, with the top of the screen 704 ft bls.

However, in both northeastern Covington and north-central Geneva Counties, several wells have been identified that produce potable water from the Tuscahoma Sand.

WELL DEPTH

Depths of wells constructed in the Tuscahoma aquifer vary from less than 200 ft, southeastward to more than 400 ft (plate 35). The shallowest identified well is in central Henry County at a depth of 120 ft and the deepest is in eastern Henry County at a depth of 500 ft.

DEPTH TO WATER

Depth to water in the Tuscahoma aquifer from available wells in the project area varies from 60 to 212 ft bls (plate 36). Water levels in the Tuscahoma are highly variable and are influenced by surface topography. Depth to water values were not contoured on plate 36 due to variability and sparse well control.

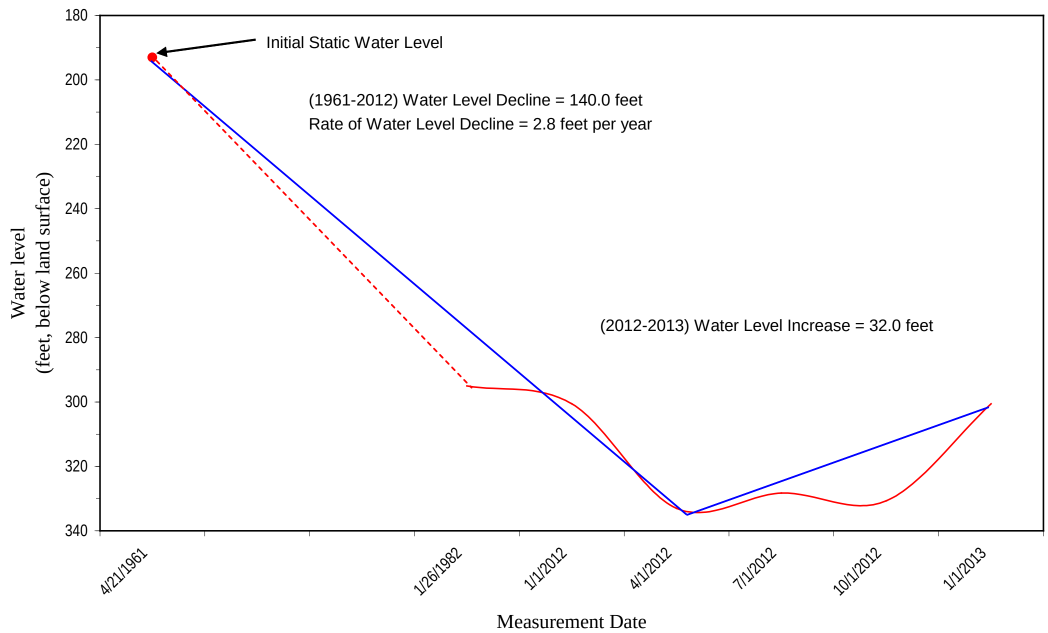


Figure 45.—Hydrograph of Houston County well I-1, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 714 ft, with the top of the screen 539 ft bls.

PUMPING RATES

Wells constructed in the Tuscahoma are primarily small diameter private supply and irrigations wells. Pumping rates range from 8 to 50 gpm (plate 37). Pumping rates in the Tuscahoma were not contoured due to sparse well control and the close proximity of small and larger capacity wells (plate 37). However, all pumping rates are relatively small and indicate that the Tuscahoma Sand is a minor aquifer in southeast Alabama.

SPECIFIC CAPACITY

Plate 38 shows specific capacities for wells constructed in the Tuscahoma aquifer. Specific capacities of private wells for domestic use varied from less than 1 gpm/ft to 2.5 gpm/ft. There were no public supply wells producing from the Tuscahoma aquifer in the study area.

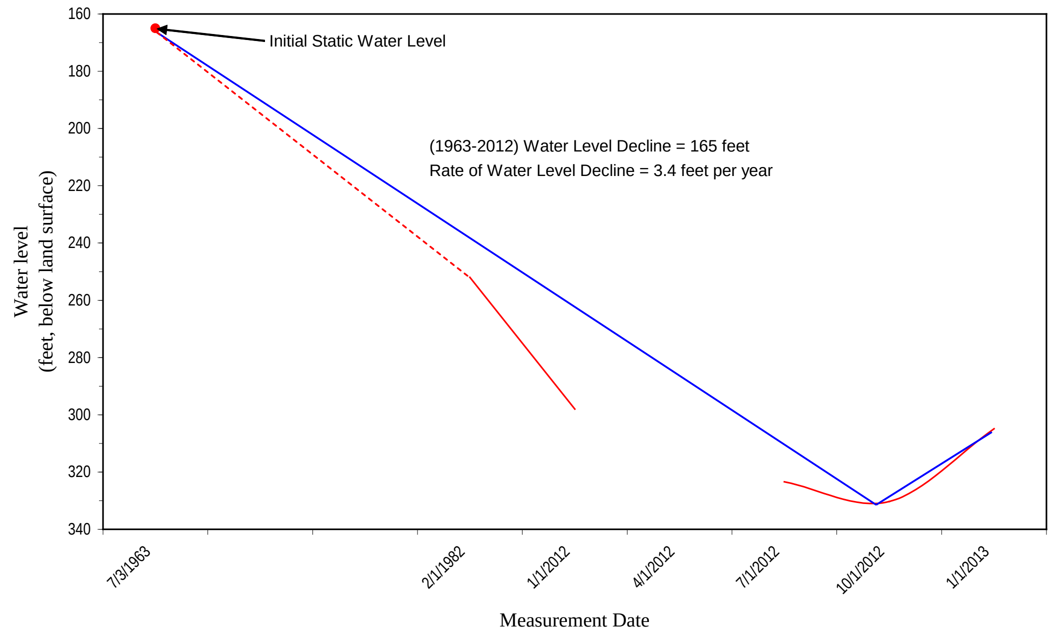


Figure 46.—Hydrograph of Houston County well I-12, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 867 ft, with the top of the screen 595 ft bls.

NET POTENTIAL PRODUCTIVE INTERVALS

Due to sparse well control and lack of geophysical logs from wells constructed in the Tuscahoma Sand, no NPPI mapping was performed.

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 19 private, state owned, and public water supply wells constructed in the Tuscahoma aquifer. Initial static water level elevations vary from 319 ft MSL near the recharge area in north-central Henry County to 137 ft MSL in eastern Houston County. The hydraulic gradient is 0.0024 (12.9 ft/mi). Groundwater flow is southward in Covington, Geneva, Coffee, Dale, and Houston Counties and south 60º east in eastern Henry County where the Chattahoochee River influences the direction of groundwater flow (plate 39).

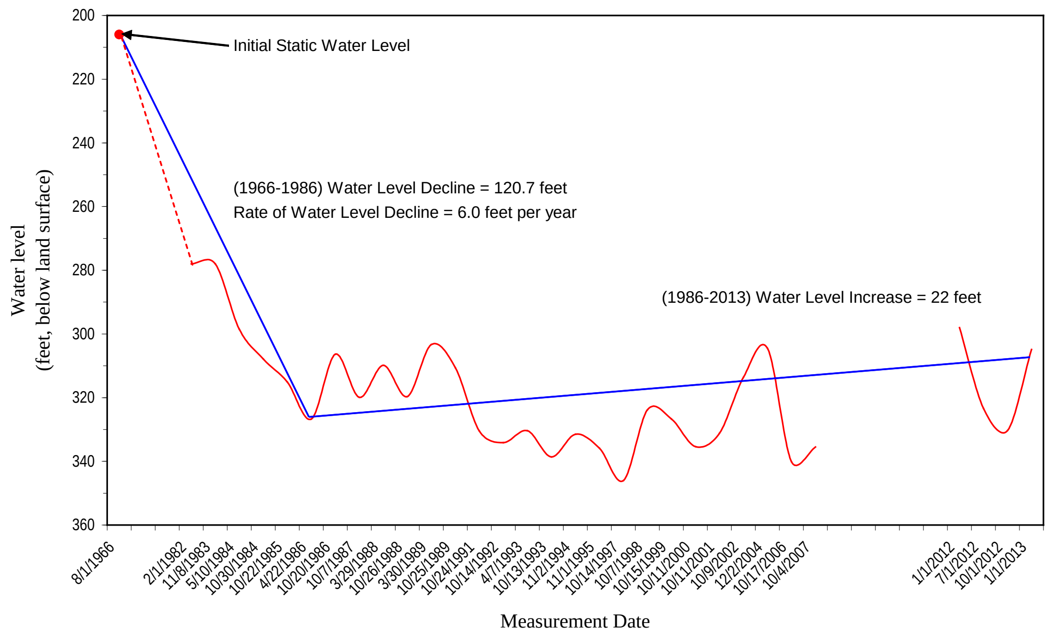


Figure 47.—Hydrograph of Houston County well I-18, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 777 ft, with the top of the screen 560 ft bls.

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 9 private, state owned, and public water supply wells constructed in the Tuscahoma aquifer. Comparison of initial and current potentiometric surfaces indicate there have been only minor hydrologic changes within the Tuscahoma aquifer since the initial static water level measurement period, except for an apparent regional steepening of the hydraulic gradient in the eastern part of the area. Current groundwater level elevations in the Tuscahoma aquifer vary from 308 ft MSL near Headland in southwest Henry County to 53 ft MSL in central Geneva County. The hydraulic gradient is approximately 0.00365 (17.2 ft/mi). The hydraulic gradient appears to steepen in the eastern portion of the study area from the initial gradient of 0.0024 (12.9 ft/mi) to a current gradient of 0.0048 (25.4ft/mi). There is currently no sound explanation for this change; however, additional data and investigation is needed to confirm the change. Groundwater flow is southward in Covington, Geneva, Coffee, Dale, and western Houston Counties and south 70º east

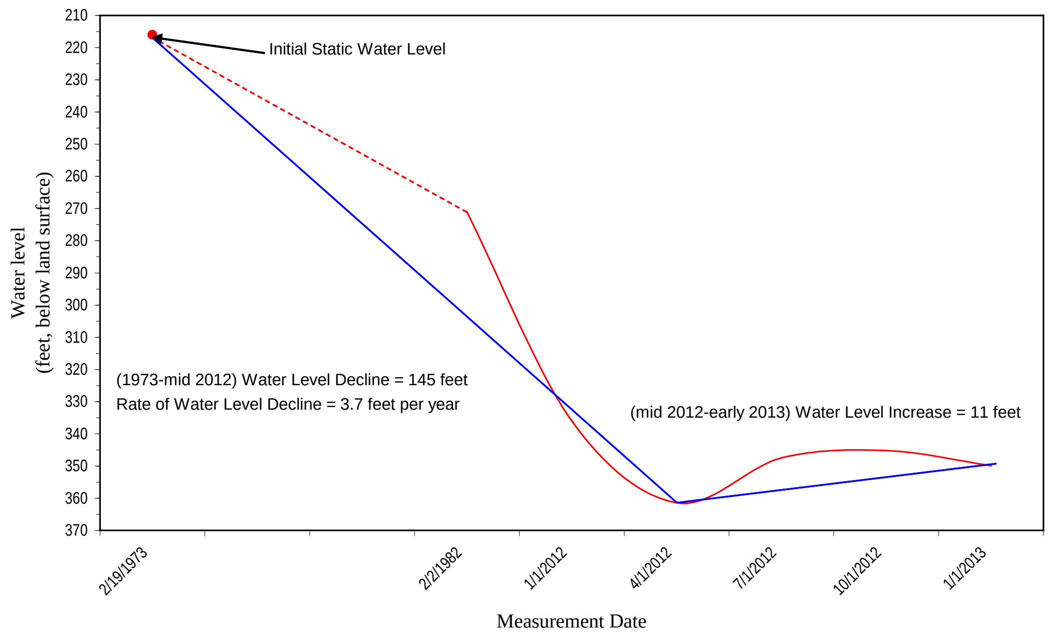


Figure 48.—Hydrograph of Houston County well I-19, a public supply well constructed in the Nanafalia and Tuscahoma aquifers to a depth of 761 ft, with the top of the screen 651 ft bls.

in eastern Henry County where the Chattahoochee River influences the direction of groundwater flow (plate 40).

GROUNDWATER LEVEL IMPACTS

Groundwater production impact levels were determined from a total of 8 private, state owned, and public water supply wells constructed in the Tuscahoma aquifer. Isolated disruptions in the potentiometric surface occur near Columbia (northeast Houston County) where the groundwater level declined 112 ft in well A-4. The groundwater level has declined 79 ft in well G-02 near Wicksburg (western Houston County “panhandle”), 108 ft in well B-8 at Skipperville (northern Dale County), and 39 ft in well J-04 (northeastern Covington County) (plate 41).

The Tuscahoma Sand is a minor aquifer in the southern part of the project area and is primarily used for domestic water supplies. Declining water levels in the Tuscahoma aquifer are isolated to individual wells.

Two domestic and stock supply wells constructed in the Tuscahoma aquifer in Dale County were selected, based on the quantity and quality of information available to generate long-term hydrographs that show the varying conditions in the aquifer.

Well B-8 is near the updip limits of the Tuscahoma aquifer and has a continuing water level decline at 0.5 ft per year since the well was constructed in 1963 (fig. 49). The hydrograph shows minor seasonal fluctuations and probable drought impacts of 15 and 25 ft in 1991 and 2009, respectively. The top of the screen is set at 250 ft bls, and, as of the last water level measurement of 200 ft bls on October 15, 2012, there was 50 ft of water in well B-8.

Well N-6 has three water level trends that begin with a decline of 19 ft from 1963 to

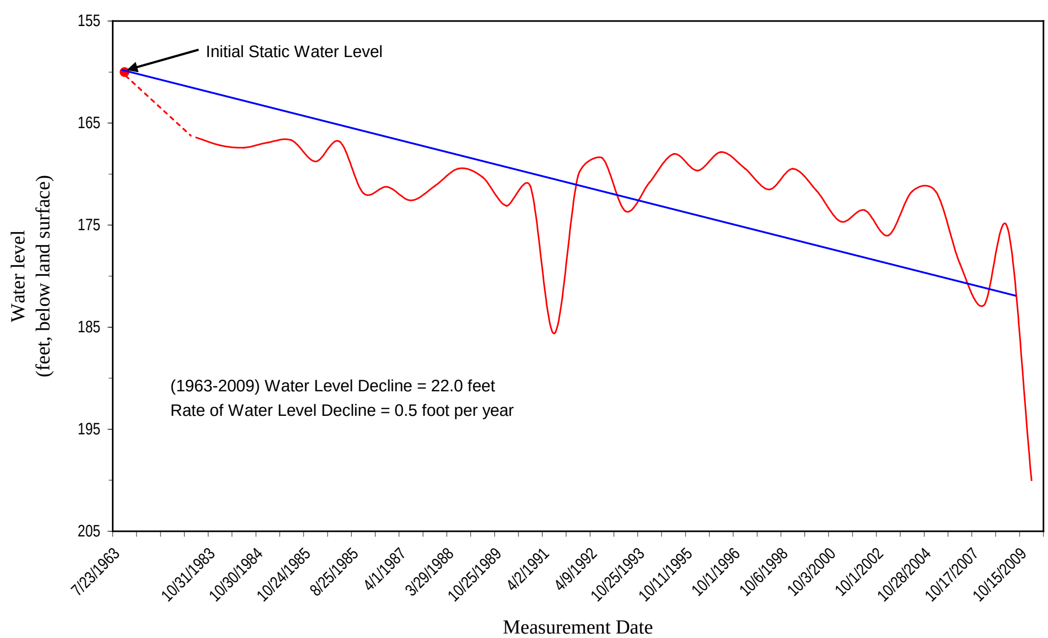


Figure 49.—Hydrograph of Dale County well B-8, a domestic and stock supply well constructed in the Tuscahoma aquifer to a depth of 270 ft, with the top of the screen 250 ft bls.

1982, at about 1.6 ft/yr (fig. 50). The second trend is a decline of 9 ft from 1982 to 1991 at 1 ft/yr and the third is an increase of 8 ft from 1991 to 2012 at 0.7 ft/yr (fig. 50). Well N-6 is not screened; however, the bottom of the well is set at 355 ft bls, as of the last water level measurement of 182.95 ft bls on November 7, 2012, there was 172.05 ft of water in well N-6.

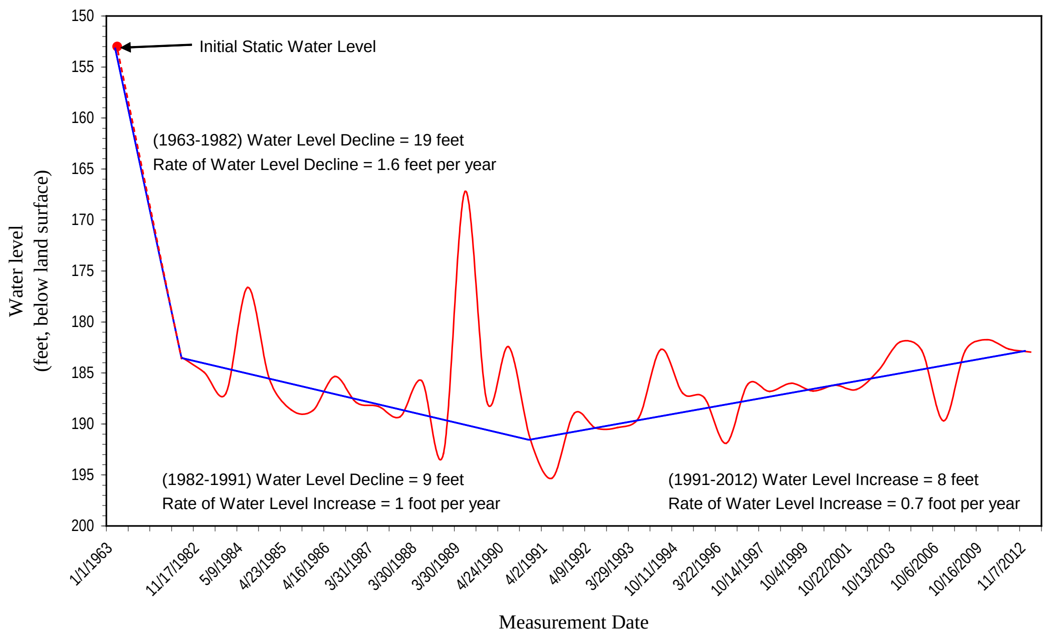


Figure 50.—Hydrograph of Dale County well N-6, a domestic and stock supply well constructed in the Tuscahoma aquifer to a depth of 355 ft and open-ended.

TALLAHATTA FORMATION

HYDROGEOLOGY

Through northern Covington County, central and southern Coffee and Dale Counties, and extending eastward through the central portion of Henry County, the Tallahatta Formation in outcrop generally consists of clayey sand, sandy clay, and thin beds of limestone (Smith, 2001).

Throughout the subsurface of the project area, the Tallahatta Formation consists predominantly of thick sands and thinner sand units interbedded with thin sandy limestones, sandy clays, and clays. Sands within the Tallahatta are usually glauconitic, poorly sorted, and fine to coarse with many grains possessing a distinctive pale-green glauconitic stain. Interbedded clays are invariably noncalcareous, usually of pale-green to moderate-green color, and somewhat “oily” or “waxy” in appearance (Smith, 2001).

WELL DEPTH

Depths of identified wells constructed in the Tallahatta aquifer vary from less than 100 ft to more than 700 ft southward (plate 42). Well depth increases from the up gradient part of the aquifer in southern Coffee, Dale, and Henry Counties to the Florida State Line at about 39 ft/mi, which is controlled by the dip of the formation. The shallowest identified well is in southern Coffee County at a depth of 80 ft and the deepest is in southern Geneva County at a depth of 702 ft.

DEPTH TO WATER

Depth to water in the Tallahatta aquifer in the project area varies from 0 to more than 120 ft bls (plate 43). Water levels in the Tallahatta are highly variable and difficult to contour. Deeper water levels are in southern Henry, Geneva and Coffee Counties. Shallower water levels are also found in these areas as well as in northern Houston County, in association with stream valleys and areas of low elevation.

PUMPING RATES

Most wells constructed in the Tallahatta aquifer are small diameter private supply and irrigation wells. Pumping rates vary from 10 to 40 gpm (plate 44). Pumping rates in the Tallahatta aquifer are difficult to contour due to sparse well control and the close proximity of small and large capacity wells (plate 44). Higher capacity wells are located in southwest Henry County. Lower capacity wells are located throughout the study area.

SPECIFIC CAPACITY

Plate 45 shows the specific capacities for wells constructed in the Tallahatta aquifer. Specific capacities of private wells for domestic use varied from less than 1 gpm/ft to 5.0 gpm/ft. There were no public supply wells producing from the Tallahatta aquifer in the study area.

NET POTENTIAL PRODUCTIVE INTERVALS

The thickest NPPIs for the Tallahatta aquifer vary from 75 to more than 125 ft and occur in a linear trend across north-central Geneva County and northwestern Houston County (plate 46). Elsewhere, NPPI thicknesses vary from 20 to 70 ft, with thinning in the updip (northerly) direction. Sands in the Tallahatta aquifer contain fresh water, except in the southwestern part of the project area where the water is increasingly saline (plate 46). Across much of the area Tallahatta sands appear to be overlain directly by sands of the Lisbon aquifer, indicating likely hydraulic interconnection of the two aquifers.

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 19 private, state owned, and public water supply wells constructed in the Tallahatta aquifer. Initial static water level elevations in the Tallahatta aquifer vary from 335 ft MSL near the recharge area in southeastern Dale County to 70 ft MSL at Geneva in south-central Geneva County. The hydraulic gradient is 0.0027 (14.4 ft/mi) and groundwater flow is southward in Geneva County and southern Coffee and Dale Counties, except for minor influences in flow direction by the Choctawhatchee and Pea Rivers (plate 47). The flow is south 45^{o} east in Houston County and southern Henry County where the Chattahoochee River influences the direction of groundwater flow (plate 47).

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 16 private, state owned, and public water supply wells constructed in the Tallahatta aquifer. Comparison of initial and current potentiometric surfaces indicate little or no hydrologic changes within the Tallahatta aquifer. Current water level elevations in the Tallahatta aquifer vary from 329 ft MSL in northwest Houston County to 31 ft MSL at Geneva in south-central Geneva County. The hydraulic gradient is approximately 0.0027 (14.4 ft/mi) (plate 48).

Groundwater production impact levels were determined from a total of 14 private, state owned, and public water supply wells constructed in the Tallahatta aquifer. Minor isolated disruptions in the potentiometric surface occur at producing wells. The groundwater level has declined 40 ft in well Q-04 near Battens Crossroads (southeast Coffee County), 34 ft at well P-03 near Grimes (southeastern Dale County), 28 ft in well C-2 near Bellwood (north-central Geneva County), and 39 ft in well R-16 at Geneva (south-central Geneva County) (plate 49).

HYDROGRAPHS AND AQUIFER DECLINE CURVES

The Tallahatta Formation is a minor aquifer and is used in the southern part of the project area primarily for domestic water supplies. Declining water levels in the Tallahatta aquifer are isolated to individual wells.

Well B-2, a domestic supply well in northeastern Geneva County, has a long-term water level decline of 0.2 ft/yr since 1963 (fig. 51). The lowest water level

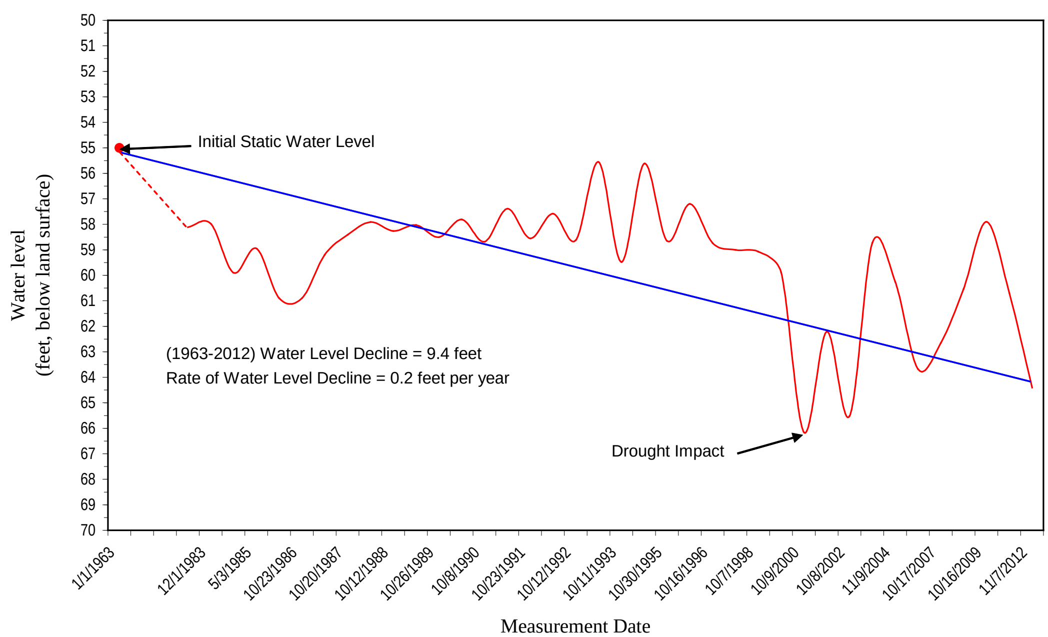


Figure 51.—Hydrograph of Geneva County well B-2, a domestic supply well constructed in the Tallahatta aquifer to a depth of 365 ft and open-ended.

measurements occurred during droughts in 1985-86 and 2000-2002 (fig. 51). Well B-2 is not screened; however, the bottom of the well is 365 ft bls and, as of the last water level measurement on November 7, 2012 (64.4 ft bls), there was 300.6 ft of water in well B-2.

Well C-2, in north-central Geneva County had a declining water level at 1.7 ft/yr from 1982 to 2000. Since 2001, the water level has increased at a rate of 0.3 ft/yr (fig. 52). Construction information is not available for well C-2; however, the bottom of the well is 127 ft bls and, as of the last water level measurement on November 7, 2012, there was 88.95 ft of water in well C-2.

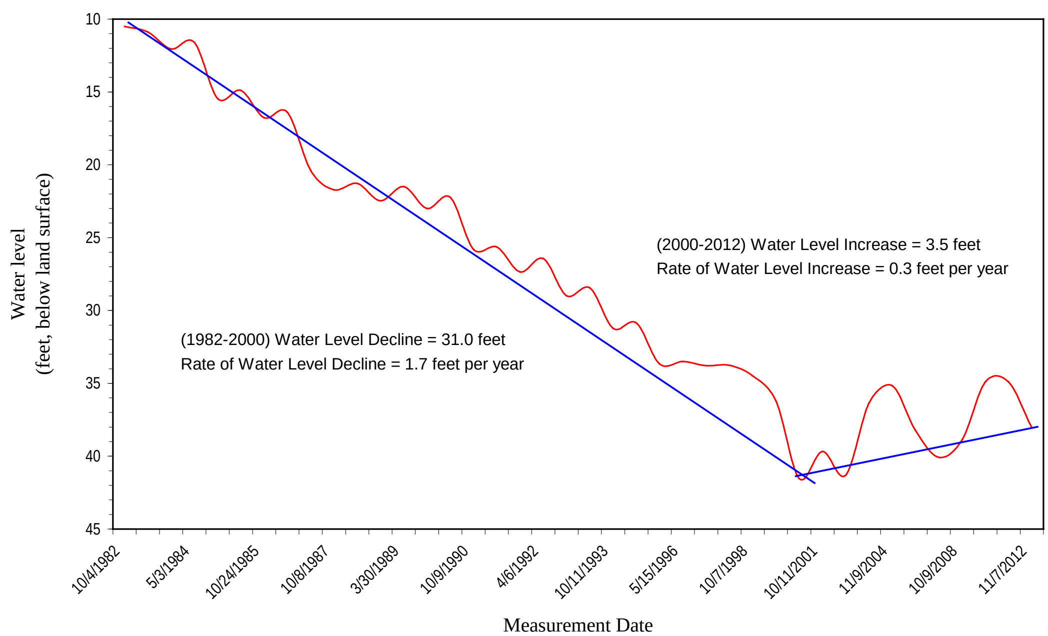


Figure 52.—Hydrograph of Geneva County well C-2, a domestic supply well constructed in the Tallahatta aquifer to a depth of 127 ft.

LISBON FORMATION

HYDROGEOLOGY

The Lisbon Formation outcrop and recharge area extends across southern Henry, Dale, Coffee, and northern Covington Counties (Szabo and others, 1988) where the formation is about 110 ft in thickness near the Chattahoochee River and thins westward to about 75 ft in Covington County. Toulmin and LaMoreaux (1963) reported that the Lisbon Formation outcrop in southeast Alabama consists primarily of sand but also contains significant amounts of limestone and sandy limestone. Smith (2001) described subsurface Lisbon sands as greenish-gray to yellowish-gray, sparingly glauconitic, quartzose silty, varying from poorly sorted to well sorted, fine to medium grained. Lisbon limestones are light-gray, indurated, quartzose sandy, and highly fossiliferous, frequently vugular, highly porous and permeable from leaching and solution of fossils and fossil fragments (Smith, 2001). In the subsurface, the thickness of the Lisbon Formation is 60 to 80 ft in central Covington County and thickens southeastward to more than 350 ft in central Geneva County (Smith, 2001). The depth of the Lisbon Formation varies from 200 ft MSL in central Houston, southern Dale and Coffee Counties, and northern Covington County to sea level in southern Houston and Geneva Counties and central Covington County (Smith, 2001).

WELL DEPTH

Depths of identified wells constructed in the Lisbon aquifer vary from less than 100 ft, near the updip limits of the aquifer, to more than 500 ft southward (plate 50). The shallowest identified well is in southwestern Henry County at a depth of 24 ft, near the updip limits of the aquifer and the deepest is in eastern Geneva County at a depth of 544 ft.

DEPTH TO WATER

Depth to water in the Lisbon aquifer in the project area varies from 0 to more than 85 ft bls (plate 51). The shallowest water levels occur in southern Houston County and in the Choctawhatchee River valley in Geneva County. Shallow water levels are most likely caused by a combination of low land surface elevations and increasing confinement of the aquifer across the southern part of the study area. The deepest water levels occur along the northern updip limit of the aquifer and in eastern Henry and Houston Counties.

PUMPING RATES

Pumping rates were obtained from public supply, private supply, and irrigation wells in the project area. Pumping rates vary from 14 to over 500 gpm. Pumping rates for wells constructed in the Lisbon aquifer are difficult to contour due to the close proximity of small and large capacity wells with highly variable rates (plate 52). Larger diameter wells located near Grimes in southeast Dale County, in central Geneva County, and in central Covington County have the highest pumping rates. Smaller diameter private wells located throughout the southern reaches of the study area have the lowest rates.

SPECIFIC CAPACITY

Plate 53 shows specific capacities for wells constructed in the Lisbon aquifer. The majority of Lisbon wells are private wells for domestic use with specific capacities that vary from less than 1 gpm/ft to over 3 gpm/ft. Only two public water supply wells with specific capacity data were identified. They are in southeastern Dale and southwestern Coffee Counties and their respective specific capacities are 1.3 and 2.8 gpm/ft.

NET POTENTIAL PRODUCTIVE INTERVALS

Due to insufficient geophysical well log information, an NPPI map for the Lisbon Formation could not be constructed.

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 30 private, state owned, and public water supply wells constructed in the Lisbon aquifer. Initial groundwater level elevations vary from 370 ft MSL near the recharge area in west-central Henry County to 85 ft MSL at Geneva in south-central Geneva County. The hydraulic gradient is 0.0018 (9.5 ft/mi) and groundwater flow is southward in Covington, Geneva, and southern Coffee Counties, except for local influences by the Choctawhatchee River in Geneva County. The flow direction changes to south 60º east in Houston and southern Henry Counties where the Chattahoochee River influences the direction of groundwater flow (plate 54).

CURRENT STATIC GROUNDWATER LEVELS

Current static groundwater levels were determined from a total of 29 private, state owned, and public water supply wells constructed in the Lisbon aquifer. Current potentiometric data indicates there have been no significant hydrologic changes within the Lisbon aquifer since the initial static water level measurement period. Current groundwater level elevations in the Lisbon aquifer vary from 358 ft MSL near the recharge area in west-central Henry County to 84 ft MSL at Geneva in south-central Geneva County. The hydraulic gradient is 0.0018 (9.5 ft/mi). Current groundwater flow data is consistent with the initial potentiometric data (plate 55).

GROUNDWATER LEVEL IMPACTS

Groundwater production impact levels were determined from a total of 26 private, state owned, and public water supply wells constructed in the Lisbon aquifer. Isolated disruptions in the potentiometric surface occur near producing wells at Geneva (southern Geneva County) where the groundwater level has declined 75 ft in well S-8 and a minor disruption at Sanford (northeastern Covington County) where the groundwater level has declined 22 ft in well M-5 (plate 56).

HYDROGRAPHS AND AQUIFER DECLINE CURVES

The Lisbon Formation is a minor aquifer and is only available in the southern part of the project area. Declining water levels in the Lisbon aquifer are isolated and only observed in individual wells.

Well M-5, an industrial supply well, is in the up gradient part of the formation near the recharge area and has regular seasonal water level fluctuations (fig. 53). The hydrograph shows a decline of 21.3 ft from 1965 to 1984 (1.2 ft/yr) and a stable water level from 1984 to 2012. The largest water level decline (more than 12 ft) occurred during severe drought conditions in 2006 and 2007. Well M-4 is not screened; however, the bottom of the well is 170 ft bls and, as of the last water level measurement on October 29, 2012 (68.76 ft bls) there was 101.2 ft of water in well M-5.

Well R-10, a domestic supply well in south-central Geneva County, has a relatively stable water level from 1983 through 2007. However, during this period, the hydrograph also shows seasonal fluctuations of 2 to 5 ft and major drought impacts in 2000, 2002,

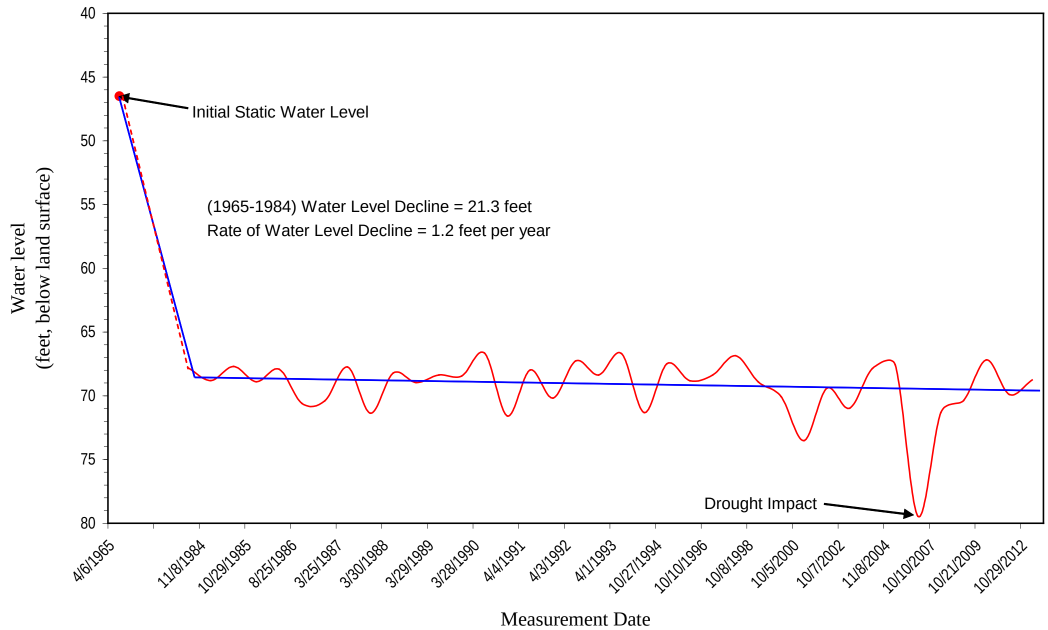


Figure 53.—Hydrograph of Covington County well M-5, a domestic supply well constructed in the Lisbon aquifer to a depth of 170 ft and open-ended.

and 2007 (fig. 54). Seasonal and drought impacts indicate that water levels in well R-10 are influenced by surface water as the well is at the confluence of the Pea and Choctawhatchee Rivers (fig. 54). Well R-10 is not screened; however, the bottom of the well is 150 ft bls and, as of the last water level measurement on October 17, 2012 (19.25 ft bls) there was 130.75 ft of water in well R-10.

Well AA-1 is in southwestern Houston County and has a constant water level decline of 0.3 ft per year since its construction in 1967 (fig. 55). The well is in an area that has a large amount of irrigation from groundwater sources and although the well is unused, it is probably influenced by nearby agricultural groundwater production from the Lisbon or overlying Crystal River aquifers. The top of the screen is 230 ft bls and, as of the last water level measurement on November 7, 2012 (46.93 ft bls) there was 183.07 ft of water above the screens in well AA-1.

Well S-8 (Geneva Water Works well no. 5), in south-central Geneva County, is screened in the Tallahatta and Lisbon aquifers, although most water contribution is likely from the Lisbon.

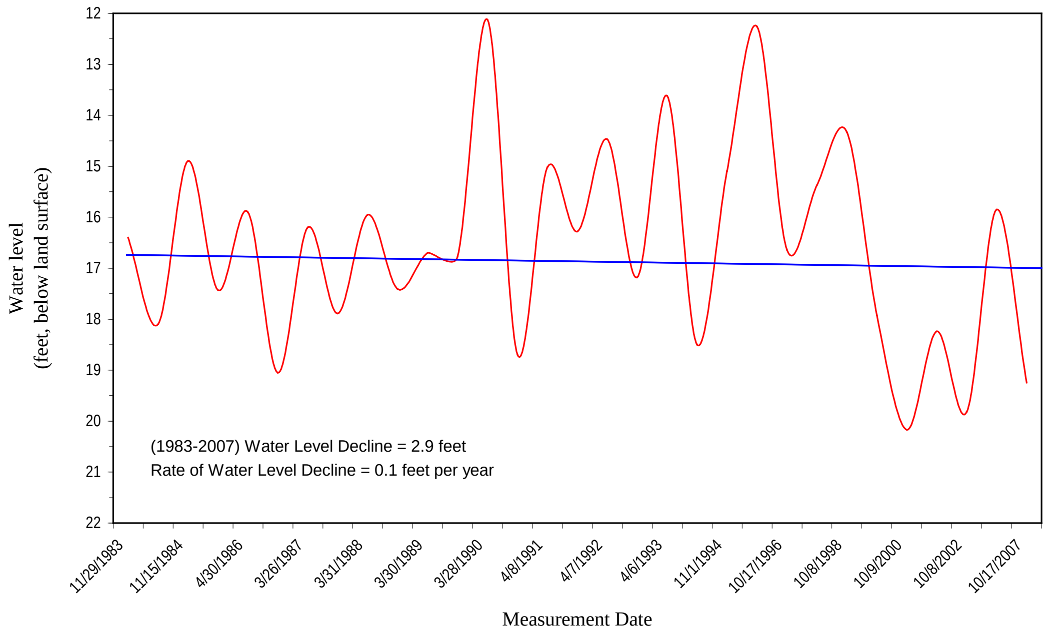


Figure 54.—Hydrograph of Geneva County well R-10, an unused industrial supply well constructed in the Lisbon aquifer to a depth of 150 ft and open-ended.

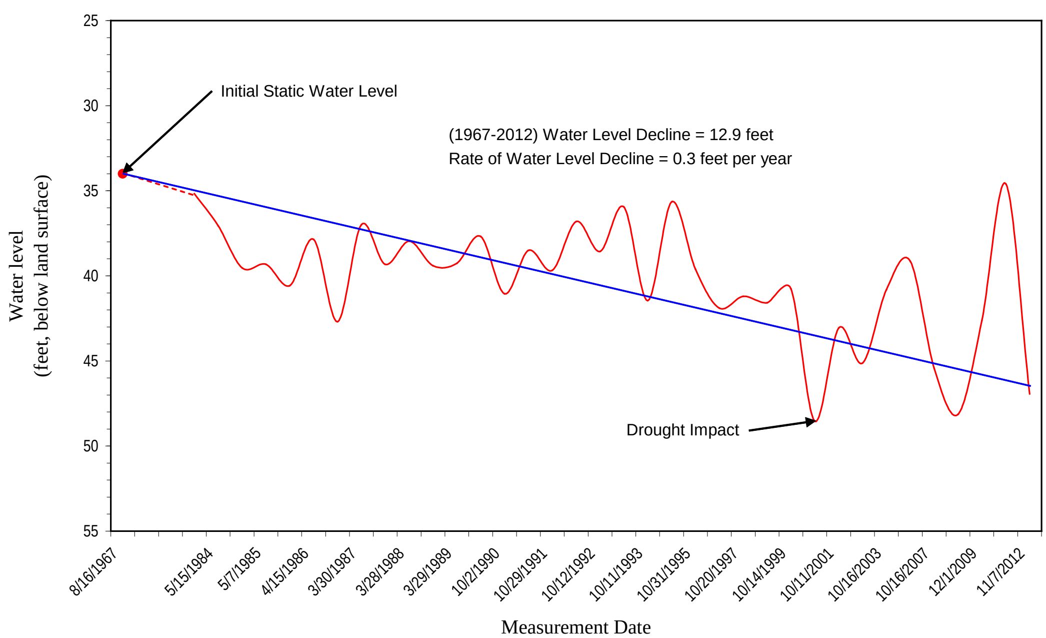


Figure 55.—Hydrograph of Houston County well AA-1, an unused well constructed in the Lisbon aquifer to a depth of 250 ft, with the top of the screen 230 ft bls.

This well has the largest water level decline identified in the Lisbon aquifer (157 ft), although it recovered slightly during 2013. The water level in well S-8 declined 24 ft (0.9 ft/yr) from 1979 to 2007 but declined rapidly (133 ft) from late 2007 to early 2011 (44 ft/yr) (fig. 56). From early 2011 to early 2013 water levels in well S-8 were characterized by ten large, rapid fluctuations of as much as 150 ft. This was caused by short periods of heavy pumping and subsequent pump shut down (fig. 56). The top of the screen is 360 ft bls and, as of the last water level measurement on February 15, 2013 (175 ft bls), there was 185 ft of water above the screens in well S-8.

Figure 56.—Hydrograph of Geneva County well S-8, a public supply well constructed in the Lisbon and Tallahatta aquifers to a depth of 480 ft, with the top of the screen 360 ft bls.

CRYSTAL RIVER FORMATION

HYDROGEOLOGY

The Crystal River Formation includes calcareous deposits of late Eocene age below limestone beds of Oligocene age (Smith, 2001). In the shallow subsurface, the Crystal River Formation is readily recognizable and in central Covington County, most of southern Geneva County, and in northwestern Houston County, it consists of about 100 to 150 ft of calcareous sands, sandy clays, and marls with thin interbedded limestones (Smith, 2001). Crystal River sediments are thought to be the weathered remnants of originally deposited limestones and chalky limestones. Downdip, in Covington County, the Crystal River sediments are at somewhat greater depth, less intensely weathered, and consist predominantly of somewhat oxidized, pinkish-gray to very pale-orange, very highly yet finely fossiliferous, recrystallized and sucrosic, somewhat dolomitized and vugular, highly porous and permeable limestone (Smith, 2001). Toward the east, in southeastern Geneva and southwestern Houston Counties, the Crystal River Formation, although weathered, consists predominantly of chalky sands, chalks, and limestones similar to those in southern Covington County (Smith, 2001).

WELL DEPTH

Depths of identified wells constructed in the Crystal River aquifer vary from 90 to 380 ft with the majority of the deepest wells occurring in southern Covington County, influenced by the southwest dip of the formation (plate 57). The shallowest identified well constructed in the Crystal River aquifer is in central Houston County at a depth of 90 ft and the deepest is in southern Covington County at a depth of 380 ft.

DEPTH TO WATER

Depth to water in the Crystal River aquifer in the investigated area varies from 0 to more than 90 ft bls (plate 58). The aquifer is unconfined or partially confined throughout the entire study area. Therefore, the shallowest water levels in the Crystal River are along the northern, updip limit of the aquifer, and the deepest water levels occur along the Alabama-Florida state line in southern Covington, Geneva and Houston Counties. Generally, depth to water increases downdip from north to south at about 5 ft/mi (plate 58).

PUMPING RATES

Pumping rates observed from public supply, private supply, and irrigation wells constructed in the Crystal River aquifer in the project area vary from 23 to 1,100 gpm. Four of the 17 identified wells produce greater than 500 gpm. Pumping rates generally increase southward from the recharge area, with the largest rates occurring in large diameter public supply wells in southern Houston, Geneva, and Covington Counties (plate 59). Smaller diameter private supply wells with relatively small pumping rates are located throughout the study area and cause difficulty with contouring pumping rates (plate 59).

SPECIFIC CAPACITY

Plate 60 shows that specific capacities for the majority of wells constructed in the Crystal River aquifer are private wells for domestic use. Specific capacities varied from less than 1 gpm/ft to over 140 gpm/ft. Only two wells with specific capacity data are constructed in the Crystal River aquifer for public supply use and their values are 82 gpm/ft and 750 gpm/ft, respectively (plate 60).

NET POTENTIAL PRODUCTIVE INTERVALS

Due to insufficient geophysical well log information, an NPPI map for the Crystal River Formation could not be constructed.

POTENTIOMETRIC SURFACES

INITIAL STATIC GROUNDWATER LEVELS

Initial static groundwater levels were determined from a total of 21 private, state owned, and public water supply wells constructed in the Crystal River aquifer. Initial water level elevations vary from 203 ft MSL near the recharge area in east-central Covington County to 87 ft MSL in southern Geneva County (plate 61). The hydraulic gradient is 0.0012 (6 ft/mi). Only the updip part of the Crystal River aquifer is present in Alabama. Therefore, it lacks confinement so that water flow in the aquifer is profoundly influenced by surface topography and surface-water bodies. Groundwater flows eastward in western Covington County and westward in eastern Covington County where the Yellow River influences the direction of flow (plate 61). Groundwater flow is south 45^{o} west in central Geneva County where it is influenced by the Choctawhatchee River and south 45^{o} east in eastern Houston County where the Chattahoochee River influences the direction of flow (plate 61). Only in western Houston County is the flow to the south along regional stratigraphic dip (plate 61).

CURRENT STATIC GROUNDWATER LEVELS

Current groundwater levels indicate there have been no significant hydrologic changes within the Crystal River aquifer since the initial static water level measurement period. Current static groundwater levels were determined from a total of 21 private, state owned, and public water supply wells constructed in the Crystal River aquifer. Current groundwater level elevations in the Crystal River aquifer vary from 201 ft MSL near the recharge area in east-central Covington County to 84 ft MSL in southern Geneva County (plate 62). The hydraulic gradient is approximately 0.0012 (6 ft/mi). All groundwater flow directions are consistent with initial static water level data.

GROUNDWATER LEVEL IMPACTS

Groundwater production impact levels were determined from a total of 21 private, state owned, and public water supply wells constructed in the Crystal River aquifer. Water use from the Crystal River aquifer includes public water supply at Florala (southeastern Covington County) and private water supply throughout the aquifer area, although the primary use of water is agricultural irrigation from a number of high capacity wells in southern Houston County. However, only minor disruptions in the potentiometric surface were observed and all occur from individual wells. Those disruptions occur at producing wells near Crosby (southern Houston County) where water levels declined 24 ft in both the U-7 and X-2 wells and at Florala where water levels declined 11 ft in well CC-3 and 7 ft in well CC-4 (plate 63). Long-term declines rarely occur in irrigation wells because water production from these wells is limited to the southeast Alabama growing season.

HYDROGRAPHS AND AQUIFER DECLINE CURVES

The Crystal River Formation is a minor aquifer but is the primary groundwater source in the southern part of the project area along the Florida state line. All selected wells are observation wells in the GSA groundwater level monitoring program. Declining water levels in the Crystal River aquifer are isolated to individual wells. Generally, water levels in all monitored Crystal River wells are relatively stable with only minimal rates of water level change. Also, all wells have regular seasonal water level fluctuations, which indicate the unconfined or partially confined nature of the Crystal River aquifer.

Well Z-4, an observation well in southwestern Covington County, had a stable water level from 1980 to 1993 and a decline of 6 ft (0.3 ft/yr) from 1993 to 2012 (fig. 57). This well was impacted by drought in 2002, but recovered, although not to pre-drought levels. The hydrograph for well Z-4 shows a continuous water level decline at 0.3 ft/yr and impacts by drought in 2006 and 2007 (fig. 57). Well Z-4 is not screened; however, the bottom of the well is 300 ft bls and, as of the last water level measurement on October 29, 2012 (75.22 ft bls), there was 224.78 ft of water in well Z-4.

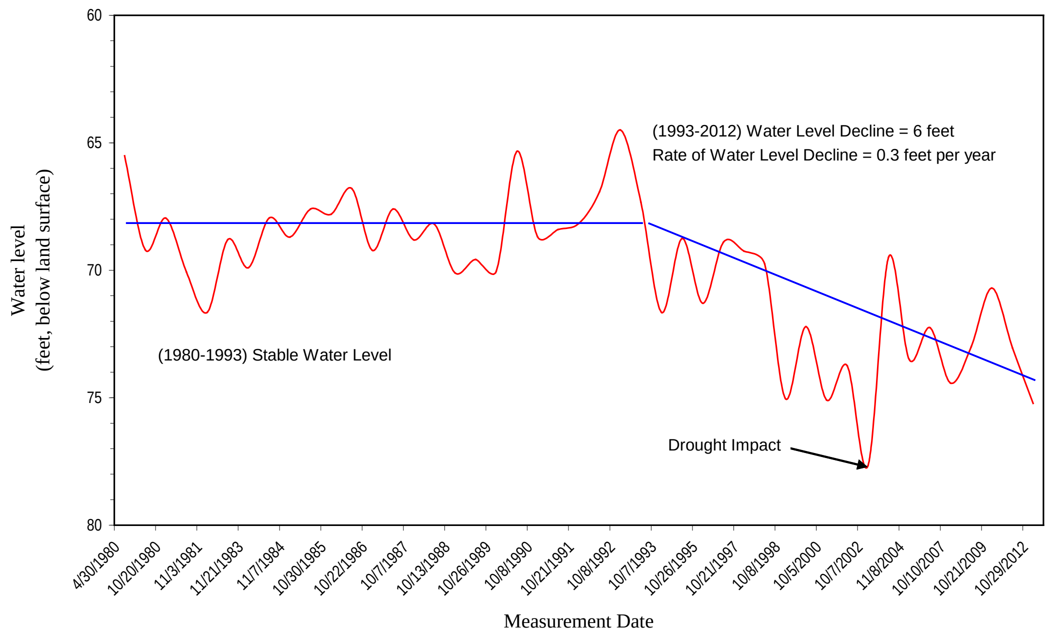


Figure 57.—Hydrograph of Covington County well Z-4, an observation well constructed in the Crystal River aquifer to a depth of 300 ft and open-ended.

Well AA-2, in southeastern Geneva County, has a minimal water level decline rate of 0.2 ft/yr (fig. 58). The hydrograph for well AA-2 shows the impact of the 2000 drought (about 7 ft) (fig. 58). Construction information is not available for well AA-2; however, the bottom of the well is 150 ft bls and, as of the last water level measurement on November 7, 2012 (64.28 ft bls) there was 85.72 ft of water in well AA-2.

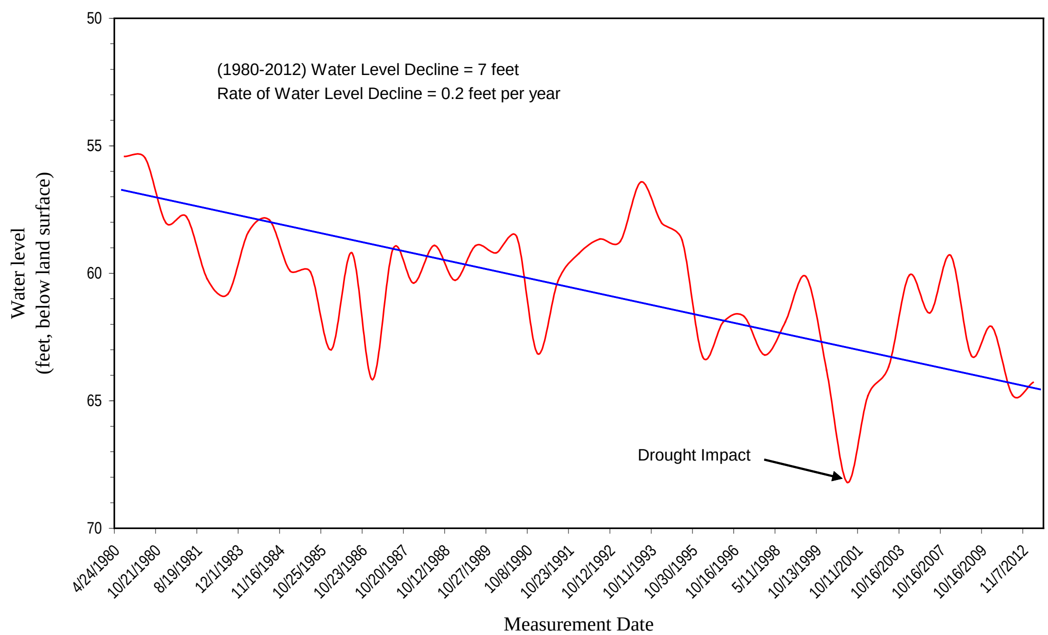


Figure 58.—Hydrograph of Geneva County well AA-2, an observation well constructed in the Crystal River aquifer to a depth of 150 ft.

Of the three observation wells selected in Houston County, only well HOU-1 shows a water level increase. Well HOU-1 (GSA real-time observation well), in southeastern Houston County, is in close proximity to large capacity irrigation wells and has seasonal water level fluctuations of more than 10 ft related to growing season groundwater production and winter season recovery. As a result, between 1980 and February 2013, the water level declined about 6 ft (0.2 ft/yr). Due to above average rainfall during the 2013 growing season, the water level in HOU-1 increased more than 13 ft to a level well above the 100th percentile (fig. 59). Well HOU-1 is not screened; however, the bottom of the well is 118 ft bls and, as of the last water level measurement on January 13, 2014 (20.2 ft bls) there was 97.8 ft of water in well HOU-1.

Well O-12, a GSA periodic observation well and irrigation well supplying a center pivot irrigation system in east-central Houston County, has a water level decline of 0.2 ft/yr since 1980 (fig. 60). The hydrograph shows pumping impacts during the growing season and recovery during the winter season. The top of the screen is 100 ft bls and,

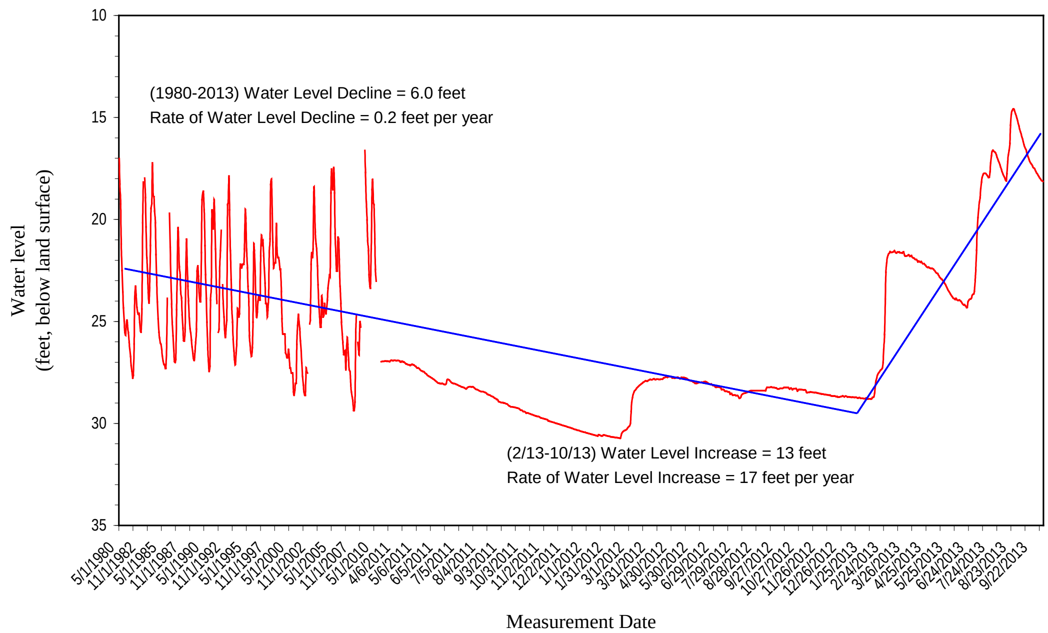


Figure 59.—Hydrograph of Houston County well HOU-1, a real-time observation well constructed in the Crystal River aquifer to a depth of 118 ft and open-ended.

as of the last water level measurement on November 7, 2012 (20.88 ft bls) there was 79.12 ft of water above the screens in well O-12.

Well R-6, in southwestern Houston County, has fluctuating water levels related to irrigation and a general decline of 0.2 ft/yr since 1980 (fig. 61). Construction information is not available for well R-6; however, the bottom of the well is 150 ft bls and, as of the last water level measurement on November 7, 2012 (28.58 ft bls) there was 121.42 ft of water in well R-6.

AQUIFER PRODUCTIVE CHARACTERISTICS

GROUNDWATER AVAILABILITY

Groundwater availability may be generally defined as the total amount of groundwater of adequate quality stored in the subsurface. However, groundwater availability is more complex than this simple definition. Unlike oil and gas, which is trapped in isolated subsurface accumulations with no generation of additional resource,

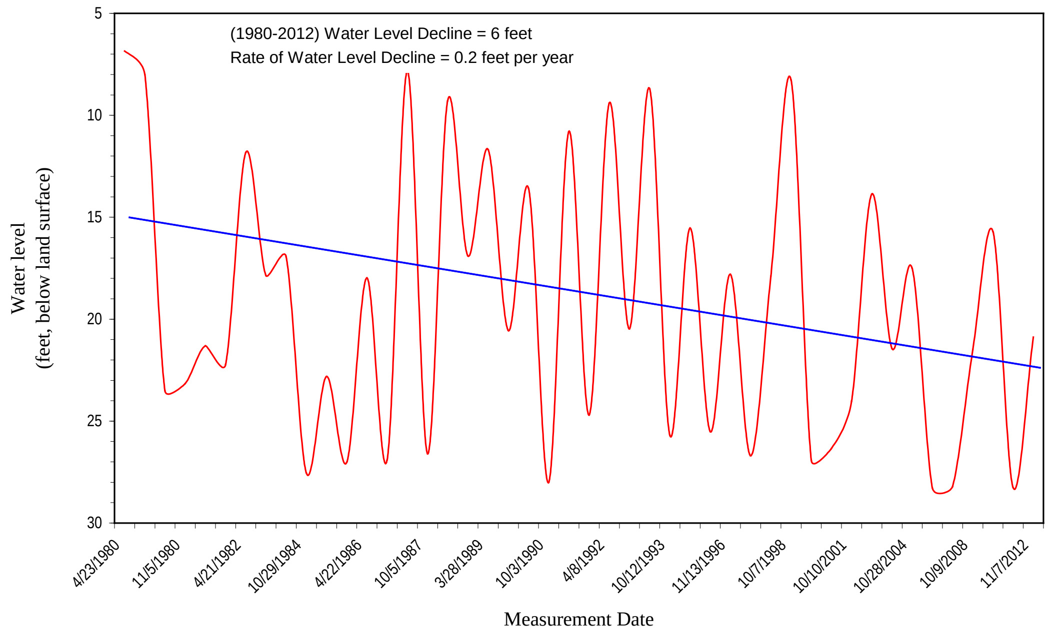


Figure 60.—Hydrograph of Houston County well O-12, an irrigation and observation well constructed in the Crystal River aquifer to a depth of 115 ft, with the top of the screen 100 ft bls.

water moves relatively freely, sometimes for great distances and in most cases, is constantly replenished from the land surface. In order to adequately determine availability, we must understand processes involved in recharge, storage, and sustainable production of groundwater.

Groundwater recharge involves infiltration of precipitation into the subsurface and down gradient flow under water table conditions through the unconfined recharge area. Some of this water continues down gradient as confined flow where it exists under artesian conditions. Water in the unconfined aquifer zone is situated in the pore spaces of granular formations and in open fractures of less permeable rocks (pore water). The total volume of pore water is determined by multiplying the saturated thickness of an aquifer by the area by its average total porosity. Water stored in the confined aquifer zone (total storage volume) is under pressure and can be determined by the volume of water discharged from an aquifer due to a specified change in hydraulic head (Fetter, 1994).

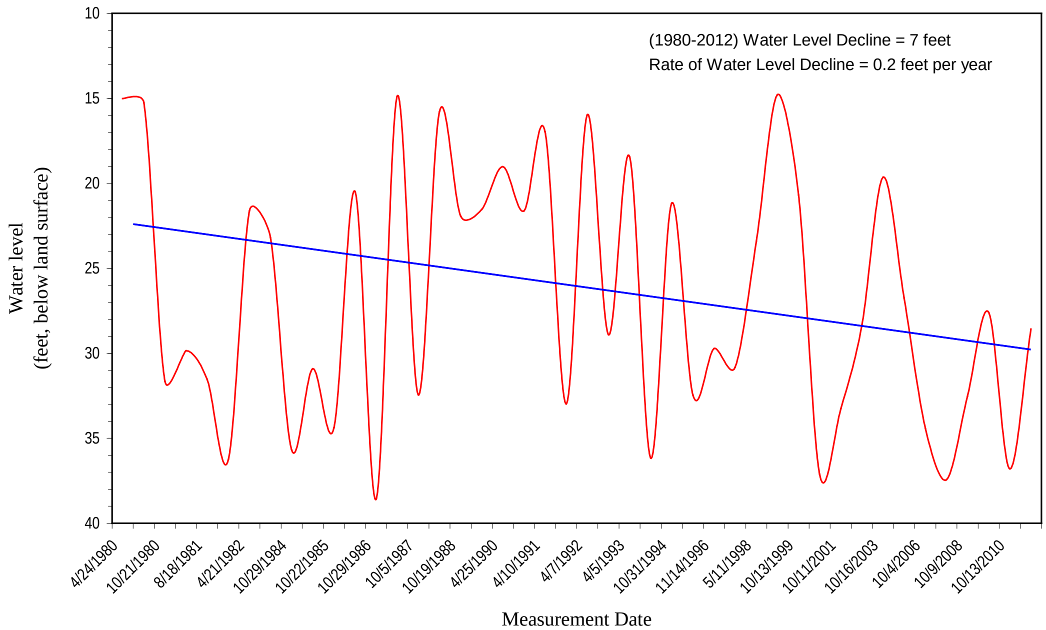


Figure 61.—Hydrograph of Houston County well R-6, an irrigation supply well constructed in the Crystal River aquifer to a depth of 150 ft.

GROUNDWATER RECHARGE

Volumes of groundwater recharge and distances of groundwater movement in Alabama coastal plain aquifers are highly variable and are influenced by a number of factors including precipitation, permeability of recharge areas, hydraulic connection and exchange of groundwater between aquifers, and aquifer confinement and hydraulic gradient. On average, the coastal plain of Alabama receives from 55 to 60 inches (in.) of precipitation each year. However, precipitation may be substantially less during periods of drought. Permeability of Alabama coastal plain aquifer recharge area is highly variable. However, on average, most aquifers receive adequate recharge to maintain long-term sustainability. Although few studies have been performed to determine the hydraulic connection of coastal plain aquifers in Alabama, knowledge of the stratigraphy of aquifers leads to the assumption that most aquifers that are in close vertical proximity have some degree of hydraulic connection. In southeast Alabama, pump tests and potentiometric surface mapping have shown that the Salt Mountain aquifer is hydraulically connected to the overlying Nanafalia and underlying Clayton aquifers (Cook and others, 2007). It is also known that the Eutaw aquifer is hydraulically connected to the underlying Gordo aquifer in Bullock, Barbour and Pike Counties in southeast Alabama (Cook and others, 2013). The down gradient parts of all aquifers in southeast Alabama are highly confined although exchange of water between adjoining aquifers is likely. The direction of groundwater flow and the hydraulic gradient of aquifers in the coastal plain are controlled by the position of a particular locale relative to the Gulf of Mexico basin. Groundwater in southeast Alabama generally flows south-southeast and hydraulic gradients vary from 20 to 50 ft/mi.

Subsurface water movement occurs in two primary environments. The first is in and near the recharge area, where aquifers are unconfined or partially confined, groundwater movement is under water table conditions, and groundwater/surface-water interaction is common. In this environment, precipitation infiltrates into the subsurface, moves down gradient and laterally to areas of low topography where the water discharges into streams or as seeps and springs. Groundwater/surface-water interaction is driven by hydraulic head (head) and serves to sustain streams during periods of drought when runoff is absent (groundwater head is higher than surface-water head) and contributes aquifer recharge when stream levels are high (surface-water head is higher than groundwater head). Groundwater discharge to streams forms the base flow component of stream discharge, forms the sustainable flow of contact springs and wetlands and supports habitat and biota. Subsurface water movement in this environment is generally less than 15 miles and occurs from the updip limit of an aquifer down gradient to the point where the aquifer is sufficiently covered by relatively impermeable sediments and becomes confined in the subsurface.

The second environment is characterized by subsurface water that underflows streams and areas of low topography down gradient to deeper parts of the aquifer. Groundwater in this environment is separated from the land surface by relatively impermeable sediments that form confining layers. Groundwater in the coastal plain can move relatively long distances from recharge areas in aquifers that contain fresh water at depths that exceed 2,500 ft (Cook, 2002). With increasing depth, groundwater becomes highly pressurized and moves slowly down gradient or vertically and laterally along preferential paths of highest permeability. As it moves, minerals are dissolved from the surrounding sediments and accumulate to transform fresh water to saline water. This deep, highly mineralized groundwater eventually discharges into the deep oceans.

UNCONFINED OR PARTIALLY CONFINED AQUIFER RECHARGE

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 southeast Alabama is 52 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. 62). However, for the purposes of this report, the pathways of precipitation movement shown in figure 62 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.

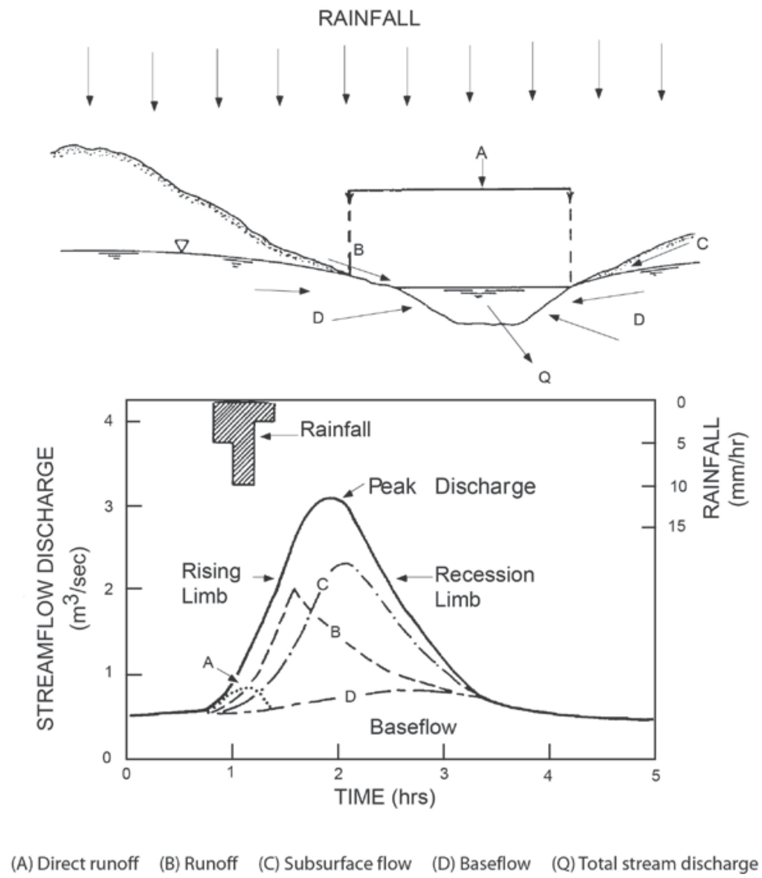


Figure 62.—Diagram and stormflow hydrograph illustrating pathways of movement of rainfall into stream (modified from Sellinger, 1996).

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 $0.1Q_0$.

Discharge data for 12 ungauged stream sites (nodes) in the southeast Alabama pilot project area were used in the recharge evaluation (fig. 63). Selected sites were on main stems or tributaries of the Choctawhatchee, Pea, Yellow, and Conecuh Rivers. Nodes were selected in strategic locations relative to critical aquifer recharge area boundaries. Estimates of discharge from ungauged sites were obtained from the Alabama Department of Economic and Community Affairs Office of Water Resources (OWR). Raw discharge values were estimated by the U.S. Geological Survey (USGS) using the Precipitation Runoff Modeling System (PRMS) with measured discharge from the USGS Choctawhatchee River near the Newton, Alabama, gauge (USGS site 02361000). The period of record for estimated discharge for each node is October 1, 1980, to September 30, 2008.

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. Discharge node information and recharge rates and volumes for individual nodes are shown in table 1.

Estimates of base flow contributions of individual aquifers or related aquifer groups (unconfined and partially confined aquifer recharge) indicate that the largest recharge rate occurs in the Crystal River aquifer (408.4 million gallons per day (mgd)) (table 2). This was expected, due to the size of the recharge area, stratigraphic composition of the formation (sandy residuum and karst limestone) that maximizes infiltration of

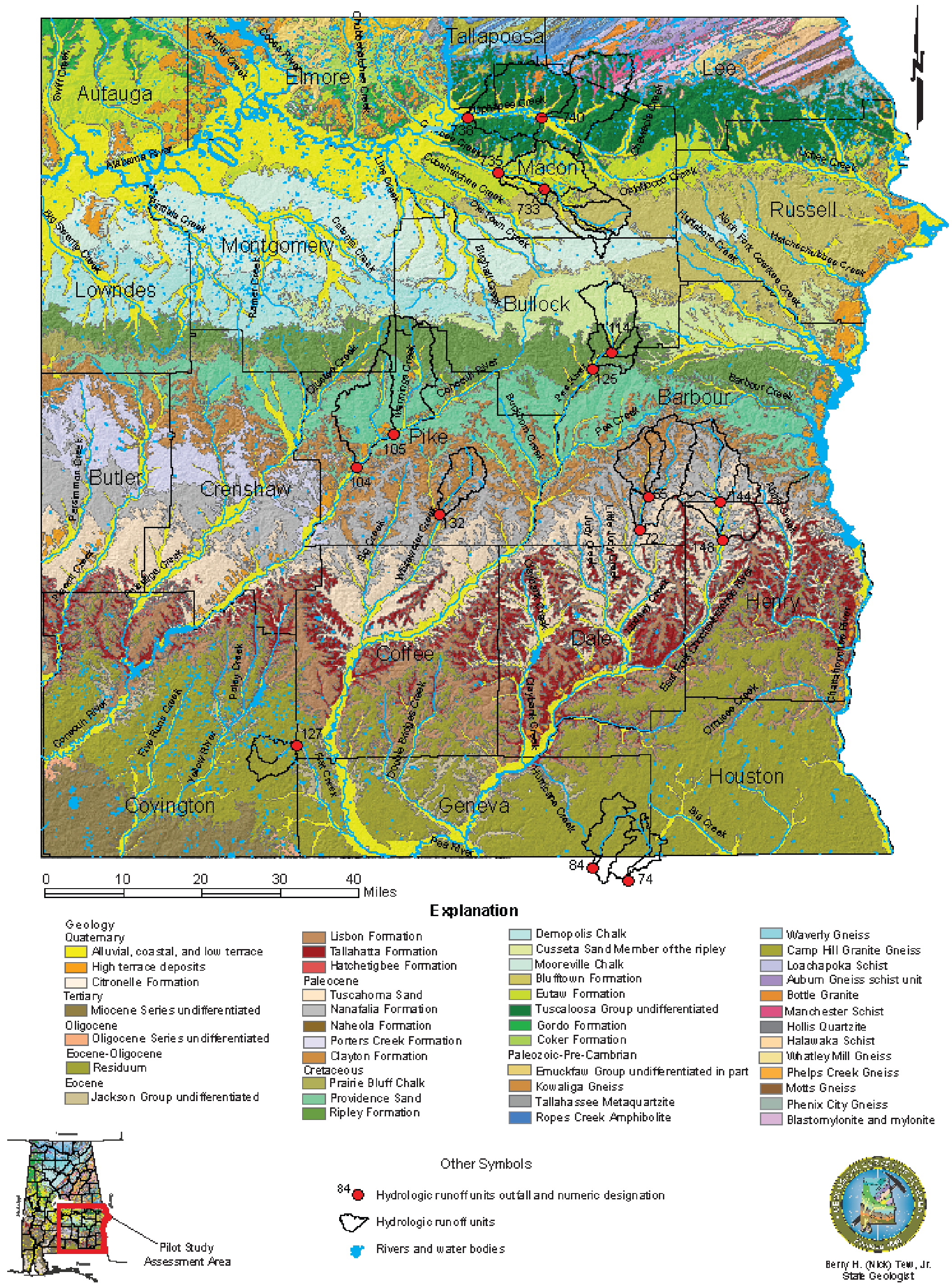


Figure 63.—Ungauged stream sites in the southeast Alabama pilot project area used for recharge evaluation.

Table 1.—Estimated discharge data and recharge estimates in selected ungauged nodes for unconfined and partially confined aquifer recharge areas in southeast Alabama.

Discharge node	Stream	Node area (mi^2)	Aquifer	Base flow (percentage of total discharge)	Recharge (in./yr)	Recharge ($gal/d/mi^2$)
738	Uphapee Creek	86	Tuscaloosa Group	26	4.4	209,511
735	Calebee Creek	53	Eutaw Formation	28	5.8	276,173
114	Pea River	37	Cusseta Member Ripley Formation	16	2.6	111,803
125	Pea River	59	Ripley Formation	18	2.9	136,352
105	Conecuh River	244	Ripley Formation/ Providence Sand	25	4.0	189,078
104	Conecuh River	325	Providence Sand	26	4.3	51,041
132	Pea River	32	Clayton Formation	18	2.6	124,380
55	Choctawhatchee River	33	Clayton/Nanafalia Formations	28	4.6	217,412
72	Choctawhatchee River	54	Nanafalia/Clayton Formations	32	4.8	229,827
144	Choctawhatchee River	51	Nanafalia/Clayton Formations	28	4.7	220,522
148	Choctawhatchee River	47	Nanafalia Formation	28	4.7	220,591
142	Claybank Creek	76	Lisbon and Tallahatta Formations	24	5.0	239,050
74	Choctawhatchee River	29	Crystal River Formation	25	5.4	256,019
84	Choctawhatchee River	41	Crystal River Formation	19	3.2	152,634
127	Pea River	25	Crystal River Formation	30	6.7	319,272

precipitation into the subsurface, and relatively low topographic relief that minimizes runoff. Recharge for the Lisbon and Tallahatta aquifers were estimated together due to the proximity of the recharge areas and had the second largest recharge rate (269.9 mgd). The Nanafalia aquifer had the third largest rate (133.9 mgd). When recharge data were normalized relative to recharge area size, the Eutaw aquifer had the largest rate (273,900 gallons per day per square mile ($gal/d/mi^2$)), followed by the Crystal River (242,700 $gal/d/mi^2$), Lisbon and Tallahatta (239,100 $gal/d/mi^2$), and Nanafalia (237,800

Table 2.—Unconfined or partially confined recharge for aquifers in the southeast Alabama pilot project area.

Aquifer	Recharge			
	Area (mi^2)	mgd	gal/d/mi^2	in./yr
Tuscaloosa Group	643	106.3	165,300	4.4
Eutaw Formation	445	121.9	273,900	5.8
Cusseta Member Ripley Formation	267	32.9	123,200	2.6
Ripley Formation	453	61.8	136,400	2.9
Providence Sand	569	29.0	51,000	1.1
Clayton Formation	461	78.3	169,800	3.7
Nanafalia Formation	563	133.9	237,800	5.0
Lisbon and Tallahatta Formations	1,129	269.9	239,100	5.0
Crystal River Formation	1,683	408.4	242,700	5.1

gal/d/mi^2) aquifers. Table 2 shows recharge rates for unconfined and partially confined aquifer recharge areas in the southeast Alabama pilot project area.

CONFINED AQUIFER RECHARGE

Aquifers in the southeast Alabama pilot project area generally dip to the south-southeast into the subsurface at rates of 20 to 40 ft/mi. As the distance from the recharge area (outcrop) increases, aquifers are overlain by an increasing thickness of sediments, some of which are relatively impermeable. At some point, down gradient aquifers become fully confined and have no hydraulic connection with the land surface.

Groundwater flow can be estimated using Darcy’s law, which states that discharge is related to the nature of a porous medium (hydraulic conductivity), multiplied by the cross-sectional area of the medium, multiplied by the hydraulic gradient (Fetter, 1994),

$$Q = -KA\ (dh/dl)$$

Darcy's law can be modified to estimate the total volume of flow in a confined aquifer by adding terms to account for aquifer thickness and aquifer area (Fetter, 1994). Darcy's law then becomes

$$Q = -Kb\ (dh/dl) \times width$$

where b is aquifer thickness and width is the lateral length of the aquifer. Aquifer thickness was taken from average net potential productive interval thicknesses previously discussed. Volumes of groundwater flow were determined for confined areas of major aquifers in the pilot project area using recently measured water levels, aquifer thicknesses, and hydraulic gradients and published estimates of transmissivity (Baker and Smith, 1997, Cook and others, 1997; Smith and others, 1996a, b, c, 1977; Kuniansky and Bellino, 2012) from wells in the project area (table 3). Note that the recharge area (unconfined area) for the Tuscaloosa Group in southeast Alabama is designated as Tuscaloosa Group undifferentiated; however, in the subsurface (confined area), the Tuscaloosa Group is differentiated into the Gordo and Coker Formations. Therefore, recharge rates for unconfined and confined zones are designated in like manner in tables 2 and 3. Confined aquifer recharge for the Eutaw, Cusseta Member, Providence, and Lisbon and Tallahatta aquifers was not determined due to a lack of adequate transmissivity data. Also, the Crystal River aquifer is not included due to the fact that this aquifer is unconfined or partially confined throughout the project area. Figure 64 shows unconfined and confined recharge for evaluated aquifers in the project area. Comparisons of estimated recharge rates reveal that confined rates are about 6% of unconfined or partially confined rates for the Gordo aquifer, 61% for the Ripley and

Table 3.--Confined recharge for selected aquifers in the southeast Alabama pilot project area.

Aquifer	Transmissivity (ft^2/d)	Thickness (ft)	Hydraulic gradient (ft/mi)	Recharge (mgd)
Gordo Formation	3,000	175	3.3	6.5
Ripley Formation	7,500	100	11.4	37.8
Clayton Formation	10,000	150	7.5	48.1
Nanafalia Formation	4,470	50	8.3	24.6

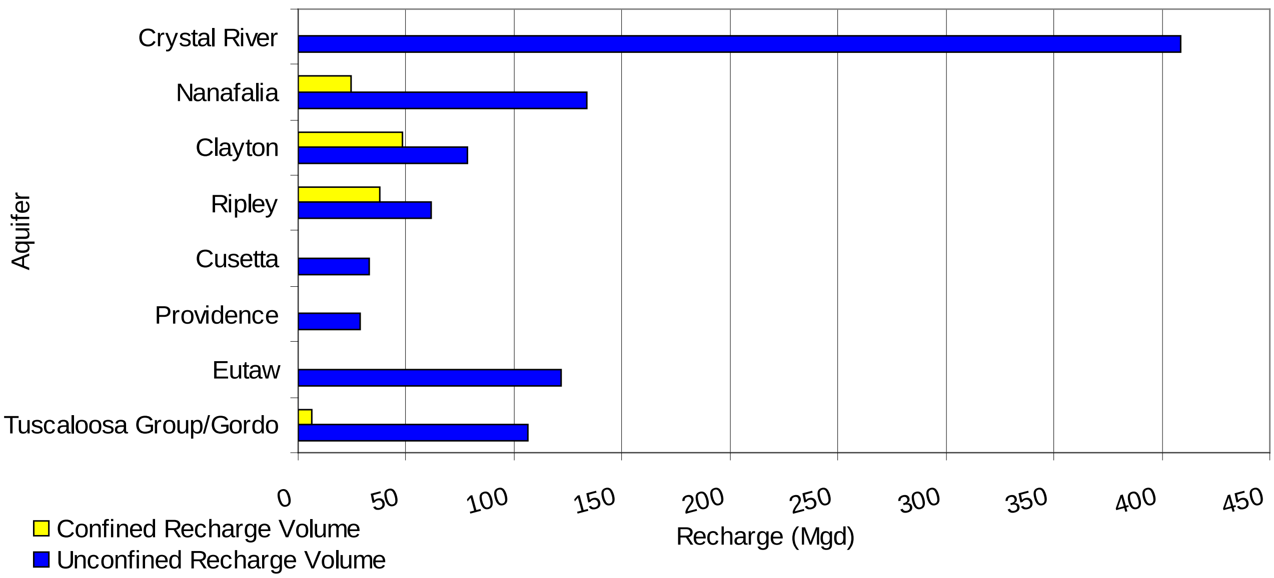


Figure 64.—Recharge volumes for unconfined and confined zones of major aquifers in the southeast Alabama project area.

Clayton aquifers, and 18% for the Nanafalia aquifer, illustrating the importance of subsurface groundwater storage for future groundwater supplies.

SUBSURFACE GROUNDWATER STORAGE

As previously defined, available groundwater is the total amount of groundwater of adequate quality stored in the subsurface. However, this simple definition is not adequate to describe the complexities of groundwater occurrence and use, particularly in Alabama where complex geologic/hydrologic relationships are common. Alley and others (1999) defined groundwater sustainability as the development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. The definition of "unacceptable" is largely subjective, depending on the individual situation. The term safe yield should be used with respect to specific effects of pumping, such as water level declines or reduced stream flow. Thus, safe yield is the maximum pumpage for which the consequences are considered acceptable (Ponce, 2007).

Groundwater sustainability is based on the rate of water removal, volume of water available (water in storage and rate of replenishment), and the ability of an aquifer to yield water (effective porosity). The hydraulic impact of water production is observed in declining hydraulic head and aquifer water levels. In confined aquifers with acceptable rates of groundwater production, water is removed and head declines, yet aquifers remain fully saturated and potentiometric surfaces remain above the stratigraphic tops of geologic units. Therefore, useable aquifer storage is the volume of water that can be removed while maintaining head above the stratigraphic top of the aquifer.

Specific storage (S_s) is the amount of water per unit volume of a saturated formation that is expelled from storage due to compressibility of the mineral skeleton and the pore water per unit change in head (Fetter, 1994). Accurate determination of specific storage requires a number of terms including density of water, gravitational acceleration, compressibility of the aquifer skeleton, compressibility of water, and average effective porosity. All terms are generally known except effective porosity. Effective porosity is that portion of the total void space of a porous material that is capable of transmitting water (Barcelona and others, 1984 [see refs]). One of the most accurate determinations of porosity is obtained from neutron/density geophysical logs. Two neutron/density logs were available from oil and gas test wells in the project area in Henry and Bullock Counties. However, only the Eutaw Formation, Tuscaloosa Group, and Lower Cretaceous were logged in the fresh-water section. Values were recorded for coarse-grained units with effective porosities identified by GSA Net Potential Productive Interval mapping.

The storage coefficient, or storativity (S), is the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head (fig. 65). Therefore, storativity of a confined aquifer is the product of the specific storage and the aquifer thickness (b) (Fetter, 1994):

$$S = bS_s$$

When storativity is multiplied by the surface area overlying an aquifer and the average hydraulic head above the stratigraphic top of a confined aquifer, the product is the volume of available groundwater in storage in a confined aquifer (Fetter, 1994):

$$V_w = SA\,h$$

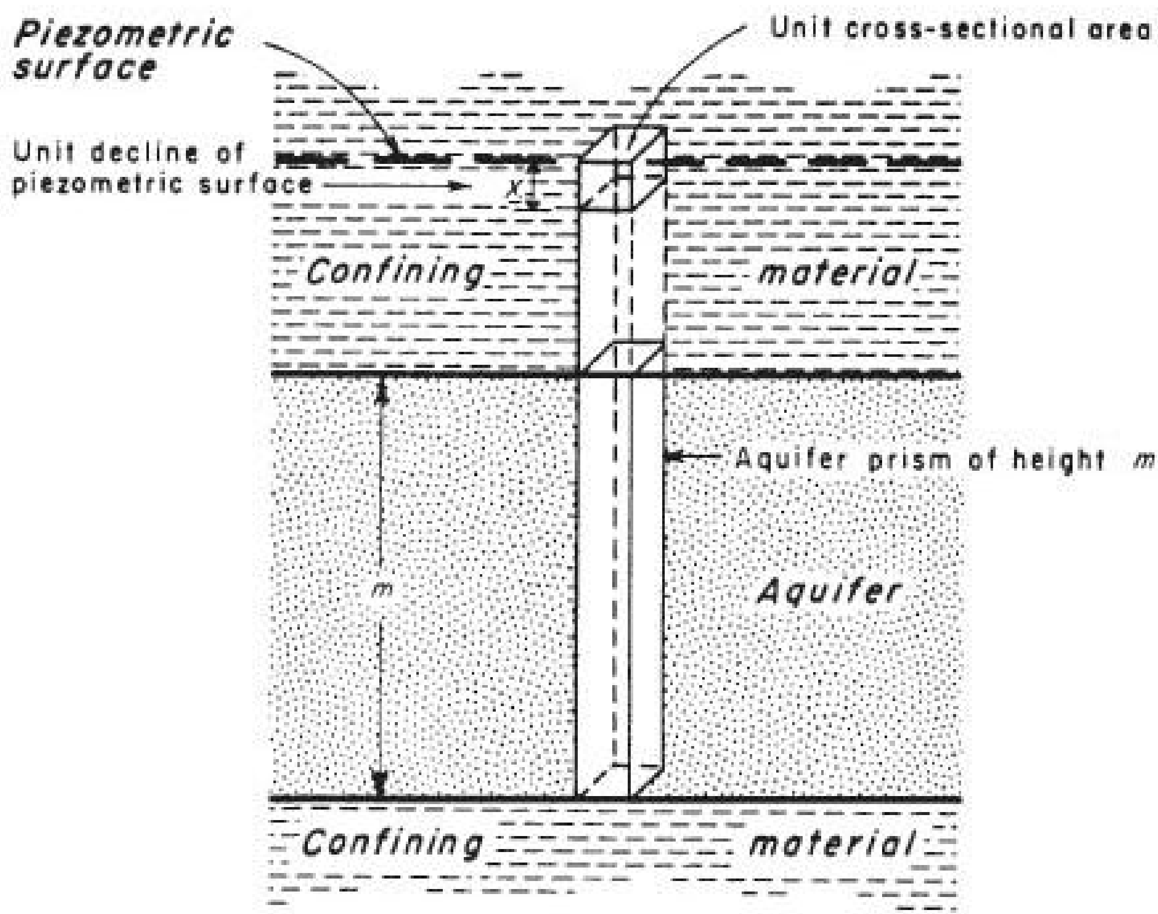


Figure 65.—Storativity of a confined aquifer (modified from Ferris and others, 1962).

Table 4 shows measured and estimated effective porosity, aquifer thickness, storativity, and the volume of available groundwater in storage for major confined aquifers in the project area. Groundwater in storage for the Lower Cretaceous undifferentiated is included in table 4. Currently, Lower Cretaceous sediments are not developed as water sources in Alabama. However, evaluations of electric and geophysical logs and drill cutting descriptions in oil and gas test wells in the project area indicate that Lower Cretaceous sediments may have future potential as sources of fresh water. Total fresh groundwater in storage for the project area is given in table 4.

WELL CAPTURE ZONES

A capture zone is the area of groundwater contribution to a water well (fig. 66). Knowledge of capture zones is used to construct wells with proper spacing and production rates to avoid over production and excessive aquifer drawdown. Also, it is

Table 4.—Storativity, related aquifer characteristics, and available groundwater in storage for major confined aquifers in the project area.

Aquifer	Average effective porosity (percent)	Confined aquifer area (fresh water) (mi²)	Aquifer potential productive interval thickness (ft)	Storativity	Available groundwater in storage	
					(million ft³)	(million gal)
Lower Cretaceous	28	2,400	350	0.0000044	294.4	2,202.4
Coker Formation	32	4,500	210	0.0000026	293.6	2,196.1
Eutaw and Gordo Formations	36	4,000	175	0.0000030	281.0	2,102.3
Ripley Formation	30*	4,600	100	0.0000013	58.4	436.5
Clayton Formation and Salt Mountain Limestone	40*	1,980	325	0.0000019	124.5	931.2
Nanafalia Formation	30*	2,900	50	0.00000062	15.6	116.5

*Estimated effective porosity

important to know the area of groundwater contribution to a well so that contaminant sources may be monitored and controlled. Capture zone analysis provides critical information for groundwater source development and infrastructure planning.

Numerous models have been developed to estimate well capture zones. The General Particle Tracking Module (GPTRAC), developed by the U.S. Environmental Protection Agency (USEPA) (Blandford and Wu, 1993) was used to determine capture zones for numerous wells constructed in major aquifers in southeast Alabama (Cook and others, 2007). The model has numerical and semi-analytical options that estimate time-dependent capture zones from temporal, spatial, and hydrologic data inputs. The numerical option utilizes hydraulic head fields determined by finite difference or finite element groundwater flow models. The semi-analytical option, used in this assessment, delineates capture zones for pumping wells and assumes that aquifers are homogeneous, with steady and uniform ambient groundwater flow. A time-dependent capture zone is a subsurface area surrounding a pumping well that will supply groundwater recharge to the well within some specified period of time. The model utilizes the particle tracking technique, a method that employs hydraulic mathematical

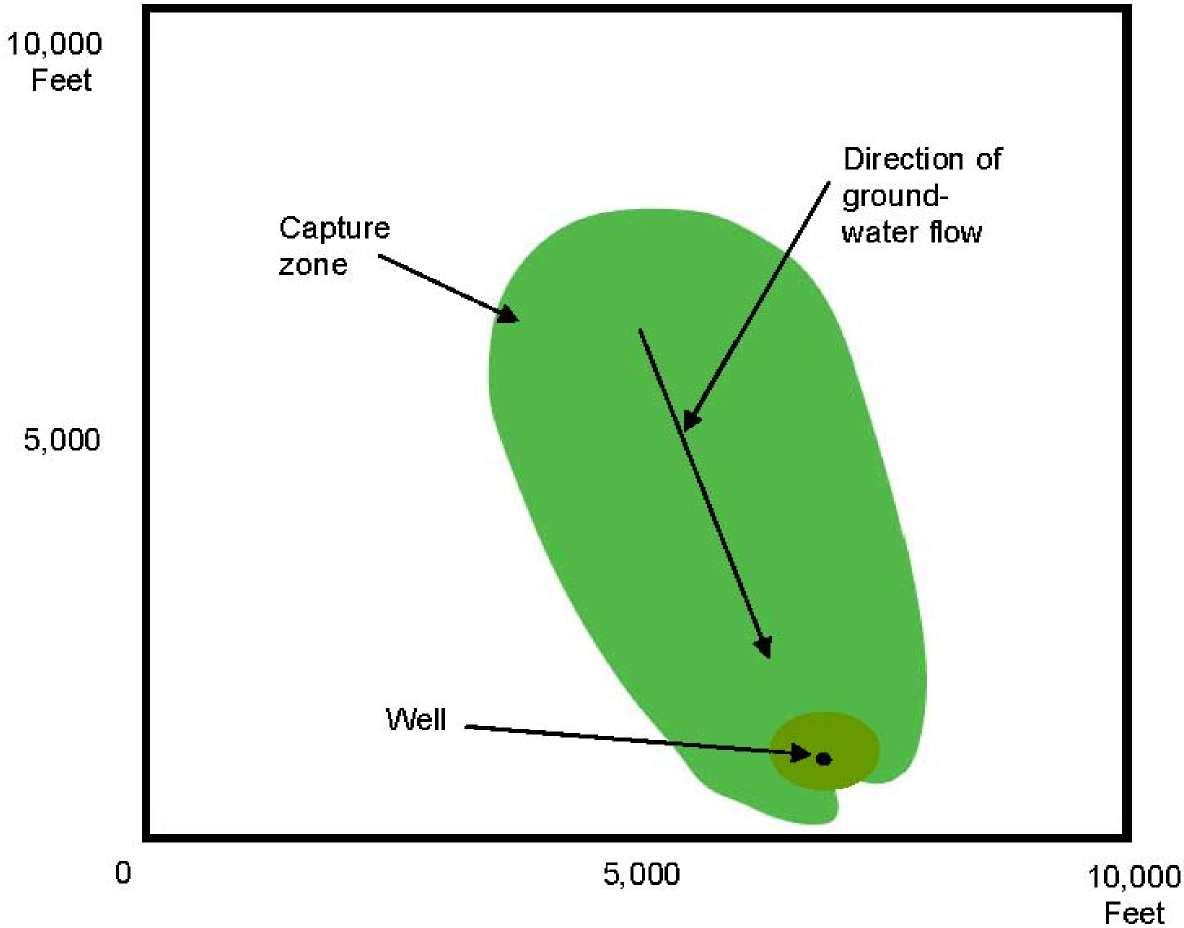


Figure 66.—Capture zone for city of Dothan well 20.

estimation of the movement of a conceptual particle or molecule of water from a time-dependent stagnation point (point of zero velocity) to the well bore (Blandford and Wu, 1993). This technique employs a modification of Darcy's Law, which may be written as:

$$Q = KiA$$

Where Q is the volumetric flow rate, K is the hydraulic conductivity, i is the hydraulic gradient, and A is the cross-sectional area of flow. The specific discharge (Darcy Velocity) may be written as:

$$q = Q/A = Ki$$

The average pore-water velocity for an individual water particle moving through the aquifer may be written as:

$$v = q/\theta$$

Where v is the seepage velocity and θ is the effective porosity of the aquifer. Two-dimensional, horizontal flow velocity may be written as:

$$V_x = q_x / \theta \qquad v_y = q_y / \theta$$

Once velocities are determined, pathlines for movement of individual particles may be delineated by calculating the distance dl that is traversed during a given time period dt. This is defined by:

$$Dl = (d_x^2 + d_y^2)^{1/2}$$

Capture zones may be used to determine the likelihood of interference of wells constructed in the same aquifer or for determining adequate well spacing in areas where groundwater development is occurring or may occur in the future. Capture zones were modeled for 120 wells constructed in eight major aquifers in southeast Alabama. Hydrologic data were collected from GSA well files, open-file reports, and field assessments. The GPTRAC program requires well location, aquifer confinability, transmissivity, hydraulic gradient, flow direction, the quantity of water production, production time, and aquifer thickness. The hydraulic gradient (head loss per unit length of water movement) is a particularly important factor in groundwater production and in the ability to model groundwater flow and the affects of water production. Groundwater flow rates are directly proportional to the hydraulic gradient, so that a 50% increase in the hydraulic gradient will result in a 50% increase in the rate of water flow in a given aquifer sand (Driscoll, 1986). Information required for implementation of the GPTRAC program was obtained from GSA well files and GSA open file wellhead protection reports (Baker and Smith, 1997; Smith and others, 1996a, b, c, 1997).

Model output is presented as tabular x-y water particle location coordinates and two-dimensional graphic images of capture zones. Capture zones for multiple wells may be presented on a single graph to demonstrate the proximity of contribution areas. The shape of each modeled capture zone is based on the hydrologic conditions in the aquifer and average water production rates. Most capture zones are asymmetrically shaped and are characterized by a linear component oriented in the direction of groundwater flow. Optimum well spacing for wells constructed in major aquifers in the project area is given in table 5.

Table 5.—Well capture zone and spacing data for southeast Alabama aquifers.

Aquifer	Range of residual drawdown (feet)	Average capture zone area (mi^2)	Optimum well spacing (miles)	
			Along strike of hydraulic gradient direction	Up or down gradient direction
Gordo	0-154	1.9	1.5	2.0
Ripley	0-149	2.6	1.0	2.5
Clayton	0-204	2.0	1.0	2.0
Nanafalia	0-189	1.2	1.0	2.0
Tallahatta	1-119	0.5	1.0	1.5
Tuscahoma	31-119	3.5	1.5	2.5
Lisbon	0-33	0.6	1.0	1.0
Crystal River	0-27	1.0	1.0	1.0

SUSTAINABLE GROUNDWATER YIELD

Sustainable groundwater yield may be defined as: “The groundwater extraction regime, measured over a specified planning timeframe, that allows acceptable levels of stress and protects dependent economic, social, and environmental values” (Australia Department of the Environment, 2013). The groundwater extraction regime consists of wells in a specified area, producing at specified rates, for specified periods of time, in a specified aquifer or group of aquifers, and the impacts of these wells on groundwater levels, and/or surface water bodies. Sustainable yields may include groundwater extraction rates greater than recharge rates, depending on groundwater levels, rates of groundwater level drawdown, available groundwater in storage, impacts of groundwater extraction from unconfined or partially confined aquifers on surface-water levels or flows, and an extraction period that allows for reduced pumping or down time that provides time for aquifers to replenish. Levels of acceptable stress must be determined that provide balance between economic, social, and environmental needs.

Generally, groundwater extraction regimes characterized by wells with adequate spacing, wells constructed in multiple aquifers, if available, and extraction rates that prevent excessive water level drawdown will acquire acceptable levels of aquifer stress and will be sustainable for the long term. Aquifer stress areas in southeast Alabama are generally in and near population centers where water demand is high and where relatively large numbers of high capacity wells are extracting groundwater in close proximity. Evaluations of groundwater levels, drawdown, well spacing, and extraction rates for groundwater extraction regimes in southeast Alabama are included in this report. Based on these evaluations, a number of areas in southeast Alabama have readily identifiable aquifer stress, yet no well or group of wells in southeast Alabama currently has an unacceptable level of stress.

In order to ascertain the sustainability of groundwater resources in a specified area, available volumes of groundwater of adequate quality must be compared to current groundwater use. As mentioned previously, current water use values are not available. Therefore, total volumes of available groundwater in subsurface storage and confined aquifer recharge were compared to 2005 water use values in the assessment area. An exact comparison is not possible, since groundwater use data are compiled for geographic areas and are not available for specific aquifers. However, improved insights into groundwater availability and current groundwater production impacts can be developed by comparing available information. Unconfined or partially confined recharge was not included in the comparison, since water use from unconfined aquifers in southeast Alabama is relatively minimal. Also, groundwater use data includes all aquifers, which are compared to groundwater availability values for selected aquifers.

Total available groundwater in subsurface storage for all assessed confined aquifers (Lower Cretaceous, Coker, Eutaw/Gordo, Ripley, Clayton/Salt Mountain, and Nanafalia) is about 8.0 billion gallons, and the Gordo, Ripley, Clayton, and Nanafalia aquifers are being replenished at a rate of 117.0 mgd. This is compared with total 2005 groundwater use for 13 counties in the assessment area, which is about 123 mgd. Therefore, when confined recharge rates for minor aquifers are considered, 2005 groundwater use is equivalent to confined recharge.

CONCLUSIONS AND RECOMMENDATIONS

The economic future and quality of life for Alabamians is dependent upon the availability and protection of the state’s water resources. Planning for prudent development and protection of Alabama’s water resources is essential to preserve and improve the quality of life desired by all of Alabama’s citizens. The purpose of this report and the scientific research on which it is founded is to provide hydrogeologic data for stakeholders and decision makers to formulate policy and management strategies for Alabama's water future. Utilization of scientific data as a basis for water resource management is a prudent approach that can prevent needless, costly, and inappropriate management decisions that may damage the future availability of this critical resource. Conclusions and recommendations drawn from this research include current groundwater availability, development, and production impacts and future groundwater development potential and strategies.

The largest production impact areas and hydraulic head declines in the Gordo aquifer are currently located in Bullock County and in the cities of Eufaula (east-central Barbour County) and Troy (central Pike County). The city of Union Springs (north-central Bullock County) has a production impact area covering about 50 mi^2 with more than 160 ft of drawdown. The rate of water level decline at Union Springs is more than 3 ft/yr, although currently, there is more than 394.5 ft of water above the bottom of the casing in well F-1. The city of Eufaula had more than 150 ft of drawdown as of 2004, but more recent water levels from Eufaula wells have not been acquired. The primary water source for the city of Troy is the Gordo aquifer, where drawdown is more than 50 ft in an area of about 5 mi^2. However, there is more than 1,300 ft of water above the top of the screened interval in well F-23 at Troy so current drawdown in this area is relatively insignificant. A westward trending regional area of apparent natural declining head of more than 80 ft covers more than 300 mi^2 in north and central Bullock County The rate of water level decline for this area of regional drawdown was 1.7 ft/yr from 1978 to 2012 and is most likely caused by severe drought and reduced aquifer recharge.

Net potential productive interval mapping for the assessment area indicates that there is excellent potential for future development of large quantities of water from the Gordo aquifer. A fairway of thick potential productive sands from 150 to 200 ft extends from southern Crenshaw County eastward through southern Pike, northern Coffee, southern Barbour, northern Dale and northern Henry Counties. A northern extension of the fairway goes from northeastern Pike to southwestern Bullock Counties.

Proper well spacing is a critical component of future groundwater development strategies. Digital simulation of well capture zones were used to develop adequate spacing guidelines for southeast Alabama aquifers. Suggested spacing for wells constructed in the Gordo aquifer is 1.5 mi along strike of the hydraulic gradient direction (east-west in southeast Alabama) and 2.0 mi up or down the hydraulic gradient direction (north-south in southeast Alabama).

The unconfined or partially confined part of the Gordo aquifer (outcrop or recharge area) in the assessment area is about 10 mi wide and extends from northern Russell and southern Lee Counties westward through northern Macon, southern Tallapoosa, southern Elmore, and central Autauga Counties. The eastern part of the area from the Georgia state line to western Macon County is formally designated Tuscaloosa Group undifferentiated due to the inability to stratigraphically separate the Coker and Gordo Formations. Estimates of recharge for the Tuscaloosa Group, and resulting base flow to streams in the recharge area, is 106.3 mgd or 4.4 in./yr. Although hydraulically connected in the confined subsurface, unconfined or partially confined recharge for the Eutaw aquifer was estimated to be 121.9 mgd or 5.8 in./yr.

A relatively small part of total recharge to the Gordo aquifer underflows streams in the recharge area and enters the confined aquifer. Confined aquifer recharge for the Gordo aquifer in the assessment area is about 6.5 mgd or about 0.3 in./yr.

Since most wells produce water at rates that exceed aquifer recharge rates, groundwater stored in the subsurface is critical to long-term sustainability of groundwater use. The oldest sediments evaluated during this assessment are in the undifferentiated Lower Cretaceous and overlying Coker Formation. Although the Lower Cretaceous undifferentiated is currently undeveloped as a water source in Alabama, stratigraphic and electric log analysis indicates that it has potential as an aquifer in southeast Alabama. Currently, only a few wells are screened in the Coker Formation, primarily due to the availability of adequate quantities of shallower water sources. However, the Lower Cretaceous undifferentiated and the overlying Coker Formation can potentially provide large quantities of groundwater in the northern part of the assessment area. Evaluations indicate that each unit has about 2.2 billion gallons of water in subsurface storage. The Gordo aquifer has about 2.1 billion gallons of water in subsurface storage.

Water quality is not an impediment to development of water supplies from the Gordo aquifer in southeast Alabama with the exception of naturally occurring saline water, expressed in concentrations of chloride, which is depth dependent. A down gradient limit for water in the Gordo aquifer with chloride less than drinking water standards (250 mg/L) has not been established. However, well F-23 (Ozark Utilities well no. 9) in north-central Dale County is the deepest public water supply well in Alabama, with the bottom of the screened interval in the Gordo Formation at 2,736 ft bls. Although chloride in water from this well is minimal, sodium was elevated, leading to the conclusion that chloride in excess of drinking water standards would occur in a relatively short distance down gradient.

The largest production impact areas and hydraulic head declines in the Ripley/Cusetta aquifer are currently located at Ozark (north-central Dale County), where the impact area covers about 5 mi^2 with more than 100 ft of drawdown, and in Rutledge and Luverne (central Crenshaw County) with 142 and 82 ft, respectively.

Rates of water level decline for wells F-16 and F-17 at Ozark were 1.9 and 2.8 ft/yr until 2000 when the water levels in both wells stabilized. The water level in well F-17 has risen 1.9 ft/yr since 2000, due to construction of an additional high capacity well in the Gordo aquifer, which allowed reduced pumping of well F-17.

Net potential productive interval mapping for the Ripley Formation, including the Cusetta Member indicates that there is potential for future development of groundwater from these aquifers. A fairway of thick potential productive sands from 100 to more than 175 ft extends from southern Crenshaw County eastward through southern Pike, northeastern Coffee, northern and east-central Dale and central Henry Counties.

Suggested spacing for wells constructed in the Ripley aquifer is 1.0 mi along strike of the hydraulic gradient direction (east-west in southeast Alabama) and 2.5 mi up or down the hydraulic gradient direction (north-south in southeast Alabama).

The unconfined or partially confined part of the Ripley aquifer (outcrop or recharge area) in the assessment area is about 6 mi wide and extends from central Barbour, westward through southern Macon, southern Montgomery, and southern Lowndes Counties. The Cusetta Member forms the basal part of the Ripley Formation in southeast Alabama and outcrops north of the Ripley in northern Barbour and central

Bullock Counties before terminating in southeastern Montgomery County. Estimates of recharge for the Cusetta Member, and resulting base flow to streams in the recharge area, is 32.9 mgd or 2.6 in./yr. Estimates of recharge for the upper part of the Ripley Formation, and resulting base flow to streams in the recharge area, is 61.8 mgd or 2.9 in./yr. Confined area recharge for the Ripley aquifer in the assessment area, including the Cusetta Member is 37.8 mgd or about 3.4 in./yr.

The Cusetta Member and overlying upper Ripley Formation can potentially provide large quantities of groundwater in the central part of the assessment area. Evaluations indicate that these units have about 437 million gallons of water in subsurface storage.

Water quality is not an impediment to development of water supplies from the Ripley aquifer in southeast Alabama with the exception of naturally occurring saline water, expressed in concentration of chloride, which is depth dependent. A down gradient limit for water in the Ripley aquifer with chloride less than drinking water standards (250 mg/L) has been established from southern Crenshaw County, eastward to southeastern Coffee County, southern Dale and northern Houston Counties.

The largest production impact areas and hydraulic head declines in the Clayton aquifer (including the Salt Mountain aquifer, which is hydraulically connected) are currently located at Headland (southwestern Henry County), Dothan (northwestern Houston and southeastern Dale Counties) where the impact area covers about 18 mi^2 north and west from downtown Dothan, Ozark (north-central Dale County), and Enterprise (southeastern Coffee County), where two impact areas cover about 18 mi^2 in and north of downtown Enterprise and 9 mi^2 north and west of the city. Isolated, single well disruptions in the Clayton-Salt Mountain potentiometric surface occur sporadically across the assessment area. The water level in well X-2 at Headland declined 139 ft from 1946 to 2000 but has increased at a rate of 0.8 ft/yr from 2001 to 2013. The rate of water level decline for Dothan well D-02 was 2.2 ft/yr from 1974 to 2012. However, during 2012 the water level stabilized and has risen slightly. Well D-02 has about 450 ft of water above the top of the screened interval. The water level in well F-01 (city of Enterprise) declined at 1.5 ft/yr from 1981 to 2000 but the rate of decline slowed to 0.8 ft/yr from 2001 to 2013 due to improved well management and construction of additional wells.

Net potential productive interval mapping for the Clayton Formation and Salt Mountain Limestone indicates that there is potential for future development of groundwater from these aquifers. A fairway of thick potential productive sands and limestone from about 140 to more than 250 ft in the Clayton aquifer extends from southern Crenshaw and northern Covington Counties eastward through central and southeastern Coffee, southern Dale, northern Geneva, and northwestern Houston Counties. Although some of this area is fully developed, a large number of high capacity wells could be constructed in selected locations throughout the area, using proper well spacing and production rate guidelines. A fairway of thick Salt Mountain Limestone extends from northern Covington County southeastward through southern Coffee, north-central Geneva and southwestern Dale Counties.

Suggested spacing for wells constructed in the Clayton/Salt Mountain aquifer is 1.0 mi along strike of the hydraulic gradient direction (northwest-southeast in southeast Alabama) and 2.0 mi up or down the hydraulic gradient direction (northeast-southwest in southeast Alabama).

The unconfined or partially confined part of the Clayton aquifer (outcrop or recharge area) in the assessment area is about 10 mi wide and extends from central Barbour County westward through central Pike and Crenshaw Counties, northern Butler, and southern Lowndes Counties. Estimates of recharge for the Clayton Formation (the Salt Mountain Limestone is only observed in the subsurface in southeast Alabama), and resulting base flow to streams in the recharge area, is 78.3 mgd or 3.7 in./yr. Confined area recharge for the Clayton/Salt Mountain aquifer in the assessment area is 48.1 mgd or about 2.3 in./yr.

The Clayton and Salt Mountain aquifers can potentially provide large quantities of groundwater in the central part of the assessment area. Evaluations indicate that these units have about 931 million gallons of water in subsurface storage.

Water quality is not an impediment to development of water supplies from the Clayton/Salt Mountain aquifer in southeast Alabama with the exception of naturally occurring saline water, expressed in concentrations of chloride, which is depth dependent. A down gradient limit for water in the Clayton aquifer with chloride less than drinking water standards (250 mg/L) extends from the city of Andalusia in northern

Covington County, southeastward through southern Coffee County (about 12 miles south of Enterprise) through central and eastern Geneva County and into southwestern Houston County immediately north of the Florida state line. A down gradient chloride limit for the Salt Mountain aquifer extends from central Covington County eastward through the southwest corner of Coffee County into central Geneva County.

The largest production impact areas and hydraulic head declines in the Nanafalia aquifer are currently located at Dothan (northwestern Houston County) and Daleville (southwestern Dale County) where long-term high production rates in multiple wells in close proximity created large, deep depressions in the potentiometric surface of the Nanafalia.

Water levels in nine public supply wells operated by Dothan Utilities were evaluated. These wells are screened in multiple aquifers. However, the Nanafalia aquifer is the dominant water source in these wells, so they are considered here as Nanafalia wells. Long-term water level measurements to 2012 indicate that average water level declines in the evaluated wells was 4.0 ft/yr. From 2012 to 2014, water levels in three of the wells continue to decline at an average rate of 2.4 ft/yr, the water level in one well is stable, and water levels in five wells recovered an average of almost 21 ft. Due to confinement and resulting hydraulic heads of the Nanafalia and Clayton aquifers at Dothan, and even with long-term water level declines, the evaluated wells, on average, continue to have more than 270 feet of water above the tops of the screened intervals.

Most recent water level trends in Dothan wells are more stable, due to construction of additional wells, improved water production management, and a water rate structure that promotes conservation.

Three public supply wells in Daleville (southwestern Dale County) are located in close proximity to one another and all have similar water level histories. Long-term water level measurements to 2007 indicate that average water level declines in the evaluated wells was 2.6 ft/yr. Since 2007 water levels in the wells have recovered at a rate of 2.5 ft/yr, due to a new high capacity well, constructed in the Clayton aquifer, east of town.

Net potential productive interval mapping for the Nanafalia Formation indicates that there is potential for future development of groundwater from this aquifer. A fairway of thick potential productive sands and limestone from about 75 to 125 ft in the Nanafalia aquifer extends from southern Coffee County eastward through southern Dale and northwestern Houston Counties. The Nanafalia aquifer can potentially provide large quantities of groundwater in the southern part of the assessment area and contains about 116.5 million gallons of water in subsurface storage.

Although some of this area is fully developed (Dothan, Daleville, and Fort Rucker), a large number of high capacity wells may be constructed in selected locations throughout the area, using proper well spacing and production rate guidelines. Suggested spacing for wells constructed in the Nanafalia aquifer is 1.0 mi along strike of the hydraulic gradient direction (north-south in southeast Alabama) and 2.0 mi up or down the hydraulic gradient direction (east-west in southeast Alabama).

The unconfined or partially confined part of the Nanafalia aquifer (outcrop or recharge area) in the assessment area is about 15 mi wide and extends from southern Barbour and northern Henry Counties westward through northern Dale and Coffee Counties, southern Pike, and central Crenshaw and Butler Counties. Estimates of recharge for the Nanafalia Formation, and resulting base flow to streams in the recharge area, is 133.9 mgd or 5.0 in./yr. Confined area recharge for the Nanafalia aquifer in the assessment area, is 24.6 mgd or about 0.9 in./yr.

Water quality is not an impediment to development of water supplies from the Nanafalia aquifer in southeast Alabama with the exception of naturally occurring saline water, expressed in concentrations of chloride, which is depth dependent. A down gradient limit for water in the Nanafalia aquifer with chloride less than drinking water standards (250 mg/L) has been established from central Covington County southeastward through southwestern Geneva County and into Holmes County, Florida.

The Crystal River Formation is a minor aquifer but is important as the primary source of groundwater for irrigation and public water supplies in the southern part of the project area along the Florida state line. It is also important as the source of base flow for streams in the southern part of the project area as well as northwest Florida. The Crystal River also serves as a recharge zone for the Floridan aquifer, which is the major water source for the Florida panhandle.

Declining water levels in the Crystal River aquifer are isolated to individual wells. Generally, water levels in all monitored Crystal River wells are relatively stable with only minimal rates of water level change. Also, all wells have regular seasonal water level fluctuations, which indicate the unconfined or partially confined nature of the Crystal River aquifer. Water levels in five observation wells constructed in the Crystal River aquifer were evaluated. Long-term water level measurements indicate that water production impacts to the Crystal River aquifer are minimal with average water level declines of about 0.2 ft/yr.

Suggested spacing for wells constructed in the Crystal River aquifer is 1.0 mi along strike of the hydraulic gradient direction (north-south in southeast Alabama) and 1.0 mi up or down the hydraulic gradient direction (east-west in southeast Alabama).

The entire Crystal River Formation is unconfined or partially confined and covers about 1,700 mi^2 in the southern part of the assessment area. Estimates of recharge for the unit, and resulting base flow to streams in the recharge area, is 408.4 mgd or 5.1 in./yr. Although water in the Crystal River aquifer is relatively shallow and under water table conditions, additional large quantities of groundwater in the extreme southern part of the assessment area can be developed in the future. However, most of this water would be for irrigation purposes only. Water quality is not an impediment to development of water supplies from the Crystal River aquifer in southeast Alabama.

In order to ascertain the sustainability of groundwater resources in a specified area, available volumes of groundwater of adequate quality must be compared to current groundwater use. As mentioned previously, current water use values are not available. Therefore, total volumes of available groundwater in subsurface storage and confined aquifer recharge were compared to 2005 water use values in the assessment area. An exact comparison is not possible, since groundwater use data are compiled for geographic areas and are not available for specific aquifers. However, improved insights into groundwater availability and current groundwater production impacts can be developed by comparing available information. Unconfined or partially confined recharge was not included in the comparison, since water use from unconfined aquifers in southeast Alabama is relatively minimal. Also, groundwater use data includes all aquifers, which are compared to groundwater availability values for selected aquifers.

Total available groundwater in subsurface storage for all assessed confined aquifers (Lower Cretaceous, Coker, Eutaw/Gordo, Ripley, Clayton/Salt Mountain, and Nanafalia) is about 8.0 billion gallons and the Gordo, Ripley, Clayton, and Nanafalia aquifers are being replenished at a rate of 117.0 mgd. This is compared with total 2005 groundwater use for 13 counties in the assessment area, which is about 123 mgd. Therefore, when confined recharge rates for minor aquifers are considered, 2005 groundwater use is equivalent to confined recharge. Potentiometric surface mapping indicates that pumping rates exceed recharge rates for major aquifers in several population centers and in a number of individual wells in rural areas, causing minimal removal of groundwater from subsurface storage. However, comparisons of groundwater use and availability data indicate that large quantities of additional groundwater can be sustainably developed in southeast Alabama.

REFERENCES CITED

Alley, W. M., Reilly, T. E., and Franke, O. E., 1999, Sustainability of groundwater resources: Denver, Colorado, U.S. Geological Survey Circular 1186, 79 p.

Australia Department of the Environment, 2013, Annex A, Sustainable groundwater use, http://www.environment.gov.au/system/files/resources/25838e76-ceab-469a-b11c-dec6dd7d7f05/files/annex.pdf, accessed December 15, 2013.

Baker, R. M., Smith, C. C., 1997, Delineation of wellhead protection area boundaries for the public-water supply wells of the town of Luverne, Crenshaw County, Alabama: Geological Survey of Alabama Open File Report, 10 p.

See TEXT (“and others”) Barcelona, M. J., 1984, A laboratory evaluation of ground water sampling mechanisms: Ground Water Monitoring Review 4, no. 2, p. 32-41.

Blandford, T. N., and Yu-Shu-Wu, 1993, Addendum to the WHPA code version 2.0 user’s guide: implementation of hydraulic head computation and display into the WHPA code, GPTRAC module: U.S. Environmental Protection Agency, 268 p.

Bradbury, K. R., and Rothschild, E. R., 1985, A computerized technique for estimating hydraulic conductivity of aquifers from specific capacity data: Ground Water, v. 23, no. 2, p. 240-245.

Cook, M. R., 1993, The Eutaw aquifer in Alabama: Alabama Geological Survey Bulletin 156, 105 p.

Cook, M. R., 2002, 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., Jennings, S. P., and Moss, N. E., 2007, Assessment of aquifer recharge, ground-water production impacts, and future ground-water development in southeast Alabama: Geological Survey of Alabama Open-file Report 0803, 38 p.

Cook, M. R., Kopaska-Merkel, D. C., and Puckett, T. M., 1997, Hydrologic characterization of the Choctawhatchee-Pea Rivers watershed phase II, A report to the Choctawhatchee-Pea Rivers Watershed Management Authority: Geological Survey of Alabama Open-file Report, p. 36.

Cook, M. R., Smith, K. M., and Rogers, A. L., 2013, Hydrogeologic characterization and groundwater source development assessment for the South Bullock County Water Authority: Geological Survey of Alabama Open-file Report 1309, 26 p.

Davis, M. E., 1987, Stratigraphic and hydrogeologic framework of the Alabama coastal plain: U.S. Geological Survey Water-Resources Investigations Report 87-4112, 45 p.

DeJarnette, S. S., Gillett, Blakeney, Hicks-Wells, Lawanna, and Moore, J. D., 2002, Ground-water levels in Alabama: 1997-2001: Geological Survey of Alabama Circular 112Q, 315 p. with plate.

Driscoll, F. G., 1986, Groundwater and wells: St. Paul, Minnesota, Johnson Division, 1089 p.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536 E, 174 p.

Fetter, C. W., 1994, Applied hydrogeology, Third Edition: New York, New York, Macmillan, Inc., 691 p.

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

Kunianshy, E. L., and Bellino, J. C., 2012, Tabulated transmissivity and storage properties of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Data Series 669, 31 p.

Langdon, D. W., 1891, Variations on the Cretaceous and Tertiary strata of Alabama: Geological Society of America Bulletin, v. 2, p. 587-605.

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.

Mace, R. E., 1997, Determination of transmissivity from specific-capacity tests in a karst aquifer: Ground Water, v. 35, no. 5, p. 738-742.

Maher, J.C., and Applin, E. R., 1968, Correlation of subsurface Mesozoic and Cenozoic rocks along the Eastern Gulf Coast: American Association of Petroleum Geologists Cross Section Publication 6, p. 11-12.

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

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

Ponce, V. M., 2007, Sustainable groundwater: URL http://www.gwsustainability.sdsu.edu html, accessed December 7, 2013.

Purdue University, 2004, WHAT-web-based hydrograph analysis tool: URL http://cobweb.ecn.purdue.edu/~what/ accessed 2013.

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.

Robertson, C. E., 1963, Well data for water well yield map: Missouri Geological Survey and Water Resources, 23 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.

Smith, C. C., 2001, Implementation assessment for water resources availability, protection, and utilization for the Choctawhatchee, Pea, and Yellow Rivers watersheds: Geological Survey of Alabama Open-file Report, 148 p.

Smith, C. C., Gillett, Blakeney, and Baker, R. M., 1996a, Delineation of wellhead protection area boundaries for the public-water supply wells of the city of Enterprise, Coffee County, Alabama: Geological Survey of Alabama Open-file Report, 33 p.

Smith, C. C., Gillett, Blakeney, and Baker, R. M., 1996b, Delineation of wellhead protection area boundaries for the Water-Works and Sewer Board, city of Eufaula, Barbour County, Alabama: Geological Survey of Alabama Open-file Report, 42 p.

Smith, C. C., Gillett, Blakeney, and Baker, R. M., 1996c, Delineation of wellhead protection area boundaries for the public-water supply wells, Utilities Board, city of Ozark, Dale County, Alabama: Geological Survey of Alabama Open-file Report, 26 p.

Smith, C. C., Gillett, Blakeney, and Baker, R. M., 1997, Geology and hydrology in support of the delineation of wellhead protection area boundaries city of Dothan, Houston County, Alabama: Geological Survey of Alabama Open-file Report,114 p.

Southeast Regional Climate Center, 2009, [2012 in text, p. 108] Historical Climate Summaries for Alabama, URL http://www.sercc.net/climateinfo/historical/historical_al.html, accessed November 13, 2013.

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.

Theis, C. V., 1963, Estimating the transmissivity of a water table aquifer from the specific capacity of a well: U.S. Geological Survey Water Supply Paper 1536-I, p. 332-336.

Toulmin, L. D., and LaMoreaux, P. E., 1963, Stratigraphy along the Chattahoochee River, connecting link between the Atlantic and Gulf Coastal Plains: American Association of Petroleum Geologists Bulletin, v. 47, no. 3, p. 385-404.

Walton, W. C., and Neill, J. C., 1963, Statistical analysis of specific-capacity data for a dolomite aquifer: Journal of Geophysical Research, v. 68, p. 2251-2262.

GEOLOGICAL SURVEY OF ALABAMA
420 Hackberry Lane
P.O. Box 869999
Tuscaloosa, Alabama 35486-6999
205/349-2852

Berry H. (Nick) Tew, Jr., State Geologist

A list of the printed publications by the Geological Survey of Alabama can be obtained from the Publications Office (205/247-3636) or through our web site at http://www.gsa.state.al.us/.

E-mail: publications@gsa.state.al.us