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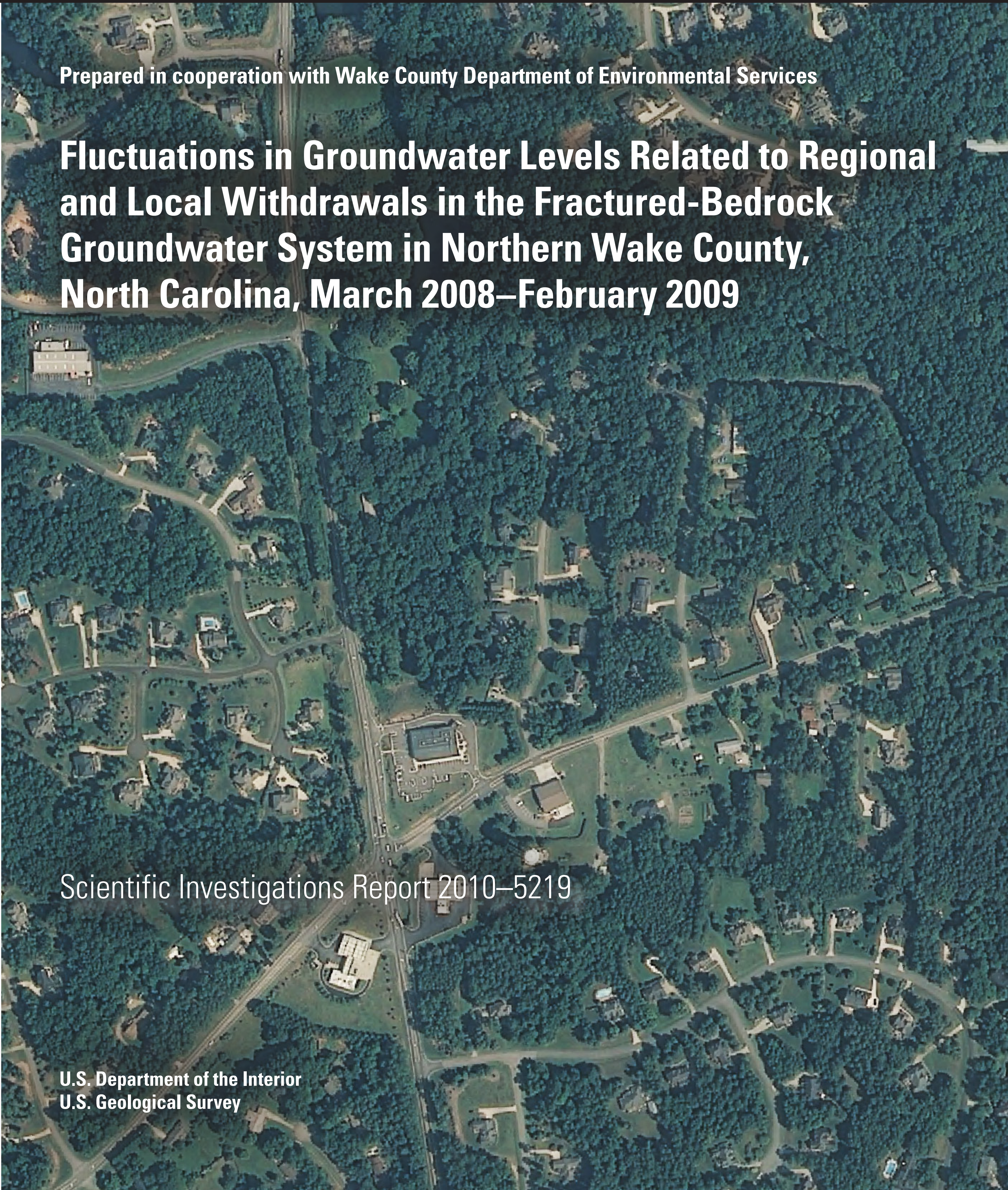

Prepared in cooperation with Wake County Department of Environmental Services

Fluctuations in Groundwater Levels Related to Regional and Local Withdrawals in the Fractured-Bedrock Groundwater System in Northern Wake County, North Carolina, March 2008–February 2009

Scientific Investigations Report 2010–5219

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Pressure	
pound-force per square inch (psi)	6.895	kilopascal (kPa)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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

Acronyms and Abbreviations

bls	below land surface
BTC	Bayleaf Trail Catchment
CDM	Camp Dresser & McKee Consultants, Inc.
CW	community well
CWS	community water system
DEH	Division of Environmental Health
ET	evapotranspiration
FID	field identification number
LIDAR	light detection and ranging
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NCDENR	North Carolina Department of Environment and Natural Resources
NWIS	National Water Information System
psi	pounds per square inch
PVC	polyvinyl chloride
PWSS	Public Water Supply Section
OTV	optical televiewer
USB	universal serial bus
USGS	U.S. Geological Survey
WK	Wake County

Fluctuations in Groundwater Levels Related to Regional and Local Withdrawals in the Fractured-Bedrock Groundwater System in Northern Wake County, North Carolina, March 2008–February 2009

By Melinda J. Chapman[1], Naser Almanaseer[2], Bryce McClenney[1], and Natalie Hinton[3]

Abstract

A study of dewatering of the fractured-bedrock aquifer in a localized area of east-central North Carolina was conducted from March 2008 through February 2009 to gain an understanding of why some privately owned wells and monitoring wells were intermittently dry. Although the study itself was localized in nature, the resulting water-resources data and information produced from the study will help enable resource managers to make sound water-supply and water-use decisions in similar crystalline-rock aquifer setting in parts of the Piedmont and Blue Ridge Physiographic Provinces.

In June 2005, homeowners in a subdivision of approximately 11 homes on lots approximately 1 to 2 acres in size in an unincorporated area of Wake County, North Carolina, reported extremely low water pressure and temporarily dry wells during a brief period. This area of the State, which is in the Piedmont Physiographic Province, is undergoing rapid growth and development. Similar well conditions were reported again in July 2007. In an effort to evaluate aquifer conditions in the area of intermittent water loss, a study was begun in March 2008 to measure and monitor water levels and groundwater use.

During the study period from March 2008 through February 2009, regular dewatering of the fractured-bedrock aquifer was documented with water levels in many wells ranging between 100 and 200 feet below land surface. Prior to this period, water levels from the 1980s through the late 1990s were reported to range from 15 to 50 feet below land surface. The study area includes three community wells and more than 30 private wells within a 2,000-foot radius of the dewatered private wells. Although groundwater levels were low, recovery was observed during periods of heavy rainfall, most likely a result of decreased withdrawals owing to less demand for irrigation purposes. Similar areal patterns of low groundwater levels were delineated during nine water-level measurement periods from March 2008 through February 2009. Correlation of groundwater-level distribution patterns with orientations of geologic structures obtained from surficial mapping, borehole geophysical measurements, and interpretation of fracture traces suggests two dominant trends striking north-south and N. 65° W.

A variation in overall response to groundwater withdrawals was noted in the continuous groundwater-level records for the monitored observation wells and dewatered private wells. The largest overall declines during the study period were observed in an observation well in which the water-level declined as much as 247 feet from mid-July through early August 2008, during a period of heavy usage. A private well had a water-level decline of about 94 feet during the same monitoring period. The large declines recorded in the observation well and the private well indicated a substantial temporary loss of storage in the fractured-bedrock aquifer near the wells, thus reducing the amount of water available to shallow wells in the area (those wells with total depths of about 300 feet), and resulting in temporary well failures until such time as the aquifer recovered.

Introduction

Although the fractured crystalline-rock aquifers of the Piedmont and Blue Ridge Physiographic Provinces in the eastern United States typically do not yield large amounts of groundwater, the resource remains the primary water supply for most rural households and some suburban areas in North Carolina. Groundwater is the primary water supply resource for much of unincorporated Wake County, North Carolina, despite the use of several large surface-water reservoirs, which supply water to the Raleigh-Durham-Chapel Hill metropolitan area. Groundwater supplies in the Wake County area, as in other areas in the Piedmont and Blue Ridge Physiographic Provinces of the State (fig. 1), are withdrawn from fractures in

[1] U.S. Geological Survey, North Carolina Water Science Center.

[2] North Carolina State University, Water Resources Research Institute.

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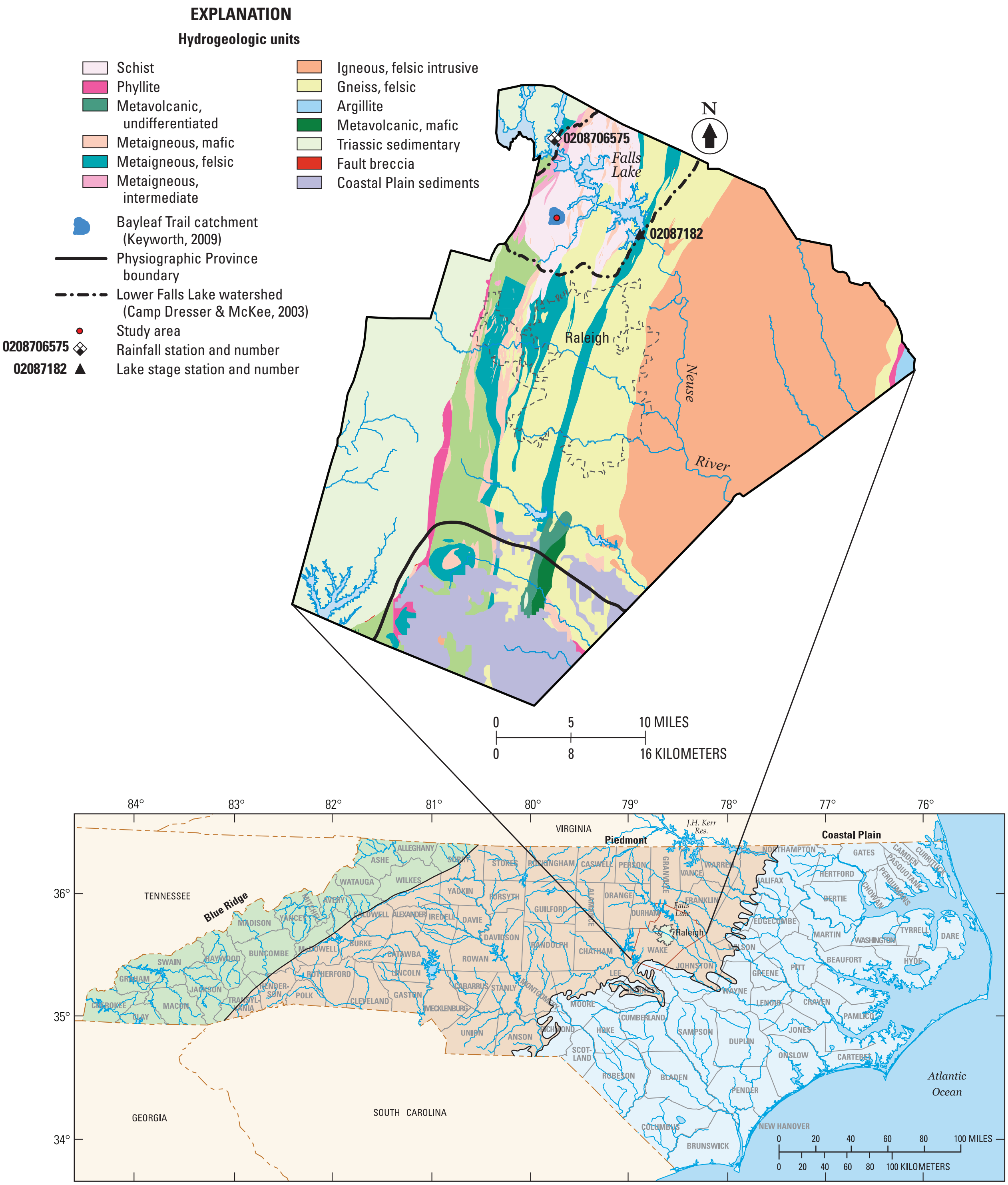


Figure 1. Hydrogeologic units mapped in Wake County, North Carolina, and location of the study area (modified from Camp Dresser & McKee, 2003).

the bedrock aquifer. The bedrock has limited storage capacity, and recharge occurs from the overlying, porous regolith. As a result, drawdown from the bedrock aquifer occurs quickly and can be on the order of 100 feet (ft) or more within a few hours. Aquifers in the area are not as prolific or regional in extent as the porous-media sand and limestone aquifers in the North Carolina Coastal Plain Physiographic Province, but are local in nature with recharge estimated to occur on the scale of local topographic boundaries (LeGrand, 2004).

Total groundwater withdrawals in Wake County in 2005 were estimated to be 16 million gallons per day (Mgal/d; U.S. Geological Survey, 2008). Of that total, about 7.72 Mgal/d was withdrawn by individual wells serving about 110,280 people, or about 15 percent of the total Wake County population of 748,815 (U.S. Census Bureau, 2005). This amount is the largest number of individuals served by domestic wells of any county in the State. An additional 4.76 Mgal/d was withdrawn by community wells and served 61,780 people, or 8 percent of the county population. In North Carolina, a community water system (CWS) is defined as having at least 15 connections or serving at least 25 people (North Carolina Department of Environmental and Natural Resources, 2004). An estimated 600 community wells are in Wake County, which is probably the largest number of such wells in any county in the State (Greg Bright, Wake County Department of Environmental Services, oral commun., 2008). Additional groundwater use in Wake County includes 2.03 Mgal/d for irrigation, of which 1.34 Mgal/d was used for golf courses and 0.69 Mgal/d for crops. The mining industry also withdrew 1.36 Mgal/d of groundwater, 0.23 Mgal/d was used for livestock, and 0.09 Mgal/d was used for aquaculture (U.S. Geological Survey, 2008).

It is important to note that only the larger groundwater withdrawals for community supplies are measured (daily water-use reports) in North Carolina, and the total Wake County groundwater withdrawals are based on estimates for other uses, such as individual wells (domestic use) or irrigation wells. For example, the number of people supplied by individual wells is estimated as the difference between the total population and the population served by public utilities and community systems. Groundwater withdrawals for public supply are then estimated as the number of people using groundwater multiplied by an estimated water use per capita, which was 70 gallons per person for North Carolina in 2005 (U.S. Geological Survey, 2008). Groundwater withdrawals for irrigation are estimated from the acres of individual crops multiplied by an average application rate (Douglas G. Smith, U.S. Geological Survey, written commun., 2009). Withdrawals for irrigation of individual lawns are not known but likely are increasing.

North Carolina General Statute 130A-328 (1992) requires that all wells serving at least 25 people for at least 6 months out of a year be permitted. These types of wells include community systems and non-community non-transient systems. The permit is issued by the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Environmental Health (DEH) Public Water Supply Section (PWSS). The PWSS has the responsibility to ensure adequate water supplies are available (North Carolina General Statute 130A-328) and thus permits the amount of water to be withdrawn from a community well. The permitted daily withdrawal rate typically is based on a 24-hour (hr) drawdown test, and only a totalizing meter (total volume) is required to report the daily volume of groundwater withdrawn from the aquifer. The drawdown of any water-supply well must not interfere with the required yield of another well, but monitoring of nearby water levels in surrounding wells is not required by most permits. Water-use reports are compiled monthly by the CWS operators and sent to the PWSS. Water-level monitoring in the supply well is not required after the initial drawdown test (North Carolina Department of Environment and Natural Resources, 2004). Without water-level data, however, the PWSS cannot determine if water levels recover after seasonal high water-use periods or after recharge events and whether the aquifer is sustaining the withdrawals or is being dewatered. The only location requirements regarding the well are general setback rules for septic fields and wellhead protection area (North Carolina Department of Environment and Natural Resources, 2004); the appropriate county agency also must be notified when a CWS is installed (Greg Bright, Wake County Department of Environmental Services, oral commun., 2008).

In August 2009, Wake County passed a local ordinance that addresses monitoring requirements for well interference when complaints of degradation in water quality or yield in a private, semiprivate or large capacity well are forwarded to the county in writing. The well is considered “degraded” if the well yield can no longer “effectively support human consumption or basic sanitation requirements.” The radial distance of the “zone of influence” monitoring requirement is 2,000 ft outward from the degraded well (Wake County Department of Environmental Services, 2009).

Background

On June 18, 2005, several homeowners using individual domestic wells for water supply in the Norwood Oaks subdivision and along Bayleaf Trail in northern Wake County, North Carolina (figs. 1, 2), reported a loss of water pressure severe enough to indicate dry wells. This was the first reported occurrence of dry wells in the neighborhood, which was about 11 years old at the time. Similar problems occurred again in this same area in July 2007. Some private wells eventually required modification, including deepening, hydrofracturing, or pump replacement. Because withdrawals of about 30,000 gallons per day (gal/d) from a nearby community well (WK-415, fig. 2) had commenced about 2 weeks earlier (June 2005) and concern arose that the private well problems were related to the community well (Elliott Cornell, Wake County Department of Environmental Services, written commun., 2008), the homeowners drafted a letter to a Wake County commissioner requesting county oversight of

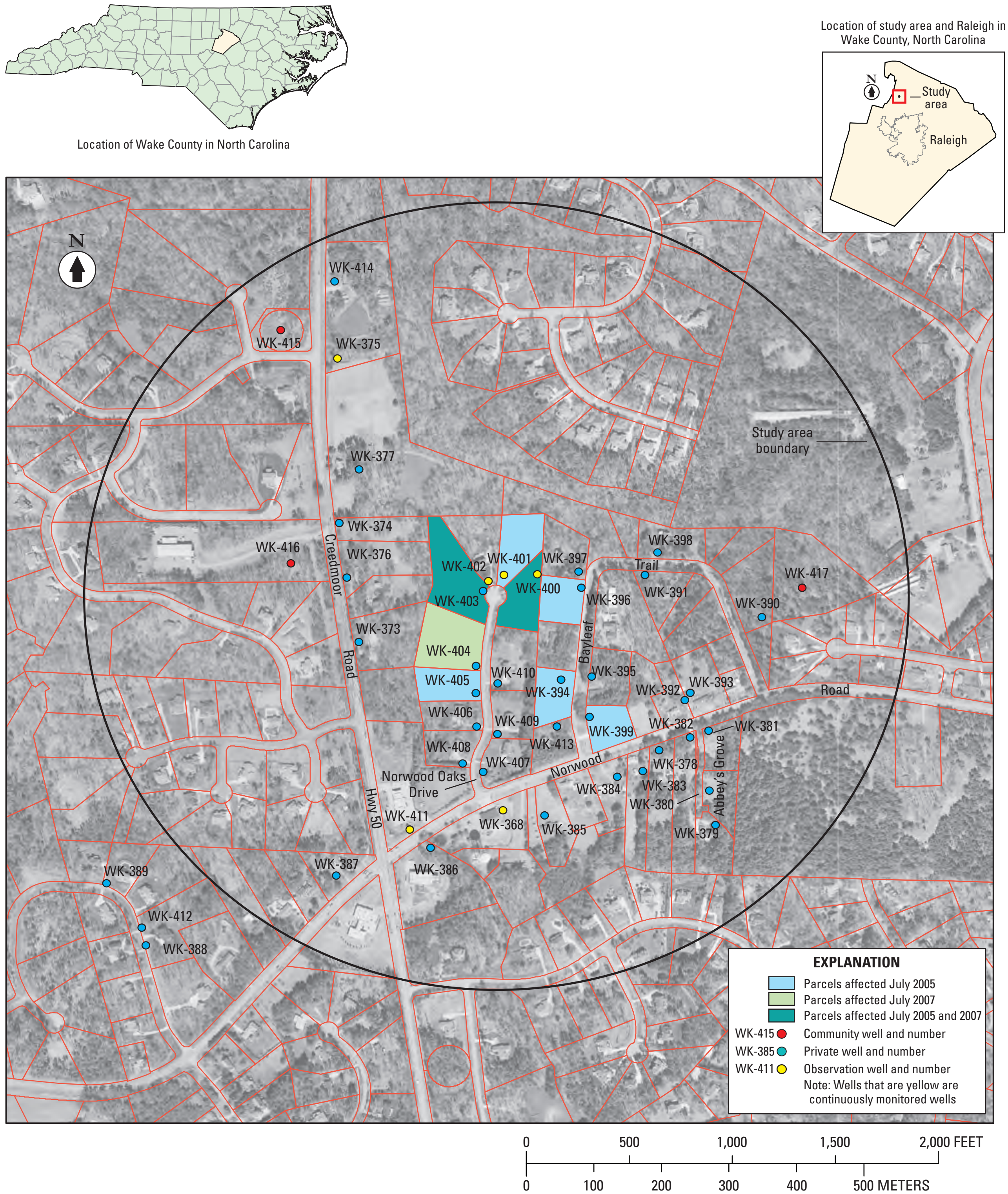


Figure 2. Norwood Oaks study area showing parcels where private wells went dry during July 2005 and July 2007, and nearby community supply wells.

well locations and volumes withdrawn by commercial water utilities. The county responded by convening a "Groundwater Sustainability Committee" in June 2006, which developed a report of recommendations to address the subject issues (Wake County Groundwater Sustainability Stakeholder Committee Report, 2007).

In October 2007, Wake County Department of Environmental Services requested the U.S. Geological Survey (USGS) to develop an approach to understand the apparent decrease in groundwater supplies in the Norwood Oaks area. This request led to the initiation of a cooperative investigation that began in January 2008, with field work and monitoring beginning in March 2008. This report describes data collected as part of this cooperative study and related findings. A primary mission of the USGS is to provide reliable and impartial information on the health and management of the natural resources of the Nation (*http://www.usgs.gov/aboutusgs/*). To that end, the USGS provides resource managers and planners with current information on water resources for domestic, agricultural, commercial, industrial, recreational, and ecological use, as well as for the protection and enhancement of water resources for human and aquatic health and environmental quality (*http://water.usgs.gov/mission.html*). Results from this study will be transferable to other similar fractured-rock aquifer settings in other areas of the Piedmont and Blue Ridge physiographic regions throughout the eastern United States where similar groundwater resource-management issues have developed.

Purpose and Scope

The purpose of this report is to describe conditions in the fractured-bedrock aquifer in northern Wake County, North Carolina, which may have contributed to temporary dewatering of the aquifer as an example of competitive use by both individual homeowners and community water suppliers. Groundwater-level fluctuations were measured and monitored during March 2008 through February 2009 for the study area to identify potential causes of declining groundwater levels in the area. Groundwater-level data were collected from 35 private wells and 8 observation wells for the entire study period, for one community well from July through December 2008, and for a second community well from December 2008 through January 2009. Withdrawal data were collected from two private wells during August and September 2008 and compiled from PWSS reports for the three community wells during January through November 2008.

The potential effects of the combined withdrawals by community wells and private wells on water-level declines are described. Groundwater levels, including fluctuations in water levels resulting from both local and potentially regional withdrawals, are documented. Withdrawal data compiled from reports of water usage from community wells and recorded using flowmeters on private wells were used in the analysis. Comparisons of recorded groundwater-level fluctuations to naturally occurring effects, such as precipitation, barometric pressure fluctuations, evapotranspiration, and earth tides, were made. Correlations were made between low water-level patterns with geologic structural features mapped at land surface and within boreholes in the area.

Description of the Study Area

The study area generally is defined by a radial distance of 2,000 ft outward from Norwood Oaks Drive cul-de-sac and includes the nearest community wells (fig. 2). Regionally, the study area is located within the lower Falls Lake watershed in northern Wake County, North Carolina (NC), in the Piedmont Physiographic Province (fig. 1). Falls Lake is the major drinking water-supply reservoir for the city of Raleigh, NC, and the nearest embayment of the lake is about 1.1 miles northeast of the study area (fig. 1) along Upper Barton Creek.

The study area is located within the schist hydrogeologic unit (Camp Dresser & McKee, 2003), which makes up about 5 percent of the total county area (Camp Dresser & McKee, 2003; fig. 1). The schist hydrogeologic unit has the lowest mean yield (7 gallons per minute (gal/min)) for domestic wells of all hydrogeologic units mapped in the county (Camp Dresser & McKee, 2003), with a range of about 3 to 8 gal/min based on data from 143 wells. The community wells for the schist hydrogeologic unit have an overall higher yield than individual wells, likely because of their greater depth, with yields of about 20 to 70 gal/min. It is not uncommon for residential developers in this area of the county to drill several to a few dozen wells to find adequate groundwater yield for community water supply (Allen Hardy, North Carolina Department of Environment and Natural Resources, oral commun., 2008).

Keyworth (2009) defined the Bayleaf Trail Catchment (fig. 1), which includes the study area, and reported groundwater use from three community wells and 35 individual private wells. The three community wells connect to two distribution networks that consist of a large network of 67 wells in northern Wake County (Keyworth, 2009). The three community wells are substantially deeper (about 700 to 800 ft) than the private wells (about 150 to 500 ft), and two of the three community wells have yields of about 60–80 gal/min (table 1). The average private well yield is about 7 gal/min. In general, domestic wells require yields of only a few gallons per minute, but with the overall aquifer yield being low in this area, a larger number of wells drilled could stress the aquifer, resulting in yields even lower than the initial yield, and low pressure in the wells from withdrawals could be expected. Reported pumping rates for the community wells were between 5,000 and 30,000 gal/d per well during the spring through summer in 2005 and 2007 (Elliot Cornell, Wake County Department of Environmental Services, written commun., 2008).

Table 1. Well characteristics in the study area in northern Wake County, North Carolina.

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; OW, observation well; PW, private well; and CW, community well; —, information not available. Note: All well-construction characteristics were recorded from well tags in the field as part of this study unless otherwise noted]

USGS county number	USGS station number	Type of well	Latitude (decimal degrees)	Longitude (decimal degrees)	Date drilled	Well depth (feet below land surface)	Well elevation (feet above NAVD 1988)	Casing depth (feet below land surface)	Yield (gallons per minute)	Static water level at time of construction	Monitoring
WK-368	355635078385101	OW	-78.684	35.943	2/11/1992	500[a]	408	70	12	15	Continuous water levels
WK-373	355643078411201	PW	-78.687	35.945	2003	400	388	—	1	20	Periodic water levels
WK-374	355648078411301	PW	-78.687	35.947	1981	150	371	65	7	—	Periodic water levels
WK-375	355659078411401	OW	-78.687	35.950	4/19/1999	301[a]	338	39[a]	40	20	Continuous water levels
WK-376	355646078411301	PW	-78.687	35.946	11/15/1994	305	378	61	3	—	Periodic water levels
WK-377	355651078411201	PW	-78.687	35.947	5/15/1980	225	356	43	3	50	Periodic water levels
WK-378	355637078405501	PW	-78.682	35.944	12/9/1981	300	417	73	1	—	Periodic water levels
WK-379	355634078405301	PW	-78.681	35.943	—	—	404	—	—	—	Periodic water levels
WK-380	355635078405301	PW	-78.681	35.943	—	305	407	165	10	30	Periodic water levels
WK-381	355638078405301	PW	-78.681	35.944	10/14/2005	505	415	102	1	100	Periodic water levels
WK-382	355638078405401	OW	-78.682	35.944	12/8/1981	225	416	76	4	—	Periodic water levels
WK-383	355636078405601	PW	-78.682	35.943	—	—	415	—	—	—	Periodic water levels
WK-384	355636078405801	PW	-78.683	35.943	—	—	413	—	—	—	Periodic water levels
WK-385	355634078410201	PW	-78.684	35.943	—	508	407	90	—	15	Periodic water levels
WK-386	355632078410801	OW	-78.686	35.942	—	—	395	—	—	—	Periodic water levels
WK-387	355631078411301	PW	-78.687	35.942	3/7/2001	285	410	90	4	40	Periodic water levels
WK-388	355628078412401	OW	-78.690	35.941	8/8/2003	345	410	92	0	40	Periodic water levels
WK-389	355631078412601	PW	-78.691	35.942	4/13/2001	305	406	61	5	—	Periodic water levels
WK-390	355644078404901	PW	-78.680	35.945	—	—	400	—	—	—	Periodic water levels
WK-391	355646078405601	PW	-78.682	35.946	2/4/1985	312	358	53	1	—	Periodic water levels
WK-392	355640078405401	PW	-78.682	35.944	—	—	416	—	—	—	Periodic water levels
WK-393	355640078405301	PW	-78.681	35.944	—	—	416	—	—	—	Periodic water levels
WK-394	355641078410101	PW	-78.683	35.945	—	—	398	—	—	—	Periodic water levels
WK-395	355641078405901	PW	-78.683	35.945	—	—	408	—	—	—	Periodic water levels
WK-396	355645078410001	PW	-78.683	35.946	11/30/2001	400	397	23	3	100	Periodic water levels
WK-397	355646078410001	PW	-78.683	35.946	9/17/1980	334	394	58	3	40	Periodic water levels
WK-398	355647078405301	PW	-78.681	35.946	—	—	362	—	—	—	Periodic water levels
WK-399	355645078410401	OW	-78.683	35.944	11/15/2004	320	408	68	10	20	Periodic water levels

Table 1. Well characteristics in the study area in northern Wake County, North Carolina.—Continued

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988; OW, observation well; PW, private well; and CW, community well; —, information not available. Note: All well-construction characteristics were recorded from well tags in the field as part of this study unless otherwise noted]

USGS county number	USGS station number	Type of well	Latitude (decimal degrees)	Longitude (decimal degrees)	Date drilled	Well depth (feet below land surface)	Well elevation (feet above NAVD 1988)	Casing depth (feet below land surface)	Yield (gallons per minute)	Static water level at time of construction	Monitoring
WK-400	355635078410401	PW	-78.684	35.946	5/23/1995	400	394	60	5	—	Continuous water levels
WK-401	355646078410401	PW	-78.684	35.946	6/15/1995	410	387	64	1	30	Continuous water levels and flow
WK-402	355646078410501	PW	-78.685	35.946	5/16/1994	290	380	37	8	30	Continuous water levels and flow
WK-403	355645078410501	PW	-78.685	35.946	2/22/1999	380	376	47	25	25	Periodic water levels
WK-404	355642078410601	PW	-78.685	35.945	6/30/1994	405	388	45	12	—	Periodic water levels
WK-405	355640078410501	PW	-78.685	35.945	—	—	396	—	—	—	Periodic water levels
WK-406	355639078410601	PW	-78.685	35.944	11/9/1995	515	404	80	3	20	Periodic water levels
WK-407	355636078410501	PW	-78.685	35.943	5/13/1994	270	409	76	3	20	Periodic water levels
WK-408	355637078410601	PW	-78.685	35.944	10/25/1994	230	406	58	8	—	Inventory only
WK-409	355638078410401	OW	-78.685	35.944	4/28/1994	505	408	82	2	—	Periodic water levels
WK-410	355640078410401	PW	-78.685	35.945	10/1/1994	375	392	49	10	20	Periodic water levels
WK-411	355634078410901	OW	-78.686	35.943	—	306[a]	400	—	—	—	Continuous water levels
WK-412	355628078412402	PW	-78.690	35.941	2/8/2006	500	410	48	20	40	Periodic water levels
WK-413	355638078410001	PW	-78.684	35.944	—	—	403	—	—	—	Periodic water levels
WK-414	355656078411301	PW	-78.687	35.949	2/27/1974	325	330	52	5	—	Inventory only
WK-415[b]	355705078411601	CW	-78.688	35.951	1/29/1999	695	351	60	63	60	Continuous water levels
WK-416[b]	355646078411601	CW	-78.688	35.946	3/1/2000	805	396	65	79	120	Continuous water levels
WK-417[b]	355645078404501	CW	-78.679	35.946	—	700	401	—	8	—	—

[a] Determined from geophysical logging.

[b] Reported information.

Previous Studies

The most recent comprehensive report on groundwater resources in Wake County, North Carolina, was compiled in 2003 by Camp Dresser & McKee (CDM), which was produced under the direction of the Wake County Department of Environmental Services. The report addresses a wide array of groundwater issues, focusing on availability and sustainability of the resource. At that time, almost one-fourth of the county's residents relied on groundwater for their primary water supply. In 2003, 275 CWSs provided water to about 48,000 people, while about 93,000 people obtained water from individual domestic-supply wells.

CDM (2003) also estimated water budget components for 14 surface-water drainage basins in Wake County based on long-term and most recent available data at that time. Total estimated groundwater withdrawals for the county were about 14 Mgal/d. The largest groundwater withdrawals were in the lower Falls Lake Basin, which had the highest per capita withdrawal rate of about 100 gallons per person per day (gal/person/d), with daily withdrawals in 2000 estimated to be 1.8 Mgal/d or 641 million gallons per year (Mgal/yr). Recommendations in the CDM 2003 study included the need to address potential effects from development projects on groundwater resources at the local scale and implementation of a long-term groundwater-monitoring network.

Keyworth (2009) used a water-balance approach to address concerns regarding groundwater-resource sustainability in the midst of large population growth. The Bayleaf Trail Catchment (BTC) used in the study as a typical local-scale example encompasses the study area described in the current report. Keyworth describes the three community wells previously mentioned and a total estimate of 35 private wells within the approximately 0.4 square mile (mi^2) BTC watershed. The three CWS wells in the BTC were reportedly part of a larger distribution system that included 67 wells.

Keyworth's (2009) water-balance approach included precipitation and wastewater recharge return from onsite septic systems as input parameters to the hydrologic system in the BTC. Outputs for the water-balance approach included groundwater withdrawals from private wells and CWSs, and evapotranspiration (ET; both at land surface (irrigation/surface water) and within septic fields). For households having a private well and onsite septic system, water use was estimated to be 55 gal/person/d, which differs from the 100 gal/person/d estimated by CDM (2003), and the return of wastewater (recharge to the groundwater system) by way of septic systems was estimated to be 85 percent of that total use. The return from septic systems also was estimated at the same 85 percent of total use for households receiving their water supply from the three community wells in the BTC. The estimates of wastewater return were based on the assumption of a comparable percentage of water returned to sewered systems from the nearby city of Raleigh and the town of Holly Springs in Wake County, NC. Within the septic field, ET was estimated to be 15 percent of the water use, resulting in an 85 percent recharge to the groundwater system. The water balance for the BTC was then solved for streamflow, assuming no change in storage in the hydrologic system. The only known estimates of streamflow were based on 7Q10 (7-day consecutive flow with 10 year return frequency) low-flow data for the Upper Barton Creek watershed (partial record station for the years 1951 through 1970 (Weaver, 1998)) that were applied to the smaller BTC catchment. Water-balance calculations were made for an average year, recent dry years (2005 and 2007), and a wet year (2006).

The combined annual withdrawal of the three CWS wells was reported to have increased yearly during 2001–2007 (Keyworth, 2009). The average daily pumping volumes for community wells WK-415 and WK-416 were about 15,000 to 16,000 gal/d each, whereas the pumping volume for well WK-417 was about 5,000 gal/d (Keyworth, 2009, table 2). The total reported daily water withdrawals by the three CWSs in the BTC was much greater than would be needed to supply the 60 homes using 55 gal/person/d (Keyworth, 2009).

A local investigation of groundwater and soil contamination in the study area was published in 1992 (Turner Environmental Consultants, 1992). The contamination included gasoline and kerosene compounds that were released from underground storage tanks near the intersection of Highway 50 (Creedmoor Road) and Norwood Road (fig. 2). The investigation reported an average depth to the water table of about 20 to 25 ft below land surface (bls) in May 1992. The shallow regolith consisted of silt and silty clay to silty sand residuum, with some quartz stringers, and the presence of weathered gneiss at a depth of about 57 ft bls. Depth to bedrock was estimated to be about 54 ft bls at one location at the site. Shallow groundwater flow was to the north toward Upper Barton Creek. The dissolved contaminant plume was described as having a north-south elongation, suggesting anisotropy likely related to geologic controls. Relict metamorphic foliation and the quartz stringers observed in excavations at the site were reported to have a north-south trend.

Methods of Investigation

Data collection in the current study included well inventory, geologic structural mapping, borehole geophysical logging, periodic groundwater-level measurements, continuous groundwater-level monitoring, and groundwater-withdrawal monitoring. A well inventory was conducted early in the study to obtain access for water-level measurements and to record information obtained from the well tag. NCDENR has required that well tags be affixed to the surface casing of newly constructed wells since the late 1970s (North Carolina Department of Environment and Natural Resources, 2002). The well tags are required to contain the following information: date drilled, driller's name, static water level at the time of drilling, yield, depth of casing, and total depth of the well. A total of 8 observation wells and 35 private wells were inventoried within the study area, and data from the associated well tags (where found) are presented in table 1 along with information reported for the three community wells.

Measurements of foliation (rock fabric) and fracture (joints) orientations were recorded in the field by using a traditional magnetic compass corrected for local magnetic declination. Only a few outcrops were measured near the study area, as the rocks were deeply weathered. Geologic structural measurements were made at five stations in or near the study area. Regional geologic mapping structural information previously collected near the study area also is presented in this report.

Borehole geophysical logging was conducted in two wells in the study area and included the traditional caliper, natural gamma, electrical resistivity, and fluid (temperature and resistivity) logs, as well as optical and acoustical televiewer logs. The purpose of the geophysical logging was to delineate and characterize bedrock fractures and orientations at depth by using optical or acoustic televiewer images. Borehole geophysical logs were run in two wells in the study area. Orientations of structural features were interpreted from optical or acoustic televiewer images by using propriety manufacturer's software. Primary fractures are those that are open from visual interpretation of the optical televiewer image, compared to secondary fractures which may be only weathered or partially open.

Electrical tapes, steel tapes, and acoustical meters were used to measure groundwater levels in both observation wells (no pump) and private wells (pump installed). Because the water levels in many of the wells in the study area frequently exceeded 100 ft bls, problems with reading electric and steel tapes from cascading water and moisture in the well were prevalent. In addition, because of reduced access through the 0.5-inch vent pipe in the sanitary seal on the well head and because of the downhole equipment in the well (the pump and associated electrical wiring and discharge lines), acoustical methods were used throughout the study for measuring deep groundwater levels (generally if the water level was greater than 100 ft bls) in private wells. All of the private wells were in use and thus may have been withdrawn recently prior to a measurement. Care was taken to determine if a pump was on and to avoid making a measurement during noticeably rapid water-level declines.

The acoustical water-level meters are acoustic ranging instruments designed to find the distance to the water surface within the borehole. A low-frequency (100 hertz) acoustic pulse is used for the source signal. The sound speed is affected by the air temperature within the borehole and the groundwater temperature. In the field, the manufacturer's table of temperature control settings was used for this region of North Carolina for each month of field readings. Sensitivity to temperature settings in general was found to be within one or two tenths of a foot distance to the water level. Water levels measured using the acoustical instruments were quality assured by comparing readings to electric tapes and steel tapes (generally when the water level was shallow; less than 100 ft bls or within the casing), electrical geophysical logs, and pressure transducers. Most readings in private wells were made using acoustical meters. If obstructions were present in the well, the acoustic meter may have read the water level too shallow. In general, the acoustical readings were within 0.5 ft of the electrical or steel water-level measurements with the largest error being 0.4 ft; thus, the acoustical readings were rounded to the nearest foot for entry into the USGS National Water Information System (NWIS) database and inclusion in this report.

Both traditional pressure transducers and acoustical methods were used to record continuous water levels at six wells in the study area. Recording intervals ranged from 1-minute intervals in the three private wells to 15-minute intervals in the three observation wells. Acoustical monitoring equipment was used on all three private wells.

Three observation wells were equipped with pressure transducer water-level monitors during this study. Pressure transducers measure water pressure in pounds per square inch (psi) above an internal silicon strain gage sensor, which is converted to depth to the water level below land surface. The pressure transducers used in this study were equipped with internal dataloggers that were used to record continuous water levels. The pressure transducers used in this study had an operating range of 0 to 100 psi for wells WK-368 and WK-375 and 0 to 30 psi for well WK-411. One psi is equal to 2.31 ft of water, so a 100-psi transducer has an operating range of 231 ft, and a 30-psi transducer has an operating range of about 69 ft. All data were recorded at 15-minute intervals in each of the three observation wells. Cable lengths ranged from about 50 to more than 200 ft. Data were downloaded from the pressure transducers by using the manufacturer's software and then quality assured against periodic independent electrical, steel-tape, or acoustical water-level measurements. Few problems were observed with the pressure transducers. The batteries are internal and seldom need replacing, and the clocks are reset each time the device is connected to a computer.

Continuous groundwater levels reported for two of the three community wells (Bill Gordon, Aqua America Inc., written commun., 2009) also were recorded by using pressure transducers having internal dataloggers. Community well water levels were recorded at 5-minute intervals. Data were available for wells WK-415 and WK-416.

Acoustical water-level monitors also were used to record water levels at 1-minute intervals in the three private wells and at 15-minute intervals (alongside a pressure transducer/data-logger setup) in one observation well. The acoustical probe was placed in the vent access (about 0.5 inch in diameter) after removing the vent screw. (A similar setup was used for the observation well by using a plastic shield across the top of the well at the opening.) The datalogger was connected to the probe and placed on a surface above the ground. Standard 12-volt, 12 ampere per hour batteries were used to power the acoustical monitors, which would typically retain power for as much as 2 weeks for the 1-minute recording intervals and up to 1 month for the 15-minute recording interval. A terminal emulator program was used to communicate with and download the data from the acoustical monitors.

Problems noted with the acoustical monitors included drifting of the internal clocks, which were somewhat difficult to reset. In addition, the lock on the water-level reading (for recording) was sometimes difficult to establish. Abnormalities in the well's construction could have been a factor in the locking problem. The manufacturer was asked to modify the probe as part of this study, resulting in improved durability in the field.

As part of the quality assurance for the continuous acoustical water levels, a traditional pressure transducer (100 psi rating) was placed alongside the acoustical monitor in well WK-368 for the entire recording period. The acoustical water levels were within 0.1 to 0.4 ft of the pressure transducer readings. Thus, as with the acoustical water-level measurements, the continuous acoustical readings were rounded to the nearest foot for entry into the USGS NWIS database and inclusion in this report.

Two digitally recording ultrasonic flowmeters were installed on two private wells for a few weeks to measure groundwater withdrawals. These data were recorded at 1-minute intervals to be consistent with the continuous water levels being recorded in the same well. Total flow per the 1-minute interval was recorded in units of gallons per minute. These ultrasonic flowmeters determined the rate of flow through the polyvinyl chloride (PVC) discharge pipe and were attached to the outside wall of the pipe. Initial setup of the flowmeter involved specifying the type of pipe material, diameter of the pipe, and setting up the 4-20 milliamp output range for the device to send data to the data logger. A standard universal serial bus (USB) connection was used for data logger connection. Setup of the data logger was done using a laptop computer with the associated manufacturer's software.

An example of a problem with the flowmeter equipment included the wiring from the flowmeter to the connections on the data logger USB receptacle being too heavily gaged and thus the connection was easily broken. This was corrected by replacing the receptacle with a lighter gaged wire. Also, some recurring corrosion was evident inside the USB connections, which affected logging capabilities. The flowmeters were powered by a deep-cycle marine battery, which lasted from 10 to 15 days before needing to be replaced. Two standard 55-ampere per hour batteries also could be used in parallel and normally would last about the same amount of time.

The flowmeters initially were mounted inside the well houses on a 1-ft straight section of pipe. This proved to be a poor location, however, as the flowmeter would give a poor signal, likely as a result of turbulence from a sharp bend in the pipe both before and after the section where the flowmeters were installed. The well houses also had limited space for storing the large batteries. For these reasons, the flowmeters were relocated from both wells to crawlspaces under the homes where a 15-ft straight section of pipe ran from the well into the holding tanks.

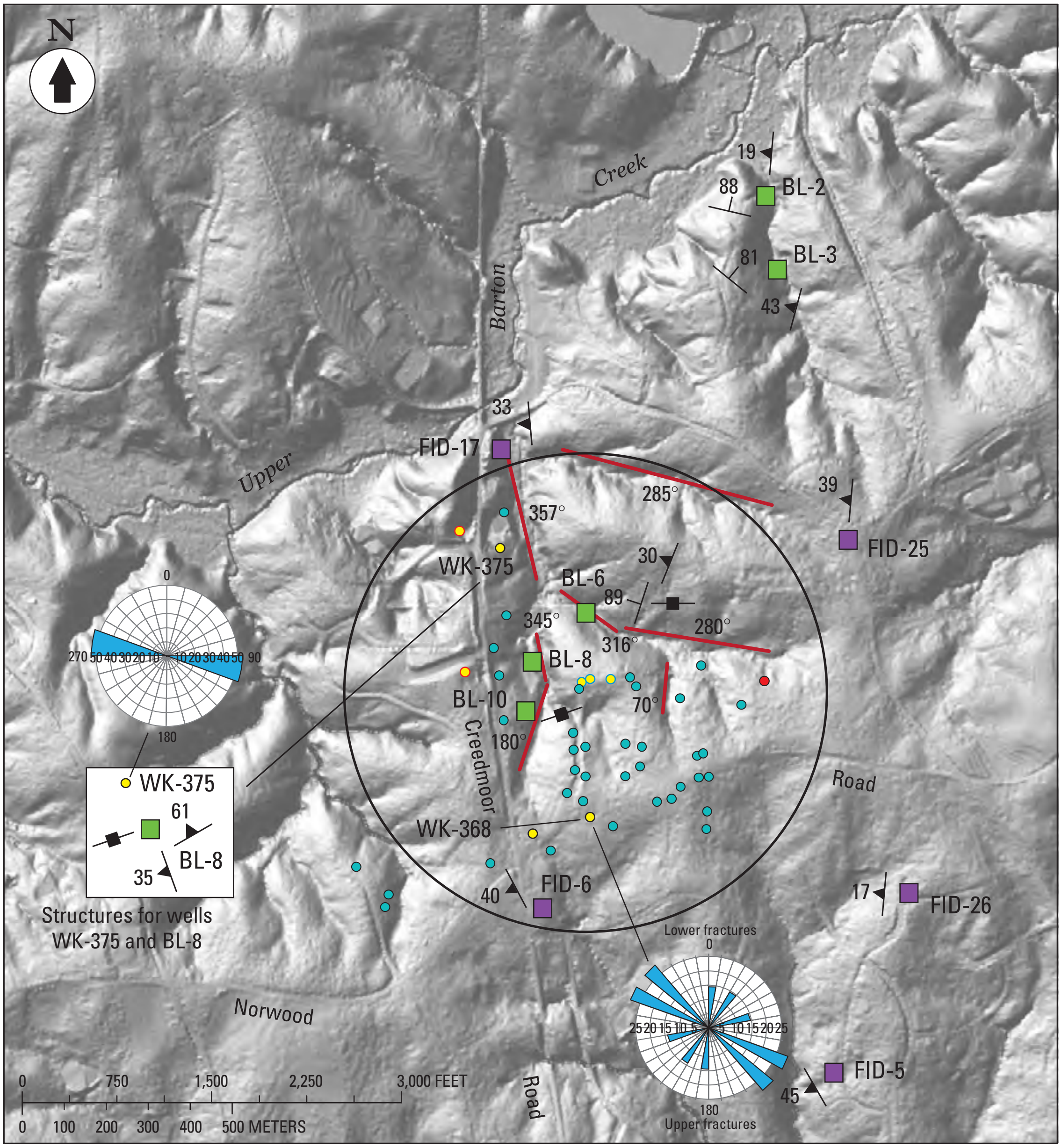
Water-level and flowmeter data were downloaded from each continuously recording well each week during the study period. The acoustical monitors could store about 10 days at 1-minute intervals before the memory was filled. At the time of the data download, a manual measurement was recorded for quality assurance. These data also were entered into the USGS NWIS database. Manual water-level measurements were made using acoustical instrumentation in most wells having deep water levels (greater than 100 ft bls). Electrical or steel tapes were used when water levels were shallow (less than 100 ft bls).

The calculation of the cross-correlation function of continuous groundwater-level datasets was conducted using 15-minute samples in paired comparisons to determine relations between two of the same types of datasets. Cross correlation is a standard method of estimating the degree to which two data series are correlated. A value of cross correlation at delay time was calculated (Bourke,1996). The cross-correlation analytical method can be used to test the magnitude of correlation as well as the time lag between two time series of the same length and time interval (preferably with no missing values). The time lag with the highest correlation coefficient gives information on the difference in time with which groundwater levels in two hydraulically connected wells respond to the same stress. Groundwater-level data were correlated using the nearest 15-minute time-stamped data. Free software used for the analyses can be accessed online at *http://www.wessa.net/* (Wessa, 2009).

Hydrogeologic Setting

The study area is located within the Bayleaf 1:24,000 topographic quadrangle in northern Wake County, North Carolina (figs. 1, 2). The local geologic unit underlying the study area is the Falls Lake schist, described as a medium- to coarse-grained, biotite-white mica-oligoclase-quartz schist having garnet, staurolite, kyanite, and chlorite porphyroblasts with pods of talc schist (Michael Medina, North Carolina Geological Survey, written commun., 2007).

Foliation data recorded as part of the regional mapping by the USGS and the North Carolina Geological Survey (Michael Medina, North Carolina Geological Survey, written commun., 2007) from stations within and near the study area indicate that the Falls Lake schist strikes near north-south (N. 5° E. to N. 5° W.), dipping 17 to 39 degrees (°) to the east or west (respectively), north and east of the study area (sites FID-17, -25, and -26; fig. 3), and N. 28–30° W., dipping 40–45° southwest of the study area (sites FID-5 and -6; table 2; fig. 3; Michael Medina, North Carolina Geological Survey, written commun. 2007). Minor rock types described in this area include amphibolite pods (secondary igneous intrusions). Differential weathering where the schist country rock is intruded by amphibolite pods may serve as zones of higher well yields as a result of differential weathering along the



Base from North Carolina Center for Geographic Information and Analysis
Light Detection and Ranging Imagery

Figure 3. Fracture orientation intrepretations from geologic mapping, fracture traces, and borehole geophysical image logs.

EXPLANATION

- Fracture trace lineament interpretation from lidar image
- Community well
- Private well
- Continuous record observation well
- Continuous record community well
- Continuous record private well

Field geologic measurements

FID-5 Field identification number (Michael Medina, North Carolina Geological Survey, written commun., 2007)

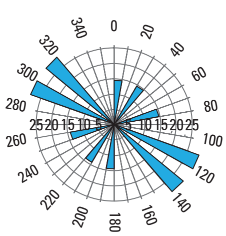
BL-10 Field station number from reconnaissance work done for this study (Phil Bradley, North Carolina Geological Survey, written commun., 2007) and associated structural measurements

40 Strike orientation and dip angle of foliation

89 Strike orientation and dip angle of joint set

Borehole geophysical measurements

Note: WK-375, acoustic televiewer image
WK-368, optical televiewer image



Rose diagram displaying strike azimuth of measured borehole fractures. Length of petal corresponds to percentage of measurements.

lithologic contact (Chapman and others, 1998; Williams and others, 2005). Similarly, differential weathering along foliation and fracturing associated with joints provide pathways for groundwater flow and higher well yields.

Additional geologic structural data were recorded as part of this study (table 2; fig. 3). These data indicate similar foliation strike for three different rock types: amphibolite striking N. 5° E. to N. 20° W., the quartzofeldspathic gneiss striking N. 15° E., and the mica schist striking N. 22° E. (Phil Bradley, North Carolina Geological Survey, written commun., 2008; table 2; fig. 3. The quartzofeldspathic gneiss and mica schist likely represent the regional Falls Lake schist.) All three rock types had moderate dip angles for foliation, ranging from about 19 to 43°. In contrast, the joint sets were steeply dipping, generally dipping at angles of 80° to vertical. The mica schist and amphibolite rock types commonly had two joint set groups: (1) E-W (N. 73° W. to N. 71° E.) and (2) N. 50–60° E. Additional joint sets included N. 51° W. in the quartzofeldspathic gneiss and N. 18° E. in the mica schist; the latter of which parallels foliation strike.

Strike orientations of seven topographic fracture traces were interpreted from the recently collected light detection and ranging (lidar topographic data (fig. 3) in the study area (North Carolina Center for Geographic Information and Analysis, written commun., 2009). These drainage features may follow areas of enhanced weathering or fracturing along structural features in the subsurface bedrock and generally correlate with many of the local structural geologic features listed in table 2. The fracture traces have a dominant 280–285° (N. 75–80° W.) orientation (three lineaments), as well as the following additional orientations: 7° (N. 7° E.), 15° (N. 15° E.), 316° (N. 42° W.), 345° (N. 15° W.), and 357° (N. 3° W.; fig. 3). The fracture traces striking N. 15° W. to N. 15° E. correspond in general to the strike direction of foliation in all three rock types (table 2). The N. 75–80° W. fracture trace parallels one of the joint sets mapped in the amphibolite and mica schist rock types, and the N. 42° W. fracture trace generally parallels the joint set mapped in the quartzofeldspathic rock type (table 2).

The groundwater system in the study area consists of two components, which is typical of most aquifers in the Piedmont region of North Carolina (fig. 4). The shallow part of the groundwater system is referred to as the “regolith” (fig. 4*A*) and may be composed of soil, residuum, alluvium, colluvium, and saprolite (Chapman and others, 2005). The deeper part of the groundwater system consists of the “fractured bedrock” (fig. 4). Anisotropy can occur in both parts of the groundwater system associated with relict structures in saprolite in the regolith or as fracture networks in the bedrock. Primary storage for the groundwater system is in the shallow regolith, with the deeper bedrock fracture storage orders of magnitude lower (fig. 4). Water stored in the overlying regolith provides recharge to the deeper fractures in the bedrock. Because of the reduced storage of groundwater in the bedrock, large drawdowns in the aquifer can be observed if depletion (dewatering) of water in the bedrock fractures occurs during withdrawals.

Table 2. Geologic structure measurements recorded near the study area in northern Wake County, North Carolina.

Station number	Structural feature	Rock type	Strike (360 degree reference)	Quadrant strike direction	Dip angle (degrees)	Dip direction	Spacing
Regional measurements from Horton and others, 2004							
FID 26	foliation	Falls Lake schist	185	N. 5° E.	17	NW	
FID 25	foliation	Falls Lake schist	185	N. 5° E.	39	NW	
FID 17	foliation	Falls Lake schist	175	N. 5° W.	33	SW	
FID 6	foliation	Falls Lake schist	152	N. 28° W.	40	SW	
FID 5	foliation	Falls Lake schist	150	N. 30° W.	45	SW	
Measurements recorded as part of this study							
BL-2	foliation	Amphibolite	185[a]	N. 5° E.	19	NW	
BL-2	joint	Amphibolite	283[a]	N. 73° W.	88	NE	8–12 inch spacing
BL-3	foliation	Quartzofeldspathic gneiss	195[a]	N. 15° E.	43	NW	
BL-3	joint	Quartzofeldspathic gneiss	309[a]	N. 51° W.	81	NE	12–18 inch spacing
BL-6	foliation	Mica schist	202[a]	N. 22° E.	30	NW	
BL-6	joint	Mica schist	270[a]	E-W	90	N	
BL-6	joint	Mica schist	198	N. 18° E.	89	NW	
BL-6	joint	Mica schist	60	N. 60° E.	90	SE	
BL-8	foliation	Amphibolite	160	N. 20° W.	35	NW	
BL-8	joint	Amphibolite	71	N. 71° E.	90	SE	
BL-8	joint	Amphibolite	240	N. 60° E.	61	NW	2–18 inch spacing
BL-10	joint	Amphibolite	50[a]	N. 50° E.	90	SE	

[a] Averaged value.

Borehole geophysical logs run in well WK-368 (figs. 2, 5) included caliper, electrical resistivity, fluid resistivity and temperature, and optical televiewer imaging. This well had a reported yield of 12 gal/min (table 1), and interpretations from borehole geophysical logging indicated that small fractures were present at depths of 80–89 ft, 128 ft, and 398–400 ft bls (fig. 5; table 3). The shallow fractures at 80–89 ft and 128 ft are present within a feldspathic unit that has a schist texture, likely correlating with the mica schist listed in table 2 and shown in figure 2 (regionally, Falls Lake schist). The 128-ft fracture is at a contact with a minor (thin, 0.5 ft) feldspathic vein or pegmatite. Manganese-oxide or "black" staining is present along the borehole wall near the steeper-dipping fractures in the 80- to 89-ft zone. This staining could be the result of the natural flow of oxygenated groundwater when the fracture zone was saturated or downward flow of recharge occurring when the fractures were dewatered; water levels were below this zone throughout the study period. The deeper fracture zone is within a more mafic lithology, perhaps amphibolite or amphibolite gneiss, or simply a mineralogic variation of the mica schist. More mafic regions generally have relatively lower natural gamma readings (fig. 5). Variations of the schist to more gneissic (banded) rock types, potentially the quartzofeldspathic gneiss mapped in the area, also were observed in well WK-368. Although quantitative flow was not measured in this well, from the fluid specific conductance log (fig. 5), groundwater is flowing into the well at depth near the 398–400 ft fracture zone and again at 456 ft (no obvious fractures). It is likely that water is flowing down the borehole from the 80- to 89-ft and 128-ft fractures and up from the deeper 398–400+ fractures and then flowing out of the well somewhere in between those depths.

The dominant fracture orientations measured in the shallow (81–87 ft) fracture zones in well WK-368 had an average strike of N. 67° W. (variable dip angle) and N. 63° W. (steep dip angle), with an additional fracture striking N. 45° W. (figs. 3, 5; table 3). Fracture orientations in the deep (398–400 ft) zone had a more variable strike and low dip angles (fig. 5; table 3), with one orientation of N. 42° W. similar to a fracture in the shallow 80- to 87-ft zone. The strike of fractures in the shallow and deep zones generally correlate with joint sets that were mapped in the amphibolite (N. 73° W. and N. 71° E.; table 2) and the fracture traces having a N. 75–80° W. strike orientation (fig. 3). An additional fracture orientation measured in well WK-368 had a strike of N. 42–45° W. (318–315° azimuth; figs. 3, 5; table 3) for both the upper and lower fracture zones, which correlates with the N. 42° W. fracture traces traced near station BL-6 (fig. 3; table 2), and a joint set measured striking N. 40–45° W. in the quartzofeldspathic rock type at station BL-3 (fig. 3; table 2), as well as the fracture orientation measured at a depth of 82.6 ft in well WK-368 (table 3; fig. 5). A third orientation of N-S to N. 10° E. (0–10° azimuth; fig. 5) measured for both the upper and lower fractures in well WK-368 parallels foliation measurements from the regional and local mapping (table 2). The N. 30–40° E. orientation measured in the lower fractures

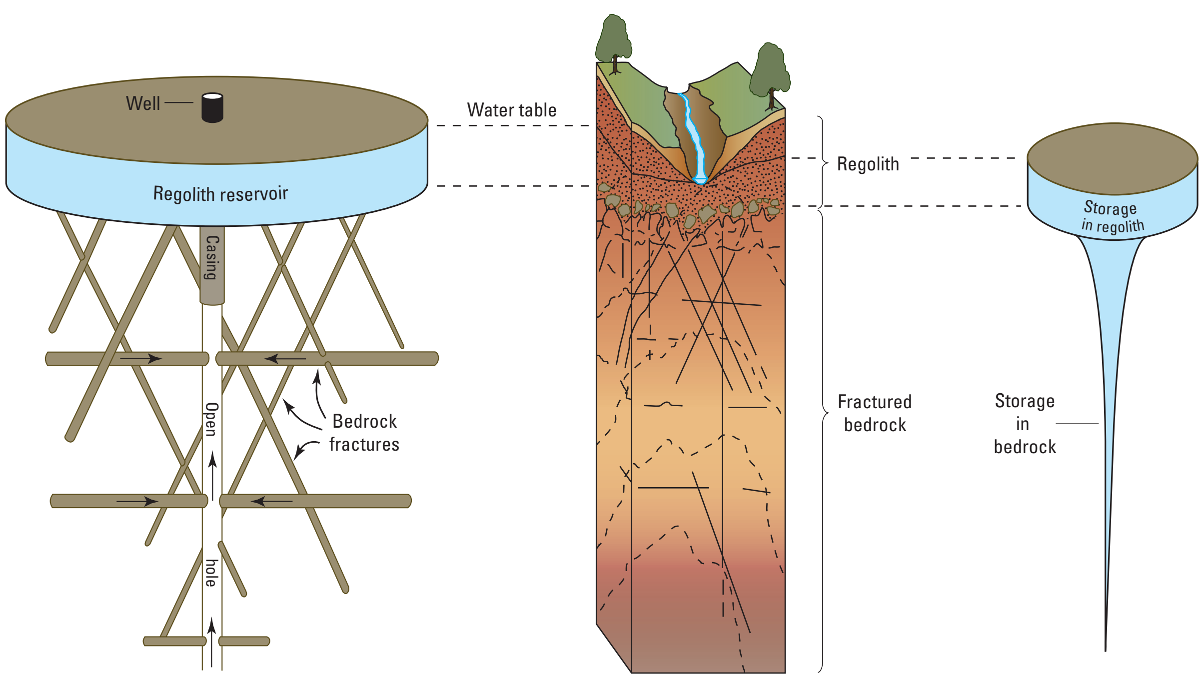


Figure 4. Two-component groundwater system in the Piedmont region showing the storage comparison between the shallow regolith and deeper bedrock components (modified from Heath, 1984).

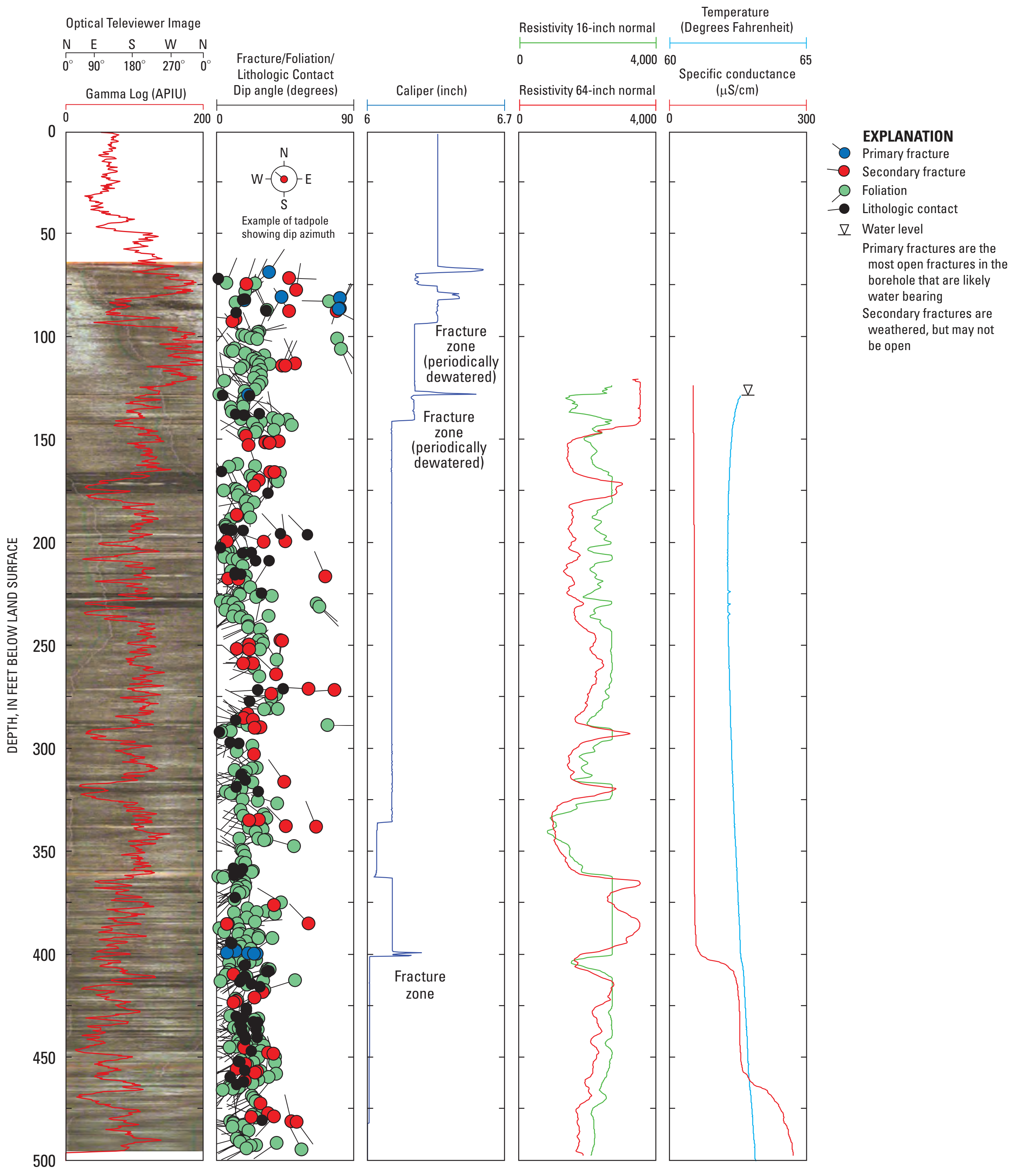


Figure 5. Geophysical logs and orientation of borehole structural measurements in well WK-368. [APIU, American Petroleum Institute units; µS/cm, microsiemens per centimeter]

Table 3. Well fracture characteristics.

[Note: Average orientations are calculated from the group above]

Well number	Fracture depth (feet below land surface)	Dip azimuth (degrees)	Dip angle (degrees)	Strike azimuth (degrees)	Strike	Dip direction
WK-368[a]	80.8	209	43	119	N. 61° W.	SW
	81.4	197	81	107	N. 73° W.	SW
	average	*203*	*62*	*113*	*N. 67° W.*	*SW*
	82.6	45	18	315	N. 45° W.	NE
	86.4	24	80	294	N. 66° W.	NE
	86.6	29	80	299	N. 61° W.	NE
	average	*27*	*80*	*297*	*N. 63° W.*	*NE*
	398.4	277	13	187	N. 7° E.	NW
	399.2	306	7	216	N. 54° E.	NW
	399.6	48	21	318	N. 42° W.	NE
	399.8	348	26	258	N. 78° E.	NW
	399.9	341	25	251	N. 71° E.	NW
	average	*345*	*26*	*255*	*N. 75° E.*	*NW*
WK-375[b]	282.6	186	31	96	N. 84° W.	S-SW
	284.2	180	20	90	E-W	S
	286.7	186	8	96	N. 84° W.	S-SW
	average	*184*	*19*	*94*	*N. 86° W.*	*S-SW*
	285.2	12	20	282	N. 78° W.	NE

[a] Measured using an optical televiewer tool.

[b] Measured using an acoustical televiewer tool.

does not appear to directly correlate with measured geologic structural measurements or fracture traces.

Borehole geophysical logs run in well WK-375 (figs. 2, 6) included caliper, electrical resistance and resistivity, fluid resistivity and temperature, and acoustical televiewer imaging. Logs run in well WK-375, which is located about 300 ft east-southeast of community well WK-416 (fig. 2) and has a reported yield of 40 gal/min, indicated the presence of a large, open fracture at a depth of about 282.5 to 284.5 ft (table 3; fig. 6). Shallow fractures also were noted at depths of about 40, 45–47, and 92 ft from the caliper log. These shallow fractures were dewatered at the time of logging (July 29–30, 2008) when the water level in the well was about 130 ft bls and, therefore, could not be measured by the acoustic televiewer tool. Strike orientations of the open, deeper fractures at the 282–285 ft zone were dominantly east-west (N. 86° W. and N. 78° W., azimuth 94° and 282°, respectively (fig. 3; table 3), which is similar to the near E-W orientations (N. 75° E.; table 3; fig. 3) measured in well WK-368. The orientation of these fractures also corresponds to the joint sets that were mapped in the amphibolite (N. 73° W. and N. 71° E.; table 2) and the fracture traces having a N. 75–80° W. strike orientation (fig. 3).

Specific conductance was elevated in the deep fracture zone of WK-375 about 282.5 to 284.5 ft bls (fig. 6), indicating inflow to the well at that depth. The temperature log has no typical (natural) geothermal gradient that can be recognized and indicates downward flow (remains the same rather than increasing with the geothermal gradient) to a depth of about 200 ft, where the natural geothermal gradient slope is recognizable. A temperature increase at the deepest fracture also indicates inflow within the borehole at that depth. All three fractures (two shallow and one deep) correspond to low gamma readings, suggesting a more mafic rock type, such as the amphibolites pods that are mapped at land surface near the study area (Michael Medina, North Carolina Geological Survey, written commun., 2007).

Groundwater Withdrawals

Groundwater withdrawals in the study area are from both community-supply and individual private wells. Three known CWS wells and about 35 individual private wells use groundwater (fig. 2; table 1) in the study area.

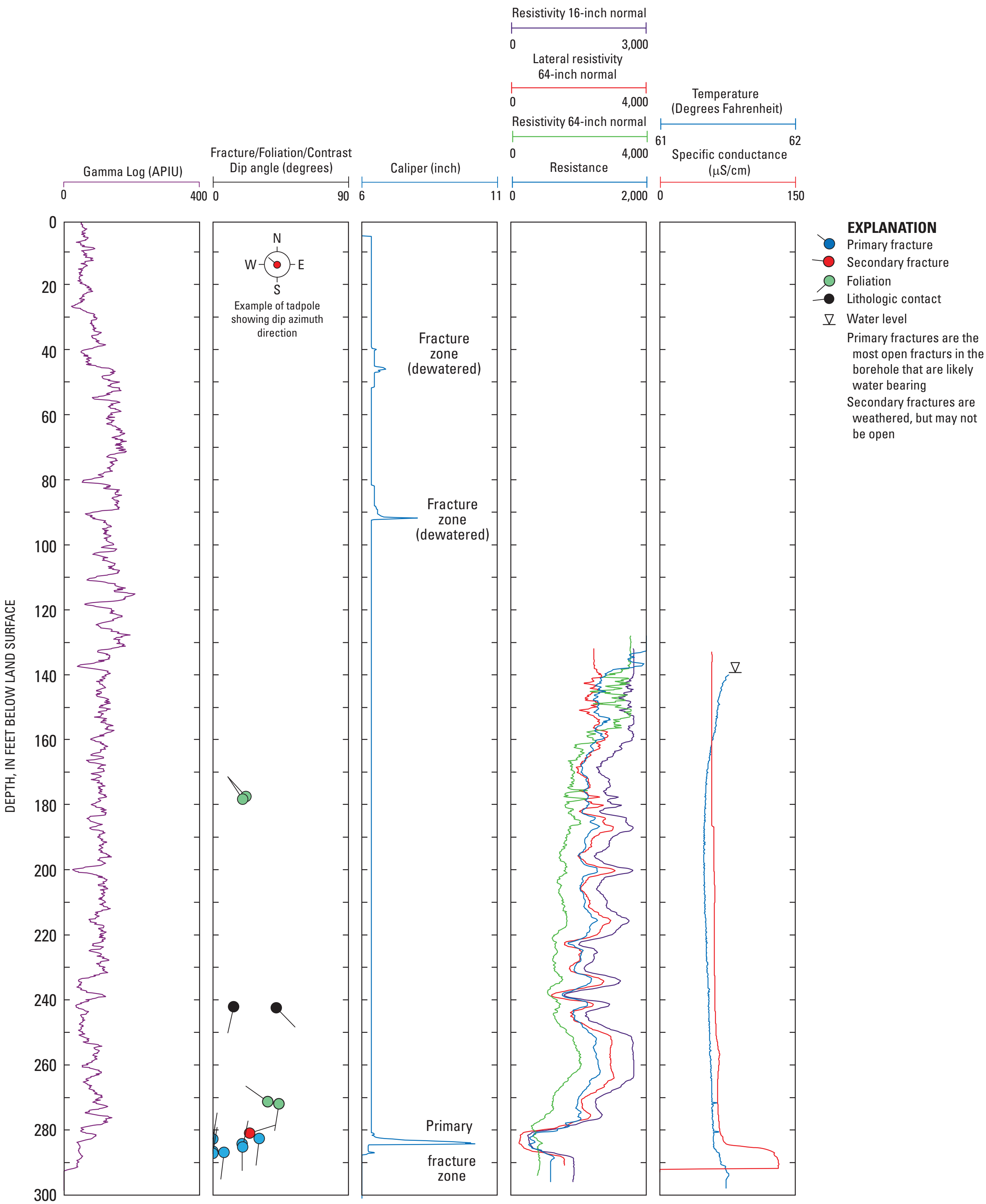


Figure 6. Geophysical logs and orientation of borehole structural measurements in well WK-375. [APIU, American Petroleum Institute units; µS/cm, microsiemens per centimeter]

Community Wells

As part of the assessment of the effects of large groundwater withdrawals on the aquifer system in the study area, monthly withdrawal reports were compiled for the three community wells by the NCDENR PWSS (Debbie Lyles, written commun., 2008) for January through November 2008 (fig. 7). During this period, pumping volumes for each of the three community wells ranged from about 2,000 to 54,000 gal/d, with a fivefold increase in withdrawals from well WK-416 (fig. 2; table 1) during June 2008 (fig. 7). The combined annual withdrawal of the three CWS wells was reported to have increased yearly during 2001–2007 (Keyworth, 2009). This increase shows the large range of pumping volumes from these types of supply wells and the potentially associated dynamic effects on water levels in the aquifer in the study area.

For some areas that the community wells serve, it is reported that the average household uses more than 100 gal/person/d (Michael Melton, Aqua America, Inc., oral commun., 2009), which is similar to what was reported by CDM (2003) and likely reflects increased irrigation use from in-ground sprinkler systems that are common in the recently developed subdivisions near the study area. It should be noted that two of the three CWS wells are part of a larger system that serve other areas outside of the study area. The USGS 2005 water-use report for North Carolina estimates the per capita use rate at 77 gal/person/d for Wake County for public supply (community) wells (U.S. Geological Survey, 2008).

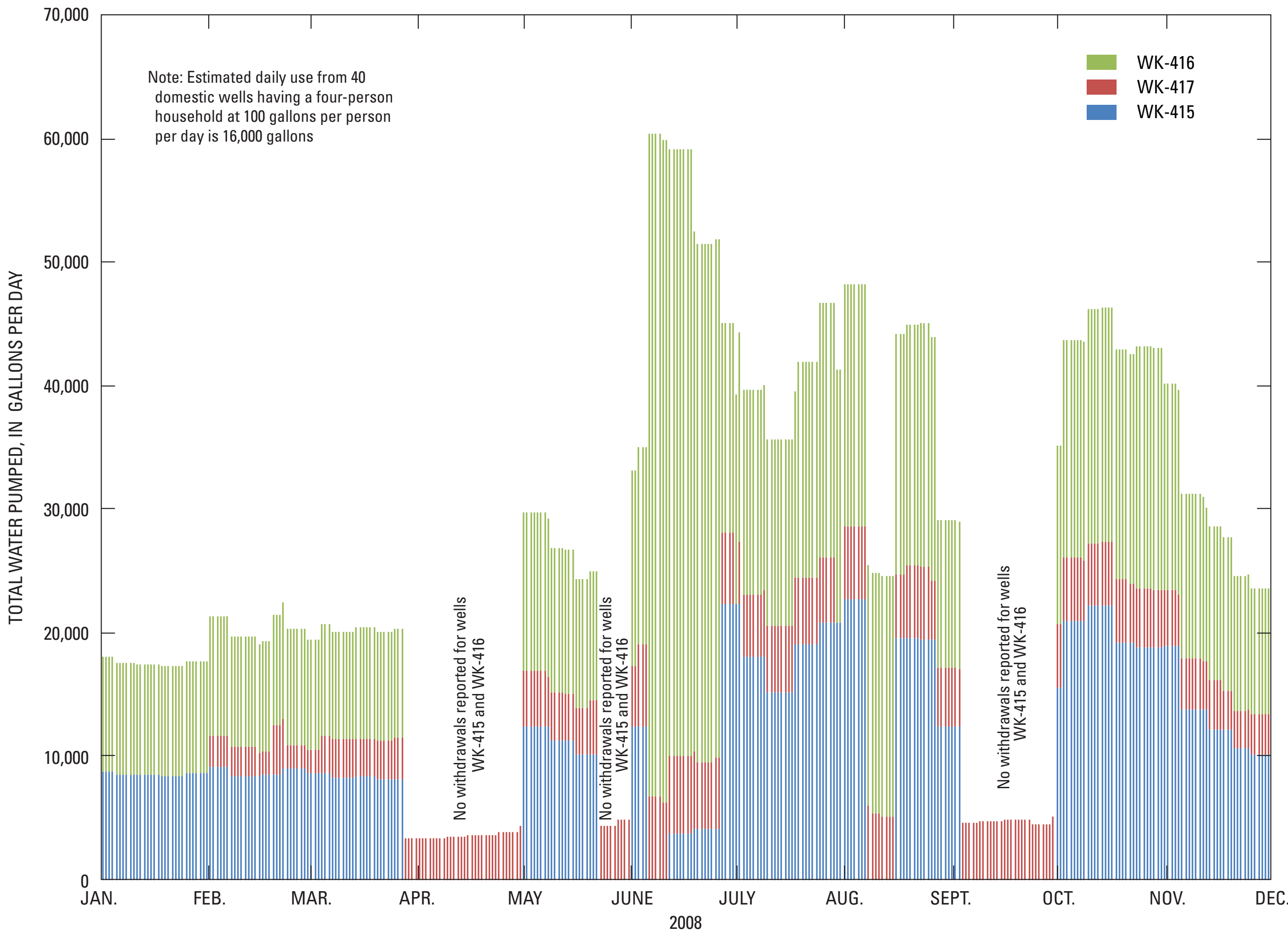


Figure 7. Reported daily withdrawals for the three individual community wells in the study area, January through November 2008. See figure 2 for locations.

Private Wells

Flowmeters were installed on two private observation wells, WK-401 and WK-402 (fig. 2), to better quantify local groundwater use (fig. 8). Both households had one or two full-time residents, with well WK-401 also being used for some hand-held garden hose irrigation. Water use from well WK-401 was monitored for a period of 4 days from August 29 through September 1, 2008 (fig. 8*A*). Water use from well WK-402 was monitored for 14 days, from September 5 through September 18, 2008 (fig. 8*B*). Most homeowners have storage tanks that hold about 30 to 50 gallons of water. These storage tanks generally fill quickly, and the two pumps monitered as part of this study typically ran from 1 to more than 50 minutes per cycle. For the water-use category grouping (fig. 8), it was assumed that household uses had lower flow rates of less than 1–2 gal/min, whereas the garden hose irrigation use had a much higher flow rate of more than 11 gal/min. The range in water use for household purposes recorded in well WK-401 was from about 105 to 152 gal/d

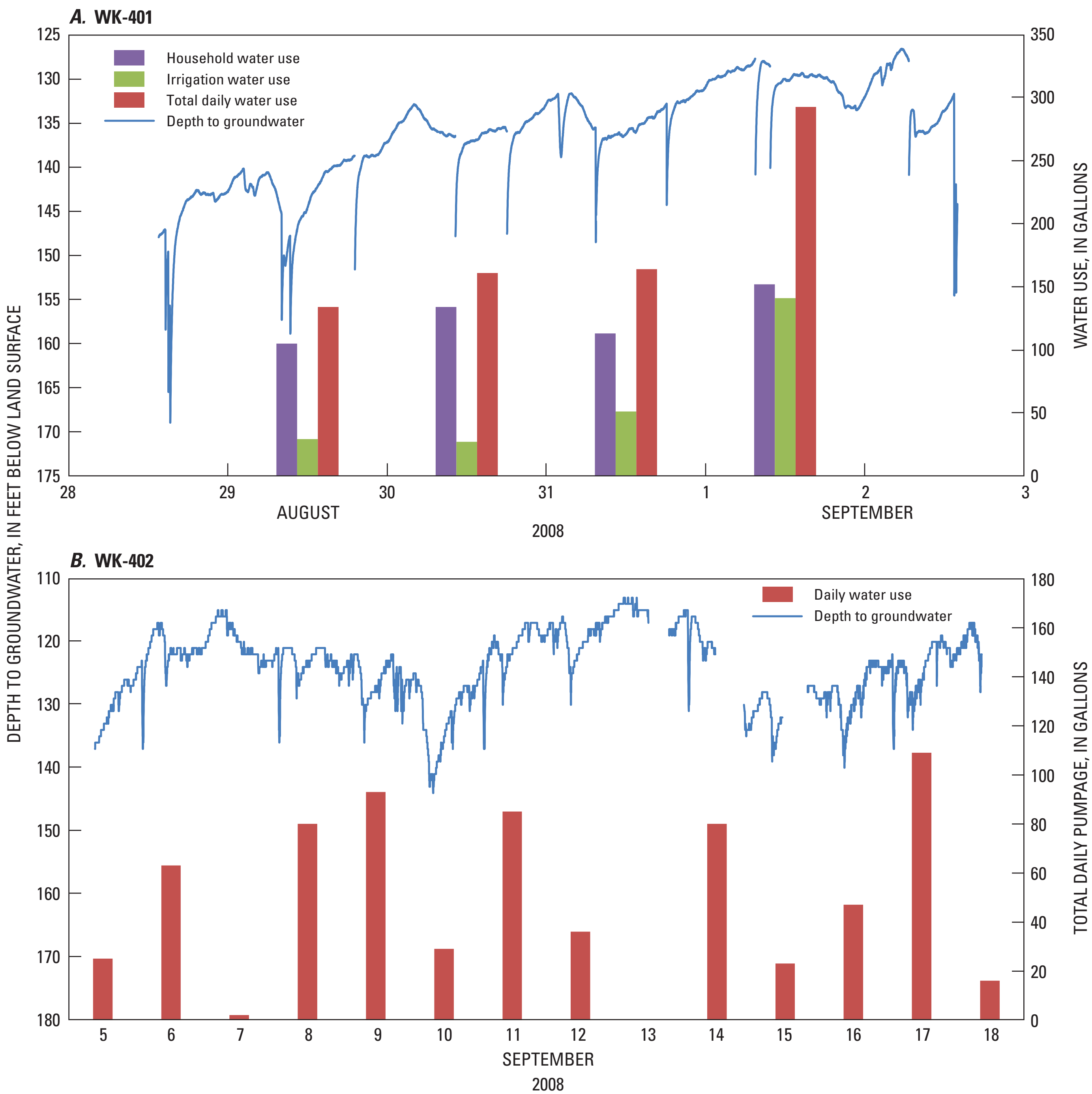


Figure 8. Groundwater levels in relation to withdrawals recorded in private observation wells (*A*) WK-401 and (*B*) WK-402.

(lower flow-rate events). The range of use for garden hose irrigation purposes (higher flow-rate events) recorded in well WK-402 was from about 29 to 141 gal/d. Total use recorded for well WK-401, a two-person household, ranged from about 134 to 293 gal/d, averaging 188 gal/d during the 4-day monitoring period, or 94 gal/person/d, comparable to the 100 gal/person/d reported by CDM (2003) and by the CWS water provider. This amount is higher than the estimated historical 55 gal/person/d usage generally assumed for domestic supply in water-use studies by Keyworth (2009) and more recently the estimate of 70 gal/person/d made by the U.S. Geological Survey (2008).

In comparison, the household at well WK-402 primarily had one resident and one part-time resident. Because of prior well problems with the well temporarily going “dry,” the household was conservative in their use of water and they did not irrigate during the flowmeter monitoring period. Water use for well WK-402 ranged from about 2 to 93 gal/d, averaging 49 gal/d for the 14-day monitoring period, which is comparable to the 55 gal/person/d use commonly reported.

Groundwater Levels in Northern Wake County, March 2008–February 2009

Groundwater levels were measured within the 2,000-ft radius study area centered on the Norwood Oaks neighborhood cul-de-sac in the lower Falls Lake watershed in northern Wake County, North Carolina, from March 2008 through February 2009. These measurements included both continuous and periodic water-level readings recorded in observation wells and private wells. Additionally, data were acquired from nearby community wells as available.

Groundwater-Level Fluctuations

Groundwater-level data from continuously and periodically monitored wells are presented in this section. Water levels in six wells were continuously monitored, three of which were observation wells, and three were private wells (table 1). Periodic water levels also were measured on an approximately monthly basis in 35 to 37 private and observation wells. Withdrawals were monitored in two private wells for a period of 5 days to 2 weeks. Total daily withdrawals reports also were compiled by the NCDENR PWSS for the three community wells in the study area for January through November 2008. Available continuous groundwater-level data recorded in community wells for the study period also were compiled from the water provider.

Groundwater-level data were evaluated to determine the magnitude of fluctuation and extent of correlation between pumped (supply wells) and unpumped (observation) wells at both the local scale (private withdrawals) and regional scale (community well withdrawals). The magnitude and timing of water-level fluctuations in the continuously monitored wells were quite varied, depending on whether the well was being used (pumped) or affected by larger-use wells, such as those used for community supply or irrigation purposes. Correlation of continuous water levels was difficult because of the inherent complexities of the fractured-bedrock aquifer and large number of pumped wells in the study area. Both local and regional cycles were evident in the continuous groundwater-level data. Statistical data smoothing methods were used to visualize larger regional patterns, and cross-correlation analyses were used to determine the potential statistical correlation and interference between wells.

Continuous Measurements

Continuous groundwater-level measurements were recorded in six wells in the study area (WK-368, -375, -400, -401, -402, and -411; fig. 2; table 1) to monitor fluctuations associated with both natural effects and stresses, such as withdrawals. Three observation wells were monitored and three adjacent private wells were monitored as part of this study (fig. 2). Additional, continuous groundwater-level records were provided for two community wells (Bill Gordon, Aqua America,Inc., written commun., 2009).

Observation Wells

Groundwater levels in three observation wells were monitored during the summer and early fall of 2008 (table 4). Wells WK-368 and WK-411 were located at the southern end of Norwood Oaks Drive, and well WK-375 was located at the northern end of the study area (fig. 2).

Well WK-368

The first well monitored as part of this study was observation well WK-368, located along Norwood Road (fig. 2), where data collection began in late June 2008 and continued through late October 2008 (table 4). This well is 500 ft deep (table 1; verified with borehole geophysical logging) and has a reported yield of about 12 gal/min (table 1). No open fractures were evident in the borehole optical televiewer images. Two small, weathered fracture zones were noted at depths of 80–89 and 398–400 ft bls (fig. 5).

Daily and seasonal cyclic fluctuations were observed throughout the period of record for well WK-368 (fig. 9). Daily water-level fluctuations ranged from 0 to 10 feet per day (ft/d), with a decline of as much as 10 ft/d and a rise of as much as 7 ft/d (fig. 10). The drawdown cycles generally occur once per day, often beginning in the early to mid-morning hours, and continuing into the next day. Short-term declines for this well were noted on August 2, when the water level declined 6 ft in 14 hrs, and on August 4, when the water level declined 9 ft in 15 hrs (fig. 9). Water-level fluctuations in bedrock well WK-368 ranged from 98 to 130 ft bls from late June through late October 2008 (table 4). An overall

Table 4. Period of record and range of groundwater levels recorded in continuously monitored observation wells, private wells, and community wells.

[WK, Wake County, NC; ft, feet; bls, below land surface; bmp, below measuring point]

Well number	Well category	Period of record	Lowest groundwater level and date	Highest groundwater level and date	Recording interval	Total well depth
WK-368	Observation	06/26/08–10/24/08	130 ft bls, 8/10–11/08	98 ft bls, 9/13/08	15 minutes	500
WK-375	Observation	7/20/08–10/24/08	214 ft bls, 8/6/08	75 ft bls, 9/6 and 9/13/08	15 minutes	305
WK-411	Observation	07/29/08–10/22/08	38.40 ft bls, 8/29/08	33.03 ft bls, 9/14/08 and 9/27/08	15 minutes	306
WK-400	Private	8/22/08–10/24/08	209 ft bls, 10/15/08	126 ft bls, 9/13/08	1 minute	400
WK-401	Private	7/6/08–10/24/08[a]	228 ft bls, 8/8/08	123 ft bls, 9/18/08	1 minute	410
WK-402	Private	8/22/08–10/24/08	187 ft bls, 8/25/08	113 ft bls, 9/13/08	1 minute	290
WK-415	Community	0729/08–12/16/08	261 ft bmp, 8/8/08	68 ft bmp, 12/12–13/08	5 minutes	695
WK-416	Community	12/19/08–01/21/09	229 ft bmp, 01/04/09	139 ft bmp, 1/17/09	5 minutes	805

[a] Data missing 9/6/08 through 9/15/08.

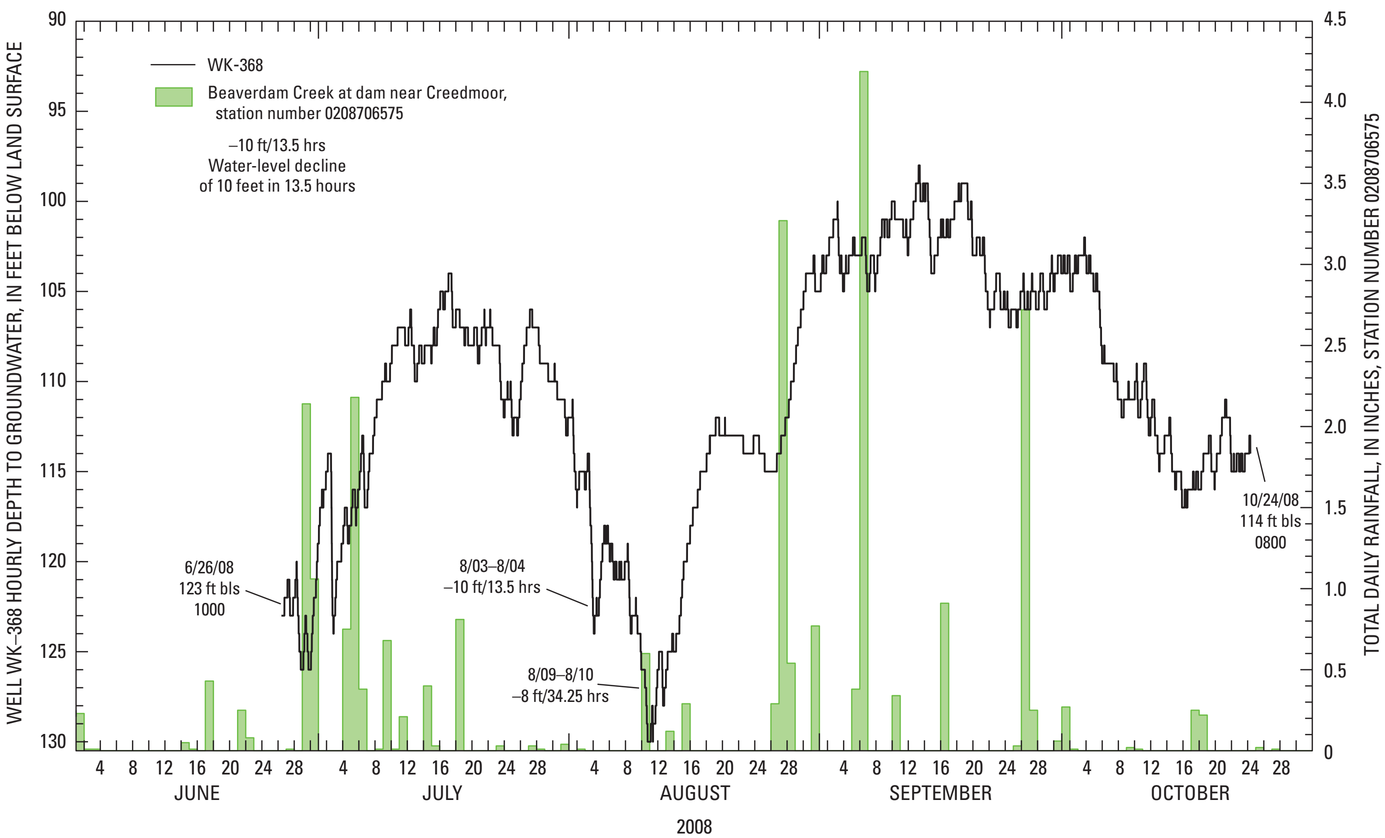


Figure 9. Continuous groundwater levels recorded in observation well WK-368 and nearby rainfall recorded at station 0208706575, June–October 2008. [ft, feet; bls, below land surface; hr, hour]

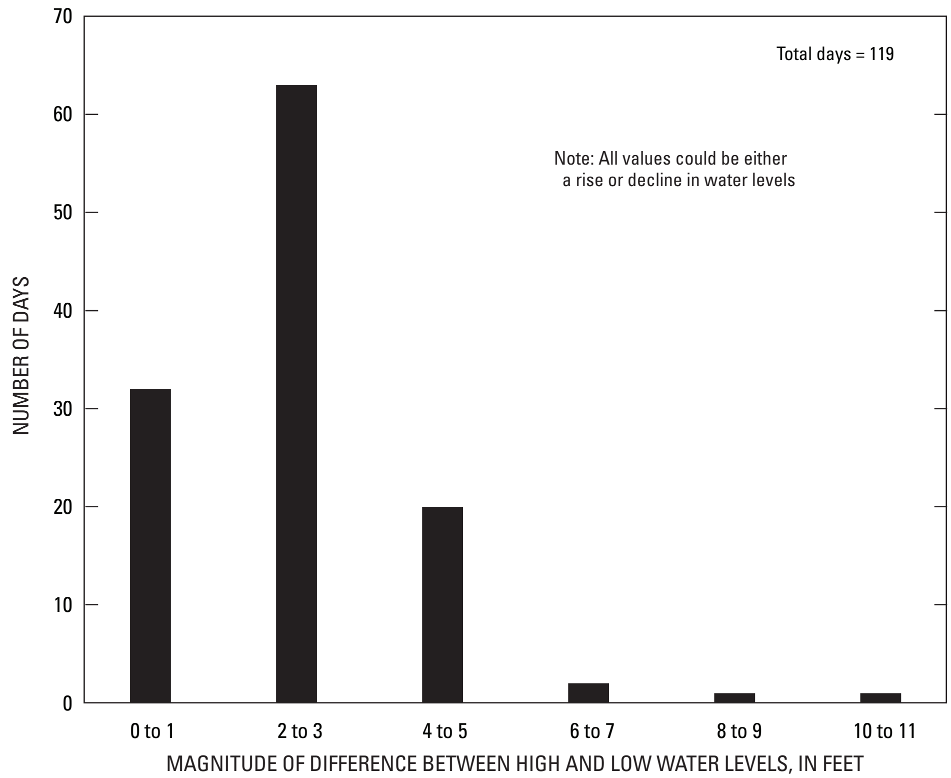


Figure 10. Histogram of daily water-level fluctuations (difference between high and low readings) recorded in observation well WK-368, June 26 through October 24, 2008.

decline occurred in mid-July through mid-August, when the water level decreased by about 26 ft. An overall rise in the high water level (recovery of the groundwater system) was observed in mid-August through mid-September 2008, with an increase of about 32 ft (fig. 9; table 4). This large recovery indicated that the aquifer system had not lost permanent storage and had recovered at least to some degree. This rise likely is a function of both recovery of the aquifer from a reduction in pumping (reduced irrigation use during periods of increased rainfall) and recharge from precipitation through a higher water table in the overlying regolith (figs. 4, 9).

Well WK-375

Of the three observation wells monitored as part of this study, bedrock well WK-375 (fig. 2; table 4) had the largest magnitude of short-term drawdowns; the largest water-level declines were as high as about 75 ft within a few hours (fig. 11). For example, on July 30 the water level declined about 75 ft in 5 hrs, on August 20 the water level declined by 76 ft in 5.75 hrs, and on October 21 the water level declined by 60 ft in 3.25 hrs. These large declines generally began in the early morning hours, possibly related to increased use from people showering before work or school, or irrigation of landscape or lawns. Daily groundwater-level fluctuations for this well during the July through October 2008 study period ranged from a decline of 78 ft per day to a rise of 73 ft (figs. 11; 12). Often during the servicing and downloading of continuous data at this well, water-level measurements indicated a decline during the few minutes that field personnel were at the well. Water levels recorded from July through October 2008 in well WK-375 ranged from 75 to 214 ft bls.

An overall long-term decline of about 108 ft in the high water level occurred from July 21 through August 6 and about 100 ft from September 6 through October 24 at the end of the study period (fig. 11). As was observed in well WK-368 (fig. 2), the minimum water level recorded in well WK-375 rose about 139 ft from late August through mid-September 2008. The timing of this overall rise was similar to that observed in well WK-368, most likely related to reduced pumping for irrigation purposes because of recent rainfall and recharge from precipitation through a higher water table in the overlying regolith (figs. 4, 11). Again, this large recovery indicated that the aquifer system had not lost permanent storage and had at least recovered for a period until the recharge period ended and the stress increased.

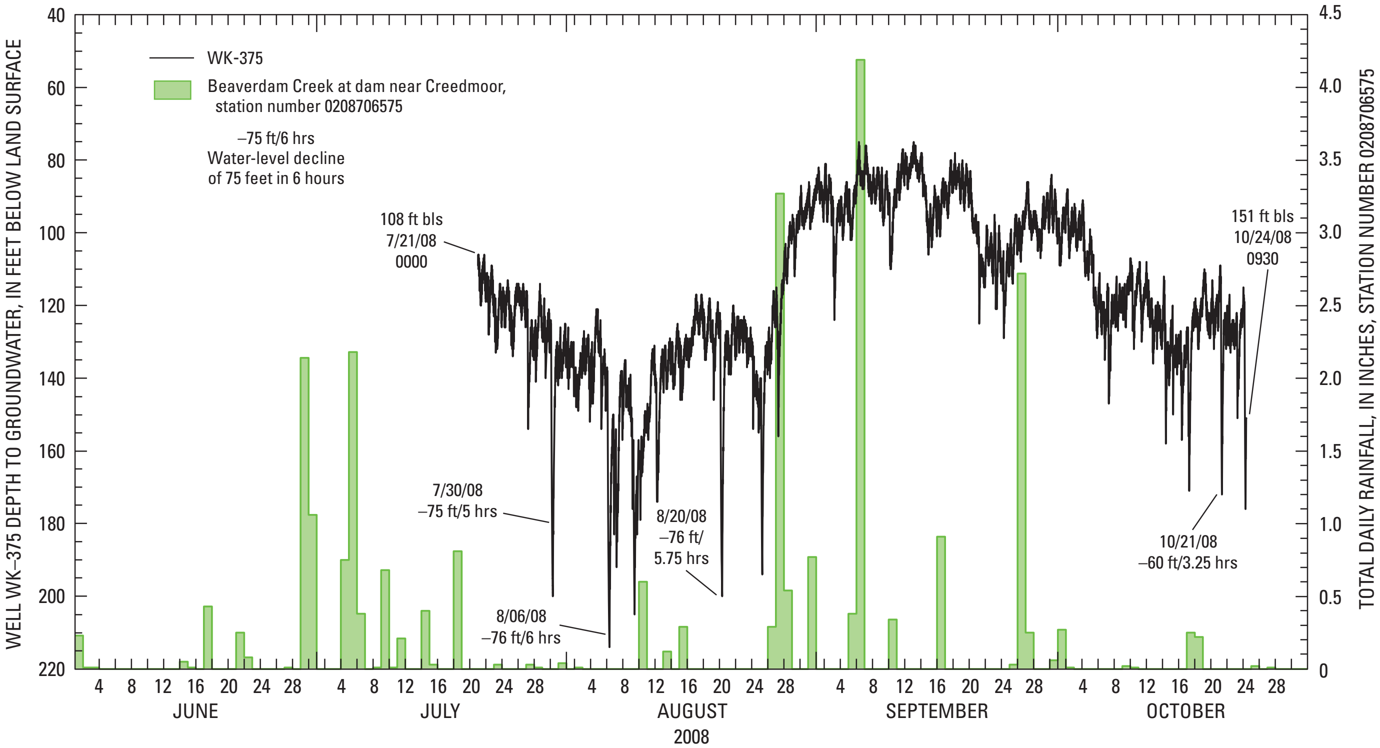


Figure 11. Continuous groundwater levels recorded in observation well WK-375 and nearby rainfall recorded at station 0208706575, June–October 2008. [ft, feet; bls, below land surface; hr, hour]

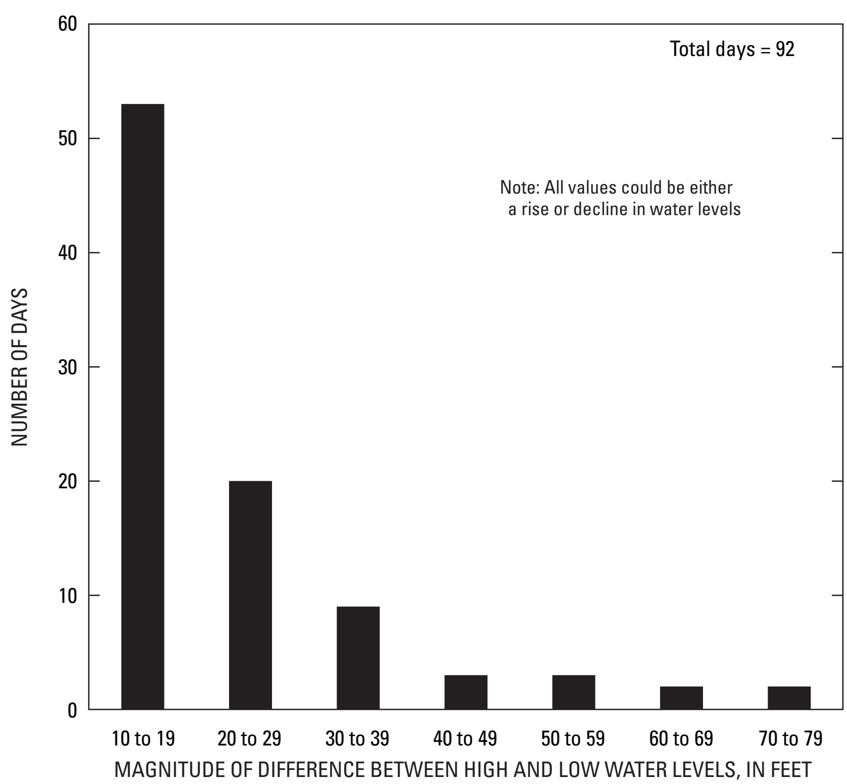


Figure 12. Histogram of daily water-level fluctuations (difference between high and low readings) recorded in observation well WK-375, July 21 through October 24, 2008.

Well WK-411

Both shallow and deep groundwater levels were recorded in the two continuously monitored wells along Norwood Road (fig. 2). While well WK-368 recorded relatively deep groundwater levels generally greater than 100 ft in depth (fig. 9), water levels recorded in well WK-411 had much shallower water levels ranging from 33.03 to 38.40 ft bls from late July through late October 2008 (fig. 13; table 4). These two wells are located about 500 ft apart (west-southwest direction from WK-368 to WK-411; fig. 2) and have different total depths; well WK-368 is about 500 ft deep and well WK-411 is about 300 ft deep (table 1). Daily groundwater-level declines recorded in well WK-411 generally were less than 1 ft (fig. 14). Two larger short-term declines of about 3 ft (fig. 14) were recorded on August 29 and 30 (fig. 13). The water level in this well responded similarly to the overall regional trends, with an overall rise in the water level from mid-August through mid-September 2008 of about 5 ft during a similar time period in which water levels in the other two observation wells, WK-368 and WK-375, also increased (table 4; fig. 13).

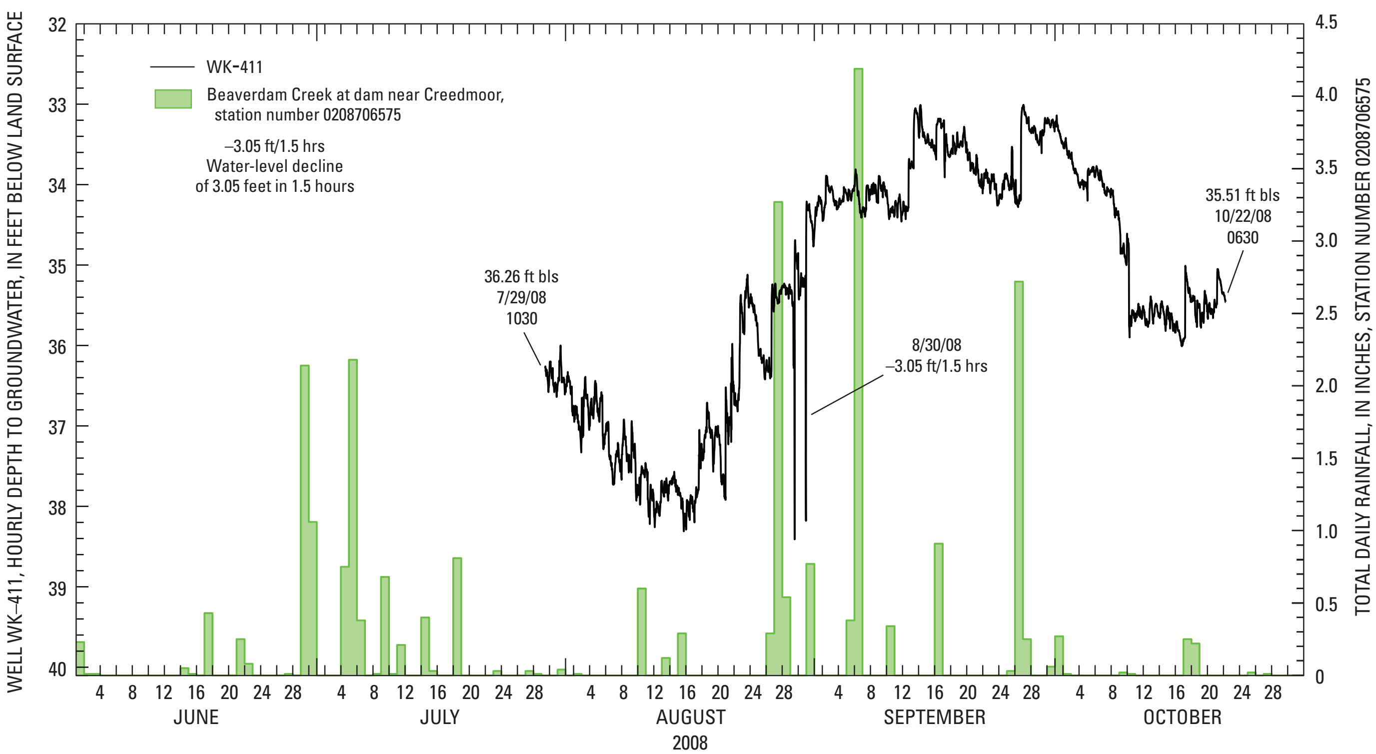


Figure 13. Continuous groundwater levels recorded in observation well WK-411 and nearby rainfall recorded at station 0208706575, June–October 2008. [ft, feet; bls, below land surface; hr, hour]

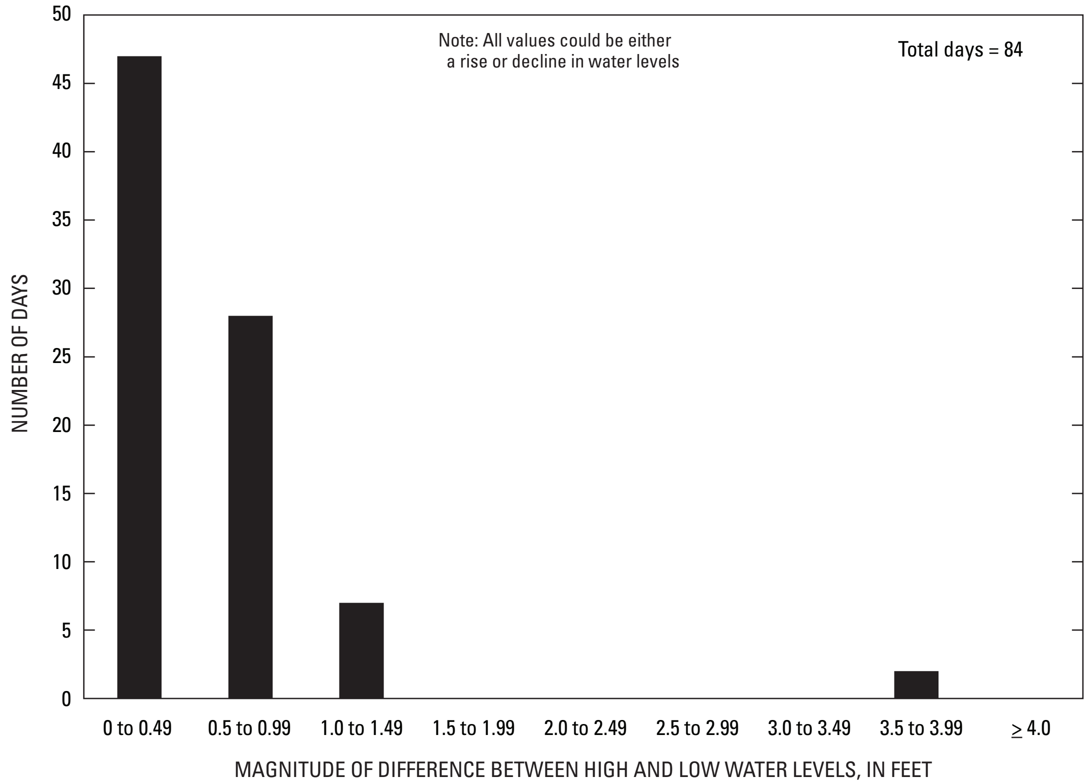


Figure 14. Histogram of daily water-level fluctuations (difference between high and low readings) recorded in observation well WK-411, July 29–October 22, 2008.

Private Wells

Three private wells in the Norwood Oaks subdivision were continuously measured to monitor water-level declines from local withdrawals. All three private wells (WK-400, -401, and -402; table 1; fig. 2) had the same pattern of fluctuation and similar magnitudes of decline and recovery (fig. 15). Two of the wells (WK-400 and -401) are about 400 ft deep, whereas WK-402 is about 290 ft deep (table 1). Water levels in all three wells ranged from about 113 to 228 ft bls during the July through late-October 2008 monitoring period (table 4). The highest water levels recorded were in mid-September, similar to the continuously monitored observation wells (table 4). The range of daily water-level fluctuations measured in the three private wells was more than a 40-ft decline and as much as a 50-ft rise per day (fig. 16). Private wells with water levels that exceed 200 ft in depth are the most susceptible to becoming "dry" (near the shallower depth of 300 ft in wells such as WK-402; table 1). When the initial problem of wells going dry (water level below the pump) was reported in July 2005, some homeowners either had their wells deepened (for example, WK-400, table 1), or hydrofractured to improve yield (resulting in less drawdown during pumping, which can prevent the water in the well from declining to a level near the pump). Well WK-400 has not gone dry since the well was deepened to 400 ft.

Successive changes in daily mean groundwater levels in the six observation wells are shown in figure 17, with observation well WK-375 and the three private wells (WK-400, -401, and -402) showing the largest magnitude of change. These variations in magnitude of fluctuation are common in fractured-bedrock aquifers, because the network of fractures being affected by stress is complex.

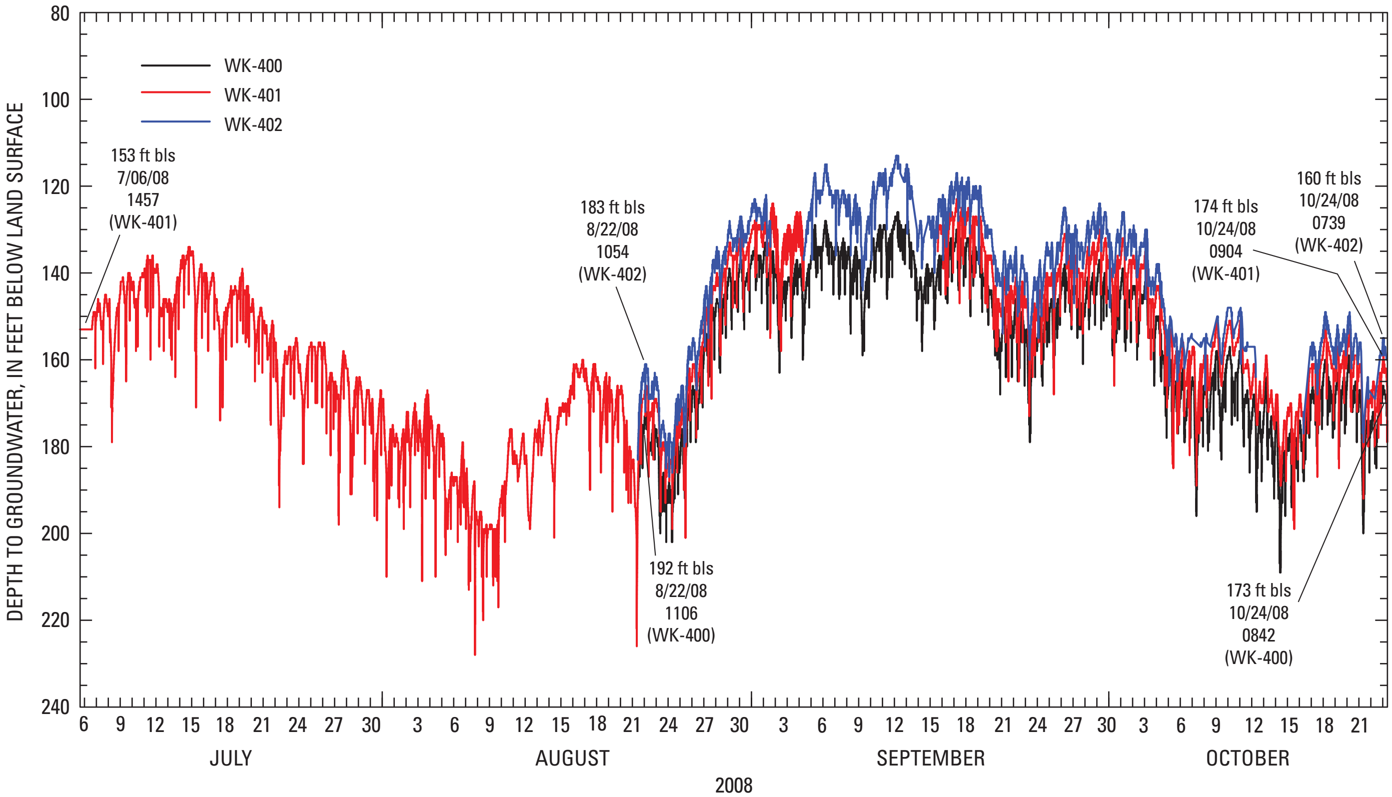


Figure 15. Water-level fluctuations in private wells WK-400, WK-401, and WK-402 showing a similar regional pattern, July–October 2008. [ft, feet; bls, below land surface]

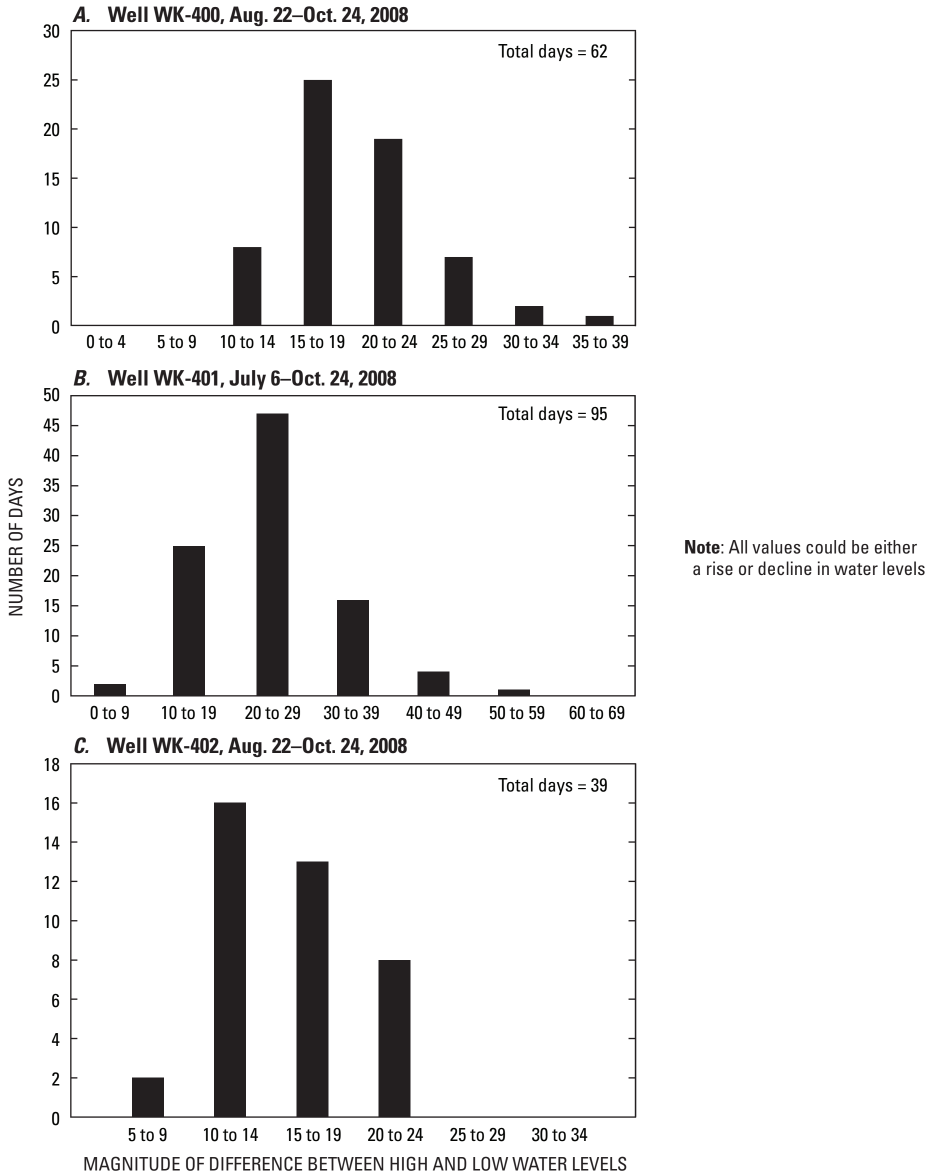


Figure 16. Histograms of daily water-level fluctuations in private wells (*A*) WK-400, (*B*), WK-401, and (*C*) WK-402, July–October 2008.

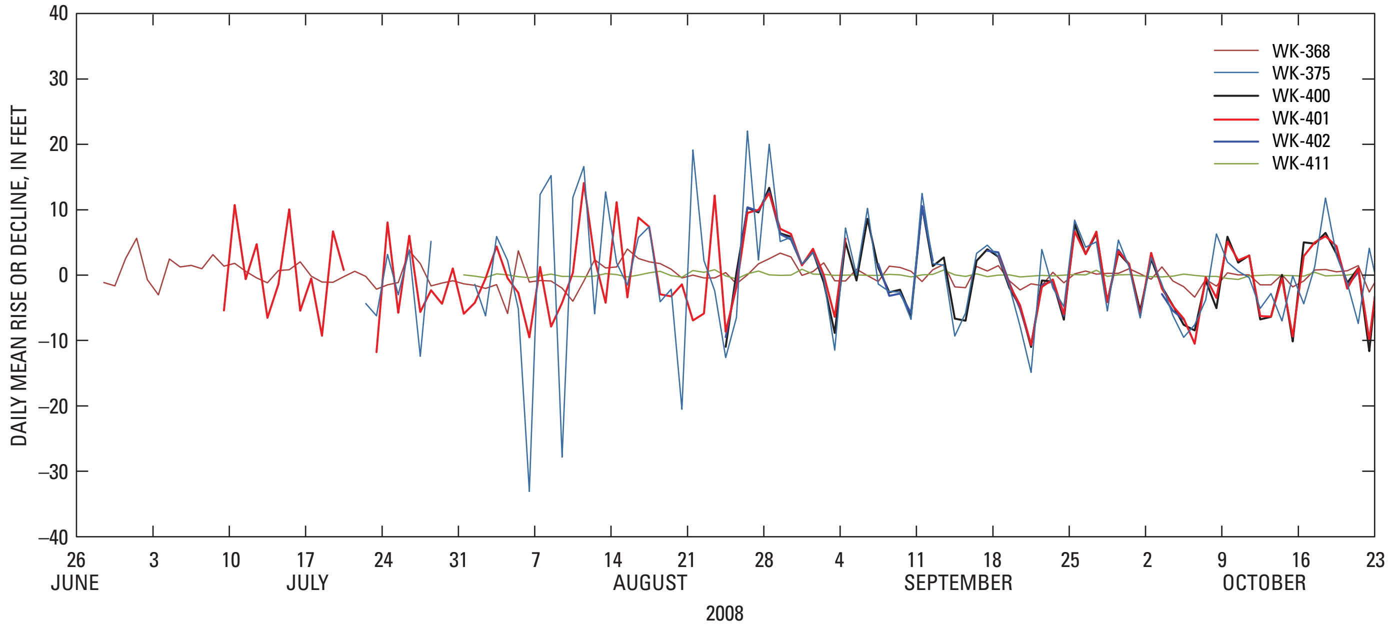


Figure 17. Successive rises or declines in daily mean groundwater levels in the six observation wells in the study area.

Community Wells

Water-level data were obtained for two of the three community wells (WK-415 and -416; fig. 2; table 1) for months overlapping the study period (Bill Gordon, Aqua America, Inc., written commun., 2009). The range of water-level fluctuation in each well is listed in table 4, and the hydrographs of available data are shown in figure 18. Pump intake depth for well WK-415 was reported to be 420 ft (Mike Melton, Aqua America, Inc., written commun., 2009). Well WK-415 had similar but somewhat deeper groundwater levels compared to continuously monitored private wells (WK-400, -401, and -402) and observation well WK-375, with water-levels fluctuating between 68 and 261 ft bls from late July through December 2008 (fig. 18*A*). A regional pattern of fluctuation also was evident, similar to other wells monitored as part of this study. Daily water-level declines ranged from about 43 to 121 ft for this monitoring period, with the pump being turned on and off nearly every hour each day during high-use periods. Well WK-415 did recover to within 50 percent of the pre-withdrawal level within 10 minutes; however, the well did not rest for long periods with at least 15 or more cycles per day (fig. 18*A*).

Well WK-416 was only monitored from December 2008 through January 2009, but had similar water-level fluctuations with a high water level of about 139 ft bls and a low water level of about 229 ft bls (Bill Gordon, Aqua America, Inc., written commun., 2009; fig. 18*B*; table 4). Pump intake depth in this well was reported to be 378 ft bls (Mike Melton, Aqua America, Inc., written commun., 2009). Daily water-level declines for the monitoring period in well WK-416 ranged from about 71 to 84 ft of drawdown; however, no continuous record monitoring data were available from either observation wells or private wells for the same time period (table 4). The short-term water-level fluctuations recorded in community well WK-416 show similar frequent use per day and rapid recovery for each cycle, similar to community well WK-415; however, again, the well did not rest for long periods.

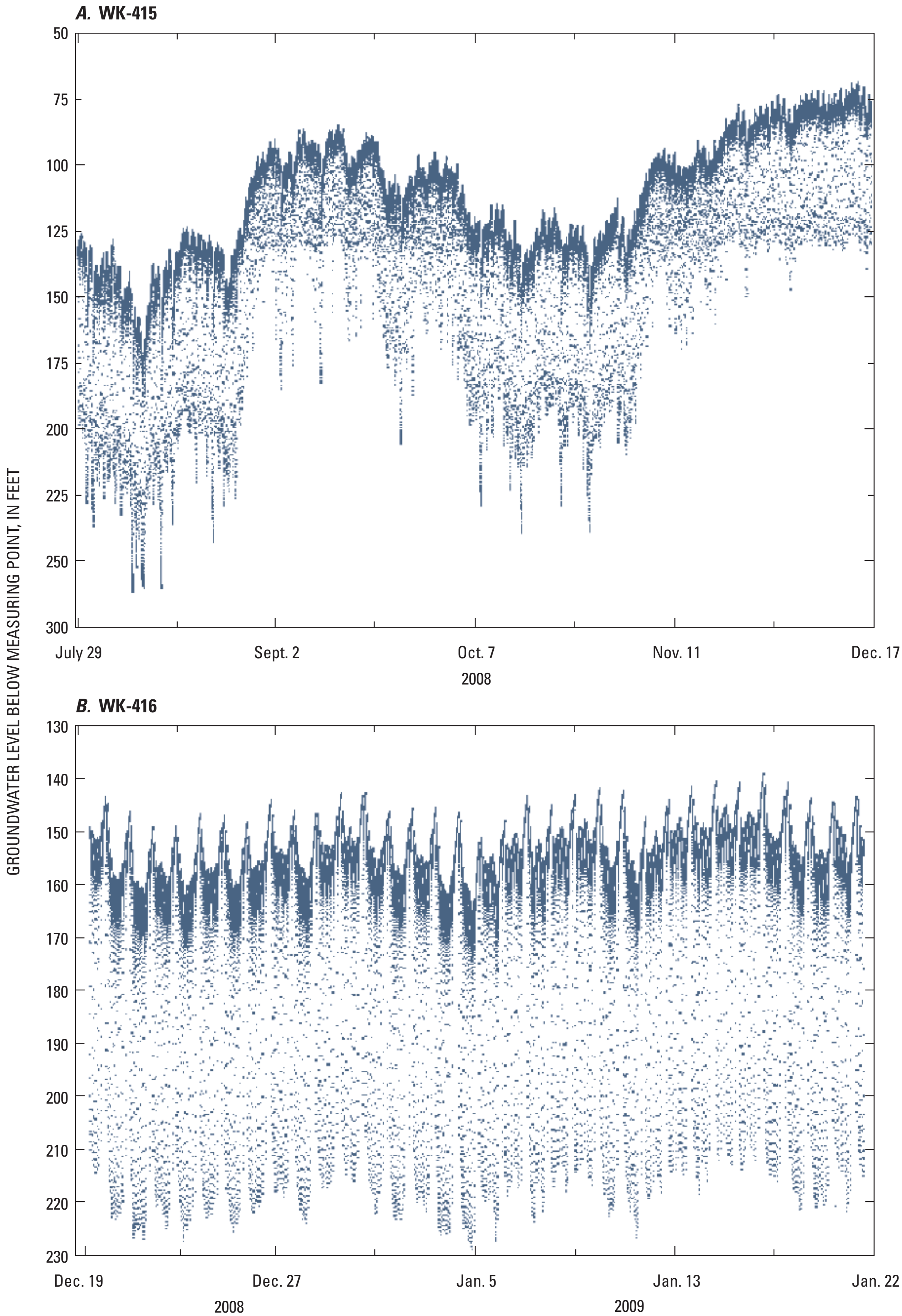


Figure 18. Water-level fluctuations recorded in community wells (*A*) WK-415, July 29–December 16, 2008, and (*B*) WK-416, December 19, 2008–January 21, 2009, collected at 5-minute intervals.

Periodic Measurements

Periodic acoustic tape downs recorded from March 2008 through February 2009 indicated similar areal patterns of the lowest groundwater levels in the study area. These periodic water-level measurements were conducted on a bimonthly or monthly basis. Water levels were recorded in about 35 to 37 private and unused observation wells (table 1; fig. 2; appendix 1) during the nine field visits on the following dates: March 28 (with a few additional wells measured on April 2 and 16), June 16 (with a few additional wells measured on June 26), July 25 (with a few additional wells measured on August 12), September 19, October 17, November 21, December 19, 2008, and January 29, and February 29, 2009. When possible, the nearest reading from the community well groundwater-level monitoring dataset is plotted for comparison to the measured private and observation wells in the area. Selected water-level measurements are referenced to land surface in figure 19, and all datasets are referenced to altitude (above North American Vertical Datum 1988) in appendix 1.

In the Norwood Oaks neighborhood, water levels in eight wells (WK-410, -406, -405, -404, -403, -402, -401, and -400, fig. 2) ranged from 96 to 265 ft bls from March 2008 through February 2009 (figs. 19*A*; 20*A*); water levels were below 200 ft bls in June 2008 (fig. 19*B*) and approached 200 ft bls again in October 2008 (fig. 19*E*). In addition, groundwater levels in a second set (five wells) of private wells to the east and southeast along Bayleaf Trail had water levels that approached 250 ft bls in June 2008 (fig. 19*B*) and ranged from about 58 to 248 ft bls (fig. 20*B*). A third area, including two private wells along Norwood Road and Abbey's Grove Trail, had deep groundwater levels; one private well, WK- 381, had a water level of 331 ft bls measured in October 2008 (fig. 19*E*).

The decline in water levels in some wells of as much as 100 ft in a little more than 2 months, late March–early April to mid- to late-June 2008, (figs. 19*A*; *B*) and 50 ft in 1 month from September to October 2008 (figs. 19*D*, *E*) implies a substantial loss of storage in the aquifer, if only short term. The water levels did recover, however, from November 2008 to February 2009 (figs. 19*F*–*I*). Trends in depth-to-groundwater levels in the areas having the deepest water levels (Norwood Oaks neighborhood, Bayleaf Trail area, and Abbey's Grove area (fig. 2)) are shown in figure 19. Compared to the water levels reported for wells that were drilled in the mid-1990s (table 1), water levels in the aquifer appear to have declined several tens of feet. Some wells drilled in 2001 and 2005 reported water levels of 100 ft at the time (table 1); thus, aquifer dewatering below typical unstressed groundwater levels in the area was evident by 2001.

Some long-term storage loss is evident in the local aquifer from water levels reported when the wells were drilled. During the study period from March 2008 through February 2009, regular dewatering of the fractured-bedrock aquifer was documented with water levels in many wells ranging between 100 and 200 feet below land surface, which were much lower than original reported water levels of 15 to 50 feet below land surface from the 1980s through the late 1990s (table 1). For example, well WK-368 had a static water level of 15 ft bls in February 1992 (table 1) compared to water levels ranging from 83 to 130 ft bls from March 2008 to February 2009. Well WK-375 had a static water level of 20 ft bls when the well was drilled in April 1999 compared to water levels ranging from 75 to 214 ft bls from July to October 2008. Private wells WK-401 and WK-402 had static water levels of 30 ft bls when they were originally drilled in June 1995 and May 1994, respectively; whereas, the range of water levels in these two wells was between 99 and 228 ft bls from March 2008 to February 2009. An indication of deep groundwater levels was noted when wells WK-381 and WK-396 had static water levels reported at 100 ft bls in October 2005 and November 2001, respectively (table 1). Of note is the large range of fluctuation recorded in periodic water levels in well WK-381 from 120 to 331 ft bls from March/April 2008 through February 2009 (fig. 20*C*).

The pattern of lowest groundwater levels measured during the water-level runs was similar for each measurement date (fig. 19; appendix 1), primarily grouping along the northern section of Norwood Oaks Drive (wells WK-406, -405, -404, -403, -402, -401, -400, -410, -396, and -394, fig. 2) and along Bayleaf Trail (wells WK-396, -394, fig. 2) elongated in a north-south direction. A secondary orientation of lowest groundwater levels of N. 65° W. was to the southeast along Norwood Road (delineated from wells WK-399, -378, and -381, fig. 2). The north-south trend was measured at a depth in well WK-368 at 398.4 ft bls (N. 7° E.), and the N. 65° W. orientation was measured in well WK-368 at depths of 80.8–81.4 ft bls (average N. 67° W., table 3) and 86.4–86.6 ft bls (average N. 63° W., table 3). The north-south trend in the Norwood Oaks Drive area and along the western side of Bayleaf Trail is parallel to foliation measurements in the regionally mapped Falls Lake schist (FID stations 25 and 26 (N. 5° E.), and 17 (N. 5° W.), fig. 3; table 2) as well as the amphibolite rock type (station BL-2 (N. 5° E.); fig. 3; table 2). A similar trend to the secondary N. 65° W. drawdown pattern, the N. 60° W. trend, was measured in a joint set within the quartzofeldspathic gneiss (N. 51° W., station BL-3, table 2; fig. 3). Fracture traces mapped near the Norwood Oaks neighborhood vary somewhat from the north-south orientation, striking 7° (N. 7° E.) to 15° (N. 15° E.) and 357° (N. 3° W.) to 345° (N. 15° W.).

A third potential orientation was observed from the water-level altitude maps; a N. 40° W. trend is evident when water-level measurements were recorded in well WK-375 beginning in July 2008 (appendix 1C–I). This trend corresponds to two fractures measured in well WK-368 at depths of 82.6 ft bls (N. 45° W.) and 399.6 ft bls (N. 42° W.; station BL-3, table 2) or the foliation measurements of N. 28–30° W. (FID stations 5 and 6, table 2). From local surficial geologic mapping, the N. 51° W. joint set measured in the quartzofeldspathic gneiss (table 2) and the N. 42° W. fracture trace (near station BL-6, fig. 3) are most similar to this orientation. However, data from more wells in the area between well

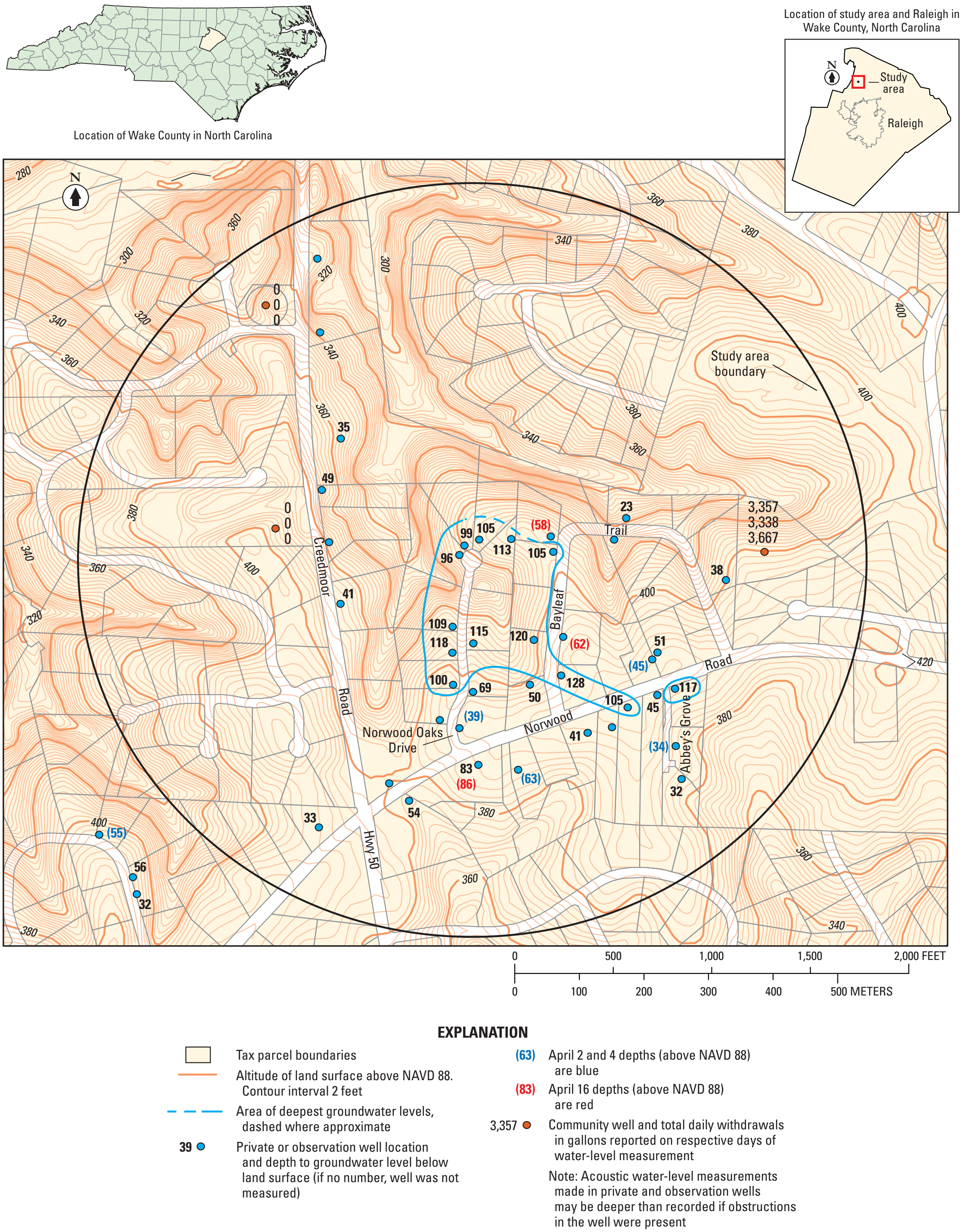


Figure 19*A*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on March 28 and April 2, 4, and 16, 2008. [NAVD 88, North American Vertical Datum of 1988]

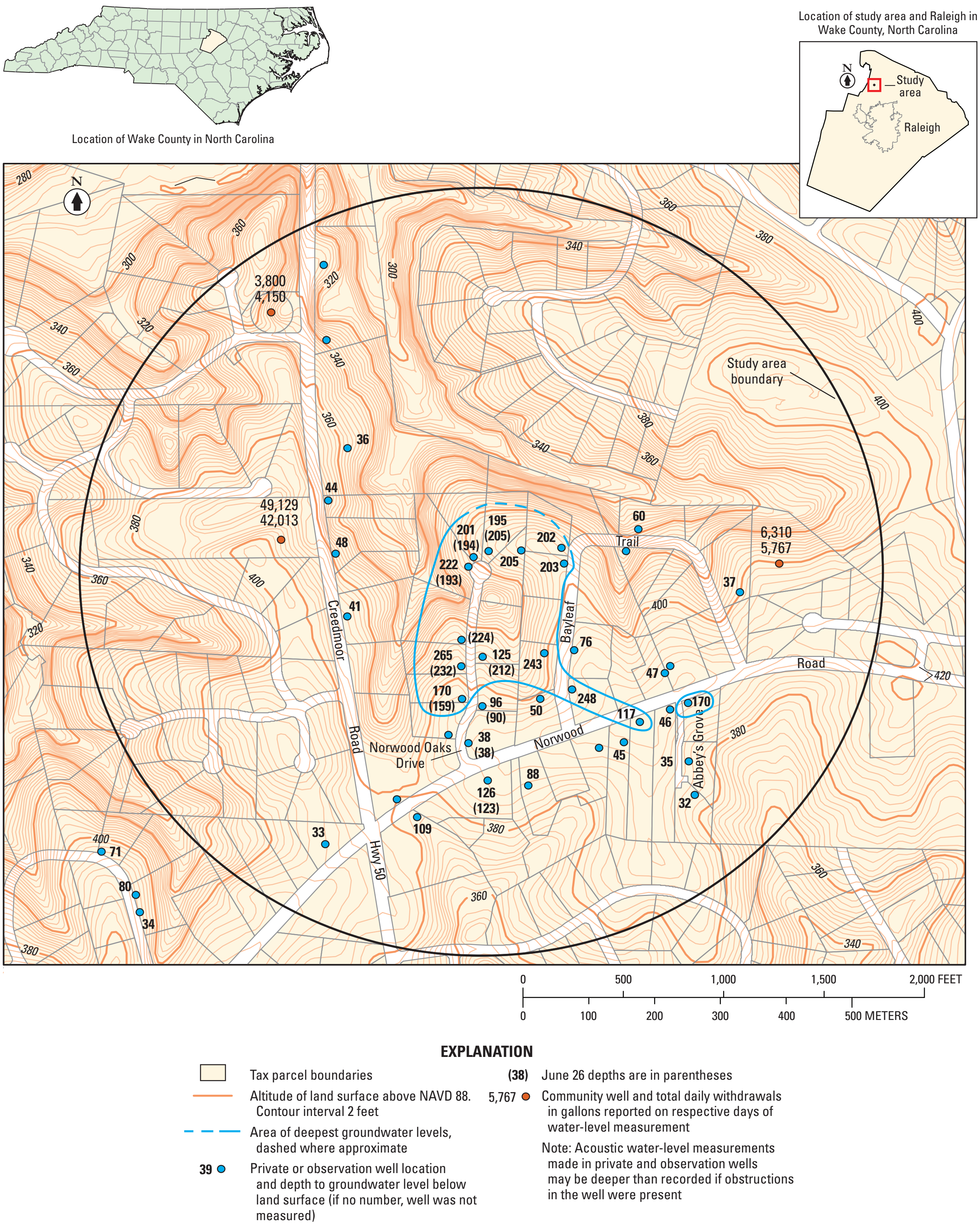


Figure 19*B*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on June 18 and 26, 2008. [NAVD 88, North American Vertical Datum of 1988]

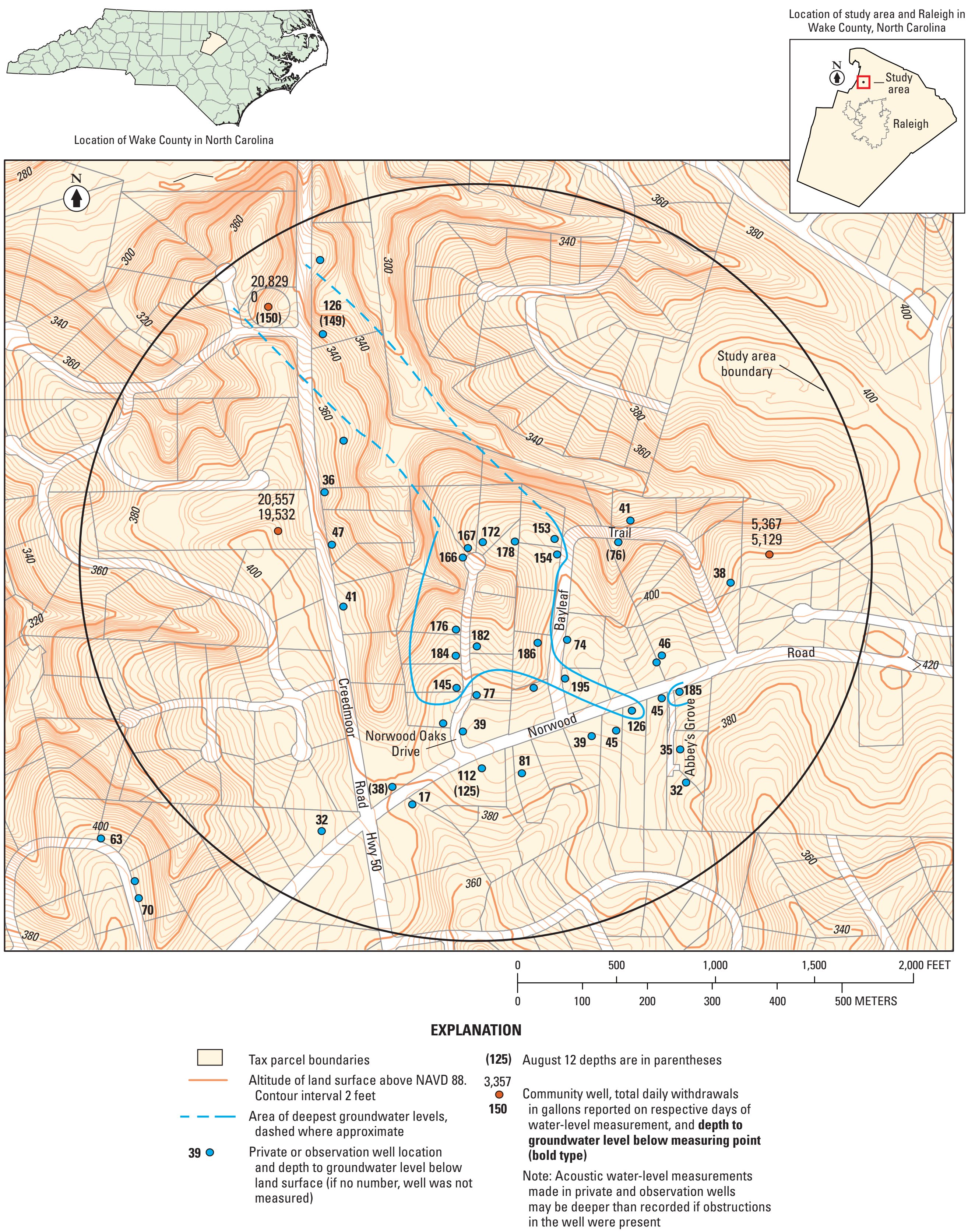
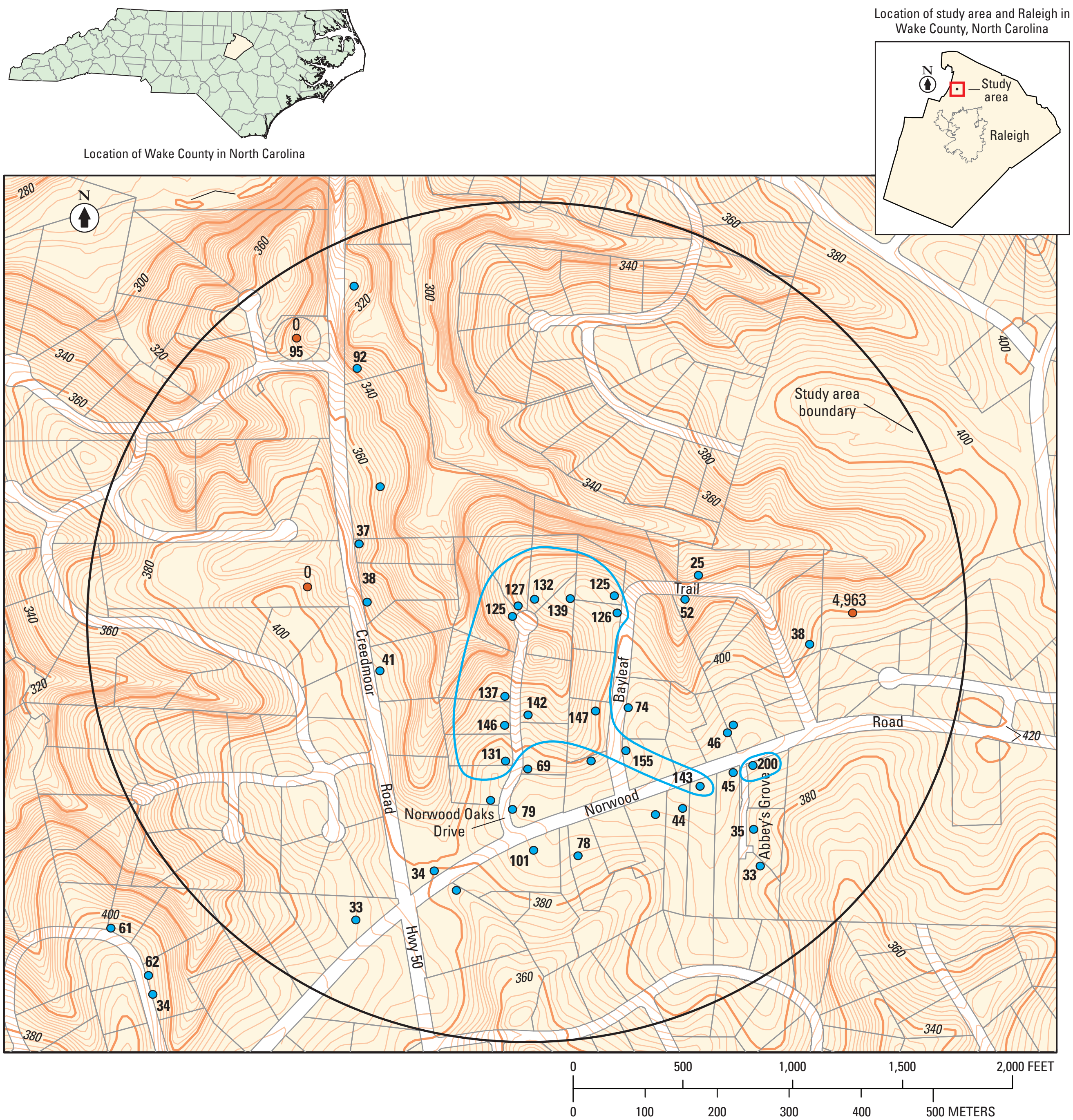


Figure 19*C*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on July 25 and August 12, 2008. [NAVD 88, North American Vertical Datum of 1988]

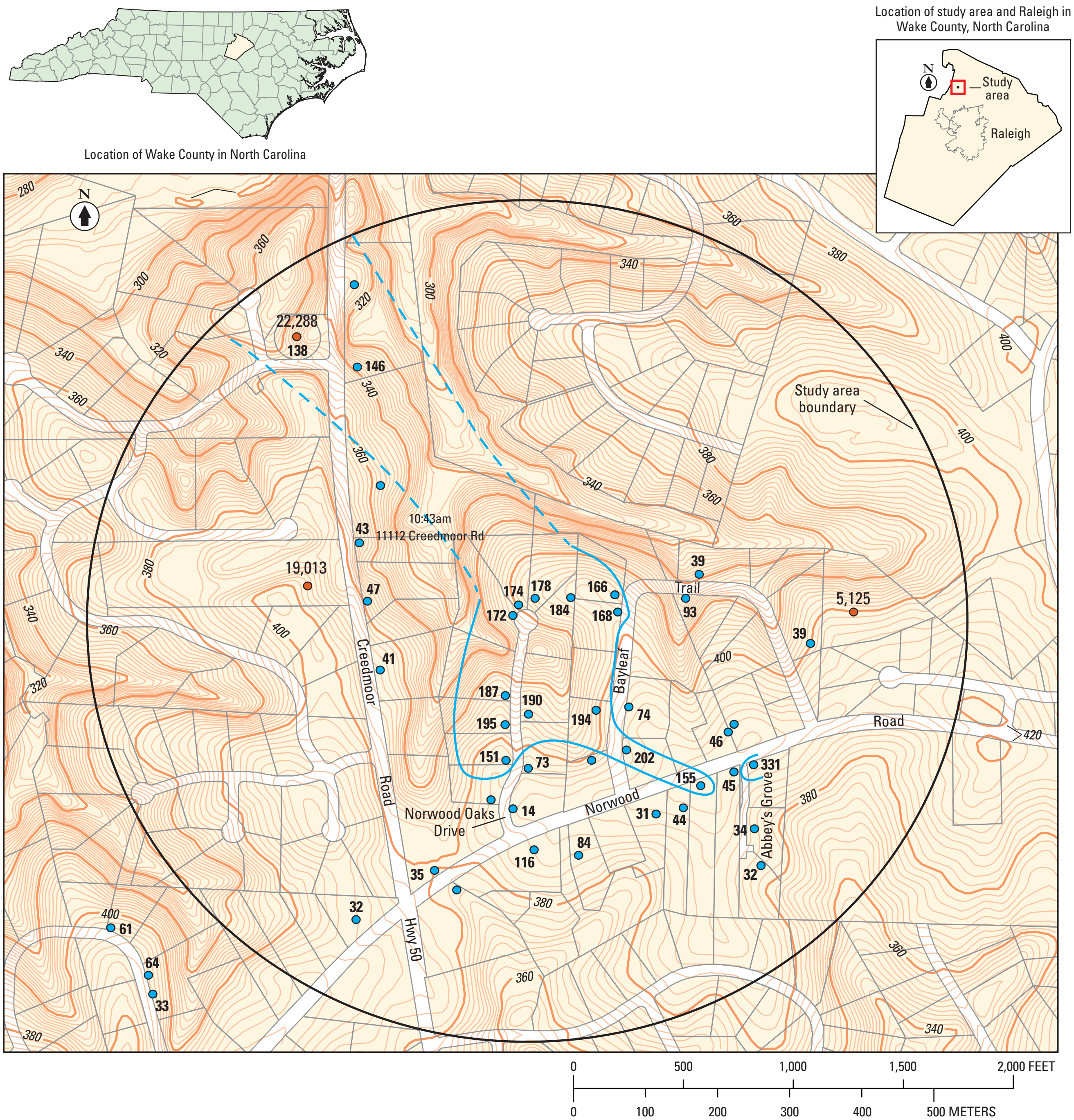


EXPLANATION

- Tax parcel boundaries
- Altitude of land surface above NAVD 88. Contour interval 2 feet
- Area of deepest groundwater levels
- 39 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)
- 4,963 / 95 Community well, total daily withdrawals in gallons reported on respective days of water-level measurement, and **depth to groundwater level below measuring point (bold type)**

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Figure 19*D*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on September 19, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

Altitude of land surface above NAVD 88. Contour interval 2 feet

Area of deepest groundwater levels. Dashed where approximate

39 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

5,125 / **138** Community well, total daily withdrawals in gallons reported on respective days of water-level measurement, and **depth to groundwater level below measuring point (bold type)**

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Figure 19*E*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on October 17, 2008. [NAVD 88, North American Vertical Datum of 1988]

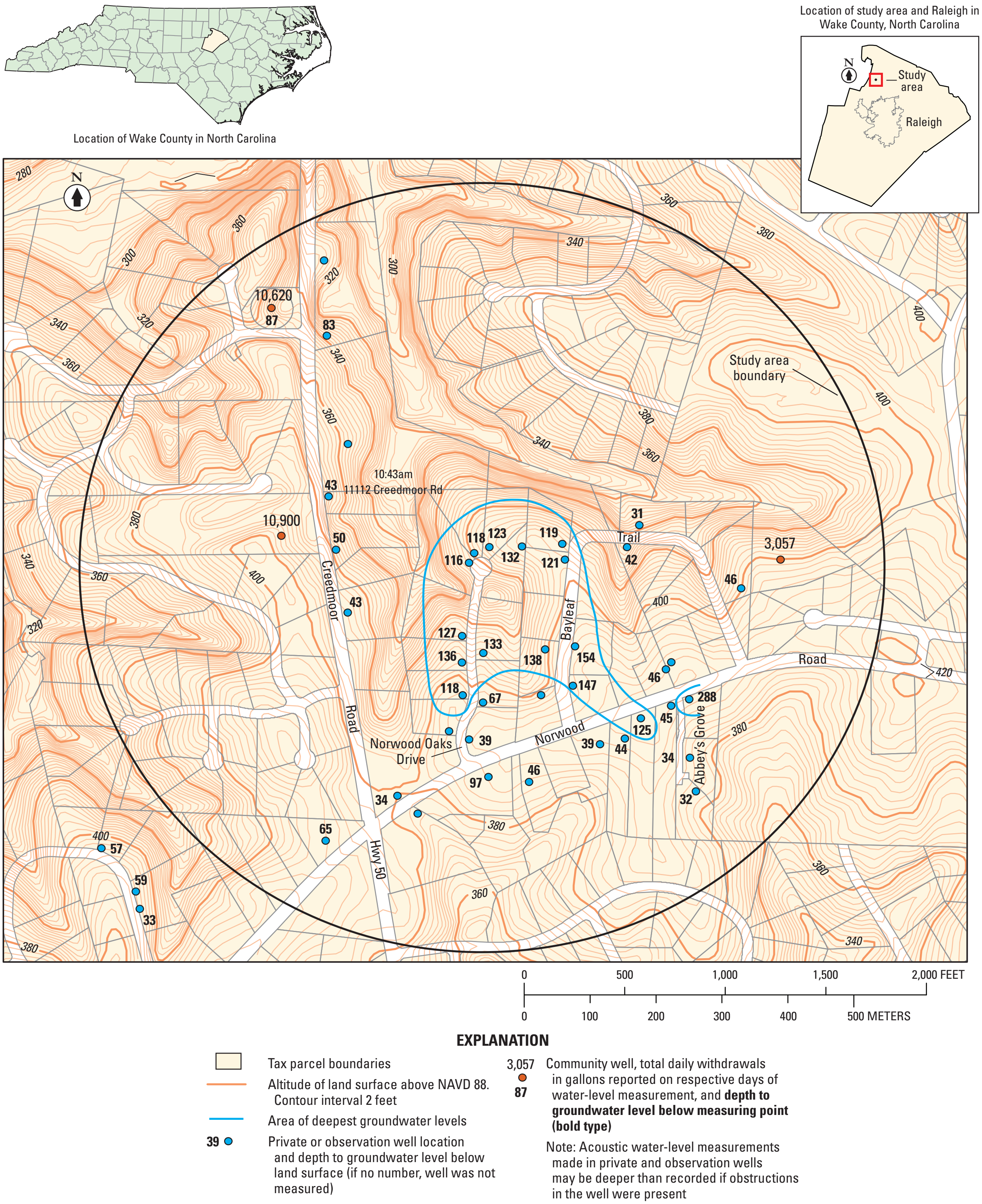
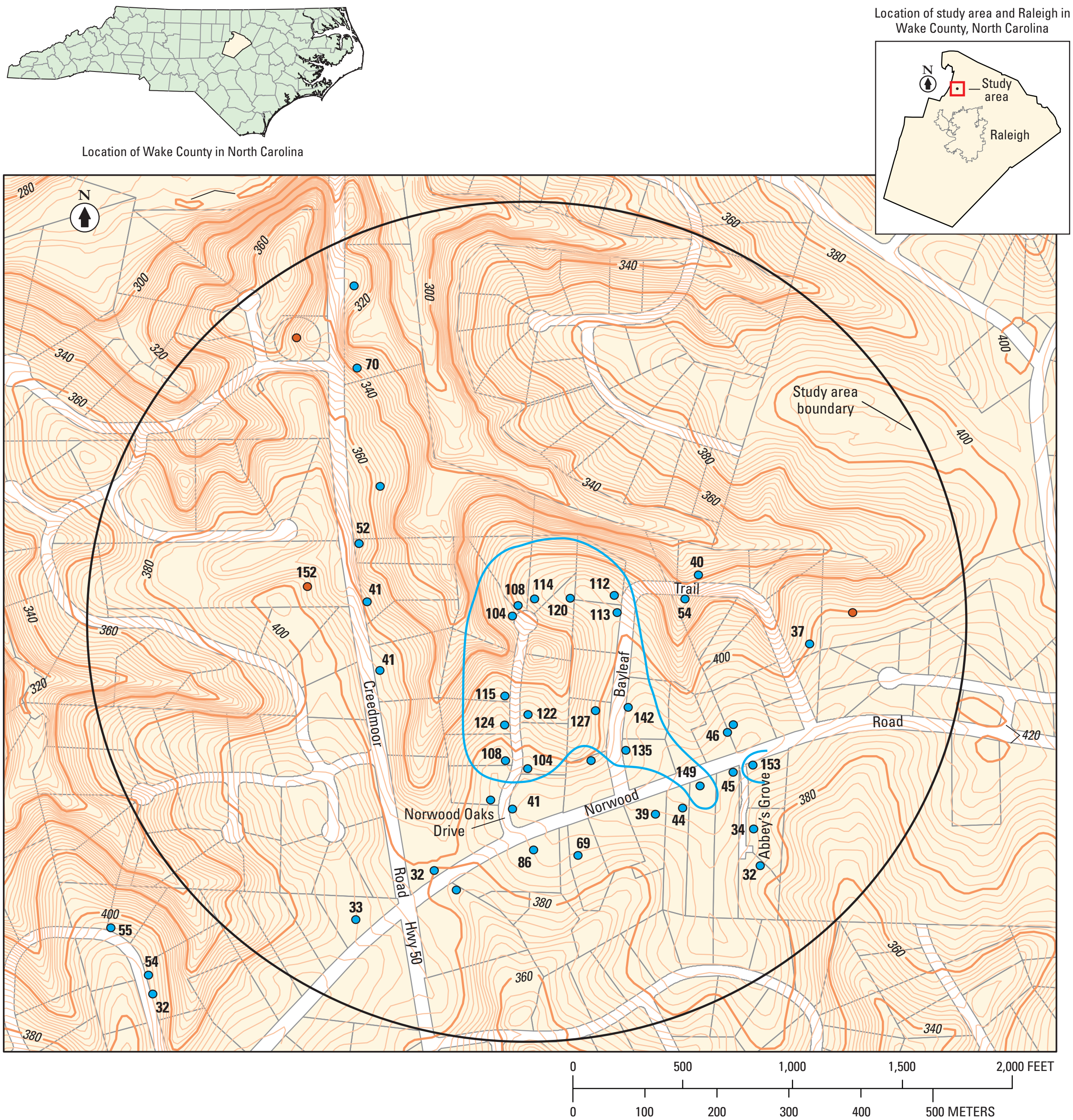


Figure 19*F*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on November 21, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

Altitude of land surface above NAVD 88. Contour interval 2 feet

Area of deepest groundwater levels

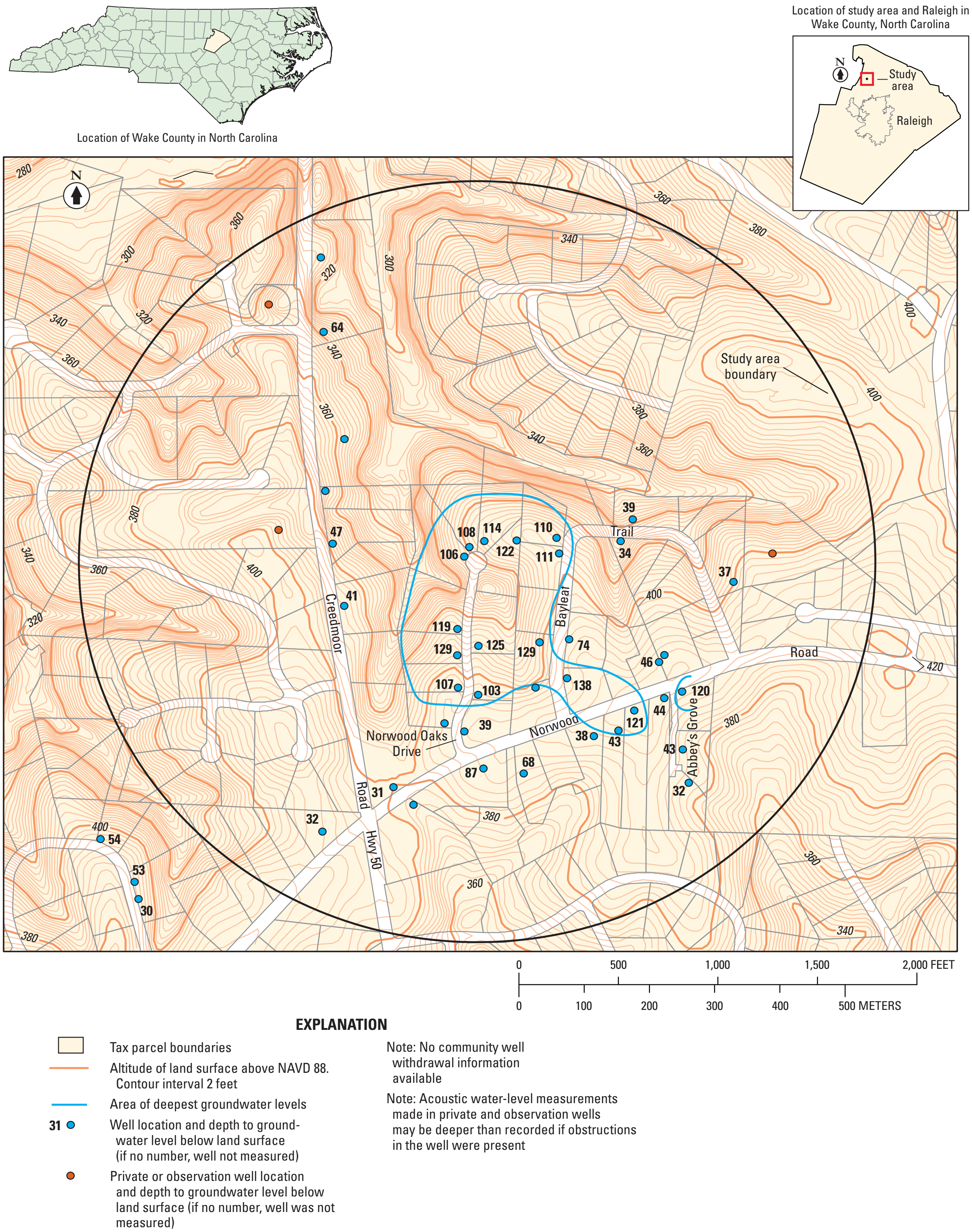
39 Well location and depth to groundwater level below land surface

152 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

Note: No community well withdrawal information available

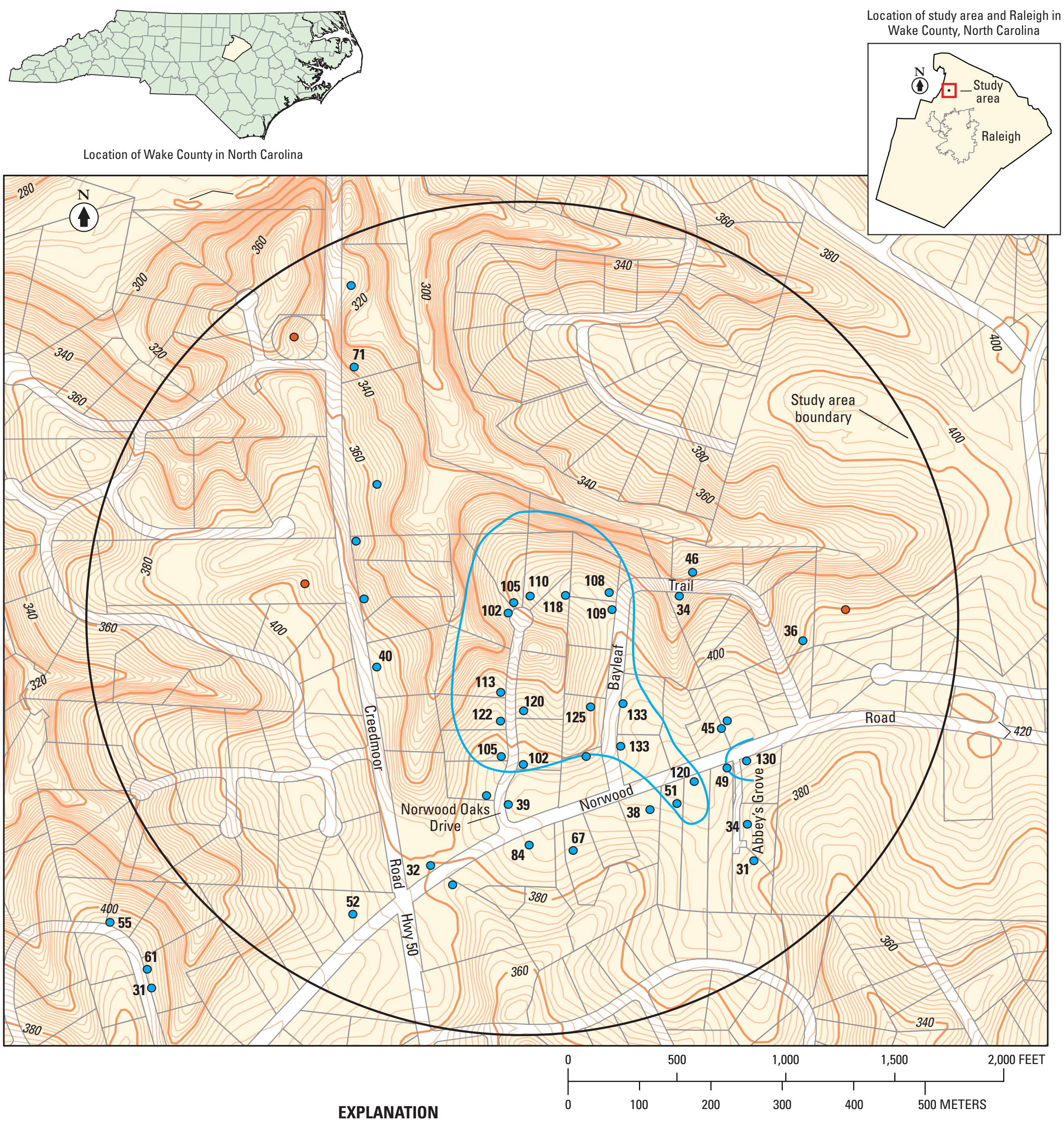
Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Figure 19*G*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on December 19, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Figure 19*H*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on January 29, 2009. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

- Tax parcel boundaries
- Altitude of land surface above NAVD 88. Contour interval 2 feet
- Area of deepest groundwater levels
- 52 Well location and depth to groundwater level below land surface (if no number, well not measured)
- Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

Note: No community well withdrawal information available

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Figure 19*I*. Depths to groundwater levels measured in private and unused bedrock wells in the study area on February 27, 2009. [NAVD 88, North American Vertical Datum of 1988]

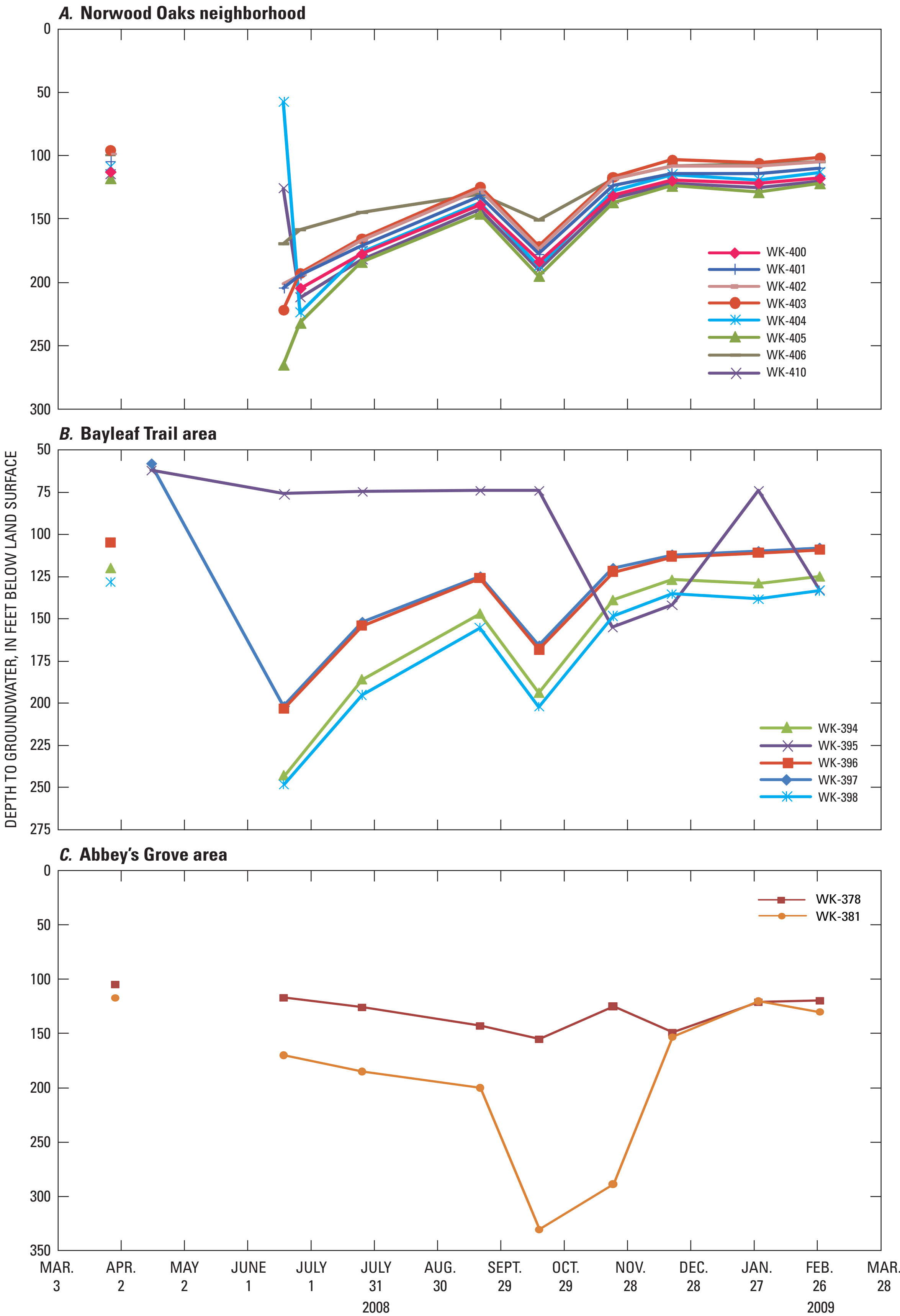


Figure 20. Trends in depths to groundwater levels in private and observation wells having the deepest groundwater levels. *A*, Norwood Oaks neighborhood. *B*, Bayleaf Trail area. *C*, Abbey's Grove area.

WK-375 and the Norwood Oaks subdivision are needed to confirm this trend.

A fourth orientation not depicted in the water-level maps but may be important if drawdown areas continue to develop is the N. 80° W. to N. 75° E. (E-W) orientation measured in wells WK-375 (282.6 to 286.7 ft bls N. 86° W. average trend and 285.2 ft bls N. 78° W., table 3; fig. 3) and WK-368 (399.8–399.9 ft bls N. 75° E., table 3; fig. 3). Two major fracture traces also parallel this orientation (fig. 3).

Regional Patterns in Groundwater Levels

All six wells in which groundwater levels were continuously recorded indicated similar overall fluctuation patterns (figs. 9, 11, 13, 15). Because these wells are separated by distances ranging from about 100 ft to 0.45 mi, the pattern likely was regional. A similar regional pattern is evident when data from observation wells and private wells is modeled using a common smoothing method for nonlinear scatterplots (Friedman method; Friedman and Tibshirani, 1984; fig. 21). This method attempts to capture the trend of points on the y-axis as a function of points on the x-axis, using isotonic regression and monotone scatterplot smoothing. The smoothed comparison of water levels allows separation of short-term fluctuations caused by local withdrawals from the overall regional pattern of water-level fluctuation, which is most likely related to climate and recharge to the aquifer. Water levels recorded in observation well WK-375 were compared to private well WK-401 (fig. 21*A*), considered representative of the three private wells monitored (fig. 15) and having the longest record (table 4). Additionally, a similar regional pattern was observed when the smoothing model of water levels in observation well WK-375 was applied to the other two observation wells WK-368 (fig. 21*B*) and WK-411 (fig. 21*C*).

Because of the large short-term water-level fluctuations in the community well WK-415, a more detailed Kernel scatterplot smoothing method (Wand and Jones, 1993) was used to approximate the regional pattern. Figure 21*D* shows a similar comparison of an observation well (WK-375), a private well (WK-401), and a community well (WK-415) during late July through late October 2008. This regional pattern also was compared to smoothed barometric pressure fluctuations; however, no relation (typically inverse) could be determined. The pattern most likely reflects a dynamic response to the combination of withdrawals from both community wells and private wells, with reduced withdrawals during periods of decreased demand as a result of rainfall (figs. 9, 11, 13, 15), and may be affected by withdrawals outside of the study area boundary.

Hydrologic conditions reported during the study for this area of central North Carolina varied from extreme drought to normal. The North Carolina Drought Management Council presents a map of drought conditions across the State each week (*http://www.ncdrought.org/index.php*). Evaluating conditions during the study period from March 2008 through February 2009 for Wake County saw a variety of drought categories, from "extreme drought" to "normal" conditions. At the beginning of the study in March 2008, Wake County, was categorized under extreme drought conditions by the North Carolina Drought Management Council (*http://www.ncdrought.org/archive*; accessed November 9, 2010). For April through May 2008, conditions improved from the "severe drought" category enough where some parts of the county were under normal hydrologic conditions in early June 2008. In June through early July 2008, conditions worsened to the severe drought category again. During July through late September 2008, hydrologic conditions in the county improved back to normal conditions by late September as a result of increased rainfall and tropical events. The county was categorized as having normal conditions through mid-February 2009 when the drought category changed to "abnormally dry."

Regional groundwater levels were recorded for the study period in regolith well WK-284 (Lake Wheeler Road Research Station well MW-3S), located in Wake County. A new record low water level was recorded in December 2008, surpassing the prior record recorded during drought conditions in the fall of 2002. By February 2009, the water level had nearly recovered to the level recorded in late June 2008, but remained at below-normal conditions. Groundwater levels in a second regolith well, OR-069 located in nearby Orange County, North Carolina, rose throughout the study period, but were below normal overall.

Factors Affecting Groundwater Levels

Groundwater systems respond to hydrologic conditions, such as recharge from rainfall, as well as other natural effects, including evapotranspiration processes, earth tides, and barometric pressure fluctuations. In the study area, the response to natural stresses could not be identified on a regular basis because of the stress of groundwater withdrawals (withdrawals) were of higher magnitude and a different frequency than natural effects on groundwater levels, where drawdown cycles occurred at least once per day. The bedrock aquifer responds dynamically to withdrawals because of the lack of storage in the fracture networks, even though the fractured bedrock part of the aquifer receives recharge through the overlying regolith (average thickness (from recorded casing depth) is 67 ft, with a range from 23 to 165 ft) in the study area (table 1). The bedrock wells recovered during periods of increased rainfall in September 2008, likely from decreased use and withdrawals for irrigation purposes and downward recharge from a higher water table in the overlying regolith.

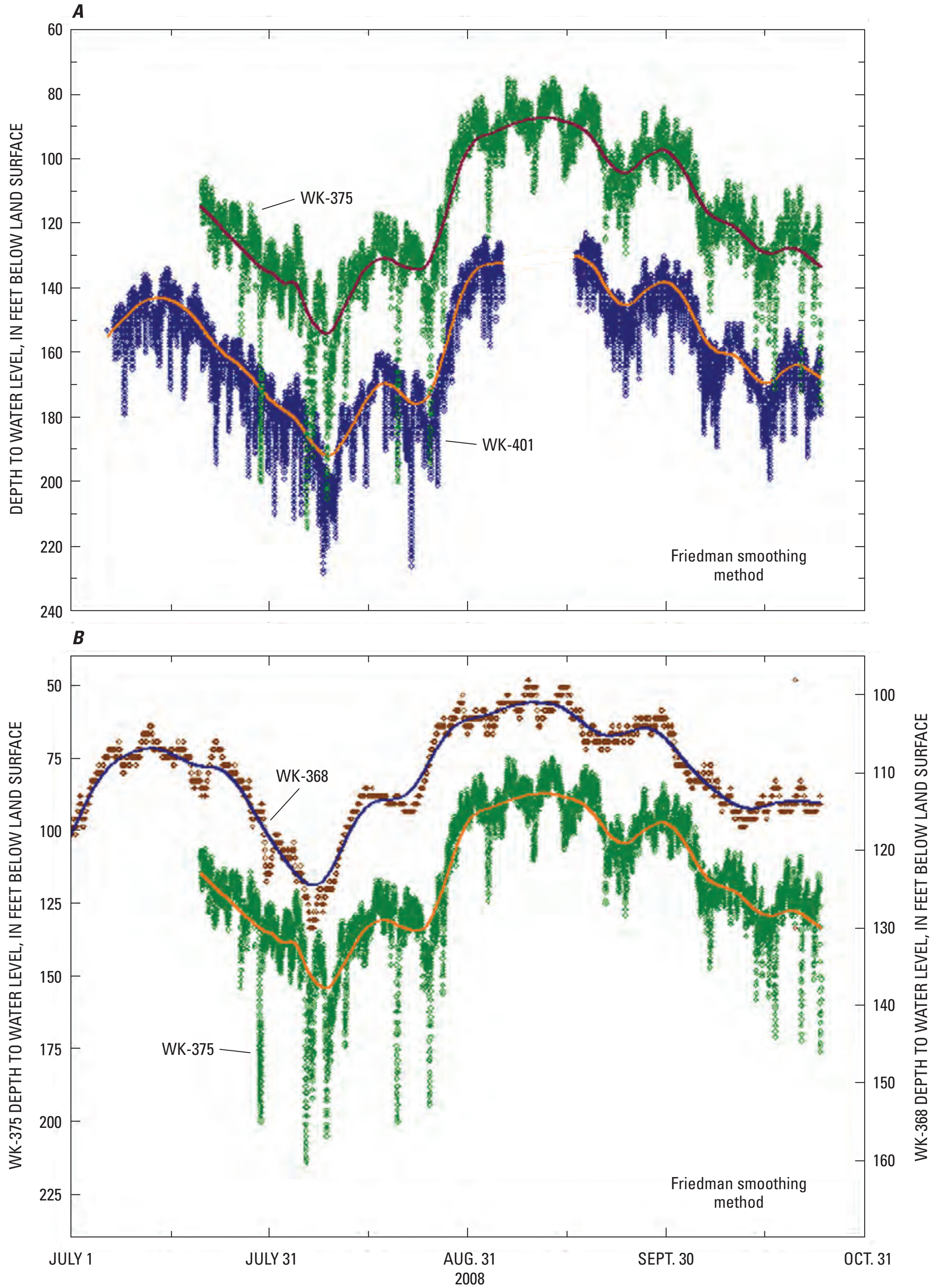


Figure 21. Overlay of water levels from wells showing a similar modeled regional pattern of fluctuation. *A*, observation well WK-375 and private well WK-401. *B*, observation wells WK-375 and WK-368.

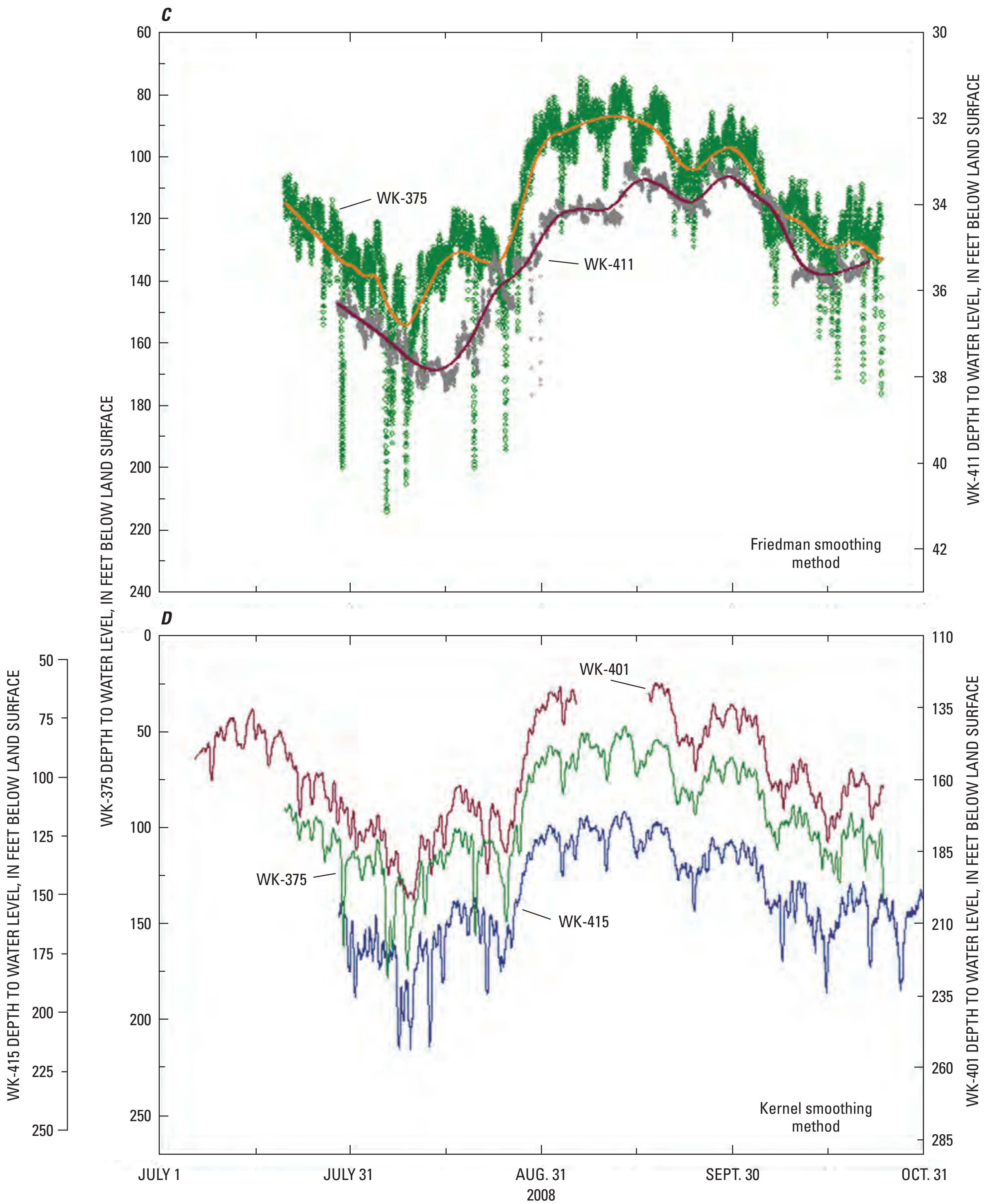


Figure 21.—Continued Overlay of water levels from wells showing a similar modeled regional pattern of fluctuation. *C*, observation wells WK-375 and WK-411. *D*, observation well WK-375, private well WK-401, and community well WK-415.

Natural Effects

The magnitude of the larger groundwater-level declines (a few to tens of feet per day; figs. 9, 11) observed in the observation wells WK-375 and WK-368 is greater than typically is observed with natural effects such as evapotranspiration (ET), earth tides, or barometric pressure fluctuations. ET effects on groundwater levels generally are on the order of a few tenths of a foot per day and are recognized as regular cycles with high water levels in the morning when ET is low and low water levels in the afternoon when ET is high (Chapman and others, 2005, fig. 19). Additionally, water levels recorded in well WK-368 were compared with barometric pressure fluctuations recorded at the Raleigh-Durham International Airport (located about 7 mi southwest of the study area); however, no direct (inverse) correlation could be made. Barometric pressure fluctuations affect groundwater levels inversely (Chapman and others, 2005, fig. 18) with typical fluctuations of 0.3 ft or less for a similar hydrogeologic setting in Wake County. Earth tides, resulting from the gravitational pull of the sun and moon, also may be observed in tight formations, such as the bedrock. Earth-tide fluctuations also generally are a few tenths of a foot and occur regularly, with two high and low water levels noted per day (see *http://waterdata.usgs.gov/nc/nwis/uv/?site_no=354302081433201&PARAmeter_cd=72019,72020,62611*: accessed November 9, 2010; well BK-126 in Burke County, NC). It should be noted that the majority of the water levels presented in this report were rounded to the nearest foot as per the accuracy of acoustical water-level measurements. Thus, earth tide and ET signals were not discernable. Although the daily water-level declines recorded in observation well WK-411 (data not rounded to the nearest foot) were of lesser magnitude, ranging from 0.5 to 3.5 ft, no obvious cyclic patterns, such as ET or earth tide effects, were identified on a daily basis (fig. 13).

Magnitude of Groundwater-Level Declines

A variation in overall response to groundwater withdrawals was noted in the continuous groundwater-level records for the monitored observation and private wells. The largest overall declines observed during the study period were in observation well WK-375, which had a water-level decline of about 247 ft from July 21 through August 6 (3 weeks; fig. 11) during a heavy use period in the summer (fig. 7), and about 101 ft from September 3 through October 24, near the end of the study period. For observation well WK-368, the decline from mid-July through mid-August was substantially less, about 27 ft (fig. 9). For the private well WK-401, which had the longest record, water levels declined about 94 ft from mid-July through early August 2008 (fig. 15). The large declines recorded in wells WK-375 and WK-402 (as much as 78 and 40 ft, respectively) suggest a substantial change in storage in the fractured-bedrock aquifer near each well and would have substantial impact on wellbore storage, especially in wells having a total depth of 300 ft, such as wells WK-375 and WK-402.

For the Norwood Oaks neighborhood, the lowest groundwater levels ranged from about 96 to 265 ft bls during the March 2008 through February 2009 study period (fig. 20*A*), 60 to 200 or more ft below the unstressed water level for this area (see *http://waterdata.usgs.gov/nc/nwis/current/?type=gw*, Real-Time Groundwater; well WK-284.) In comparison, static water levels reported when several of the wells were drilled in the mid- to late-1990s ranged from about 20 to 30 ft bls. Because of the presence of deep water levels that exceed 200 ft bls in this area, homeowners that have the shallowest wells near 300 ft in depth are the most susceptible to becoming dry (having water levels reach the pump intake depth). When the initial problem of wells going dry was reported in July 2005, some homeowners either had their wells deepened (see WK-400, table 1, for example) or hydrofractured to improve the yield. A glimpse of declining water levels was recorded when well WK-396 (Bayleaf Trail area) was drilled in November 2001 and had a reported static water level of 100 ft bls, and well WK-381 (Abbey's Grove Trail area) was drilled in October 2005 and had a static water level of 100 ft bls (table 1). Well WK-381 had the lowest reported groundwater level measured of about 331 ft bls on October 17, 2008 (fig. 20*C*). Construction dates for community wells in the study were not available; however, Keyworth (2009) reports withdrawal data for well WK-415 since 2000 and for well WK-416 since 2001.

Although the proximity of a private well to a larger-capacity community well may not necessarily be of immediate concern in fractured-bedrock aquifers, if the wells tap fractures that are connected as part of a network, then pumping can collectively affect groundwater levels. The observed relations between the CWS, observation, and private wells and respective distances are described here to document the findings of this study. Of the three observation wells monitored as part of this study, bedrock well WK-375 was closest to a community well (WK-415, fig. 2, about 300 ft west-northwest). Well WK-368 is located about 1,600 and 1,700 ft (0.3 mi) from community wells WK-416 and WK-417, respectively (fig. 2). (WK-417 does not withdraw nearly as much water as WK-416 (29 percent of the total volume withdrawn by well WK-416 for the January through November 2008 reporting period; fig. 7), because of the lower well yield of about 8 gal/min (table 1)). The closest community well to WK-411 is WK-416 at a distance of about 1,400 ft. For the private wells, the distance to the nearest community well WK-416 (fig. 2) is about 900 ft, and the distance to well WK-415 is about 1,600 ft (0.3 mi). Additional community wells located outside of the study area as well as larger-capacity irrigation wells also could affect groundwater levels.

The deepest water levels measured during the study period in June 2008 (figs. 19*B*, 20) are similar to the timing of increased withdrawals from WK-416, likely for irrigation use (fig. 7). Within a little more than 1 week, the water level in well WK-410 (fig. 2) declined by nearly 90 ft (figs. 19*B*, 20*A*). Withdrawals from community well WK-416, located within about 900 ft of the Norwood Oaks subdivision, were five times the volume reported in prior months (fig. 7). Domestic usage could have increased during this dry period (figs. 7, 9, 11, 13), also likely for irrigation purposes. Because of a lack of storage in the bedrock part of the aquifer, water levels respond dynamically to any changes in stress (withdrawals) on the system. The water levels appear to have stabilized between approximately 100 to 150 ft bls during November 2008 through February 2009 (fig. 19; appendix 1), suggesting increased recharge, groundwater withdrawals, and no large short-term demands.

Recovery of Groundwater Levels

The groundwater system recovered during periods of increased rainfall, most likely from direct recharge from a higher water table in the overlying regolith (fig. 4) and reduced withdrawals for irrigation. An overall recovery of the groundwater levels was observed in mid-August through mid-September 2008 in the three observations wells, and the three monitored private wells (figs. 9, 11, 13, 15). Water levels rose about 32 ft in observation well WK-368 and about 139 ft in well WK-375 (table 4; figs. 9, 11). Groundwater levels recorded in well WK-375 had the largest decline with a similar rise in magnitude during this period. The water level in private well WK-401 (the only private well monitored in mid-August) rose about 105 ft during this same period (table 4; fig. 15), which indicates a significant increase in hydraulic head in the fractured-bedrock part of the aquifer. This recovery is likely a result of reduced water usage from recent increased rainfall and associated decreased demand (fig. 22) from the nearby community wells related to reduced irrigation. Recharge rates for the fractured bedrock part of the groundwater system are expected to be slow; however, a higher perched water table in the shallow regolith part of the groundwater system from the increased rainfall also could result in increased recharge to the deeper fractures in the bedrock.

Groundwater levels in all six continuously monitored wells in the study area rose from mid-August through September 2008, after four large rainfall events (each more than 2.5 inches total rainfall per day) occurred from remnants of tropical storms (figs. 9, 11, 13, 15; table 4). Evaluating withdrawals

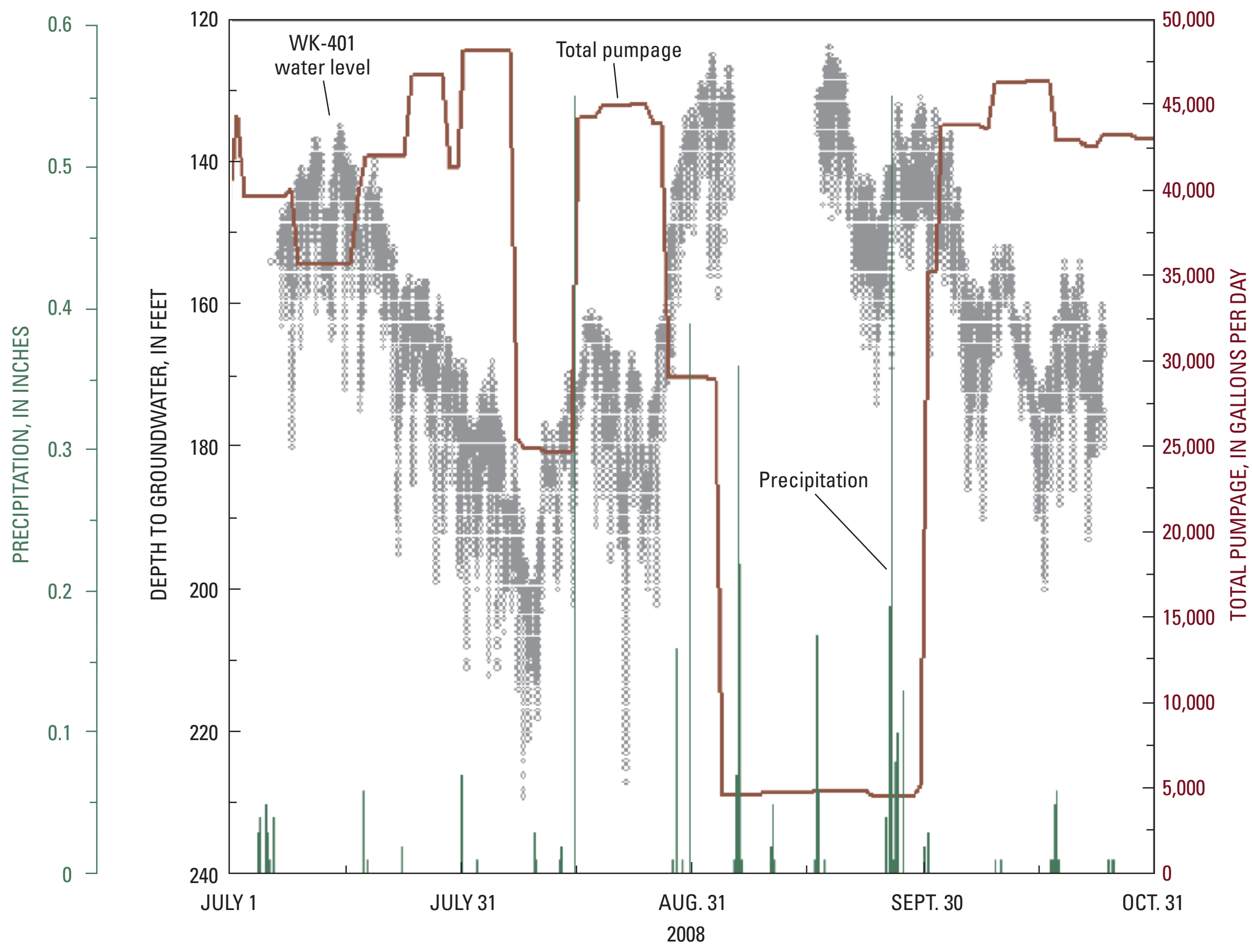


Figure 22. Overlay of private well WK-401 water-level records, precipitation, and total withdrawals from the three community wells in the study area, July–October 2008.

reports for the community wells located in figure 2, WK-415 was not pumped for a week from August 8 through August 15, and both WK-415 and WK-416 were reportedly not pumped from September 4 through September 30 (fig. 7). However, the water-level fluctuations recorded in WK-415 indicate that pumping for this well did not stop in September (fig. 18*A*); therefore a projection of withdrawals was made for wells WK-415 and WK-416 through the remainder of September 2008 on the basis of the gallons per minute rate reported earlier that month (fig. 23). The projection of withdrawals shown in figure 23 indicates reduced withdrawals for the month of September 2008 compared to June through August 2008. The reduced withdrawals during frequent large rainfall events in September 2008 appear to correlate with the overall rise in groundwater levels (figs. 9, 11, 13, 15). In the study area, the water-level rise most likely is a factor of both reduced withdrawals from the bedrock part of the aquifer and recharge as a result of a higher water table from recent precipitation in the overlying regolith.

Connectivity of Fracture Networks

Because the magnitude of both daily and longer-term groundwater-level fluctuations in observation wells WK-375, WK-368, and WK-411 vary substantially, these wells most likely reflect different degrees of connection to the local fracture networks that are stressed by groundwater withdrawals. Areally, evaluating the periodic water-level measurements from a large number of wells, the subset of wells having the lowest water levels (fig. 19; appendix 1) most likely are more connected to the stressed local fracture network.

The regional pattern of fluctuations observed in all continuously monitored wells in the study area does not appear to be recognizably affected by natural stresses, such as diurnal earth tides or daily ET fluctuations, and the water levels do not appear to be noticeably affected by large barometric pressure fluctuations on a regular basis. As withdrawals from both higher-capacity (greater than 50 gal/min) community wells and a large number of private wells (nearly 40) occur in this area, both types of groundwater stresses likely are cumulatively affecting groundwater levels. However, withdrawals most likely are not proportional, with the community wells pumping a greater volume than the combined private wells. The cumulative effect of 40 wells using 200 gal/d (four-person household at 100 gal/person/d) would be about 16,000 gal/d, which is similar to a lower capacity community well, such as WK-417, affecting groundwater levels. Water levels in both community wells and a substantial number of private wells exceeded 100 ft bls throughout the study period, water levels in private wells exceeded 200 ft bls during periods of high demand and subsequent increased groundwater withdrawals (fig. 7, 23), and water levels in the two community wells also exceeded 200 ft bls on a daily basis.

From the direct comparison of recorded continuous groundwater levels from observation wells, private wells, and community wells, it is difficult to discern the potential interference or connectivity of the fracture networks tapped by the wells. Thus, a documented method of statistical cross correlation of time series datasets (Wessa, 2009) was conducted

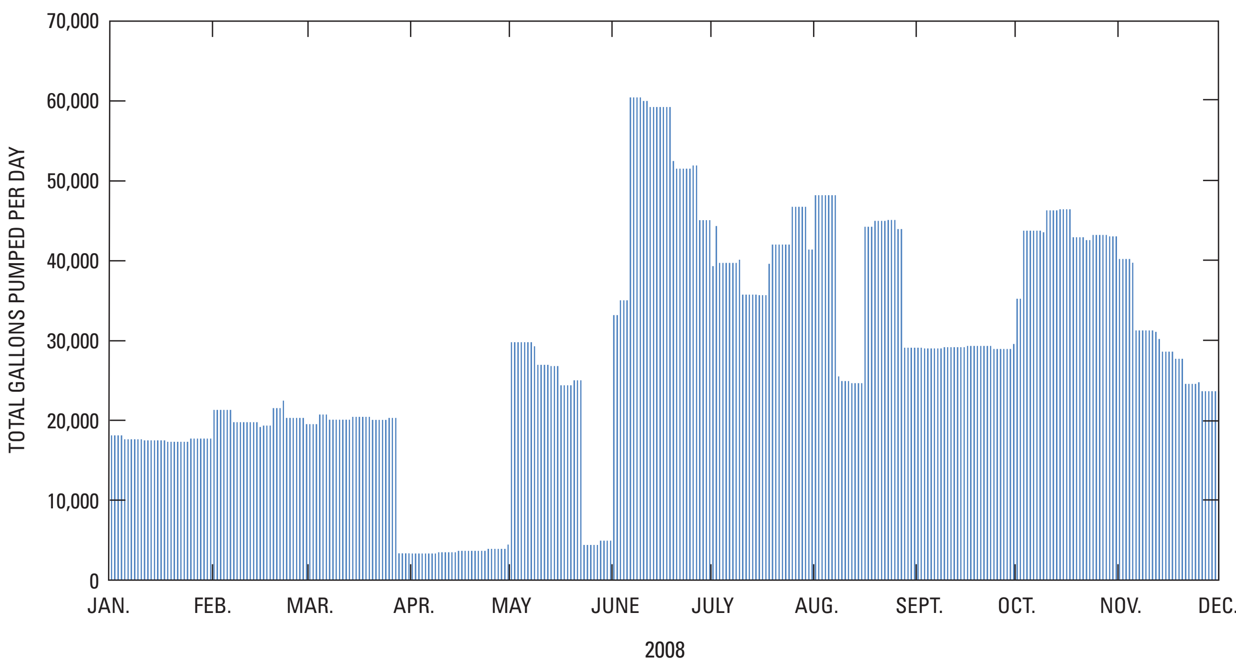


Figure 23. Total groundwater withdrawn from the three community wells for January–November 2008, using projected withdrawals for wells WK-415 and WK-416 for September 2008.

on the continuous groundwater records collected from the observation wells, private wells, and the compiled community well water-level data. A correlation coefficient and time lag were calculated for the following well pairs for their respective common overlapping period of monitoring (table 4): community well WK-415 and observation well WK-375; private well WK-401 and community well WK-415; private well WK-401 and observation well WK-375; and private well WK-400 and community well WK-415. The time lag having the highest correlation coefficient (peak) gives information on the difference in time (delay) with which groundwater levels in two wells respond to the same stress.

Because observation well WK-375 was closest to a community well (WK-415, located about 300 ft west-northwest, fig. 2), a paired cross-correlation analysis was performed. The pattern of daily withdrawal cycles noted in the record for community well WK-415 was observed within the record for observation well WK-375 as smaller magnitude cycles on the order of a few feet of fluctuation (fig. 24). A cross-correlation analysis for the entire overlapping monitoring period for wells WK-415 and WK-375 (July 29 through October 24, 2008) indicated that the water levels were correlated and that the stress affecting the groundwater level in observation well WK-375 occurred about 45 minutes prior to a similar response in well WK-415 (negative time delay, see peak in fig. 25). Because well WK-375 was not being pumped and exhibited large declines during the study period (fig. 11) with no other sources of large groundwater withdrawals being located on the property, the cross-correlation results likely mean that an unknown large-capacity well affected groundwater levels in observation well WK-375 and then 45 minutes later, community supply well WK-415. Stress could be a result of withdrawals from a nearby large-capacity well such as community well WK-416 (no overlapping data for the continuous monitoring part of this study were available to confirm or refute), another community well outside of the study area, collective domestic well withdrawals, or an unknown large-capacity irrigation well within or outside of the study area.

To evaluate the potential interference of withdrawals from both community wells and private wells, a cross-correlation comparison of continuous water-level records was made between private wells WK-401 and WK-400 and community well WK-415 (analyzed in separate pairs). For the comparison between WK-401 and WK-415, two periods of record were compared because of missing data. The peak of the correlation coefficient for the time period from July 30 to September 5, 2008, ranged from about 260 to 300 minutes (mins; 4.3 to 5 hrs) and for September 16 to October 24, 2008, the peak ranged from about 200 to 280 mins (3.3 to 4.7 hrs), with the stress being observed in private well WK-401 first (negative time delay, fig. 26). Additional cross correlation was conducted using a second private well WK-400 and community

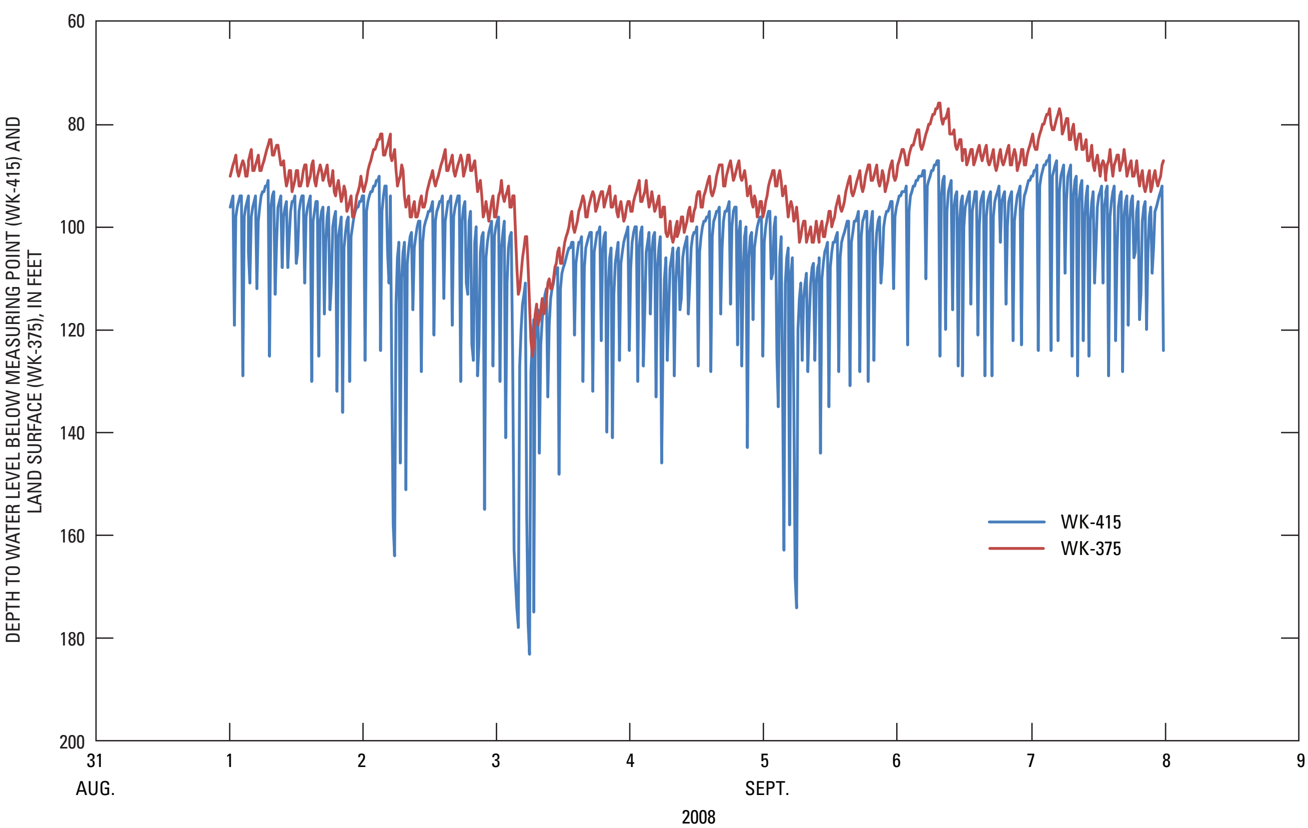


Figure 24. Overlay of water levels recorded in community well WK-415 and observation well WK-375, September 1–7, 2008.

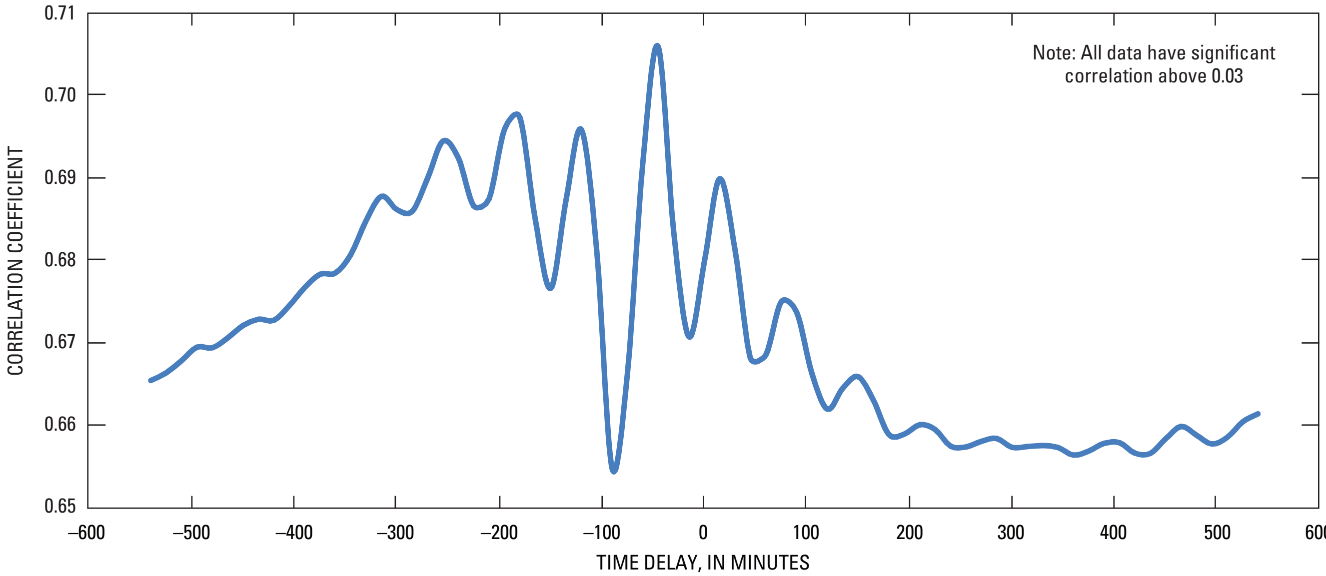


Figure 25. Cross-correlation coefficient calculations for water levels recorded in community well WK-415 in relation to water levels recorded in observation well WK-375, July 29–October 24, 2008.

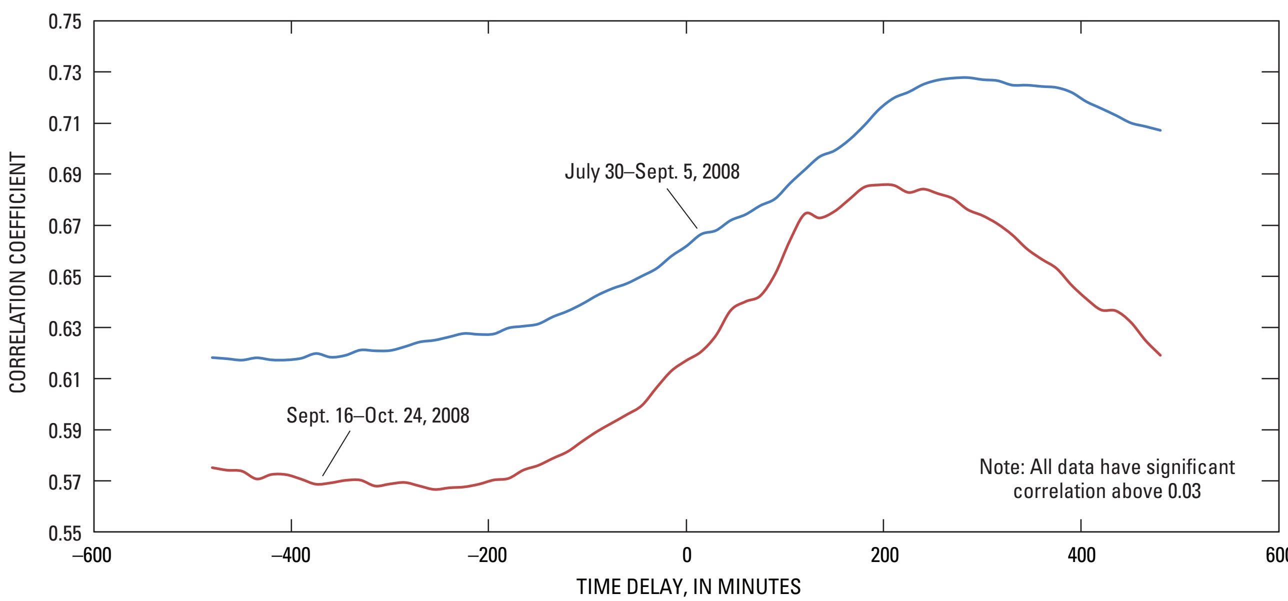


Figure 26. Cross-correlation coefficient calculations for water levels recorded in private well WK-401 and community well WK-415, July 30–October 24, 2008.

well WK-415. The results also indicated a response from the homeowner well first (negative time delay), with a peak delay to well WK-415 of about 150 mins (2.5 hrs) (fig. 27), similar to the comparison of the homeowner well WK-401 and the community well WK-415. The shorter period of data collection, however, may affect the time delay calculated. Similar to the comparison of observation well WK-375 and community well WK-415, it appears as though the stress most affecting water levels in the private wells occurs prior to correlated fluctuations in community well WK-415. Again, this could be community well WK-416 (no overlapping monitoring period; table 4) or an unknown large-capacity community supply outside of the study, or an unknown large-capacity irrigation well within or outside of the study area.

Further comparison of water levels recorded in observation well WK-375 with private well WK-401 resulted in a time delay ranging from about 0 to 150 min (2.5 hrs) with the stress observed in WK-401 first when there was a delay calculated (fig. 28). Thus, the stress observed in well WK-375 may be directly correlated with the same stress observed in the private wells, or the private wells may be affected by the unknown stress prior to the stress observed in well WK-375.

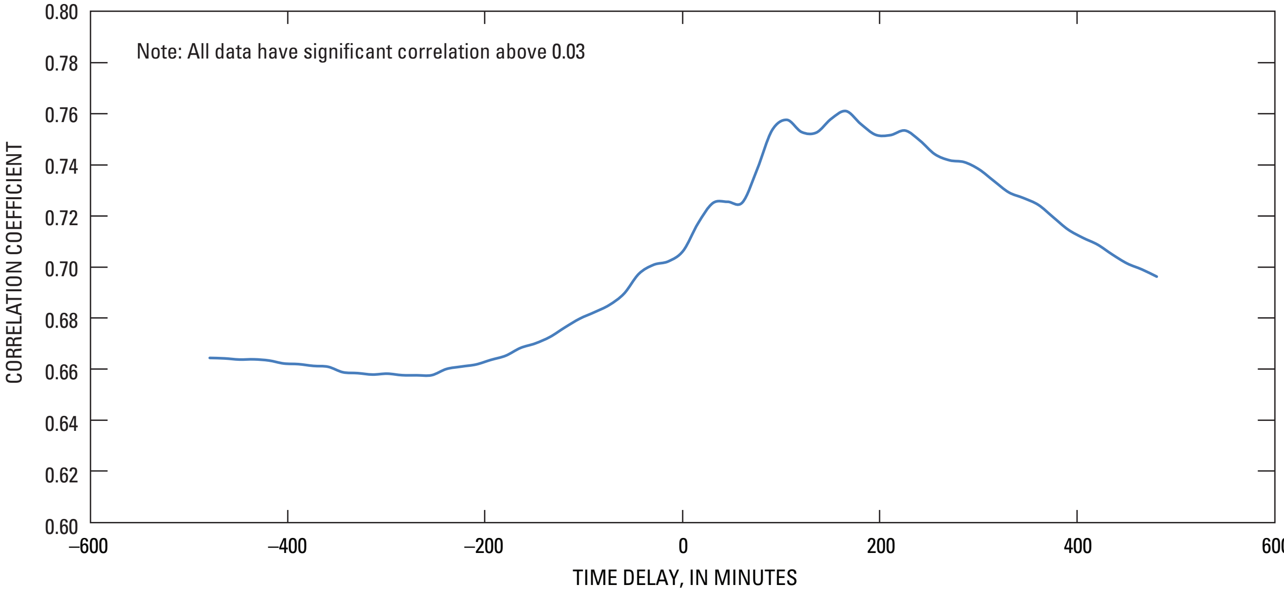


Figure 27. Cross-correlation coefficient calculations for water levels recorded in private well WK-400 and community well WK-415, August 22–October 24, 2008.

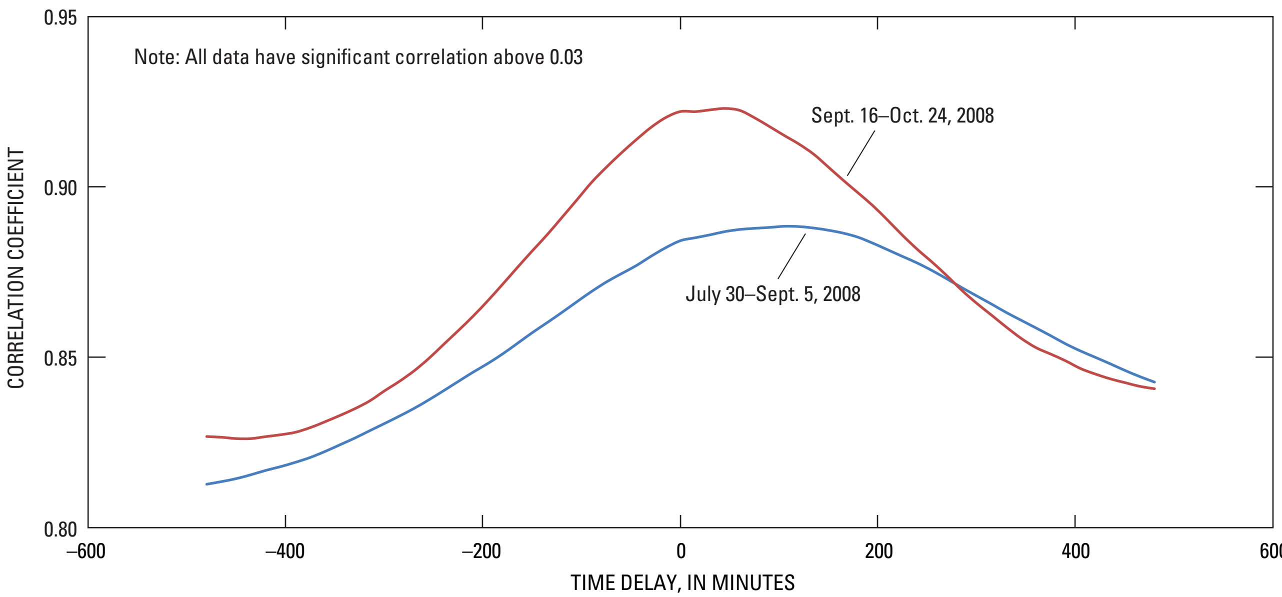


Figure 28. Cross-correlation coefficient calculations for water levels recorded in private well WK-401 and observation well WK-375, July 30–October 24, 2008.

Summary and Conclusions

Conditions in the fractured-bedrock aquifer described in this report represent an assessment of the effects of competitive use of the groundwater resource that may be comparable to similar hydrogeologic settings in the Piedmont and Blue Ridge Physiographic Provinces in the eastern United States where local groundwater resource-management issues have developed.

Groundwater levels in the study area of northwestern Wake County, North Carolina, were well below the reported water levels at the time of initial well drilling during the 1980s through the late 1990s, indicating that withdrawals in the area could potentially be exceeding groundwater recharge to the bedrock part of the aquifer. Well depths range from 150 to 515 ft and average 356 ft for private wells and 733 ft for three community wells in the area. As groundwater levels in the most dewatered areas typically ranged from about 100 to more than 200 ft below land surface during the study period (March 2008 through February 2009), a substantial thickness of the bedrock part of the aquifer tapped by the private wells became temporarily dewatered. Water levels in two community wells ranged from about 68 to 261 ft below land surface, also indicating a substantial dewatering of fractures in excess of 200 ft and approaching 300 ft near the shallower private wells. Based on findings from this study, the aquifer dewatering likely will continue without a reduction in withdrawals from the aquifer.

The aquifer recovered during a period following increased rainfall and reduced withdrawals during a period of lower demand in mid-August through mid-September 2008, with water levels rising 32 to 139 ft. However, as withdrawals increased in September 2008, an overall decline was observed through October 2008. Another recovery was observed in November, and water levels appeared to stabilize between 100 and 150 ft bls in the most dewatered areas through February 2009 at the end of the study period. This response suggests that the upper part of the aquifer was temporarily dewatered during periods of high water use, but during periods of high recharge and low water use, the aquifer recovered to near undeveloped water levels, indicating that dewatering was not necessarily permanent.

The deepest groundwater levels in the study area exhibit a correlation with regional and local geologic structural measurements, fracture traces, and borehole fracture orientations. Similar areal patterns of low groundwater levels were delineated during nine water-level measurement periods from March 2008 through February 2009. The lowest groundwater levels were noted along Norwood Oaks Drive, Bayleaf Trail, and Abbey's Grove Trail. Correlation of groups of groundwater-level distribution patterns with orientations of geologic structures from surficial mapping, borehole geophysical measurements, and interpretation of fracture traces suggests two dominant trends striking north-south and N. 65° W. The north-south trend was observed as an elongated area at the northern section of Norwood Oaks Drive and along the western side of Bayleaf Trail. The north-south trend is parallel to foliation measurements in the regionally mapped Falls Lake schist (N. 5° E. and N. 5° W.) as well as the amphibolite rock type (N. 5° E.). A secondary trend of N. 65° W. was observed from three wells having low water levels along Norwood Road. The N. 65° W. trend is similar to a joint set in the quartzofeldspathic gneiss (N. 51° W.). The north-south orientation was measured in well WK-368 at a depth of 398.4 ft bls (N. 7° E.), and the N. 65° W. orientation was measured in well WK-368 at depths of 80.8–81.4 ft bls (average N. 67° W.) and 86.4–86.6 ft bls (average N. 63° W.). Fracture traces mapped near the Norwood Oaks neighborhood vary somewhat from the north-south orientation, striking 7° (N. 7° E.) to 15° (N. 15° E.) and 357° (N. 3° W.) to 345° (N. 15° W.).

Because of a lack of storage in the bedrock part of the aquifer, the water levels respond dynamically to any changes in stress (withdrawals) on the system. The lowest water levels measured during the study period were in June 2008 and likely can be correlated with increased withdrawals to meet the high demand for irrigation purposes during the dry summer months. One community well located within about 900 ft of the Norwood Oaks subdivision was pumped at five times the volume reported in prior months. As an evaluation of fracture network interconnectivity, a statistical comparison of continuous water-level records from well pairs was made using cross-correlation methods. Results of the cross-correlation analyses suggested that an unknown stress was observed in the private wells and observation well WK-375 before the same stress was observed in community well WK-415. Time delays of 45 to 280 mins (more than 4 hrs) were calculated. Potential sources of this stress could be (1) community well WK-416, which had no overlapping monitoring period to analyze, (2) an unknown community well or large-capacity irrigation well either within or outside of the study area, and (3) domestic withdrawals.

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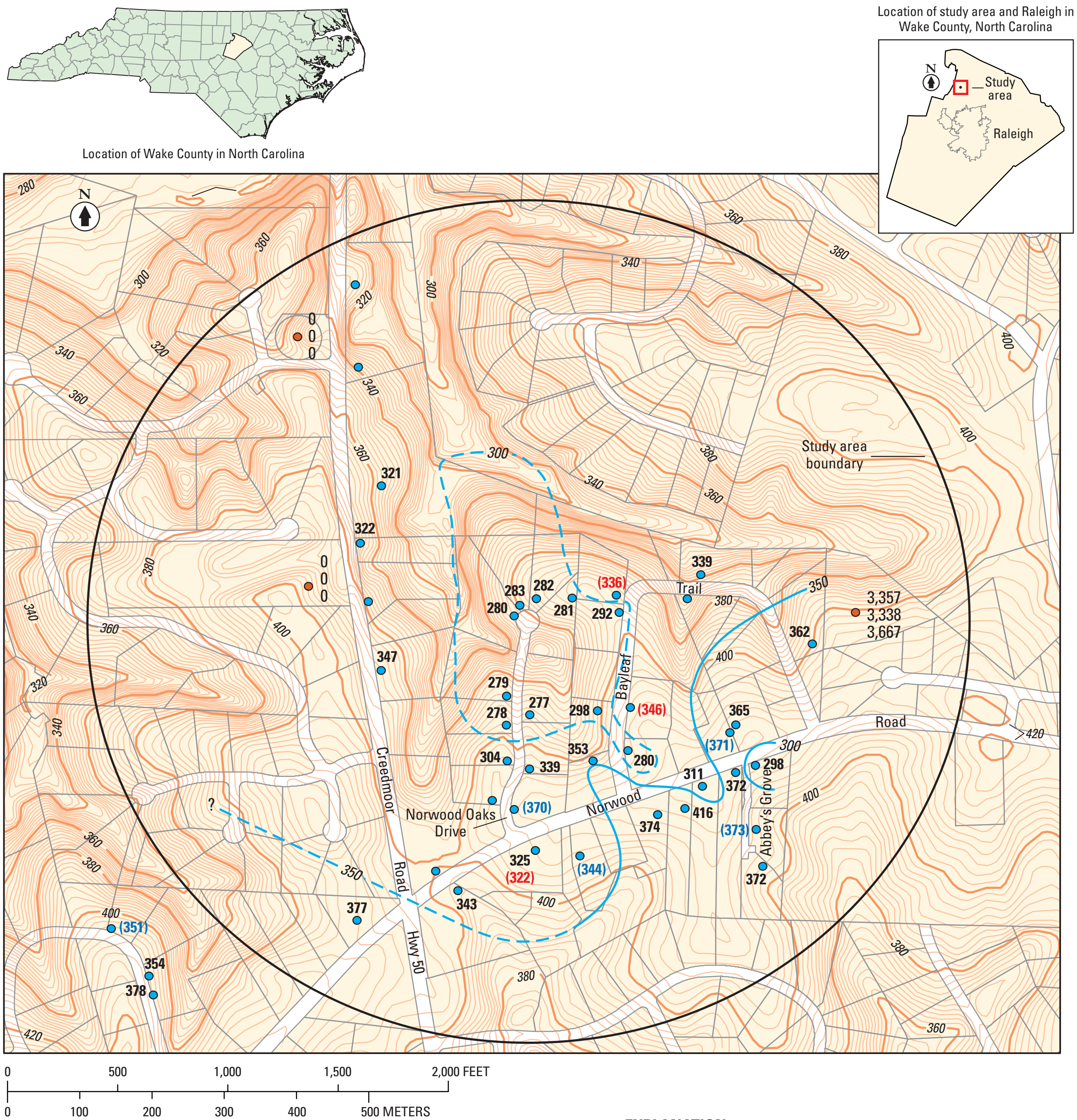
Appendix 1

Bedrock groundwater-level altitude maps showing the water-level measurements in private and observation wells in the study area on

A. March 28, April 2, 4, and 16, 2008
B. June 18 and 26, 2008
C. July 25 and August 12, 2008
D. September 19, 2008
E. October 17, 2008
F. November 21, 2008
G. December 19, 2008
H. January 29, 2009
I. February 27, 2009

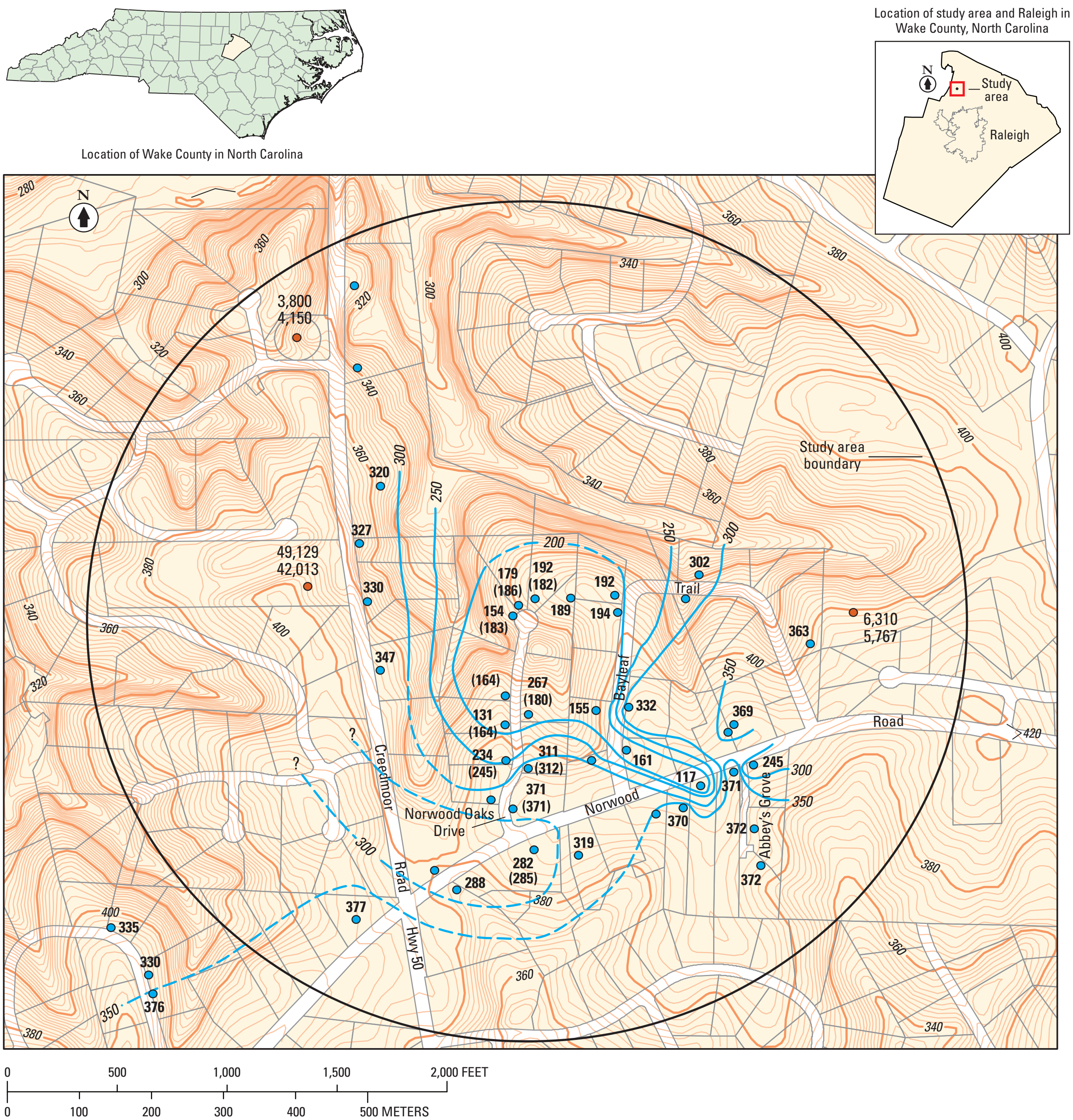


EXPLANATION

- Tax parcel boundaries
- 300 Water-level altitude contour above NAVD 88. Contour interval 50 feet. Dashed where approximate
- 300 Altitude of land surface above NAVD 88. Contour interval 2 feet
- 277 Privateor observation well location and depth to groundwater level below land surface (if no number, well was not measured)
- (353) April 2 and 4 altitudes (above NAVD 88) are blue
- (322) April 16 altitudes (above NAVD 88) are red
- 3,357 Community well and total daily withdrawals in gallons reported on respective days of water-level measurement

Note: Acoustic water-level measurements made in privateand observation wells may be deeper than recorded if obstructions in the well were present

Appendix 1A. Bedrock groundwater-level altitude map showing the water-level measurements in private and observation wells in the study area on March 28 and April 2, 4, and 16, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

300 Water-level altitude contour above NAVD 88. Contour interval 50 feet. Dashed where approximate

300 Altitude of land surface above NAVD 88. Contour interval 2 feet

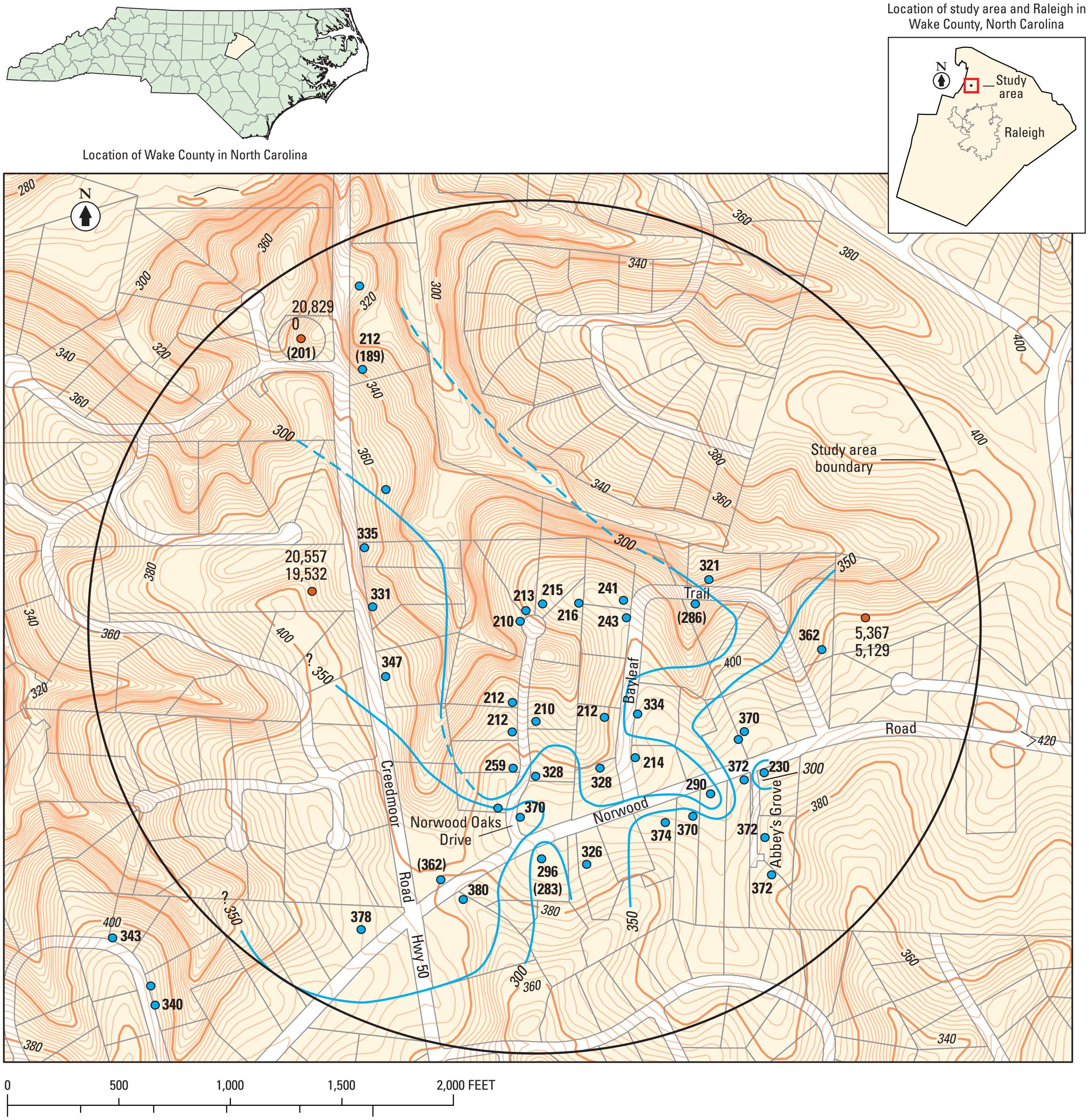
362 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

(180) June 26 altitude in parentheses

5,767 Community well and total daily withdrawals in gallons reported on respective days of water-level measurement

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Appendix 1B. Groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on June 18 and 26, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

300 Water-level altitude contour above NAVD 88. Contour interval 50 feet. Dashed where approximate

300 Altitude of land surface above NAVD 88. Contour interval 2 feet

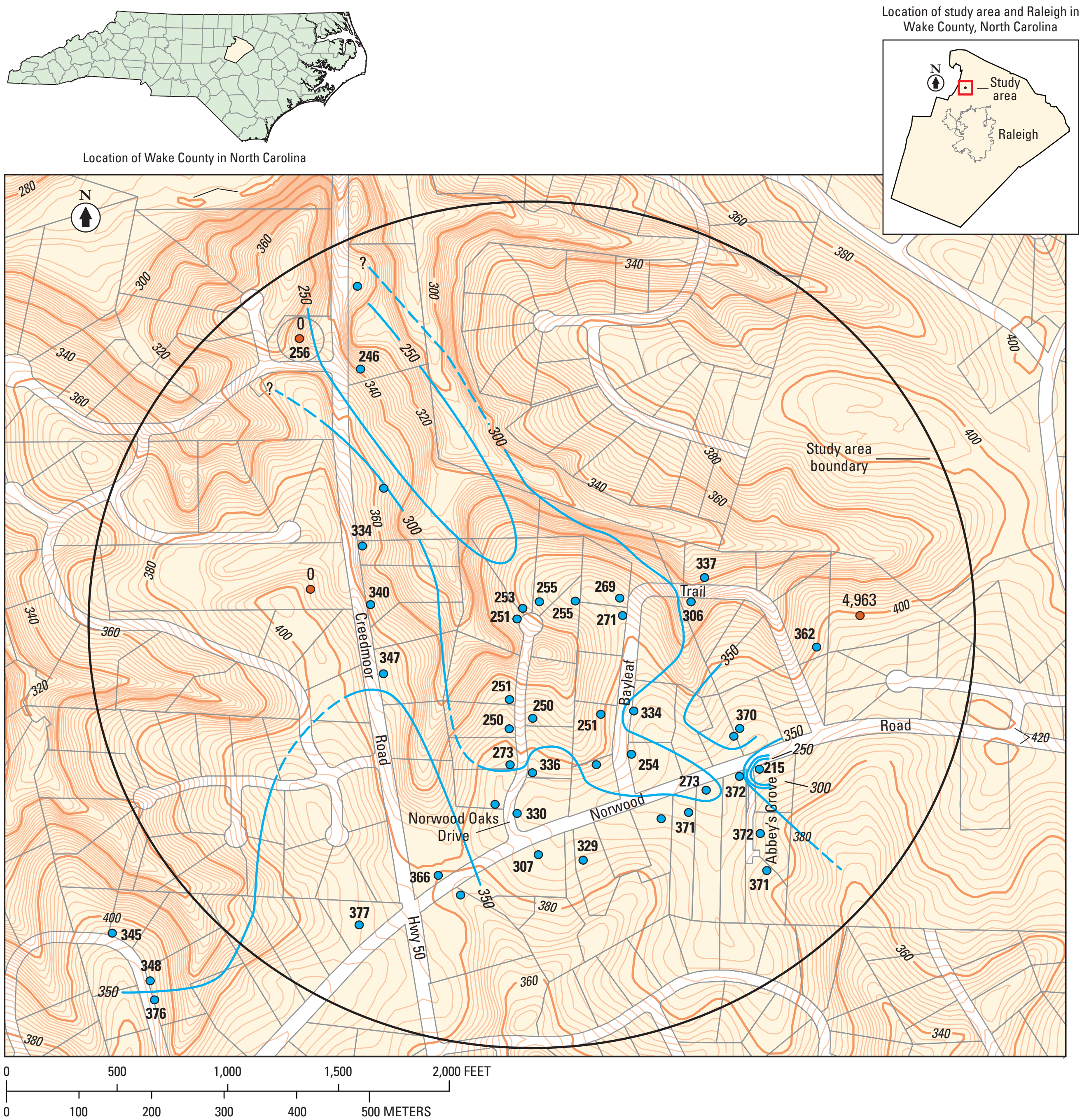
374 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

(283) August 12 altitude in parentheses

20,829 **(201)** Community well, total daily withdrawals in gallons reported on respective days of water-level measurement, and **water-level altitude above NAVD 88 (bold type)**

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Appendix 1C. Groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on July 25 and August 12, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

300 Water-level altitude contour above NAVD 88. Contour interval 50 feet. Dashed where approximate

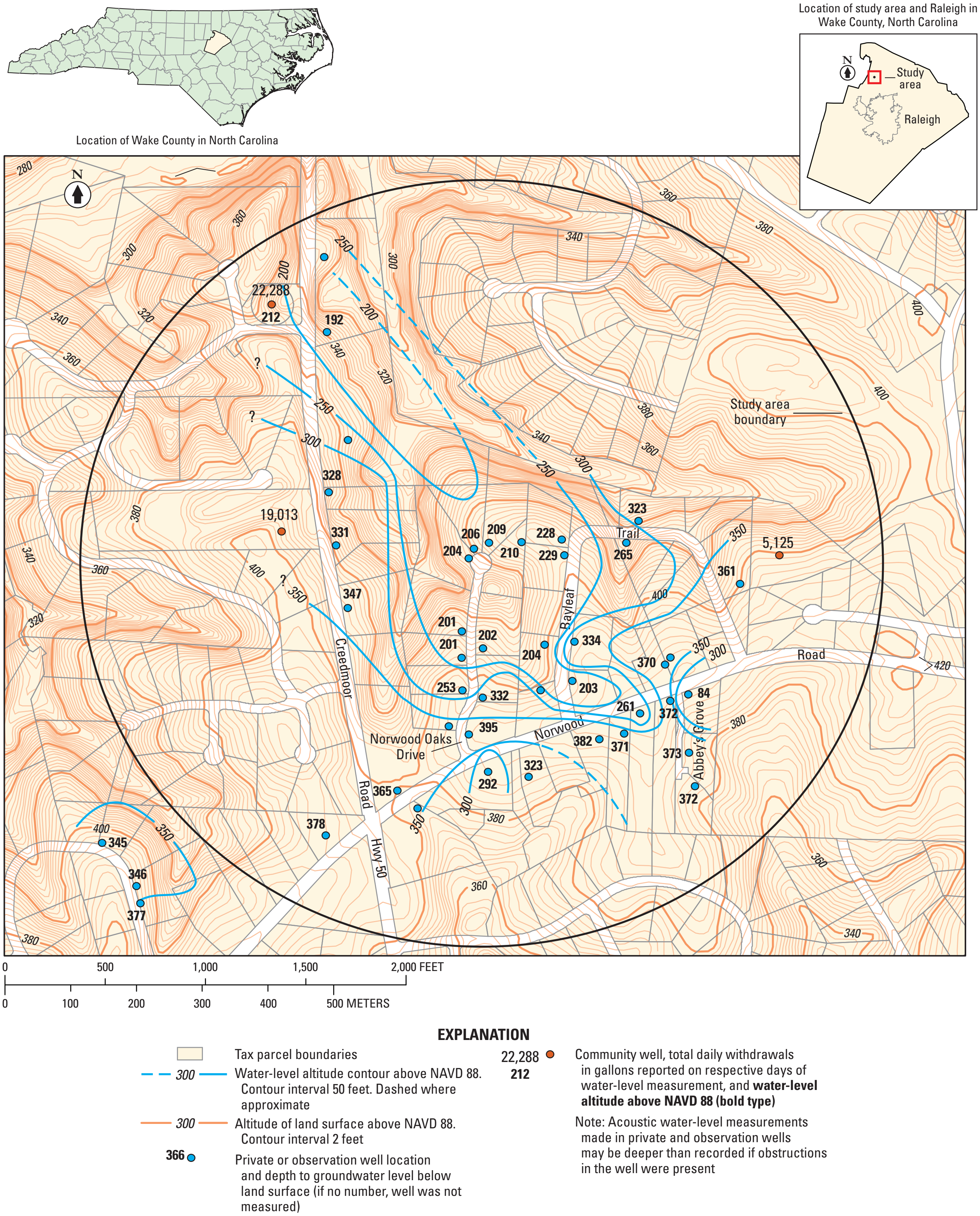
300 Altitude of land surface above NAVD 88. Contour interval 2 feet

366 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

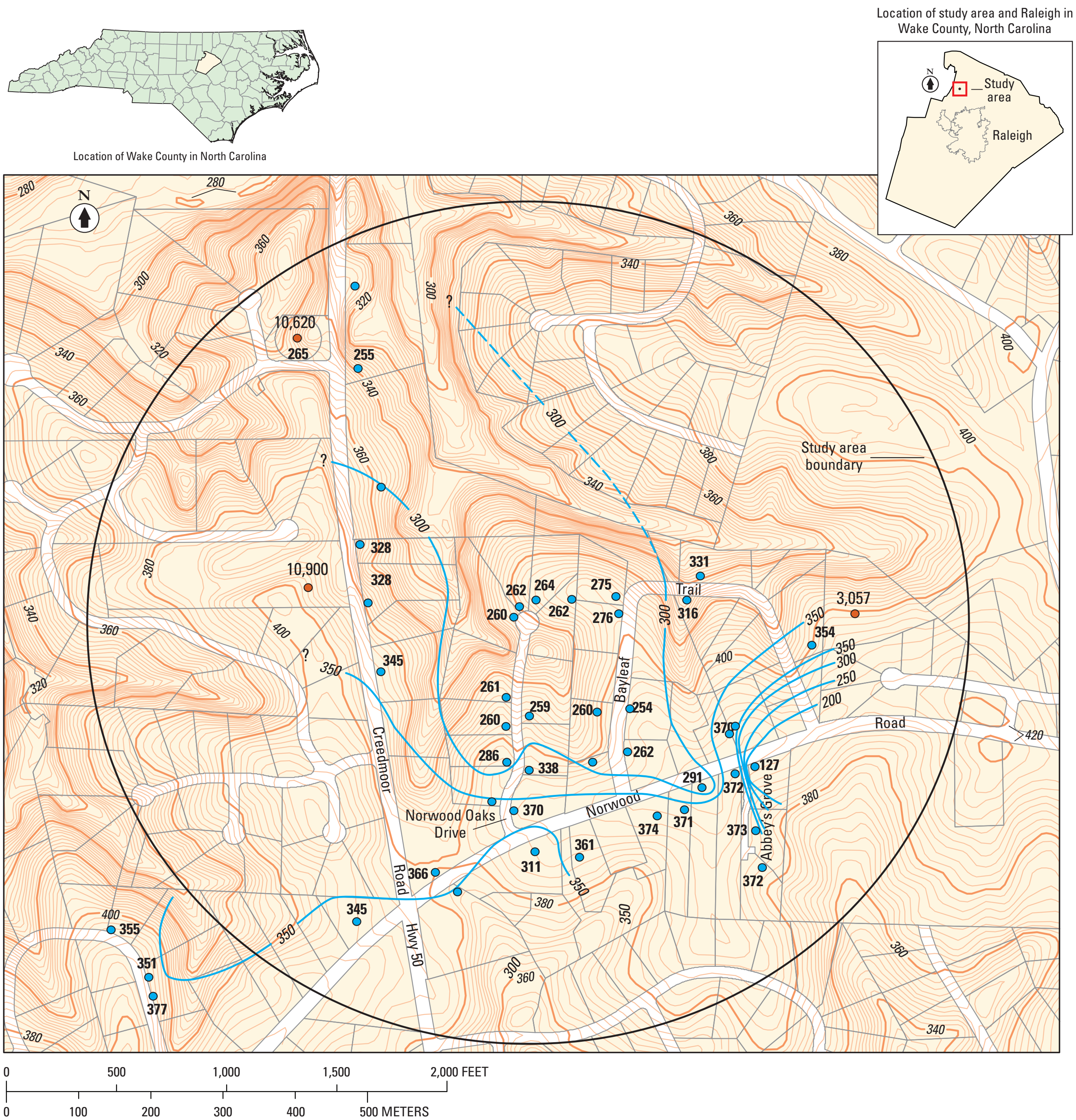
0 **256** Community well, total daily withdrawals in gallons reported on respective days of water-level measurement, and **water-level altitude above NAVD 88 (bold type)**

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Appendix 1D. Bedrock groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on September 19, 2008. [NAVD 88, North American Vertical Datum of 1988]



Appendix 1E. Bedrock groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on October 17, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

300 — Water-level altitude contour above NAVD 88. Contour interval 50 feet. Dashed where approximate

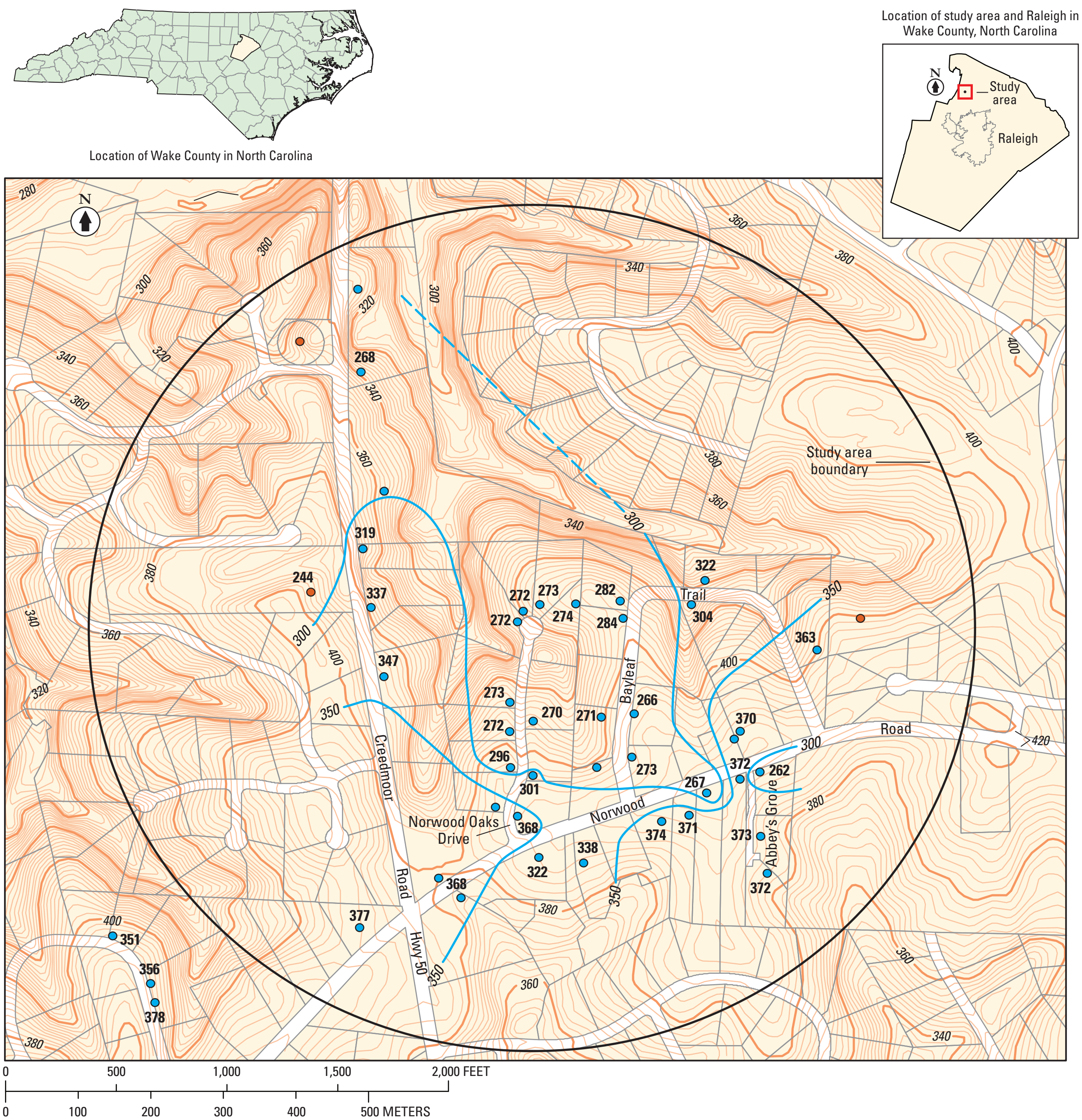
300 — Altitude of land surface above NAVD 88. Contour interval 2 feet

277 ● Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

3,057 ● **265** Community well, total daily withdrawals in gallons reported on respective days of water-level measurement, and **water-level altitude above NAVD 88 (bold type)**

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Appendix 1F. Bedrock groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on November 21, 2008. [NAVD 88, North American Vertical Datum of 1988]



EXPLANATION

Tax parcel boundaries

300 — Water-level altitude contour above NAVD 88. Contour interval 50 feet. Dashed where approximate

300 — Altitude of land surface above NAVD 88. Contour interval 2 feet

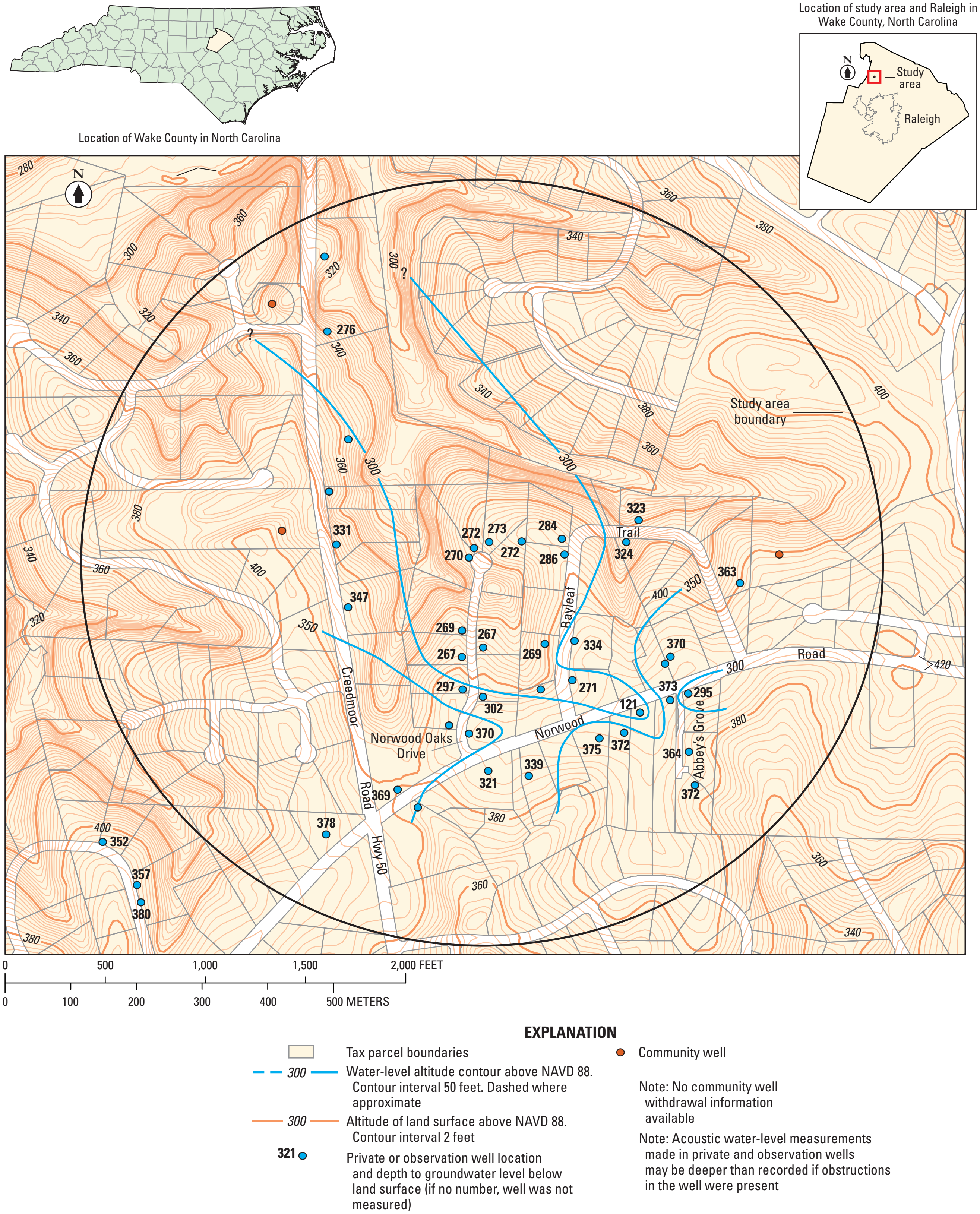
368 Private or observation well location and depth to groundwater level below land surface (if no number, well was not measured)

245 Community well, total daily withdrawals in gallons reported on respective days of water-level measurement, and **water-level altitude above NAVD 88 (bold type)**

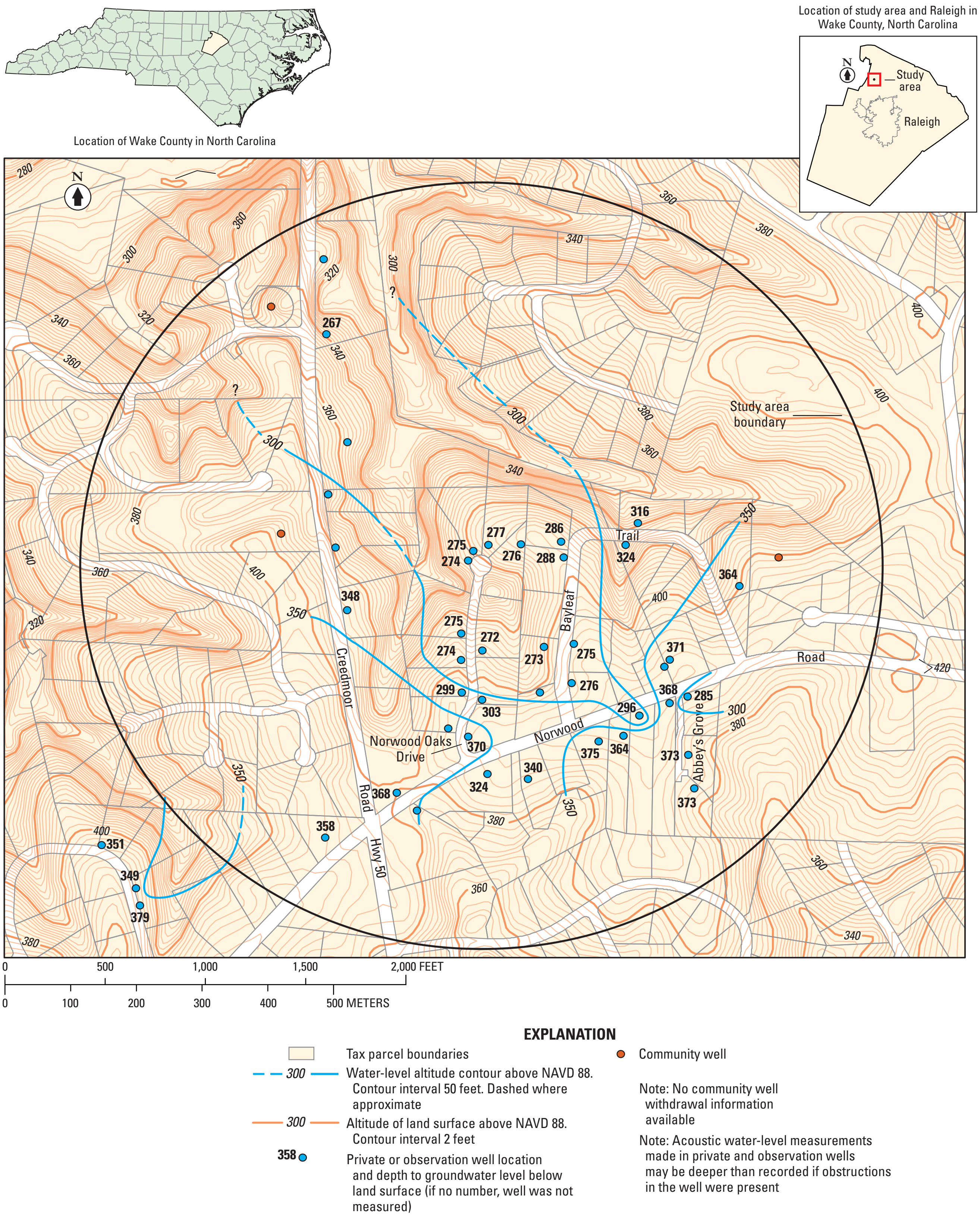
Note: No community well withdrawal information available

Note: Acoustic water-level measurements made in private and observation wells may be deeper than recorded if obstructions in the well were present

Appendix 1G. Bedrock groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on December 19, 2008. [NAVD 88, North American Vertical Datum of 1988]



Appendix 1H. Bedrock groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on January 29, 2009. [NAVD 88, North American Vertical Datum of 1988]



Appendix 1I. Bedrock groundwater-level altitude map showing the water levels measured in private and observation wells in the study area on February 27, 2009. [NAVD 88, North American Vertical Datum of 1988]

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