Hydrogeology of the Barnesville Hydrologic Research Site, Lamar County, Georgia

William M. Steele, David A. Brackett,
Madeleine F. Kellam, and Mark E. Hall

GEORGIA DEPARTMENT OF NATURAL RESOURCES
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Atlanta
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INFORMATION CIRCULAR 93

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ABSTRACT

The Barnesville Hydrologic Research Site, located 50 miles south of Atlanta and 1.8 miles northwest of Barnesville in Lamar County, Georgia, lies in the Piedmont Physiographic Province. A complex drainage pattern is predominant around the study area, indicating geologic control resulting from compositional layering, foliation, joints, contacts, faults, or other types of fracture systems. The purpose of this study was to measure the area and degree of influence of pumping from the City of Barnesville's Well #2 (Production Well) on ground-water levels in the immediate vicinity, as a part of a larger effort to understand ground-water movement in fractured-rock aquifer systems.

The site lies in the Towaliga fault zone, and rocks underlying the area consist of quartzite, augen gneiss, and sheared schist. The mean orientation of foliation within the fault zone and within a one-mile radius of the site is N77°E, dipping 50°NW, and the dominant joint orientation is roughly north-south within the Towaliga fault zone.

In the Piedmont and Blue Ridge provinces, precipitation infiltrates the earth's surface, flows into the regolith, then flows into an often complex system of fractures (joints, contacts, compositional layering, faults, weathered zones, etc.). Normal precipitation, measured at a climatological station located 16 miles north of the site, is 52.53 inches per year, but was less-than-normal for each year in the 1980's. Water levels in the six soil and three bedrock wells drilled at this site are directly affected by precipitation and evapotranspiration. The major water-bearing zone in the Production Well is from 50 to 60 feet. This zone of production is considered to be the transition zone where saprolite grades into less weathered rock.

Discharge from the Production Well stabilized between 65 and 70 gallons per minute during the April, 1990 24-hour aquifer test and between 80 and 85 gallons per minute during the July, 1990 72-hour test. The water levels in all observation wells (soil and bedrock), including those located across Big Towaliga Creek, drew down rapidly in both the 24- and 72-hour pumping tests. The maximum amount of drawdown recorded in observation wells ranged from 2.5 feet to almost 22 feet during the April, 1990 test, and from 3.1 feet to almost 22.5 feet during the July, 1990 test. Water levels in observation wells located closer to the Production Well drew down more than those located farther away. Twenty four hours after the pump was shut off in April, 1990 water levels recovered to slightly below the pre-pumping levels. Water levels generally recovered to a higher level following the 72-hour test when compared to the 24-hour test performed in April, due to recharge as a result of high amounts of rainfall during the 72-hour test.

All of the observation wells responded to pumping in a consistent manner, indicating a hydrologic connection between the observation wells and the Production Well. The rapid response of all soil wells to pumping indicates that the permeable regolith is the primary storage reservoir for water that resupplies the Production Well.

Additional observation wells would be needed to completely define the area of influence at this site. Ground-water flow in the transition zone and bedrock is primarily through fractures, and flow paths are more complicated than flow through the porous regolith. Therefore, defining the area of influence in the bedrock would probably be more difficult than defining the area of influence in the regolith and transition zone.

Only a portion of the recharge area was delineated during this study. The recharge area, at this site and most others, is not the same as the area of influence of a well. The recharge area of a porous media aquifer under water-table conditions (i.e. the regolith at this site) is usually considered to be the immediate drainage basin. However, the recharge area of a Piedmont crystalline-rock aquifer system may extend across drainage basin boundaries and can be elliptical, multi-elliptical, or other atypical shape. These shapes and extent are more likely during pumping conditions.

The rapid response of soil wells to pumping at this site and the relatively shallow water-bearing transition zone demonstrate the need for protecting affected areas around municipal supply wells from contamination, and for further study of ground-water flow in crystalline-rock aquifer systems.

INTRODUCTION

Location

The Barnesville Hydrologic Research Site is located in Lamar County, approximately 50 miles south of Atlanta (Figure 1). The site is 1.8 miles northwest of the county seat of Barnesville, 600 feet west of US Highway 41, just north of Big Towaliga Creek and just east of an unnamed intermittent stream (Figure 2).

Purpose

This study was conducted as part of the Georgia Geologic Survey's five-year program to evaluate the Groundwater Resources of the Piedmont and Blue Ridge Provinces. Some major goals of the program are to develop geologic techniques to locate favorable drilling sites, measure the response of crystalline-rock aquifers to pumping, and publish results of these investigations to aid in future groundwater development and protection. The purposes of this study were to investigate the patterns of ground-water movement in a crystalline-rock aquifer and, specifically, to measure the area and degree of influence of the City of Barnesville's Well #2 (Production Well).

Methodology and Quality Assurance/Quality Control

This investigation is divided into five general and sometimes overlapping phases: 1) geologic investigations, 2) drilling, 3) background water-level monitoring, 4) aquifer testing, and 5) data analyses.

Geologic Investigations

Geologic mapping was conducted in the vicinity of Barnesville during the summer of 1988 for the purpose of choosing favorable sites for ground-water development. Mapping was focused on describing rock types and describing and measuring the orientations of potential water-bearing fractures. The term "fracture" is used, in this report, to refer to any break or differential weathering in a rock and includes contacts, faults, joints, compositional layering, and foliation. The Production Well was drilled at a location recommended on the basis of lithology, structure and topography. Additional geologic mapping was conducted in the Barnesville 7.5 minute USGS quadrangle by Sneyd in 1990 and 1991. Details on quality assurance/quality control for Sneyd's investigation are included in her report (Sneyd, 1994).

A magnetometer survey was conducted as a part of the geologic investigation. The survey was intended to reveal whether or not there was a change in magnetic intensity due to a change in rock type in the vicinity of the Production Well. Prior to the magnetometer survey, all metal objects (keys, change, watches, pocket knives, etc.) were removed from the investigators' persons to eliminate anomalous

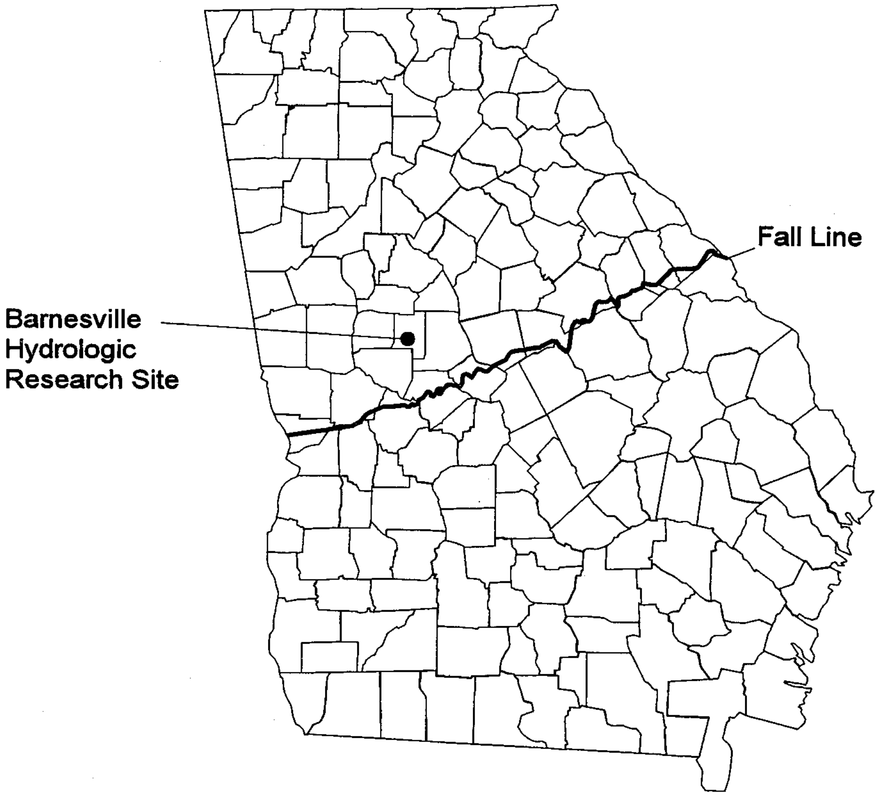


Figure 1. Location of the Barnesville Hydrologic Research Site.

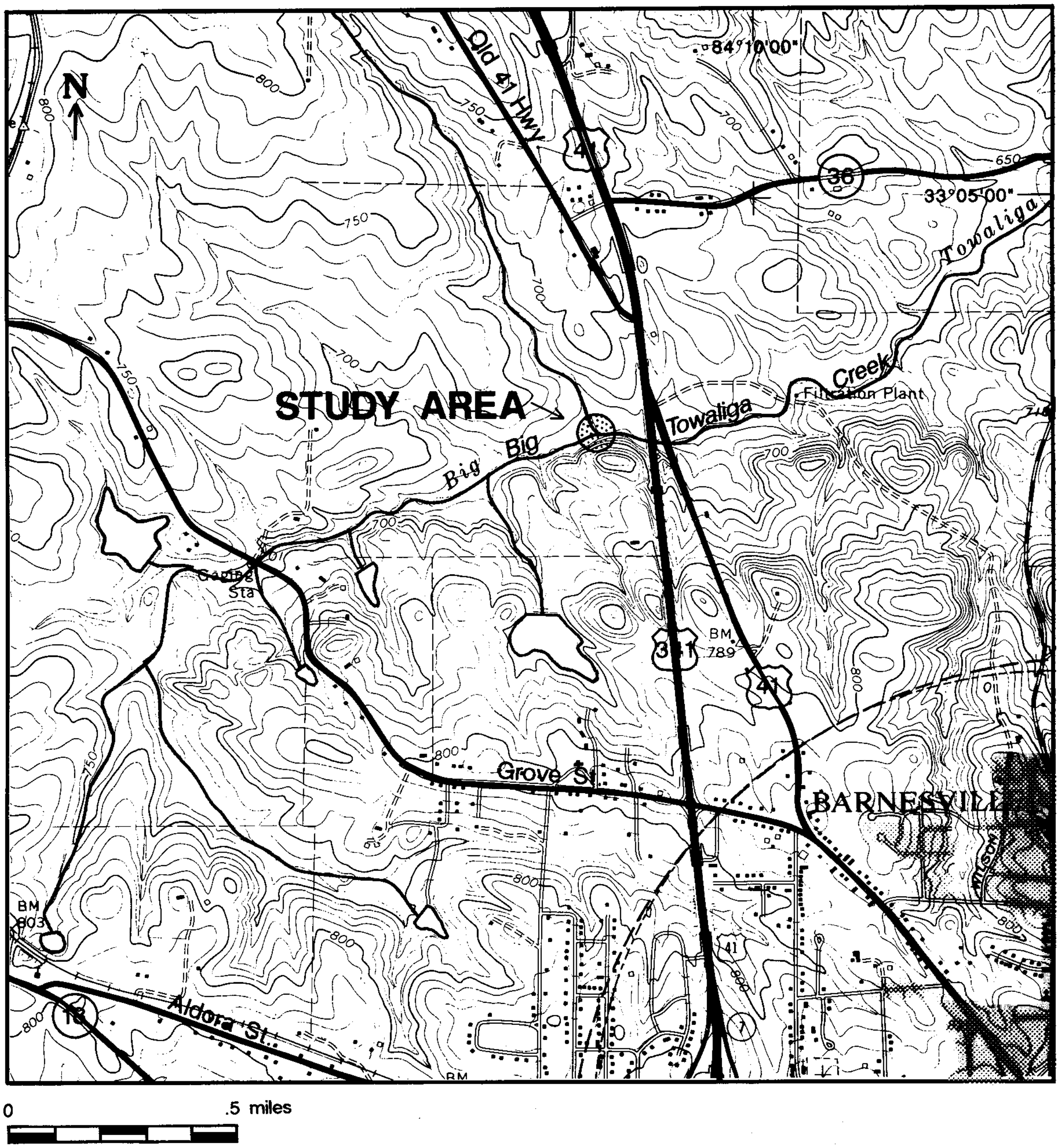


Figure 2. Topography of the Barnesville Hydrologic Research Site.

readings these items could have caused. Base station readings were taken before, during and after each profile to allow for adjustment due to the natural changes in the Earth's field of magnetic intensity. All measurements were recorded within 1000 feet of the Production Well at approximately 50-foot intervals. Measurements were made with an EG&G Model G-856A proton precession magnetometer.

A Georgia Geologic Survey (GGS) geologist was present during borehole geophysical logging to insure that data gathered were accurate and consistent with regard to instrument and depth calibrations. Digitally generated logs were compared with analog charts to further insure consistency.

Drilling

Observation well drilling sites were selected on the basis of structural geology, distance from the Production Well, and accessibility. The goal was to locate one deep well along strike from the Production Well and one deep well perpendicular to strike from the Production Well. The planned location of shallow monitoring wells, also based on geology, was to determine if the effect of pumping would extend beneath a perennial stream. Observation well drilling sites were selected to ensure all of the wells would be affected by pumping. Corehole 1 was drilled along strike

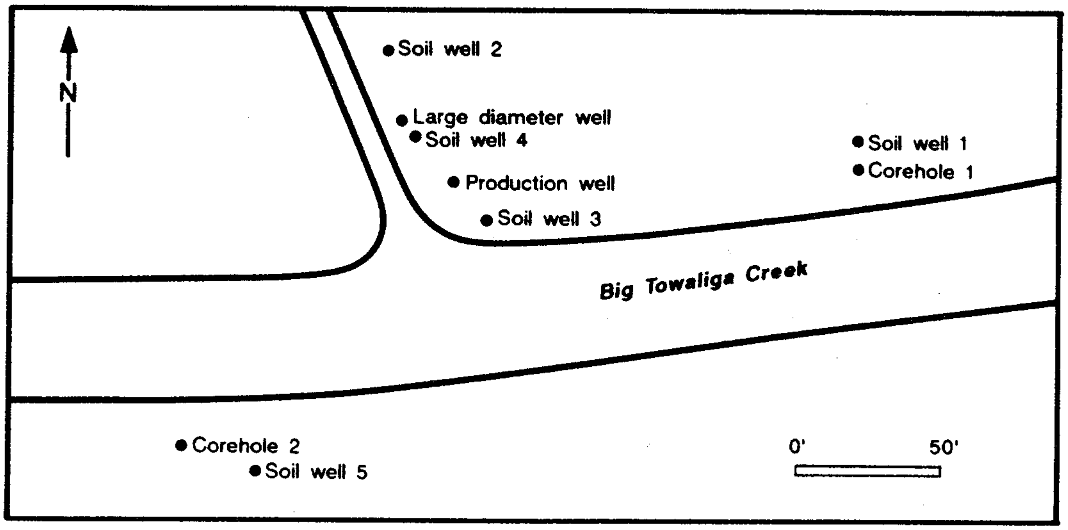


Figure 3. The Barnesville Hydrologic Research Site.

from the Production Well, as shown on Figure 3. In relation to the Production Well, Corehole 2 was drilled diagonal to the strike of rocks in the area and updip of the Production Well. An underground natural gas pipeline prevented drilling of Corehole 2 perpendicular to strike. Corehole 2 and Soil Well 5 were drilled across Big Towaliga Creek from the Production Well to determine if the areal effects of pumping would extend across the creek which is considered, under static conditions, to be a discharge point for shallow ground water. Accessibility problems prevented any observation wells from being drilled across the tributary, west of the Production Well.

The GGS Drill Crew drilled all observation wells. The principal investigator was on site to select drill sites, log cores and cuttings, record well construction data, and determine drilling completion depth. An on-site geologist insured accurate data collection and prevented miscommunications between the drill crew and project geologist.

Background Water-Level Monitoring

Background water-level monitoring was conducted from July, 1989 to August, 1990 to obtain a relatively long-term record of fluctuations. The majority of the records were collected on a monthly basis from the Production Well using a continuous-record water-level recorder. The recorder was set on a weekly time period, during drilling of Coreholes 1 and 2, so that a detailed record of the effect of drilling on static water levels could be obtained. The recorder was moved to the Large Diameter Well (Figure 3) after a pump was installed in the Production Well. Dataloggers equipped with pressure transducers were used to measure water levels at various times at the site from March to August, 1990. In order to insure the accuracy of data collected by the recorders and pressure transducers, water levels were measured using a steel tape or conductive probe during the analog chart replacement on the float recorder or the downloading of data from the dataloggers.

Aquifer Testing

Two constant-head pumping tests were attempted for the Barnesville test site; one 24- and one 72-hour test. The constant-head pumping test methodology developed by Brackett and others (1989) was attempted. During the constant-head pumping test, the water level is rapidly lowered and maintained a safe level above the pump throughout the test. The purpose of this test is to induce maximum stress on water stored in the bedrock and regolith aquifers. However, the pump installed for the tests proved inadequate to stress the aquifer sufficiently for a constant-head test, therefore, the standard constant-rate methods were used. A description of constant-rate methods is discussed in Driscoll (1986).

Discharge from the Production Well was measured by an orifice bucket designed, constructed and modified by the GGS (unpublished data on file at the GGS). For all tests, the water level in the orifice bucket was measured periodically by reading a manometer attached to the side of the bucket. A water-level recorder was used, in addition to the manometer, to measure water levels continuously for the April, 1990 and July, 1990 tests. Both types of measurements were made to test the viability of continuous measuring by the water-level recorder.

During the pumping tests, water-level changes in the wells were measured using pressure transducers and dataloggers, conductive probe tapes, and water-level recorders. Pressure transducers were set to measure water levels at one-minute intervals , analog recorders measured water levels continuously, and wells were periodically measured using conductive probe tapes to provide backup information in case of equipment failure. A stilling well, consisting of one inch diameter pvc pipe, was used for water-level measurements in the Production Well to minimize the effects of cascading water and turbulent water produced by pumping.

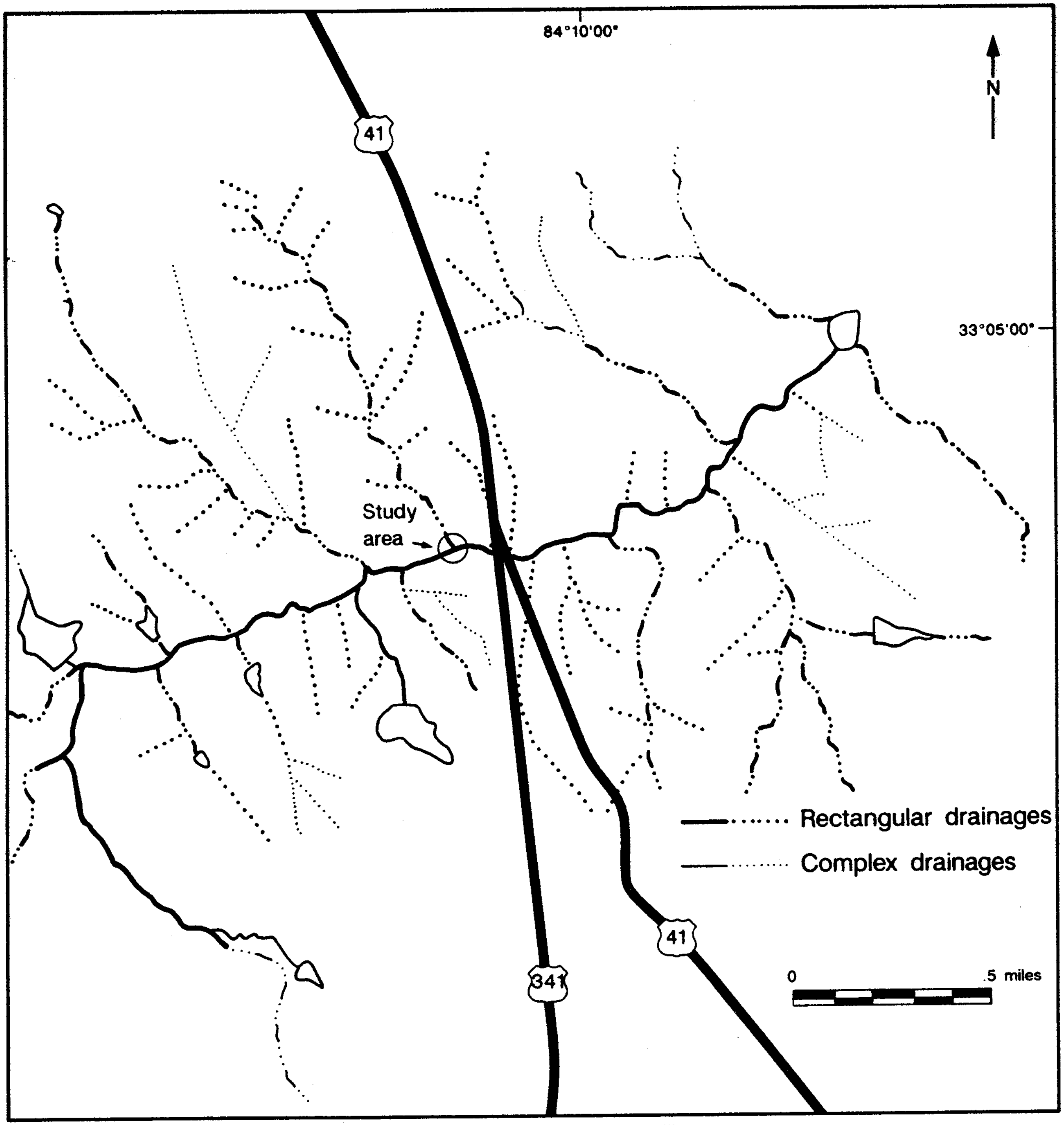


Figure 4. Drainage in the Barnesville area.

Field measurements of some water-chemistry properties were conducted at various times during the aquifer testing portion of this investigation by GGS's Ground-Water Management Program. Instruments used were calibrated prior to making measurements.

Data Analyses

The vast majority of data reduction and analysis focused on the aquifer tests and, to a lesser extent, background water-level monitoring data. Measurements from pressure transducers and water-level recorders were checked against hand-measured data to insure consistency. Datalogger measurements were imported into spreadsheet software for data reduction and verification and later into graphics software to produce charts for this report. All entries on the spreadsheet program were verified against entries on the data sheets. All data collected for this report are on file at the GGS.

Previous Investigations

Numerous regional and statewide geologic and hydrogeologic investigations have included Lamar County. This following section includes a discussion of those studies that are specific to the Barnesville/Lamar County area.

A field trip guidebook by Grant (1967) describes the geology of the Barnesville area, concentrating specifically on the Towaliga fault zone. Grant states that the fault dips 50 degrees to 70 degrees to the north, and that movement has been both strike-slip and dip-slip, and that the fault zone has undergone three periods of movement. Grant's report includes a geologic map and cross section.

Flavilla (1985) performed a gravity survey of Lamar County. His report indicates that gravity gradients are parallel to sub-parallel to the strike of the Towaliga fault zone.

Atkins (1988, unpublished) mapped the geology of the Barnesville area in some detail for the purpose of selecting geologically favorable drilling sites. The City of Barnesville's Production Well was drilled at one of the sites he recommended.

Gorday (1989) studied the hydrogeology of Lamar County. He investigated different field and office techniques for selecting potential high-yielding well sites. These techniques included analysis of topographic maps and aerial photographs, field geology and surface geophysical methods (magnetometry and resistivity). An inventory of drilled wells was compiled for that report. Gorday also studied the ground-water chemistry and quality of Lamar County. He found that iron and manganese were the most common naturally occurring water chemistry problems.

Clarke and Peck (1991) provided a general evaluation of the ground-water resources of the southern metropolitan Atlanta region, which included the Barnesville area. Estimates of ground-water availability for the south-metro region were discussed in that report.

In late 1990 and early 1991, Sneyd conducted detailed lithologic and structural mapping of the Barnesville 7.5 minute USGS quadrangle. An area within one mile of the Barnesville Hydrologic Research Site was studied in detail. The purpose of that investigation was to provide a more comprehensive geologic characterization of the research site and explore its relation to the hydrogeology of the area (Sneyd, 1994).

Acknowledgments

The authors wish to thank Patricia and Joe Edwards for allowing GGS the use of their property for extensive drilling and hydrogeologic testing. Appreciation is also extended to Joanne Cannafax, City Manager of Barnesville for granting permission to the GGS for use of the City's well as the production well at this site. Jim Traywick of Middle Georgia Water Systems patiently worked with the authors in having pumps installed and providing generators for numerous pumping tests.

PHYSIOGRAPHY AND CLIMATE

The study area lies in the Washington Slope District of the Piedmont Physiographic Province. The Washington Slope District is characterized by a gently undulating land surface where streams occupy broad, shallow valleys with long gentle slopes separated by broad rounded divides (Clark and Zisa, 1976). Big Towaliga Creek flows through a valley with a gently sloping north side and a much steeper south side (Figure 2). Elevations range from approximately 665 feet above mean sea level (MSL) on the valley floor to over 760 feet above MSL on a hill just south of the site. The research site lies in a wooded floodplain with numerous large deciduous trees and moderate undergrowth.

The research site lies within the Ocmulgee River Basin. Streams in this basin eventually flow into the Atlantic Ocean. Big Towaliga Creek flows east-northeast, joins with several other streams to form the Towaliga River, and flows into the Ocmulgee River about 15 miles (airline) east of the study area. A complex drainage pattern is prevalent in the immediate area (Figure 4). This pattern reflects some control by joint or fault systems (Thornbury, 1969, p. 120) or other fracture systems. The overall drainage pattern of Big Towaliga Creek is controlled by the Towaliga fault zone. The upper reaches of seven intermittent streams and small drainages exhibit a more dendritic drainage pattern (Figure 4).

Background climatological data were obtained from published reports by the National Oceanic and Atmospheric Administration for the two active weather stations located closest to the study site. The most comprehensive information was obtained from the University of Georgia's Experiment Station which is located about 16 miles (airline) north-northwest of the site. Additional data from the Forsyth 6 NNW Station, located approximately 12 miles (airline) east of the site, were also used. The average annual temperature at the Experiment Station is 61.8 degrees Fahrenheit (F) with an average January temperature of 43.2 degrees F and an average July temperature of 78.6 degrees F. Normal (30-year average) precipitation at the Experiment Station is 52.53 inches per year; however, annual precipitation was below that amount for each year in which data are available from 1980 to 1989 (Figure 5, p. 6). The greatest amount of precipitation usually occurs in March and July, while the lowest precipitation is usually in October and November (Figure 6, p. 6). At the Forsyth 6 NNW station, annual precipitation ranged from a high of 57.33 inches in 1982 to a low of 38.06 inches in 1988 (Figure 7, p. 7). Average annual and monthly data were not available for this station.

GEOLOGY

A general discussion of the geology of the area is included in the following section to provide a more comprehensive picture of the hydrogeologic characteristics of this site. The authors recommend that readers consult the report by Sneyd (1994) to obtain a complete and detailed under-

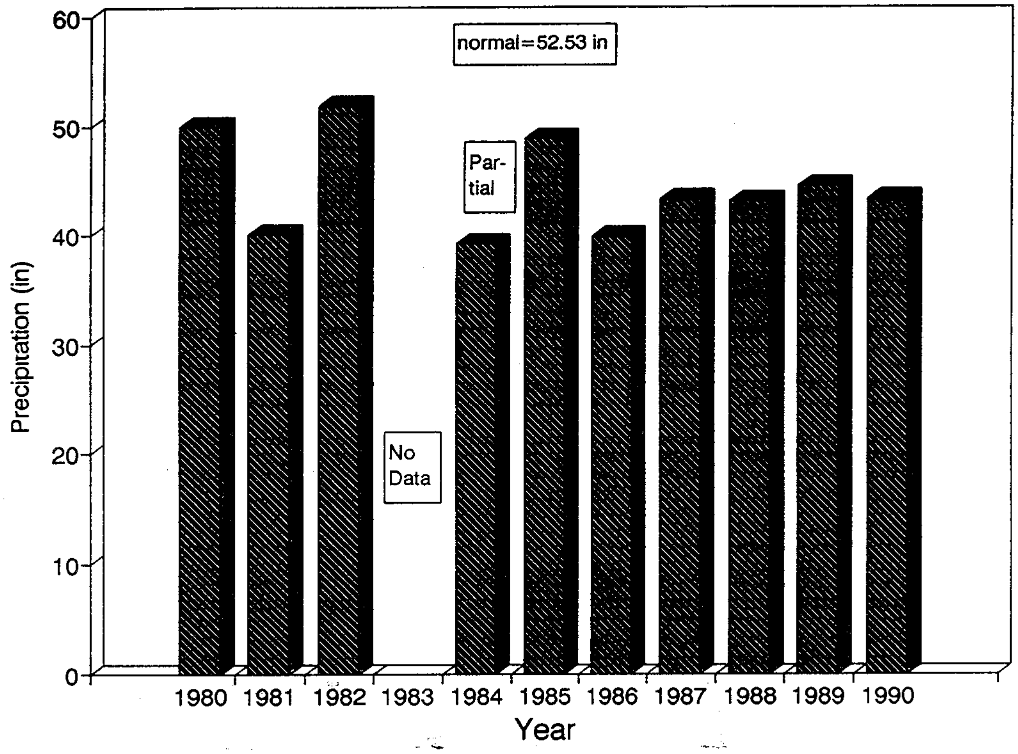


Figure 5. Annual precipitation at the Experiment Station, 1980-1990.

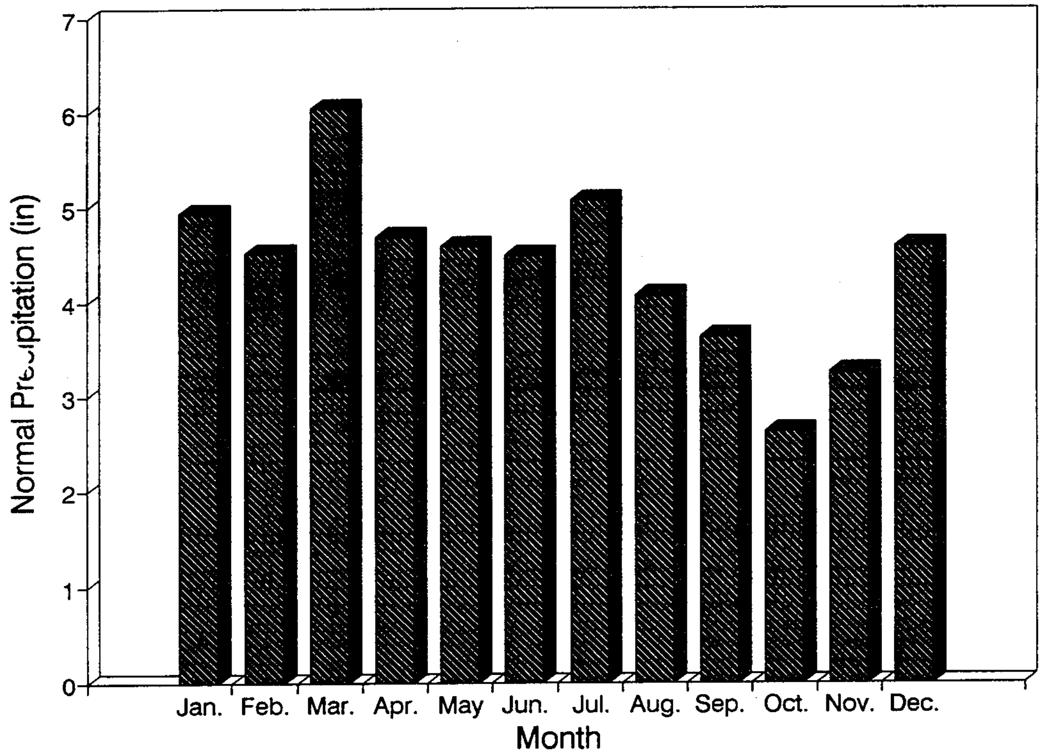


Figure 6. Normal monthly precipitation at the Experiment Station.

standing of the geology of the Barnesville Hydrologic Research Site. Her report focused on the detailed lithologic and structural characteristics of the area within a one mile radius of the site and the general geologic characteristics of most of the Barnesville 7.5 minute quadrangle.

Regolith

Soils at the site adjacent to Big Towaliga Creek and its tributary are of the Wehadkee series and consist of surface layers of sandy loam and silty clay loam to sandy clay loam

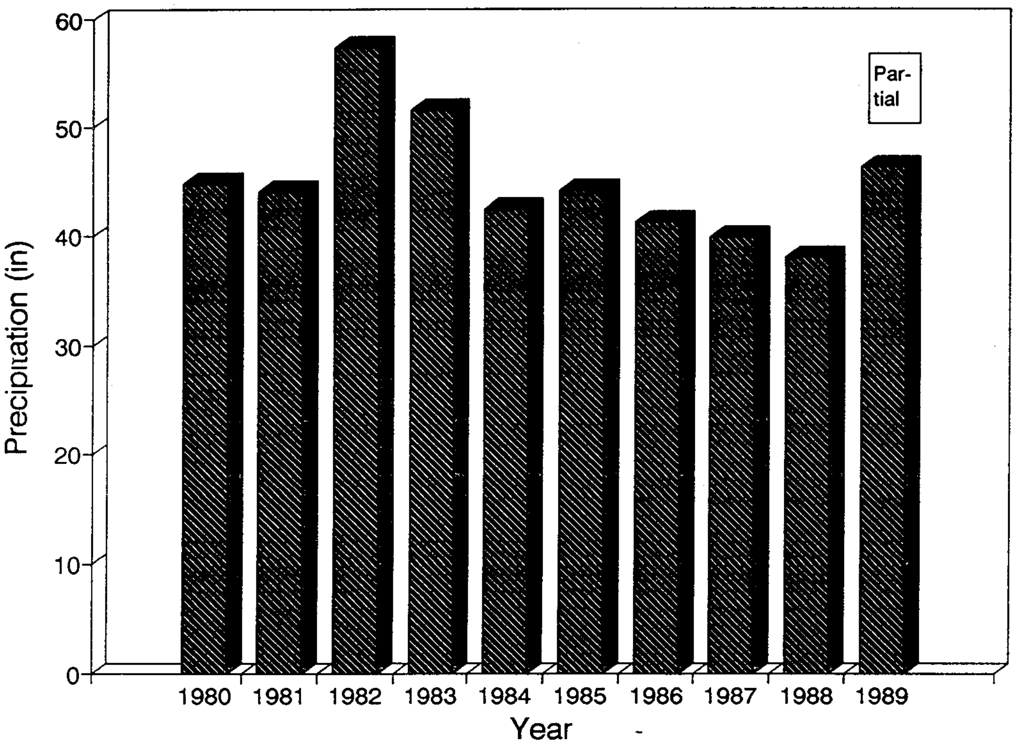


Figure 7. Annual precipitation at the Forsyth 6 NNW Station, 1980-1989.

(Davis, 1972). In areas outside of the immediate floodplain of Big Towaliga Creek and its tributary, 8-10 inches of yellowish-brown to dark grayish-brown sandy loam are present at the surface (Davis, 1972). Yellowish-brown to yellowish-red sandy clay loam or sandy clay, and red clay, 4 to 25 inches thick, underlie surface soils in areas away from the creeks. Soils outside of the immediate floodplain on the north side of Big Towaliga Creek are Appling sandy loam, while soils outside the immediate floodplain on the south side of Big Towaliga Creek are Cecil sandy loam (Davis, 1972).

Alluvium was encountered in at least three wells at the research site. In Corehole 2 (Figure 3), a tan to very light brown, poorly sorted, fine- to very coarse-grained sand having pebble- to cobble-sized mylonitic quartzite was encountered from 16 to 22 feet below land surface. Soil Well 1 intersects a buff to tan and gray, poorly sorted, fine sand to gravel-sized sediments with quartz pebbles from 7-14 feet. A buff to tan, moderately to poorly sorted, medium- to coarse-grained quartz sand was encountered from about 12-20 feet in Soil Well 2. Alluvium was logged from core in Corehole 2 and Soil Well 1, and from well cuttings in Soil Well 2. Depth intervals of alluvium in the remainder of the observation wells were difficult to determine due to the mixing of cuttings and the delay in cuttings reaching land surface; however, alluvium was present in samples collected at these observation well locations. Based on this evidence, the authors interpret that a continuous layer of alluvium, having a minimum thickness of 6 to 8 feet, underlies this site due to the presence of alluvium in cuttings or core collected at all of the observation well locations. The hydraulic conductivity of this alluvium is probably relatively high due to its high sand content.

Saprolite was encountered during the drilling of all wells from the base of the alluvium to depths between 50 and 60 feet. Tan to brown, foliated, highly weathered, schistose saprolite is predominant at the site on the south side of Big Towaliga Creek. This type of saprolite also occurs, to a lesser extent, on the north side of the creek. A buff to tan, very fine- to coarse-grained gneissic saprolite with structures such as compositional layering and relic foliation, occurs just below the alluvium and above the schistose saprolite on the north side of Big Towaliga Creek. Quartzite and mylonite layers occur at various intervals, especially on the north side of Big Towaliga Creek. These layers are weathered and broken, and are probably discontinuous in that they were encountered at variable depth intervals in the observation wells. Thickness of the layers varies from a few inches to about one foot.

Transition Zone/Bedrock

A zone of transition from saprolite to relatively unweathered rock occurs at a depth of 50-60 feet throughout the study area. This zone ranges in thickness from about 15 feet to as much as 40 feet. The transition zone appears to be the major water-bearing zone underlying the site based on observation during drilling, a significant increase in borehole diameter just below casing in the Production Well and the presence of highly fractured rock with alternating weathered and unweathered layers just below the saprolite in the coreholes. This interpretation is consistent with the findings of Harned and Daniel (1989) from an investigation in the North Carolina Piedmont.

Relatively unweathered rocks underlying the transition zone consist of feldspathic, micaceous quartzite, which is locally mylonitic, sheared, silicified, garnet-muscovite-biotite-quartz-feldspar gneiss, ranging from augen gneiss to blasto- and ultramylonite, and sheared biotite-feldspar-quartz-muscovite schist (Sneyd, 1994). The schist may represent a section of the gneiss that has been sheared to a greater degree (Sneyd, 1994). The quartzite underlies the southern part of the site and is penetrated by Corehole 2 (Figure 3). This quartzite is resistant to weathering and underlies the hill on the southern side of the site. The gneiss is less resistant to weathering and underlies the northern part of the site, which is relatively flat. Sheared schist occurs within the gneiss unit. Corehole 1 penetrates both the schist and gneiss units.

Structure

The Towaliga fault zone is the major geologic structure underlying the study site and is about 4000 feet wide in the Barnesville area. The Towaliga fault itself is a normal fault that strikes N60° to 70°E and dips 50°-70°NW. The trace of the fault is located about 1100 ft. north of the site. The fault has undergone at least three periods of strike-slip and dip-slip movement (Grant, 1967). A thrust fault within the Towaliga fault zone underlies the site and is penetrated by Corehole 1 between 205 and 225 feet and by Corehole 2 at about 90 feet. A second, deeper thrust fault is interpreted to be present 300 to 500 feet below land surface at the site (Sneyd, 1994).

A total of 167 foliation orientations were measured in the Towaliga fault zone, within a one-mile radius of the research site. The mean foliation orientation of this data set is N77°E, 50°NW within the fault zone (Sneyd, 1994). Similarly, the mean orientation for 141 foliations measured within a one-mile radius of the site is N77°E, 50°NW. These measurements appear as well defined groups on plots, with little scatter. The general direction of flow of Big Towaliga Creek near the study area is parallel to the strike of foliation, indicating that the creek is structurally controlled by differential weathering and erosion.

Prominent joint sets were also described and measured during Sneyd's study. The orientation of the dominant joint set near and within the Towaliga fault zone is about due north-south (Sneyd, 1994). An east-west joint set, and a less-developed northeasterly to northwesterly aligned set also are present within the Towaliga fault zone. Joint orientations for an area within a one-mile radius of the study site show a dominant north-south and a northeast trend (Sneyd, 1994). The north-northwest trending tributary to Big Towaliga Creek at the site may be controlled, at least partially, by the dominant north-south joint set.

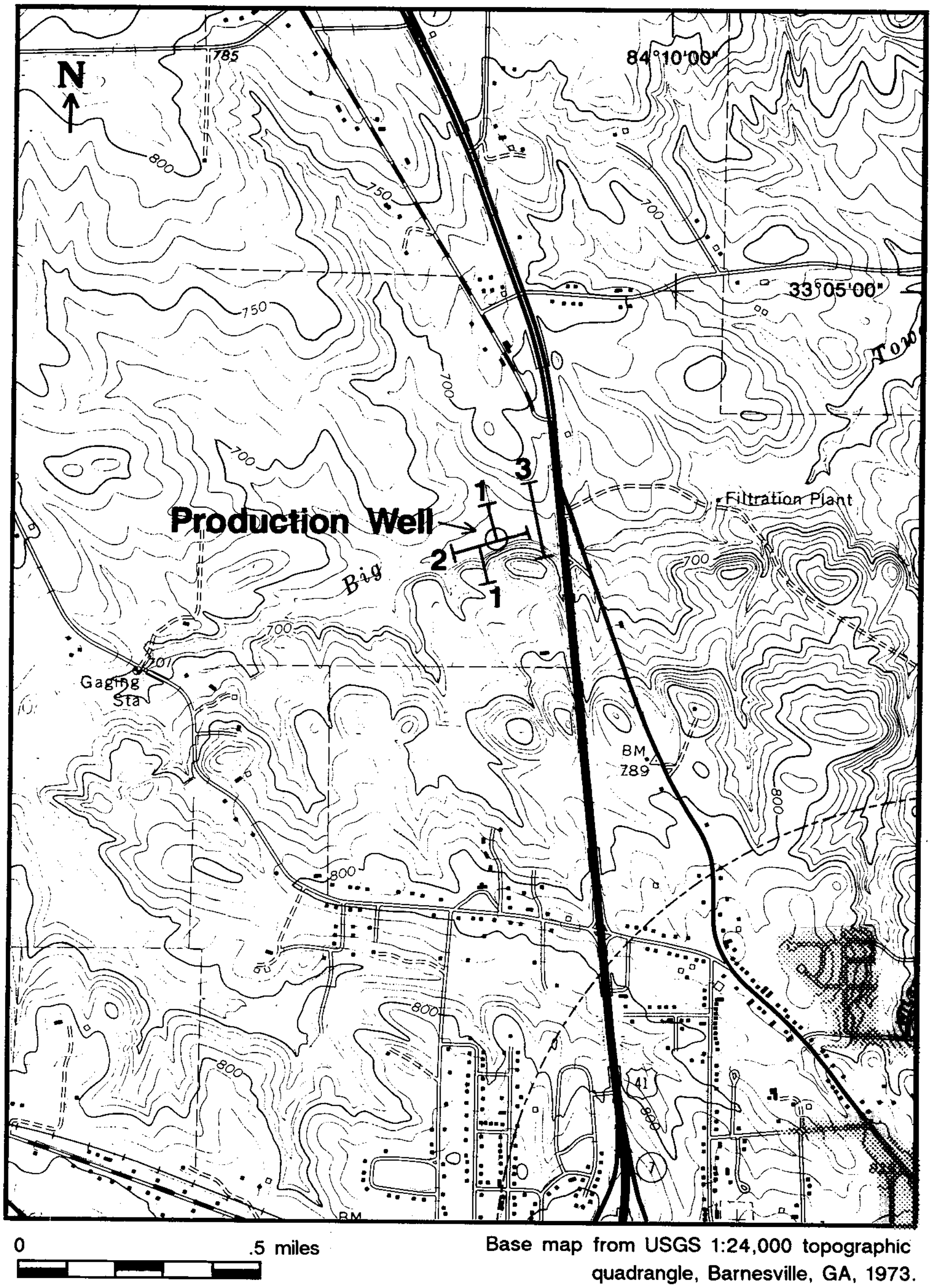
GEOPHYSICS

Surface Geophysics

On December 8, 1988, three magnetic profiles were measured at the Barnesville Hydrologic Research Site. The purpose of this survey was to ascertain if a natural change in the earth's magnetic intensity occurred in the immediate area around the Production Well. A change in magnetic intensity can indicate a change in mineralogy and overall rock type or shear zone, thereby indicating a contact zone where ground-water flow may be enhanced through differential weathering. Determining the locations of possible water-bearing zones is important in the siting of wells.

Magnetic Profile 1 was 925 feet in length, oriented approximately N20°-25°W along the east side of the intermittent stream (Figure 8). The direction of the survey line was chosen because it was roughly perpendicular to the strike of rocks in the area. Running the profile perpendicular to strike enhanced the possibility of transecting a geologic contact. The southern half of this profile was shifted about 300 feet southwest along the creek to avoid the underground gas pipeline located near the center of the profile. From 0 to 450 feet along the profile line, the magnetic field steadily declined by only 19 gammas (Figure 9, p. 10), demonstrating that there was no significant change in magnetic intensity. A 15-gamma decline occurred between 450 and 500 feet; however, this change was probably due to the shifting of the profile to avoid interference from the underground gas pipeline. From 500 to 675 feet, a slight decline occurred, followed by a slight increase from 675 to 775 feet. The increase could be due to elevation changes in the profile line, away from the deeply weathered area in the flood plain where unweathered rock was farther from the land surface. A sharp increase then a sharp decline occurred between 825 and 925 feet. These distinct variations were due to the previously-mentioned underground gas pipeline. Base station readings recorded at the beginning and end of this profile declined by only five gammas.

The second profile (Profile 2) was 1020 feet long, located immediately north of and parallel to Big Towaliga Creek (Figure 8). This profile is roughly parallel to the strike of rocks in the area. From 0 to 300 feet along the profile line, a gradual decline in magnetic intensity occurred, followed by a gradual increase between 300 and 500 feet (Figure 10, p.10). The cause of the slight decline is unknown, but the increase could be due to the influence of metal well casing of the Production Well located nearby. A sharp increase and decline, followed by another increase and moderate decline occurred between 550 and 770 feet. The causes of this anomaly are the underground gas pipeline and, to a lesser extent, the Production Well casing. From 770 to 1020 feet, there is an overall slight decline in magnetic intensity. If the changes caused by the pipeline and well casing are ignored, the profile shows an overall moderate decline that is almost parallel to the decline in base station values. This indicates that natural changes in magnetic intensity during the time the second profile was run



Base map from USGS 1:24,000 topographic quadrangle, Barnesville, GA, 1973.

Figure 8. Approximate location of magnetic profiles.

were probably the result of natural fluctuations in the earth's magnetic field.

The third profile (Profile 3) was 900 feet long, oriented approximately N25°W, and the center of the profile was approximately 350 feet east of the Production Well (Figure 8). This profile, similar to Profile #1, is roughly perpendicular to the strike of rocks in the area. Several anomalies appear to be present in this profile; however, the overall change is less than 30 gammas (Figure 11, p. 11). The increasing anomaly from 0 to 100 feet is probably the result of interference from the gas pipeline and an overhead power line. The low reading at 600 feet could be due to trash and debris (cans, boards with nails, bottles, etc.) observed in the area. An overall decline in magnetic intensity appears to be indicated from the beginning to the end of this profile, whereas an increase in base station values was noted. The cause of this slight decline is unknown but is probably not related to a change in rock type because the change is small and gradual.

In summary, no marked change in magnetic intensity attributable to a change in rock type was detected from the magnetometer survey.

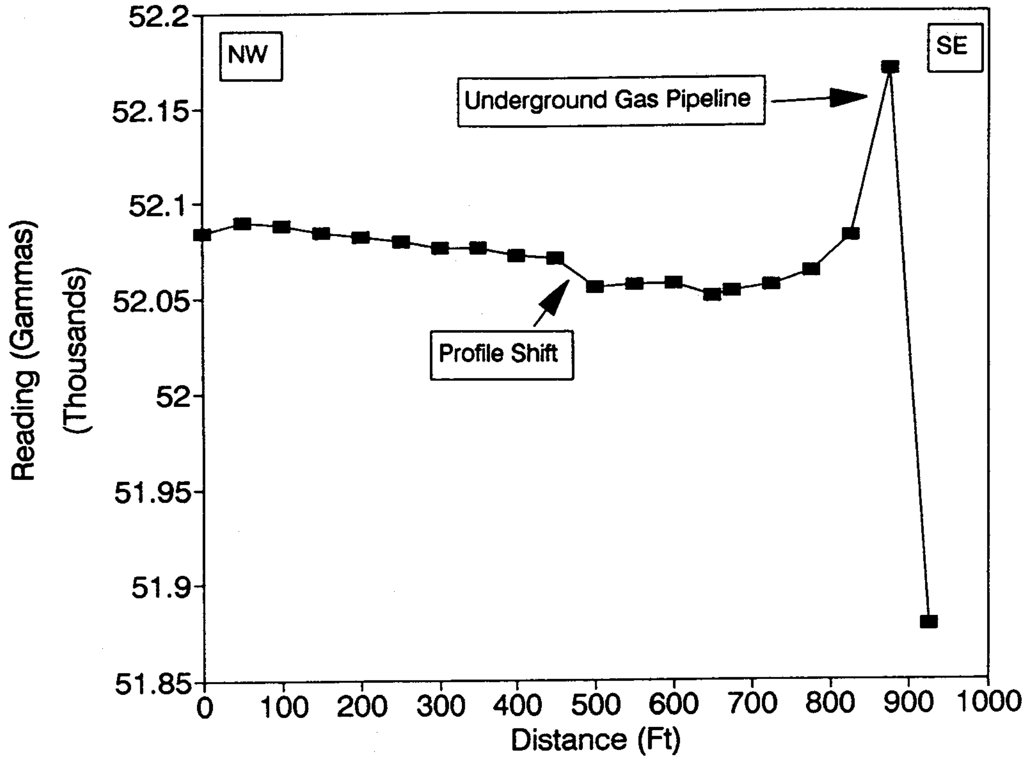


Figure 9. Magnetometer profile 1, northwest to southeast.

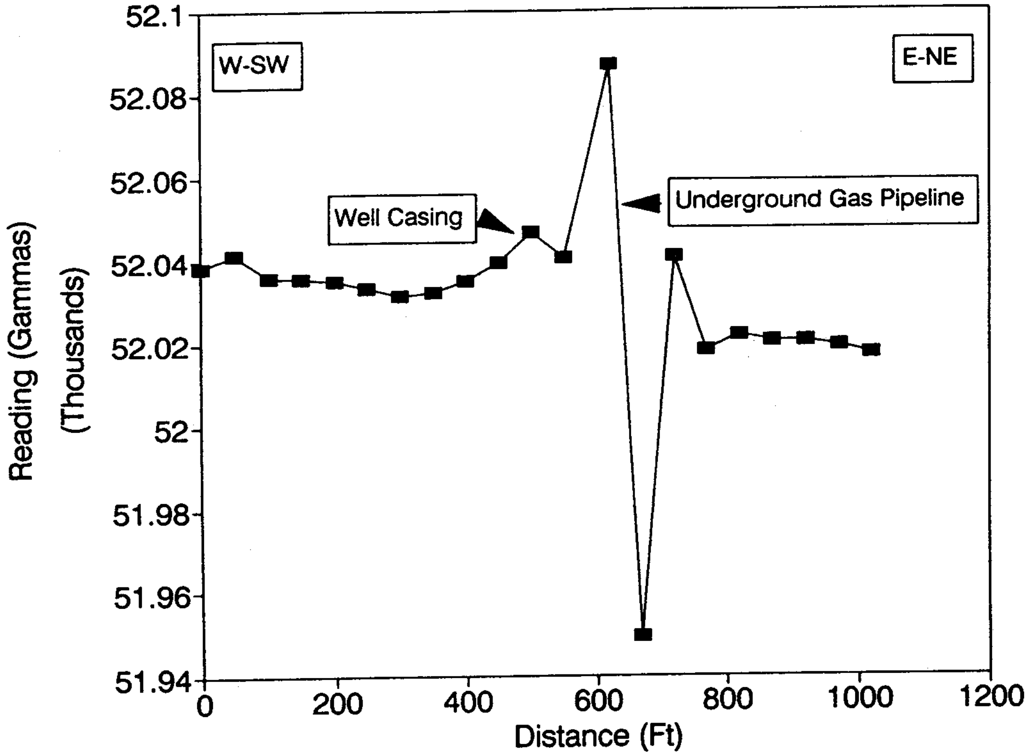


Figure 10. Magnetometer profile 2, west-southwest to east-northeast.

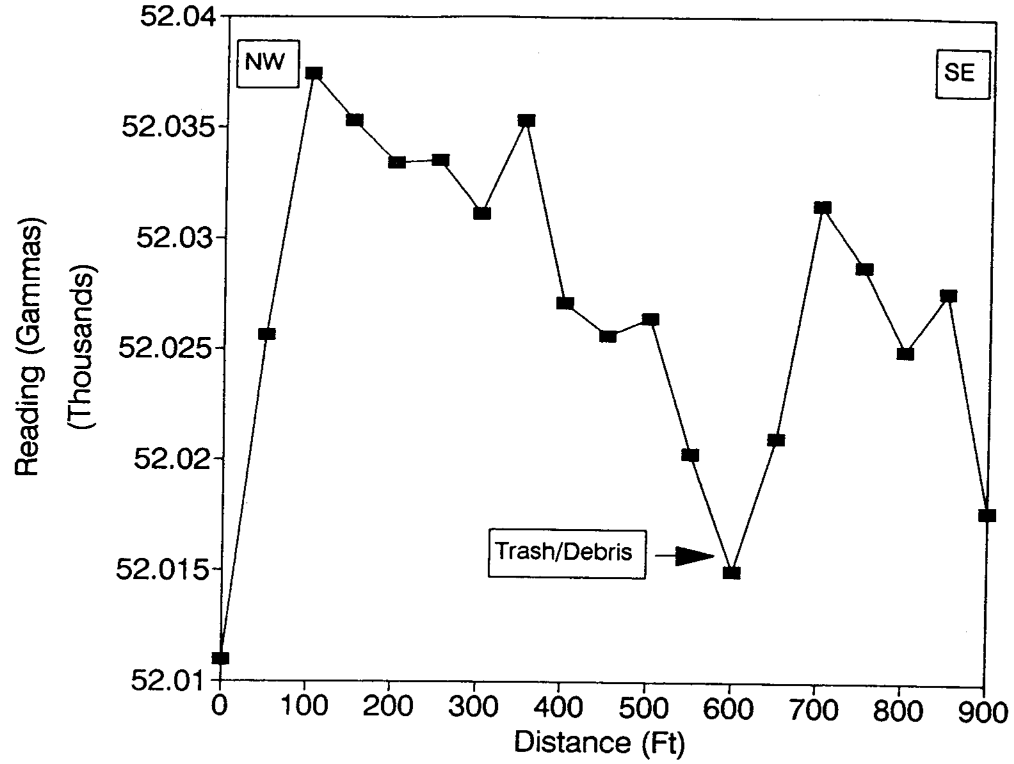


Figure 11. Magnetometer profile 3, northwest to southeast.

Borehole Geophysics

The U.S. Geological Survey's (USGS) Borehole Geophysical Services Unit conducted a suite of geophysical logs on the Production Well. Logs completed were: sonic televiewer, caliper, temperature, acoustic velocity, single-point resistance (includes spontaneous potential and resistivity), and natural gamma. Observation wells were not completed at the time the Production Well was logged. The primary objective of collecting borehole geophysical data was to establish the location of water-bearing fractures. The sonic televiewer log was also used to measure the orientation of all observable fractures.

The sonic televiewer logging tool uses sound to produce an image of the borehole wall. The signal is electronically converted to visual images, recorded on videotape and photographed to provide a permanent record (Cressler and others, 1983, p. 17). The resulting log provides an oriented view of the borehole wall with north at the left margin, east one-fourth of the distance across the log, south at the center, west three fourths of the distance and north again at the right margin (Figure 12, p. 13). From the sonic televiewer log of the Production Well, weathered zones and fractures appear as dark areas indicating the presence of water-bearing zones at 50-60 feet, 82-89 feet (Figure 12) and 141-143 feet (Figure 13, p.14). The orientations of all inclined fractures were measured and plotted on a stereonet (Figure 14, p. 15). The purpose of measuring these orientations was to qualitatively compare surface and subsurface fracture orientations. Orientations of water-bearing fractures and weathered zones could not be measured because their extensive weathering results in a nondistinct pattern on the log. The majority of measured surficial fractures had strikes ranging from N62°W-N25°E, dipping 30°-71°NE and NW. Due to the small number (18) of fractures observed and the wide range of orientations measured from the sonic televiewer log, a comparison with any surface structural features was unfeasible.

The caliper log (Figure 15, p. 16) provides a measurement of casing and borehole diameter. Fractures and weathered zones are indicated where the borehole diameter increases. From the caliper log of the Production Well, water-bearing zones are indicated where the borehole diameter enlarges to more than 14 inches wide between the depths of 50 and 60 feet, to 8-9 inches between 82 and 89 feet, and to about 7.75 inches at 141 feet. Further information on determining water-bearing zones from geophysical logs is provided in a later paragraph of this section. Casing diameter is shown as about 8.75 inches and extends to about 50 feet. Average borehole diameter is about 6.5 inches from a depth of 60 to 140 feet and 6.2 inches from a depth of 140 to 390 feet. This slight change in borehole diameter at 140 feet could be the result of a change in drill bits.

Temperature logs provide a continuous recording of ground-water temperature in the well and can provide information on both the source and movement of ground water in the borehole (Keys and MacCary, 1971, p. 99). The apparent decrease in water temperature in the Production Well from 8 to 20 feet (Figure 16, p. 16) is due to the tool equilibrating from warm air to cooler ground-water temperature (log run in July 1988). The decrease in temperature from 53 to 20 feet is most likely due to radiative and convective cooling of the ground water. The slope of the log remains near-constant from 84 to 400 feet. Temperature increases in this interval at a rate of 0.49°C/100 feet (0.88°F/100 feet). This rate is similar to temperature gradients reported in Smith and others (1978).

Acoustic velocity logs record the transit time of acoustic pulses between the transmitter and receiver on the borehole logging tool. Increases in acoustic velocity are used to identify fractures in crystalline-rock hydrogeology (Keys and MacCary, 1971, p. 88). Significant increases in acoustic velocity in the Production Well occur at 51 feet, 83 feet, 138 feet, 300, 310, 365, 372, and 382 feet (Figure 17, p. 17), indicating the possible presence of water-bearing zones at these depths.

The spontaneous potential (SP) log records the natural electric potentials developed between ground water and surrounding rock materials. Water moving into the borehole may be located by SP "noise" (Keys and MacCary, 1971, p. 30). Increasing SP log inflections occur at 46-100 feet, 118 to 138 feet, 163 feet, and 168 feet (Figure 18, p. 17).

The single-point resistance log measures the electrical properties in rocks, and its primary use in fractured-rock hydrogeology is to identify water-bearing zones (Keys and MacCary, 1971, p. 31). Decreases in resistance (increases in conductance) may indicate the location of fractures. The single-point resistance logging tool is susceptible to changes in borehole diameter and, in this case, the reversed image of the resistivity log (Figure 19, p. 18) is somewhat similar to the caliper log (Figure 15). Significant decreases in resistance in the Production Well occur at 52 feet, 108 feet, 140 feet, 150 to 170 feet, 214 feet, and 394 feet.

Natural gamma logs record the amount of natural gamma radiation in rocks and may indicate changes in lithology (Keys and MacCary, 1971, p. 64). Significant natural gamma peaks occur at 112 feet, 122-134 feet, and 196 feet in the Production Well (Figure 20, p. 18). The cause of these inflections could be changes in lithology or mineralized zones.

The major water-bearing zone in the Production Well is inferred to be located from 50 to 60 feet based primarily on geophysical log interpretation and observations during drilling. Minor water-bearing zones occur from 82 to 89 feet and from 141 to 143 feet. The water-bearing zone at 50-60 feet is indicated by enlargement of the borehole diameter to over 14 inches, as shown on the caliper log (Figure 15), a significant deflection of the acoustic velocity log (Figure 17), an increasing SP log inflection (Figure 18) and a decreasing single-point resistance log peak (Figure 19). This interval is in the transition zone where saprolite grades into less weathered rock. The water-bearing zone at 82-89 feet is indicated by a darkening of the sonic televiewer log (Figure 12), an increase in the borehole diameter to over 9 inches, as shown on the caliper log, an increasing peak on the acoustic velocity log, and part of an overall increasing peak on the SP log. The minor water-bearing fracture at 141-143 feet is indicated by a darkening of the sonic televiewer log (Figure 13), an increase in borehole diameter to almost 8 inches (Figure 15), an acoustic velocity log peak near this interval, an increasing SP log peak inclusive of this interval, and a decreasing single-point resistance log peak. The geologist present during drilling reported that water was also encountered in other zones of the borehole in volumes too low to determine the exact depth.

Borehole geophysical logs and the geologist's log were used to interpret the depth of significant water-bearing zones; other deflections on geophysical logs may indicate changes in porosity, but most likely are not significant water-bearing zones.

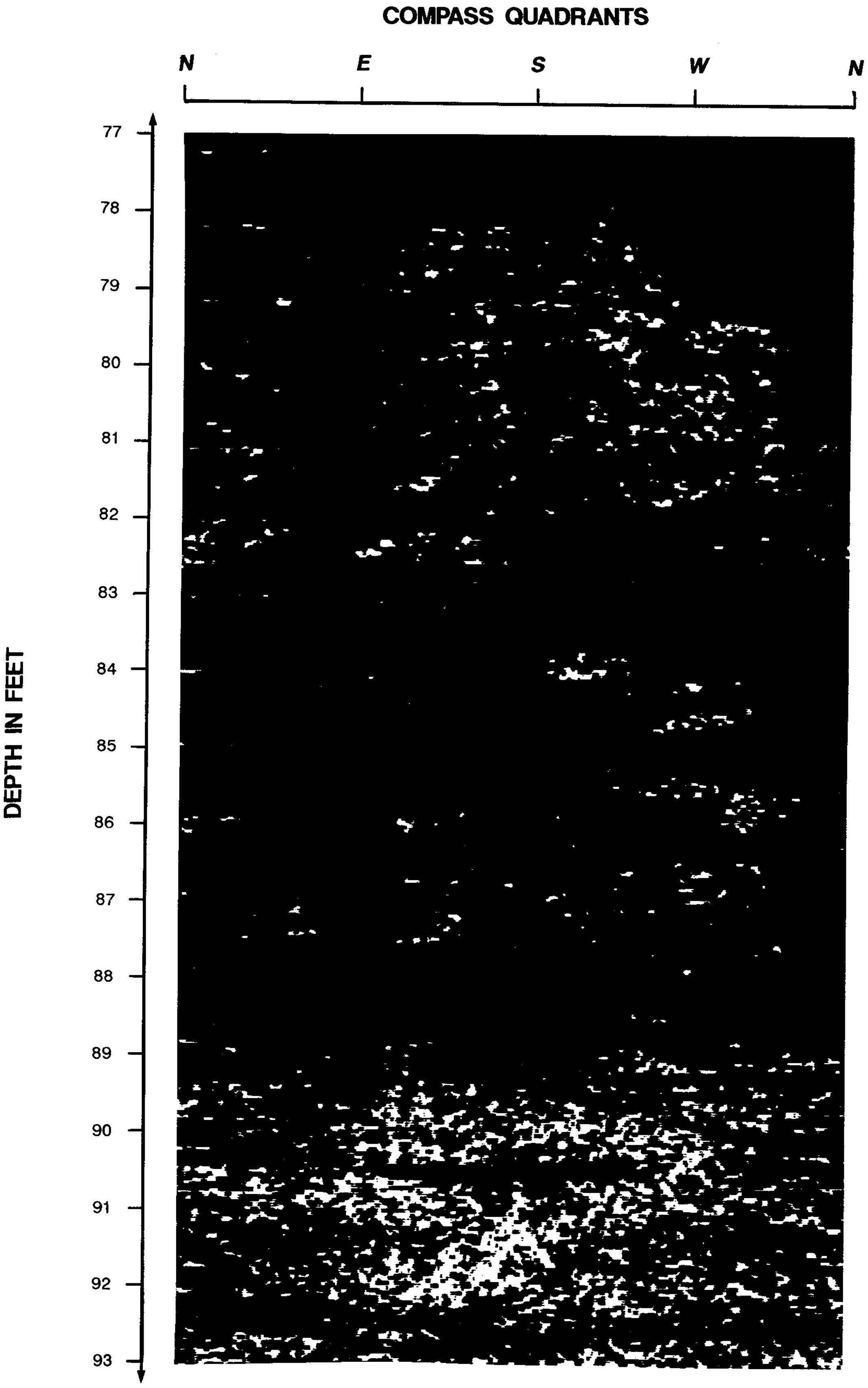


Figure 12. Sonic televiewer log of the Production Well, 77 to 93 feet.

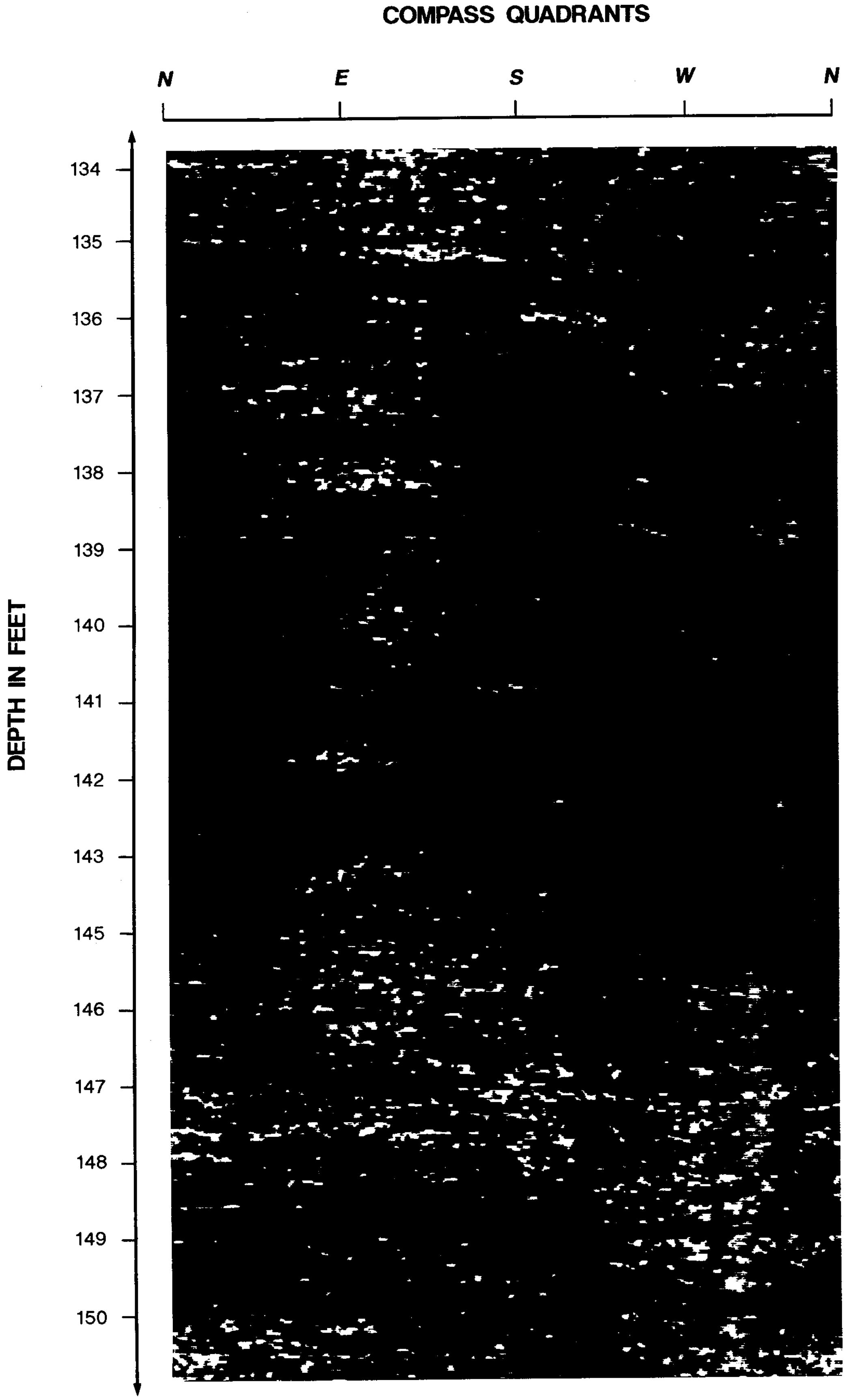


Figure 13. Sonic televiewer log of the Production Well, 134 to 150 feet.

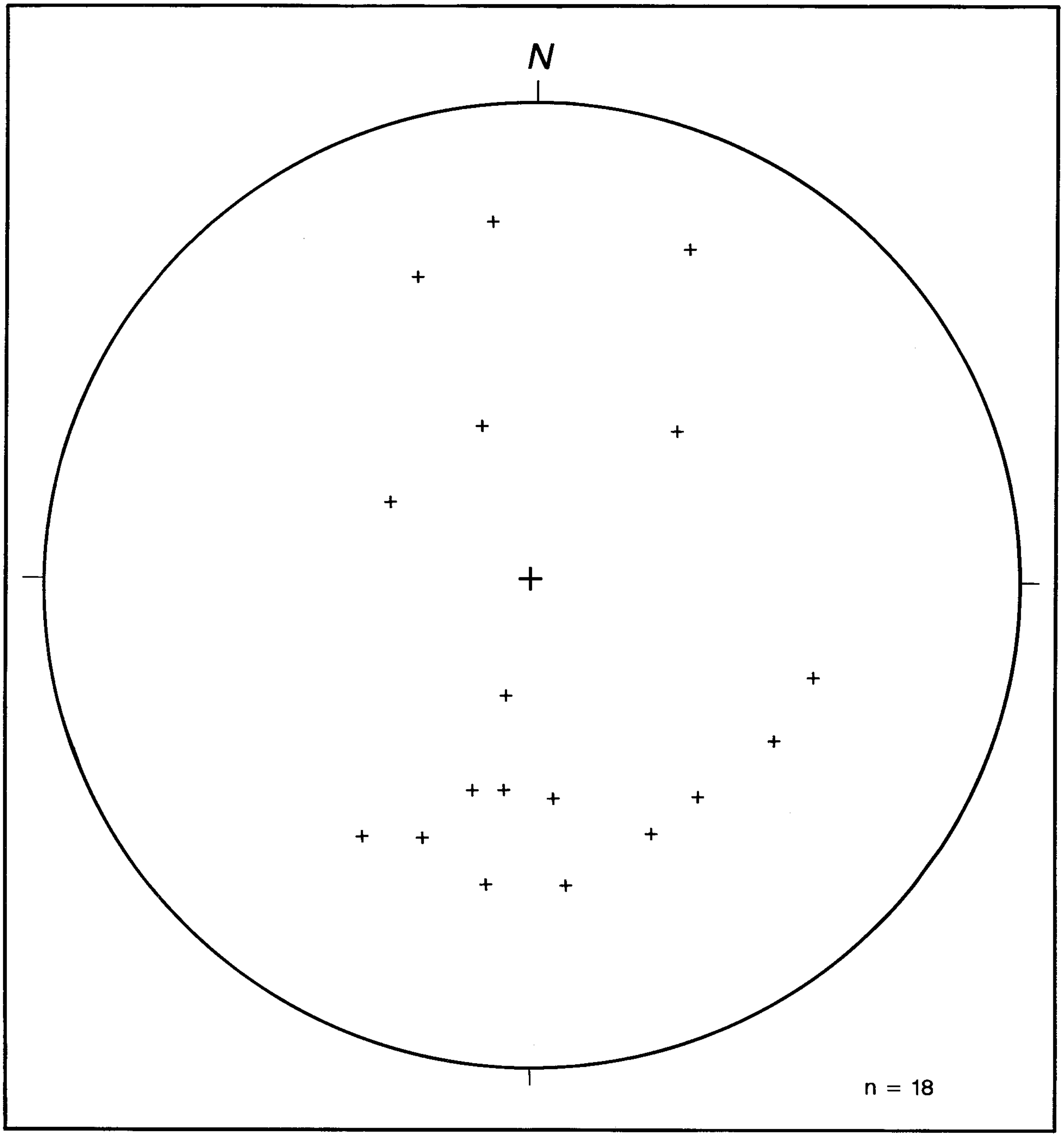


Figure 14. Poles to fracture orientations measured from the sonic televiewer log of the Production Well.

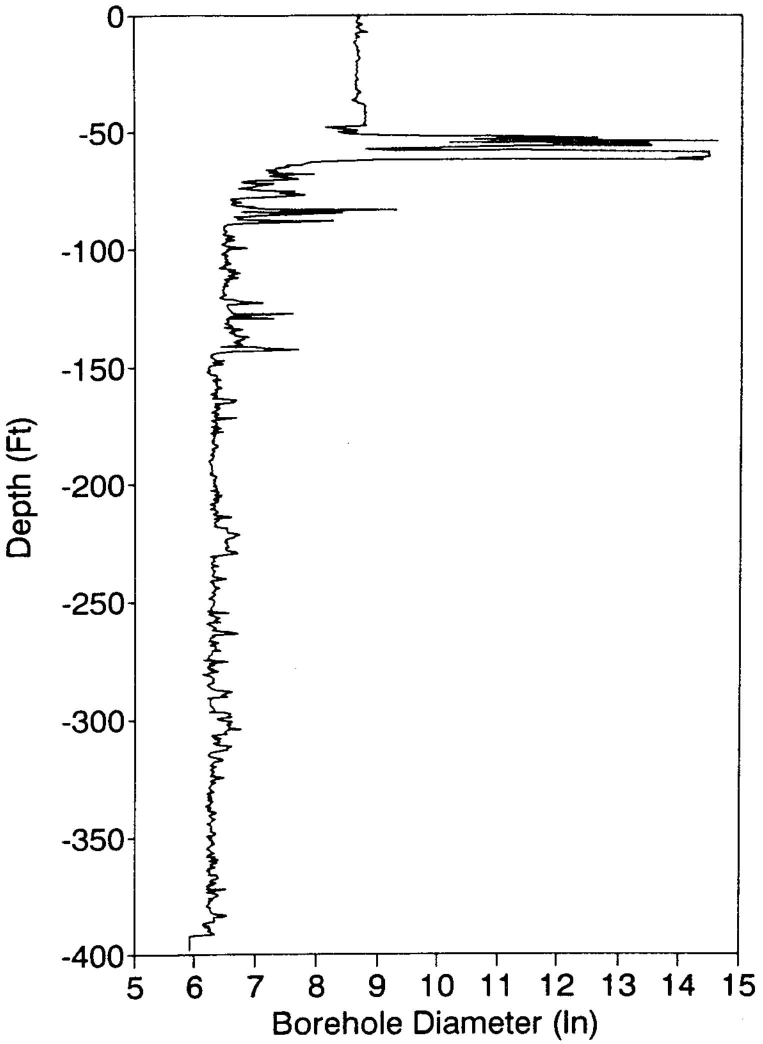


Figure 15. Caliper log of the Production Well.

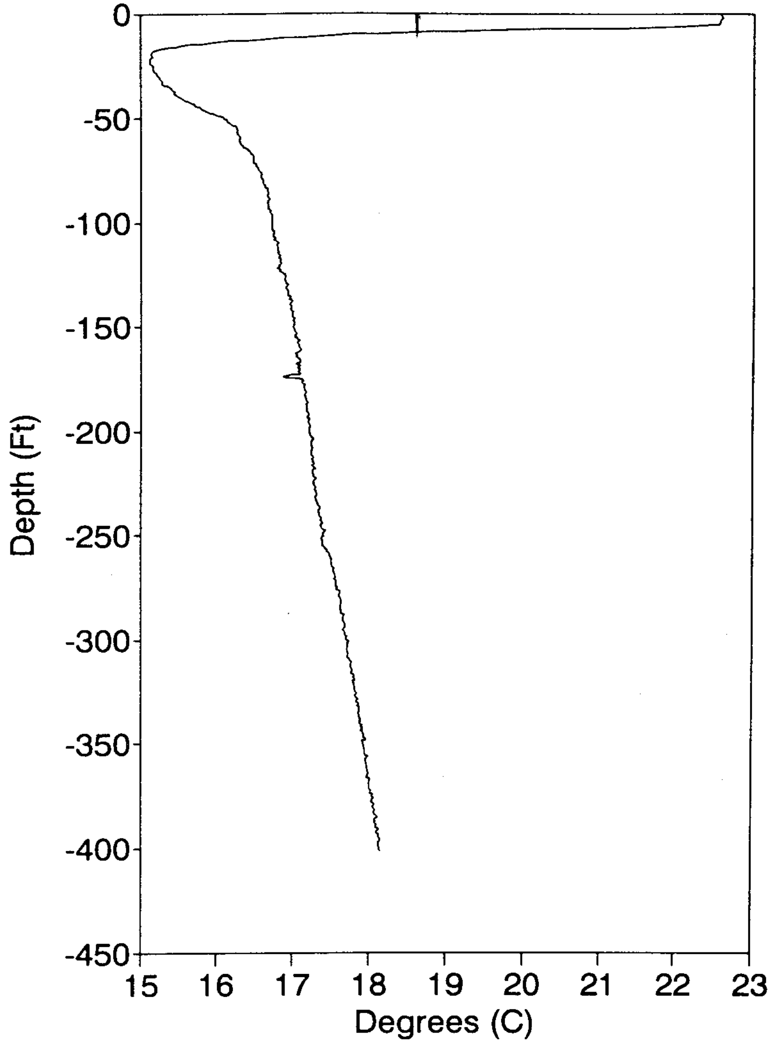


Figure 16. Temperature log of the Production Well.

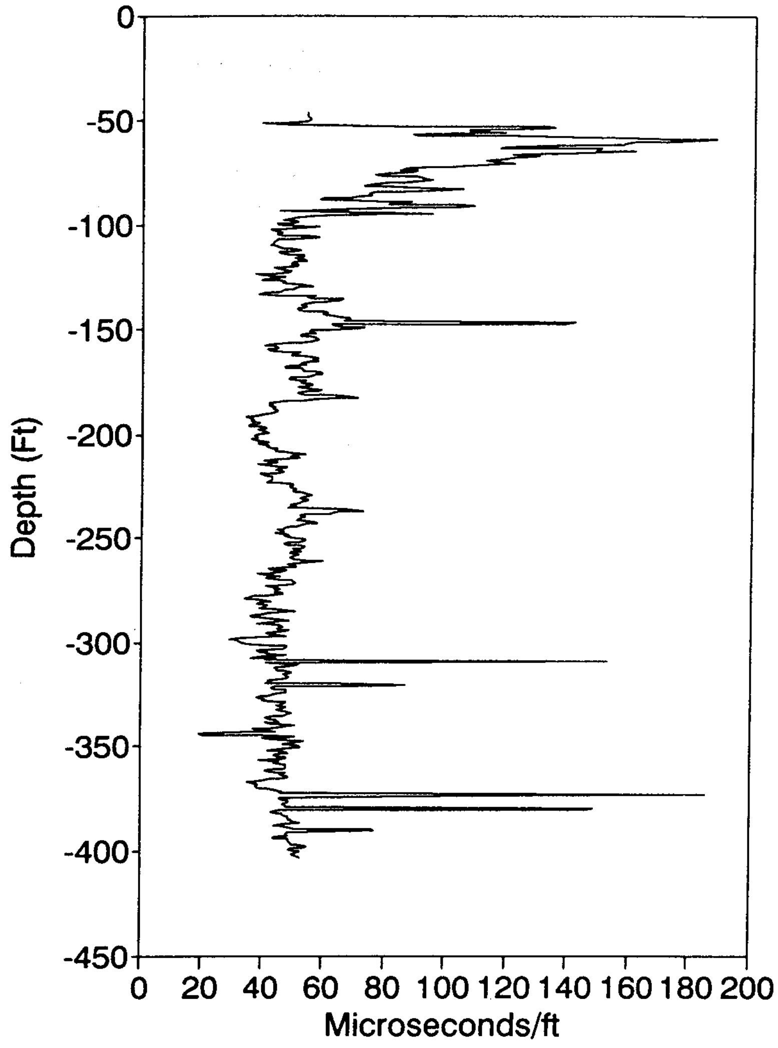


Figure 17. Acoustic velocity log of the Production Well.

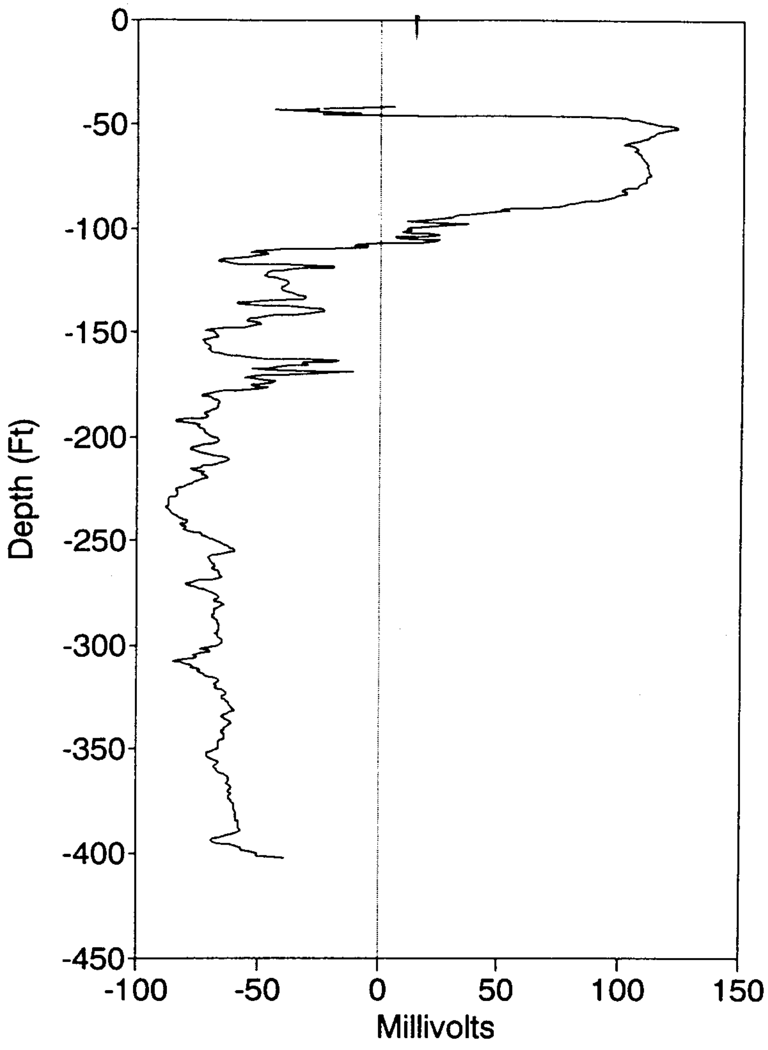


Figure 18. Spontaneous potential log of the Production Well.

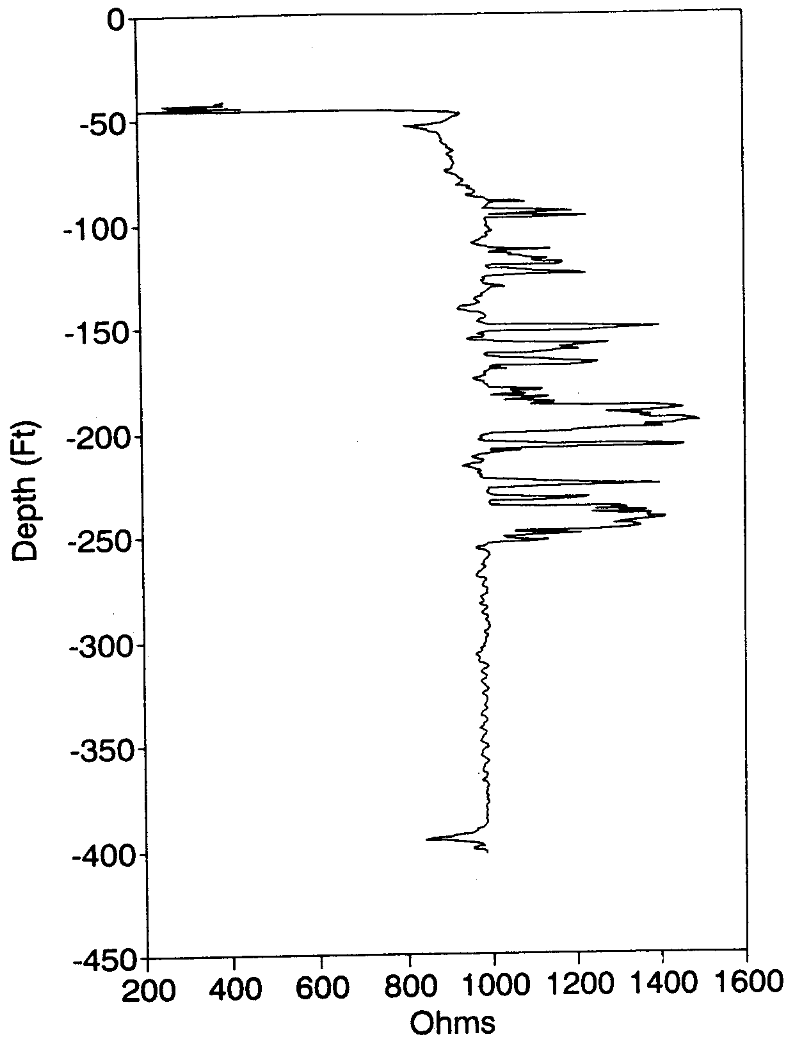


Figure 19. Single-point resistance log of the Production Well.

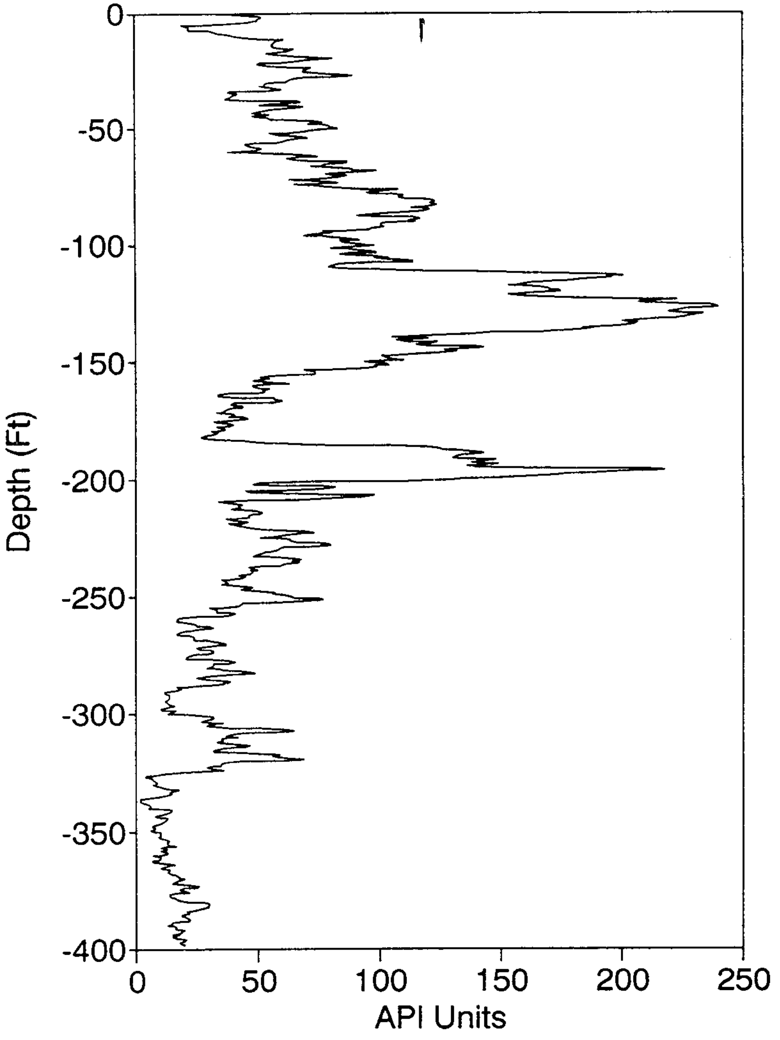


Figure 20. Gamma log of the Production Well.

HYDROLOGY

Background

An understanding of the basic hydrologic cycle is essential in any investigation of a ground-water system. Average precipitation in Georgia is about 50 inches per year (Figure 21, p. 20). Runoff to streams, rivers, lakes and the ocean accounts for about nine inches per year of total precipitation, while evaporation and transpiration (evapotranspiration) account for around 35 inches per year. Evapotranspiration increases significantly during warmer months. The remaining six inches of precipitation infiltrates into the earth as ground-water (Carter and Stiles, 1983). Some ground-water is discharged to streams as baseflow. In the Piedmont and Blue Ridge Provinces, water infiltrates the surface and flows into regolith consisting of soil, alluvium and saprolite. Ground-water flow in the regolith is similar to classical ground-water flow through porous media. In crystalline-rock areas, the water then flows into a complex system of joints, contacts, compositional layering, foliation, faults and weathered zones.

Precipitation

Normal precipitation at the Experiment Station, located about 16 miles north of the site, is 52.53 inches per year (Figure 5). Annual precipitation was lower than normal for each year in the 1980's, where complete records are available. Normal monthly precipitation at the Experiment Station ranges from a high of 6.04 inches in March to a low of 2.63 inches in October (Figure 6). Daily precipitation from July, 1989 through August, 1990 is shown in Figure 22, p. 21. Significant precipitation over this time period was concentrated in late September-early October, 1989, middle-late December 1989, January-February, 1990, middle March, 1990, and middle-late July, 1990. Over six inches of rainfall was recorded at the Experiment Station on March 17, 1990. The study site flooded at this time. No significant rainfall occurred during the 24-hour pumping test performed from April 4 to 6, 1990. Significant rainfall did occur on July 11 and 14, 1990, during the 72-hour pumping test.

Surface Water

The Barnesville Hydrologic Research Site is located along Big Towaliga Creek. No stream gage data are available for this section of Big Towaliga Creek. The catchment upstream of the site is 4.03 square miles in area, as shown on Figure 23, p. 23. Assuming that at least six inches of precipitation reaches the water table annually, recharge to the basin is estimated to be over 420 million gallons per year. However, nearly all of this ground water is discharged to streams in the basin as baseflow.

Well Construction

Eight observation wells, in addition to the Production Well, were drilled in order to monitor changes in ground-water levels. Figure 3 shows the locations of these wells. The Production Well is 400 feet in depth and is cased to 50 feet with 8-inch steel casing (Figure 24, p. 24). From 50 to 400 feet, the well is an open borehole.

Two deep coreholes were drilled to obtain lithologic and structural information, and completed as wells to monitor water-level changes in the unweathered rock. Corehole 1 is 328.5 feet deep and is cased to 50 feet with 4 inch pvc casing (Figure 25, p. 24). This well is open from 50 feet to 328.5 feet below land surface. Water-bearing fractures are concentrated in the transition zone, between 50 and 65 feet in Corehole 1. Corehole 2 is 227 feet deep and is cased to 60 feet with 4 inch pvc casing (Figure 26, p. 24). The well is open from 60 feet to 227 feet. Major water-bearing fractures are between 70 and 120 feet in Corehole 2.

Five shallow, soil wells (Figure 3) ranging from 26 to 60 feet in depth, were drilled to monitor water-level changes in the regolith. These wells were constructed using 5-foot sections of 2-inch diameter PVC casing and completed with a 5-foot 0.01 inch slotted pvc screen at the base (Figures 27 to 31, p. 24). A clean sand filter pack was installed from the base of each well to a few feet above the top of the well screen. A bentonite seal was installed above the filter pack to prevent vertical infiltration into the screened interval. The borehole annulus was then backfilled with cuttings up to land surface.

A large-diameter shallow well (Large Diameter Well, Figure 3) was also constructed to assess the viability of utilizing a relatively inexpensive well for domestic or other small-quantity supply. This well was drilled to a depth of 29 feet (Figure 32, p. 24); however, cuttings could only be removed to a depth of 23.5 feet. A five foot section of 6.25 inch diameter, 0.01 inch slotted pvc screen was installed at the base of the well. The remainder of the borehole was cased with 6.25 inch diameter PVC casing. A clean sand filter pack was installed from the base of the well to just above the top of the screen and bentonite was installed above the sand to isolate the screened interval. The borehole annulus was then backfilled with well cuttings.

Ground-water Monitoring

Water levels in the Production Well were monitored on a nearly continuous basis from July, 1989 to April, 1990. From April to August, 1990, static water-level monitoring was intermittent due to pump installation and testing. Figure 33, p. 25 is a hydrograph showing the depth to water in the Production Well over time. Figure 34 is a graph of the water level in the Production Well compared with daily precipitation amounts at the Experiment Station. The Experiment Station is the closest climatological station for which complete precipitation data are available. An overall decline in the static water level in the Production Well

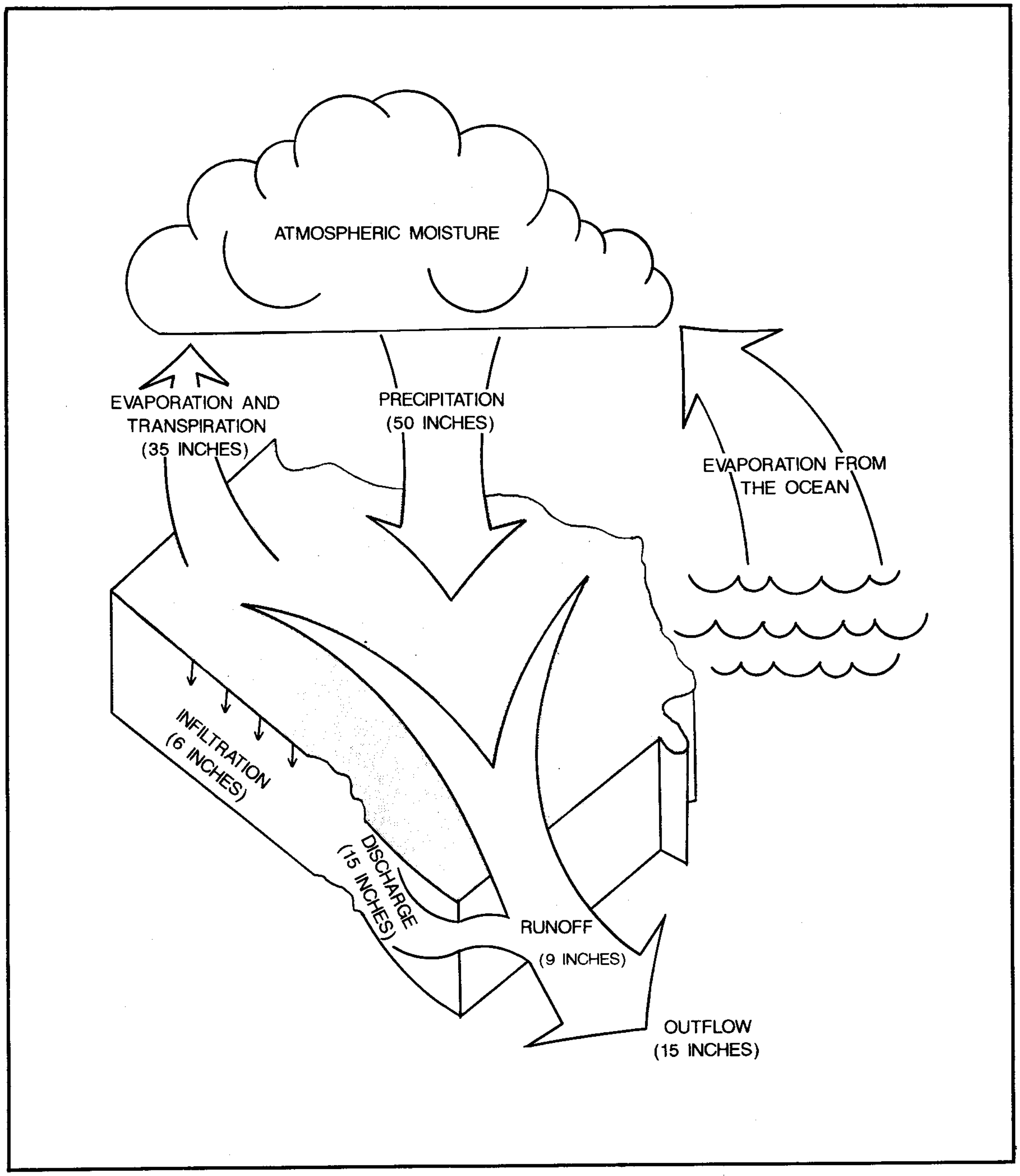


Figure 21. The hydrologic cycle in Georgia (from Carter and Stiles, 1983).

occurred from mid-July to late September, 1989. This general decline is typical of ground-water levels which are affected by evapotranspiration (Joiner and others, 1989). Minor increases in the water level on July 16 and 21, 1989 (Days 15 and 20) are, most likely, a result of rainfall (Figure 34). Significant increases in the water level around August 16, 22, 28, and September 6, 12 and 18, 1989 (Days 46, 52, 58, 67, 73, and 79, respectively) were caused primarily by the drilling of Corehole 1. This is probably due, at least in part, to the injection of water as part of the drilling process. The effect of drilling Corehole 1 on the water level in the Production Well was almost immediate. This was confirmed by observing increases on the water-level recorder chart at the start of drilling. Drilling of the soil wells from mid-September to mid-October, 1989 did not significantly affect water levels in the Production Well. Rainfall on September 27, 1989 did not cause an appreciable increase in the water level in the Production Well, however; a slightly greater amount of rainfall on October 1, 1989 (Day 92) caused a rise of 0.84 feet. This could be due to depletion of soil moisture prior to the September 27 rainfall caused by higher evapotranspiration during the summer months. Soil

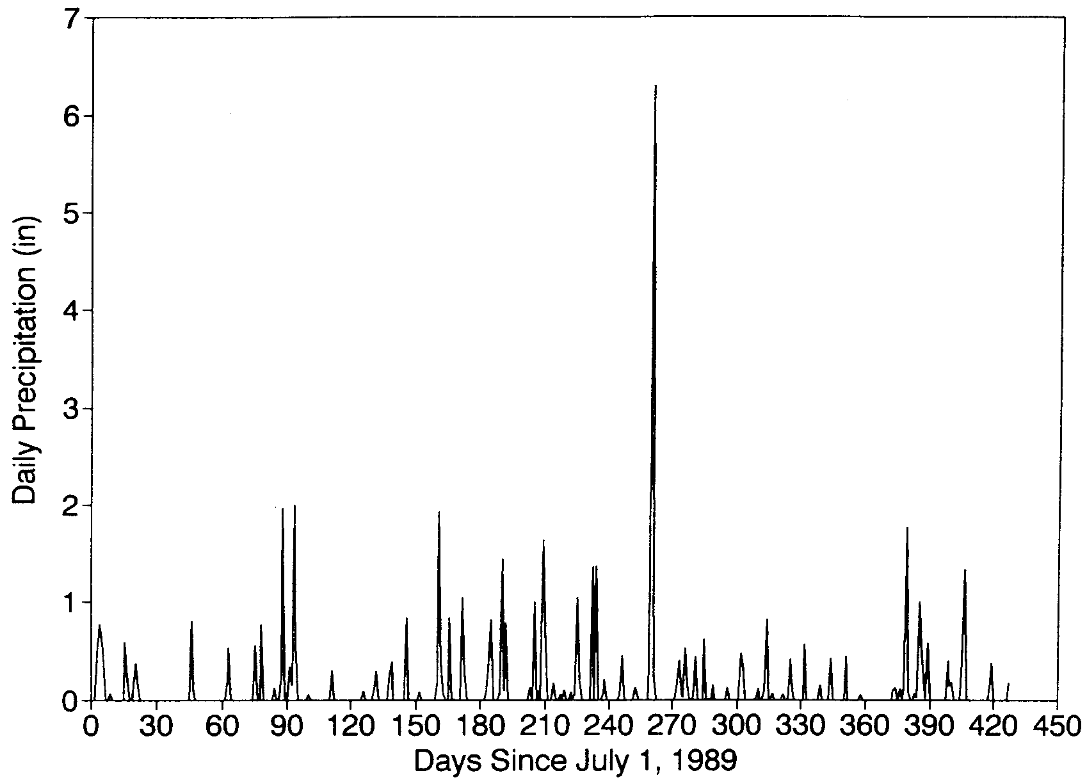


Figure 22. Daily precipitation data from the Experiment Station, Spalding County, July, 1989-August, 1990.

moisture was probably replenished in late September, resulting in the higher water level following rainfall on October 1. Minor increases around October 17, 19, 23, and 31 (Days 108, 110, 114, and 122, respectively) are, most likely due to drilling of Corehole 2. This well is located about 10 feet closer to the Production Well than Corehole 1 but is across Big Towaliga Creek from the Production Well (Figure 3). Increasing peaks in water levels on December 8, 13, 20, and 31, 1989 and January 1, 8, 21 and 26, 1990 (Days 160, 165, 172, 183, 184, 191, 204, and 209, respectively) are all due to precipitation. Significant rainfall also resulted in higher water levels around February 10, 16, and 19, 1990 (Days 224, 230 and 233), as shown on Figure 34. On March 17, 1990 (Day 259), 6.3 inches of rain fell at the Experiment Station. This high amount of rainfall caused Big Towaliga Creek to overflow its banks. The water level in the Production Well was 2.14 feet above land surface on this date which is a record high for the period the well was monitored. Static water-level records are somewhat sparse from mid-March to mid-July, 1990 due to pump installation and pumping tests. The increase in water level on July 20, 1990 (Day 384) was, again, due to rainfall.

Figure 34, p. 25 indicates that ground-water levels in the Production Well at this site are directly affected by precipitation. These figures also show that drilling in the bedrock has an effect on water levels in the Production Well while drilling in the regolith has little appreciable effect.

Static water levels were measured periodically in observation wells from September, 1989 to July, 1990. The purpose of these measurements was to obtain data on longer-term variations in water levels and to compare the pattern of changes between the observation wells.

Figures 35 to 42, p. 26-29, are graphs depicting depth-to-water values over time for each of the observation wells. Water levels in Corehole 1 rose from mid-September to early October, 1989. A slight decline occurred from early to late October, 1989 in all wells drilled at that time. From late October to late December, 1989, water levels in all wells were generally rising. Measurements in all wells at this site revealed a decline in water levels between late December, 1989 and mid-January, 1990, an increase between mid-January and mid-February, 1990 followed by a decline from mid-February to mid-March, 1990 and an increase between middle and late March, 1990. Finally, water levels in all wells showed a decline from early April to early July, 1990. These general patterns of water-level changes in both bedrock and soil observation wells are consistent with long-term water-level records where the annual high generally occurs during late winter and the annual low generally occurs during late summer or early fall. In summary, the overall changes in water levels in all of the observation wells were comparable.

Ground-water Chemistry

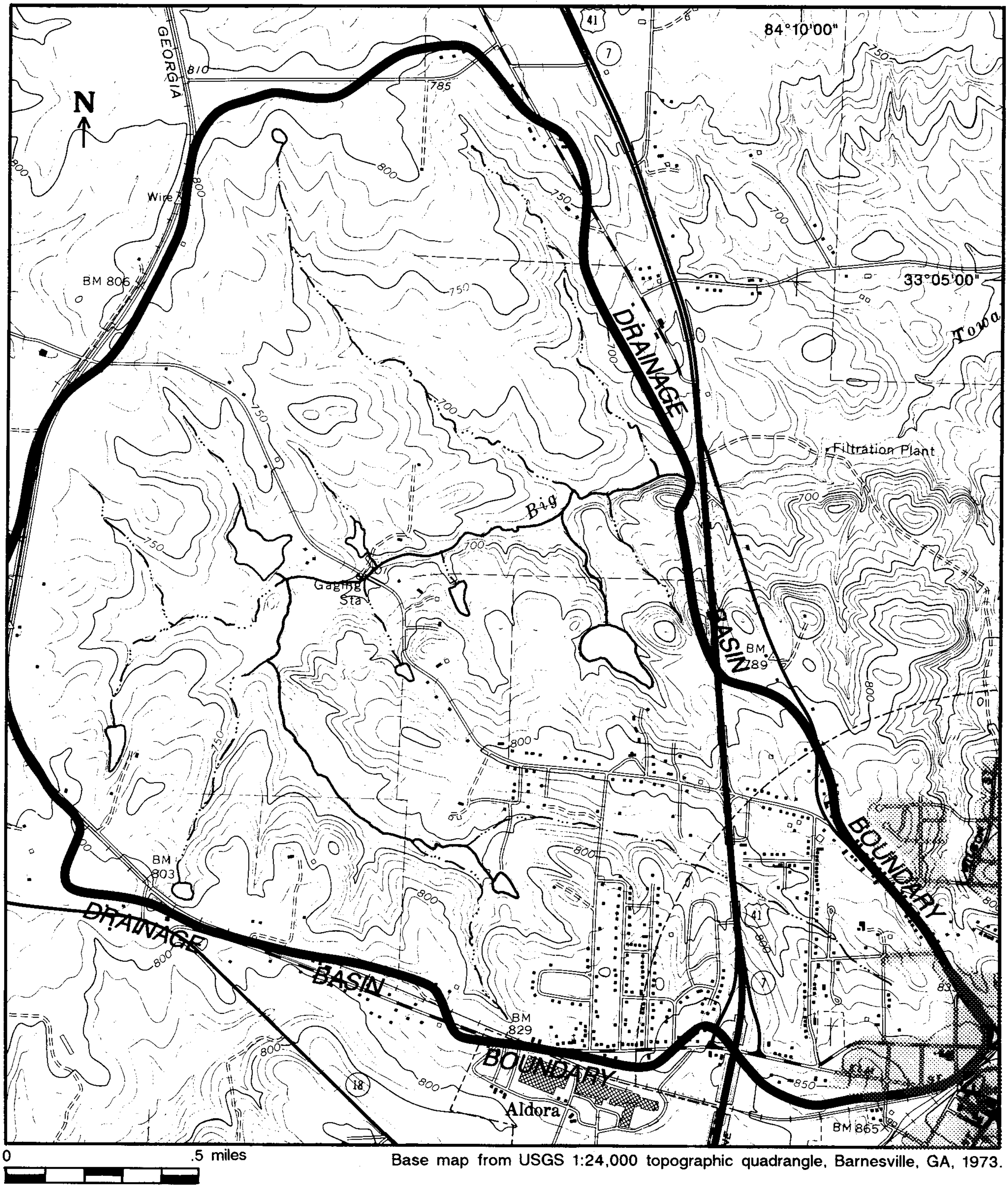
Field measurements of specific conductance, dissolved oxygen, pH and temperature were conducted on April 4, June 18, and July, 10, 1990. These measurements were taken at the point where water was discharged from the Production Well. Geologists from the Geologic Survey's Ground-Water Management Program performed these field measurements. Results of these tests are shown on Table 1.

Specific conductance is a measurement of the ease with which an electrical current flows through water. Because the presence of ionized dissolved solids increases the ability of water to conduct electricity, specific conductance is directly proportional to the dissolved solids concentration. Values of specific conductance are usually reported in micromhos/centimeter (μmhos/cm). The initial specific conductance reading for the April 4, 1990 pumping test was 124 μmhos/cm, but rapidly dropped off and stabilized between 60 and 70 μmhos/cm (Table 1, p. 30). Values occasionally dropped below 60 μmhos/cm; however, these readings were not consistent. Measurements taken on June 18 and July 10, 1990 also fell between the 60 and 70 μmhos/cm, similar to values reported above. Stabilized values (60-70 μmhos/cm) from the Production Well were lower than values from all but two of 25 water samples from Piedmont and Blue Ridge wells sampled by GGS's Ground-water Monitoring Program as reported by Davis (1990). These lower values from the Production Well suggest that water from the Barnesville Production Well is lower in dissolved solids than typical Piedmont ground-water. The source of this low-conductivity water may be the regolith where the residence time of ground water is generally shorter than the residence time in bedrock (Charles Daniel, written communication).

The pH of water is a measure of hydrogen ion activity. A pH of less than seven denotes acidic water while a pH of more than 7 indicates alkaline water (Davis, 1990). The pH of water is measured in standard units (SU). Measurements of pH stabilized between 6.6 and 6.8 on April 4, 1990 and around 6.2 on June 18, 1990 (Table 1). High pH readings on July 10, 1990 are probably a result of instrument error. Values of pH measured on April 4 and June 18, 1990 are within the normal range for Piedmont wells in the Survey's Ground-Water Monitoring Network.

Dissolved oxygen is a measurement of the amount of oxygen dissolved in ground water. Oxygen is supplied to ground water through recharge and by movement of air through unsaturated material above the water table (Hem, 1985). Values are reported in milligrams per liter (mg/l). Dissolved oxygen values were unstable for the first few minutes of the April 4, 1990 test, increased to 7.8 mg/l, and then steadily declined to 6.13 mg/l.

Temperature of the water was also measured. These readings ranged between 17.4 and 18 degrees C for the periods tested (Table 1). A very minor and gradual increase in temperature was measured during the April 4, 1990 test.



Base map from USGS 1:24,000 topographic quadrangle, Barnesville, GA, 1973.

Figure 23. Outline of the Big Towaliga Creek drainage basin, upstream from the Barnesville Hydrologic Research Site.

WELL CONSTRUCTION DIAGRAMS

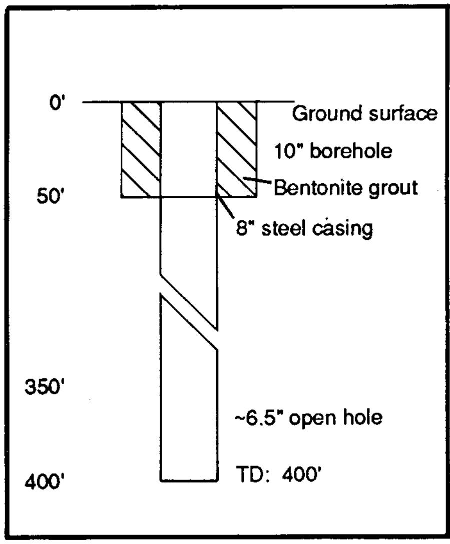


Figure 24. Production well.

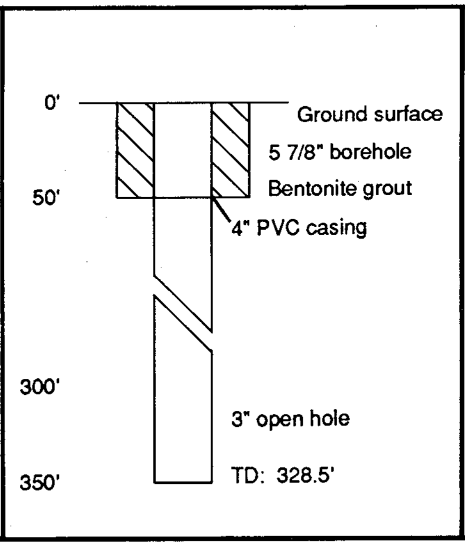


Figure 25. Corehole 1.

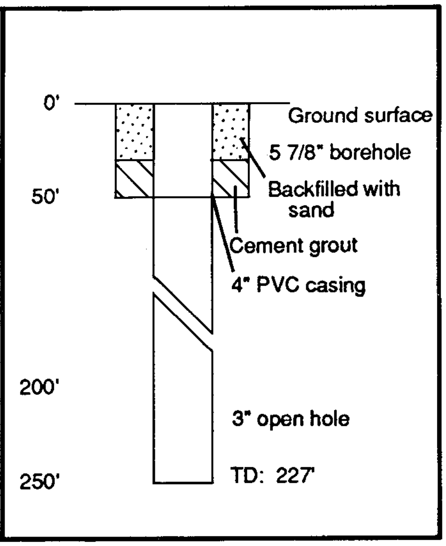


Figure 26. Corehole 2.

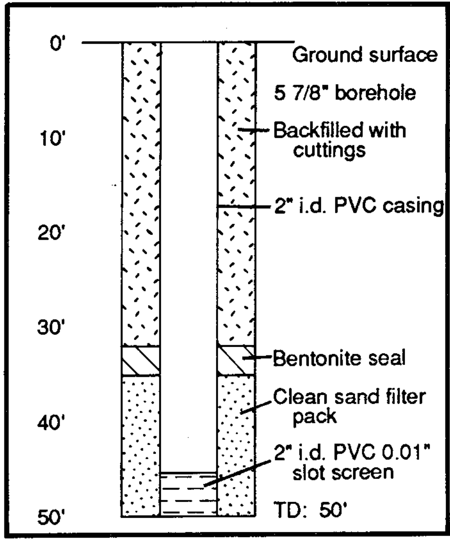


Figure 27. Soil well 1.

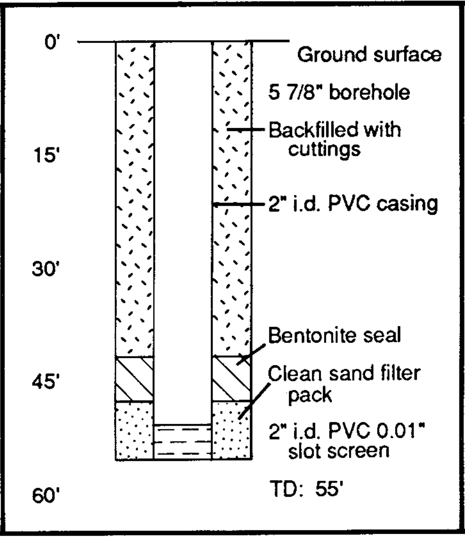


Figure 28. Soil well 2.

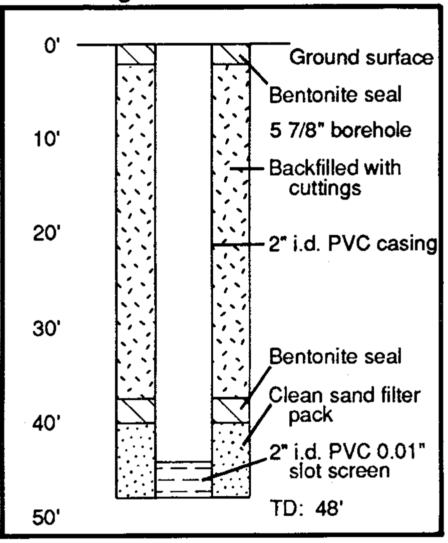


Figure 29. Soil well 3.

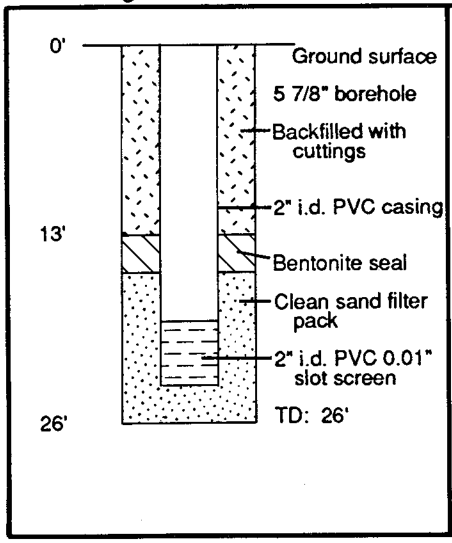


Figure 30. Soil well 4.

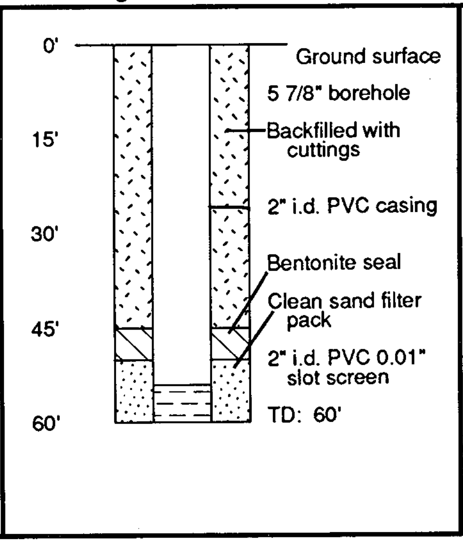


Figure 31. Soil well 5.

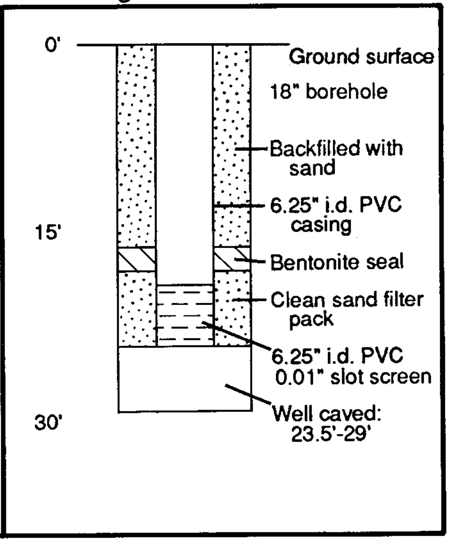


Figure 32. Large diameter well.

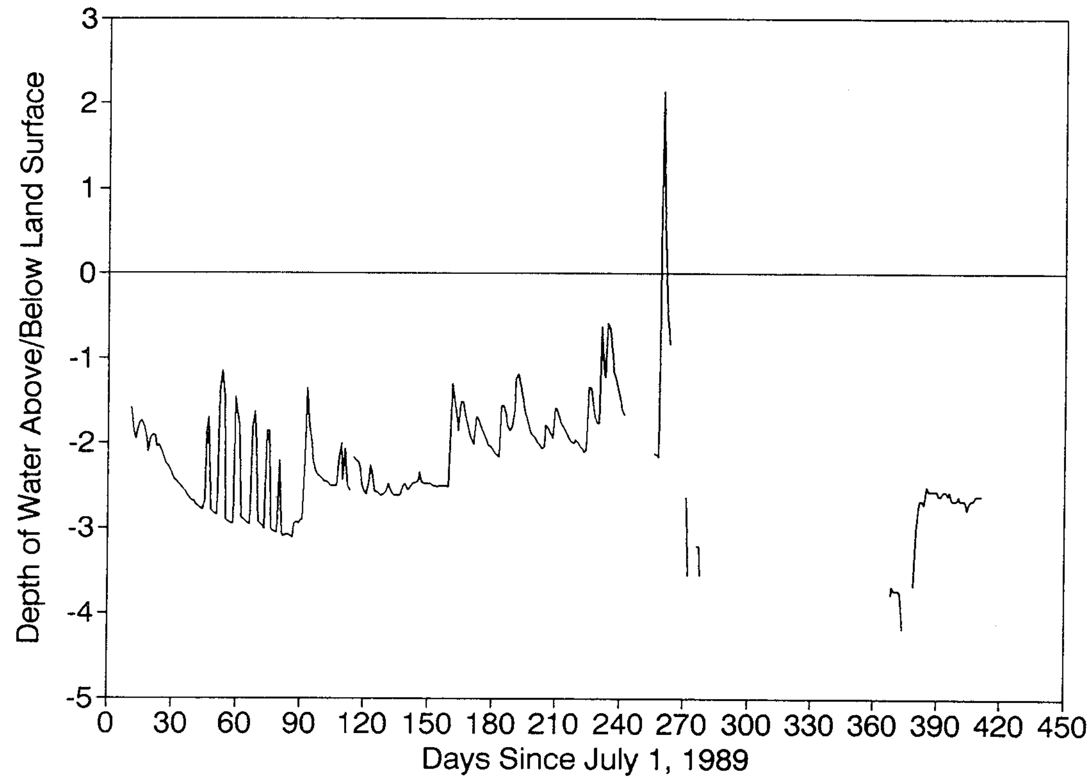


Figure 33. Hydrograph of the Barnesville Production Well, July, 1989-August, 1990.

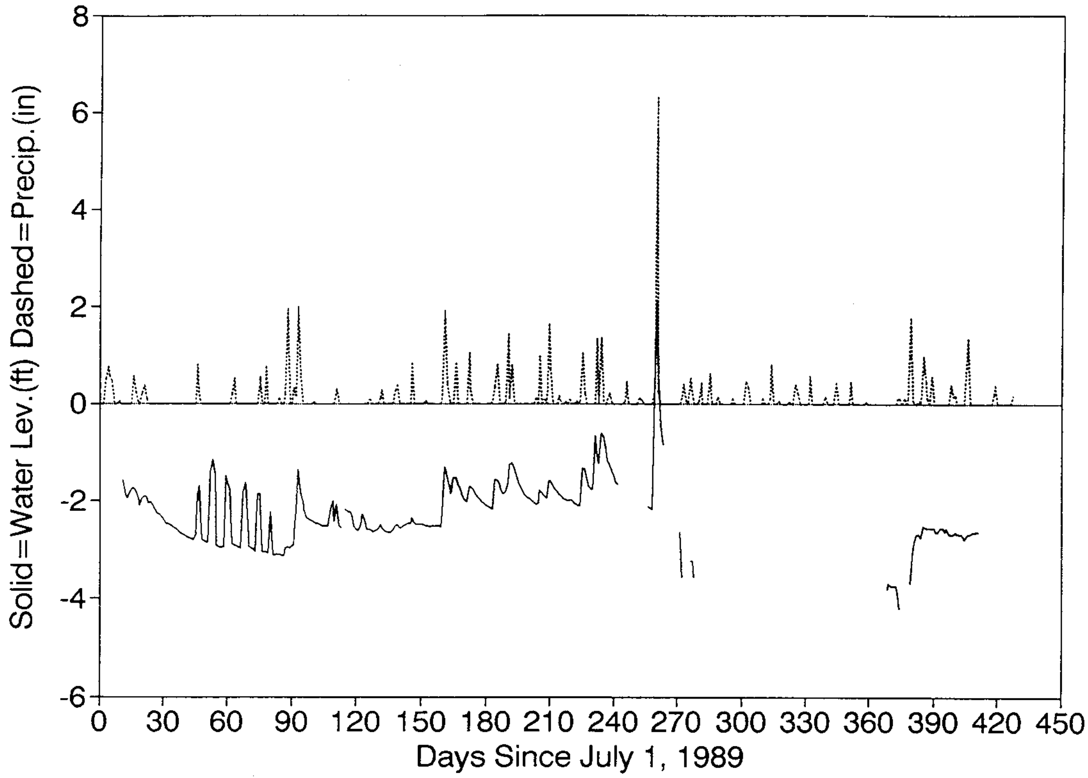


Figure 34. Daily precipitation at the Experiment Station (Spalding County) versus daily water levels in the Production Well, July 1, 1989-August 31, 1990.

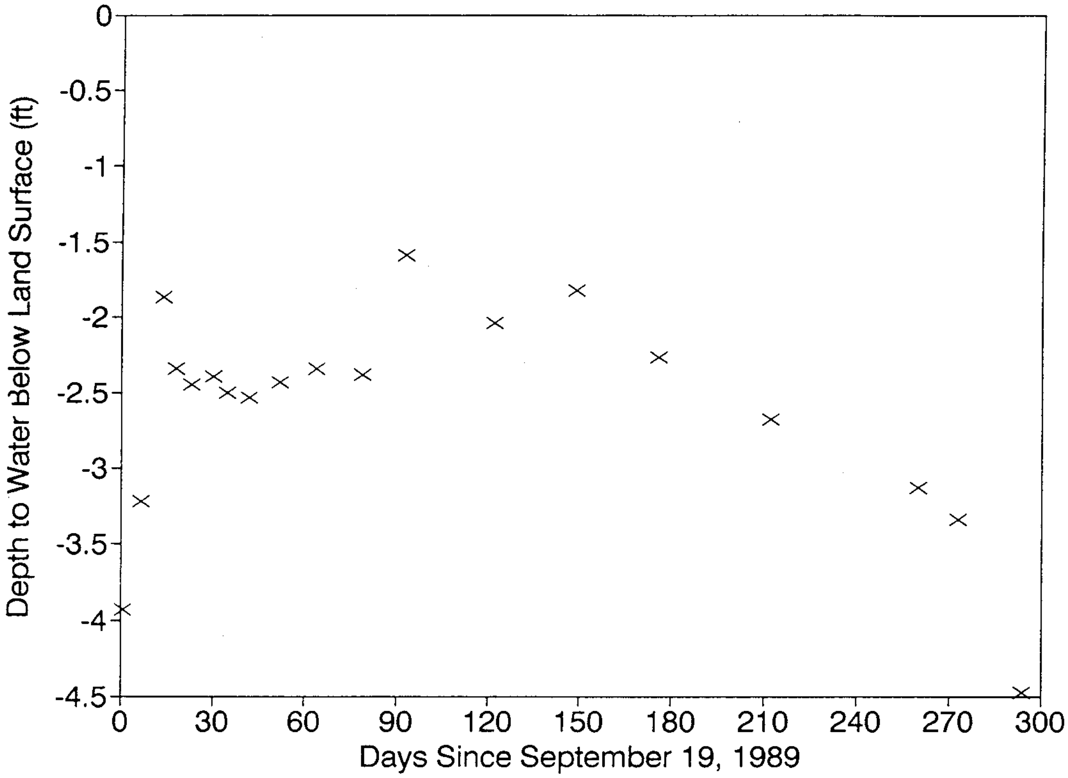


Figure 35. Static water levels in Corehole 1, September 19, 1989-July 9, 1990.

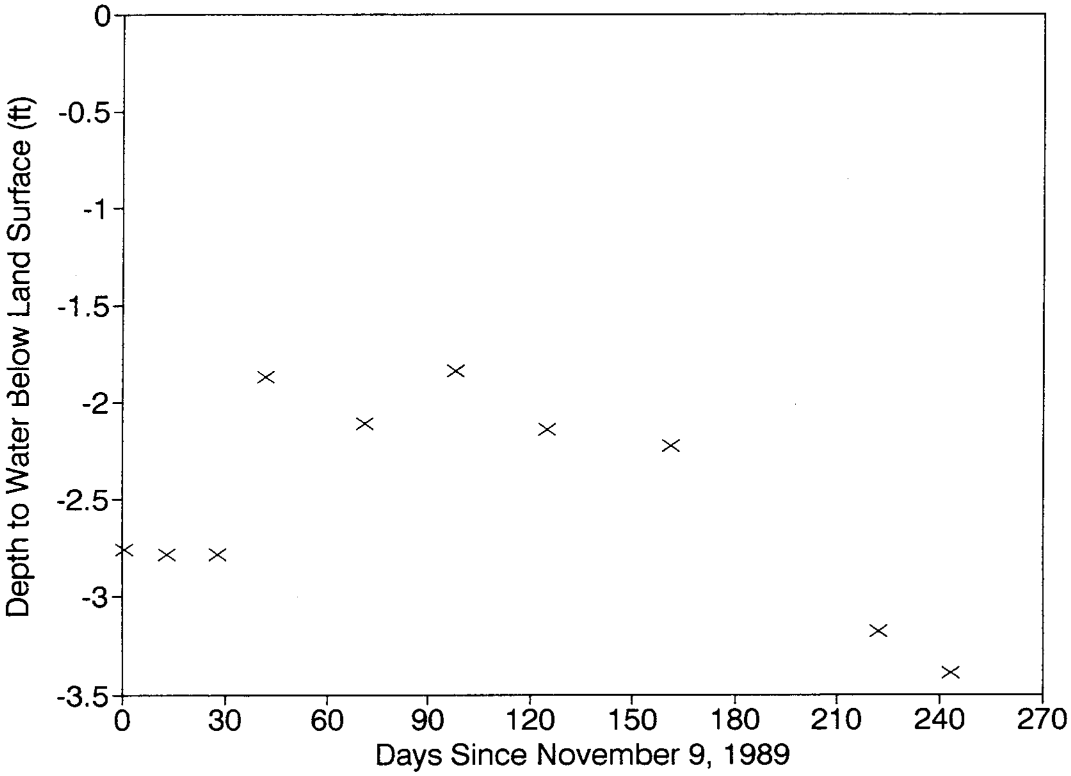


Figure 36. Static water levels in Corehole 2, November 9, 1989-July 9, 1990.

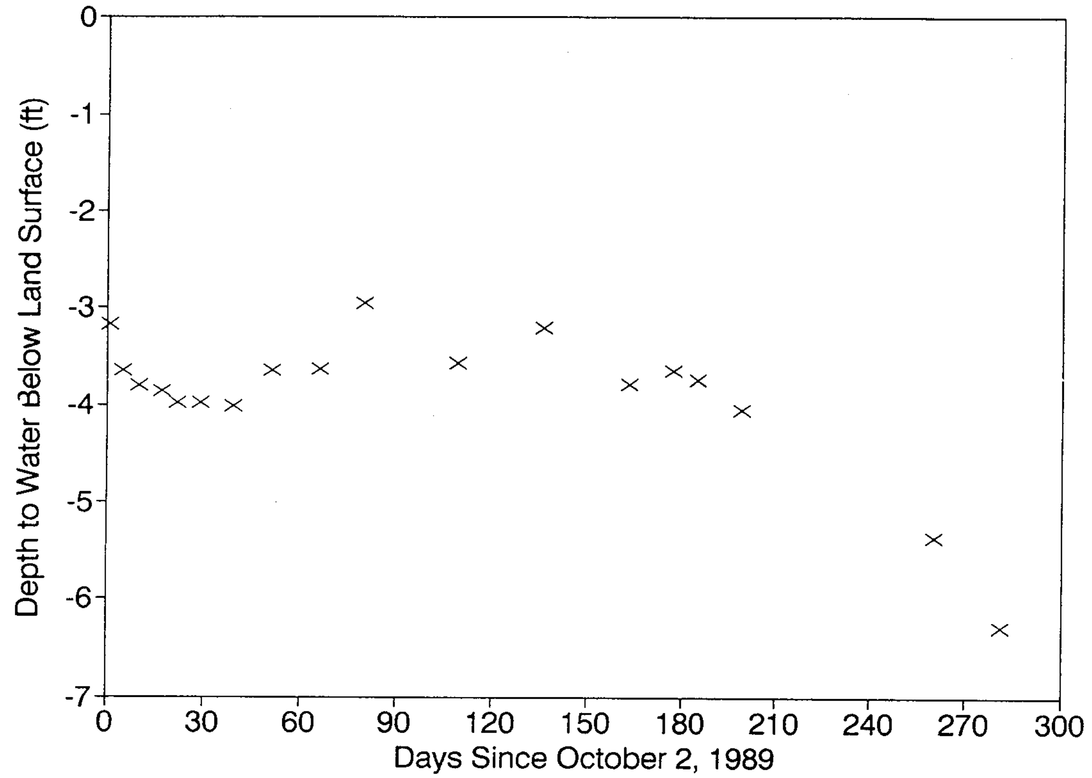


Figure 37. Static water levels in Soil Well 1, October 2, 1989-July 9, 1990.

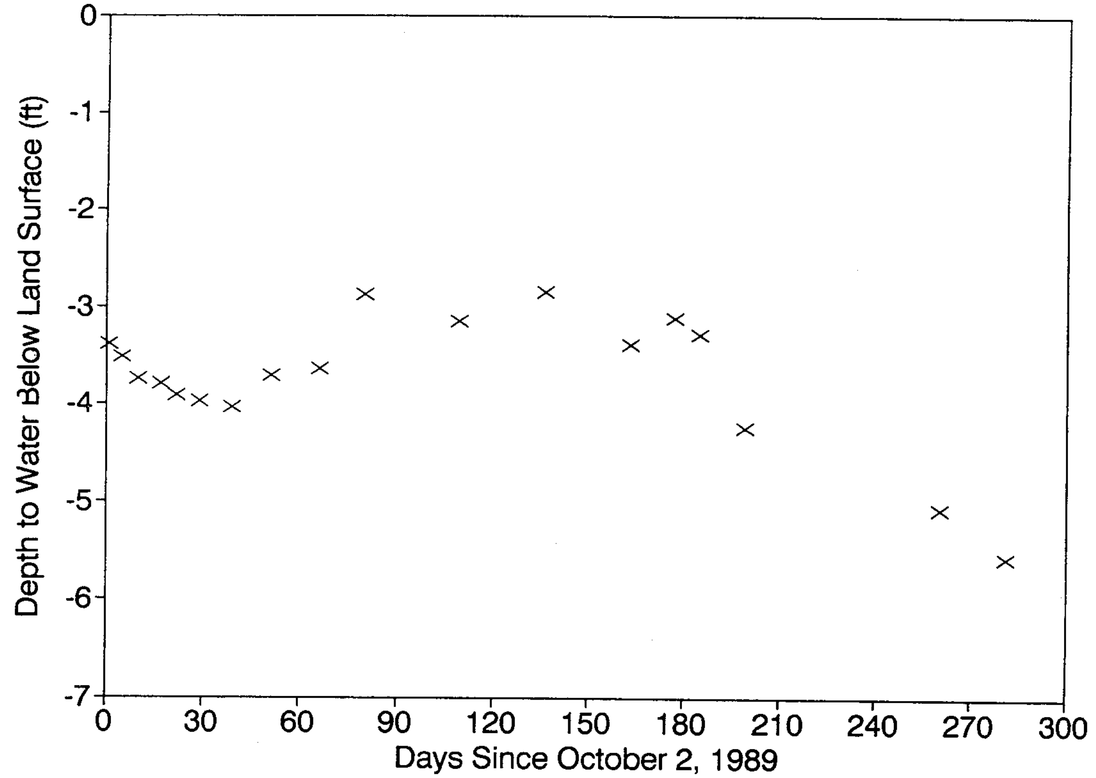


Figure 38. Static water levels in Soil Well 2, October 2, 1989-July 9, 1990.

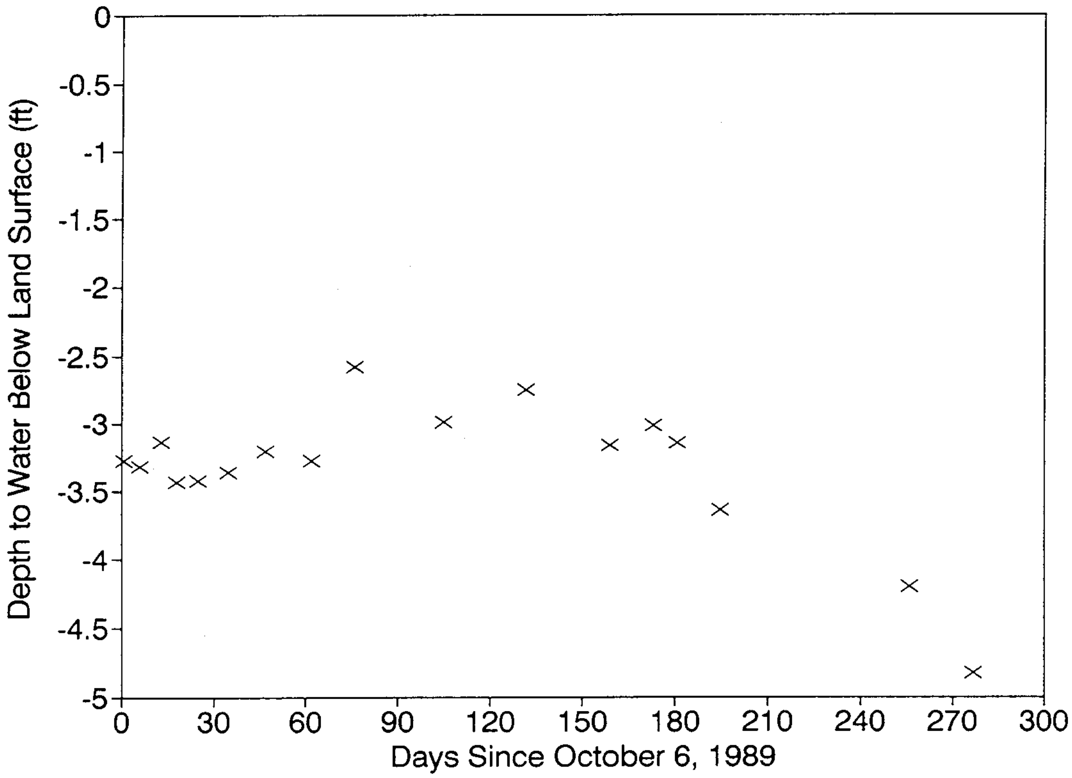


Figure 39. Static water levels in Soil Well 3, October 6, 1989-July 9, 1990.

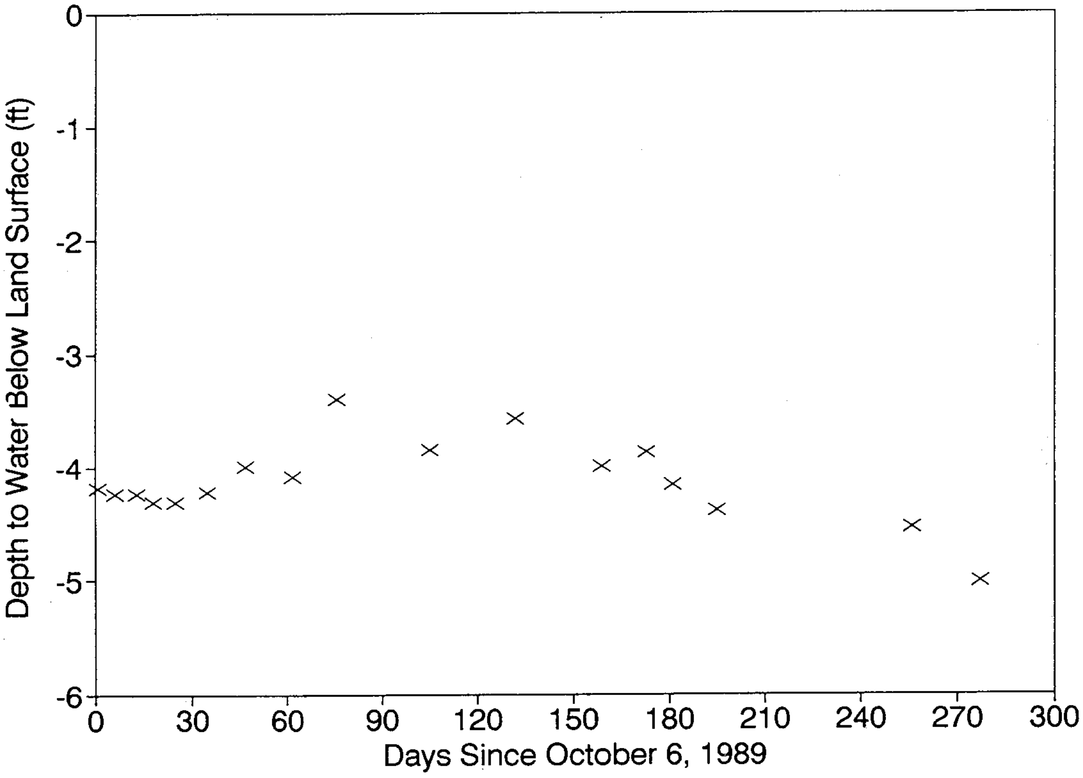


Figure 40. Static water levels in Soil Well 4, October 6, 1989-July 9, 1990.

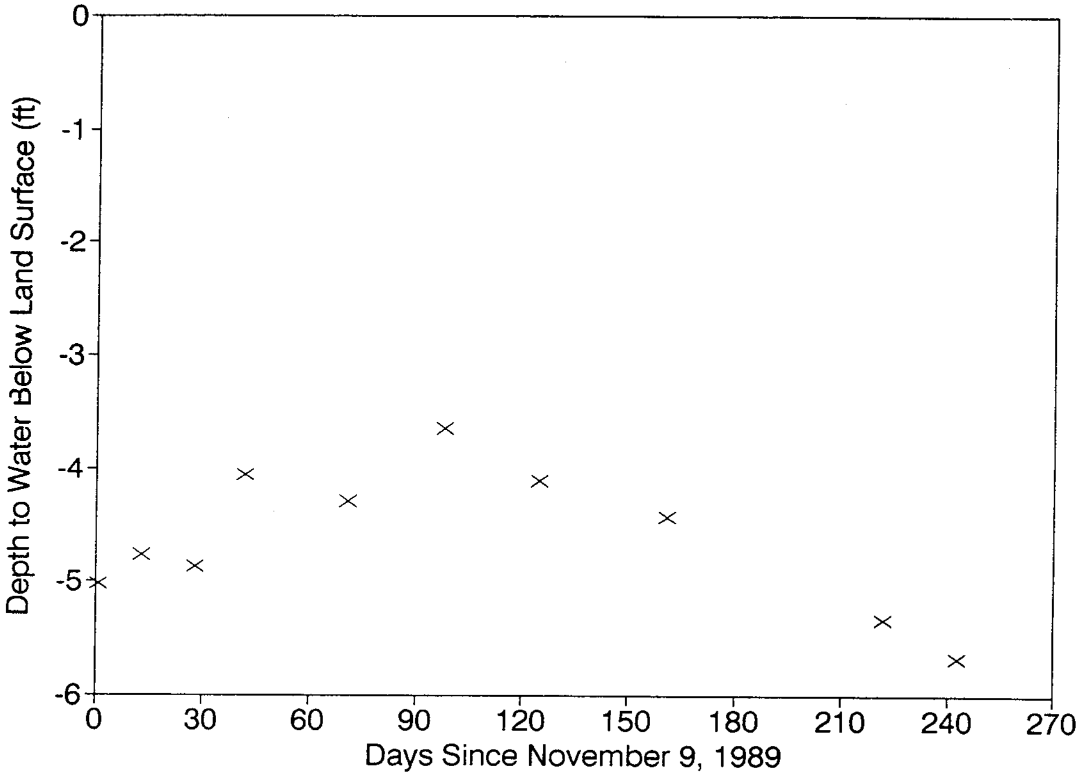


Figure 41. Static water levels in Soil Well 5, November 9, 1989-July 9, 1990.

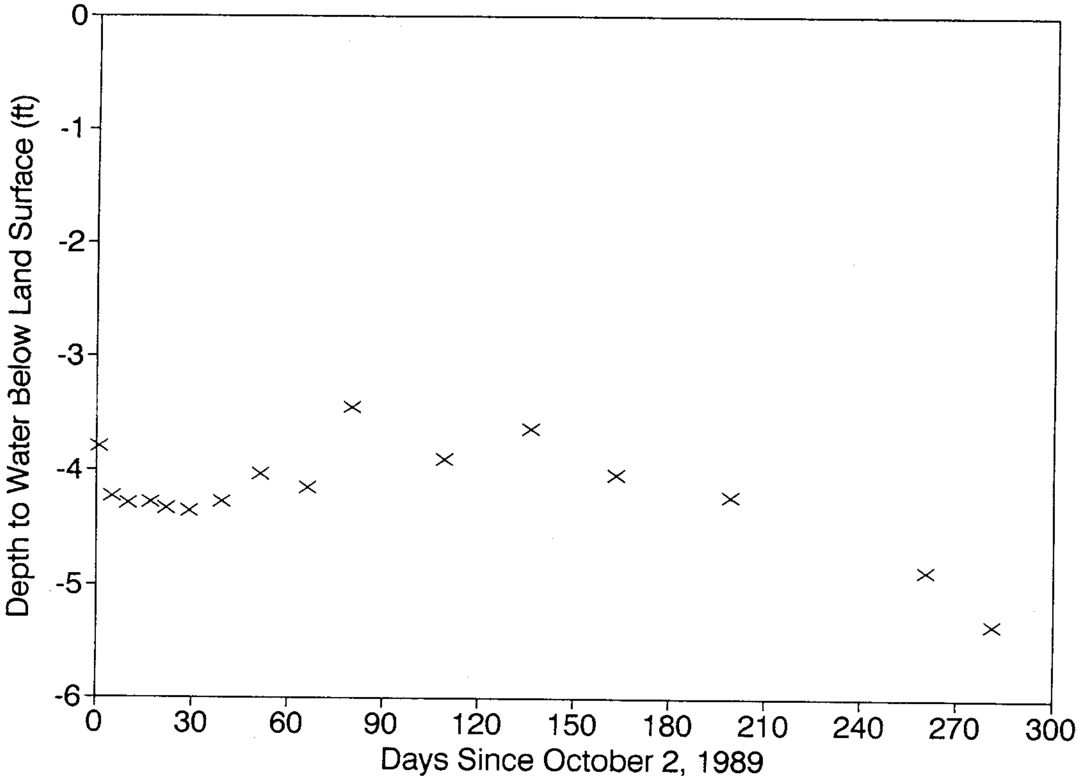


Figure 42. Static water levels in the Large Diameter Well, October 2, 1989-July 9, 1990.

Table 1: Barnesville PW Water Chemistry Field Test Results

Date	Time	SC (µmho/cm)	pH (SU)	DO (mg/l)	T (°C)	Comments
4-4-90	10:21	124	7.31	4.39	17.4	
4-4-90	10:24	99	6.94	6.21	17.4	
4-4-90	10:29	83	6.86	5.57	17.5	
4-4-90	10:34	79	6.89	5.15	17.4	
4-4-90	10:39	74	6.85	6.15	17.5	
4-4-90	10:44	72	6.86	7.38	17.5	
4-4-90	10:49	71	6.85	7.45	17.6	
4-4-90	10:54	70	6.84	7.58	17.6	
4-4-90	10:59	70	6.82	7.80	17.6	
4-4-90	11:04	59	6.75	7.63	17.6	
4-4-90	11:09	58	6.76	7.50	17.6	
4-4-90	11:14	58	6.75	7.42	17.6	
4-4-90	11:19	57	6.74	7.40	17.7	
4-4-90	11:24	53	6.75	7.32	17.7	
4-4-90	11:29	43	6.73	7.33	17.7	
4-4-90	11:39	53	6.72	7.15	17.9	
4-4-90	11:49	47	6.70	7.09	17.8	
4-4-90	11:59	62.4	6.71	6.98	17.7	
4-4-90	12:09	64.1	6.71	7.17	17.7	
4-4-90	12:19	67.5	6.69	7.03	17.7	
4-4-90	12:29	50.4	6.69	6.40	17.7	
4-4-90	12:39	47.7	6.68	6.73	17.7	
4-4-90	12:49	48.4	6.68	6.77	17.7	

SC (µmho/cm): specific conductance in micromhos per centimeter
pH (SU): pH in standard units
DO (mg/l): dissolved oxygen in milligrams per liter
T(°C): temperature in degrees Celsius
-----: not measured

Table 1: Barnesville PW Water Chemistry Field Test Results (con't.)

Date	Time	SC (µmho/cm)	pH (SU)	DO (mg/l)	T (°C)	Comments
4-4-90	12:59	56.3	6.68	6.98	17.7	
4-4-90	13:09	65.8	6.67	6.61	17.7	
4-4-90	13:29	68.3	6.71	6.74	17.7	
4-4-90	13:49	68.4	6.68	6.97	17.7	
4-4-90	14:00	68.5	6.65	6.61	17.7	
4-4-90	14:29	69.0	6.62	6.39	17.7	
4-4-90	14:49	68.0	6.62	6.39	17.7	
4-4-90	15:20	49.9	6.66	6.26	17.7	SC err?
4-4-90	15:40	69.3	6.66	6.13	17.7	
4-4-90	16:00	69.4	6.67	6.25	17.7	
6-18-90	10:50	62.0	-----	-----	-----	
6-18-90	10:55	64.5	-----	-----	-----	
6-18-90	11:00	65.0	-----	-----	-----	
6-18-90	11:05	62.0	6.32	-----	18.0	
6-18-90	11:10	63.8	6.25	-----	17.8	
6-18-90	11:15	65.0	6.23	-----	17.8	
6-18-90	11:20	64.8	6.23	-----	17.8	
6-18-90	11:25	64.9	6.22	-----	17.8	
6-18-90	11:30	65.5	6.21	-----	17.8	
6-18-90	11:35	64.9	6.20	-----	17.8	
6-18-90	11:40	64.7	6.21	-----	17.8	
6-18-90	11:45	65.4	6.20	-----	17.8	
6-18-90	11:50	65.1	6.19	-----	17.8	

Table 1: Barnesville PW Water Chemistry Field Test Results (con't.)

Date	Time	SC (µmho/cm)	pH (SU)	DO (mg/l)	T(°C)	Comments
6-18-90	12:00	65.4	6.20	-----	17.8	
6-18-90	12:10	65.5	6.20	-----	17.8	
6-18-90	12:20	65.6	6.21	-----	17.8	
6-18-90	12:30	66.0	6.19	-----	17.8	
6-18-90	12:40	66.0	6.20	-----	17.8	
6-18-90	12:50	65.1	6.21	-----	17.8	
6-18-90	13:00	65.8	6.19	-----	17.8	
6-18-90	13:10	65.8	6.22	-----	17.8	
6-18-90	13:20	65.6	6.22	-----	17.8	
6-18-90	13:30	55.3	6.23	-----	17.8	
6-18-90	13:40	57.4	6.22	-----	17.8	
6-18-90	13:50	60.0	6.19	-----	17.8	
6-18-90	14:00	62.1	6.21	-----	17.8	
6-18-90	14:10	67.6	6.20	-----	17.8	
6-18-90	14:20	60.8	6.22	-----	17.8	
6-18-90	14:30	61.7	6.22	-----	17.8	
6-18-90	14:40	66.7	6.21	-----	17.8	
6-18-90	14:50	62.0	6.21	-----	17.8	
6-18-90	15:00	60.2	6.22	-----	17.8	
7-10-90	10:08	70.0	7.92	-----	17.8	pH err?
7-10-90	10:20	68.0	8.09	-----	17.9	pH err?
7-10-90	10:25	69.0	8.03	-----	17.9	pH err?
7-10-90	10:30	71.0	80.6	-----	17.9	pH err?

AQUIFER TESTING

Background

Three complete pumping tests were conducted at the research site between July, 1988 and July, 1990. The first test was performed to provide the City of Barnesville and the GGS with data on short-term well yield. Observation wells had not yet been drilled for this test. The second and third tests completed at this site were performed to establish the area and degree of influence of the Production Well on ground-water levels in the immediate area. Two additional pumping tests were attempted in March and June of 1990. These two tests were prematurely terminated due to well cuttings clogging the pump and problems with the diesel generators used to power the pumps. Records of the failed tests are on file at the GGS; however, these tests will not be further discussed in this report.

24-hour Test, July, 1988

The first pumping test on the Production Well was a 24-hour modified constant-head test, performed July 27-28, 1988 by GGS personnel. A 7.5 hp submersible pump installed at a depth of about 210 feet, powered by a diesel generator, was used to withdraw water from the well. Discharge was measured using both a utility flow-meter and the GGS orifice bucket. Measurements from the GGS orifice bucket were used to determine actual discharge because the flow meter clogged on several occasions. The orifice bucket was not equipped with a water-level recorder for this test. The pumping rate ranged from 70 to 76 gallons per minute (gpm), as shown on Figure 43, p. 34. The discharge rate dropped to zero numerous times during the test when it was necessary to shut off the pump to clear it of cuttings that were causing a reduction in the pump's capacity. The total volume of water discharged from the Production Well during this test was approximately 109,000 gallons (gal). Drawdown stabilized between 180 and 190 feet, and recovery was over 90 percent complete 30 minutes after the pump was shut off (Figure 44, p. 34). The Production Well had recovered to within one foot of the pre-pumping water level seven hours after the pump was shut off.

24-hour Test, April, 1990

The second complete pumping test was performed at this site from April 4 to 6, 1990. This was designed to be a constant-head test and was 24 hours in duration. The purpose of this test was to measure the effects of pumping on ground-water levels in both saprolite and bedrock. A 7.5 hp submersible pump, installed at a depth of 295 feet, powered by a diesel generator, was used to withdraw water from the Production Well. The initial pumping rate was about 85 gpm but this rate soon declined and stabilized between 65 and 70 gpm for the duration of the test (Figure 45, p. 37). Total discharge from the Production Well was about 91,000 gal. In reality, the test was a constant-rate test rather than a constant-head test because the discharge rate was fairly constant after the first hour or so and drawdown stabilized well above the pump level. This was because the pump capacity was insufficient to adequately stress the well. Reasons for this may be that the pump was partially clogged with well cuttings or that the generator was not operating at maximum capacity. The discharge rate dropped to zero several times at the beginning and end of the test when the pump was shut off to clear it of cuttings that were causing generator overload and a reduction in the pump's capacity. Maximum drawdown in the Production Well was about 90 feet (Figure 46, p. 37). Fluctuations in drawdown in the earlier portion of the test are a result of reduced pump efficiency due to partial clogging of the pump and shutting the pump down on several occasions to clear it of cuttings. A portion of the drawdown data was lost due to datalogger or computer software failure. This is noted on Figure 46. It was assumed that water level in the Production Well remained relatively stable (drawdown about 86-87 feet) throughout the pumping portion of the test. It was further assumed that the water level in the Production Well recovered rapidly after the pump was shut off, similar to the behavior seen during other tests on the Production Well. Backup water-level measurements were made on all remotely measured wells after this test. Recovery in the Production Well was 90 percent complete 40 minutes after the pump was shut off, and the water level was within 0.33 feet of the static water level when the final recovery measurement was made 24 hours after the pump was shut off.

The water level in Corehole 1 showed an almost instantaneous response to pumping (Figure 47, p. 38). Maximum drawdown in this well was almost 18 feet and had essentially stabilized by 300 minutes into the test. Fluctuations in drawdown are believed to be due to periodically shutting the pump off. The water level was within 0.65 feet of the static level 24 hours after pumping ceased.

Corehole 2, located across Big Towaliga Creek from the Production Well, also responded rapidly to pumping (Figure 48, p. 38). Maximum drawdown was about 1.55 feet in this well and had not stabilized by the end of the test. The water level in the well recovered to within 0.38 feet of the static level 24 hours after the pump was shut off.

Soil Well 1 experienced a 2.5 feet maximum decline in water level (Figure 49, p. 39). This well also showed a quick response to pumping, but the response was slower than in the adjacent Corehole 1. Drawdown essentially stabilized in Soil Well 1 about 960 minutes into the test. The water level recovered to within 0.13 feet of the static level 24 hours after the pump was shut off.

The water level in Soil Well 2 did not significantly respond to pumping until 34 minutes into the test. Maximum drawdown was about 4.5 feet in this well (Figure 50, p. 39). Drawdown appears to have stabilized about 1260 minutes into the test. The water level was within 0.21 feet of the static level 24 hours after pumping ceased.

The water level in Soil Well 3 responded almost immediately to pumping (Figure 51, p. 40). Maximum drawdown

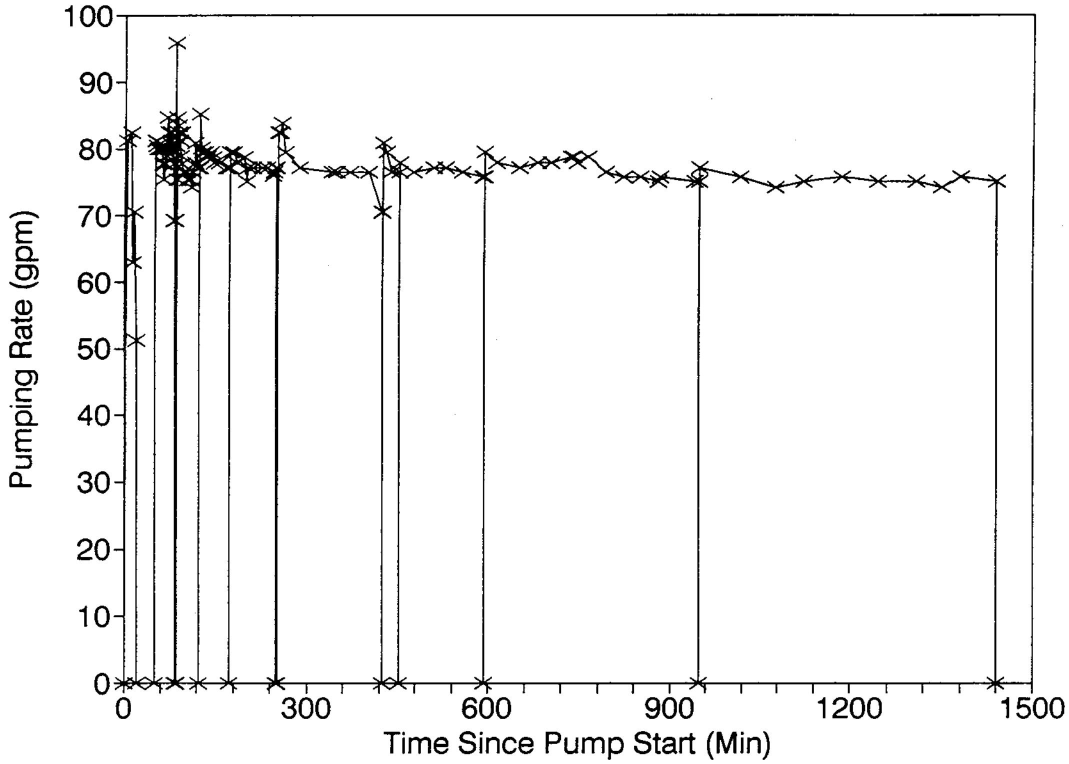


Figure 43. Pumping rate of the Production Well, July 27-28, 1988.

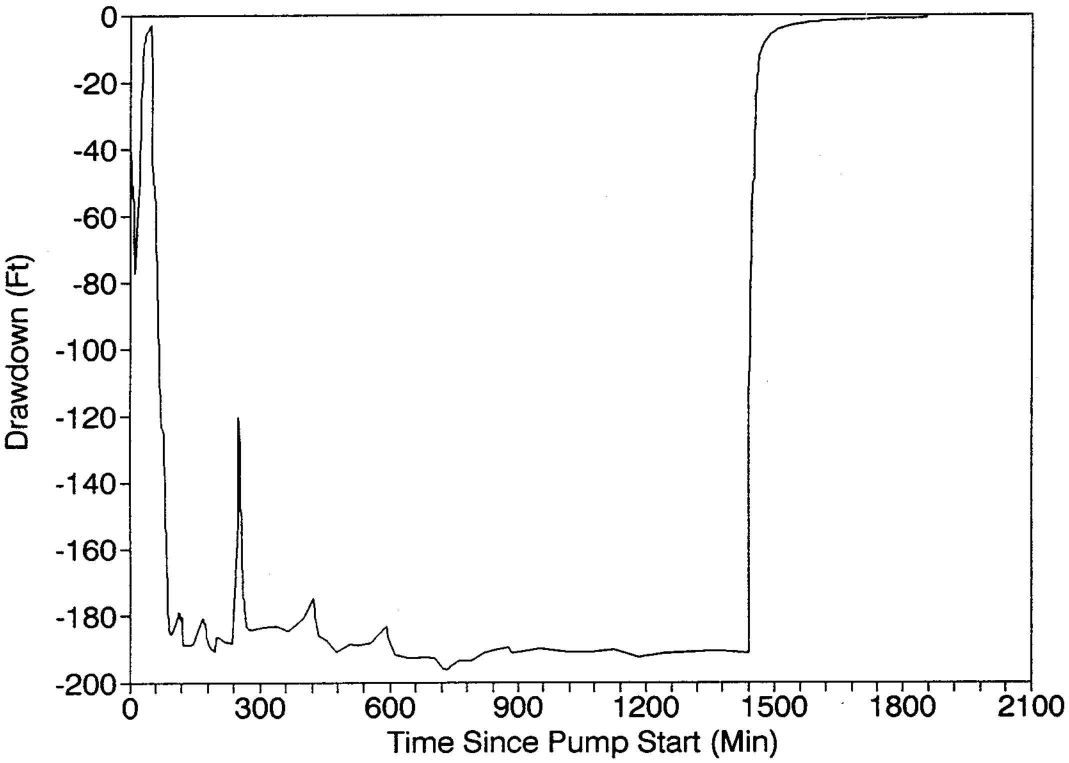


Figure 44. Drawdown and recovery of the Production Well, July 27-28, 1988.

was almost 22 feet and stabilized about 360 minutes into the test. The water level recovered to within 0.42 feet of the static level 24 hours after the pump was shut off.

Soil Well 4 also responded rapidly to pumping and the water level drew down a maximum of 8.78 feet (Figure 52, p. 40). This well almost stabilized, but the water level was still declining at a slow rate at the end of the test. Twenty four hours after the pump was shut off, the water level in this well was within 0.26 feet of the static level.

The water level in Soil Well 5 also responded quickly to pumping (Figure 53, p. 41). Maximum drawdown was 3.2 feet and occurred at the end of the test. This well is located across Big Towaliga Creek from the Production Well. According to Figure 53, the well recovered to above the static water level. The shape of the drawdown-recovery curve for Soil Well 5 is uneven when compared to curves for the other soil wells and coreholes. A pressure transducer was used to measure water-level changes in this well. The pressure transducer was probably affected somewhat by barometric pressure changes which resulted in the uneven shape of the curve. Again, verification measurements were made in all wells equipped with pressure transducers after this test.

The water level in the Large Diameter Well responded almost immediately to pumping (Figure 54, p. 41). This was confirmed by observing changes on the water-level recorder chart. Drawdown maximized at 9.04 feet and stabilized in this well. The water level in the Large Diameter Well recovered to within 0.23 feet 24 hours after the pump was shut off.

Figures 55a through 55e (p. 42-43) show changes in water levels in the soil wells for 30, 60, 360, 720 and 1440 minutes after the start of the April, 1990 pumping test. The rapid drawdown in Soil Well 3 is illustrated on Figure 55a. Little drawdown occurred in Soil Well 1 and Soil Well 2 for the first 30 minutes of the test (Figure 55a). The water-level changes in Soil Well 5 are questionable because the pressure transducer used in this well was probably affected by barometric pressure. These readings are further suspect in that drawdown in Soil Well 5 is shown as 2.62 feet 360 minutes into the test and only 2.11 feet 720 minutes into the test. This response to pumping is inconsistent with the other soil wells. Near stabilization of water levels in Soil Well 3, Soil Well 4 and the Large Diameter Well is shown in Figures 55c, 55d, and 55e, where water-level changes are slight toward the middle and end of the test.

In summary, during the 24-hour pumping test, both coreholes and all soil wells were rapidly affected by pumping the Production Well. Drawdown essentially stabilized in all observation wells, with the exception of Corehole 2 and Soil Well 5. These two wells are located across Big Towaliga Creek from the Production Well. In general, soil wells located closer to the Production Well were affected by pumping to a greater degree than soil wells located at some greater distance. However, drawdown in Soil Well 3 (Figure 51), located 15 feet from the Production Well, was much greater than drawdown in Soil Well 4 (Figure 52), located 18 feet from the Production Well. This difference in drawdown could be caused by Soil Well 3 tapping a greater portion of the water-bearing transition zone than Soil Well 4 or by an influence from foliation, joint, or other fracture sets located near the Production Well. Finally, the water levels in all wells recovered to slightly below the pre-pumping levels 24 hours after pumping ceased.

72-hour Test, July, 1990

The final pumping test for this project was conducted at the Barnesville Hydrologic Research Site on July 9-15, 1990. This test was designed as a constant-head test and the pumping portion was 72 hours in duration. The purpose of the test was to measure the effects of pumping on ground water in both saprolite and bedrock over a 72-hour period. A larger capacity pump was installed prior to this test to produce greater discharge and drawdown in the Production Well. This pump was installed at a depth of 295 feet, the same as for the 24-hour test. A more reliable diesel generator was used for this test to lessen the chances of pump failure due to generator problems. The initial pumping rate was just over 120 gpm but this rate soon stabilized to between 80 and 85 gpm (Figure 56, p. 44). The larger capacity pump resulted in a net increase in pumping rate of about 15 gpm. Total discharge from the Production Well was just over 353,000 gal. This test was, in effect, a constant-rate test rather than a constant-head test because the discharge rate remained fairly consistent after the first few hours, and drawdown stabilized above the pump level, similar to the April, 1990 test. This may have been because the pump, even though larger than in the April test, was not of sufficient capacity to adequately stress the well or that the pump was partially clogged with well cuttings. Maximum drawdown in the Production Well was 258.37 feet (Figure 57, p. 44). The specific causes of fluctuations in the water level in the Production Well between zero and 500 minutes and between 900 and 2100 minutes are not known. Potential causes include partial and temporary clogging of the pump, reduced generator output and/or rainfall replenishing the aquifer system. Recovery was 90 percent complete 20 minutes after the pump was shut off and the water level was 0.34 feet of the static level 72 hours after pumping ceased.

The water level in Corehole 1 responded almost immediately to pumping and had a maximum drawdown of 21.46 feet, which is about 3.4 feet greater than in the 24-hour test (Figure 58, p. 45). Maximum drawdown rates occurred relatively early in the pumping test, then gradually decreased a small amount. Otherwise, the water level remained stable. The water level recovered to within 0.36 feet of the static level 72 hours after the pump was shut off.

Corehole 2 also responded rapidly to pumping, as shown on Figure 59. Maximum drawdown was 5.17 feet, which is about 3.6 feet greater than in the 24-hour test performed in April, 1990; however, the overall shape of the curve is similar to the April test. Drawdown did not stabilize in this well. The water level recovered to within 0.37 feet of the static level, 72 hours after pumping ceased.

Soil Well 1 responded quickly to pumping and maximum drawdown was 3.11 feet (Figure 60, p. 46). Maximum drawdown in Soil Well 1 was 0.61 feet greater for this test than for the 24-hour test performed in April, 1990. The water level was still declining at a slow rate at the end of the test. Seventy two hours after the pump was shut off, the water level in this well had recovered to 0.18 feet above the pre-pumping level.

The water level in Soil Well 2 responded rapidly to pumping and maximum drawdown was 5.57 feet (Figure 61, p. 46). Maximum drawdown in this well was 1.07 feet greater for this test than for the April, 1990 test. The water level continued to decline throughout the test. At the end of recovery, the water level was 0.13 feet below the static level.

Soil Well 3 responded almost immediately to pumping (Figure 62, p. 47). Maximum drawdown was 22.48 feet which was 0.53 feet greater than maximum drawdown for the April, 1990 test. The water level in this well nearly stabilized, but was declining very slowly from 360 minutes into the test until the end of the test. The water level recovered to within 0.25 feet of the static level 72 hours after the pump was shut off.

Soil Well 4 quickly responded to pumping and maximum drawdown was 9.38 feet (Figure 63, p. 47). Maximum drawdown was 0.60 feet greater for this test than for the 24-hour test performed in April, 1990. From 300 minutes until the end of the test, the water level declined at a slow, relatively constant rate. The water level recovered to 0.37 feet above the pre-pumping level 72 hours after pumping ceased.

Soil Well 5, located across Big Towaliga Creek, responded rapidly to pumping and maximum drawdown was 4.83 feet (Figure 64, p. 48). Maximum drawdown in Soil Well 5 was 1.63 feet greater for the 72-hour test when compared to the April, 1990 test. The water level in this well continued to decline throughout the test. The final recovery measurement showed that Soil Well 5 was 0.22 feet below the static water level.

The water level in the Large Diameter Well responded almost immediately to pumping, as confirmed by observing the response on the water-level recorder chart. Maximum drawdown was 9.71 feet in this well (Figure 65, p. 48) which is 0.67 feet greater than for the 24-hour test performed in April. The water level continued to decline at a slow rate from about 400 minutes into the test until the pump was shut off. The well recovered to within 0.23 feet of the static level 72 hours after the pump was shut off.

Figures 66a through 66g (p. 49-51) depict changes in water levels in the soil wells for 30, 60, 360, 720, 1440, 2880, and 4320 minutes after the start of the July, 1990 pumping test. Changes in the water level in the Large Diameter Well are not shown on Figures 66a and 66b. The rapid drawdown in Soil Well 3 is again illustrated on Figure 66a. Little drawdown occurred in Soil Well 1 and Soil Well 2 for the first 30 minutes of the test (Figure 66a). The drawdown rate in Soil Well 1, Soil Well 2, Soil Well 3, Soil Well 4, and the Large Diameter Well slowed down but continued to drop at the end of the test (Figures 66c, 66d, 66e, 66f, and 66g).

In summary, during the 72-hour pumping test, both coreholes and all soil wells were rapidly affected by pumping the Production Well. The rate of drawdown slowed in all observation wells, with the exception of Corehole 2 and Soil Well 5. Again, these two wells are located across Big Towaliga Creek from the Production Well. However, water levels were still declining at end of the 72-hour test in all wells, except Corehole 1. This is in contrast to the 24-hour test, where only the water levels in Corehole 2 and Soil Well 5 were still declining significantly at the end of the test. In general, soil wells located closer to the Production Well were again affected by pumping to a greater degree than soil wells located farther away. However, drawdown in Soil Well 3 (Figure 62), located 15 feet from the Production Well, was much greater than drawdown in Soil Well 4 (Figure 63), located 18 feet from the Production Well. This difference in drawdown could be caused by Soil Well 3 tapping a greater portion of the water-bearing transition zone than Soil Well 4 or by a direct influence from foliation or joint sets located near the Production Well. Finally, the water levels in six wells recovered to within 0.4 feet of the static water level, while the water level in three wells rose to as much as 0.37 feet above the static level 72 hours after the pump was shut off. In general, water levels recovered to a higher level after the 72-hour test when compared to the 24-hour test. This is probably due to recharge as a result of heavy rain during and after the 72-hour test and little or no rain during or after the 24-hour test.

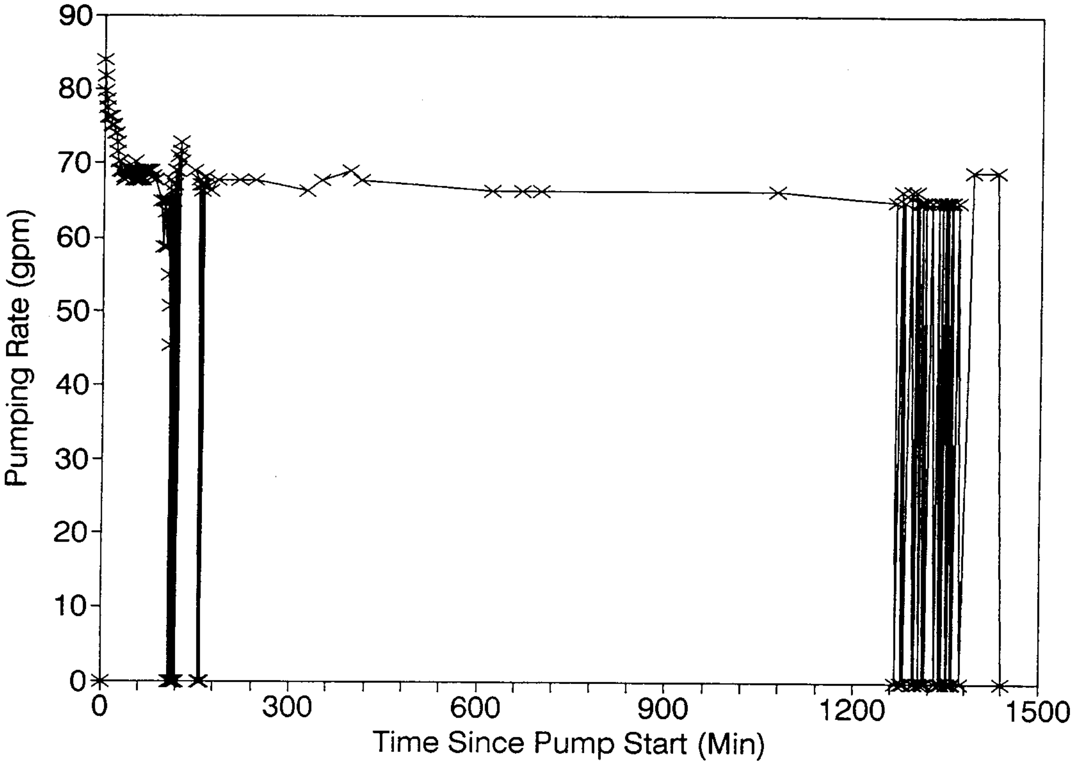


Figure 45. Pumping rate of the Production Well, April 4-5, 1990.

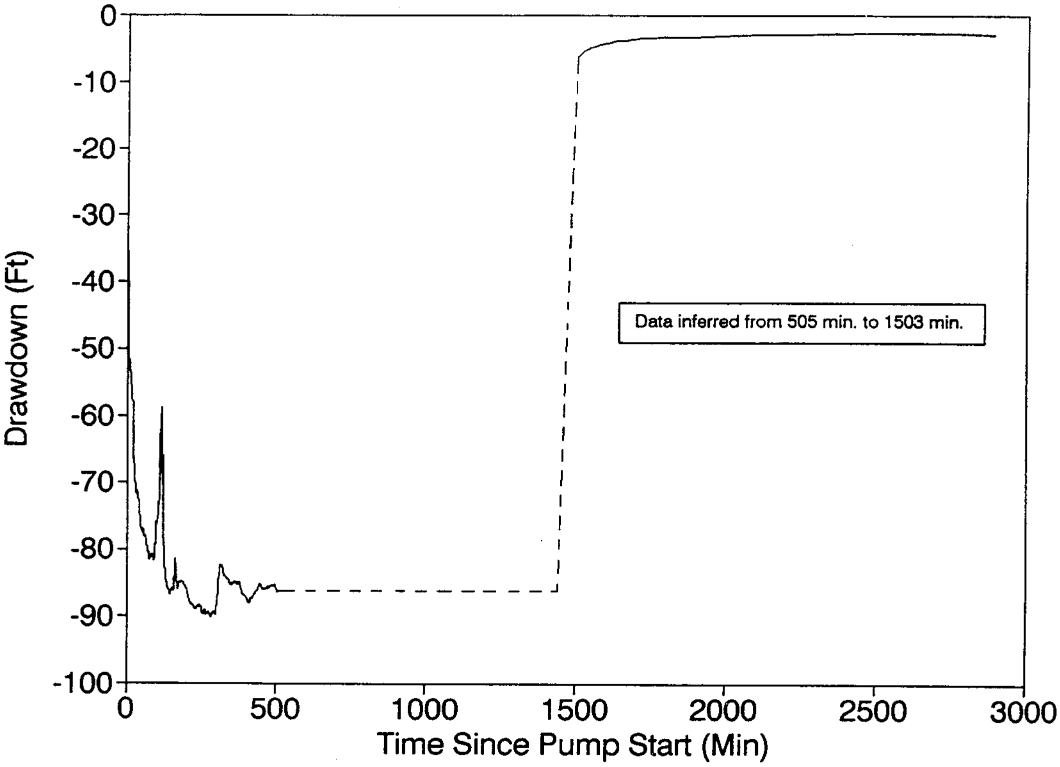


Figure 46. Drawdown and recovery of the Production Well, April 4-6, 1990.

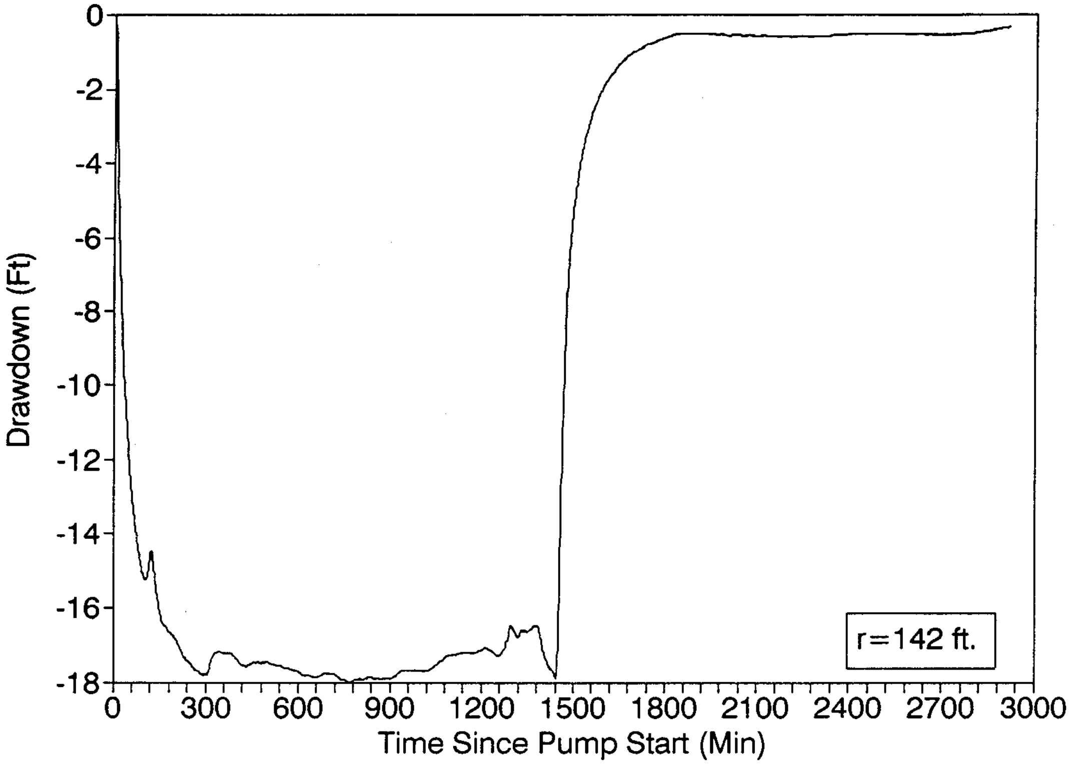


Figure 47. Drawdown and recovery of Corehole 1, April 4-6, 1990.

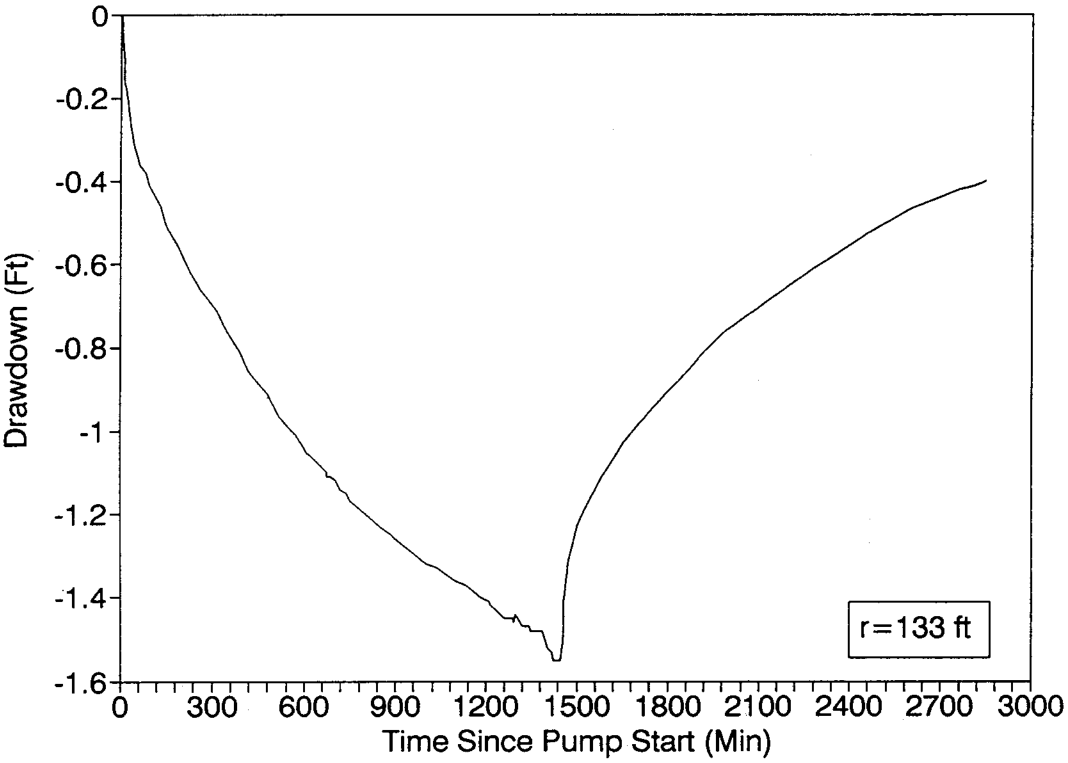


Figure 48. Drawdown and recovery of Corehole 2, April 4-6, 1990.

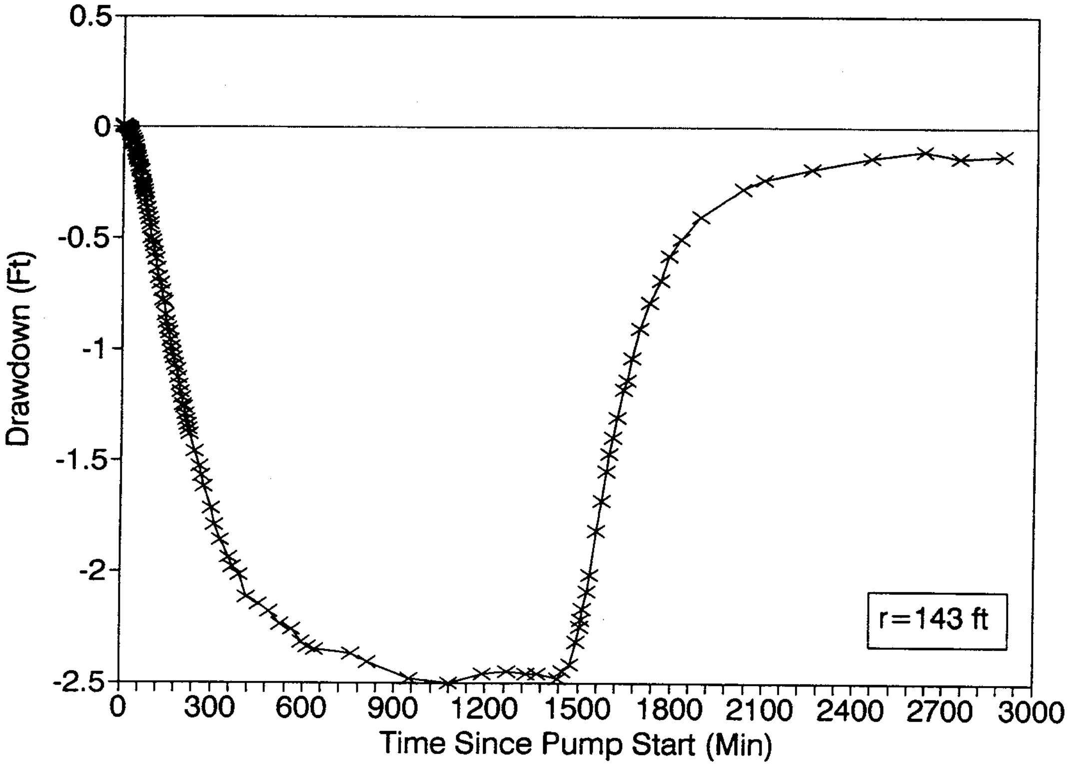


Figure 49. Drawdown and recovery of Soil Well 1, April 4-6, 1990.

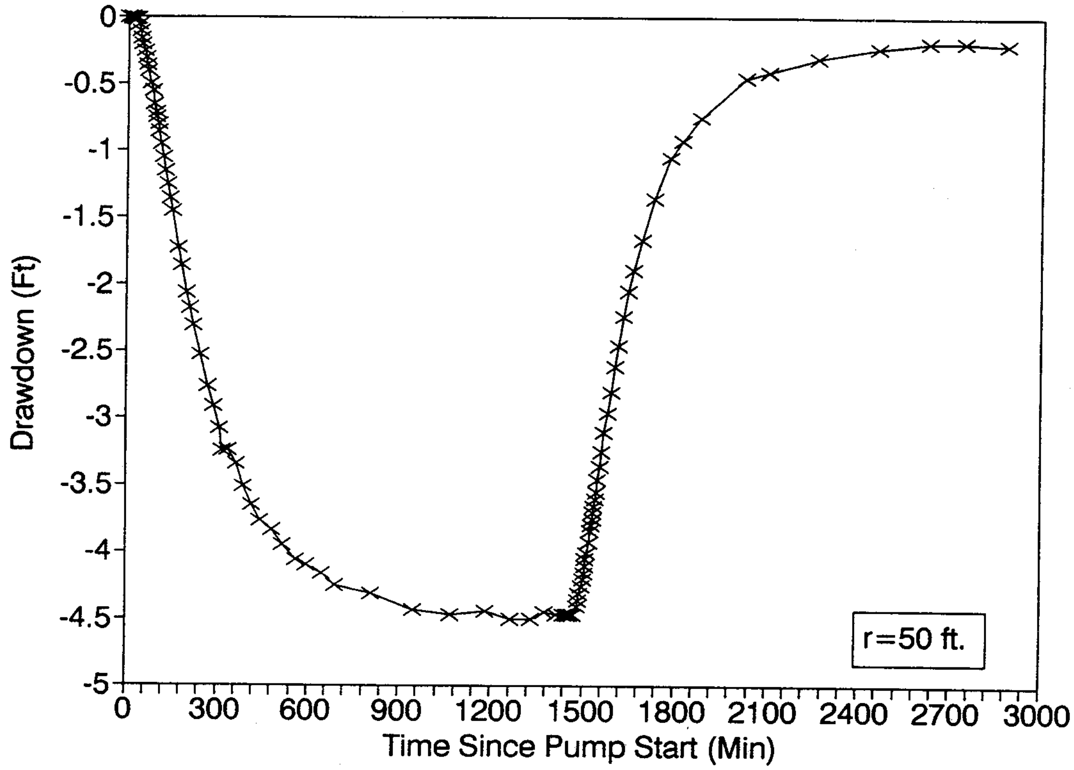


Figure 50. Drawdown and recovery of Soil Well 2, April 4-6, 1990.

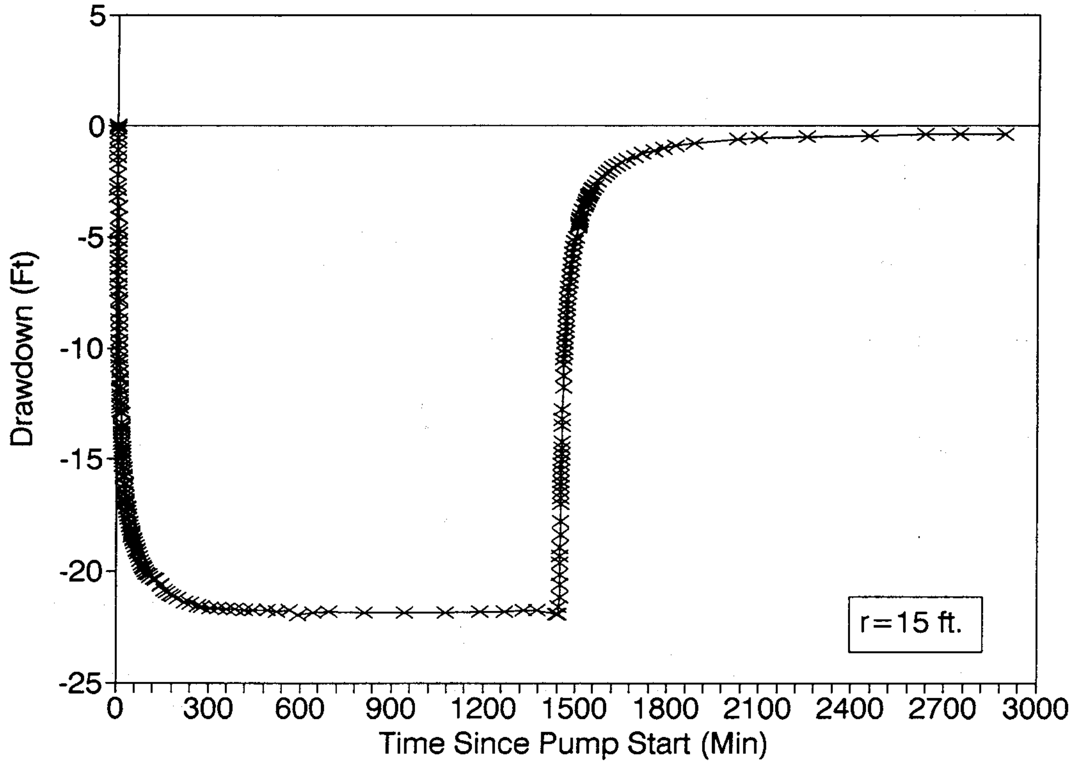


Figure 51. Drawdown and recovery of Soil Well 3, April 4-6, 1990.

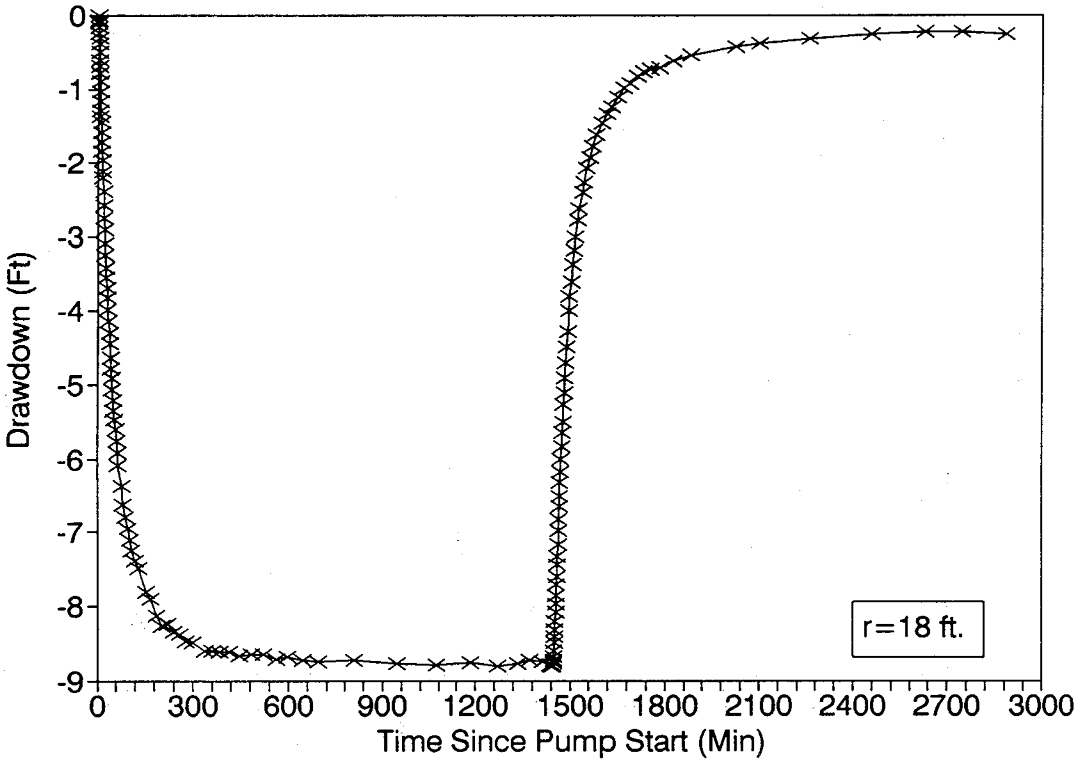


Figure 52. Drawdown and recovery of Soil Well 4, April 4-6, 1990.

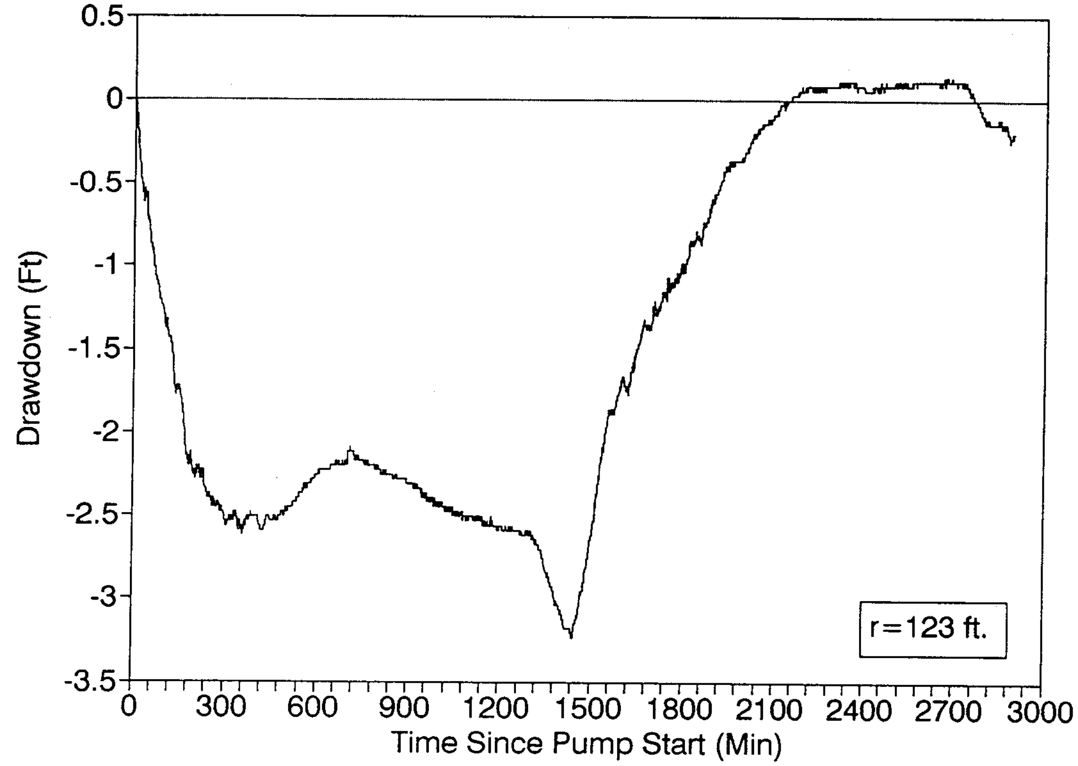


Figure 53. Drawdown and recovery of Soil Well 5, April 4-6, 1990.

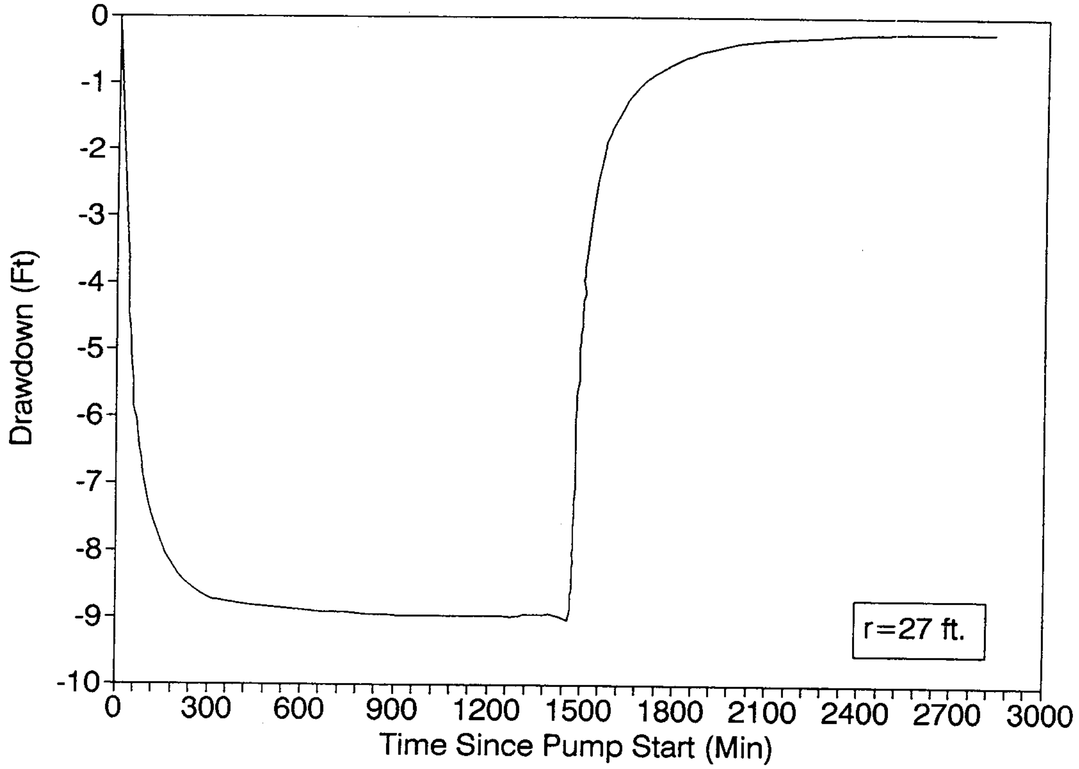


Figure 54. Drawdown and recovery of the Large Diameter Well, April 4-6, 1990.

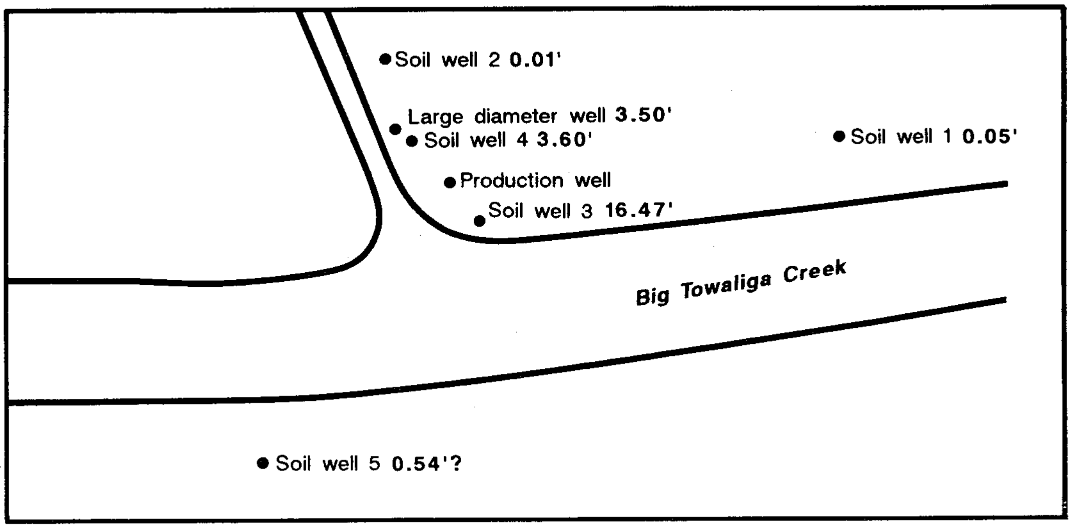


Figure 55a. Water-level change, 30 minutes after pump start (04/04/1990).

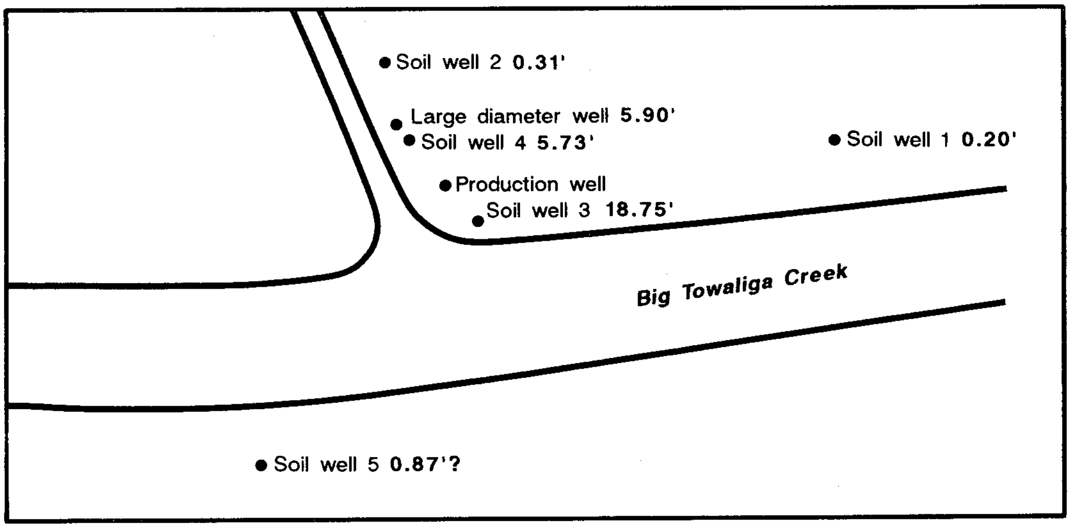


Figure 55b. Water-level change, 60 minutes after pump start (04/04/1990).

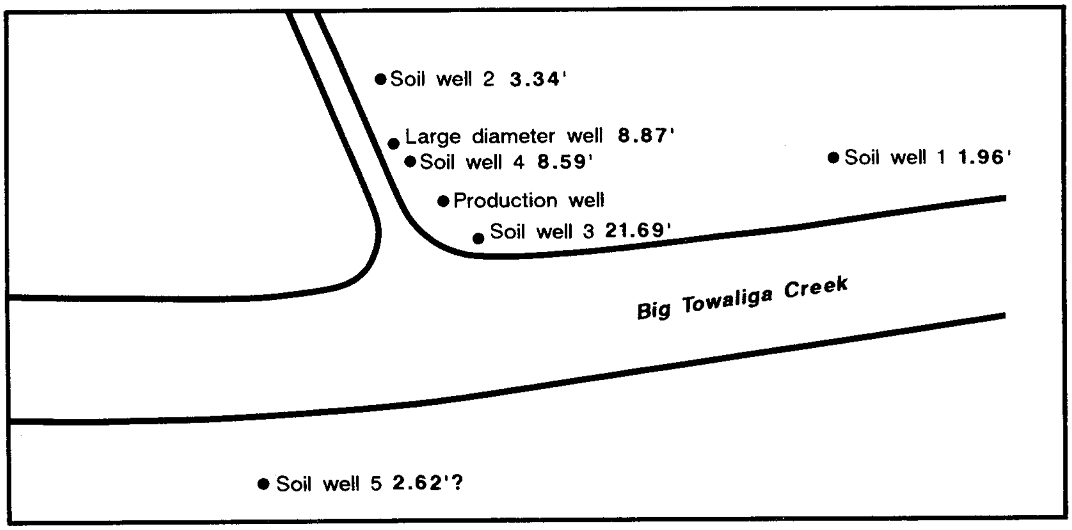


Figure 55c. Water-level change, 360 minutes after pump start (04/04/1990).

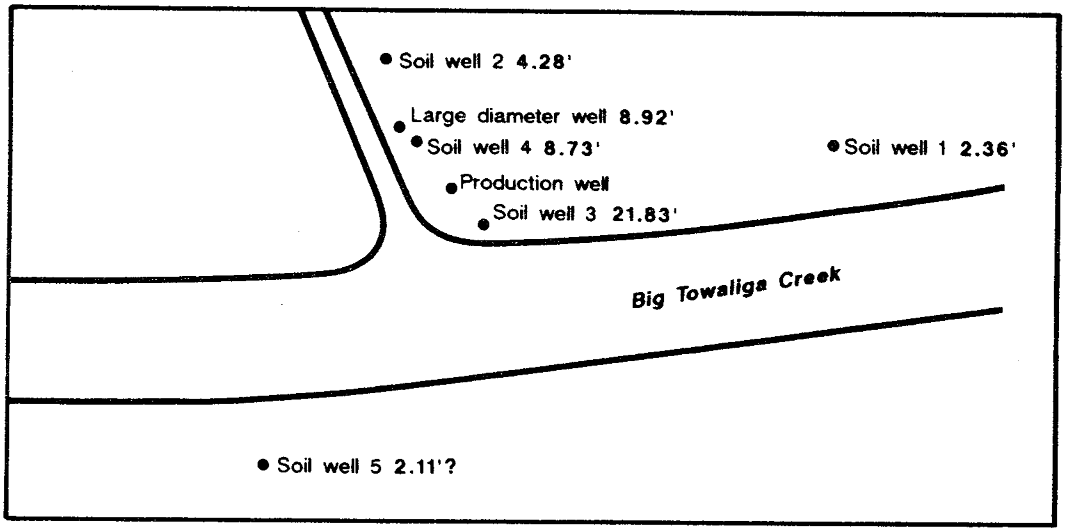


Figure 55d. Water-level change, 720 minutes after pump start (04/04/1990).

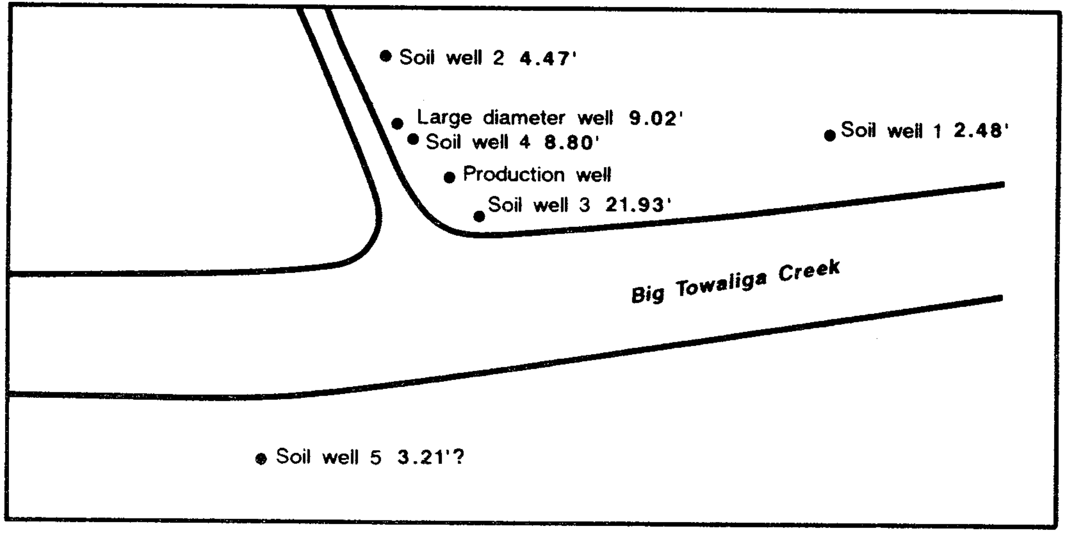


Figure 55e. Water-level change, 1440 minutes after pump start (04/04/1990).

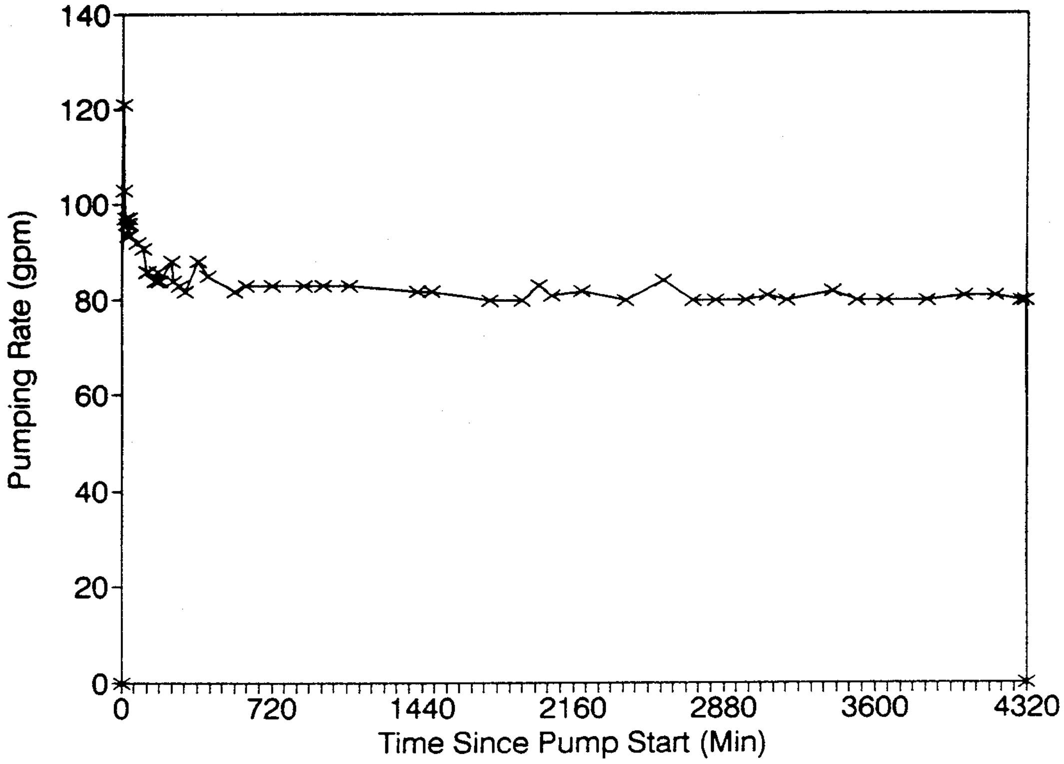


Figure 56. Pumping rate of the Production Well, July 9-12, 1990.

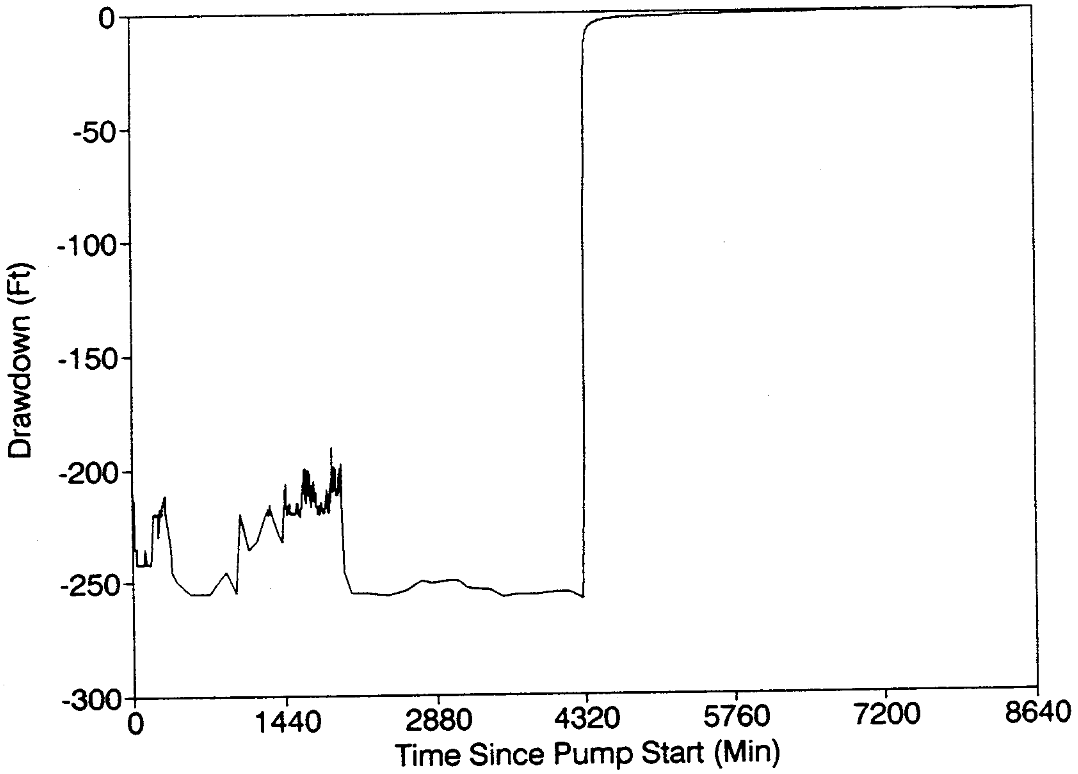


Figure 57. Drawdown and recovery of the Production Well, July 9-12, 1990.

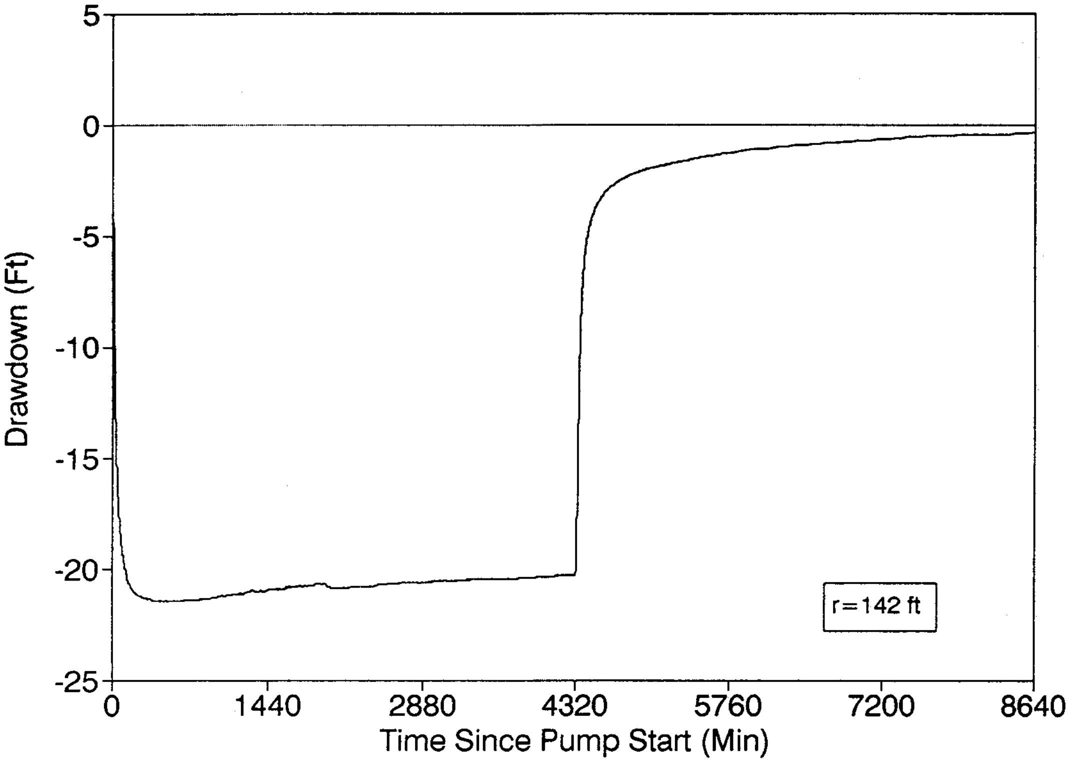


Figure 58. Drawdown and recovery of Corehole 1, July 9-12, 1990.

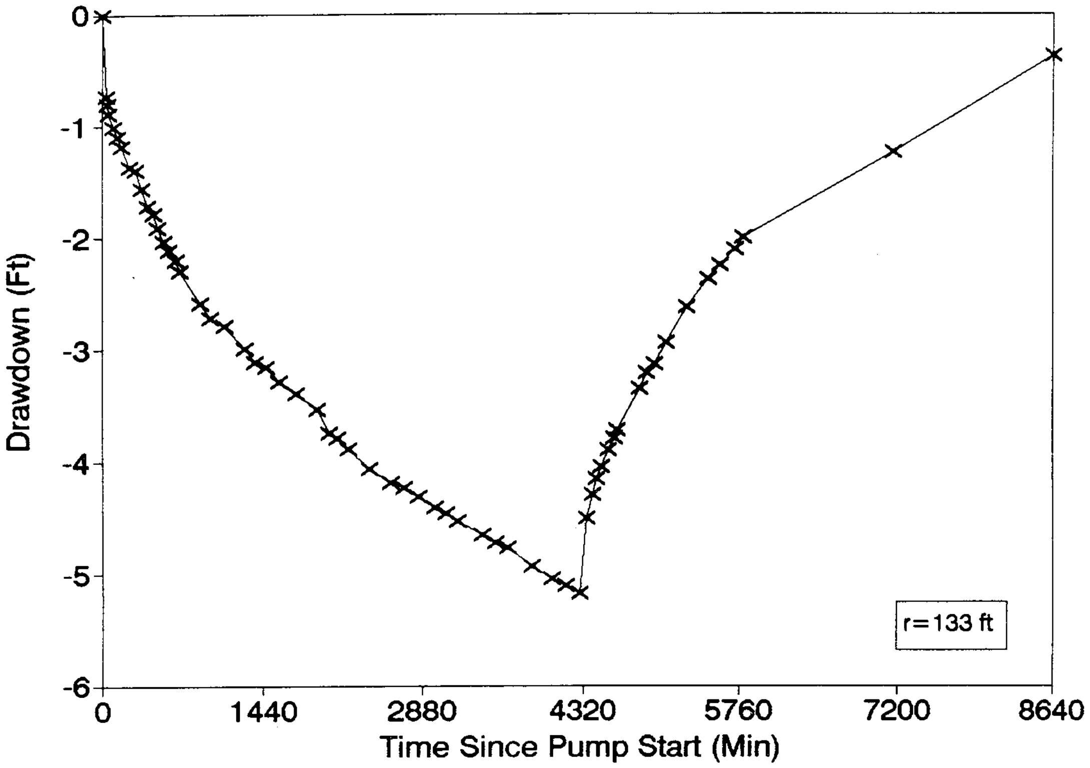


Figure 59. Drawdown and recovery of Corehole 2, July 9-12, 1990.

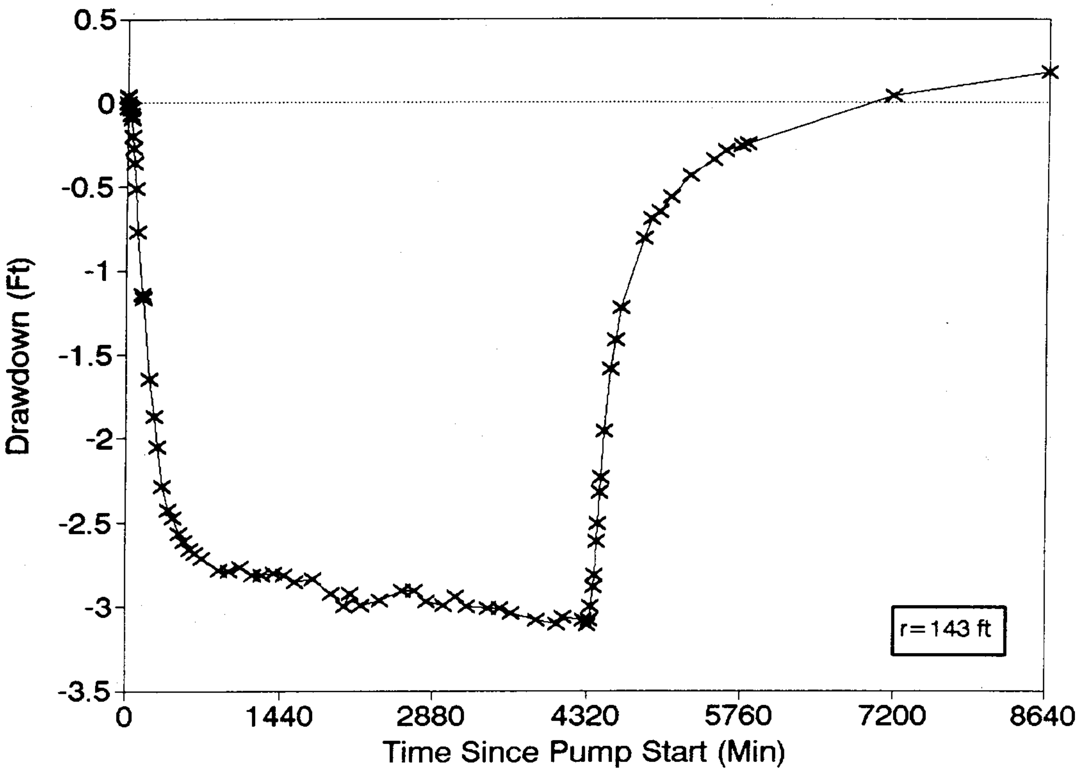


Figure 60. Drawdown and recovery of Soil Well 1, July 9-12, 1990.

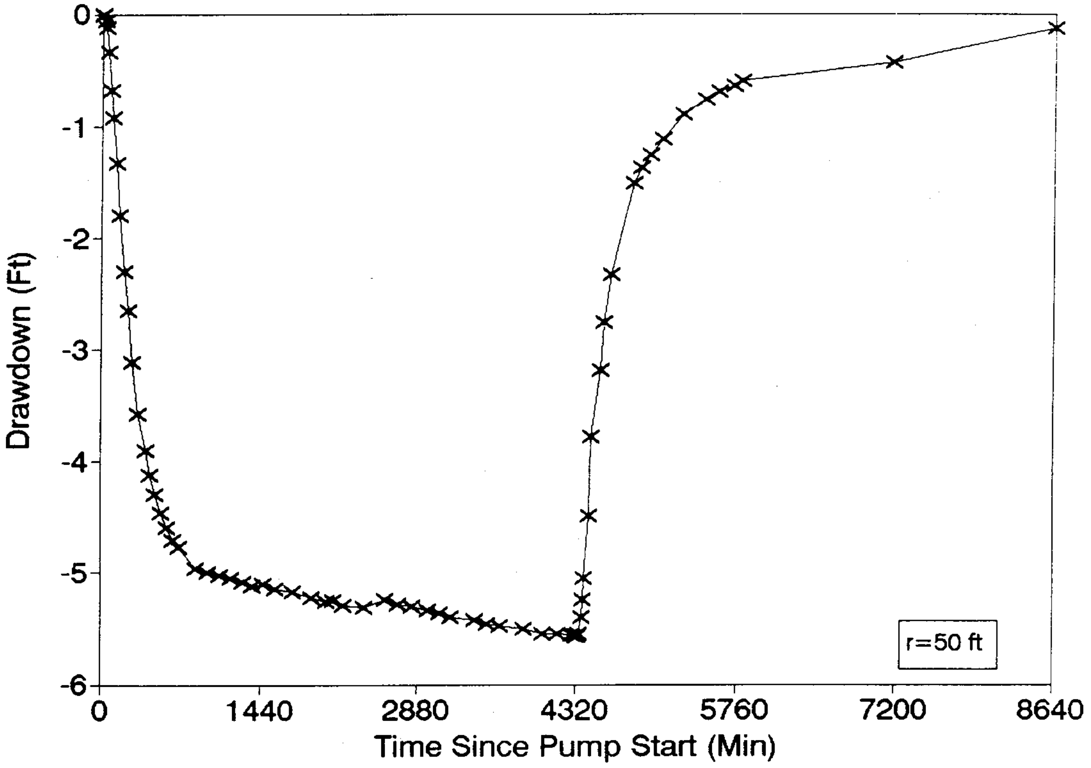


Figure 61. Drawdown and recovery of Soil Well 2, July 9-12, 1990.

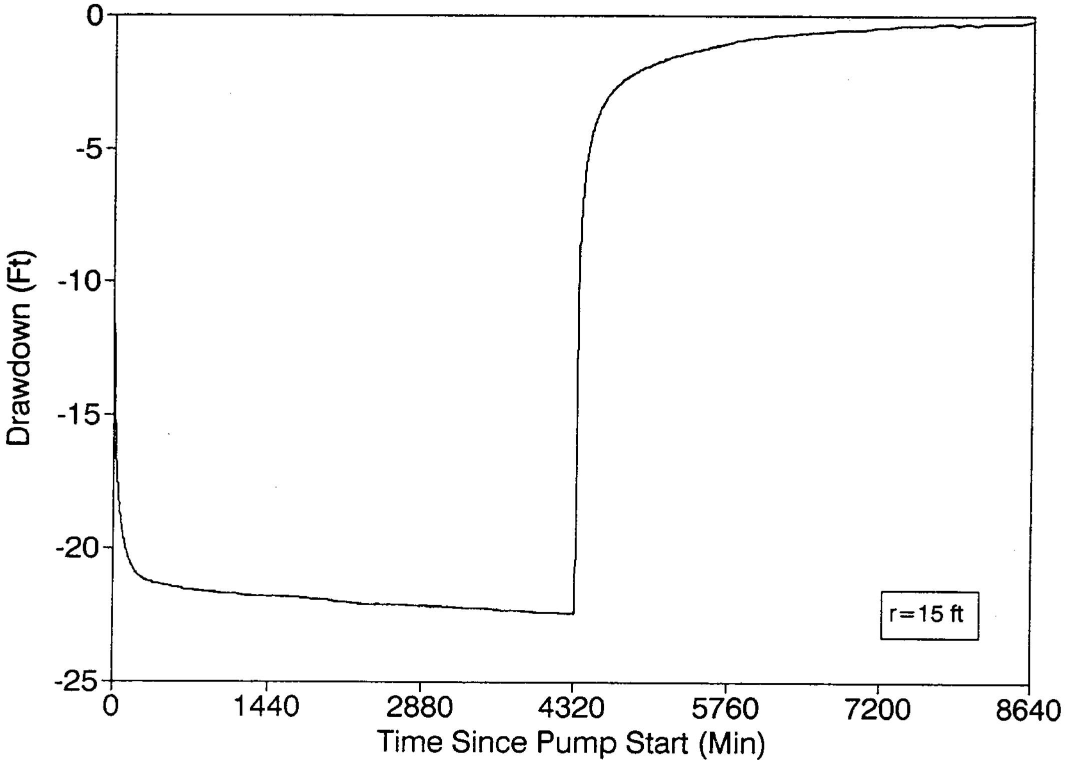


Figure 62. Drawdown and recovery of Soil Well 3, July 9-12, 1990.

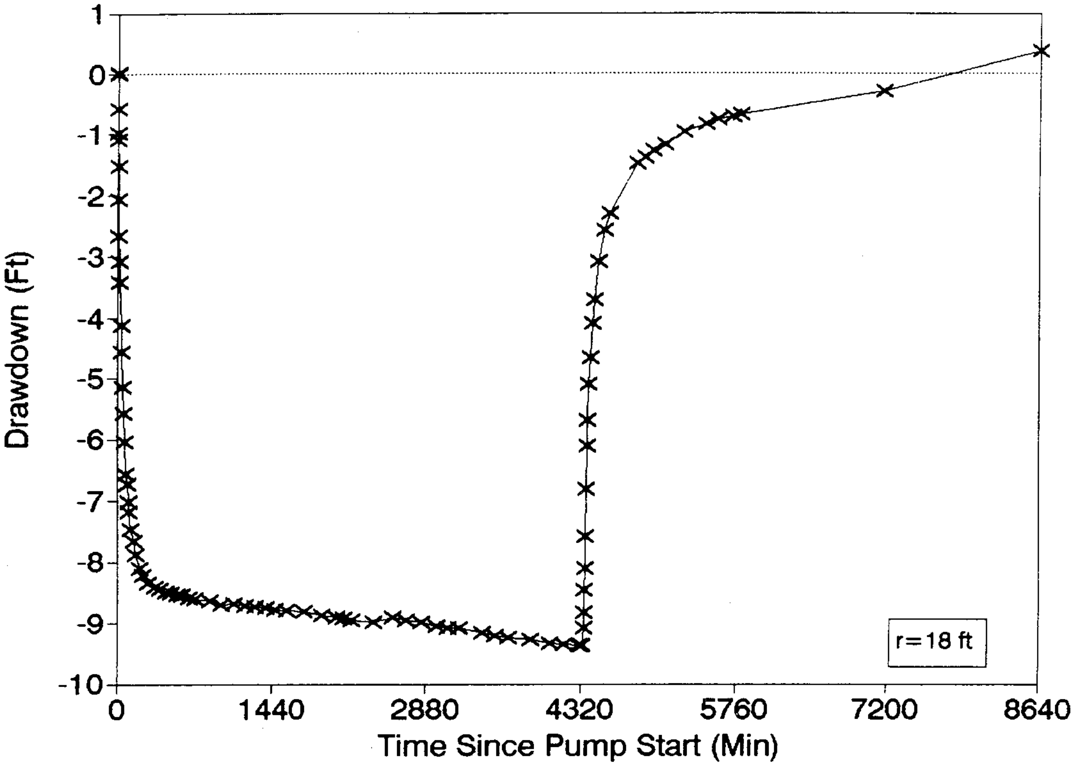


Figure 63. Drawdown and recovery of Soil Well 4, July 9-12, 1990.

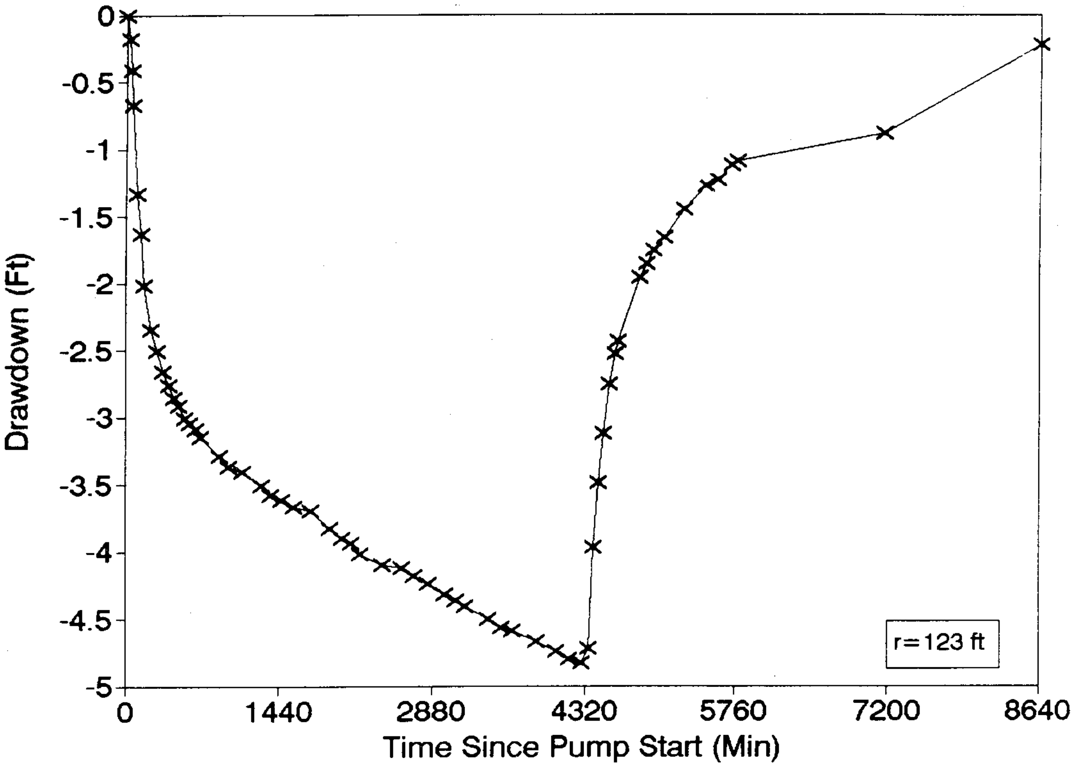


Figure 64. Drawdown and recovery of Soil Well 5, July 9-12, 1990.

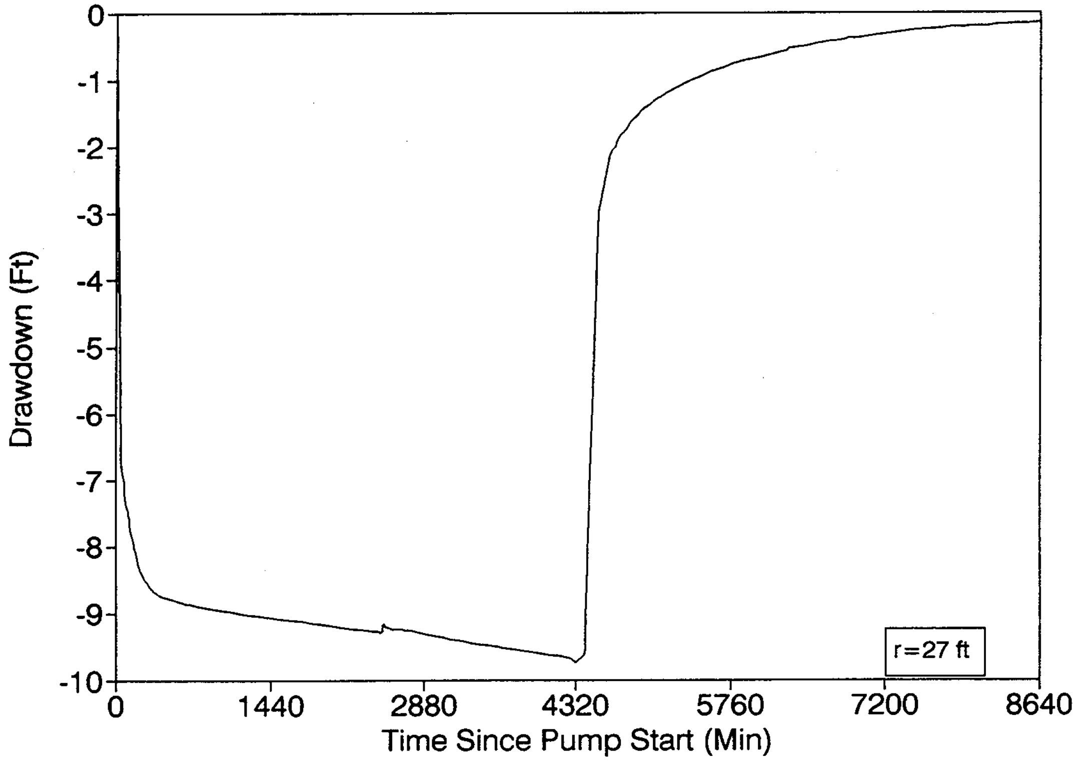


Figure 65. Drawdown and recovery of the Large Diameter Well, July 9-12, 1990.

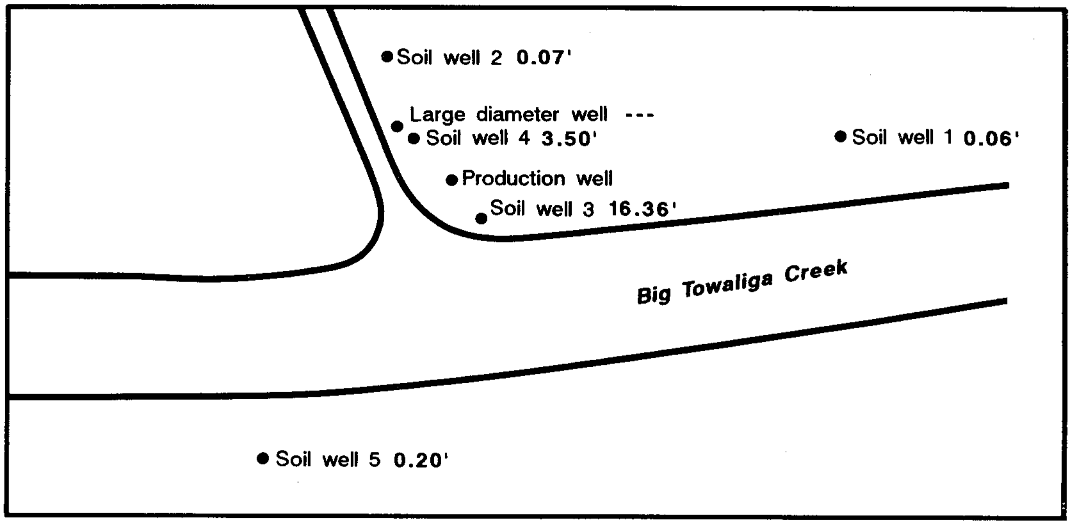


Figure 66a. Water-level change, 30 minutes after pump start (07/09/1990).

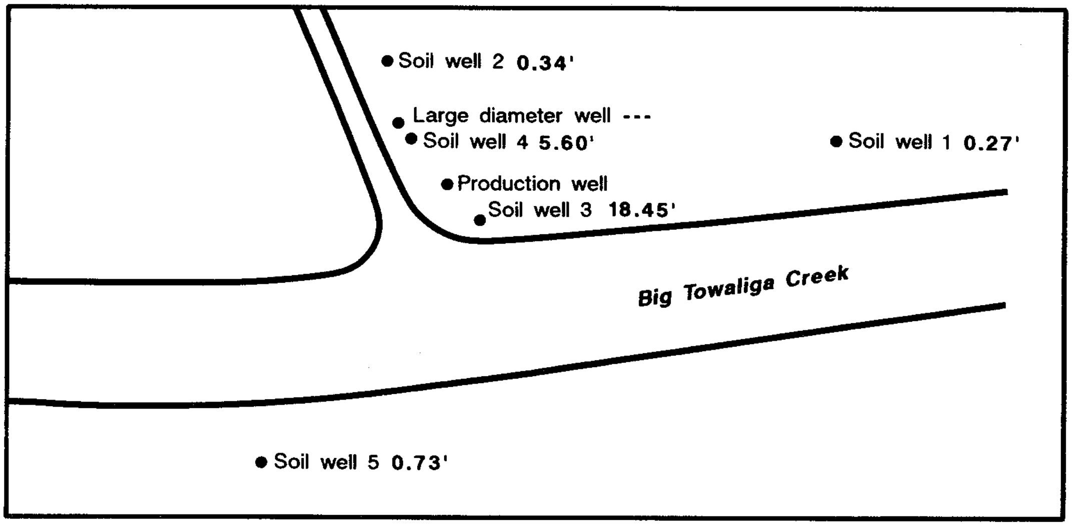


Figure 66b. Water-level change, 60 minutes after pump start (07/09/1990).

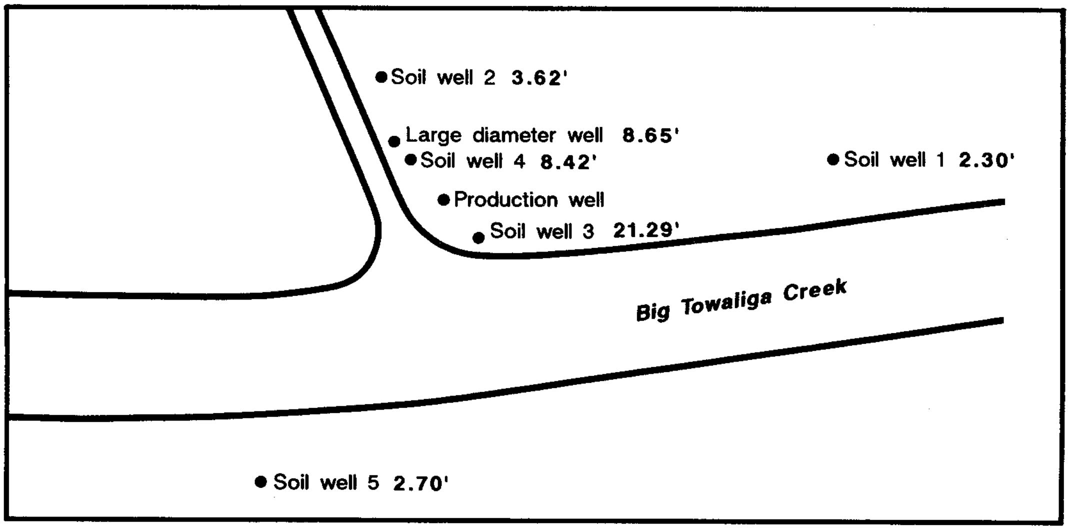


Figure 66c. Water-level change, 360 minutes after pump start (07/09/1990).

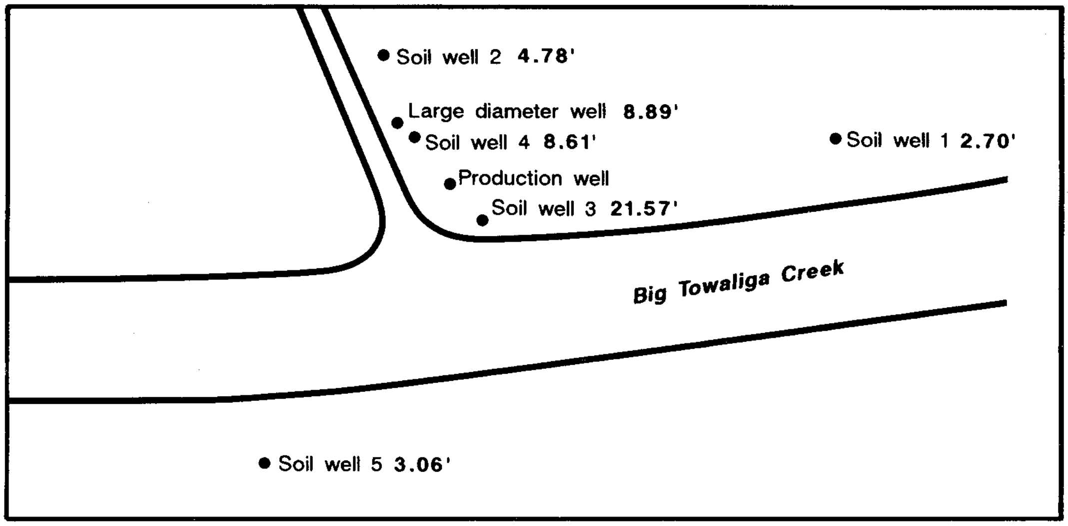


Figure 66d. Water-level change, 720 minutes after pump start (07/09/1990).

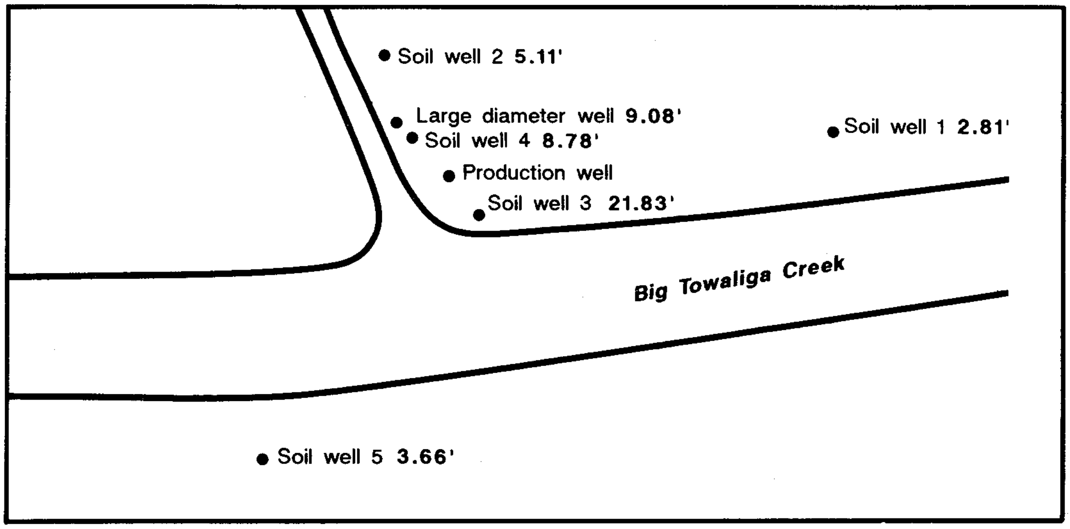


Figure 66e. Water-level change, 1440 minutes after pump start (07/09/1990).

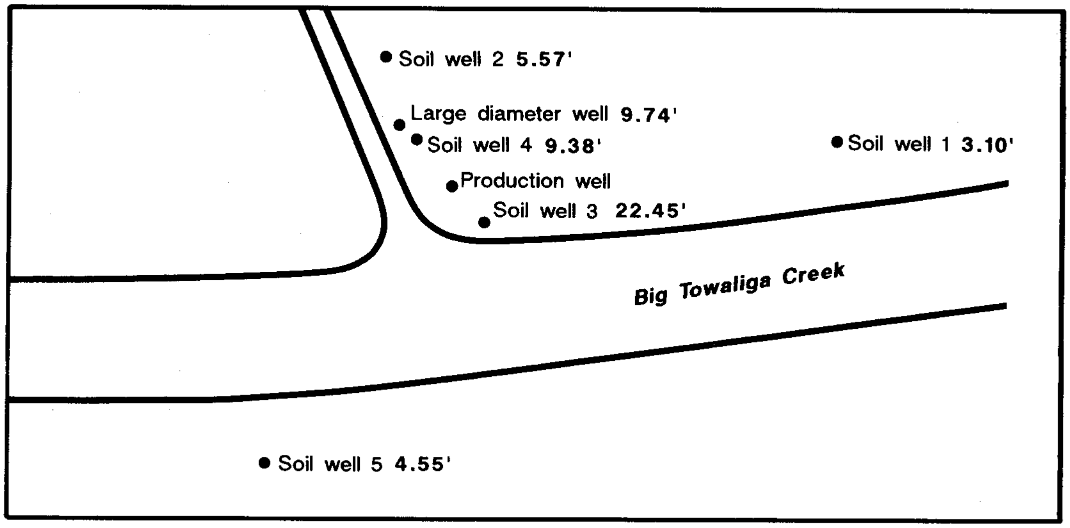


Figure 66f. Water-level change, 2880 minutes after pump start (07/09/1990).

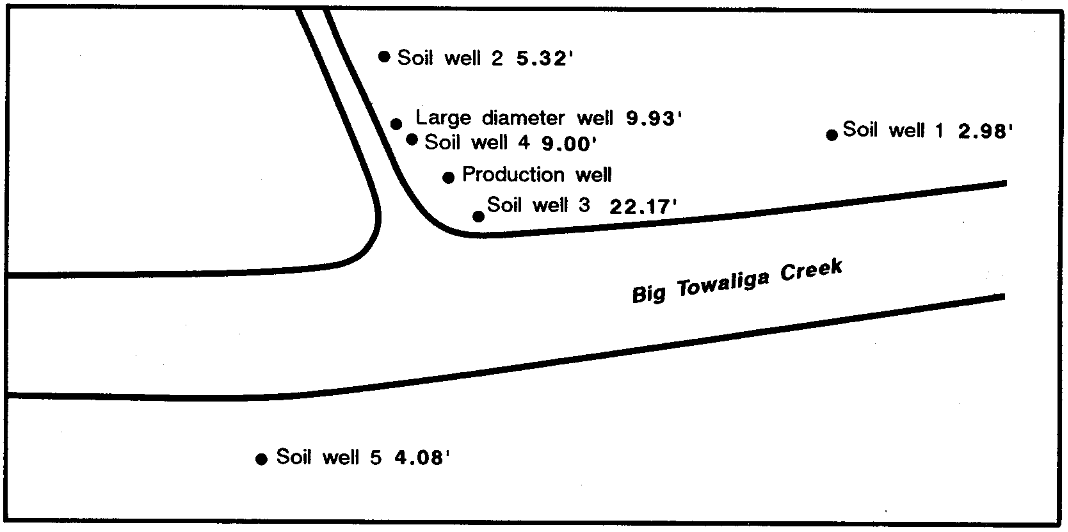


Figure 66g. Water-level change, 4320 minutes after pump start (07/09/1990).

SUMMARY OF OBSERVATIONS

Eleven major observations were derived from this study. These are as follows:

1. Quartzite, augen gneiss and sheared schist underlie the Barnesville Hydrologic Research Site.

2. The Towaliga fault zone is the major geologic structure underlying the site. The mean foliation orientation within the Towaliga fault zone and within a one-mile radius of the site is N77°E, 50°NW. The dominant joint set near and within the Towaliga fault zone is oriented roughly north-south (Sneyd, 1994).

3. The magnetometer study revealed no significant change in magnetic intensity attributable to a change in rock type. The only observed changes in magnetic intensity were caused by man-made sources (primarily a gas pipeline and well casing) and by natural fluctuations in the Earth's magnetism.

4. The major water-bearing zone in the Production Well is from 50 to 60 feet. The major water-bearing zone is between 50 and 65 feet in Corehole 1 and between 70 and 120 feet in Corehole 2. The major water-bearing zone underlying the site is the transition zone where saprolite grades into less weathered rock.

5. Ground-water levels in the Production Well were significantly affected by drilling of Corehole 1. Ground-water levels in bedrock wells at the study site were affected by drilling of Corehole 2, but to a lesser extent than effects caused by the drilling of Corehole 1. Ground-water levels in regolith observation wells at the study site were not significantly affected by drilling of bedrock wells.

6. Background water levels in both regolith and bedrock observation wells at the study site are directly affected by precipitation and evapotranspiration. Precipitation effects are shown by measured increases in water levels in the Production Well, coreholes and soil wells following precipitation recorded at a nearby weather station. Evapotranspiration effects are shown by general declines in water levels in the summer months of 1989 and 1990 for both soil and bedrock wells.

7. Values for specific conductance of ground water from this site appear lower-than-normal for water from Piedmont wells. This may indicate that water from the Production Well is lower in dissolved solids than water from other Piedmont wells. The pH and temperature values were in the normal range for Piedmont wells.

8. Pumping tests performed in April, 1990 (24-hour test; discharge rate=65-70 gpm) and July, 1990 (72-hour test; discharge rate=65-70 gpm) produced drawdown in all observation wells, including those located across Big Towaliga Creek. Furthermore, the vast majority of observation wells responded within the first 30 minutes of pumping. This is in contrast to the results of aquifer tests performed by GGS at the Reinhardt College Hydrologic Research Site, Cherokee County, where there was also significant response to pumping in deep coreholes but little or no response in soil wells (Kellam and others, 1994).

9. Drawdown in most wells stabilized during the April, 1990, 24-hour test. Exceptions to this were Corehole 2 and Soil Well 5, which are located across Big Towaliga Creek from the Production Well. The water levels in soil wells closest to the Production Well (Soil Well 3, Soil Well 4 and Large Diameter Well) essentially stabilized during the April test. Water levels in all wells recovered to slightly below the pre-pumping levels 24 hours after the pump was shut off in April, 1990.

10. During the 72-hour test performed in July, 1990, the majority of wells did not stabilize. The rate of drawdown in soil wells located closest to the Production Well (Soil Well 3, Soil Well 4 and Large Diameter Well) slowed considerably but continued to decline slowly at the end of the July test. Water levels in three observations wells recovered to above the static water level after 72 hours after the pump was shut off in July of 1990.

11. As expected, observation wells located closest to the Production Well produced greater drawdown than those farther away. Drawdown in Soil Well 3, located 15 feet from the Production Well, was much greater than drawdown in Soil Well 4, located 18 feet from the Production Well. This was true for both tests, as shown by drawdown-recovery curves and water-level change maps.

The shapes of drawdown-recovery curves for soil wells located closest to the Production Well (Soil Well 3, Soil Well 4 and Large Diameter Well) are very similar for both tests. The differences in the level of drawdown stabilization between the two tests is probably due to the fact that a higher-capacity pump was used for the 72-hour test and the test was conducted at a pumping rate 10 to 20 higher than the first test. A higher pumping rate resulted in more drawdown in all wells.

In general, water levels recovered to a higher level after the July, 1990 test when compared to the April test. This is probably due to heavy rain during and after the July test and little or no rain during and after the April test.

CONCLUSIONS

The rapid response of the soil wells to pumping indicates that the permeable regolith provides the primary storage for water that resupplies the Production Well. During pumping, water in the regolith is transmitted to the Production Well primarily via the transition zone. The transition zone, which directly underlies the saprolite, acts as a conduit that rapidly transmits water to the Production

Well. Since all of the observation wells responded to pumping in a consistent manner at this site, a hydrologic connection between the Production Well and the observation wells is demonstrated. However, the response of soil wells to pumping at this site is in sharp contrast to the results of aquifer tests performed at the Reinhardt College site (Cherokee County, Georgia) where there was very little or no response to pumping in the soil wells (Kellam and others, 1994).

Baseflow that, under non-pumping conditions, would usually contribute to flow in Big Towaliga Creek and its tributary at the site probably recharges the aquifer during pumping. Under static conditions, these are usually gaining streams; i.e., ground-water levels in the soil wells are, in non-drought conditions, above stream levels. This was confirmed by measuring water levels and observing the stream levels. Under pumping conditions, these streams are technically, losing streams i.e., the water levels in the soil wells are significantly below stream levels in the immediate area. The gradient reverses from the creek during pumping, but the aquifer was stressed in a manner that shows the creek may have little effect. The streams were not gaged to determine the volume of water loss during pumping. Another investigator reports observing fractures exposed in stream bottoms that may be heavily clogged with sediment and that little water is lost from streams during pumping of a nearby well (Charles Daniel, written communication).

The area of influence of the Production Well extended beyond the study area as shown by the fact that all observation wells showed a response to pumping within a relatively short time (Figures 55a-55e and Figures 66a-66g). However, the site was designed so that all wells would probably be affected to some degree. Additional soil observation wells, drilled farther away and roughly on a line between the Production Well and existing soil wells would better define the area of influence in the regolith. Soil wells drilled across the tributary from the Production Well, out of the immediate floodplain, would also further define the Production Well's area of influence in the regolith.

A more complete definition of the area of influence and patterns of ground-water flow, under stress (pumping) conditions, in the transition zone and bedrock may be more complicated than in the regolith because ground-water flow occurs predominantly in oriented fractures such as joints and along foliation, and compositional layering. Corehole 1 is located roughly parallel to the strike of rocks in the area, in relation to the Production Well. One direction that ground water flows, under stress (pumping), in the transition zone and bedrock at this site is parallel to the strike of rocks, as shown by the rapid response and relatively large amount of drawdown in Corehole 1 (Figures 47 and 58). The majority of water-bearing fractures in Corehole 1 are high angle, similar to the mean dip angle of 50 degrees measured during geologic mapping, and are interpreted to be along foliation, which further supports the contention that, at this site, some ground-water flow is along strike. Ground-water flow also occurs along the dip of foliation of rocks at this site. Evidence for this point is that Corehole 2, located updip of the Production Well, was affected by pumping. The effect of pumping on wells located across Big Towaliga Creek (Corehole 2 and Soil Well 5) was probably buffered by the creek, which may have provided recharge to the aquifer system. Ground-water flow can occur in numerous directions along the planar surfaces of fractures during pumping, not only parallel to strike or dip. Additional bedrock observation wells would need to be drilled to completely define the area of influence in the transition zone and regolith system. The general location of these wells should be;

- much farther away and on a line passing through the Production Well and Corehole 1,
- updip of the Production Well and perpendicular to strike, perhaps on the hill just south of the site,
- across the tributary and parallel to strike in relation to the Production Well and,
- downdip of the Production Well, perpendicular to strike and on a line parallel to the tributary from the Production Well.

Only a portion of the recharge area was delineated by this study. Further study is needed to delineate the entire recharge area. The recharge area is not the same as the area of influence of a well in the vast majority of cases, including at this site. Specifically, water that recharges the aquifer system through a well's area of influence will not necessarily flow to the well if the well is not pumping, and water that recharges the aquifer outside the area of influence may travel to the well (Morrissey, 1987, from USEPA, 1987, p. 2-5). Recharge often occurs hydrologically upgradient of the well, but outside the area of influence. Under water-table conditions, the recharge area of a porous aquifer, or similar system, is usually considered to be the immediate drainage basin around the site. The shape of the water table is a subdued image of the topography of the land surface. However, although the regolith may behave much like a porous aquifer, the recharge area of a fractured aquifer system is much more complicated. It may extend across drainage basin boundaries and be elliptical, multi-elliptical or other atypical shapes. These shapes and extent are more likely during pumping conditions.

In final summary, the rapid response of the shallow observation wells to pumping, at this site, demonstrates the need for protecting affected areas near municipal-supply wells from contamination, and for further study of ground-water flow in fractured-rock aquifer systems.

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