Evaluation of Site-Selection Criteria, Well Design, Monitoring Techniques, and Cost Analysis for a Ground-Water Supply in Piedmont Crystalline Rocks, North Carolina

United States Geological Survey Water-Supply Paper 2341–B

Prepared in cooperation with the North Carolina Department of Natural Resources and Community Development and Town of Cary, North Carolina

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Chapter B

Evaluation of Site-Selection Criteria, Well Design, Monitoring Techniques, and Cost Analysis for a Ground-Water Supply in Piedmont Crystalline Rocks, North Carolina

By CHARLES C. DANIEL III

Prepared in cooperation with the North Carolina Department of Natural Resources and Community Development and Town of Cary, North Carolina

Site-selection criteria, techniques for maximizing sustained yields, and system costs were evaluated during expansion of a municipal ground-water system

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2341

GROUND-WATER RESOURCES OF THE PIEDMONT-BLUE RIDGE PROVINCES OF NORTH CAROLINA

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4,047	square meter (m^2)
	.4047	hectare (ha)
	.004047	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
million gallons per day (Mgal/d)	.04381	cubic meter per second (m^3/s)
gallon per day (gal/d)	.0038	cubic meter per day (m^3/d)
gallon per minute (gal/min)	3.785	liter per minute (L/min)
	.003785	cubic meter per minute (m^3/min)
gallon per minute per acre (gal/min)/acre	9.353	liter per minute per hectare (L/min)/ha

ALTITUDE DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Evaluation of Site-Selection Criteria, Well Design, Monitoring Techniques, and Cost Analysis for a Ground-Water Supply in Piedmont Crystalline Rocks, North Carolina

By Charles C. Daniel III

Abstract

A statistical analysis of data from wells drilled into the crystalline rocks of the Piedmont and Blue Ridge provinces of North Carolina verified and refined previously proposed criteria for the siting of wells to obtain greater than average yields. An opportunity to test the criteria was provided by the expansion of the town of Cary's municipal ground-water system. Three criteria were used: type of rock, thickness of saturated regolith based upon topography, and presence of fractures and joints based upon drainage lineations. A conceptual model of the local hydrogeologic system was developed to guide the selection of the most favorable well sites, and on the basis of the model, six type sites were determined. Eleven of 12 test wells that were located on the basis of type sites yielded from slightly above average to as much as six times the average yield to be expected from particular rock types as reported in the literature. Only one well drilled at a type site had a less than average yield. One well not located at any of the type sites produced little water.

Long-term testing and monitoring after the wells were put into production showed that an 18-hour-on, 6-hour-off pumping cycle was much more effective in terms of total production, reduced head loss, and less drawdown than a 5-day-on and 2-day-off cycle. It was also observed that long-term yields by the production wells were about 75 percent of those predicted on the basis of 24-hour pumping tests and only about 60 percent of the driller's reported yields.

Cost analysis showed that, by using criteria-selected well sites, a cost-effective well system can be developed that will provide water at an equivalent or lower cost than a surface-water supply. The analysis showed that the system would be cost effective if only one high-yield well were obtained out of every four drilled.

INTRODUCTION

A statistical analysis of well data from the Piedmont and Blue Ridge provinces of North Carolina (Daniel, 1985, 1987) showed that there are certain geologic, topographic, and construction characteristics of wells that can be statistically related to well yield. The analysis also indicated that, by following selected criteria in siting wells, the odds for obtaining greater than average yields were greatly increased.

While the statistical analysis was still ongoing, an opportunity to test the tentative site-selection criteria and to monitor and evaluate production wells that were selected by the criteria occurred when the town of Cary, N.C., decided to drill additional wells to supplement its existing water supply. A cooperative agreement was entered into between the U.S. Geological Survey and the town of Cary that enabled the Survey to observe and evaluate the resulting yields of wells as related to the criteria suggested by the statistical analysis.

The goal of the study was the development of site-selection procedures suggested by the statistical analysis and earlier studies (LeGrand, 1967) that would improve the odds of drilling wells of above average yield. The procedures would be tested by the selection of well sites, drilling of wells, and careful determination of well yield.

Until the development program began in 1981, all the town's water was being purchased from a neighboring city that had surplus surface-water resources. However, the town of Cary had historically relied on ground water and prior to the decision to purchase water had operated its own independent ground-water system. This multiwell system was used until the late 1960's (May and Thomas, 1968). By 1970, the town was buying most of the water it needed and using only one of its wells (Jackson, 1972). The use of this well was later discontinued. Because of the town's experience with ground-water supplies and anticipated increases in the cost of purchasing water and surcharges for additional water, town management decided that ground water was a less expensive alternative and could be developed much more rapidly than developing its own surface-water supply.

The first tasks of the ground-water development program were to make a reconnaissance geologic survey of the Cary area (fig. 1) to identify geologic and topographic features and to make a review of existing maps and literature. After the survey and literature review were completed, a conceptual model of the local hydrogeologic system was developed. Nearly three dozen potential well sites (fig. 2) were identified on the basis of the conceptual model. The site-selection process was tempered by such practical constraints as location of property boundaries and existing waterlines and distances from sewers and other possible sources of contamination. Once the sites were identified, they were grouped by site characteristics and ranked according to apparent favorability. Between November 1981 and October 1982, 13 wells were drilled. Eleven of these had sufficient yield to warrant construction of treatment and distribution facilities so that the wells could be put into production as part of the town supply. In addition, two preexisting wells were scheduled for reactivation after extensive testing.

When the combined estimated yield of all usable wells approached the town goal of 1 million gallons per day (Mgal/d), drilling was discontinued and further activity was directed toward bringing the wells into production. By May 1983, the first of the 13 wells was in routine operation. At this time, a monitoring program was initiated to keep records of pumpage, pumping rates, water levels, and other operational information. Two reasons for collecting these data were (1) the town provided itself with accurate summaries of well operation on a daily basis and (2) the accumulated data would be used later to compute long-term sustained yields that could then be compared to the yields reported by the well drillers and to the estimates of well yield determined from pumping tests. This comparison would provide a measure by which to judge the reliability of reported yields and results from short-term pumping tests. The drilling program also proved to be beneficial in determining the cost benefits of a well unit as related to the design of a system based upon site-selection criteria.

Although the data analyses and related interpretations described in this report focus on a small area of the eastern Piedmont of North Carolina, it is believed that the methods of well-site selection, well construction, and water-supply management can be applied to the evaluation of ground-water supply systems throughout the Piedmont of the southeastern United States. The findings from related studies in the Piedmont (Cressler and others, 1983; Daniel and Sharpless, 1983; Daniel, 1985, 1987) suggest that this is possible.

Purpose and Scope

This report describes major aspects of ground-water supply development in Piedmont crystalline rocks. These aspects are (1) evaluation of well site-selection criteria, (2) well-construction design, (3) techniques for monitoring well performance, and (4) analysis of cost. The data are concentrated near the town of Cary, N.C., which set out to supplement its potable water supply in 1981.

This report describes the Cary ground-water development program from its beginning in early 1981. It describes the geologic mapping, structural geologic analysis, and development of a conceptual hydrogeologic model in the early months of the program. It describes well-site selection and the drilling and testing of wells from late 1981 through most of 1982, and it also describes system operation beginning in the spring of 1983. As the system became operational and wells were placed into production, a monitoring program was begun to track well performance. Data from the monitoring program through December 1984 have been analyzed, and the results are described in this report. Finally, a cost analysis of the nonoperating costs of developing the system was made and is presented here for the benefit of those who might consider ground water as an alternative or supplement to surface water in the Piedmont.

Area of Intensive Data Collection

The area of intensive data collection, in and around the town of Cary in western Wake County, N.C. (fig. 1), can be considered fairly typical of the eastern Piedmont of North Carolina. The topography of the area consists of rolling hills that are cut by numerous streams. About two-thirds (91 mi^2) of the study area is underlain by crystalline bedrock of metavolcanic and metaigneous origin. Approximately the western one-third (48 mi^2) of the study area (fig. 2) is underlain by sedimentary rocks of Triassic age. Most of the area that is underlain by sedimentary rocks lies west of the Cary town limits.

Because the identification of potential well sites was constrained by access to existing or planned municipal waterlines, the study area was limited to the town of Cary and the area within a 5-mi distance outside the municipal boundary. The total study area covered 139 mi^2; about 9 percent of this area lies within the town limits of Cary. In 1980, the population of Cary was 21,800 (U.S. Bureau of the Census, 1982). The area outside the town consists of numerous homesites of 1 to 5 acres, woodlands, and small farms ranging from 20 to 300 acres in size.

The town of Cary and the town of Apex (in the southwest corner of the study area) (fig. 2) occupy two prominent hilltops that have altitudes in the central parts of both towns ranging from 500 to 550 ft above sea level. The northern part of the study area (fig. 2) is drained by Crabtree Creek and its tributaries; the southern part of the study area is drained by Swift Creek and its tributaries. These two streams generally flow to the east-southeast with the channel of Crabtree Creek at an altitude of about 220 ft

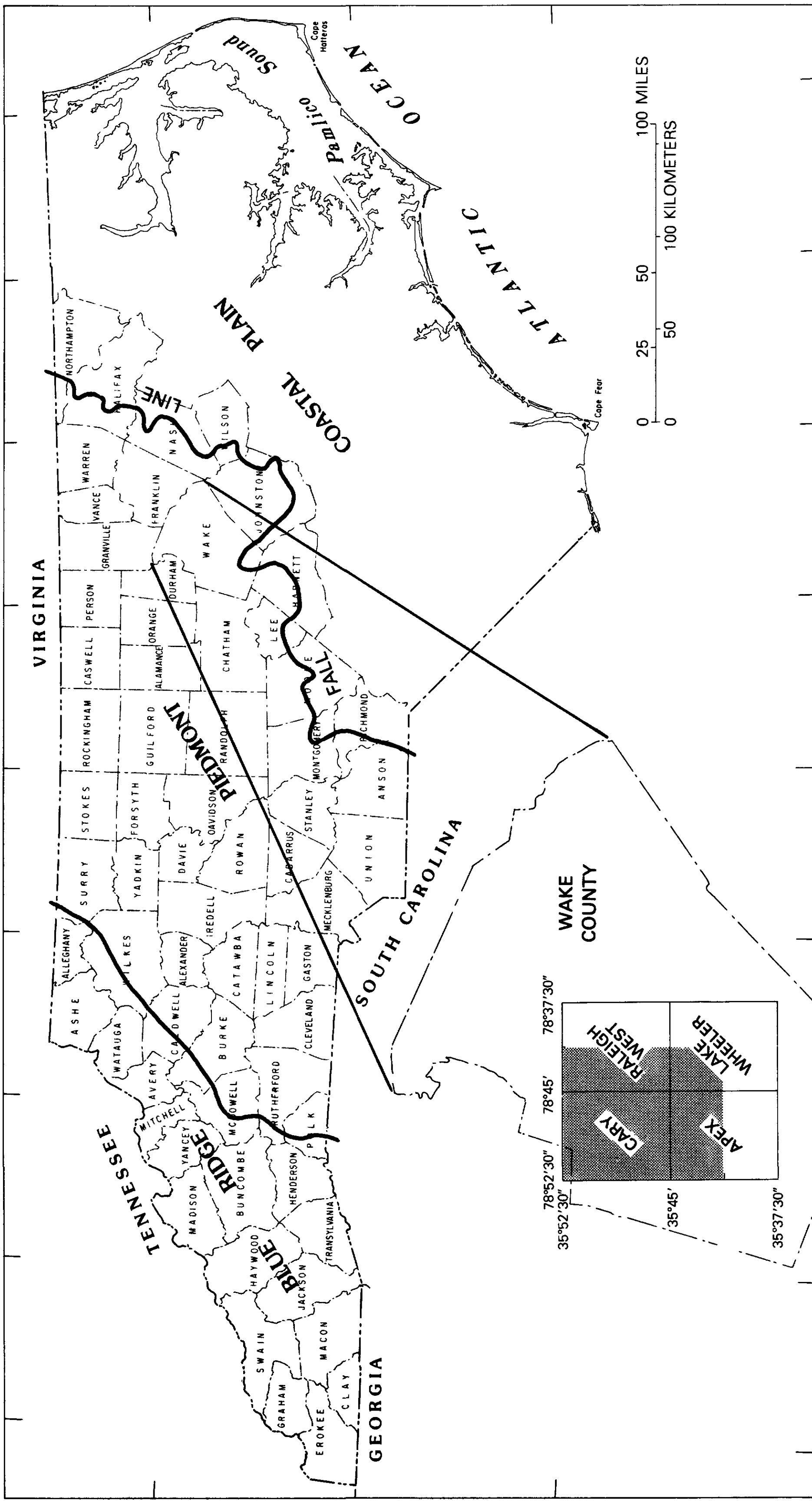

Figure 1. Location of Wake County and the Cary study area (shaded) in the east-central Piedmont of North Carolina.

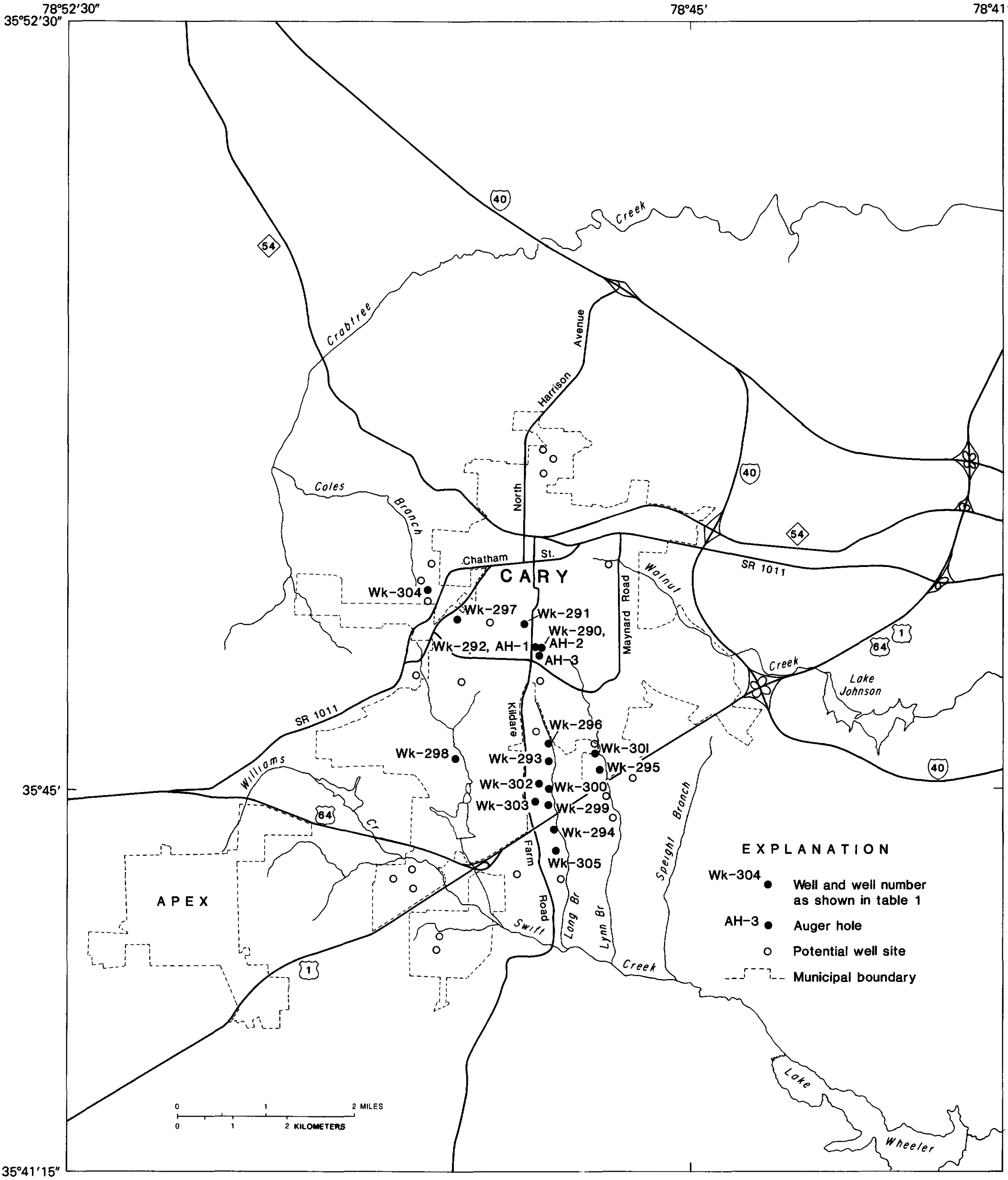

Figure 2. The Cary study area showing potential and drilled well sites.

where it leaves the study area and the channel of Swift Creek at an altitude of 350 ft in the southeast corner of the study area.

Topographic relief is most prominent in the eastern two-thirds of the study area that is underlain by crystalline rocks, while the relief is more subdued in the western one-third that is underlain by the Triassic sedimentary rocks. The area that is underlain by the sedimentary rocks is often called the "Triassic lowlands" because altitudes of the interstream areas, which range from 350 to 400 ft, are generally 50 to 150 ft lower than altitudes of the interstream areas on the adjacent crystalline bedrock.

Cooperation and Participation

This study was conducted by the U.S. Geological Survey in cooperation with the North Carolina Department of Natural Resources and Community Development (NRCD) and the town of Cary. The author wishes to acknowledge the many people and organizations who provided assistance and made information available to the study staff.

The Cary Town Council and Mayor Fred G. Bond are acknowledged for their support of the ground-water study. The assistance of the many people on the Cary town staff and, in particular, the staffs of the Utilities and Engineering Departments is gratefully acknowledged. Without their help, by providing access to well sites, production records, and financial information, much of the scientific data that were collected during this study would not have been available. The assistance of Braxton R. Matthews, Town Manager, and Hugh J. Gilleece, John Harris, Steven Janowski, William D. Vick, and Ricky T. Jones of the town staff is particularly recognized.

Several companies were involved in the ground-water program at various times during the course of the study. William G. Daniel and Associates, engineering consultants to the town of Cary, assisted with well-site evaluation and site selection and were responsible for development of drilling specifications and coordination of the drilling program. The assistance of William K. Hardin of this firm is particularly appreciated.

Heater Well Company, Inc., Cary, N.C., was responsible for drilling new wells for the town of Cary. The assistance of Robert B. Heater and members of his staff with the compilation of drilling logs, yield estimates, and collection of samples is acknowledged.

Soil and Materials Engineers, Inc., Raleigh, N.C., assisted in the construction of observation wells.

HYDROGEOLOGY OF PIEDMONT CRYSTALLINE ROCKS

Components of the Bedrock-Regolith System

The principal components of the ground-water system for a typical area in the Piedmont province of North Carolina are shown in figure 3. Bedrock exposures occur infrequently; they usually occur in areas of rugged topography on ridges and steep slopes or in the bottoms of river and stream channels. Elsewhere, bedrock is covered by unconsolidated material that may reach depths of more than 100 ft (LeGrand, 1967). Collectively, this unconsolidated material, which is composed of saprolite, alluvium, and soil, is referred to as regolith. Saprolite is the clay-rich, residual material derived from in-place weathering of the bedrock. In many valleys, the saprolite has been removed by erosion, and bedrock is exposed or thinly covered by alluvial deposits. Soil is present nearly everywhere as a thin mantle on top of both the saprolite and alluvial deposits.

Stream channels are often aligned along zones of more easily weathered and eroded rock (fig. 3*A*). These zones of weakness may be due to the composition and textural properties of a particular layer of rock, but they may also be associated with fractures that facilitate the circulation of ground water and the more rapid weathering of otherwise resistant bedrock. Thus, linear sections of stream channels may provide a clue to zones of fracture concentration in the underlying bedrock.

The regolith, not including stream valley alluvium, can generally be divided into three horizons—the soil zone, saprolite, and a transition zone between saprolite and unweathered bedrock (fig. 3*B*). The three horizons represent stages in the breakdown of the bedrock due to the processes of weathering. Weathering is greatly influenced by the climatic regime of an area; a warm humid climate like that of central North Carolina favors the development of a thick and extensive layer of regolith. The soil zone is usually on the order of 3 to 8 ft thick, and the texture has been so modified by the intensity of weathering and biologic activity that any textural resemblance to the parent bedrock has been destroyed. The saprolite, however, tends to retain the textural characteristics of the bedrock from which it is derived. The total thickness of the regolith in the Piedmont averages about 52 ft (Daniel, 1987).

The transition zone between unweathered bedrock and the overlying saprolite is often more permeable than the rest of the saprolite, and where it is sufficiently thick, it is the zone through which most of the lateral ground-water movement takes place (Stewart and others, 1964; Nutter and Otton, 1969). The high permeability is a result of the weathering process; the transition zone is chemically altered to a lesser degree than the rest of the saprolite and contains fewer clay-size particles. As bedrock starts to weather, hydration of the more unstable minerals, particularly feldspars, results in an increase in the volume of these minerals. This initial expansion ruptures the fabric of the rock and creates minute cracks and voids and increases its permeability. Further weathering is accompanied by further increases in volume and porosity, but the increase in clay and clay-size particles as the rock becomes completely weathered to saprolite reduces the interconnection of the openings created in the initial stages of weathering, thereby reducing the permeability.

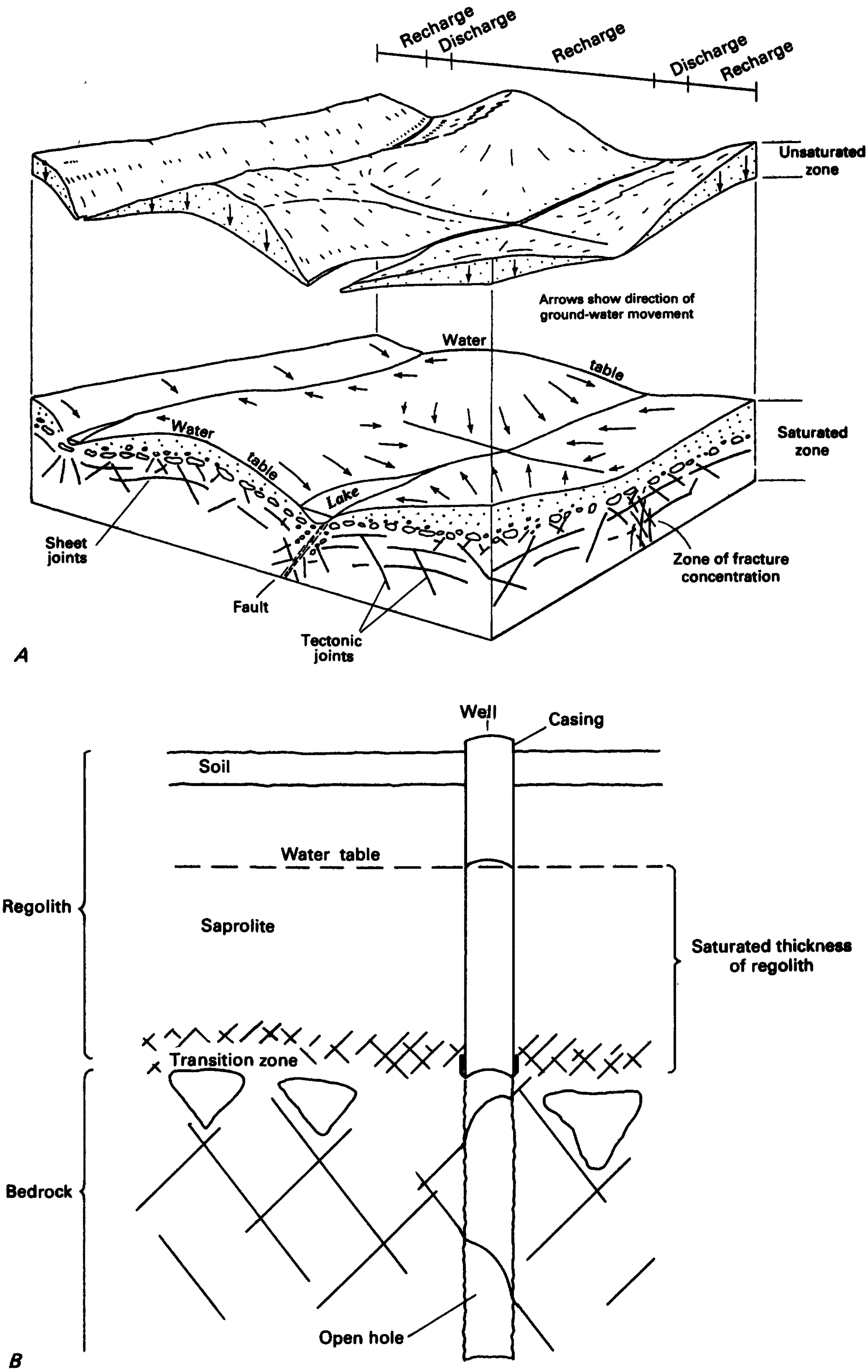

Figure 3. Principal components of the ground-water system in the Piedmont province of North Carolina. (*A*) Conceptual view of the unsaturated zone (lifted up), the water-table surface, and the direction of ground-water flow for a typical area in the Piedmont and (*B*) detailed view of the ground-water system showing typical construction of a drilled open-hole well that has casing installed to the top of unweathered bedrock.

The porosity of the regolith is on the order of 35 to 55 percent near land surface but decreases with depth as the degree of weathering decreases. Because of its high porosity, the regolith acts as a reservoir that slowly feeds water downward into fractures in the bedrock. The consolidated bedrock, on the other hand, contains very little intergranular pore space. Rather, the water within the bedrock is contained primarily in planar secondary openings that developed as a result of fracturing. Fractures are most numerous and have the largest openings near the top of the bedrock. These fractures are the openings along which water can move. As depth increases, the pressure of the overlying material, or lithostatic pressure, holds these fractures closed and the total porosity can be less than 1 percent. The base of the ground-water system is indistinct because the fractures tend to decrease in size and number with increasing depth.

Ground-Water Movement and Water-Level Fluctuations

Under natural conditions, ground water in the bedrock fractures and intergranular pore spaces of the regolith is derived from infiltration of precipitation. As shown in figure 3*A*, water enters the ground-water system in the recharge areas, which generally include all the land surface above the lower parts of stream valleys. Following infiltration, the water slowly moves downward through the unsaturated zone to the water table, which is the top of the saturated zone. Water then moves laterally through the saturated zone and discharges naturally as seepage springs on steep slopes and as bank and channel seepage into streams, lakes, or swamps.

The depth to the water table varies from place to place and from time to time depending on the topography, climate, growing season, and properties of the water-bearing materials. Topography probably has the greatest influence on the depth to the water table in a specific area with the other effects superimposed to cause short-term fluctuations. In stream valleys and areas adjacent to ponds and lakes, the water table may be at or near land surface. On the upland flats and broad interstream divides, the water table generally ranges from a few feet to a few tens of feet beneath the surface, but on hills and rugged ridge lines, the water table may be at considerably greater depths. In general, the shape of the water table is similar to the topography of the land surface, but the relief of the water table is less than that of the land surface. The water-table divides tend to coincide with ridges and hilltops, which are also the surface-water drainage divides.

Seasonal changes in water levels can be related to seasonal changes in the use of water by vegetation and the rate of soil moisture evaporation. During the growing season, vegetation intercepts and consumes large amounts of water before it reaches the water table, especially from mid-April through October. During the same period, warmer temperatures contribute to higher rates of soil moisture losses through evaporation. As a result, the water table declines gradually throughout the summer and fall months and is usually lowest in the late fall. It is at this time of year that the ground-water system has the least amount of water in storage. The long steady rains, lower temperatures, and low transpiration losses during the winter and early spring months favor the recharge of ground water. Barring unusual weather conditions, the water table will rise and fall cyclically on an annual basis and at a given time each year will be approximately at the same level.

Response of the System to Pumping Stress

The regolith is composed of fine-grained material, and water moves through it slowly, but water in storage per unit volume will exceed that contained in the bedrock fractures many times. Although the fractures in the bedrock contain little water in storage, they offer little restriction, however, to the flow of water through them. In addition, water in the regolith is under unconfined conditions, whereas that in the bedrock is confined by the overlying regolith even though they are hydraulically connected. A well pumping from the unconfined regolith—because this aquifer is open to the atmosphere and is being dewatered—will have relatively little drawdown, and a small cone of depression will form around the well because the water is released from storage by gravity drainage of the aquifer material. During pumping of water from the confined bedrock aquifer, however, water is released from storage by means of a reduction in hydrostatic pressure; drawdown is large, and the cone of depression formed around the well is much larger than one that would be caused by the same discharge from the unconfined aquifer. In the Piedmont, therefore, two rather disparate aquifers are joined as a single hydraulic system, yet behave quite differently in reaction to pumping stresses.

Water levels in a well pumping from the bedrock aquifer reflect not only the yield but also (1) the number and size of fractures penetrated by the well, which limits the amount of water able to enter the well bore because the fractures act principally as a conduit between the regolith and the well, and (2) that part of the fracture system at the regolith-bedrock interface that enables water to move from the regolith into the fracture system intersected by the well. In the Piedmont, pumping of bedrock wells sometimes results in dewatering the upper part of the bedrock aquifer in the vicinity of a well, thus causing the bedrock aquifer to be subject locally to unconfined conditions.

Water that replenishes the bedrock fractures must be supplied from the regolith. Because of the low hydraulic conductivity of the regolith, it may not be able to deliver to the bedrock fractures the same volume of water that is being withdrawn by a well, particularly if pumping continues for a long period at a rate greater than recharge. Water levels in a well will then continue to decline until the fractures in the vicinity of the well are dewatered and the well yield declines. Usually only at modest pumping rates or where there are extensive fracture systems in the bedrock will equilibrium in the movement of water from the regolith to the bedrock fractures be reached.

WELL-SITE SELECTION

Because of the complexity of the bedrock-regolith ground-water system in the Piedmont, sound criteria based on hydrogeologic principals are of the utmost importance in the selection of those sites that will offer the greatest potential for the construction of high-yield wells. For this investigation, hydrogeologic criteria were used to select sites around Cary, N.C., having the greatest potential for maximum yield to wells. However, nonhydrologic restraints—nearly all manmade—often made the best well sites unacceptable for public-supply wells. Detailed discussions of criteria, restraints, and the site-selection process follow.

Hydrogeologic Site-Selection Criteria

The three hydrogeologic criteria that were used in the selection of well sites are hydrogeologic unit, saturated thickness of regolith, and bedrock fractures; these criteria are discussed in detail in Daniel and Sharpless (1983).

A statistical analysis (Daniel, 1987) indicated that 21 hydrogeologic units, each composed of rocks with different water-yielding capability, could be identified in the Piedmont and Blue Ridge provinces of North Carolina. Because of the dissimilarity in yield to wells, identification of hydrogeologic units provided a quick method of selecting rocks having potentially the highest yields.

The regolith, which is the weathered rock, alluvium, and soil that mantles the Piedmont, is the ground-water reservoir for the underlying bedrock. Thus, the porosity, permeability, and saturated thickness of the regolith are of prime importance to the long-term yield to wells tapping the bedrock. The statistical analysis also showed that topography could be used as an indicator of the thickness of saturated regolith. The greatest thickness of saturated regolith occurs in the smaller valleys and draws (Daniel and Sharpless, 1983; Daniel, 1987). Regolith in the larger valleys is often eroded away or is present only as a thin deposit of alluvium that has little water in usable storage covering the valley floor. A criterion in siting a well, therefore, would be to have the greatest possible thickness of saturated regolith around the well.

A significant factor that influences the yield to bedrock wells is the number and size of open fractures, both vertical and horizontal, that the well bore intersects. Fractures can be mapped directly from bedrock outcrops. In the Piedmont, however, few outcrops exist due to the thick regolith, and geomorphic analysis based on landforms and drainage patterns must be used as an indicator of bedrock fractures (Daniel and Sharpless, 1983, p. 30). Generally, straight-line stream segments (drainage linears) that cross lithologic boundaries or the alignment of several tributaries that join a main stream at nearly the same angle are indicative of fracture control, especially vertical or nearly vertical fractures. Horizontal fractures, usually caused by release of lithostatic pressure as overlying rocks are eroded away, cannot be identified by surficial features but often seem to be associated with vertical fractures. In general, the vertical fractures start to pinch out at depths greater than 300 ft, but large, horizontal fractures have been reported at depths of 500 ft to as much as 800 ft below land surface (Cressler and others, 1983; Daniel, 1985; Daniel, 1987).

Nonhydrogeologic Site-Selection Restraints

Manmade restraints have considerable impact on the selection of well sites. Most of these, such as the proximity to land fills, urban and industrial developments, highways, railroads, airports, reservoirs, water lines, and sewer lines, can be readily identified. These restraints, whether in existence or planned for the future, need to be taken into consideration during well-site selection. Conversely, once wells are established, the watershed around the wells needs to be protected from loss of recharge area and pollution by these same manmade features.

Public health agency regulations that address the siting and construction of wells in the Piedmont and Blue Ridge can also have considerable impact on the site-selection process. Generally, the health regulations deal with the immediate site of a well. Regulations require that a well be sited at least 100 ft from sources or potential sources of pollution such as sewers, septic tanks, feed lots, and chemical stockpiles that pose an obvious hazard to a well through leaks and spills of contaminants. Although all the health regulations have some effect on site selection, those with the greatest impact on well yield control the siting of a well in a valley or draw.

Well sites in draws or valleys are generally not approved because of a perceived danger from surface-water contamination. Well sites downstream from major roads and railroads are even less likely to be approved because of the possibility that a spill resulting from an accident or derailment might contaminate surface water and ground water flowing toward a well site. Frequent objection is made to sites on slopes where surface runoff can occur during heavy rain and to sites in low areas potentially subject to flooding. Concern for these sites usually focuses on the possibility that surface runoff or flooding might contaminate the ground-water supply either by overtopping the well casing or by entering the well through the annular space outside the well casing. As a result, most wells drilled as part of the Cary ground-water development program were not drilled in hydrogeologically optimum locations within draws and valleys but were drilled to one side, usually on a point of land at valley intersections.

Relegating wells to hilltops and interstream divides, however, is no guarantee that contaminated water will not be drawn to a well from a stream or other source of contamination through the fractured bedrock. Fractures can pass beneath streams and drainage divides, and the point at which contamination enters the fractured bedrock and the point at which it appears in a pumping well may have no relation to the surface topography and drainage. The most likely effect of locating wells on hills is not necessarily to reduce chances of contamination but to produce wells of lower yield because of fewer fractures beneath hilltops and less available recharge.

Various construction techniques can be employed that will greatly reduce or eliminate the possibility of contamination from surface runoff on slopes and flooding in low-lying areas.

Proper grouting of the annular space virtually eliminates the possibility of contamination entering through the annular space. The North Carolina Well Construction Act of 1967 (North Carolina Board of Water and Air Resources, 1971, p. 11) requires that a supply well be cased at least to a depth of 20 ft and that the annular space be grouted with cement to a depth of 20 ft. However, these are minimum requirements. Wells are usually cased to greater depths, and grouting can also go to greater depths. Drilling techniques used to install casing larger than 6 inches (in.) in diameter often create an open annular space nearly the full length of the casing from bedrock to land surface, a distance usually more than 20 ft. This entire annular space can be grouted prior to proceeding with drilling.

On slopes, trenches and berms can be used to divert surface runoff away from well sites. In draws and valleys where there is a possibility of flooding, well casing can be extended above land surface to a height above predicted flood elevations, and fill may be mounded around the casing to protect the casing and to provide a base on which to construct a well house. It is not even necessary that the well controls and treatment equipment be installed at the well. These could be installed in a separate shelter built on higher ground. Remote well controls are especially practical in the situation where several wells are connected by a manifold and the well controls and water treatment equipment are to be located at a single location.

When approval of a well site in a draw or valley is being weighed against concerns for contamination in the event of a highway accident or train derailment, these concerns can also be weighed against the low probability of a contaminating spill occurring in any given drainage—particularly the smaller draws and valleys of the type in which wells are usually sited. Secondly, public ground-water systems in the Piedmont rely on a number, perhaps a large number, of wells, and, properly designed, these systems have built-in reserve capacity for emergencies and shutdowns for maintenance. To deny approval for a favorable well site because of the remote future possibility of contamination does not fully account for the fact that a well may make a significant contribution to a water system for a long period of time yet could be shut down in the event of contamination.

Selection of Test Sites in the Cary Area

Well-site selection at Cary, N.C., began with a review of available geologic maps, topographic maps, reports, and a compilation of well information to determine what patterns of well yields and water quality, if any, might exist with regard to hydrogeologic unit, thickness of regolith, and drainage patterns. A detailed analysis of these data for the Cary area, as described in the following text, provided the means to refine and further evaluate site-selection criteria through a program of test drilling and well tests.

Hydrogeologic Units

Wells open to the Triassic hydrogeologic unit (TRI, fig. 4) have the lowest average yield—11.6 gallons per minute (gal/min)—of the Piedmont and Blue Ridge hydrogeologic units described by Daniel (1987, table 7). In the Cary area, wells in this unit not only yield an average of 6 gal/min, but they also are reported to contain a significantly lower quality of water (May and Thomas, 1968, p. 133). Thus, the area underlain by the Triassic hydrogeologic unit was eliminated from consideration, and the search for well sites was limited to the metamorphic rocks east of the Jonesboro fault. When site selection was completed, nearly three dozen potential well sites (fig. 2) had been identified in the area east of the Jonesboro fault.

The area east of the Jonesboro fault (fig. 4) is underlain by rocks of the Carolina slate belt and Raleigh belt (Parker, 1979) that include four identifiable hydrogeologic units. The largest areas are underlain by units consisting of metavolcanic slates (MVF) and mica gneiss and schist (GNF). There are also small areas of metaigneous felsic (MIF), and metaigneous mafic (MIM) hydrogeologic units. Numerous fractured quartz veins, including some that are locally 5 to 10 ft wide, cut the metamorphic rocks. Where penetrated by wells, the quartz veins often are significant sources of water. In the Cary area, the reported average yield of wells in the metavolcanic slates (MVF) is

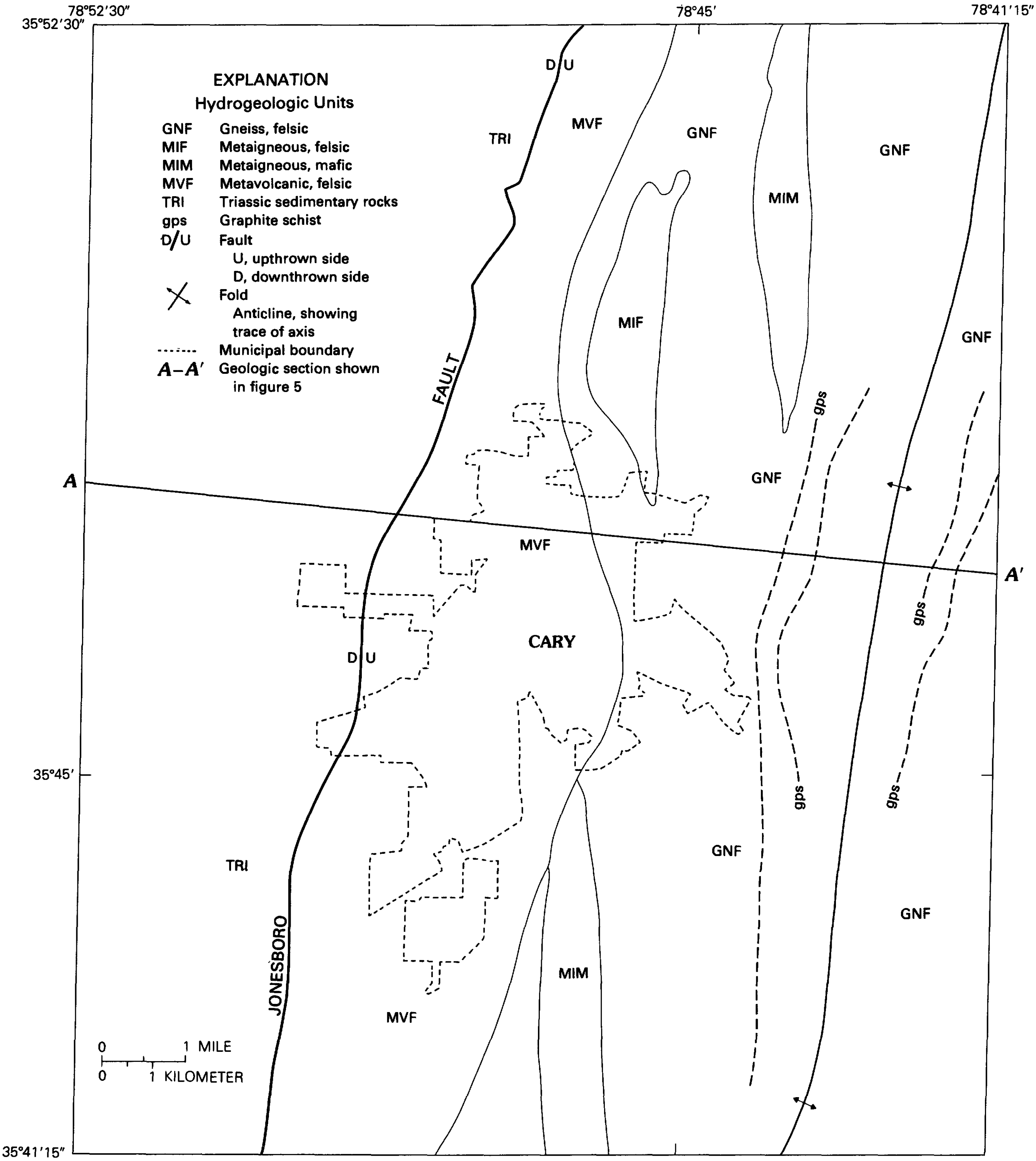

Figure 4. Hydrogeologic units in the Cary, N.C., study area.

12 gal/min and 17 gal/min in the mica gneiss and schist (GNF) (May and Thomas, 1968). This compares closely to the statewide average of 13.0 gal/min for the MVF unit and 17.4 gal/min for the GNF unit determined in a statistical analysis by Daniel (1987). The statewide average yield for rocks of the metaigneous felsic (MIF) and metaigneous mafic (MIM) hydrogeologic units is 19.1 and 19.7 gal/min respectively (Daniel, 1987).

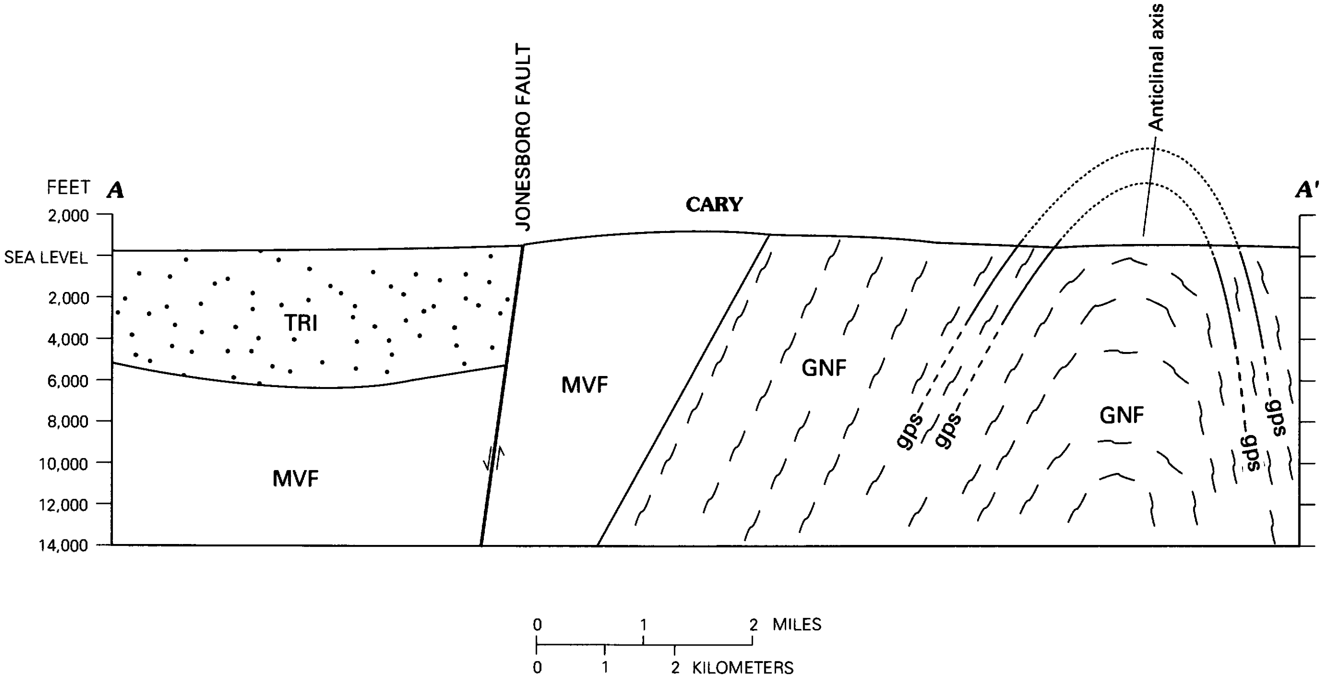

Figure 5. Geologic section through Cary, N.C., and vicinity showing major structural features and relationship of hydrogeologic units. The line of section is shown, and the hydrogeologic units are explained on figure 4.

Structural Features Related to Rock Fractures

Field work began with geologic mapping along the Jonesboro fault. The presence of a major fault that separates rocks of quite different hydrologic properties created a problem because its exact location was not known; it also created the interesting possibility of associated faulting and fracturing that might extend into the metamorphic rocks beneath Cary, thereby providing favorable zones along which to drill wells. Although the fault has been mapped and studied by a number of people (Reinemund, 1955; Stuckey, 1958; May and Thomas, 1968; Bain and Harvey, 1977; Parker, 1979), its exact location in the Cary area was only approximately known due to poor exposures and the confusion caused by weathering of the border fanglomerate within the Triassic basin that produced soil containing abundant fragments of slate and other metamorphic rocks. Subsequently, the fault was found to lie as much as 1/2 mi east of the location mapped by Parker (1979) and thus closer to Cary. Once the location of the fault was more accurately known, the area underlain by Triassic rocks was avoided for purposes of drilling.

Because fault zones and related fractures are often favorable areas in which to drill wells, it was hoped that detailed mapping of the fault would locate secondary faults that might extend into the metamorphic rocks to the east. Although outcrops containing limonite-cemented fault breccia were found at several locations east of the Jonesboro fault, none could be traced for any distance before being lost beneath the overburden.

The most common type of fractures that provide significant quantities of water are joints that in the Cary area are thought to be related to folding, stress relief, and faulting. Structurally the Cary area has been interpreted to lie on the western flank of an anticlinal fold. The axis of the fold (figs. 4 and 5), outlined by two graphitic schist belts (Parker, 1979), lies east of Cary and trends roughly north-south with no apparent plunge. The fold is asymmetrical; the west flank has moderate to steep dips, whereas the east flank is nearly vertical. The compositional layering and foliation of the metavolcanic rocks beneath Cary dip to the west between 40° and 60° . Systematic jointing of these rocks is oriented in a general northwest-southeast direction and probably represents both conjugate and extensional joint sets related to the anticlinal fold. Most of the joint surfaces are near vertical.

Horizontal or near horizontal stress-relief fractures can be observed in a few rock outcrops. Because of the thick regolith in the Piedmont, however, they are more commonly observed in deep wells with the aid of a borehole televiewer.

Thickness of Saturated Regolith

Well data and field observation showed that the saturated regolith was, as expected, thinnest on the hills and ridges and thickest in the draws and small valleys. Along north-south oriented streams, differential erosion has removed much of the regolith on the east side of the streams. The north-south streams often flow on top of bedrock, and the alluvium in the valleys of these streams is usually thin, being less than 10 ft thick. According to Daniel (1987), the regolith in the Piedmont averages 52 ft in thickness of which an average of about 24 ft is saturated. Beneath hills and ridges the saturated regolith averages 20 ft in thickness; beneath slopes and flats, 25 ft; and beneath draws and valleys, 34 ft (Daniel, 1987, table 5). The conditions in Cary are thought to approximate these average values for the Piedmont.

Analysis of Drainage Patterns

An analysis of the drainage patterns east of the Jonesboro fault (fig. 6), encompassing an area of about 91 mi^2, was made to determine if the drainage had an identifiable pattern of linear elements (fig. 7) that could be used as an indicator of fractures in the bedrock. The regional drainage pattern in the Cary area is a complex pattern with elements of radial, dendritic, trellis, and angulate patterns (Thornbury, 1969). The most obvious feature of the drainage that is shown in figure 6 is the radial arrangement of streams flowing away from Cary, which is located on a topographic high. Some individual streams that make up the radial pattern appear to have a dendritic pattern, especially in their headwaters. Further downstream most of the streams exhibit a number of linear reaches of varying length and orientation. Streams west of the Jonesboro fault generally have a dendritic pattern, although some streams have linear reaches where they cross the area of the fault.

Closer inspection of the drainage flowing away from Cary shows some subtle distinctions in the lengths of the channel linears. Streams and tributaries flowing in the east-west direction generally have shorter linear reaches than the streams flowing in the north-south direction.

The characteristics of the channel linears are summarized in figures 8*A* and 8*B*, which are rose diagrams showing the frequency of channel linears and the average length of channel linears in 5-degree intervals of azimuth. The two figures show that the channel linears fall into groups that have obvious preferred orientations. The channel linears with the highest frequency of occurrence have orientations between N. 20° E. and N. 20° W. A secondary grouping of linears occurs between N. 55° E. and S. 40° E.

The average length of channel linears is greatest in the intervals between N. 35° W. and N. 20° E. with average lengths greater than 0.4 mi in all but one interval and greater than 0.5 mi in two intervals. The average length of all channel linears in the data set is 0.37 mi.

The length of linears oriented between N. 35° W. and N. 20° E. is attributed primarily to lithologic control with the linears incised more or less parallel to compositional layering and schistosity. The high frequency of linears centered at about N. 10° E. (fig. 8*A*) is easily explained in terms of the regional strike of the bedrock. The high frequency of linears and the predominance of the longest linears oriented to the north-northwest may also be the result of lithologic control that is caused by a local deviation from the regional N. 10° E. strike. However, an alternative explanation is possible. The Mesozoic diabase dikes and associated cross faults in the North Carolina Piedmont have two (Ragland and others, 1983) and perhaps three (Bain and Harvey, 1977) dominant trends between north-south and N. 30° W. Thus, the possibility exists that faults and fracture zones may in part exert an influence on the orientation of drainage aligned in these directions. This possibility was not ignored in formulating the conceptual model of the ideal well site.

Conceptual Ground-Water Model

The conceptual ground-water model that evolved from studying the hydrogeologic characteristics of the Cary area is diagrammatically illustrated in figure 9. Compositional layering and foliation strike to the north and dip moderately to steeply to the west. The major streams flow north-south and are incised into the more easily eroded, perhaps more highly fractured rocks. In the process of downcutting their channels, the streams have moved downdip; in effect they have moved to the west and created a steep cut bank on the west and a gentler dip slope on the east. Most of the regolith along the east side of the stream has been removed, and the thickest regolith remains beneath the west valley wall and adjacent upland. Tributary streams and draws follow zones of fracture concentration that tend to localize the positions of the channels. The orientations of these channels vary between N. 55° E. and S. 40° E. and coincide with observed systematic jointing.

Based on the conceptual model, the most favorable site for a well is in a tributary valley or draw on the west side of a major north-south stream near the mouth of the east-west-trending tributary valley. A well at this site would have the best chance of intercepting fractures associated with both east-west and north-south drainage linears. Even if north-south streams are not localized above fractures, the site is still the best because of the westward dip of the north-south oriented foliation. The most favorable path for ground-water flow in foliated metamorphic rocks, excluding fractures, is in the plane of foliation (Stewart, 1962; Stewart and others, 1964; Daniel and Sharpless, 1983). This hydrologic characteristic is most pronounced in the regolith that is derived from foliated rocks such as schists and gneisses where the permeability in the plane of the relic foliation may be one or two orders of magnitude greater than the permeability normal or at an angle to the foliation.

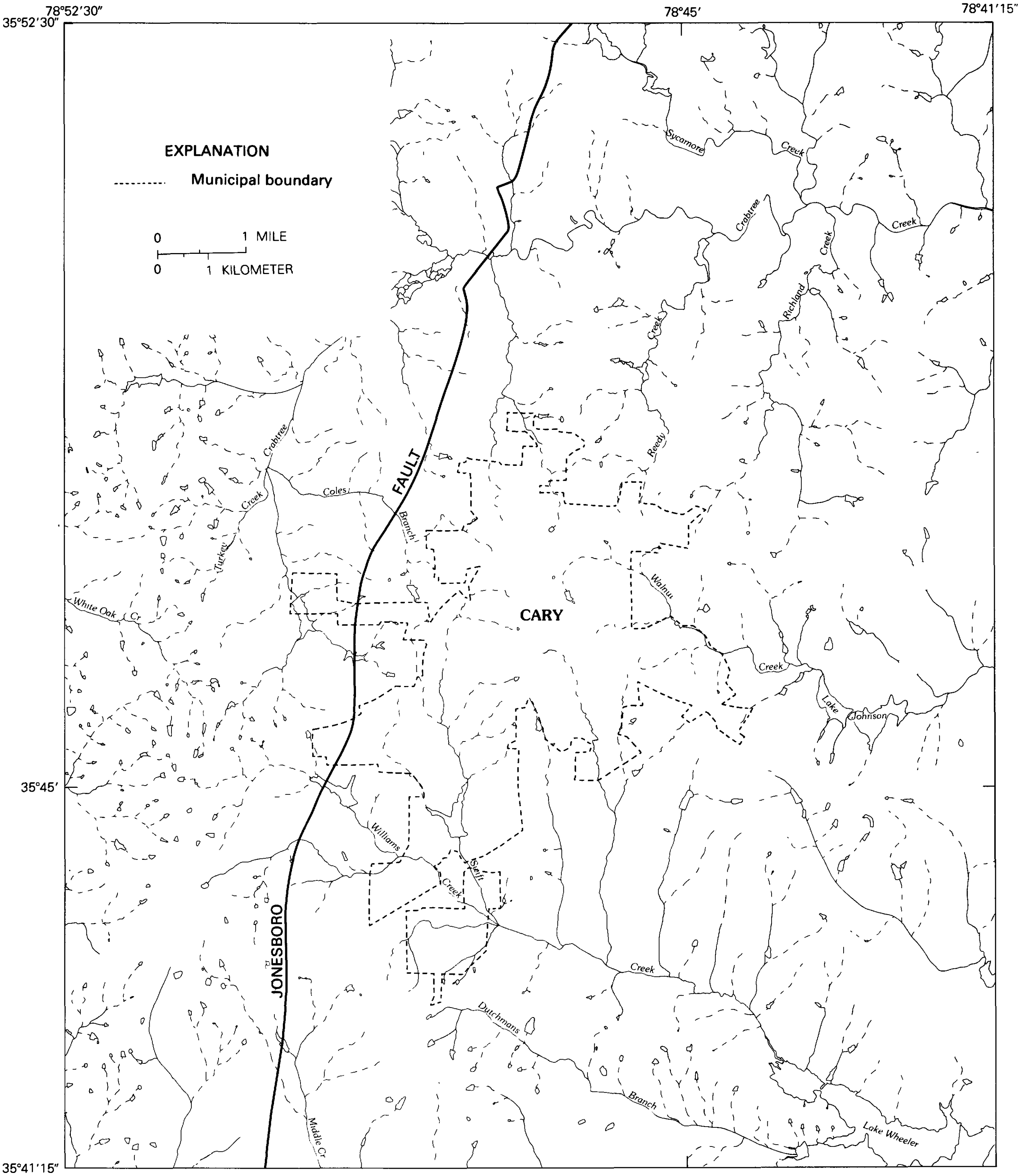

Figure 6. Surface drainage of the Cary, N.C., study area.

Therefore, wells that are located west of the main streams are in the best location to induce infiltration from the streams.

The thicker regolith of the west bank also has greater storage capacity than the thin regolith on the east side of the stream. An additional advantage of locating a well in a

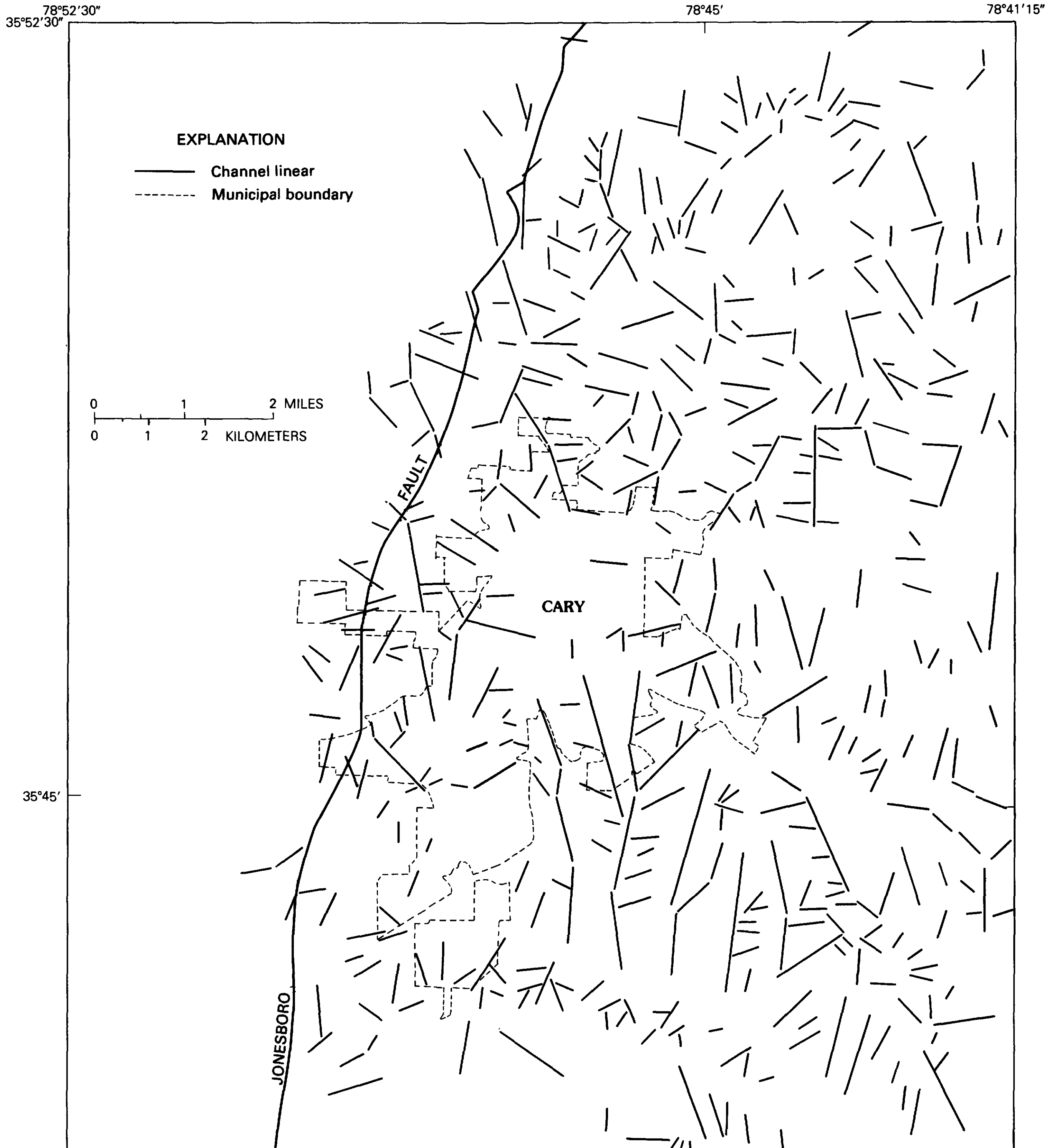

Figure 7. Linear drainage elements in the Cary, N.C., study area.

topographic low, such as near the mouth of the tributary, is that ground water naturally flows toward the site from the upland area and from the largest possible volume of saturated regolith.

As with any conceptual ideal, it is obvious that, once all considerations are taken into account, certain compromises will be necessary and other sites will also have to be used. The types of potential sites under consideration

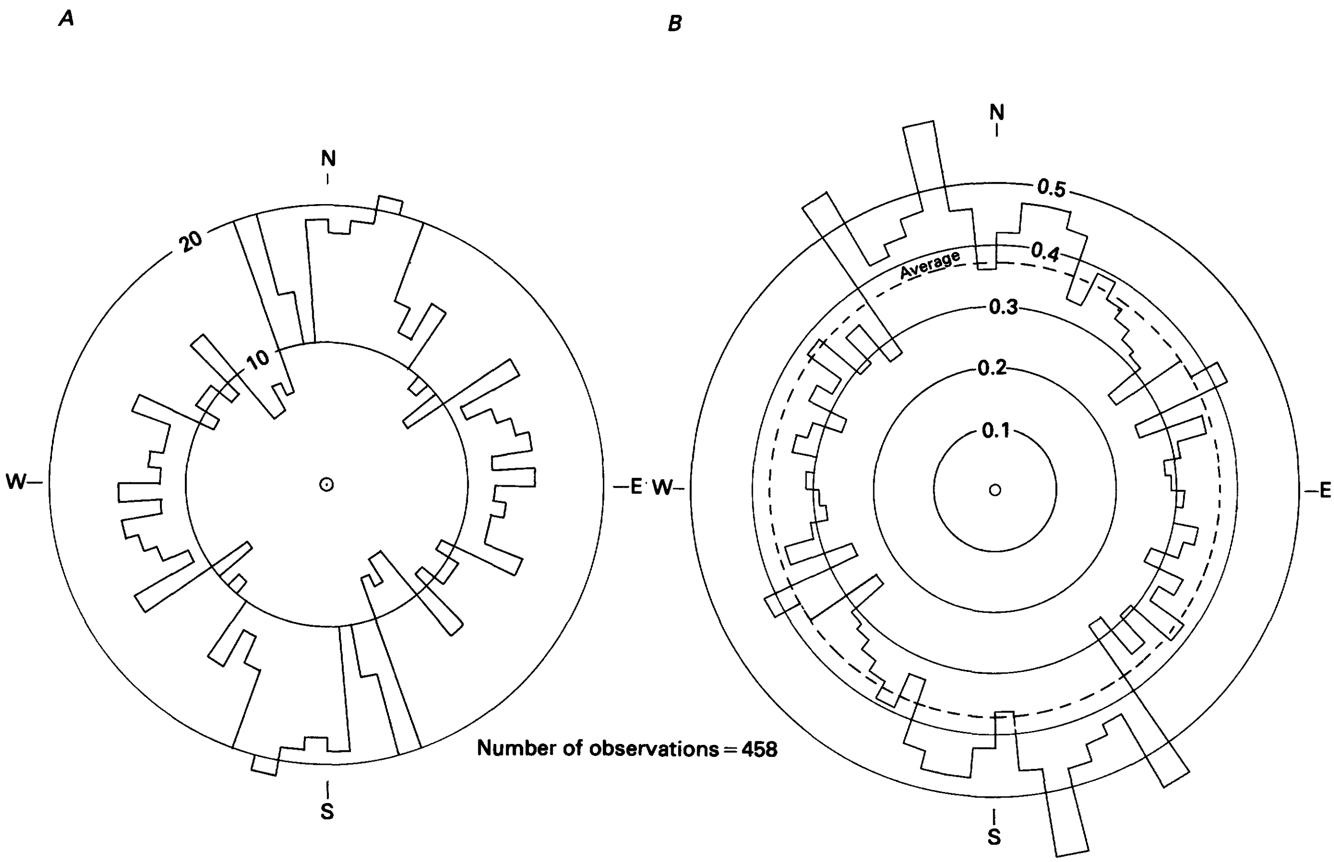

Figure 8. Rose diagrams showing (*A*) frequency and orientation of channel linears in the vicinity of Cary, N.C., and (*B*) average length (in miles) and orientation of channel linears in the vicinity of Cary, N.C.

evolved into the ideal and three semi-ideal. Two nonideal sites also were recognized.

The six site types are illustrated in figure 9*B*. Sites A–D are located within the east-west tributaries. Site A is the ideal site discussed earlier. Site B is near the channel intersection, where it might intercept north-south-trending fractures, but is less than ideal because of the thinner regolith in the up basin area on the east side of the stream, and dip of the foliation is from the well toward the main stream. Site C is located within the tributary but is some distance from the channel intersection. It still has the advantage of being in a topographic low over a suspected fracture zone, surrounded by thick regolith, and the dip of foliation is toward the well, but it is not in a good position to intercept north-south-trending fractures. Another possibility is site D in the eastern tributary comparable to site C. Such a site would be over a suspected fracture zone and in a topographic low but is probably surrounded by thinner regolith than sites in the western tributary and is not in position to intercept north-south-trending fractures. Also, the dip of the foliation is away from the interstream divide toward the well. Because the thinnest saturated thickness of regolith occurs beneath hills and ridges, there also is less water in storage that is available to this well. Although this type of site was not used during the study, it should not be entirely dismissed.

Sites E and F are nonideal sites and have less potential for the development of high yields to wells. Site E is offset from the channel intersection because of possible flooding of the ideal site A by the tributary and possible contamination of the well at site A by flood waters. Site E has the advantage of being topographically low, surrounded by thick regolith, and in the down dip area of the foliation, but it is offset from both the east-west and north-south fracture traces.

Site F is on the interstream divide in line with two tributaries that appear to be aligned over the same fracture. It has the smallest recharge area, the thinnest saturated thickness of regolith, and under nonpumping conditions ground water flows away from the well rather than toward it. Such a well may have a high initial yield because of an efficient and extensive fracture system transmitting water to the well and because of withdrawal of water from storage. The ultimate control on the sustained yield, however, is the limited recharge area contributing water to this well.

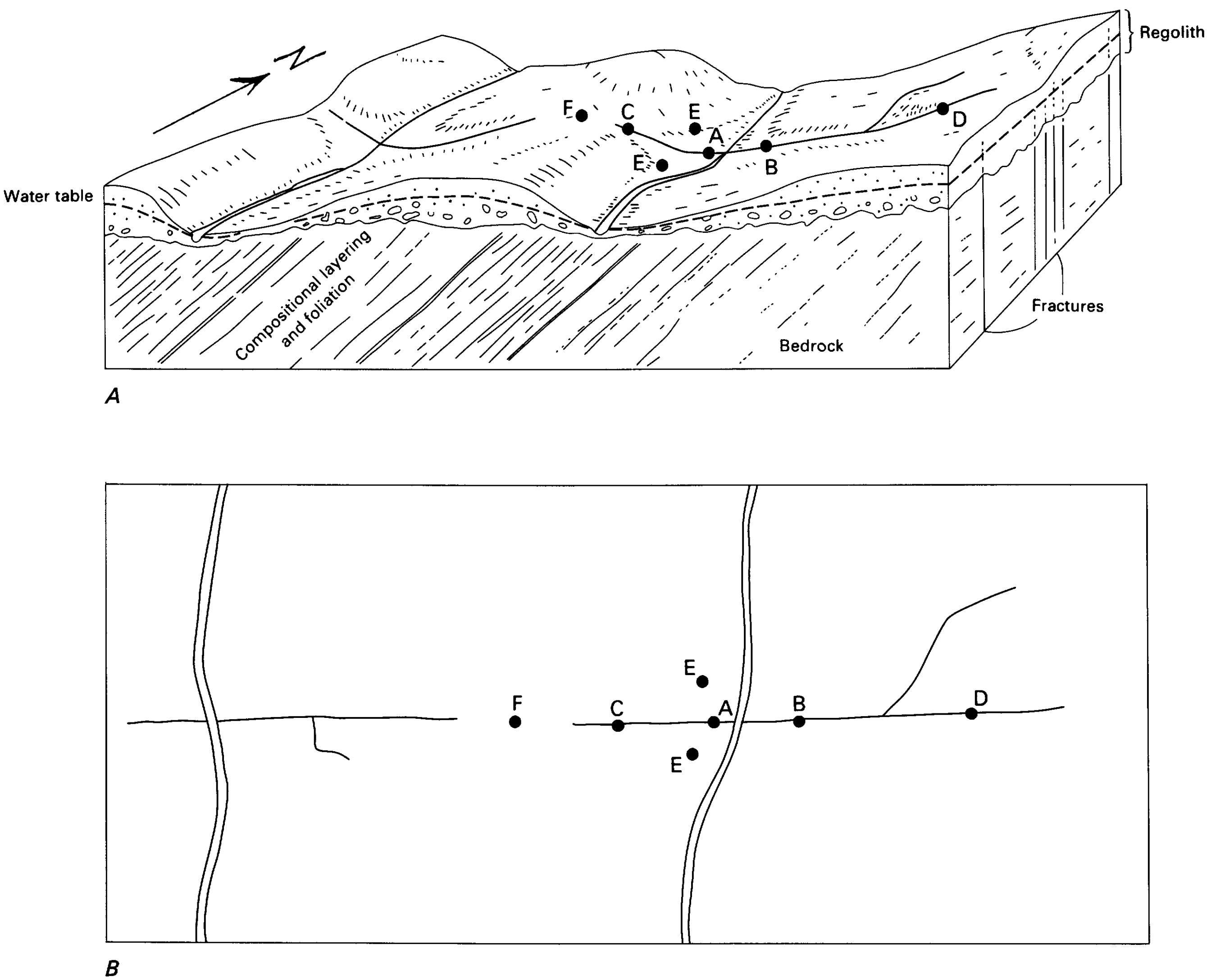

Figure 9. (*A*) Conceptual model of the ground-water situation in the Cary area and (*B*) most favorable sites for wells lettered in order of decreasing preference.

EVALUATION OF SITE-SELECTION CRITERIA BY TEST DRILLING AND PUMPING TESTS

The appraisal of site-selection criteria by test drilling began in November 1981. By late 1982 a total of 13 wells were drilled (fig. 2, table 1), two preexisting wells were reactivated, and three auger holes were completed in the regolith as observation wells for a pumping test of the Rescue Squad well (Wk-292).

The Thompson well (Wk-293) was the first drilled, followed by the Ponderosa well (Wk-294). Both wells were located at type A sites (fig. 9) in the metavolcanic felsic (MVF) hydrogeologic unit.

The valley floors where these wells are located are sufficiently broad to permit the wells to be sited on line with inferred fracture zones and still satisfy regulatory requirements regarding distances from stream channels, low probability of flooding, and ability to control surface drainage away from the well sites.

Several weathered and fracture zones were penetrated during the drilling at the Thompson well (Wk-293, fig. 2). Prominent weathered zones occurred between 95 and 105 ft and at 235 ft. Fractures were found in a quartz vein or veins from 165 to 168 ft, the most productive single zone penetrated, and in a quartz vein at 305 ft.

The Ponderosa well (Wk-294, fig. 2) penetrated what appeared to be a major shear or fault zone between 145 and 158 ft. Large rock fragments were blown out of the well. Some fragments had polished surfaces, possibly slickensides, which indicate faulting. This zone is the major producing zone in the well, although other water-bearing fractures were penetrated at 176, 200, and 258 to 260 ft.

Only one well, the Rockett well (Wk-304), was drilled in a type B setting, and this site was unique among the wells drilled because it was near a small lake, created by damming the north-south stream at the site, and in an ideal position to induce infiltration from the lake (fig. 10). The linearity of the east-west tributary in which the well is located is well defined and suggests underlying fracture control. Other topographic evidence of fracture control includes a lack of meanders or curvature of the channel, as well as the linearity, relatively even spacing, and parallelism of adjacent tributaries.

The well was drilled only a few feet from the channel of the intermittent stream exactly on line with the inferred fracture trace. Although health officials eventually required the town to route surface drainage past this site through a culvert, the extra construction that permitted placement of the well near the center of the draw was a valuable compromise on siting requirements because the Rockett well, at an initial rating of 125 gal/min, was one of the most successful.

As shown in figure 10, the drainage in the vicinity of the Rockett well is an excellent example of a complex pattern based on components of trellis and rectangular patterns (Daniel and Sharpless, 1983). The north-south stream, Coles Branch, follows the compositional layering. Several of the east-west tributaries are apparently fracture controlled because of their linearity and parallelism. The tributary in which the Rockett well is located is almost certainly fracture controlled although the subsurface evidence only comes from this one well. Several water-producing voids and fracture zones were penetrated by the well, which has a total depth of 250 ft. The most notable water-producing zones occurred between 93 and 95 ft when the bit dropped through a void and some fragments of vein quartz were observed among the cuttings and between 100 and 105 ft and 130 and 140 ft where large fragments of rock with stained faces were found with the cuttings. Some of the fragments had maximum dimensions of 1 to 2 in., were partially weathered, and had oxide coatings, all evidence that the fragments came from preexisting fracture zones in which ground-water circulation was taking place. Less significant fractures were found between 200 and 210 ft.

Because of the stringency of regulatory requirements, it was often difficult to obtain approval for well sites located within tributary valleys or draws, particularly in the lower reaches at the A and B locations (fig. 9). For this reason, most wells were drilled at type E sites that are on points of land either north or south of the channel intersection and are as close as is practical to the type A locations. These wells were relatively successful and have a projected yield that is about three times the reported average for the rock unit in which the wells were drilled. On the other hand, the yield is only about half that projected for type A wells.

Locating wells farther up draws or valleys at type C sites met with less reluctance on the part of health officials because the channels are occupied by intermittent streams and sites appeared less subject to flooding. The valleys are narrower and the sides are sufficiently steep that it is possible to have a well site several feet higher than the channel yet not too far removed laterally from the inferred fracture trace. Surface drainage off of these sites is almost never a problem.

Three new wells were drilled at type C sites (Wk-302, Wk-303, and Wk-305), and preexisting wells at a type C site (Wk-292) and at a type F site (Wk-291) were reactivated. No data are available on water-bearing zones or fractures in these wells. No wells were drilled at type D sites.

Two wells drilled at type E sites (Wk-296 and Wk-297) for which data are available obtained most of their water from fractures in quartz veins.

Only two wells, the Kildaire Club House (Wk-298) and Atkins (Wk-305) wells, had yields below the minimum determined cost effective for inclusion in the town system. The Atkins well was drilled at a type C site. The Kildaire Club House well was drilled on the steep, west valley wall of a north-south stream at a site not defined by the conceptual model. The Kildaire Club House well had been scheduled for a type A site several hundred feet north of where the well was actually drilled. The preferred site was in the path of a planned expressway, and the alternate site was obtained. The low yield was evidence supporting the opinion that wells unassociated with east-west drainage linears are unlikely to have high yields. No other wells were drilled at similar sites. Because the well was in a location unaffected by local ground-water pumpage, it was monitored for 2 years as a climatic-effects observation well to observe the seasonal changes in ground-water levels.

The drilling of wells to test the site-selection criteria began before the statistical analysis of wells drilled in the rocks of the Piedmont and Blue Ridge provinces (Daniel, 1987) was complete. Well construction practices in regard to the optimum depth of wells, which had been developed by earlier studies, indicated an optimum depth of about 300 ft, below which there was usually little increase in yield (LeGrand, 1967; Snipes and others, 1983). As a result, the test wells were drilled to an average depth of about 300 ft (table 1). The statistical analysis (Daniel, 1987), when completed, showed that many of the higher yields were to wells encountering fractures (usually horizontal) at depths as great as 500 to 800 ft and the maximum yield for the 8-in. wells that were drilled would have been reached at depths of about 600 to 675 ft.

The statistical analysis also indicated a direct relation between well diameter and well yield. Therefore, all wells were constructed 8 in. in diameter to take advantage of the potential increase in yield which, for 300-ft deep wells, represented a difference of about 45 percent between a 6-in. and 8-in. diameter well.

Table 1. Records of wells drilled or reactivated for the Cary ground-water development program

[ft, feet; in., inches; gal/min, gallons per minute; ---, no data]

Well number	Name	Location: Latitude Longitude	Well depth (ft)	Well diameter (in.)	Casing depth (ft)	Water-bearing material	Yield (gal/min): Reported by driller	Yield (gal/min): Estimated from pumping tests, this study	Yield (gal/min): Actual[1]	Site type[2]	Remarks
New Cary supply wells											
Wk-293	Thompson	35°45′17″ 78°46′43″	320	6.25	84	Sericite schist, phyllite, muscovitic quartzite.	125	120	46	A	8-in. casing to 68.5 ft, 6.25-in. casing sleeved to 84 ft.
Wk-294	Ponderosa	35°44′07″ 78°46′39″	300	8	80	Hornblend-biotite gneiss, mica schist.	105	85	68	A	
Wk-295	McDonald Woods.	35°45′12″ 78°46′06″	280	8	32	Hornblend-biotite gneiss, sericite schist, thin layer of amphibolite.	75	75	68	E	
Wk-296	Kildaire Pond	35°45′29″ 78°46′43″	350	8	57	Sericite schist, thin layers of amphibolite, hornblend-biotite gneiss.	35	---	20	E	Driller's reported yield from pumping test Jan. 12, 1982.
Wk-297	Waterford	35°46′40″ 78°47′49″	300	8	63	---	45	---	30	E	
Wk-298	Kildare Club House.	35°45′19″ 78°47′48″	240	8	41	Muscovite-biotite schist, muscovitic quartzite.	10	---		---	Unused.
Wk-299	Showalter 1	34°44′21″ 78°46′43″	300	8	80	Sericite schist, sericitic quartzite, layers of amphibolite.	60	---	31	E	
Wk-300	Showalter 2	35°45′01″ 78°46′42″	300	8	64	Biotite gneiss, biotite schist.	40	---	18	E	
Wk-301	Beaver	35°45′22″ 78°46′09″	300	8	49	---	30	---		E	Not in service at end of 1984.
Wk-302	Showalter 3	35°45′04″ 78°46′50″	260	8	61	---	55	---	33	C	
Wk-303	Showalter 4	35°44′23″ 78°46′53″	300	8	80	---	60	---	42	C	

Wk-304	Rockett	35°46′57″ 78°48′11″	250	8	56	Gray-green phyllitic slate, schist.	125	100	83	B	
Wk-305	Atkins	35°43′54″ 78°46′38″	213	8	80	Gray schist	6	---	---	C	Unused
Reactivated wells											
Wk-291	Matthews	35°46′38″ 78°47′00″	220	6.25	124	---	120	50–55	48	F	Pumping test July 13, 1964, 24 hours, 120 gal/min.
Wk-292	Rescue Squad	35°46′24″ 78°46′52″	257	6.25	129	Sericite schist, gneiss	85	70	70	C (F)	Reported depth 300 ft. Pumping test Jan. 13, 1965, 24 hours, 80 gal/min.
Observation wells											
Wk-290	Medcon Court	35°46′23″ 78°46′50″	200	6.25	80	Sericite schist, gneiss	100	---	---		Unused due to interference with Rescue Squad well.
Shallow wells											
Wk-AH-1	Rescue Squad	35°46′24″ 78°46′52″	75	4	75	Saprolite	---	---	---		Regolith observation well, lower 60 ft of casing are perforated.
Wk-AH-2	Medcon Court	35°46′23″ 78°46′50″	75	4	75	do	---	---	---		Do.
Wk-AH-3	Western Sizzler	35°46′21″ 78°46′50″	74	4	74	do	---	---	---		Do.

[1]Yields as of May 24, 1984 (Ricky T. Jones, town of Cary, written commun., 1984).
[2]Site type corresponds to topographic positions of well sites shown in figure 9.

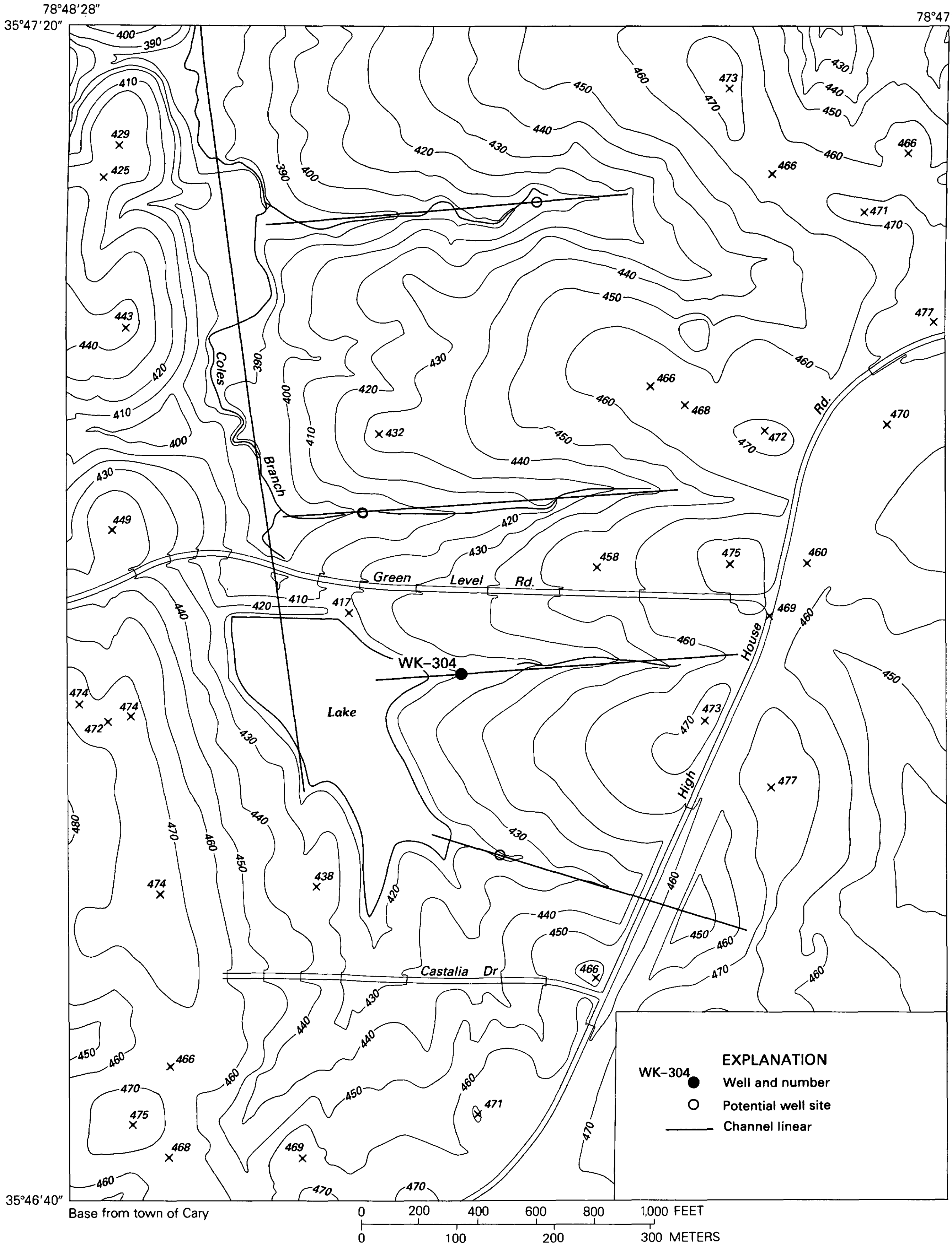

Figure 10. Topographic map of the headwaters of Coles Branch, northwest Cary, N.C., showing location of the Rockett well (Wk-304), channel linears, and favorable sites for additional wells.

The North Carolina Department of Human Resources requires that 24-hour production tests be performed on public supply wells prior to acceptance. Well yields obtained from these short-term tests proved to be considerably greater than the long-term yields obtained in actual production (table 1). Therefore, the results of short-term tests, such as these, could not be taken as reliable evaluation indicators of the site-selection criteria.

The results of short-term tests were deceptive because water-level conditions in the wells did not achieve equilibrium with the hydrologic system. One part of the system consists of open interconnected fractures in the bedrock; the fractures have a relatively high hydraulic conductivity and little storage and are under confined conditions. The other part consists of saturated regolith that has very low hydraulic conductivity and a relatively large amount of water in usable storage and is under unconfined conditions. The regolith is the principal source of water to the bedrock fractures. The system can be compared to a sponge from which water will drain slowly (the regolith) but only through a few soda straws that may or may not be connected to each other (the fractures) but are eventually connected to a single straw (the well). For a short time, a moderate amount of water can be obtained by draining the straws, but once drained, the yield is limited to the amount of water that can move from the sponge into the straws.

In the Piedmont rocks, yields during the short-term aquifer tests and yield tests performed by blowing the well with air are supported in a large part by dewatering the fractures. These are apparent yields and are usually considerably higher than the long-term sustained yield.

An example of the dewatering of a fracture system is shown in figure 11. A 24-hour step drawdown test was being run on the well (Wk-304). The figure shows the water level in the well during the last (fourth) step when the well was being pumped at a rate of 133 gal/min. Drawdown proceeded at a steady rate until the water level declined below the last large water-bearing fracture in the well. The water-level decline slowed for a while until the fracture was virtually drained of water, and then as there were no other major fractures to drain, the water level dropped rapidly.

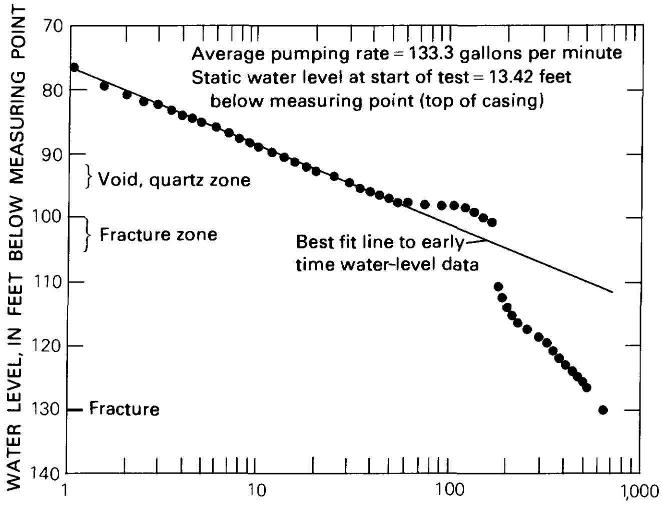

Figure 11. Decline in pumping water levels during step four of a test of the Rockett well (Wk-304), August 27, 1982.

In many of the higher yielding wells drilled into the Piedmont rocks, the dewatering of all water-bearing zones penetrated by a well does not occur during the yield test either because the pumping rate is too low or the length of time the well is pumped is too short. As a result, the potential yield estimated from a short-term test usually is considerably larger than that obtained over the long term. Sustained yield, the real test of the site-selection factors, is best determined from long-term monitoring, as will be discussed later.

DISCUSSION OF WELL DESIGN AND PUMPING FACILITIES

The careful design and spacing of wells and related pumping facilities is necessary to ensure that the system will achieve the optimum production of ground water. It is known that the construction of a well with regard to depth and diameter influences both the yield (Daniel, 1987) and drawdown characteristics (Caswell, 1987) of the well when it is pumped. The installation of the pump and various accessories also will determine how easily the well operator can monitor the yield, water levels, and pumping time so that necessary adjustments can be made to maintain optimum operating conditions.

Well and Pump Considerations

Assuming that the well, when drilled, will be successful, steps can be taken to ensure maximum production of ground water from that particular site. Maximum production begins with the design of the well itself. As shown by Daniel (1987), the average yield is related to both depth and diameter. For maximum production, drilling of wells to depths at least as great as 500 ft and as much as 800 ft appears justified for sites within the Piedmont and Blue Ridge. Certainly, drilling wells larger than 6 in. in diameter is indicated; an 8-in. well is considered minimum for facilitating the flow of water into the well bore as well as for easy installation of the pump and related equipment. The increased yield of larger diameter wells is attributed to the increased fracture aperture that reduces entrance velocity and turbulent flow in the fracture just outside the well bore. By reducing turbulent flow, entrance losses are reduced. By reducing entrance losses, the drawdown will decrease in comparison to the drawdown resulting from the same pumping rate in a smaller diameter well. This lower drawdown with the same well yield represents a higher specific capacity for the well. Specific capacity is the yield divided by the drawdown and is a common index used to compare well productivity. Flow along the well bore to the pump intake will also be less turbulent in a larger diameter well, and this also contributes to a higher specific capacity of the well.

Thus, the same amount of water can be produced from a larger diameter well but with much less drawdown than in a smaller diameter well. This has certain advantages and may affect the short-term as well as the long-term productivity of the well, because excessive drawdown can result in the dewatering of a producing fracture. When the fracture is dewatered, the immediate effect is a change from that of a fully saturated confined artesian system to unconfined water-table conditions.

Once this happens, flow is by gravity drainage into the fractures, the hydraulic properties of the aquifer change, and yield is often greatly reduced. Once the transition from saturated to unsaturated flow in the fractures takes place, drawdowns usually increase rapidly, and the pumping water level becomes very sensitive to slight changes in pumping rate. If this process is allowed to recur repeatedly during pumping cycles, the alternate wetting and drying and introduction of air into fractures can result in the precipitation of fracture-clogging mineral deposits. In time, these deposits will restrict the flow of water into the well, the yield will decline, and drawdowns will increase. A large diameter well will reduce the chance of excessive drawdown and all of its subsequent problems.

In order to properly design the pump assembly and later establish the pumping schedule, knowledge of the location and relative yields of the water-producing fractures is a necessity. This information is also invaluable for interpreting drawdown behavior. An accurate drilling log showing the depth of water-producing fractures, amount of casing, formation changes, and other data is usually compiled as the well is being drilled. If necessary, the location of fractures can be checked later by logging the well with borehole caliper or televiewer equipment. Flow rates of individual fractures also can be checked by isolating the zones with packers, but, in most cases, the expense of this type of test is not warranted. The relative yields of individual fractures can be measured with reasonable accuracy during drilling by pumping the well at intervals and measuring flow.

Knowledge of the position of the water-producing fractures is used to guide the design of the pump column, especially for submersible pumps that are cooled by water flowing past the motor. Because the intake is above the motor on a submersible pump, it is best to have the pump set above a water-producing fracture so that water entering the well will flow upward past the motor for cooling. In wells where there is only one major producing zone, selecting the pump setting is simple. Where there are multiple producing zones, some consideration has to be given to the location of the zones and the yields of the zones. At the very least, the pump is set above the deepest fracture, because if the uppermost producing zone is too shallow (less than 100 ft), setting the pump above this zone will reduce the available drawdown sufficiently that yields will be reduced. Therefore, the pump is usually set between the upper and lower producing zones. Regardless of how deep the well is, little hydrologic advantage exists in setting the pump below the lowest producing zone for, in all likelihood, such a setting will result in dewatering all the fractures, reducing the yield, and shortening the life of the pump. Setting the pump above the major producing fracture has the added benefit of helping ensure saturated flow to the well bore below the pump at all times.

As shown in figure 12, the typical well in Cary is of open-hole construction with the casing installed into the top of unweathered bedrock. The remainder of the well is a self-supporting open hole that is drilled into the bedrock. Installation of casing larger than 6 in. in diameter usually requires the use of drilling tools and techniques somewhat different from those necessary for smaller diameter wells, and the entire annular space to bedrock may be grouted, which is usually greater than the 20-ft requirement.

Figure 12 shows three producing zones, and the pump is set above the lowermost zone to ensure cooling of the motor. The motor is also equipped with a low-water-level cutoff switch that will prevent drawing the water level down to the pump intake and thus pumping air into the distribution lines. The cutoff switch is above the middle producing zone and will ensure saturated flow from the two lower zones.

Monitoring Considerations

The only way to ensure the most efficient operation of a well is to closely monitor water levels and pumping rates. Water levels in the pumped well are measured routinely, usually at the end of a pumping cycle just prior to the pump cutting off and at the end of the recovery period just prior to the pump turning on. This information can be compared to the level of the pump intake, or low-level cutoff switch, and the level of producing zones; this information can then be used to either increase or decrease the pumping rate. Wells in Cary were constructed so that this information can be easily obtained. Permanent installation of drop tubes of 3/4-in. diameter through the sanitary seal to a depth below the pump setting (fig. 12) allows the well operator to rapidly measure water levels without the danger of hanging up a tape between the discharge line and the wall of the well or becoming tangled in the power cables leading to the motor or in tubes used to inject chemical treatment. The drop tube also eliminates the chance of erroneous readings from an electric water-level sounding tape that can result from cascading water in the open well bore. The permanent

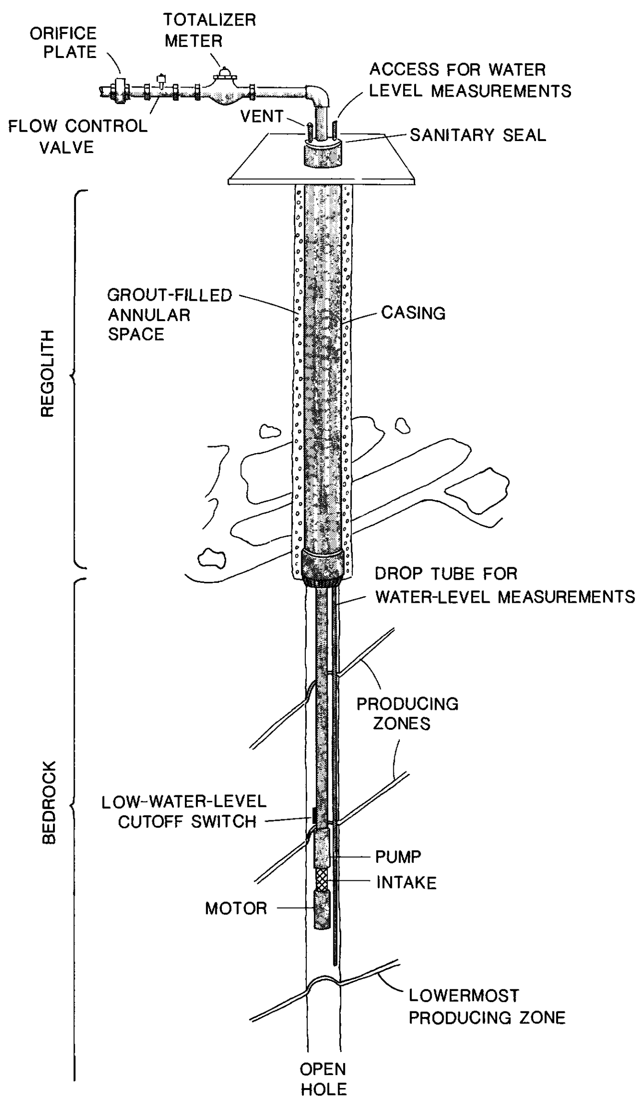

Figure 12. Typical construction of a large-diameter open-hole well in Cary illustrating optimal installation of a pump assembly having provisions for monitoring the pumping rate and water levels.

installation of a drop tube also facilitates retesting of the well should additional pumping tests be necessary.

In-line flow meters with totalizers are used for monitoring the amount and rate of discharge from the wells. These are as simple as a mechanical meter or as elaborate as an electronic meter with a recorder. Automatic timers to turn the pump on and off ensure accurate pumping cycles and can easily be reset to satisfy different pumping schedules. A chart recorder to record when the pump is running or not running is a valuable accessory on some wells, particularly when it is used in conjunction with a low-water-level cutoff switch. If the well is being overpumped so that the water level declines to the cutoff switch before the automatic timer cuts the pump off, the motor will begin to cycle, alternately turning off and then back on when the switch resets. By the time the switch resets, the water level will have recovered sufficiently that the pump will run briefly before the water level is again drawn down to the cutoff switch and the cycle starts over. To have a motor cycling in this manner is very inefficient with regard to power consumption and potentially can shorten the life of the motor. When a recorder indicates that cycling is occurring, the well operator can reduce the pumping rate or shorten the pumping period sufficiently to prevent cycling. This is not at all an unusual occurrence in the summer and fall when the rate of ground-water recharge decreases.

Finally, some means of regulating the rate of discharge is needed. This may be a simple gate valve or ball valve, but these valves have the disadvantage that, unless adjusted frequently, the rate of discharge will decline as the water level declines (known as dynamic or pumping head loss). Frequent adjustment is impractical except, perhaps, during pumping tests when the well is being closely monitored. Consequently, special flow control valves that automatically open or close to maintain a constant discharge rate were used on the Cary wells. These valves allow the operator to accurately control the discharge rate, better regulate the drawdown behavior, and keep the well producing at the intended rate during pumping periods.

Well-Spacing Considerations

In multiwell systems such as the Cary system, the most cost-effective design (discussed later) is to manifold several wells together so that water treatment equipment is needed only at one site on the manifold system. This not only reduces equipment costs but maintenance costs of having to service treatment equipment and maintain supplies of chemicals at individual wells. In order to manifold wells in an effective manner, the wells cannot be spaced too far apart. On the other hand, the wells cannot be so close together that there is excessive drawdown interference. Experience in Cary showed that a spacing of 800 to 1,000 ft along strike of the bedrock foliation and 400 to 600 ft at right angles to strike was usually sufficient to prevent interference. When interference was observed, it was usually small enough not to be a problem. Well spacings of these magnitudes will probably be sufficient for most wells in the foliated metamorphic rocks throughout the Piedmont and Blue Ridge. Little data are presently available for well spacing in areas underlain by the more massive metamorphic rocks or unmetamorphosed igneous intrusive rocks, although a spacing of 800 to 1,000 ft seems reasonable between high-yield wells.

The ability to locate wells in the most favorable sites throughout the municipal area of Cary was facilitated by the existence of an extensive public water system serving outlying subdivisions and developments that had grown out along the principal roads. The intervening undeveloped areas contained numerous well sites that were not too far removed from water lines. Thus, lines connecting the wells to the public system were not prohibitively long and expensive. The lesson to be learned here is the implication for ground-water development on a larger scale. Where counties and municipalities have extensive rural water systems, it is likely that these lines will cross or pass near many good well sites. Where in the past it would not have been practical to run water lines between many widely scattered well sites, it now may be possible to identify sites along the route of a regional water system where wells can be drilled, and these wells can be connected to the existing system at greatly reduced trouble and expense.

MONITORING TECHNIQUES FOR ACHIEVING MAXIMUM YIELDS

The successful management of high-yield wells depends upon the information supplied by a well-designed, long-term monitoring program. Data from a monitoring program are used to track both well performance and equipment performance. Knowledge of both of these is vital if the maximum long-term sustainable yield is to be realized. The goal of a monitoring program is to obtain sufficient information about discharge and drawdown behavior so that a well operator can manage a well and take corrective action when necessary.

Monitoring Techniques and Data Interpretation

By definition, monitoring requires that data be obtained on a regular basis. For a well or well system, readings of the discharge rate and the total volume of water pumped need to be taken frequently, perhaps every day or every other day. Readings from chart recorders that record the pump running time will tell how long the pump runs each pumping cycle and will also indicate if the pump is cycling off and on, as it may do if the water level declines to the low-water-level cutoff switch. The average discharge rate for each pumping cycle can then be computed from the total volume of water pumped and the time that the pump was running. Readings of water levels in the well just prior to the pump turning on and just before the pump turns off also are necessary, but it is probably not practical or necessary to do this every pumping cycle unless it can be done automatically. If measured manually, readings once or twice a week are probably sufficient.

Graphs of average discharge and water levels plotted against time (hydrographs) are useful visual aids that are used to detect changes in the operating characteristics and performance of a well. If the water levels, measured at maximum drawdown and maximum recovery, decline gradually with time and the yield also declines, two possibilities exist: (1) the well is being pumped in excess of recharge or (2) the water-producing zones are gradually becoming clogged, which also results in overpumping. If this occurs during a dry time of year, it is likely that the pumping rate exceeds recharge and that equilibrium can be reestablished by reducing the pumping rate. But, if the water-producing zones have become clogged, it may be necessary to have the well treated with acid or other chemicals to remove the clogging material.

If the water-level hydrograph shows a gradual rise and the pumping rate remains constant or increases slightly due to lower head loss, then recharge is probably exceeding the pumping rate. However, if the water level rises either gradually or suddenly and the pumping rate declines, then there is likely an equipment problem, usually in the pump assembly. The discharge control valve also should be checked to make sure that its setting has not been changed.

Yield and Water-Level Trends

In the ideal case, once the pumping cycle is established, the drawdown and recovery will fluctuate over a relatively constant range. This range can be maintained by increasing the pumping rate during the wetter, higher recharge times of the year and decreasing the pumping rate during drier periods, thus ensuring the maximum year-round production of ground water.

The above situation may be desirable in a conjunctive-use system (Maknoon and Burges, 1978) where ground water, which is usually cheaper to produce, can be used to offset the cost of treated surface water. Ironically, the winter and early spring, which will be the time of maximum ground-water production potential, is the time of lowest user demand, and the summer and fall, which have the lowest ground-water production potential, is the time of highest demand.

In systems that depend entirely on ground water, system capacity needs to be designed by giving consideration to the lower well yields that occur in the summer, and a number of wells sufficient to meet summertime demand should be included in the system. It is a safeguard to any system to have additional wells so that total capacity is in excess of expected demand in case of emergencies or shutdowns due to well or equipment failure.

In operating a system supplied only by ground water, wells can be pumped at a constant rate that is less than or equal to the average summer recharge rate, provided that there is a sufficient number of wells to meet summer demand. As shown in figure 13, the water level hydrograph will follow a cyclical pattern as the pump turns on and off. The trend lines define the maximum amount of recovery each time the pump is off and the maximum water-level decline each time the pump is on. Over a year's time, these

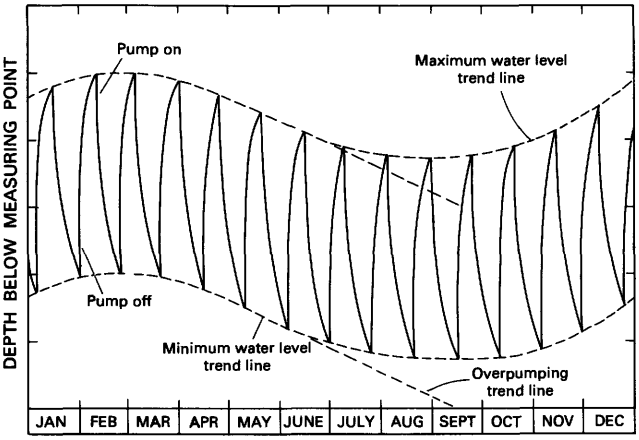

Figure 13. Schematic hydrograph for a well being pumped at a constant rate that is less than or equal to the summer recharge rate.

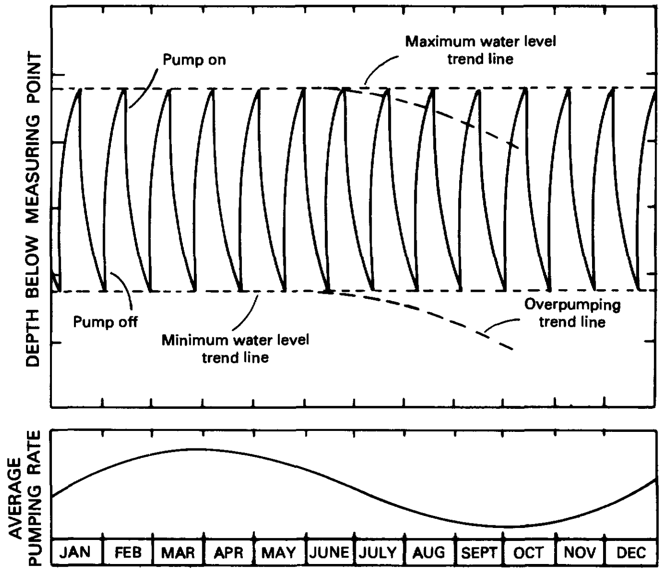

Figure 14. Schematic hydrograph and pumping rate for a well being pumped at rates equal to the seasonal recharge rates.

trend lines will follow a pattern that mimics the annual rise and fall of the water table, although the rise in the winter will probably be exaggerated due to lower demand. If the pumping rate is set too high during the winter or if the winter recharge is below normal, the trend established will continue through the summer months and the trend lines will continue downward indicating overpumping. A downward trend will also occur if summer recharge is well below average, as would occur during a drought.

In systems where the goal is to produce the maximum amount of water, the trend lines under ideal conditions will be relatively flat, and, rather than having a constant pumping rate, the system operator will adjust pumping rates seasonally to match the recharge rates, as shown in figure 14.

Pumping Cycles and Well Production

The position of the maximum water-level trend line and the minimum-level trend line relative to water-producing fractures has considerable bearing on well efficiency and is largely determined by the pumping cycle in addition to the pumping rate. Unlike wells in sedimentary confined aquifers where pumping may be continuous for long periods, wells in the fractured-rock aquifer system of the study area seem to benefit from short pumping cycles.

The shorter pumping cycles mean less drawdown in the bedrock aquifer. Hence, equilibrium of flow between the regolith and bedrock aquifers is reached in a much shorter time; the fracture system supplying the well will have saturated flow; and drawdown in the well, which determines the minimum water-level trend line, will be less. As a result, a greater part of the pumping period will take place with higher heads, and there will be greater saturated thickness about the well bore and less dynamic head loss. This usually means higher average pumping rates can be achieved.

This finding was made after several of the Cary wells were placed in service, and data from the monitoring program showed a decline in yields in a fairly short time. The first wells that were placed in operation in Cary were set to pump on a 7-day cycle—5 days pumping and 2 days off for recovery. The pumping rates were selected initially on the basis of short term (24-hour) pumping test results and included adjustments for expected long-term decline in specific capacity. After several weeks of pumping, it was found that late in each pumping period the pumps were cycling because low water levels were causing the low-water-level switch to turn the pump off and on. Pumping rates were reduced, but several weeks later the cycling began again. The wells giving the most trouble were those in which a major producing zone was many feet above the pump.

For example, in the McDonald Woods well (Wk-295, table 1) two of the major producing zones are 90 ft and 110 ft above the pump intake, which is 215 ft below the top of casing. Test data showed that, at the initial pumping rate of 75 gal/min, the water level declined below these two upper producing zones 1 to 2 hours after the pump was turned on and remained below these zones during the remainder of the 120-hour (5-day) pumping period. Toward the end of the pumping period, the water level was also near or below two lower producing zones, and at the same time, the pump was cycling off and on due to the water level reaching the low-water-level switch. Based on total pumpage from the totalizer meter, average yield was approximately 50 gal/min, much below the anticipated 75 gal/min.

Another pumping schedule was devised that would keep approximately the same total number of pumping

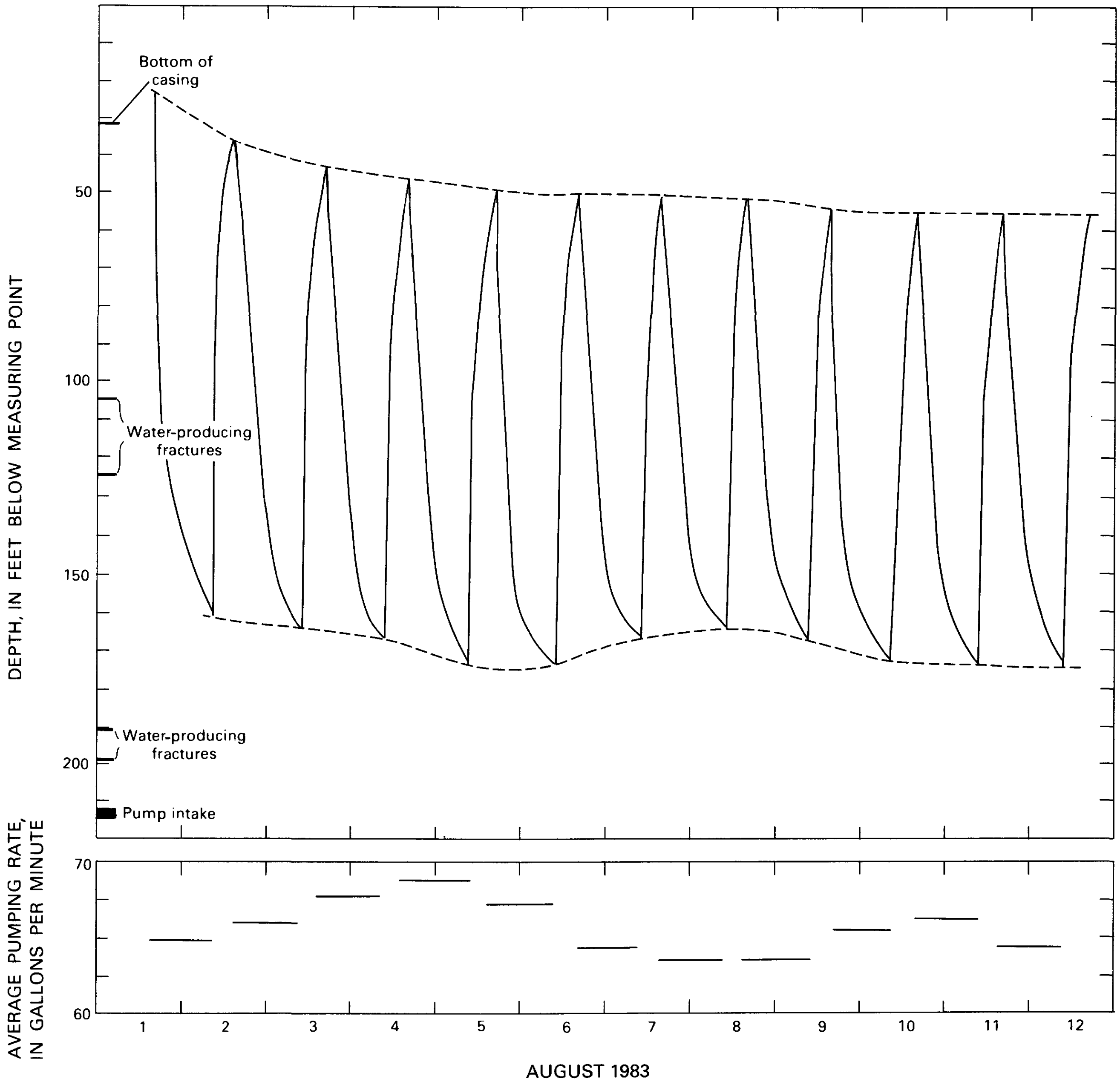

Figure 15. Hydrograph and pumping rate from test of 18-hours-on, 6-hours-off pumping schedule, McDonald Woods well (Wk-295).

hours each week but would result in more desirable drawdown characteristics. According to the new schedule, the well was to be pumped for 18 hours and allowed to recover 6 hours each day. In a 7-day period, the well would pump 126 hours, or 6 hours longer than the original continuous 120-hour pumping period. Pumping rates during the test were adjusted daily to determine the optimum rate.

The results from a 12-day test of the McDonald Woods well using the new schedule are shown in figure 15. During each pumping cycle, the water level was above the uppermost producing zones (depth 105 to 125 ft) for about 2 hours and never went below the lower producing zones (depth 190 to 200 ft) or below the low-water-level switch (depth 205 ft). The average pumping rate over the 11 pumping cycles was 65.8 gal/min. Because of the favorable results of this test, all wells in Cary were converted to the 18-hour-on, 6-hour-off daily schedule.

At the end of November 1984, after more than a year of operation, the McDonald Woods well had pumped for an average of 17.13 hours per day or 119.9 hours per week at an average rate of 67.2 gal/min. This is an average weekly production of 483,437 gallons per week. This is much

Table 2. Summary statistics for Cary, N.C., municipal supply wells from May 1983 through December 1984

Statistic	Well name and number								
	Thompson Wk-293	Thompson Pit[1]	Ponderosa Wk-294	McDonald Woods Wk-295	Waterford Wk297	Rockett Wk-304	Matthews Wk-291	Rescue Squad Wk-291	System average[2]
Average pumping rate[3] (gallons per minute)	49.7	170.3	67.4	67.2	30.5	79.5	39.8	67.6	47.7
Average pumping period (hours per day)	17.92	17.93	15.99	17.13	17.30	17.80	16.05	17.59	17.45
Daily average production (gallons per day)	53,450	182,790	64,749	68,939	31,386	84,735	38,321	71,263	49,640
Daily average production rate[4] (gallons per minute per day)...	37.1	126.9	45.0	47.9	21.8	58.8	26.6	49.5	34.5

[1]Thompson pit statistics are the total of five wells on the Thompson manifold, not including the Thompson well, which has separate instrumentation. The five wells are Showalter 1–4 and Kildaire Pond (Wk-299, Wk-300, Wk-302, Wk-303, and Wk-296).

[2]The system average is the average per day per well for 12 wells.

[3]Average rate for the time that the pump was running (approximately 18 hours per day).

[4]Average rate if the 18-hour production were spread over 24 hours.

better than the continuous 5-day pumping period (120 hours per week) at 50 gal/min that produced 360,000 gallons per week.

Evaluation of Data from Monitoring of Production Wells

Beginning in May 1983, daily records of total production and pumping time were collected during well inspections and later entered into a computerized data-management system for statistical analysis. Data compiled for this study were available for most wells through December 1984. The results of the analysis of the Cary municipal-well system are summarized in table 2. The Beaver well, Wk-301, was not in service during this period; thus, the system statistics in table 2 are averages for 12 wells. Wells in the system averaged pumping about 17.5 hours per day at an average rate of nearly 48 gal/min. The highest average pumping rate for an individual well was 79.5 gal/min from the Rockett well. Total daily production from the system averaged about 596,000 gallons per day (gal/d).

Although production did not meet the anticipated goal of 1 Mgal/d, efforts were made, nevertheless, to optimize production from the system and to produce as much water as possible. The determination of the optimum pumping cycle of 18-hours on, 6-hours off each day was described in the previous section. Careful attention to water levels and to adjustment of pumping rates during daily inspections helped to ensure that the wells would pump all available water. The results of the data analysis, described in the following text, indicate that production was at or near maximum.

As shown in figure 16, the average pumping period remained relatively constant at about 17.5 hours per day for the 12 wells in the system. If a well in the system was not operating or was cycling on the low-water-level switch, then the system average declined. If more than one well was involved, then the system average could decline substantially. However, it is apparent that this did not occur frequently. The period of record illustrated in figure 16 spans the 14-month period from September 1983 through October 1984. Data from May through August 1983 and November through December 1984 are not shown because the data are incomplete for all 12 wells.

Unlike the average pumping period, which remained relatively constant, the average pumping rate (fig. 17) shows a pattern of increasing production from September 1983 to March 1984 and then declining production from April 1984 through October 1984. Similarly, the daily average production in gal/d per well (fig. 18) and the daily average production rate in gal/min per well (fig. 19) show a rise during the winter and early spring and a decline during the summer and early fall. The daily average production rate is the pumping rate that would be realized by dividing actual daily production by 24 hours, or 1,440 minutes, and is approximately equal to the long-term recharge rate. The dip in the average pumping and daily production rates in December 1983 is due to the Ponderosa and Rockett wells, two of the higher yielding wells, being shut down for most of the month.

The significance of the pattern in figures 17, 18, and 19 is best illustrated by figure 20 in which the plot of daily average production is compared to the water-level hydrograph from the Kildaire Club House well (Wk-298). The Kildaire Club House well is an unused town well in an area of southwest Cary that is unaffected by ground-water pumpage. The well is located on a valley wall 15 to 20 ft above the adjacent flood plain, and the water level in the well is very sensitive to storms. The water-level hydrograph for the years 1983 and 1984 shows a distinct seasonal pattern rising in the cooler and wetter part of each year and declining during the warmer and dryer part of each year. From September 1983 through October 1984, the average

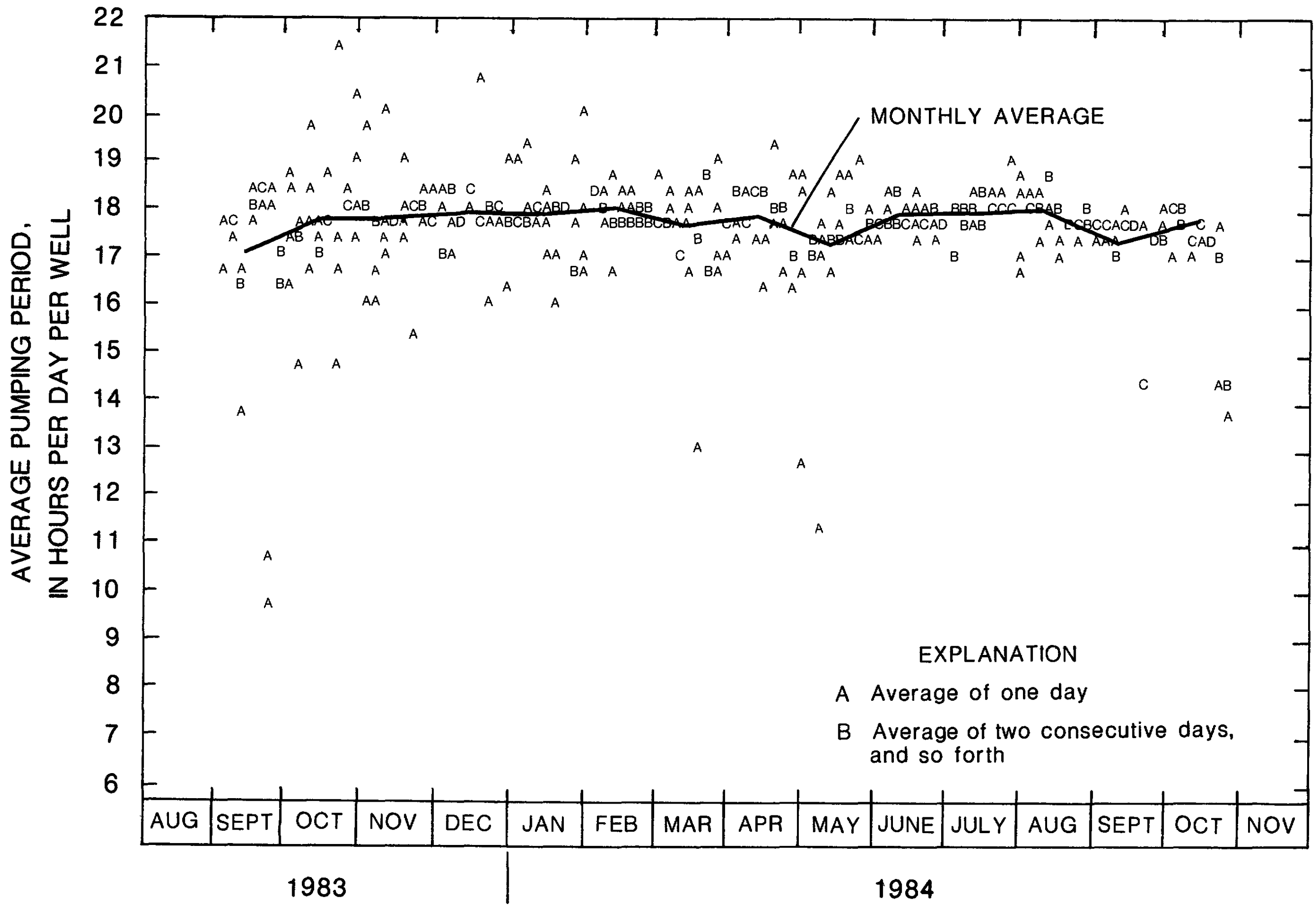

Figure 16. Average pumping period of the 12 operational wells in the Cary, N.C., municipal system, September 1983 through October 1984.

production from the Cary wells followed a similar pattern that suggests that, as ground-water recharge first increased then later decreased, the amount of water that was produced kept pace due to the adjusting of pumping rates. The sensitivity of the town well system to recharge is best shown during the unseasonable wet period in July and August of 1984 when ground-water levels rose. During this time, ground-water pumpage stabilized in response to the increased recharge before continuing its seasonal decline in September and October after the wet period passed.

Assuming that the ground-water production kept pace with ground-water recharge, as suggested by figure 20, it is possible to estimate the minimum amount of open land area that is required to receive recharge equal to the pumping rate. Cary is located just east of the drainage divide between the Neuse and Haw Rivers. Based on the annual average ground-water discharge for these two basins, the average annual ground-water recharge in the Cary area is 4.88 in. or 0.252 gal/min per acre. Therefore, to satisfy the daily average production rate of 34.5 gal/min per well, the recharge area would be 137 acres per well. It should be emphasized that this is an average area and will be less for lower yielding wells and larger for higher yielding wells. The important point is to recognize the magnitude of the land area necessary to receive recharge for these wells and to realize how rapidly the creation of impervious cover in growing urban areas can diminish recharge area. Unless a well is near a stream or body of water where pumpage may capture streamflow, such as may occur with the Rockett well (Wk-304), the recharge area for wells in the Piedmont and Blue Ridge is limited by the size of the drainage basin upgradient of the area of the cone of depression. This partially explains why wells on ridges and uplands usually have lower sustained yields than wells in draws and valleys. In upland areas the recharge is generally limited to the area of the cone of depression.

A comparison of the driller's reported yields in table 1 with the actual long-term average yields (table 2) shows that actual production was 61.5 percent of that anticipated from the driller's reported yields. Calculations based on the instantaneous pumping rates reported for May 24, 1984, (table 1) show that on that date the system was pumping at 60.0 percent of the anticipated rate or about the long-term average.

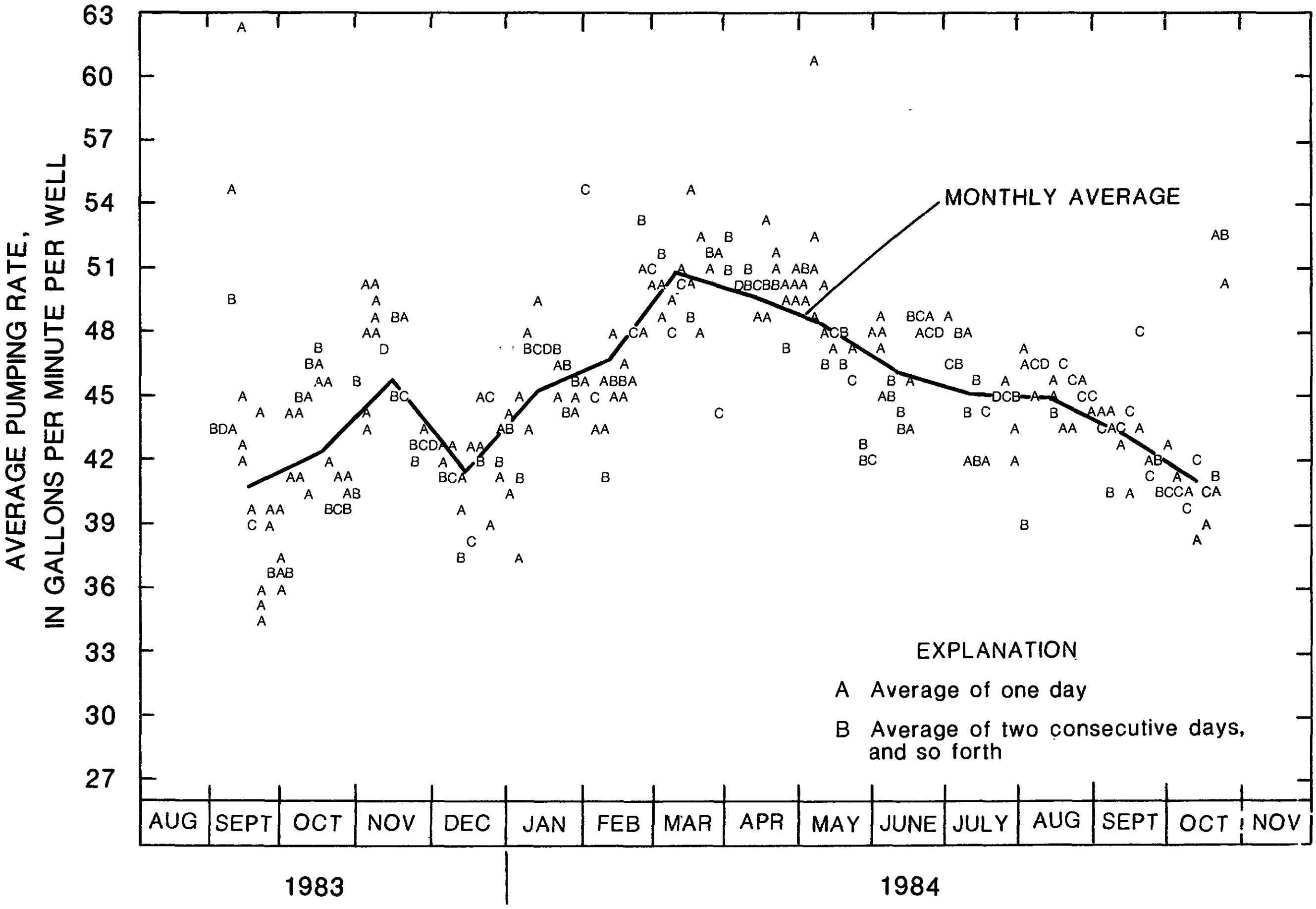

Figure 17. Average pumping rate per well of the 12 operational wells in the Cary, N.C., municipal system, September 1983 through October 1984.

These data exemplify an apparently widespread problem that comes from assuming that reported yields, based on short-term tests or less precise methods, will be the same as the long-term sustainable yield. Pumping tests were run on all the wells in the Cary system, but all tests were not conducted by the same staff, by the same methods, or for the same lengths of time except to meet the minimum state requirements of a 24-hour test. Generally, step-rate tests were run on the higher yielding wells, and constant rate tests were run on the lower yielding wells. In addition to step-rate tests, long-term constant-rate tests were conducted on the Rescue Squad (Wk-292) and Matthews (Wk-291) wells for 8 and 4 1/2 days, respectively.

Detailed analyses of test data taken from step-rate tests were made only for the highest yielding wells (table 1). Results are mixed with respect to predicting the long-term yield but generally predict more conservative (lower) yields than the yields reported by drillers. Based on the U.S. Geological Survey test results for six wells in table 1, the long-term yields for these six wells are 76.3 percent of that predicted. The largest discrepancy is found in the estimate for the Thompson well (Wk-293). The test of this well was a 24-hour step-rate test, but the test had a serious shortcoming due to a failure to pump the well long enough or at a rate high enough to draw the pumping water level to the pump intake. Otherwise the test was well conducted. Because of the large difference in yields, there is some concern that the water-producing fractures have become clogged or the well or fractures may have partially collapsed. Certainly, the recharge area, thickness of regolith, and topographic setting (site type A) favor a higher sustained yield more in line with the original rating.

COST ANALYSIS OF THE GROUND-WATER SUPPLY DEVELOPMENT PROGRAM

A brief discussion of the costs associated with the Cary ground-water supply development program and the recoupment of these costs will provide a financial reference for communities and individuals in the Piedmont and Blue Ridge who are weighing the use of ground water versus surface water. Estimated costs were originally computed in

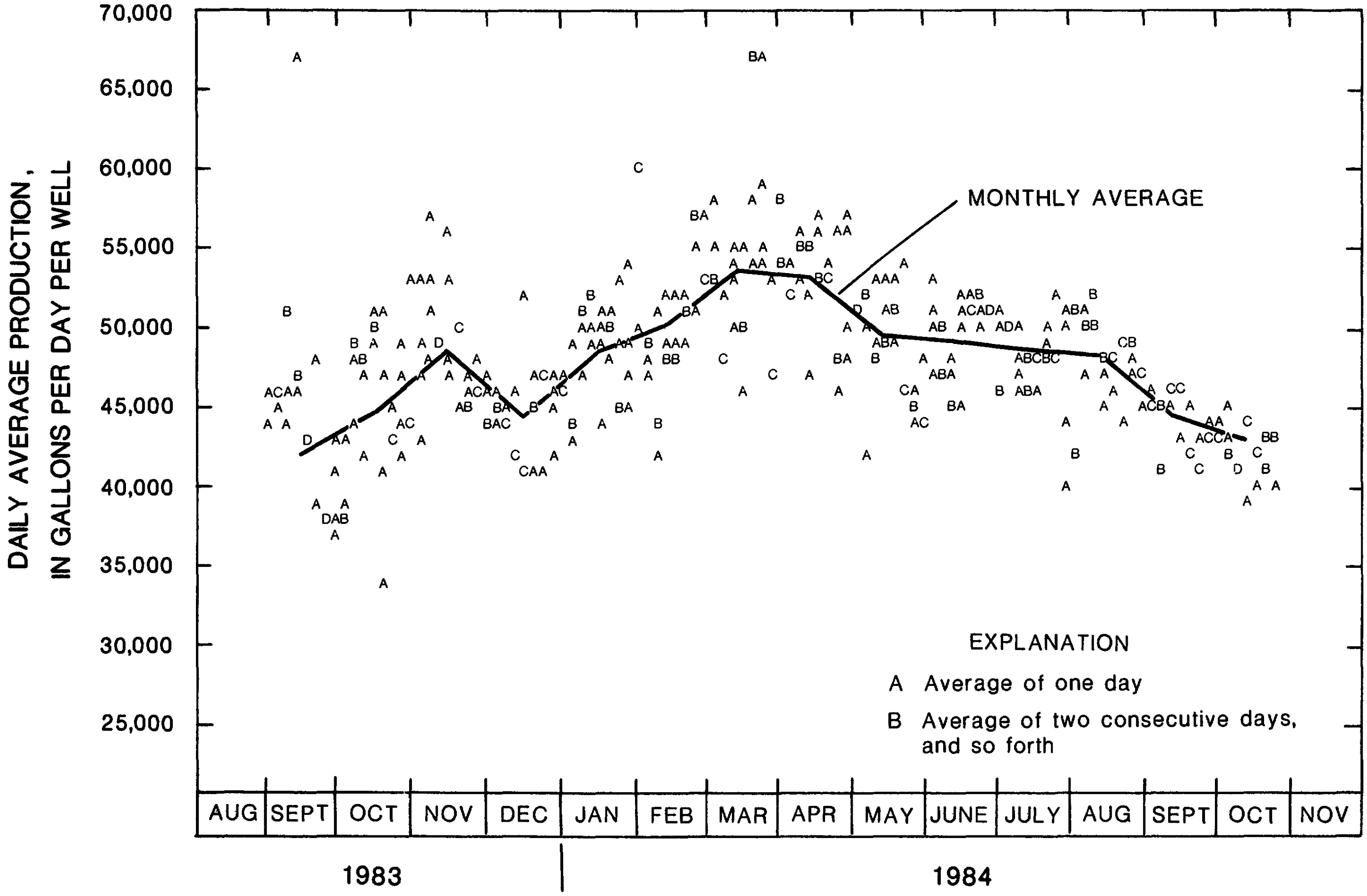

Figure 18. Daily average production per well of the 12 operational wells in the Cary, N.C., municipal system, September 1983 through October 1984.

late August 1981 but were revised in September 1982 as the drilling program came to a conclusion and construction of treatment and distribution facilities were underway. This original estimate was based on costs for 10 new wells (John W. Harris, engineer, town of Cary, written commun., Sept. 1982). The estimate presented here (table 3) has been adjusted to account for the drilling of 13 wells and reactivation of 2 existing town wells. Future cost comparisons should be referenced to this 1981–82 period.

Cost estimates were subdivided depending on whether a well was to be a stand-alone facility or part of a multiple-well manifold system, a new well, or an existing well to be reactivated. Where existing wells were found suitable for reactivation, the wells were redeveloped and cleaned, new pumps installed, and all above-ground facilities replaced. A reactivated well had the same capital costs as a new well but did not include the sunk costs associated with a new well.

As shown in table 3, the sunk cost was estimated at $12,700 per well and was money that would be spent for any new well regardless of whether the well was successful or not. These sunk costs included geological surveys and site selection, temporary access from owners with purchase options, well engineering, drilling, and pumping tests.

Once a well was successfully drilled and tested, the well could become either an independent facility or part of a multiple-well system if other wells were nearby that could be connected by a manifold line to one central treatment location. The estimated capital costs for the independent facilities were, as would be expected, more expensive than for wells on a manifold.

For a stand-alone facility, the capital cost (table 3) was estimated to be $48,600. The water treatment in the Cary system consisted of chlorination for control of bacteria and polyphosphate treatment for control of undesirable levels of iron and manganese. When wells could be grouped on a manifold system, the capital costs were divided between wells that did not have treatment facilities and were merely sources of raw water and the one well that was the hub of the system and the site of the controls and treatment equipment. Capital cost for the hub facility was estimated at $48,600, the same as for an independent well, but, in the one actual case where manifolding was employed in Cary, was probably somewhat higher. Because the wells on the

Table 3. Estimated nonoperating cost of the Cary ground-water supply system based on September 1982 data
[Data supplied by John Harris, town of Cary, written commun., 1982]

	Well status			
	Manifold system (new)	Stand alone (new)	Reactivated	Unused
Wells	Thompson (hub facility) Showalter 1 Showalter 2 Showalter 3 Showalter 4 Kildare Pond	McDonald Woods Ponderosa Beaver Rockett Waterford	Matthews Rescue Squad	Atkins Kildaire Club House
	System cost			
	Manifold system (new)	Stand alone (new)	Reactivated	Unused
	1 @ $48,600 (capital cost) 5 @ $35,400 (capital cost) 6 @ 12,700 (sunk cost)	5 @ $48,600 (capital cost) 5 @ $12,700 (sunk cost)	2 @ $48,600 (capital cost) 2 @ -$4,000 (credit for land)	2 @ $12,700 (sunk cost)
Subtotals	$301,800	$306,500	$89,200	$25,400
Total	$722,900			
	Sources of expenditures			
	Manifold well capital cost $35,400	Stand-alone well capital cost $48,600		Sunk cost $12,700
	Pump and accessories Well-head vault Engineering Easements	Pump and accessories Well house Polyphosphate equipment Chlorination equipment Control switches Waterlines (1,500 linear-foot average) Engineering Easements		Surveys Access Drilling Engineering Testing

manifold did not have treatment equipment and were enclosed in a less expensive prefabricated cast concrete utility vault, the capital cost was reduced to $35,400 per well.

The sunk costs are factored separately to account for new wells that are unusable because of low yield or perhaps poor water quality. Excluding sunk costs also permits a cost analysis based only on capital costs necessary to reactivate wells. When a well is on property that is already in possession, the land cost (easement) is removed from the estimate. Average well-site cost in 1982 was estimated at $4,000 per well. Thus, the reactivation of the Matthews and Rescue Squad wells is estimated at $44,600 per well giving a total of $89,200 in table 3. The results of the estimate for the 15 wells involved in the development program—2 abandoned as unusable, 2 reactivated, and 11 usable new wells—totals approximately $723,000.

More important than the total cost is the ability of the system to pay for itself in a reasonable period of time at a fair cost to customers. If treated surface water is also available, the cost must be competitive with that source of water. For several years Cary had been purchasing treated water from Raleigh. At the time of the Cary ground-water development program in 1981–82, the cost of water was $0.80 per 1,000 gallons. Additional allocations beyond the amount available under the purchase agreement would be at a higher rate. The decision was made by Cary to satisfy additional demand with ground water in a conjunctive-use system. For a well to be cost effective in the Cary system, it had to yield water at a rate that would cost no more than $0.80 per 1,000 gallons to produce.

Results of a cost recovery analysis for four possible situations are shown in figures 21 and 22. The cost recovery is based on a 7-year pay back period for the nonoperating costs shown in table 3 and includes the annual operating costs for maintenance, chlorine treatment, polyphosphate treatment, and electric power. It is also assumed that a well would produce water for 18 hours per day for 365 days each year. No interest payments are included in the 7-year division of capital costs.

In figure 21 the cost to produce water from stand-alone facilities is illustrated for wells producing between 25 and 90 gal/min. For a reactivated well to be cost effective, in comparison to costs for Raleigh water, it must produce at least 37 gal/min. A new well must produce at least 44 gal/min. In figure 22 the cost to produce water from wells in a manifold system is illustrated for wells producing between 25 and 90 gal/min. A new well on a manifold system (excluding the hub facility) must yield at least 33 gal/min, and a reactivated well must produce at least 25 gal/min.

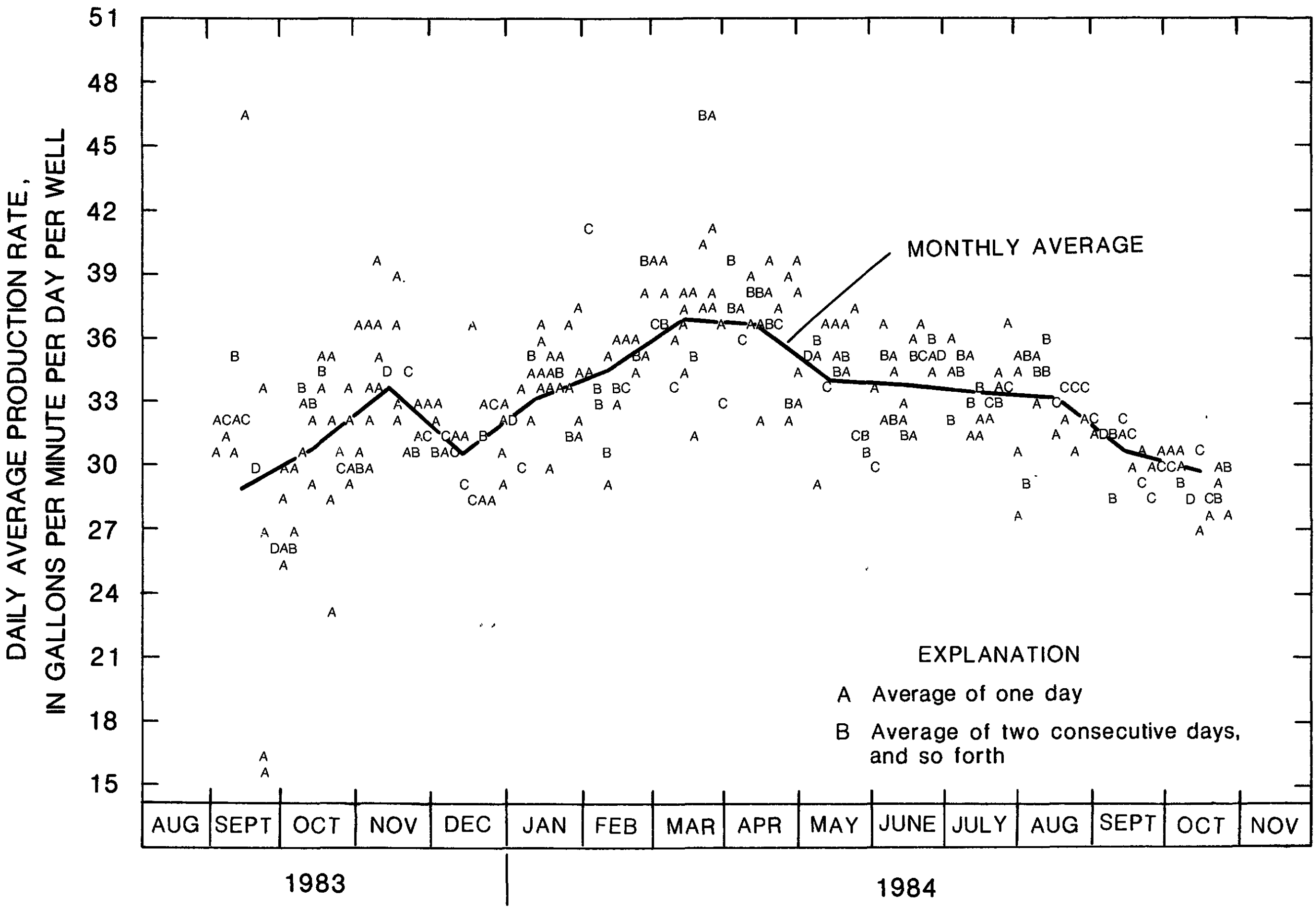

Figure 19. Daily average production rate per well of the 12 operational wells in the Cary, N.C., municipal system, September 1983 through October 1984.

Inspection of the actual yields measured on May 24, 1984, in table 1 shows that several wells are operating at a marginal or less than cost-effective rate. However, the average output from the 12 wells in operation on that date was more than 46 gal/min, which means that the system as a whole is cost effective with some higher yielding wells offsetting the cost of lower yielding wells.

The cost analysis raises some interesting questions about the number of wells drilled and placed in service. As shown in table 1 and figures 21 and 22, 5 of the 13 new wells (38 percent) have yields (33 gal/min or more) that are cost effective either as individual supplies or as a manifold well. One other manifold well, Showalter 3, is a marginal success. If this success ratio could have been maintained, would it have been better to drill more wells and only place the highest yielding wells in service? With sunk costs of $12,700 for drilling at each new site, four exploratory wells could have been drilled for about the same price as each well placed in service at a capital cost of $48,600. For about the same cost as developing two low yield wells, eight test wells could have been drilled, and experience suggests that at least three of these would have had yields considerably greater than the minimum to be cost effective.

SUMMARY

Various studies have presented criteria for selecting well sites in the crystalline rocks of the Piedmont and Blue Ridge provinces of North Carolina. A statistical analysis of data from wells drilled into these crystalline rocks verified and refined the previously proposed criteria. An opportunity to test site-selection criteria indicated by the statistical analysis occurred when the town of Cary decided to expand its municipal ground-water system.

The statistical analysis indicated that large yields to wells were controlled by the type of rocks in which the well was drilled, the thickness of saturated regolith based upon topographic features, and the siting of the well with regard to drainage lineations that might be an indication of fractures or joints in the bedrock. A conceptual model of the local hydrogeologic system was developed that served as the basis for the development of six type-well sites: the ideal

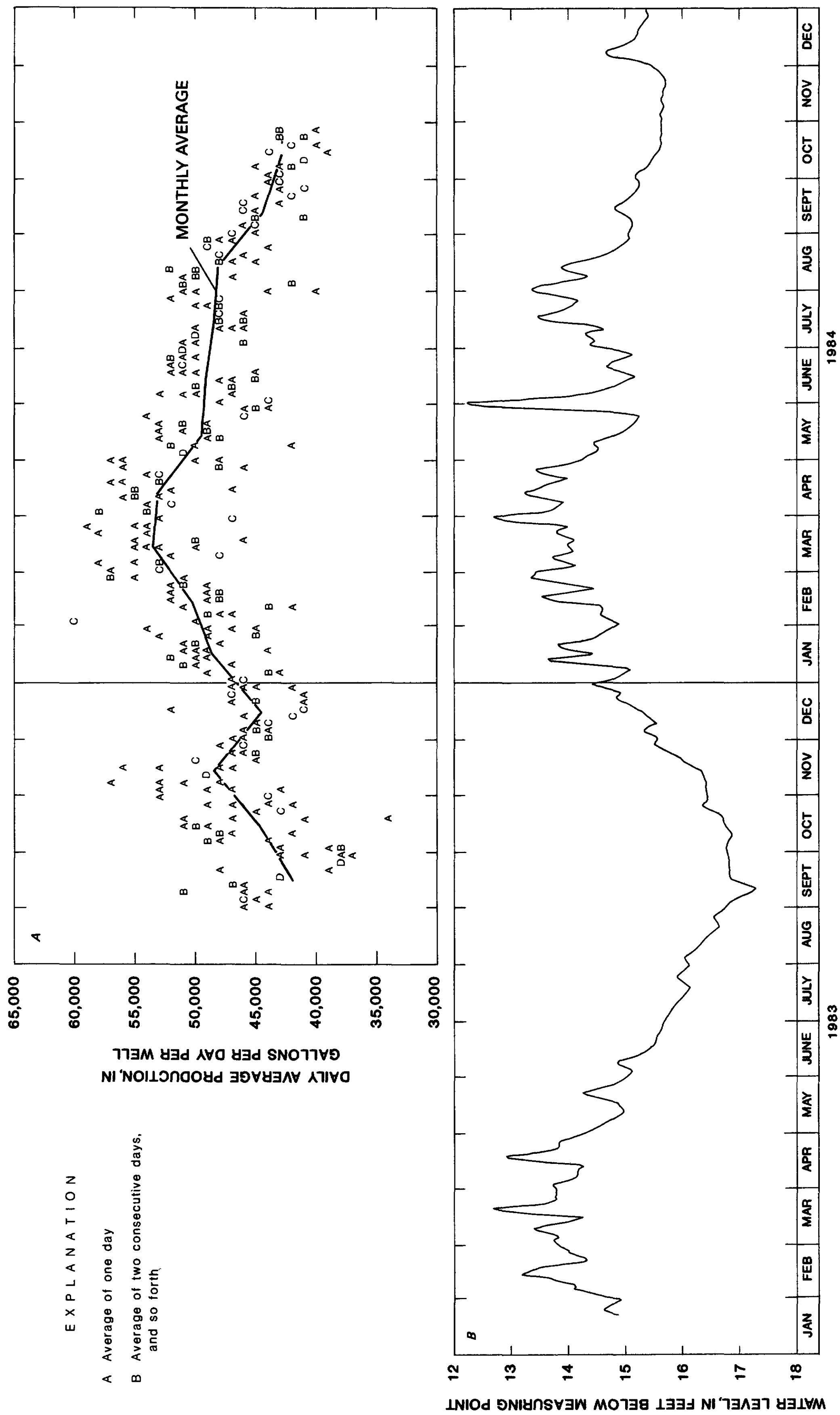

Figure 20. Comparison of (*A*) trend of daily average production per well of the 12 operational wells in the Cary, N.C., municipal system with (*B*) a hydrograph from the Kildaire Club House well (Wk-298).

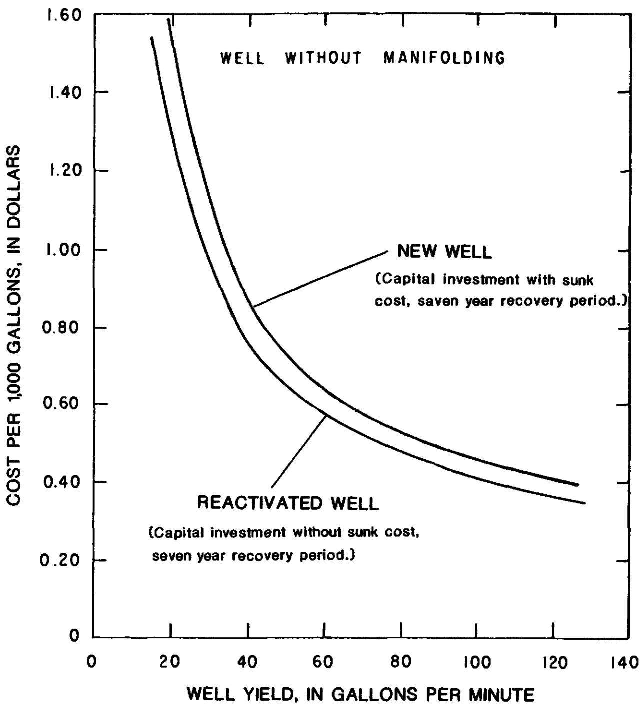

Figure 21. Ground-water development costs for new wells and reactivated wells not on a manifold system.

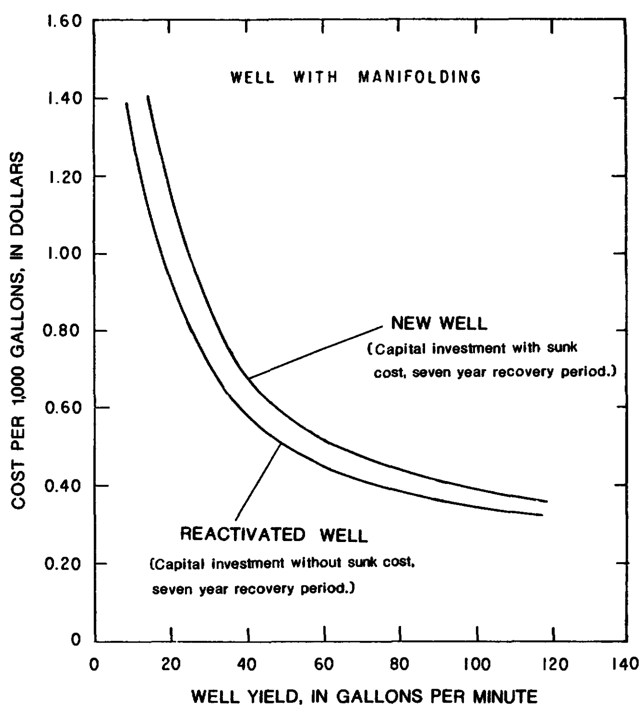

Figure 22. Ground-water development costs for new wells and reactivated wells on a manifold system.

site, three semi-ideal sites, and two nonideal sites. All sites, however, were expected to have greater than reported average yields to wells.

A total of 13 wells were drilled. Because of restrictions imposed by health regulations, only two wells were drilled at ideal sites. These wells had reported yields about six times the average yield for wells drilled at random in the same hydrogeologic unit. Yields to nine wells drilled at less that ideal sites ranged from slightly above to about six times the average yield. Only one well drilled at a type site had a less than average yield. One well not located at any of the type sites produced little water.

Based on short-term aquifer tests, production wells were initially placed on a 5-day-on, 2-day-off weekly pumping cycle that resulted in drawdown to the point where low water-level cutoff switches were cycling on and off. Experimentation showed that by going to an 18-hour-on, 6-hour-off daily pumping schedule, more water could be pumped in a week with much less drawdown during the daily pumping cycle. The shorter pumping cycle apparently enabled water contributed by the regolith, which acts as the reservoir for the bedrock, to reach an equilibrium with the water being withdrawn from the bedrock.

In conjunction with the monitoring and testing of the production wells, it was observed that predicted yields determined from 24-hour pumping tests were considerably greater than the yields obtained when the wells were actually put into production. Long-term yields were, on the average, about 75 percent of the yields predicted from the 24-hour tests and only about 60 percent of the driller's reported yields.

Long-term monitoring of production wells has provided a data base that has enabled the town of Cary to obtain maximum production from its well system and to monitor well performance and equipment performance in its maintenance program.

An analysis of the Cary well system showed that it is cost effective. Cost effectiveness could be improved by drilling wells at the more ideal type sites. The analysis showed that it would be cost effective if one high-yield well could be obtained for every four wells drilled.

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Ground-Water Resources of the Piedmont-Blue Ridge Provinces of North Carolina

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