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USE OF GEOLOGIC AND WATER YIELD DATA FROM GROUND WATER BASED COMMUNITY WATER SYSTEMS AS A GUIDE FOR GROUND WATER PLANNING AND MANAGEMENT

by

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ABSTRACT

Two hundred fourteen wells constructed to supply water to various subdivisions and mobile home parks in Wake County, NC, were used as a data base in the investigation. The ultimate purpose of the study was provision of guidelines for evaluating ground water use as an element in land-use planning for Wake County.

A two media model was recognized, consisting of saprolite and the underlying crystalline rocks. The Community Well System (CWS) well data provided well yield information which could be tested against various geologic and non-geologic parameters. Major areas where ground water yields have historically been low (< 10 gpm) and areas where yields appear consistently higher are outlined. Pumping test data and their interpretation led to use of a fracture coefficient which proved to be correlatable with lithology, field joint and fracture measurements, and specific capacity of wells. Average values of fracture coefficients grouped by rock type decreased in the same rock type order as average well depths grouped by rock type increased.

Probability curves provide a means of estimating yields for a given rock type and a means of guiding a decision on whether to deepen a well beyond about 250 ft or to drill a

new well for a given project. The probability of location of high yield wells (> 50 gpm) is improved by application of lineament analyses. Fractures and joints appear in greater abundance where the rocks are the more intensely folded, and water well yields are generally higher in these areas.

Low stream flow calculations (7-day, 10-year; 7-day, 1-year) are utilized to estimate usable recharge for various parts of the county. The data agree with estimates of recharge made using the Thornthwaite and Mather water budget model. Information about well failures indicates that roughly 25 percent of the CWS wells eventually cease to be productive for one reason or another. It is estimated that about half of the failures can be attributed to geologic factors.

From a land-use planning viewpoint the study suggests that development needing a water usage exceeding that required by a single-family residential density of one unit/acre should be concentrated in those areas where governmental planning proposes extension of water and sewer services.

TABLE OF CONTENTS

TABLES

Table No. Page

FIGURES AND PLATES

SUMMARY AND CONCLUSIONS

The nature of the two-media ground water model for crystalline rocks areas and the possibility that a multiple aquifer system may exist in places, inhibits the accurate prediction of ground water production from individual wells in Wake County prior to their drilling. However, estimates of the occurrence and availability of ground water on a geographic basis can be valuable in planning the development of ground water resources in the county. Furthermore, probability information is useful in decisions relating water needs to a drilling program and its costs.

The investigation has used Community Well System (CWS) well yield data to outline patterns of favorable and less favorable areas for ground water development in Wake County. Conjunctive use of ground water with surface water requires an understanding of an inventory of the ground water and an understanding of under what circumstances ground water may become unavailable or be in limited supply. Calculations undertaken show that ground water is not in an infinite supply..

In planning water supply distribution systems based upon ground water, the extent to which ground water is available must be recognized. Plate 6 summarizes the potential ground water availability across the county, and Plate 5 pinpoints some major areas where well yields have historically been relatively low (less than 10 gallons per minute; gpm).

Analysis of the data and the methodology used during the investigation indicate the following conclusions.

1. Specific capacity is a better parameter than yield for comparing the the water-bearing capacities of individual well sites. Specific capacity provides a measure of well "efficiency" by accounting for the drawdown to obtain a given yield. According to the chi square analysis of specific capacity lithology is the most significant variable. For a given well yield there is a maximum probable drawdown, and this maximum value increases with yield.
2. A negative correlation exists between well depth and yield or specific capacity. In general, the optimal maximum well depth of the CWS wells is approximately 250 feet. Drilling below a depth of about 250 feet is less likely to increase significantly total well yield for a requirement, or project, than will drilling a new well.
3. The failure of the multiple regression analysis to account for a significant amount of the variation in specific capacity is caused primarily by the exclusion of important geologic variables, in particular fracture characteristics, from the model. The relative significance of the geologic variables affecting specific

capacity as indicated by the multiple regression analysis are different from the results of the chi square analysis, except that lithology is the most important variable in each analysis.

The multiple regression analysis is judged to be more sensitive to the actual effects of a geologic variable on specific capacity because it accounts for the effects of the other geologic variables. Chi square analysis makes no adjustment for the effects of other geologic variables on specific capacity. Thus, it is uncertain that the variation in specific capacity as indicated by a chi square analysis is due solely to a single variable of interest.

4. The information from the linear intersection evaluation together with the lithologically related pattern of decreasing specific capacity, well yields, and fracture coefficient with average well depth support in combination a general concept that ground water is found more frequently in amounts above 50 gpm and at shallower depths in the igs[1] lithology. The mgs[1] assemblage of rocks displays the least favorable conditions for ground water production, including the average need to drill deeper for yields exceeding 50 gpm than is necessary in the other lithologies. On the other hand, the probabil-

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[1] igs = injected gneiss and schist; mgs = mica hornblende gneiss and schist.

ity of locating a well yield of more than 58 gpm in the mgs lithology is about doubled if linear feature analysis is utilized, and similar increases in the probability of obtaining a well at or above a given yield are expected for yields in the 20 to 50 gpm range. Detailed evaluation of each proposed well site with regard to relationship between potential recharge area, saprolite thickness, rock type, topographic linears, and topography may be expected to improve the discovery ratio of wells producing more than the average volumes of water as computed from the presently available data.

5. Drainage density is not a dependable index of fracture density and is in part affected by variations in rock resistance to weathering. Some linear features may also be the result of streams following less resistant layers in the bedrock.
6. The characteristics of the fracture system (frequency, size, and interconnection) are the most important factors affecting well production.
7. The Jenkins and Prentice (1982) equation of linear flow is an appropriate initial method for determining the characteristics of a fractured crystalline aquifer. The values of the fracture coefficient proved to be consistent with the fracture characteristics mapped in the field and derived from baseflow observations.

8. Lithology is the second most significant variable affecting yield. The mean yields range from 45 gpm for igs wells to 21 gpm for mgs wells. The mean yields calculated from the CWS wells are greater than the mean yields reported previously by May and Thomas (1968). The probability of high yield wells (> 75 gpm) is greatest for the fgs lithology (PR = .23), and the igs lithology has the greatest probability of providing well yields between 20 and about 58 gpm.

Topography is not related to well yield as closely as lithology. According to chi square analyses of yield, topography and saprolite thickness appear to be more significant than well site elevation and distance of well to nearest draw. The multiple regression analysis shows saprolite thickness to be of relatively low importance. This suggestion may reflect the complex relationship existing between water flow in the saprolite, the incidence of bedrock fractures accepting water, the thickness of the saprolite, and the position of the well sites. The ad[1] lithology is intermediate in its potential ground water yield, but higher yields may be anticipated along the borders of the granitic mass where fracturing appears to be more prominent.

9. Consideration of average values of well depth, specific

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[1] ad = granite; fgs = felsic gneiss and schist

capacity, and well yield discloses that average water well depth increases in the order of lithologies igs, ad, fgs[1], and mgs. There is a corresponding decrease in the average fracture coefficient, specific capacity, and well yield values with increasing average well depth. Linear regression computations show that the best correlation with the average well depth classed by rock type is with the average specific capacity and fracture coefficient values. The correlation between the lithologically grouped average well depths and the associated average well yields is relatively low.

10. Low flow stream characteristics can be used to determine relative ground water availability and to locate indirectly more intensely fractured areas. Values of $Q_{7,10}$ identify the Wake Forest-Millbrook-Bayleaf area as having the greatest ground water availability in northern Wake County. The baseflows in the Rolesville batholith indicate that fracture density is highest at the margins of the batholith and decrease eastward toward its center. This relationship is confirmed by the higher mean yield of wells drilled at the margins of the batholith. Lower potentials for ground water development lie in the Durham Basin and the Carolina Slate Belt areas.

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1. ad = granite; fgs = felsic gneiss and schist

11. Ground water recharge as determined from $Q_{7,1}$ values agree with recharge values computed by the Thornthwaite method for the Raleigh area (13 percent mean annual precipitation). The difference between $Q_{7,1}$ and $Q_{7,10}$ values can be used as an indicator of the smallest amount of ground water available for use without ground water mining and consequent lowering of the water table.

    More ground water is available during the recharge season, especially during the period December through early April than is indicated by the $Q_{7,1}$ values. However, prudent planning requires consideration of the minimal amount of water that might be available over the long term. Since the recharge values based upon the Thornthwaite method and the $Q_{7,1}$ discharge values are similar, discretion suggests that the lower recharge values be utilized in planning the development of Wake County. Such planning should also take into account the effect of introduction of impervious surfaces upon the recharge rate.

12. Based upon a *per capita* use of 100 gal/person/day and an average of two to three people per residential unit, the results of this study suggest that through the east-central portion of Wake County ground water will on the long-term average support a population density equivalent to about one acre per residential unit during

annual drought conditions. Eastward and westward the "safe density" decreases to the equivalent of two to three acres per residential unit. A larger per capita use will of course lower the limiting density. The per capita limits can be used as a guide in determining positioning of industrial areas within the country.

As development takes place over a period of years accompanied by emplacement of impervious surfaces in recharge areas, the recharge volumes will decrease. Even if no increase in volume of ground withdrawal occurs, it can be anticipated that ground water will in effect be mined if withdrawals exceed the 300 to 400 g/Ac/day. Local water supply problems can and may develop as local recharge areas are developed and accompanying decreases of ground water recharge occur.

As long as some as yet undetermined minimum open space suitable for ground water recharge is maintained around them, local population centers probably will not unduly affect the regional ground water budget. For example, so long as consumptive water use for a 100 acre tract does not exceed more than about 30,000 to 40,000 gallons per day, the water usage will not exceed that recharged and available for use during the water year. At the same time it must be realized that ground water recharge to the crystalline rocks is concentrated in the local, small drainage basins and that interception of the recharging ground water by any given fracture system does not necessarily follow a regionwide systematic pattern. In addition, the fracture patterns at each site control the shape of the drawdown relationships. The drawdown surface will in many instances probably be elongated in one direction because of the nature of the fracture system. Possible existence of a multiple aquifer system at any location must be recognized also.

13. The incidence of abandonment of CWS wells is greatest in the _igs_ and _ad_ rock types and least in the _fgs_ and _mgs_ rock types. The estimate of geology-related well failures (13%) is a minimum figure because many abandoned wells are not reported.
14. The use of CWS data as a sample is hindered somewhat by missing data which undoubtedly cause the statistical analyses to be less significant than they might have otherwise been. The CWS wells tend to occur in clusters, leaving some areas and lithologies in the county unrepresented. However, the required pumping test provides the CWS sample with a clear advantage over data from private wells. Also, the CWS yields are more representative of the maximum ground water availability than reported yields from private domestic wells. Use of the admittedly limited yield information from

drillers' logs for private wells can, however, be used supplementally to outline geographic patterns of relatively high and low yield areas.

15. Institution of requirements for carefully run pumping tests for CWS wells, including perhaps a requirement for pumping periods of more than 24 hours at a constant rate would aid in better evaluation of the ground water resource. Also, the county could improve its understanding of ground water distribution and availability if it required that the results of a properly run pumping test on private wells and CWS wells become a requirement in the subdivision approval proceedings.

INTRODUCTION

Purpose

The purpose of the investigation has been formulation of geologic guidelines for the development and use of ground water from the crystalline rocks of Wake County, N.C. The results are intended as a guide for land-use planning in Wake County; however, the study demonstrates methodology which can be used in other areas with crystalline rock aquifers. Objectives of the investigation have been to

1) ascertain the hydrogeologic variables which influence well yield and specific capacity most significantly;

2) determine the probability of obtaining a given well yield;

3) evaluate well failure frequency;

4) identify the sections of the county having the highest and lowest potential for ground water development;

5) select an appropriate ground water model and aquifer test to characterize the hydrology of the fractured crystalline rocks;

6) evaluate the use of Community Water System (CWS) data as a meaningful sample.

Previous Investigations

Parker's (1979) description of Wake County geology has served this study as the basis for distinguishing rock types and understanding the structural geology of the county. LeGrand (1967) discussed the effect of topography, saprolite thickness, well depth, and fractures on well yields in the Piedmont and Blue Ridge Provinces of the southeastern United States. An appraisal of ground water supplies in the upper Cape Fear River basin was made by Floyd and Peace (1974). Putnam and Lindskov (1973) studied the water resources of the upper Neuse River basin.

Welby (1968) developed a model for evaluating short-term pumping tests in crystalline rocks. Results of pumping tests conducted by Lewis and Burgy (1964) indicate that the hydraulics of water movement in fractured rocks is not suited to analysis by the conventional nonequilibrium equations. Marine (1966, 1967) recognized that the assumptions associated with the conventional equations were not strictly applicable to fractured crystalline aquifers. However, citing the lack of equations derived specifically for fractured aquifers, he used the available equations to calculate the apparent permeability of schist and gneiss underlying the Coastal Plain of South Carolina. The apparent permeability of finely fractured rocks averaged 0.0003 gallons per day per square foot, and for more open zones the

The apparent permeability averaged 1 gallon per day per square foot.

Summers (1972) studied wells in the fractured crystalline rocks of Wisconsin, finding that wells achieve 60 to 80 percent of their yield in the first 20 feet below the water table. He reported a mean specific capacity of 1.3 gallons per minute per foot. Davis and Turk (1964) evaluated yields and water-injection tests of over 2,500 wells and verified a general decrease of permeability with depth in fractured crystalline rocks.

Nutter and Otton (1969) studied factors governing the occurrence of ground water in the crystalline rocks of the Maryland Piedmont. Their statistical analysis showed domestic well yields to be affected more by topography than lithology. Richardson (1982) also described ground water occurrence in the Maryland Piedmont. Her summary of hydrologic budgets of drainage basins underlain by crystalline rocks showed ground water recharge to be 20 to 27 percent of average annual precipitation. Most wells had specific capacities of less than 1 gallon per minute per foot/(gpm/ft.)

May and Thomas (1968) described the water-bearing properties of the principal rock units in Wake County. They analyzed the yields of 286 domestic wells by rock type and topography.

Community Water Systems

The basic data used in this report are from community water system wells. A community water system (CWS) is defined by the North Carolina Division of Health Services as a water supply system which serves 15 or more households (N.C. Div. Health Services, 1981). A CWS usually serves a subdivision or mobile home park which is located outside the area served by municipal water lines.

Plate 1 shows the locations of 123 community water systems in Wake County for which well locations are available (Appendix III). Community size ranges from 10 to 300 households, and the number of wells in a CWS ranges from 1 to 12.

The choice of CWS wells rather than private domestic wells for evaluating ground water resources is based on the following considerations.

1) The North Carolina Division of Health Services requires and files more information on CWS wells than private domestic wells. The results of a 24-hour pumping test are required by the state for approval of a CWS well system. No pumping test is required for private wells.

2) The quantity of water needed for domestic consumption in a single household is relatively small. As a result the required yields of private domestic wells are relatively low and do not necessarily represent the true water-bearing

capability of the aquifer. Because CWS wells serve at least 10 households, maximum well yields are required, and the reported yields are more likely to be representative of the maximum ground water availability.

Acknowledgements

It is a pleasure to recognize the assistance of a number of agencies and people who freely provided information and discussed ideas relating to the investigation.

Data used in the investigation came from a variety of sources. The Community Well System data was made available by the Environmental Health Section, Division of Health Services, North Carolina Department of Human Resources; other water well information and drillers's logs were obtained from the Ground Water Section, Environmental Management Division, North Carolina Department of Natural Resources and Community Development. Water consumption figures were sought from the files of the North Carolina Utilities Commission.

Cooperation of the owners of the several stone quarries in Wake County is acknowledged as is the cooperation of the several owners of private water companies. Heater Well Drilling Company aided the investigation by making available its well log files for extraction of pertinent data.

Mr. Donald Williams of the Fayetteville office of the

N.C. Division of Health Services provided important information about well failures.

Our university colleagues, V.V. Cavaroc and H. Rooney Malcom, Jr., assisted with the statistical approaches and the surface hydrologic analyses, respectively. Stephen R. Gurley and John G. Scott of the Wake County Planning Department discussed with us various points as they related to land-use planning; part of the report was prepared by the junior author as a thesis presented in partial fulfillment of the requirements for the Master of Science degree in the Department of Marine, Earth and Atmospheric Sciences at North Carolina State University (Wilson, 1982).

METHODS

Source of Well Data

Well data for community water systems (CWS) in Wake County were collected during the period of May 1981 to January 1982 from the North Carolina Department of Human Resources, Division of Health Services, Environmental Health Section files. Supplementary data were obtained from CWS operators and owners. Most of the data was from wells constructed between 1960 and 1981. Each CWS was assigned an identification number, and the well locations were plotted on 7.5 minute topographic quadrangles.

The basic well data obtained from the state files include well depth, casing depth, static water level, well location, results of 24-hour pumping tests, drawdown, well yield in gallons per minute (gpm), drilling date, well location and driller. Casing depth was assumed to approximate saprolite thickness. From the basic data other well parameters were computed, such as specific capacity (yield ÷ drawdown) and elevation of static water level (elevation-SWL).

Well Hydraulics

The pumping test analyses are based on the theory of linear flow in fractured rocks as described by Jenkins and Prentice (1982). The theory states that in fractured rocks with negligible primary porosity the flow to a pumping well is linear along fractures rather than radial as in porous, granular media. A model study by Welby (1977) tends to support the theory. This study also suggested that water flowing in a fracture system does not always take the shortest route to the pumping well. The model experiments also confirmed the straight line relationship between drawdown and time where water was withdrawn from a more or less uniform set of fractures.

An infinite homogeneous, isotropic confined aquifer is assumed in the Jenkins and Prentice models. This contains a long, finite, vertical fracture of infinitesimal width, no storage capacity, and negligible resistance to flow. Time-dependent linear flow parallel to the fracture is controlled by the diffusion equation (Jenkins and Prentice, 1982)

$$\frac{\partial^2 s}{\partial x^2} = \frac{S}{T}\frac{\partial s}{\partial t}\,, \qquad (1)$$

subject to the following conditions,

$$\underset{0 \rightarrow \infty}{\text{limit}}\ s(x,t) = 0$$

$$-\ LT\,\frac{\partial s(0,t)}{\partial x} = Q/2$$

$$x \geq 0\ ,\ s(x,0) = 0$$

where

$s(x,t)$ = drawdown at a perpendicular distance x (ft) from the fracture at time t (min),
S = storage coefficient (dimensionless),
T = transmissivity (gal/min/ft),
Q = well discharge (gpm).

The boundary problem can be solved, and the results simplified (Jenkins and Prentice, 1982) to yield a more useful equation for the drawdown during pumping:

$$s(x,t) = \frac{Q}{2LT}\left[\sqrt{\frac{4T}{\pi S}}\sqrt{t} - x\right] . \quad (2)$$

Observation well data are not available for any of the CWS pumping tests. Therefore, drawdown at the pumping well (x = 0) is

$$s = \left[\frac{Q}{L\sqrt{TS\pi}}\right]\sqrt{t} \quad , \quad (3)$$

and the slope of a plot of s with respect to $\sqrt{t}$ is represented by the term in brackets. As the theoretical assumptions are approached, flow to the well becomes linear along a single fracture, and the data points plot as a straight line.

The pumping test data may be used to determine a fracture coefficient, $L\sqrt{TS}$:

$$L\sqrt{TS} = \frac{Q}{s}\sqrt{\frac{t}{\pi}} \quad . \quad (4)$$

The flow of water to a well in crystalline rocks is controlled largely by the characteristics of the fracture system. The fracture coefficient ($L\sqrt{TS}$) represents the effects of the fracture characteristics in terms of yield, drawdown, and pumping time. Values of the fracture coefficients provide an index to the size, density, and degree of inter-connection of the fracture system. Larger fracture coefficients correspond to better developed fracture systems.

A proper pumping test should be conducted at a constant pumping rate (Fetter, 1980). However, most of the 24-hour pumping tests conducted in Wake County for the community well systems involve variable pumping rates. Each of the steps in the step drawdown tests are of short duration and consequently less than satisfactory for estimating aquifer parameters. Use of a time-weighted average value of Q appeared reasonable in evaluating the pumping test data. Therefore, the value of Q used in equation (4) is the time-weighted average pumping rate over the period of drawdown, generally 24 hours, and is the value utilized in the statistical analysis of the well yields.

Fracture Analysis

In order to understand fracture patterns existing in the subsurface, a field study of fractures was undertaken. The dominant fracture orientations were determined by measuring the strike and dip of systematic joints at various field locations, identifying the major joint sets, and computing the mean orientation for each set.

Observations at quarry walls showed large variations of fracture spacing over short distances. It was concluded that measurements of fracture spacing at typically small outcrops would not necessarily be representative of the spacing at nearby well sites. Therefore, the field mapping of joints concentrated on "fracture density" in terms of the number of fracture sets rather than fracture spacing.

Statistical Analyses

Three statistical procedures were used in the study: chi square, multiple regression and F-test. Also simple statistics such as mean values were determined.

The chi square (χ^2) test may be used to determine the significance of differences between two or more independent groups of samples. The chi square analysis tests the null hypothesis that two or more groups (e.g., yield classes) do not differ with respect to some characteristic (i.e. lithology). The method of computing chi square from a contingency table is as follows:

$$\chi^2 = \sum_{i=i}^{r} \sum_{j=1}^{k} \frac{(O_{ij}-E_{ij})^2}{E_{ij}} \qquad (5)$$

where

O_{ij} = number of cases in ith row of jth column

E_{ij} = number of cases expected to be categorized in ith row of jth column

$$= \frac{(\text{Number of ith row cases})\ (\text{Number of jth column cases})}{\text{total number of cases}}$$

The larger χ^2 is, the more likely the groups (e.g., yield classes) are different with respect to a given characteristic (e.g., lithology). The significance of the computed χ^2 value may be determined by comparing it to tabulated chi square values.

A SAS procedure (Barr, et al., 1976) was used to perform chi square tests on yield classes and specific capacity classes against geologic variables. The test results were used to estimate which variables significantly affect yield and specific capacity.

Since well yield is a function of many hydrogeologic factors, a multiple regression analysis was used to infer the most significant variables affecting yield. However, if two wells have the same reported yield, and yet pumping of well A results in half the water level drawdown in well B, then well A is more "effective." Hence a comparison of the wells on the basis of yield alone can be misleading, and specific capacity (yield ÷ drawdown) was substituted for yield as the dependent variable in the analysis. The GLM procedure of SAS was used (Barr, et al., 1976).

A useful product of the multiple regression program is the coefficient of determination (R^2). The value of R^2 ranges from 0 to 1 and $100(R^2)$ represents a measure of the percentage of variation of the dependent variable which is accounted for by the linear regression model.

The F-test statistic of the multiple regression output provides the ability to test the adequacy of the linear model:

$$F = \frac{\text{Mean Square of Model}}{\text{Mean Square of Error}}$$

where Mean Square = Sum of Squared Residual ÷ Degrees of Freedom.

The computed F statistic is compared to tabulated values of F to test the level of significance of the model. The significance level is the percent probability that the observed variance is due to random error rather than the variables in the model.

Simple statistics (mean values, standard deviation) for the hydrogeologic variables were calculated by SAS (Barr, _et al._, 1976) procedures. In this study the data base consisted of 267 observations on 11 variables.

Probability of yield

A Log-Pearson-III distribution was used to compute probability of well yield by lithology and topography. In the crystalline rocks of the Piedmont province small values of well yield have a higher frequency of occurrence than large well yields, resulting in a positively skewed distribution curve. The Log-Pearson III distribution accounts for this skewness more completely and with less assumptions than other distributions. The calculations required for constructing the yield probability curves are summarized in Appendix I.

Low flow analysis of streams

During drought periods stream flow comes almost exclusively from ground water discharging from storage into the stream channel. Conceptually stream low flows during drought periods should provide an indication of the volume of ground water discharging from a drainage basin. As used in this context, low flow characteristics are measured by the probability of occurrence and duration of stream discharge which is sustained primarily by ground water runoff, or base flow. Low flow characteristics allow comparison of drainage basins by providing a standard measure of base flow.

An annual 7-day low flow is the lowest average discharge measured over a 7-day interval for a given water year. The 7-day low flow represents a conservative estimate of the ground water discharge to stream channels and is used to compare basins in this report. Low flow values measured over intervals of less than 7 days (1,3,5 days) are more representative of minimal ground water discharge and would result in an erroneously low estimate of ground water availability.

Likewise, intervals greater than 7 days (15,30,60,90 days) are likely to include discharge from surface runoff and would result in erroneously high estimates of ground water discharge (Riggs, 1972).

The 70 percent duration flow, or the flow equaled or exceeded 70 percent of the time, is estimated to be a reliable indication of base flow in Wake County (Floyd and Peace, 1974). It can also be used to evaluate relative ground water availability.

Values of the average 7-day, N-year low flow ($Q_{7,N}$) for ungaged streams were determined by the graphical correlation method (Yonts, 1971). Low-flow discharges have been measured sporadically at sites on ungaged streams and were obtained from annual water data reports published by the U.S. Geological Survey from North Carolina stream flow summaries by Thomas (1973) for the 32-year period from March 1949 to March, 1981. The low flows of each ungaged stream were plotted on logarithmic scales with concurrent discharges at a nearby continuous-record gaging station (index station). The line of best fit, or regression line, was calculated for the plotted points using the linear equation, $y = mx + b$. The line was used to determine the $Q_{7,N}$ for the ungaged stream given the $Q_{7,N}$ for the index station.

The discharge record for Middle Creek near Clayton, North Carolina, was selected as the most suitable index station for several reasons. 1) The period of record is long enough to include nearly all of the low flow measurements made at the ungaged streams; 2) the drainage area (80.7 mi^2) is similar to the drainage area of most of the ungaged streams; and 3) the drainage area lies almost entirely within Wake County. Daily discharge records from 1949 to 1981 at Middle Creek near Clayton were obtained from the HISARS system (Wiser, 1972).

A Log-Pearson-III distribution was used to compute the 7-day low flows for Middle Creek and for various recurrence intervals. Annual 7-day low flows were obtained from the HISARS system. The skewness coefficient of the distribution was calculated as

$$g = \frac{n^2 \Sigma \ln x^3 - 3n\Sigma \ln x \Sigma \ln x^2 + 2(\Sigma \ln x)^3}{n(n-1)\ (n-2)\sigma_{\ln}^{\ 3}} \qquad (6)$$

where g is the skewness coefficient, n is the period of record in years, x is the annual 7-day low flow in cfs, and $\sigma_{\ln}$ is the standard deviation of the values of ln x. The value of g was computed to be -1.8 which was used to enter Table C-2 (Appendix I) to find frequency factor values ($K_{p,g}$). The frequency factors are tabulated for events greater than the event of interest whereas low-flow frequencies express the recurrence interval of events less than the event of interest (Riggs, 1972). The tabulated recurrence intervals were converted to corresponding recurrence intervals for events less than the event of interest. From $K_{p,g}$ for a given recurrence interval the associated flow was determined by

$$\ln x = \ln x + (K_p,g)\sigma_{\ln} \text{ and } e^{\ln x} = \text{low flow (cfs)}.$$

The low flow frequency curve for Middle Creek was plotted on log probability paper (Appendix II). Flows corresponding to recurrence intervals of 1,2,5,10,20,50 and 100 years were used to determine the $Q_{7,N}$ values at ungaged streams by the graphical correlation method described above (Appendix II).

Flow duration data for Middle Creek were also obtained through the HISARS system, and a flow duration curve was plotted (Appendix II). Flow duration is expressed as percent of time that a discharge is equaled or exceeded during the period of record. Flows corresponding to the 1,10,30,50,60, 70,80,90,95 and 99 percent durations were used to determine flow durations at ungaged streams by graphical correlation (Appendix II). The pattern of $Q_{7,10}$ flows is illustrated in Plate 2.

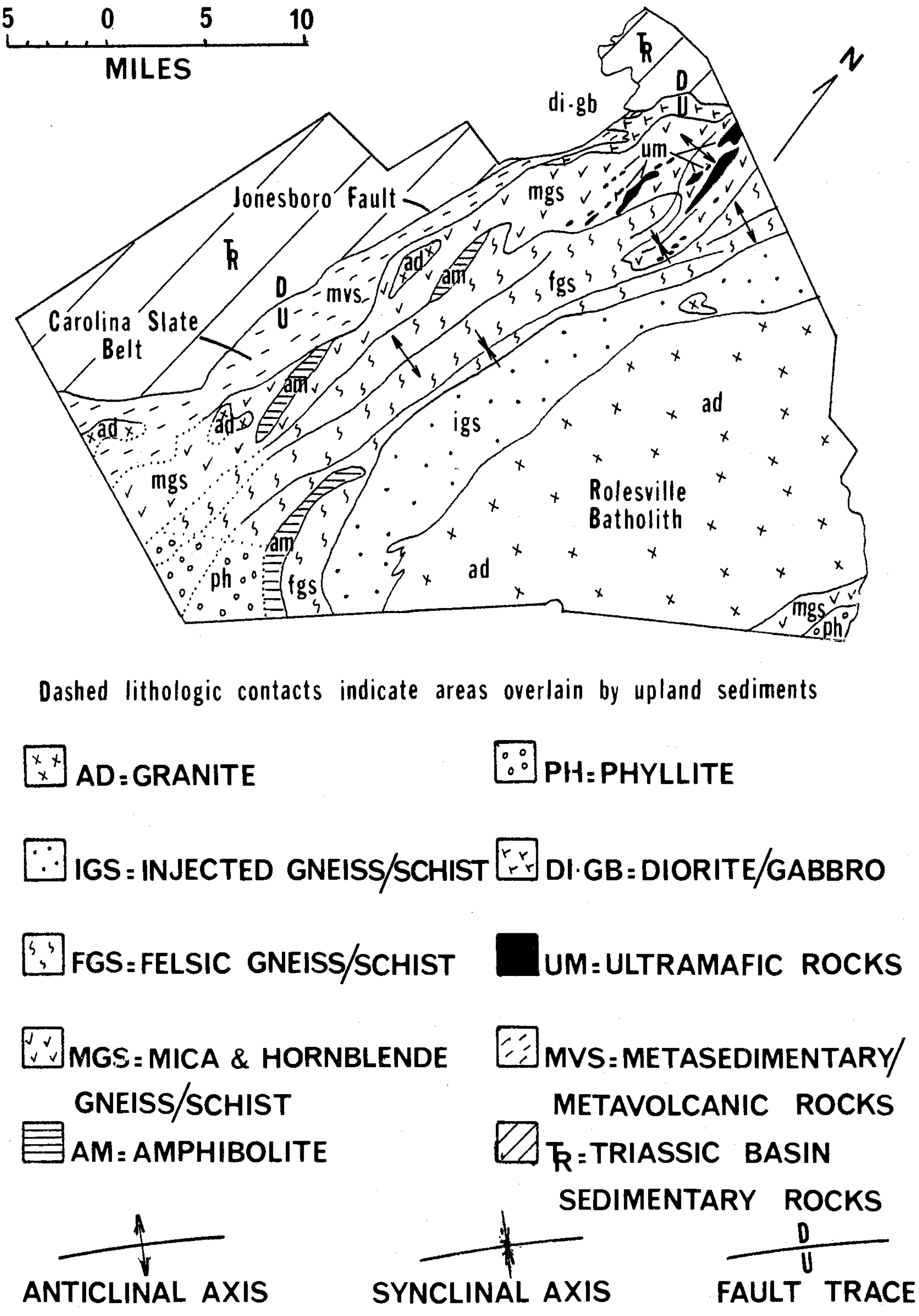
Recharge

It may be assumed for the 32-year period of record that ground water discharge through base flow approximately equals ground water recharge. Thus, ground water recharge may be derived indirectly from base flow characteristics of streams. The annual 7-day low flow ($Q_{7,1}$) represents a minimum annual recharge to a basin over a period. Based on the $Q_{7,1}$ values computed for low flow stations in the county, recharge volumes were determined for each station and expressed as a percentage of average annual precipitation (Plate 3).

HYDROGEOLOGIC SETTING

Lithology

Nine major crystalline rock types (Fig. 1) ranging from late Precambrian to middle Paleozoic in age occur in Wake County (Parker, 1979). Four of these units, the injected gneiss and schist (igs), the felsic gneiss and schist (fgs), the mica and hornblende gneiss and schist (mgs), and the granite (ad), underlie approximately two-thirds of the crystalline rock area in the county. A majority of the CWS wells studied were drilled into one or another of these rock types. Other crystalline rocks which are less extensive



Dashed lithologic contacts indicate areas overlain by upland sediments

FIG 1-GEOLOGY OF WAKE CO., NC (from Parker, 1979) areally are amphibolite, phyllite, diabase dikes ultramafic rocks, diorite-gabbro, and the metavolcanic/metasedimentary units of the Carolina Slate Belt. Although these lithologies contain only a small number of the wells studied, they serve as aquifers for private wells, and play a role in the overall hydrology of a given drainage basin.

The sedimentary rocks found in the county form three groups: the Triassic rocks in the Durham Basin (T_R), shown in Fig. 1, as well as the partly cemented, Cretaceous to Miocene upland sediments (up), and the Recent alluvial deposits. The Durham Basin lies west of the Jonesboro fault in western Wake County and contains conglomerate, sandstone, mudstone and limestone. The hydrogeology of these rocks was not studied in this investigation but is generally characterized by low permeabilities and low well yields associated with high clay contents and poor sorting (May and Thomas, 1968; Godfrey, 1978; Parker, 1979).

The upland sediments unconformably overlie the crystalline rocks in places and appear to be hydraulically similar to the Triassic sediments. These fluvial deposits (Parker, 1979) consist of poorly sorted mixtures of gravel, sand and clay. The thickness in places is 25-30 feet but is more commonly 15 feet or less.

Modern floodplain sediments and valley terrace deposits comprise the alluvium unit. Their thickness ranges from a few feet to 20 feet (Parker, 1979). The poorly sorted deposits are comprised of channel sands, floodplain sandy silts, and lacustrine and swamp sediments. The alluvial deposits are discontinuous and are more common in the Neuse River Valley and its larger tributaries than in the smaller streams.

Structure

Foliation of metamorphic rocks provides planes of weakness possibly favoring joint and fracture development, and it provides paths for ground water flow. In Wake County the northward-trending strike of the foliation parallels the orientation of five major fold axes which are located in a belt between the Rolesville batholith and the Jonesboro fault (Fig. 1). The foliation is nearly vertical in the eastern one-half of this belt. In the western portion of the felsic gneiss belt the Raleigh anticline appears as an asymetrical fold with low dips on the western flank. Foliation on the eastern flank is essentially vertical (Parker, 1979).

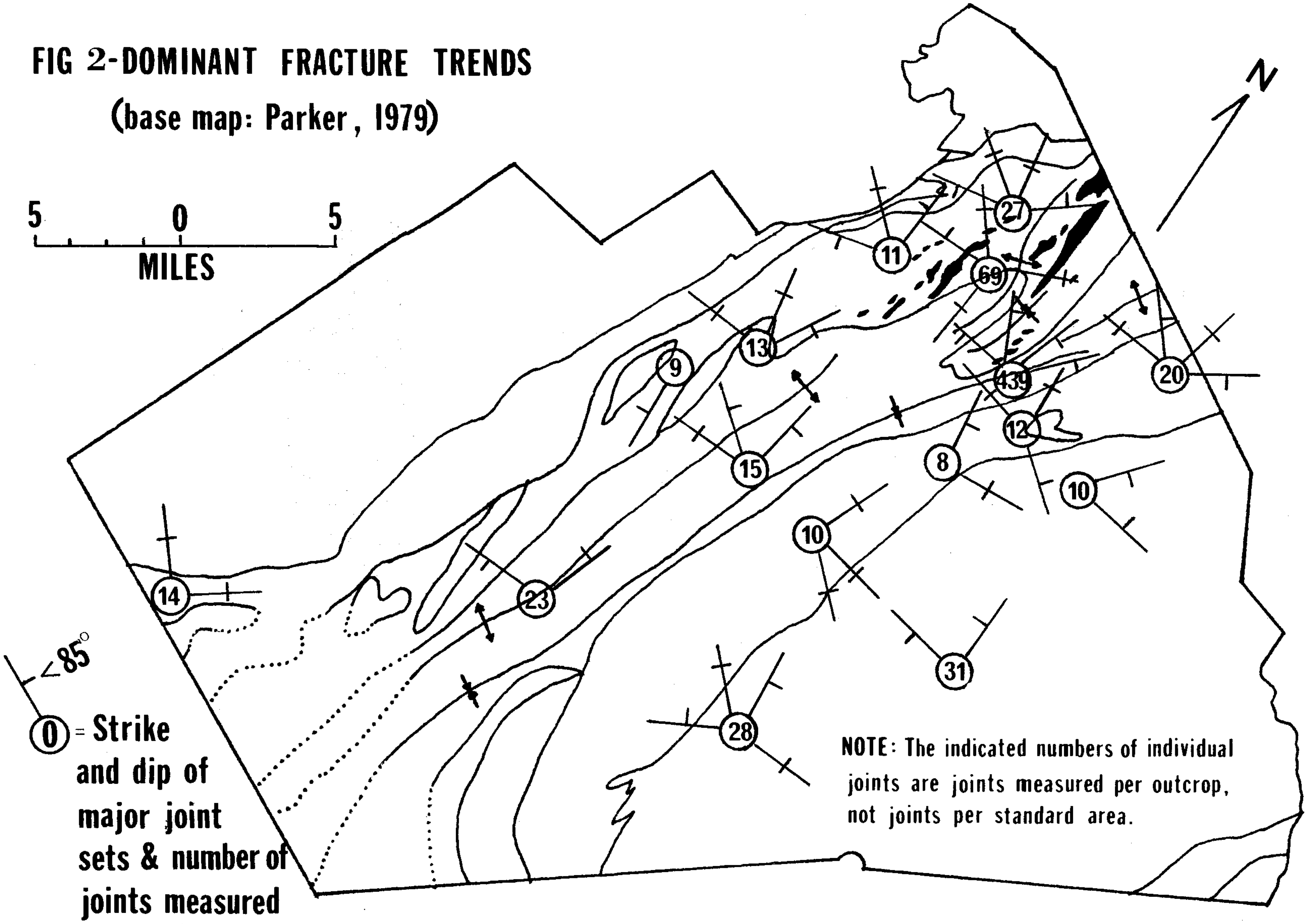
A major structural feature in the county is the Jonesboro Fault, which separates the fractured crystalline rocks from the sedimentary rocks of the Durham Basin. None of the wells studied are located near enough to the fault for any boundary effects to be imparted by the fault plane. Low angle reverse faults and high angle faults have been observed in the crystalline rocks, but their displacements are too small to be shown on a geologic map. Small faults intersecting well bores may provide pathways for ground water movement, but it is not known if any of the wells studied intersect such minor faults.

Generally, the joint systems are characterized by (1) a set which parallels foliation, (2) one or more other sets which are steeply dipping to vertical, at an angle to the foliation direction, and (3) a shallow, near-horizontal set apparently related to unloading and weathering (Marine, 1966).

The dominant joint trends for selected outcrop locations (Fig. 2) are consistent with theoretical orientation of joint sets relative to folds (Fig. 3). A comparison of joint trends to the orientation of a nearby fold axis showed one set parallel and another set perpendicular to the axis. These master joint sets are classified as extension joints (Price, 1966). One or two other sets may also develop which intersect the fold axis at an oblique angle and are classified as shear joints.

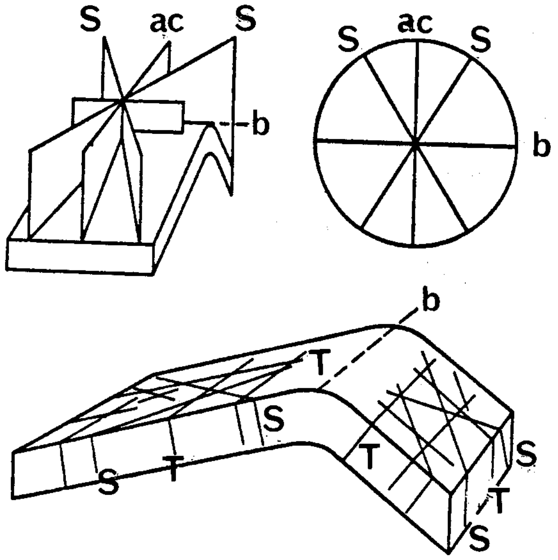
Figure 2 also illustrates the relationship between structure and the number of joint sets. The greatest number of joint sets is associated with an area having the highest density of fold axes. Four major fold axes occur in the Wake Forest-Millbrook-Bayleaf area. Outcrops within this area

FIG 2-DOMINANT FRACTURE TRENDS
(base map: Parker, 1979)



= Strike and dip of major joint sets & number of joints measured

NOTE: The indicated numbers of individual joints are joints measured per outcrop, not joints per standard area.



S=SHEAR JOINT
T=EXTENSION JOINT
b=FOLD AXIS
ac=NORMAL TO AXIS

FIG 3–TYPICAL RELATIONSHIP OF MASTER JOINTS TO AN ANTICLINE (after PRICE, 1966) commonly exhibit four or five systematic joint sets. Figure 4 illustrates typical joint patterns at selected localities in Wake County.

Ground Water Hydrology

In the crystalline rocks of the Piedmont province a two-media system forms the ground water model. The porous, granular saprolite and the fractured bedrock serve as two distinct aquifers which are hydraulically, if unpredictably, connected.

The clayey sand to sandy clay nature of the saprolite coincides with low matrix permeabilities on the order of 10^{-3} to 10^{-5} cm/sec (Welby, 1981). Cracks, burrows, root holes, and quartz seams allow water to percolate more rapidly in places, and thin clay layers may reduce permeability of the saprolite. The fractures in the bedrock are characterized by relatively higher permeabilities, and most wells are developed in the fractured bedrock to obtain larger yields than are generally achieved from the saprolite.

The saprolite layer serves as a water storage unit for the fractures which transmit ground water to the well bore (Figs. 5A and 5B). The number and configuration of the fractures supplying ground water to a well is generally difficult, if not impossible, to determine without special geophysical equipment. The fracture system is a function of

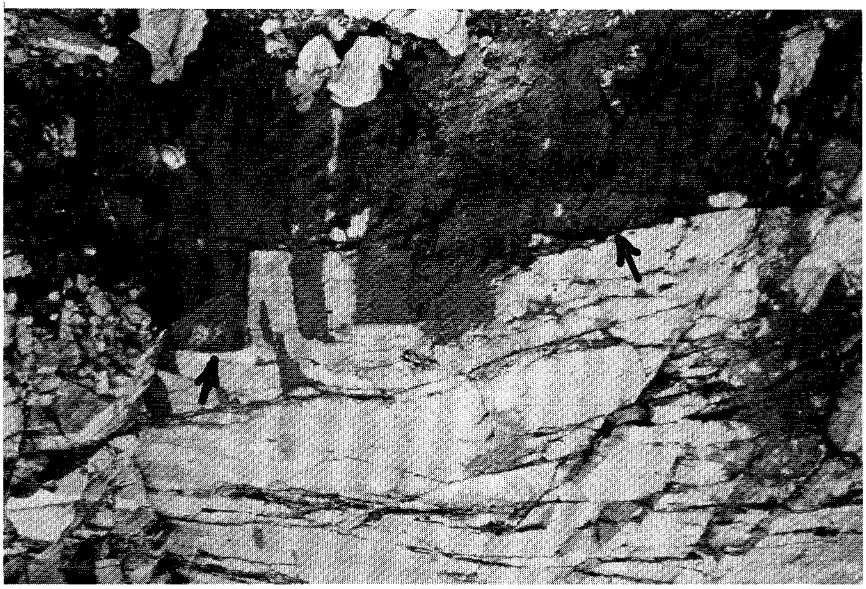


Figure 4A. Water seeping from joints in granite at Martin Marietta Quarry, Garner, N.C.

Figure 4B. Outcrop at Falls Reservoir spillway showing typical joint sets.

Figure 4C North wall of Falls Reservoir spillway showing traces of three major joints.

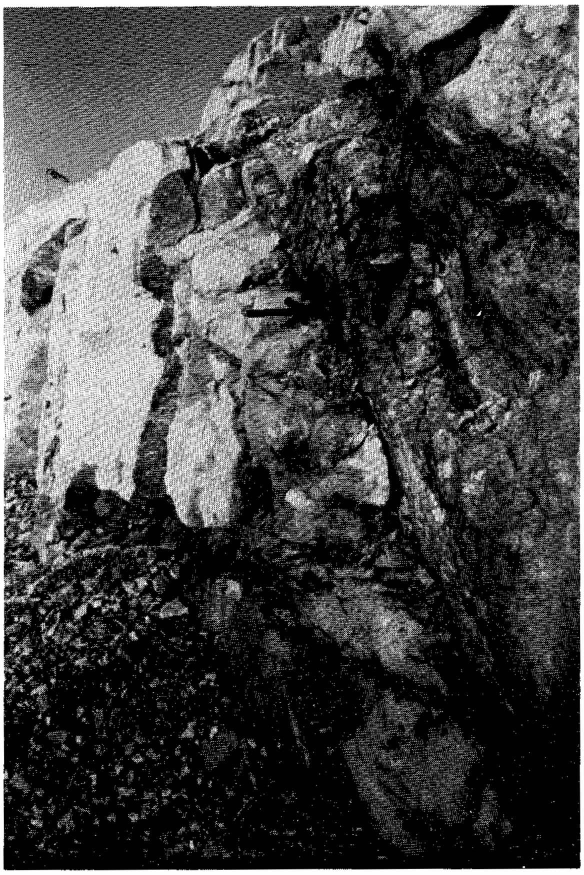


Figure 4D. Close-up of a major water-bearing joint at spillway, Falls Reservoir. Note weathered zone (darker rock) formed by ground water flowing along the joint.

FIG 5A - Hydraulic Characteristics of the Piedmont and Mountain Ground-Water System

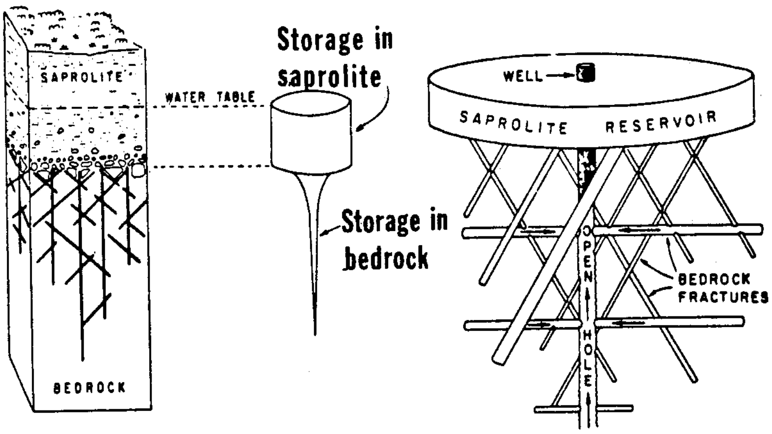
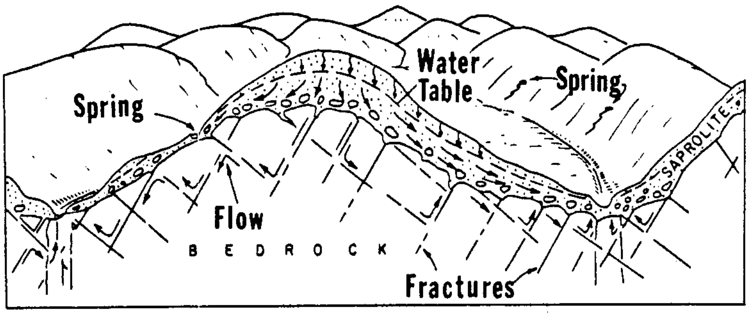


FIG 5B - Ground-Water Situation in the Piedmont and Mountains



from Heath, 1980

Figure 5. Ground Water Occurrences

rock type, depth and deformational history, and in general it can be anticipated that fracture size and frequency will decrease with depth. Moreover, exposures in quarries and excavations in Wake County show that the nature of the fractures can change even over short lateral distances and that not all well-developed fractures transmit ground water. In some areas of the county the geohydrology of the rocks may be that of a multiple aquifer system in which there is no conection between two or more sets of fractures or joints. Carlson and Olsson (1979) have described such systems in the crystalline rocks of Sweden.

Drainage Analysis

Application of geologic understanding to exploration for ground water supplies in crystalline rocks focuses on techniques required to identify potential water-bearing fractures. In the present investigation the supposition was made and tested that the drainage pattern shown by the streams of Wake County reflect in some general fashion the fracture patterns in the rocks and that lineaments and linears[1] consisting of alignments of stream segments through several small drainage basins could be identified from the

---

[1] Lineament = linear feature greater than 1 mile in length.
Linear = linear feature less than 1 mile in length.
In this report lineament analyses is a collective term summarizing analytical study of lineaments and linears.

1:24,000 scale U.S. Geological Survey topographic quadrangle maps.

The positions of the CWS wells *vis-a-vis* the linear features were determined as were the direction of the linears. Stream segment orientations within selected drainage basins were determined and plotted. Orientations of the joints determined from the field investigations, and the orientations of the stream segments were compared.

RESULTS

Factors Affecting Yields

Many hydrogeologic variables affect the probability that a given unit volume of water will infiltrate the soil, percolate through the saprolite to seep into fractures in the bedrock, and thence flow to a water well. Many of these factors are similar for various parts of the county. However, anticipated differences in response of the bedrock to various tectonic forces through geologic time suggest that ground water yields can be related to rock type. Expression of the differences in yield can be expressed in terms of probabilities of obtaining a given yield from an individual well drilled randomly in each of the rock types. Figure 6 presents the probability curves generated from the CWS well data.

The highest average yield (45 gpm) occurs in wells located in the injected gneiss and schist (igs). The lowest average yield (21 gpm) is for wells located in the mica gneiss and schist (mgs). The average values for the wells in granite (ad = 27.5 gpm) and in felsic gneiss and schist (fgs = 33 gpm) are intermediate and similar in value.

May and Thomas' (1968) study of the yields of 286 wells in Wake County by rock type found the following averages: metavolcanic unit, 27 gpm; granite, 20 gpm and mica gneiss,

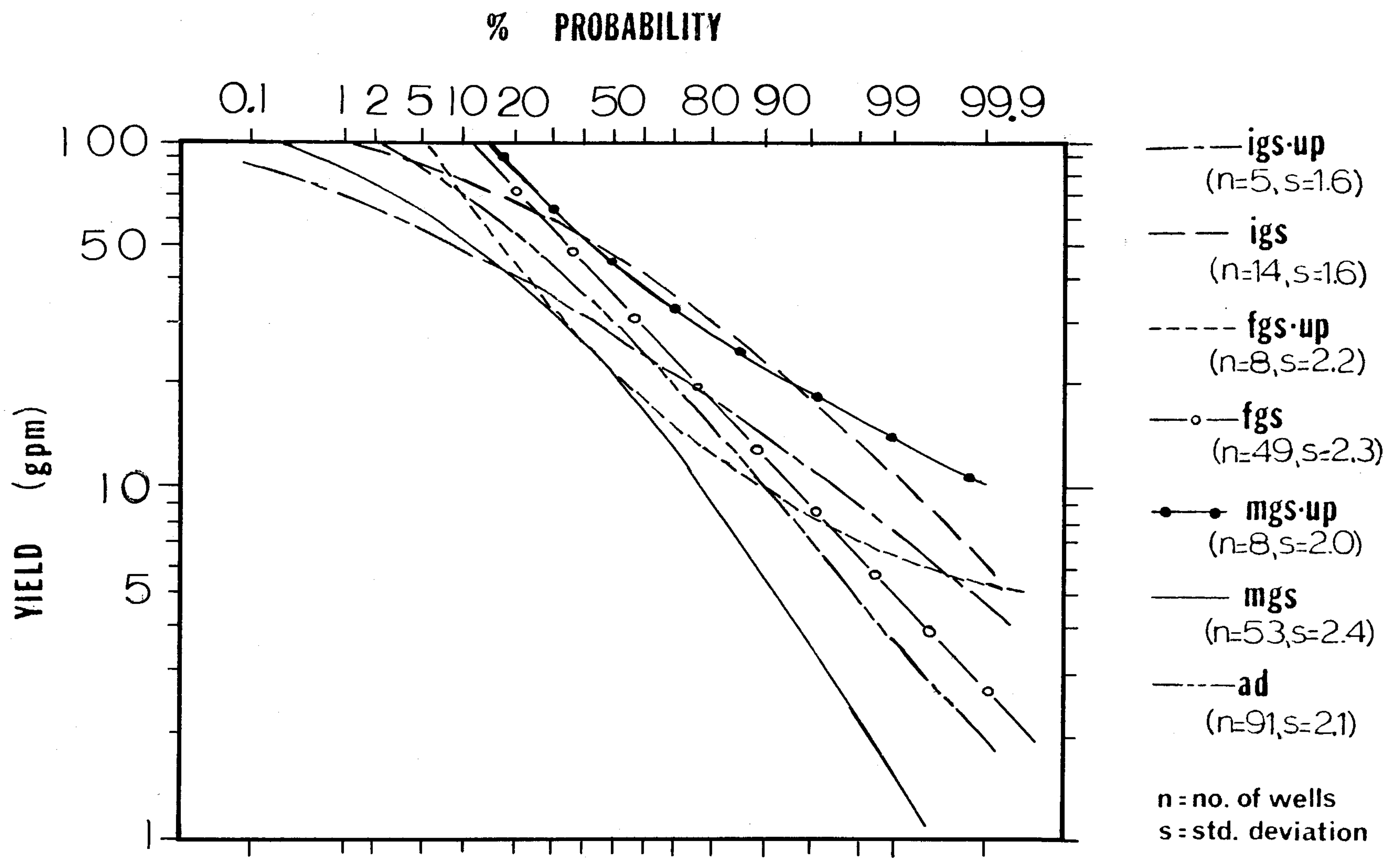


FIG. 6-YIELD PROBABILITY BY LITHOLOGY

19 gpm. The "mica gneiss" referred to by May and Thomas includes several lithologies differentiated in this study (mgs, fgs, igs). In every case the average yield by lithology determined in this study is greater than the average yield computed for the equivalent lithology in the earlier study.

Most of the wells studied by May and Thomas were private domestic wells. The quantity of water required for domestic consumption in a single household is relatively small, and frequently a one to two gallon per minute well will suffice if drilled to a sufficient depth. Consequently, the yields required of domestic wells are relatively low, and the average yields of domestic wells underestimate the general water-bearing and water-yielding capability of the aquifer. The reported average yields of CWS wells (which serve at least 10 households) are considered to be more representative of potential well yields because each well must supply greater volumes of water than is required for private domestic wells.

The position of the curves at the 10 percent probability level illustrates which lithologies are likely to produce high well yields. For example, there is a 10 percent probability that a mgs well will produce 50 gpm, but there is an equal probability that a fgs well will yield nearly 100 gpm. Although igs wells have the highest average yield, the probability of obtaining yields greater than 62 gpm is higher for an fgs well than for wells drilled in the other rock types.

Lower yields are expected in areas where poorly sorted, low permeability upland sediments (up) overlie crystalline rock. This effect is true in areas where upland sediments overlie fgs and igs but not where mgs is mantled by upland sediments (Fig. 6). Wells drilled at eight sites where the mica gneiss and schist is mantled by upland sediments consistently produce significantly higher yields than unmantled mgs sites. The explanation for this relationship is not immediately clear, but it may lie in other variables associated with the mgs lithology.

In Wake County topographic setting does not appear to influence well yield as strongly as lithology. Wells drilled in valleys or on slopes have higher mean yields than wells drilled on hilltops or upland flats, although the difference in the mean yields is not great (Fig. 7). The mean yield of CWS wells located in valleys is 36.5 ± 2.0 gpm compared to a mean yield of 29 ± 2.2 gpm for CWS wells sited on hilltops.

Simple statistics for the hydrogeologic variables are listed in Table 1 by lithologic classes. The mean values were computed by a SAS procedure which assumes a normal distribution. Consequently, SAS-computed mean yields differ from those shown on the yield probability curves (Figs. 6

and 7) by 4 to 10 gpm. The mean yield values from Fig. 6 are also given in Table 1.

The _igs_ wells exhibit the relatively highest mean specific capacity (0.90 gpm/ft) of all CWS wells, and all wells in this rock type have a relatively high mean yield. In comparison the _fgs_ wells have a similar high mean yield but possess the lowest mean specific capacity (0.61 gpm/ft). The relatively low mean yield of the _ad_ is accompanied by a relatively high mean specific capacity (0.88 gpm/ft).

Proximity of wells to topographic linear features (which may be surface expressions of subsurface fracture zones) is represented by the "distance" variable. The mean distance of the high mean-yield _igs_ wells from the nearest draw (405') is greater than for any other lithology. The low mean-yield _mgs_ wells are closer to draws than wells drilled in other lithologies (Table 1). On the otherhand, most of the high yield wells within each lithology are located in draws.

The relative influence of rock type and topography upon the probability of a given yield at a specific site is difficult to judge. However, for purposes of illustration assume that rock type and associated geologic factors influence the result by two-thirds and topographic position by one-third. Then the overall probability for a given yield based upon rock type and topography can be estimated by the sum of probabilities weighted one-third for topography and

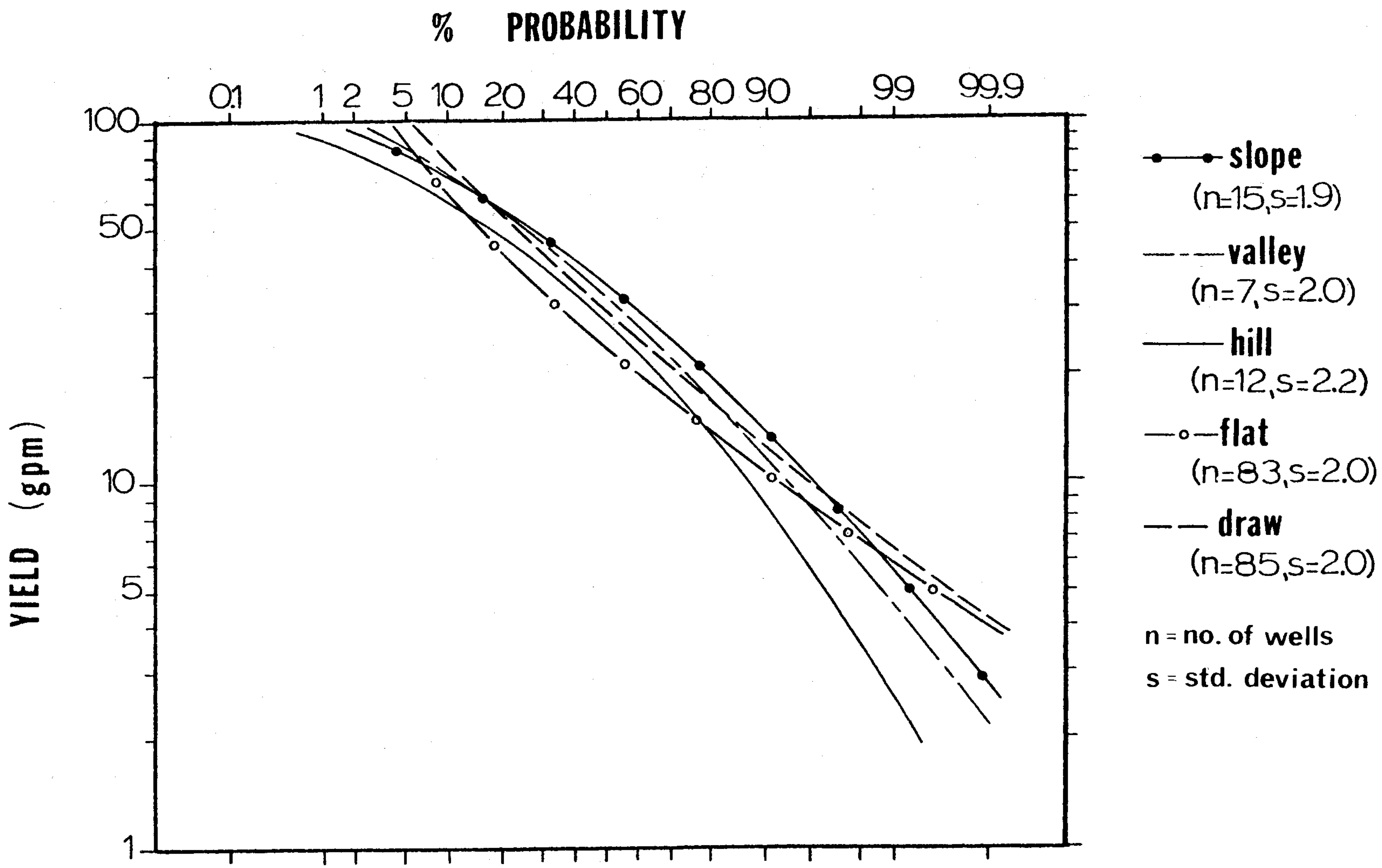


FIG. 7-YIELD PROBABILITY BY TOPOGRAPHY

Table 1

SIMPLE STATISTICS OF CWS WELLS BY LITHOLOGY

VARIABLE	N	MEAN[1]	STD DEV	MINIMUM	MAXIMUM
LITHOLOGY = AD					
YLD	91	34.1(30)	25.5	3.0	144.0
SAPRO	68	44.9	20.3	10.0	101.0
DEPTH	85	206.8	101.0	43.0	500.0
SWL	72	17.1	8.1	0.0	35.0
ELEV	74	285.1	57.7	190.0	435.0
DIST	76	333.7	293.6	1.0	1485.0
TOPOPT	79	8.5	3.9	2.0	18.0
DDN	62	115.3	75.5	3.0	292.0
FRACOF	48	52.9	92.1	2.1	568.8
SPECAP	62	0.9	1.7	.024	9.3
LITHOLOGY = FGS					
YLD	57	43.7(35)	36.7	5.0	150.0
SAPRO	42	62.2	30.1	18.0	147.0
DEPTH	55	261.4	102.9	85.0	485.0
SWL	34	21.9	11.6	3.0	45.0
ELEV	53	383.9	44.2	305.0	480.0
DIST	50	245.2	252.3	10.0	1320.0
TOPOPT	48	8.9	6.7	4.0	17.0
DDN	35	178.4	89.1	10.0	370.0
FRACOF	29	37.4	53.8	0.9	240.5
SPECAP	35	0.6	1.2	.02	6.5

---

[1] Values in parentheses represent mean values from Fig. 6.

Table 1 (continued)

VARIABLE	N	MEAN	STD DEV	MINIMUM	MAXIMUM
LITHOLOGY = MGS					
YLD	62	28.3(22)	25.5	0.0	150.0
SAPRO	44	62.2	30.8	18.0	125.0
DEPTH	60	302.7	115.8	80.0	606.0
SWL	39	16.3	12.7	2.0	30.0
ELEV	45	428.0	49.3	280.0	525.0
DIST	47	209.1	152.2	10.0	640.0
TOPOPT	46	9.5	6.0	2.0	18.0
DDN	46	172.9	15.6	2.0	522.0
FRACOF	34	17.6	31.5	1.2	170.4
SPECAP	43	0.7	1.9	.022	10.0
LITHOLOGY = IGS					
YLD	19	41.5(48)	18.7	15.0	75.0
SAPRO	16	54.3	21.6	21.0	102.0
DEPTH	19	179.2	93.4	43.0	425.0
SWL	13	24.3	19.0	0.0	80.0
ELEV	18	296.4	50.0	205.0	400.0
DIST	16	405.0	268.0	40.0	840.0
TOPOPT	18	10.0	4.8	2.0	18.0
DDN	9	107.8	112.9	2.0	365.0
FRACOF	6	147.6(27.5)[2]	294.8	5.8	747.7
SPECAP	9	4.1(0.90)	9.7	0.2	30.0

---

[2]. Excludes maximum value.

Table 1 (continued)

VARIABLE	N	MEAN	STD DEV	MINIMUM	MAXIMUM
ALL LITHOLOGIES					
YLD	267	34.5(33.8)	28.3	0.0	150.0
SAPRO	196	56.0	30.4	10.0	200.0
DEPTH	254	245.3	117.8	39.0	606.0
SWL	180	18.8	11.5	0.0	80.0
ELEV	199	350.2	79.3	190.0	525.0
DIST	196	298.2	272.3	1.0	1480.0
TOPOPT	198	9.0	4.2	2.0	18.0
DDN	174	144.9	96.4	2.0	522.0
FRACOF	133	40.7	89.5	0.9	747.7
SPECAP	174	0.9	2.7	.009	30.0

YLD = Well Yield (GPM)
SAPRO = Saprolite Thickness (FT)
DEPTH = Well Depth (FT)
SWL = Static Water Level (FT)
ELEV = Well Site Elevation (MSL)
DIST = Distance of Well from Nearest Draw (FT)
TOPOPT = LeGrand's Point Value for Topography
DDN = Pump Test Drawdown (FT)
FRACOF = Fracture Coefficient ($FT^2/DAY^{1/2}$)
SPECAP = Specific Capacity (GPM/FT)

two-thirds for rock type. For the four major rock types the probabilities for well yields of 58 gpm or greater is given in Table 2. Results of both the one-third/two-thirds assumption and an assumption of 50 percent each for topography and rock type are presented.

The results of the calculations summarized in Table 2 indicate that for the higher yield wells, at least, topographic position is less important than the factors reflected in rock type. The significant differences lie more in the differences between the yields from wells drilled in the igs and fgs lithologies and those drilled in the mgs and ad lithologies. Intuitively, it seems that the topography should exert an influence of no greater than about one-third of the total probability.

Under both assumptions wells located in draws, valleys, and on slopes have about the same probability for providing yields greater than 58 gpm. On the other hand, most of the high yield wells from the CWS population are located in draws, a fact which may reflect the influence of the probabilities and a predisposition on the part of water well drillers to place wells in this topographic position.

The resistant granitic rock (ad) has the lowest mean saprolite thickness (45 ft), and the greatest mean saprolite thickness (63 ft) occurs in the fgs and mgs outcrop areas.

Table 2

ESTIMATED PROBABILITY OF YIELDS AT 58 GPM OR GREATER, FOR ROCK TYPE INFLUENCE = 2/3, TOPOGRAPHY = 1/3

A.

Rock Type	Fig. 6 %	% from Fig. 7	TOPOGRAPHIC POSITION FLAT (11%)	DRAW (18%)	HILL (10%)	VALLEY (18%)	SLOPE (18%)
igs	28		22	25	22	25	25
fgs	26		21	23	21	23	23
mgs	6		8	10	7	10	10
ad	14		13	15	13	15	15

50 PERCENT EFFECT EACH FOR ROCK TYPE AND TOPOGRAPHIC-POSITION

B.

Rock Type	FLAT	DRAW	HILL	VALLEY	SLOPE
igs	20	23	19	23	23
fgs	19	22	18	22	22
mgs	9	12	8	12	12
ad	13	16	12	16	16

The greatest mean depth (303 ft) of wells is associated with the mgs lithology which has the lowest mean yield. Likewise, the igs wells have the highest mean yield and the lowest mean depth (179 ft) value.

A negative correlation exists between well depth and well yield. For the CWS wells the yield-per-foot increases rapidly above a depth of approximately 250 feet (Fig. 8). Below that depth the frequency of water-bearing fractures apparently diminishes rapidly, and the yield-per-foot values approach zero. Similar findings have resulted from other studies of optimum well depths in fractured crystalline rock aquifers (Davis and Turk, 1964; Summers, 1972). Thus in Wake County drilling below a depth of about 250 feet is less likely to increase total yield and to be less cost-effective than drilling a new well.

Drainage Orientation

Plots of the stream segment orientations are presented in Fig. 9 and those of the joints in Fig. 10 in the form of frequency diagrams with 20-degree classes. Table 3 lists the geographic centers of the drainage basins used in the study. The plots were prepared to investigate whether or not some lithologic control on stream segment orientation exists and whether or not the stream segment orientation patterns reflect joint orientation noted in the field.

FIG.8 -RELATION OF YIELD PER FOOT OF WELL DEPTH TO WELL DEPTH

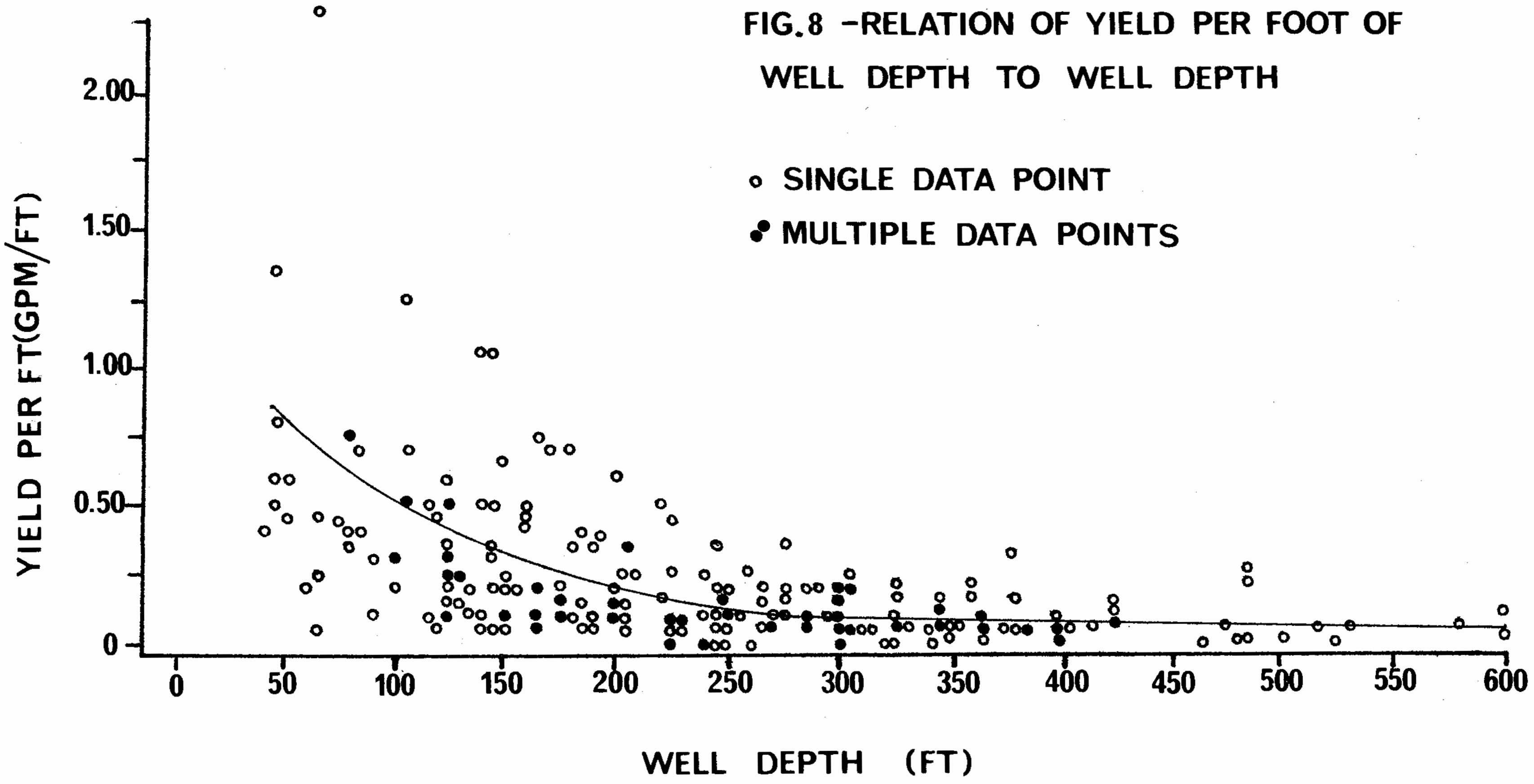
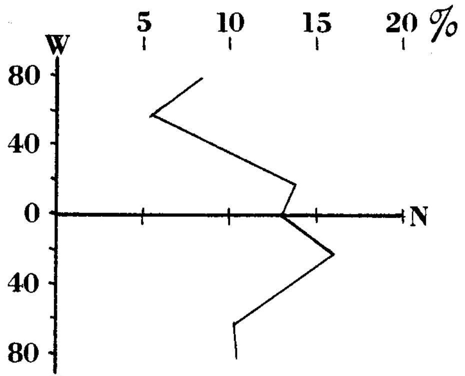


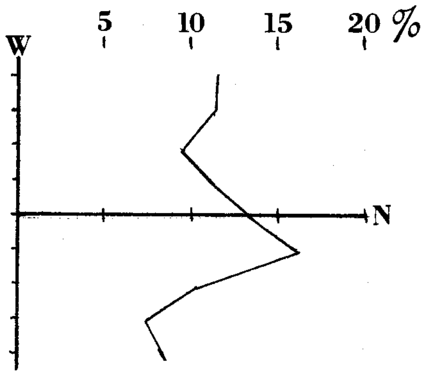
Table 3

WAKE COUNTY DRAINAGE BASIN LOCATIONS

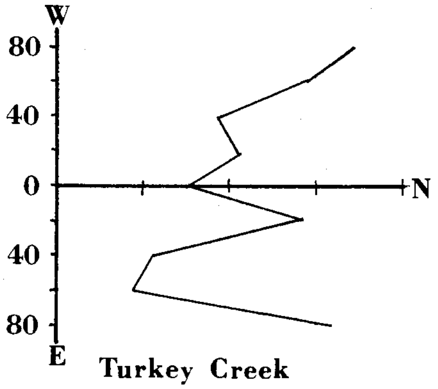
DRAINAGE BASIN	DOMINANT ROCK TYPE	USGS QUADRANGLE	CENTER OF MEASURED BASIN	
			LATITUDE	LONGITUDE
Upper Barton Cr.	mgs	Bayleaf	35° 58'	78° 41'
Hare Snipe Cr.	fgs	Bayleaf	35° 54'	78° 42'
Turkey Cr.	fgs & am	Bayleaf	35° 53'	78° 44'
Mud Cr/Horse Cr.	fgs	Wake Forest	35° 59'	78° 34'
Richland Cr.	fgs	Raleigh West	35° 49'	78° 44'
New Light Cr.	mgs	Grissom	36° 02'	78° 36'
Richland Cr.	igs	Wake Forest	35° 58'	78° 34'
Smith Cr.	ad & igs	Wake Forest	35° 56'	78° 31'
Big Br.	ad	Garner	35° 43'	78° 33'
Poplar Cr.	ad	Knightdale	35° 46'	78° 28'
Honeycutt Cr.	fgs & mgs	Wake Forest	35° 56'	78° 36'
Lower Barton Cr.	mgs	Bayleaf	35° 56'	78° 40'



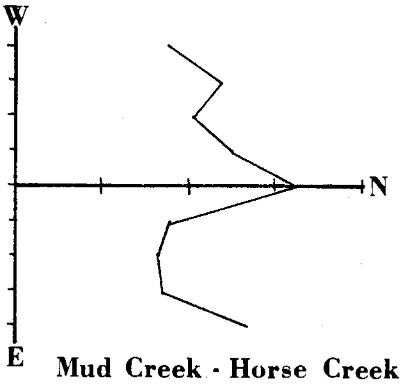
Upper Barton Creek
MGS



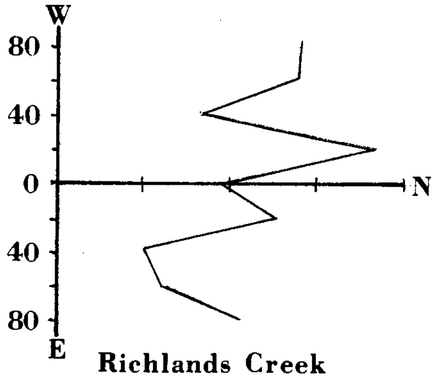
Hare Snipe Creek
FGS



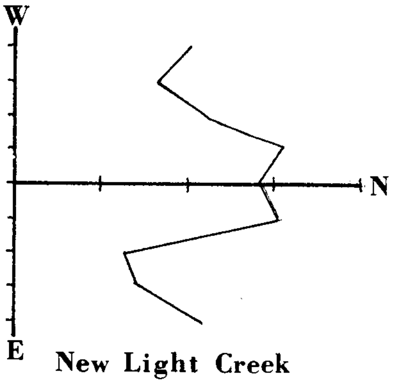
Turkey Creek
FGS & AM



Mud Creek - Horse Creek
FGS

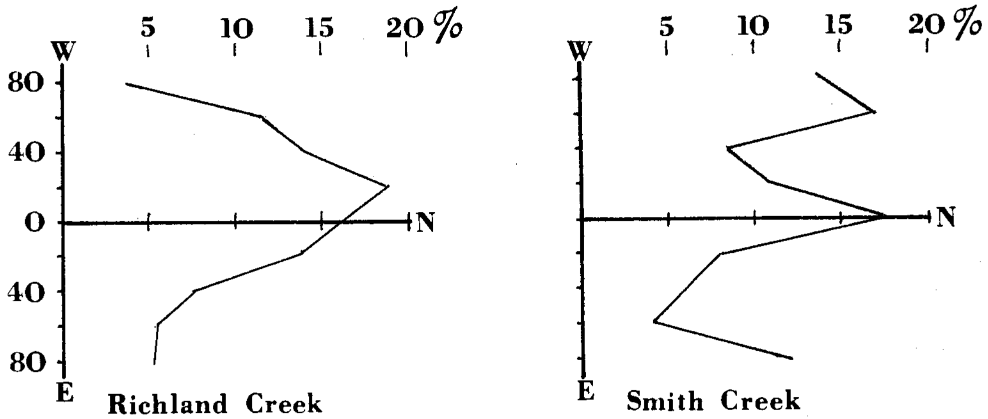


Richlands Creek
FGS



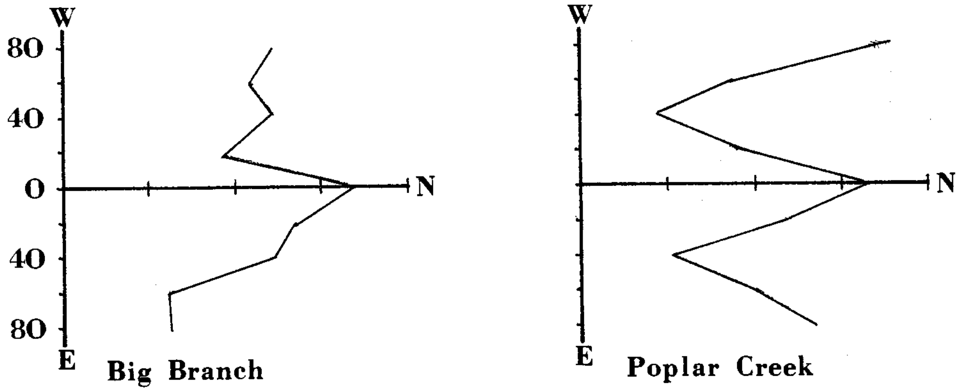
New Light Creek
MGS

Fig. 9 -Stream Segment Orientations



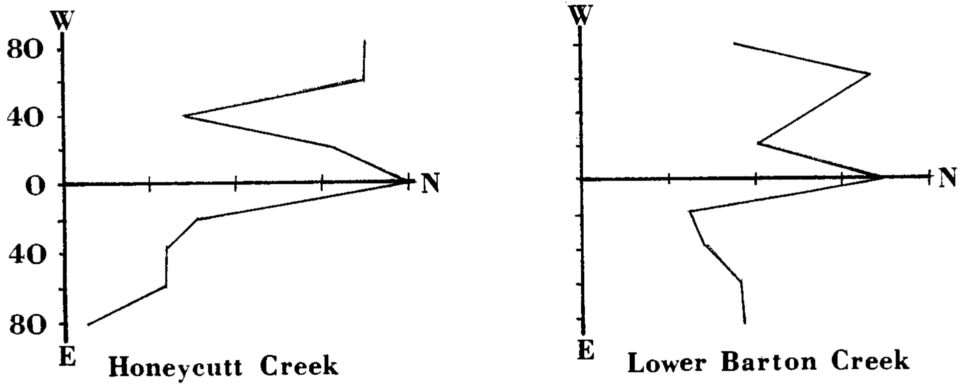
Richland Creek
IGS

Smith Creek
AD & IGS



Big Branch
AD

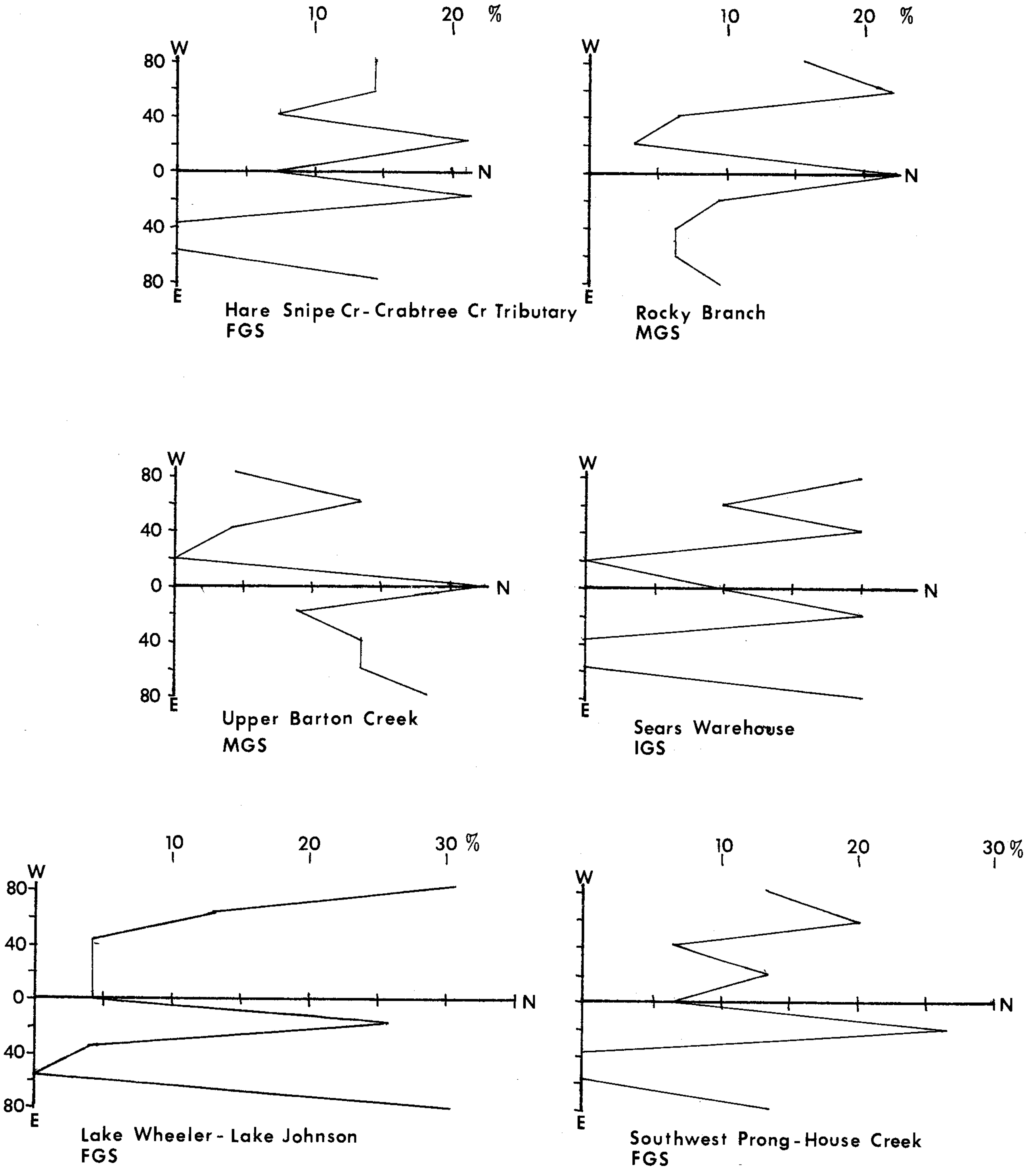
Poplar Creek
AD



Honeycutt Creek
FGS & MGS

Lower Barton Creek
MGS

Fig. 9 (cont)-Stream Segment Orientations



Hare Snipe Cr-Crabtree Cr Tributary
FGS

Rocky Branch
MGS

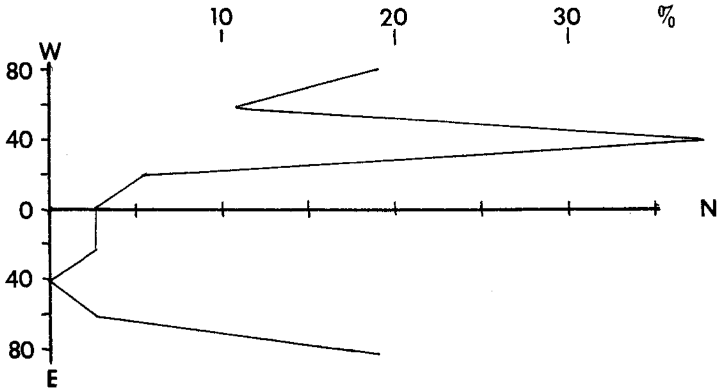
Upper Barton Creek
MGS

Sears Warehouse
IGS

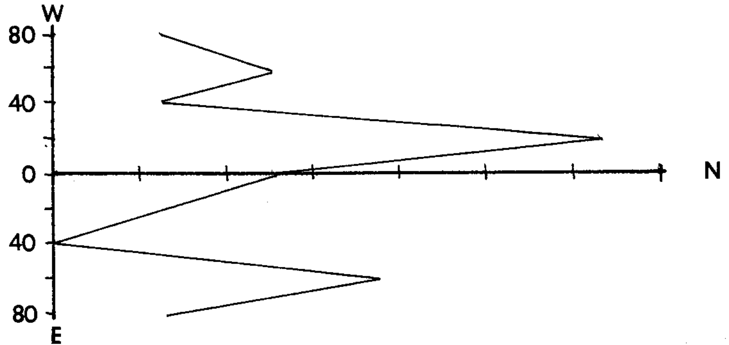
Lake Wheeler-Lake Johnson
FGS

Southwest Prong-House Creek
FGS

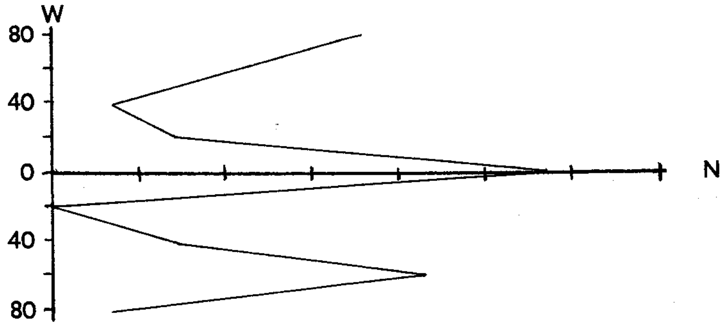
Fig.10 - Joint Orientations



Lower Barton Creek
MGS

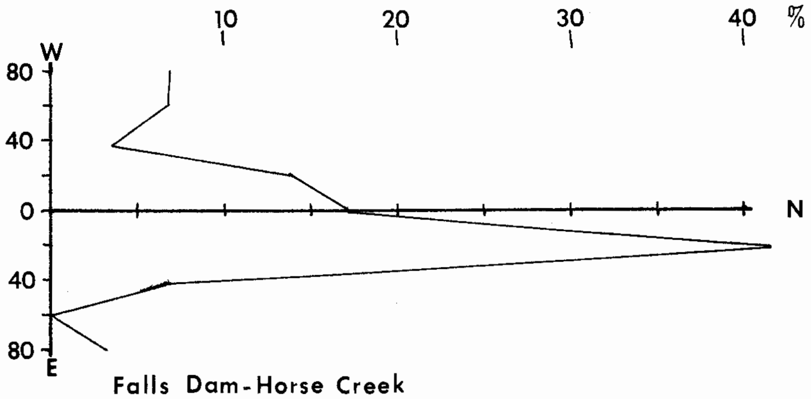


New Light Creek
MGS

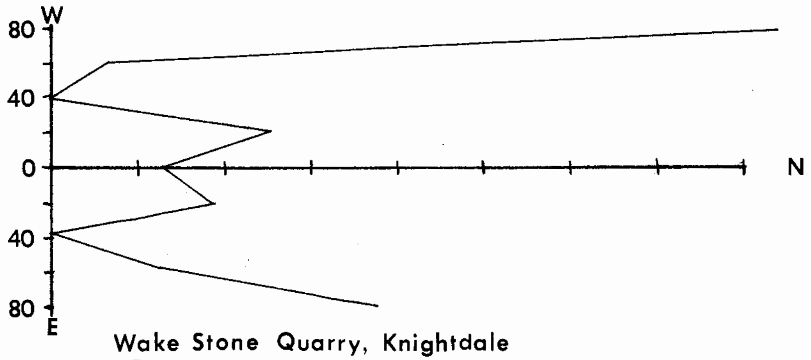


Martin-Marietta Quarry, Garner
AD

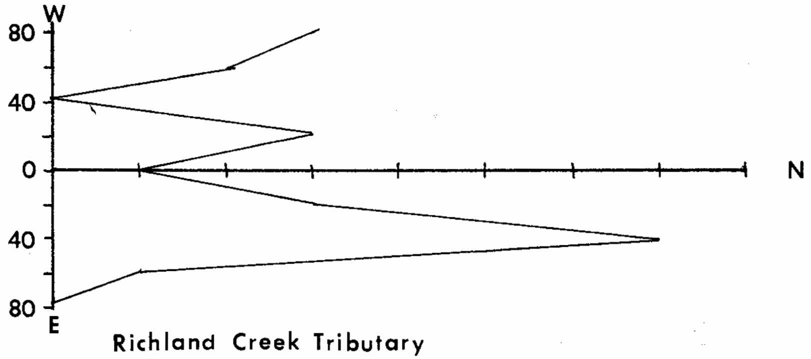
Fig.10 (cont)-Joint Orientations



Falls Dam-Horse Creek
FGS

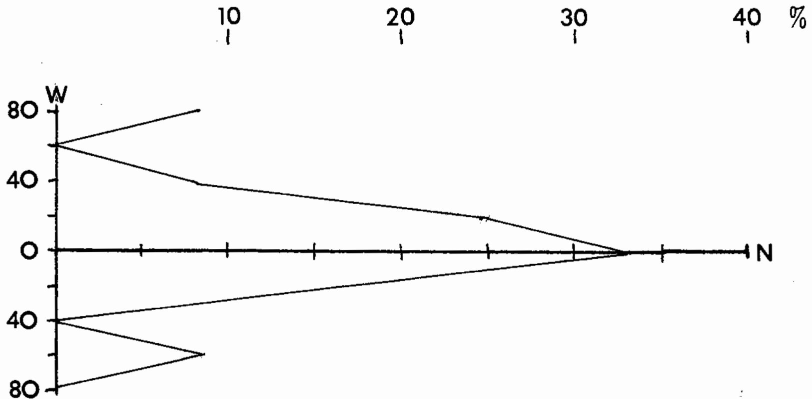


Wake Stone Quarry, Knightdale
AD

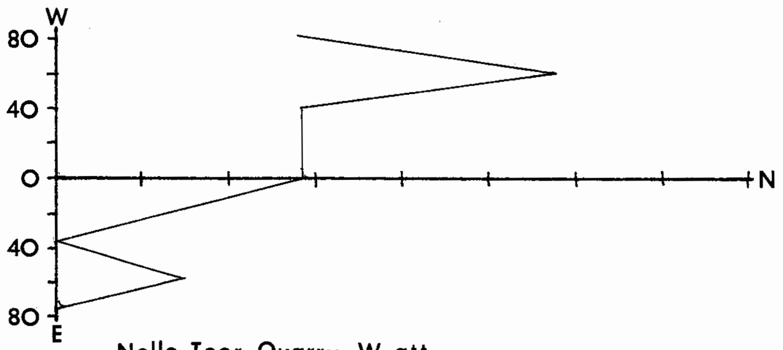


Richland Creek Tributary
IGS

Fig.10 (cont)- Joint Orientations

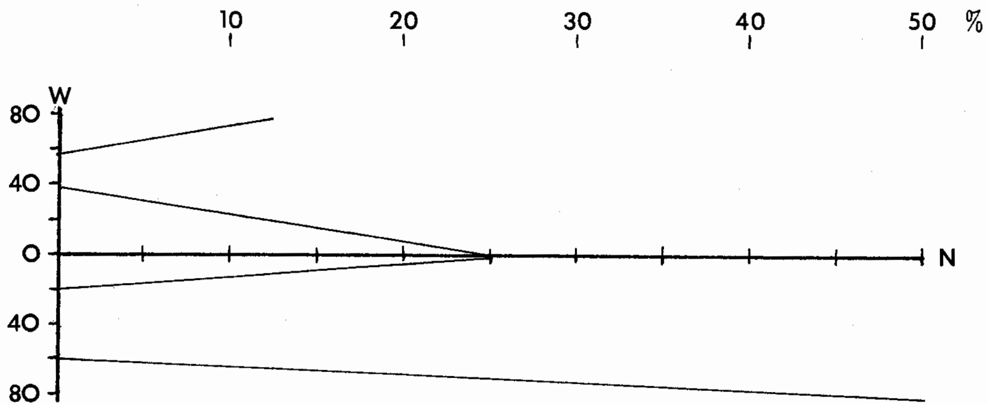


Crabtree Creek, Umstead Park
MGS

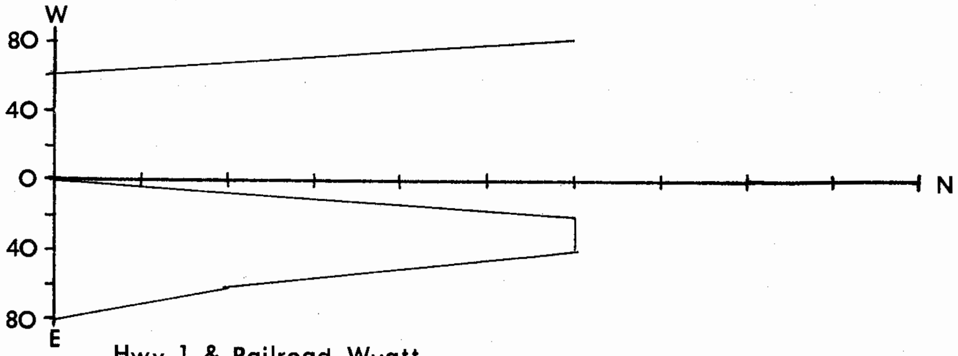


Nello Teer Quarry, Wyatt
AD

Fig.10 (cont)-Joint Orientations



Gresham Lake Quarry
IGS



Hwy 1 & Railroad, Wyatt
IGS

Fig.10 (cont)- Joint Orientations

The data present no clear evidence of a general lithologic control in stream drainage patterns. Tabulation of the modal direction of the frequency curves by rock type shows that approximately 84 percent of the stream segment modes are located between N 20°W and N 20°E. By comparison 61 percent of the joint orientation modes fall within this 40 degree interval. Although there is considerable scatter to the data, they appear to support the concept that a ground water exploration program can be enhanced by judicuous utilization of stream segment orientation analysis.

Relative Significance of Variables Affecting Yield and Specific Capacity

The results of the chi square (χ^2) analyses indicate those geologic variables believed to influence well yields significantly (Table 4). The level of significance (α) is the probability that a significant relationship has been mistakenly declared between two variables. The lower the value of α the greater is the likelihood that one variable (i.e. yield) varies significantly with another variable (i.e. lithology).

The chi square analyses demonstrate that well yield varies most significantly with lithology and saprolite thickness. Judging from the high value of alpha (α = .79), distance from nearest draw appears to be the least significant geologic variable affecting well yield.

The most significant relationship is shown to exist between specific capacity and elevation (α = .007). The chi square test indicates a moderate difference in specific capacity with lithology (α = .24). Saprolite thickness

Table 4

CHI SQUARE ANALYSIS

TEST	N	COMPUTED CHI SQUARE	DEGREES OF FREEDOM	α
YIELD VS:				
LITHOLOGY	222	34.0	4x4 = 16	$.01>\alpha>.001$
TOPOGRAPHY	201	16.3	6x2 = 12	$.20>\alpha>.10$
SAPROLITE	210	34.5	4x6 = 24	$.10>\alpha>.05$
ELEVATION	192	14.2	4x3 = 12	α = .29
DISTANCE	192	7.9	4x3 = 12	α = .79
WELL DEPTH	258	29.9	4x7 = 28	$.50>\alpha>.30$
SPECIFIC CAPACITY VS:				
LITHOLOGY	149	11.5	3x3 = 9	α = .24
TOPOGRAPHY	134	2.3	2x2 = 4	α = .68
SAPROLITE	125	6.5	3x3 = 9	α = .69
ELEVATION	134	17.7	2x3 = 6	α = .007
DISTANCE	128	6.6	3x3 = 9	α = .68

(α = .69), topography (α = .68) and distance to nearest draw (α = .68) appear to have no significant relationship with specific capacity.

The chi square analyses indicate that well site elevation affects specific capacity more than it affects well yield. If two wells at different elevations have the same reported yield, then a chi square analysis would indicate that elevation does not significantly affect yield. However, if the drawdowns at those two well sites are different, then the specific capacities of the wells are unequal and the chi square analysis would indicate that elevation does effect specific capacity. Thus the specific capacity-elevation relationship may be more related to conditions controlling drawdown than to elevation _per se_.

Success of well site evaluation depends on the ability to estimate the effect of the most important sources of yield variation. Multiple linear regression was viewed as a promising tool for specifying the relative significance of hydrogeologic variables.

Although a knowledge of optimum well depth is important during construction of a well, it is not of immediate concern when evaluating a well site prior to drilling. Only the geologic variables which can be measured or estimated are useful at the time of well site selections. Evaluation of the effects of geologic variables requires adjustment of reported yields for the effects of the "non-geological" variables, and the most important "non-geologic" factors are well depth and drawdown which have a relatively high correlation. Drawdown, on the other hand is controlled in part by the nature of the fracture system from which the water is being withdrawn. Therefore, specific capacity (yield ÷ drawdown) was used instead of yield in the multiple regression analyses.

It was anticipated that a model comprised of some combination of lithology, topography, saprolite thickness, elevation, distance to nearest draw, and estimated static water level would account for a substantial amount (⩾50%) of the variation in specific capacity. A large part of the residual variation is thought to be accounted for by fracture characteristics, and negative correlations were expected between specific capacity and distance to nearest draw, as well as elevation and static water level. Positive correlations were anticipated between specific capacity and saprolite thickness and specific capacity and LeGrand's (1967) topographic rating.

Plots of specific capacity and each geologic variable were produced to determine if a linear relationship existed. If the relationship were determined to be curvilinear, an appropriate log transformation was performed on the geologic variable.

Table 5 summarizes the results of a multiple regression run for 70 wells drilled in various rock types.

Table 5

MULTIPLE LINEAR REGRESSION

Specific Capacity as a Function of
Hydrogeologic Variables

Number of Observations Used in Analysis = 70

SOURCE	DEGREES OF FREEDOM	F VALUE	PR>F	
MODEL	6	1.50	0.17	R-SQUARE=0.18
ERROR	60	--	--	
CORRECTED TOTAL	69	--	--	
LGTOPOPT	1	1.82	0.18	
LGSAPRO	1	0	0.99	
LGEL	1	0.80	0.37	
DIST	1	1.88	0.18	
SWL	1	0.32	0.57	
LITHO	4	2.98	0.02	

LGTOPOPT = Log of LeGrand's Topographic Point Value
LGSAPRO = Log of Saprolite Thickness (FT)
LGEL = Log of Well Site Elevation (MSL)
DIST = Distance to Nearest Draw (FT)
SWL = Static Water Level (FT)
LITHO = Lithology per Parker (1979)
PR = Probability
R^2 = Coefficient of Determination

The probability of the SAS F-test value can be used to rank the individual variables by relative importance (Barr, et al., 1976). The model accounts for only about 18 percent ($R^2 = .18$) of the variation in specific capacity, and the most significant source of variation is lithology (PR = .02). An interpretation of the F-test is that a 98 percent probability exists that lithology affects specific capacity. The other sources of variation, listed in decreasing order of signif-icance, are distance to draw (PR = .18); log of elevation (PR = .37), static water level (PR = .57) and log of saprolite thickness (PR = .99).

Similar analyses were made on wells from each lithology, but in every case the significance of the model was unacceptable (PR > .50). The best multiple regression model accounts for less than 20 percent of the variation in specific capacity at the .17 significance level. The failure of the analyses to account for a significant amount of variation in the dependent variable may be caused by

1) a non-linear relationship between the variables which is not readily corrected by simple transformation;
2) the exclusion of significant independent variables from the model which may or may not be measurable;
3) a failure to adjust fully the dependent variable for non-geologic effects; and

4) the inability of geologic variables to account for specific capacity with any degree of reliability.

When non-geologic variables (e.g., well depth, drawdown) are included in the models, the results of the multiple regression improve significantly. This improvement implies that the lack of success of the other models is caused by the exclusion of significant geologic variables rather than the unsuitability of the regression method.

The most obvious missing variable is a measure of the fracture characteristics. Extent of fracture development is the key to a productive water well in crystalline rocks, but fracture density and fracture size is difficult to ascertain at each well site. However, pumping test data theoretically reflects the nature of the fracture system, and it is this information from the CWS wells that has provided insight to the hydrogeology of the several rock types.

Pumping Test Analysis

The nature of fracture systems ranges from a single fracture to intensely fractured zones which can approach the hydraulic properties of a porous granular medium. Theoretically, fracture systems may be characterized by their ability to transmit water to a pumped well. Based upon this concept, Jenkins and Prentice (1982) have developed an equation for determining the water-bearing characteristics of fractured rock from pumping tests,

$$L \sqrt{TS} = \frac{Q}{s} \sqrt{\frac{t}{\pi}}$$

where:

L = fracture length (ft),
T = transmissivity of fractures (gal/min/ft),
S = storage coefficient (dimensionless),
Q = well discharge (gpm),
s = drawdown in well (ft),
t = pumping time (min)

The fracture coefficient, $L\sqrt{TS}$, should increase with greater fracture density, size and interconnection. The highest mean fracture coefficient ($x = 52.9 \pm 92.1$ $ft^2/day^{1/2}$) is associated with *ad* wells. An anomalously high mean fracture coefficient (147.6 $ft^2 day^{1/2}$) for *igs* wells is caused by the extreme value for one of the wells (Table 1). When this extreme value is removed, a mean value of 27.5 ± 23.8 $ft^2/day^{1/2}$ results, but eliminating this value produces an apparent incongruity. The *igs* wells have the highest mean yield and specific capacity but not the highest mean fracture coefficient. On the other hand, the *igs* fracture coefficient is computed from only five wells.

The *mgs* wells present the lowest mean yield, a low mean specific capacity, and the lowest mean fracture coefficient ($\bar{x} = 17.6 \pm 31.5$ $ft^2/day^{1/2}$). This relationship suggests that the *mgs* lithology may be less intensely fractured than other lithologies. Other possible reasons for the difference include a predominance of relatively small fractures and poor interconnections between fractures or some combination of all three.

Fracture coefficient value patterns are shown on Plate 4, and the values have been grouped into three broad classes; low, medium, high. Class frequencies are tabulated by lithology and geography (Table 6). The mgs wells have the greatest frequency of relatively low fracture coefficients whereas the relatively high fracture coefficients are most frequent in the igs lithology. CWS wells in the Leesville area exhibit the greatest frequency of relatively low fracture coefficients and a low frequency of high fracture coefficients. The Leesville area has a high incidence of low yield wells (Plate 5), a fact which suggests that the area is less intensely fractured than other areas. In contrast, wells in the Bayleaf area have the greatest frequency of relatively high fracture coefficients (greater than $10 ft^2/day^{1/2}$). In a band approximately parallel to the Neuse River as it flows from US 1 south to a point four miles south of Milburnie, the fracture coefficients are about equally distributed through the three classes. This band coincides approximately with a band of low yield and abandoned wells (Plate 5).

Table 6

A - FREQUENCIES OF FRACTURE COEFFICIENTS (F) BY LITHOLOGY

LITHOLOGY: (No. wells)	$F<10$ %	$10 \leq F<40$ %	$F \geq 40$ %
igs: (n=6)	16.7	33.3	50
mgs: (n=34)	61.8	29.4	8.8
fgs: (n=29)	37.9	34.5	27.6
ad: (n=48)	31.3	33.3	37.4

B - FREQUENCIES OF FRACTURE COEFFICIENTS (F) BY AREA

AREA: (No. wells)	$F<10$ %	$10 \leq F<40$ %	$F \geq 40$ %
Leesville: (n=32)	68.8	18.8	12.5
Bayleaf: (n=17)	17.6	47.1	35.3
Neuse River: (n=29)	31.0	27.6	41.4
Wendell: (n=12)	16.7	58.3	25
Lake Wheeler: (n=18)	55.6	33.3	11.1

Low Flow Characteristics

Areas of high or low ground water availability may be identified by studying baseflow characteristics of drainage basins (Floyd and Peace, 1974). The 7-day, 10-year low stream flows ($Q_{7,10}$) represent drought conditions which are likely to occur once every 10 years. This low flow characteristic is believed to be useful from a planning perspective and to be an appropriate measure of relative ground water availability. High values of $Q_{7,10}$ should theoretically serve to locate indirectly intensely fractured areas in the county where greater ground water storage capacity and consequently higher baseflows during droughts might be found.

The smallest $Q_{7,10}$ values (cfs/mi^2) occur in the western quarter of the county (Plate 2) where low permeabilities characterize the sedimentary rocks of the Durham Basin and the metasedimentary/metavolcanic rocks of the Carolina Slate Belt. In general, the overlying weathered materials associated with these rocks are typically characterized by relatively low permeabilities (Soil Conservation Service, 1970). Because of the low ground water storage capacity of these poorly sorted sediments and metamorphic rocks, ground water storage is depleted during drought periods, base flow ceases, and the stream channels become dry ($Q_{7,10} = 0$). Eastward from the Durham Basin and along the Neuse River, the baseflows gradually increase from the diorite/gabbro (Parker, 1979) and *mgs* outcrop areas ($0.15 \leq Q_{7,10} \leq .30$) to the *fgs* and *igs* outcrop areas ($.20 \leq Q_{7,10} \leq .30$).

The $Q_{7,10}$ values indicate that the Wake-Millbrook-Bayleaf area has the greatest volume of available ground water in northern Wake County. This area encompasses several lithologies, and hence factors other than rock type must be examined to explain the relatively higher baseflows. Since fractures provide means of water storage and transmittal, distribution and number of fractures should play a role in determining $Q_{7,10}$ values.

Joint frequency is fundamentally controlled by the amount of strain in a rock and high strain energy content is associated with areas of intense folding (Price, 1966). The concentration of fold axes in the Wake Forest-Millbrook-Bayleaf area (Fig. 2) suggests the probable presence of more fractures and joints in this area than elsewhere in the county. Four asymmetrical fold axes are recognized within the Wake Forest-Millbrook-Bayleaf area (Parker, 1979). Field mapping confirms the presence of an associated relatively high joint frequency (Fig. 2) compared with other areas in the county.

The northeastern approximately one-third of the county is underlain by the Rolesville granite batholith (ad). Upon crossing into the granite, the Neuse River turns to a north-south course which parallels the igs-ad contact. One of the dominant joint sets found in the granite exhibits the same orientation (Fig. 2).

Eastward from the Neuse River toward the center of the batholith, the $Q_{7,10}$ baseflows decrease and approach a zero value at the county line. Apparently, the fracture density is highest at the margins of the batholith and decreases towards the center. The mean yield of wells drilled near the margins of the granite outcrop (41 ± 28 gpm) is greater than the SAS-computed mean yield of all the ad wells (34 ± 25 gpm). The mean specific capacity of wells drilled near the margins of the outcrop (1.0 ± 2 gpm/ft) is also slightly greater than the SAS-computed mean specific capacity for all the granite wells (0.9 ± 1.7 gpm/ft).

Baseflows decrease inside Raleigh's city limits because of urbanization which limits ground water recharge. Because of the relatively few low flow gaging stations in southeastern Wake County conclusions about baseflow and ground water availability can at best be tentative.

Recharge and Water Budget

A recharge map (Plate 3) illustrates ground water availability patterns across the county. The ground water recharge values are expressed as percent of the mean annual precipitation of 41.9 inches as measured over the 20-year period of 1958-1977 at Raleigh-Durham Airport (Tang, 1980).

For a long period of record it can be reasonably assumed that ground water recharge approximates ground water discharge. The annual 7-day low flow ($Q_{7,1}$) represents a minimum ground water discharge and consequently indirectly the smallest recharge volume reasonably expected yearly. The recharge map (Plate 3) is based on the $Q_{7,1}$ values (Appendix II). Larger volumes of water may be recharged during winter and spring, but the $Q_{7,1}$ volume represents one which can be anticipated to exist from year to year.

Configuration of the recharge contours is similar to the $Q_{7,10}$ contours (Plate 2). The least recharge volumes occur in the Durham Basin and Carolina Slate Belt ($\leq$ 1 percent), and the most recharge occurs in the relatively highly fractured Wake Forest-Millbrook-Bayleaf area ($\geq$ 15%).

Tang (1980) used the Thornthwaite method (1957) to compute a mean annual water balance for the Raleigh area (Table 7). The method includes both runoff and evapotranspiration in the calculations. Data from Table 7 permit calculation of the mean annual ground water recharge,

$$\begin{aligned}\text{Recharge} &= \text{Precipitation} - (\text{Evapotranspiration} \\ &\qquad + \text{Runoff}) \\ &= 41.9 \text{ in} - (30.6 \text{ in} + 5.9 \text{ in}) \\ &= 5.4 \text{ in} = 13\% \text{ of mean annual precipitation}\end{aligned}$$

The mean annual recharge computed by the Thornthwaite method (13%) is consistent with the "average" recharge as estimated from the $Q_{7,1}$ recharge map (Plate 3). Thus, $Q_{7,1}$ values are considered to be reliable indicators of minimum recharge in a Wake County drainage basin.

Table 7

MEAN ANNUAL WATER BALANCE IN RALEIGH-DURHAM AREA
(From Tang, 1980)

Weather Station No. 2 1959 to 1977 Latitude 35.5 N Number of Years of Record:20

Thornthwaite and Mather Method Soil Storage in Millimeters: 200

(Data in mm., Unless Specified)

	MONTH												
COMPONENT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TDEGF	38.9	41.2	49.2	59.0	66.8	73.5	77.2	76.6	70.5	59.6	50.1	39.4	
PPTIN	3.3	3.5	3.7	2.7	4.0	3.8	4.5	4.5	3.4	3.0	2.7	3.3	41.9
AROIN	0.4	0.4	0.4	0.3	0.5	0.7	0.7	0.8	0.8	0.6	0.5	0.4	5.9
HEATI	0.7	1.1	2.7	5.3	7.8	10.1	11.6	11.3	9.1	5.5	2.9	0.8	68.4
POTET	5	8	26	59	99	131	154	142	99	54	24	5	806
PPTMM	83	89	93	67	100	95	113	114	85	76	67	82	1063
P-PET	78	81	66	9	1	-36	-40	-27	-13	22	43	76	257
ACTET	5	8	26	59	99	128	144	132	93	54	24	5	776
DEPIC	0	0	0	0	0	3	10	10	6	0	0	0	30
SURPL	78	81	66	9	1	0	0	0	0	0	0	52	0
WATRO	52	66	66	38	19	10	5	2	1	1	0	26	287
SNORO	0	0	0	0	0	0	0	0	0	0	0	0	0
TROMM	52	66	66	38	19	10	5	2	1	1	0	26	287
TROIN	2.1	2.7	2.7	1.5	0.8	0.4	0.2	0.1	0.1	0.1	0.1	1.1	11.9

TDEGF = Temperature in Degrees Fahrenheit
PPTIN = Precipitation, Inches
AROIN = Actual Runoff, Inches
HEATI = Heat Index
POTET = Potential Evapotranspiration
PPIMM = Precipitation, mm
P-PET = Precipitation-Potential Evapotranspiration
STRGE = Storage

ACTET = Actual Evapotranspiration
DEFIC = Deficit
SURPL = Surplus
WATRO = Water Runoff
SNORO = Snow Runoff
TROMM = Total Runoff, Millimeters
TROIN = Total Runoff, Inches

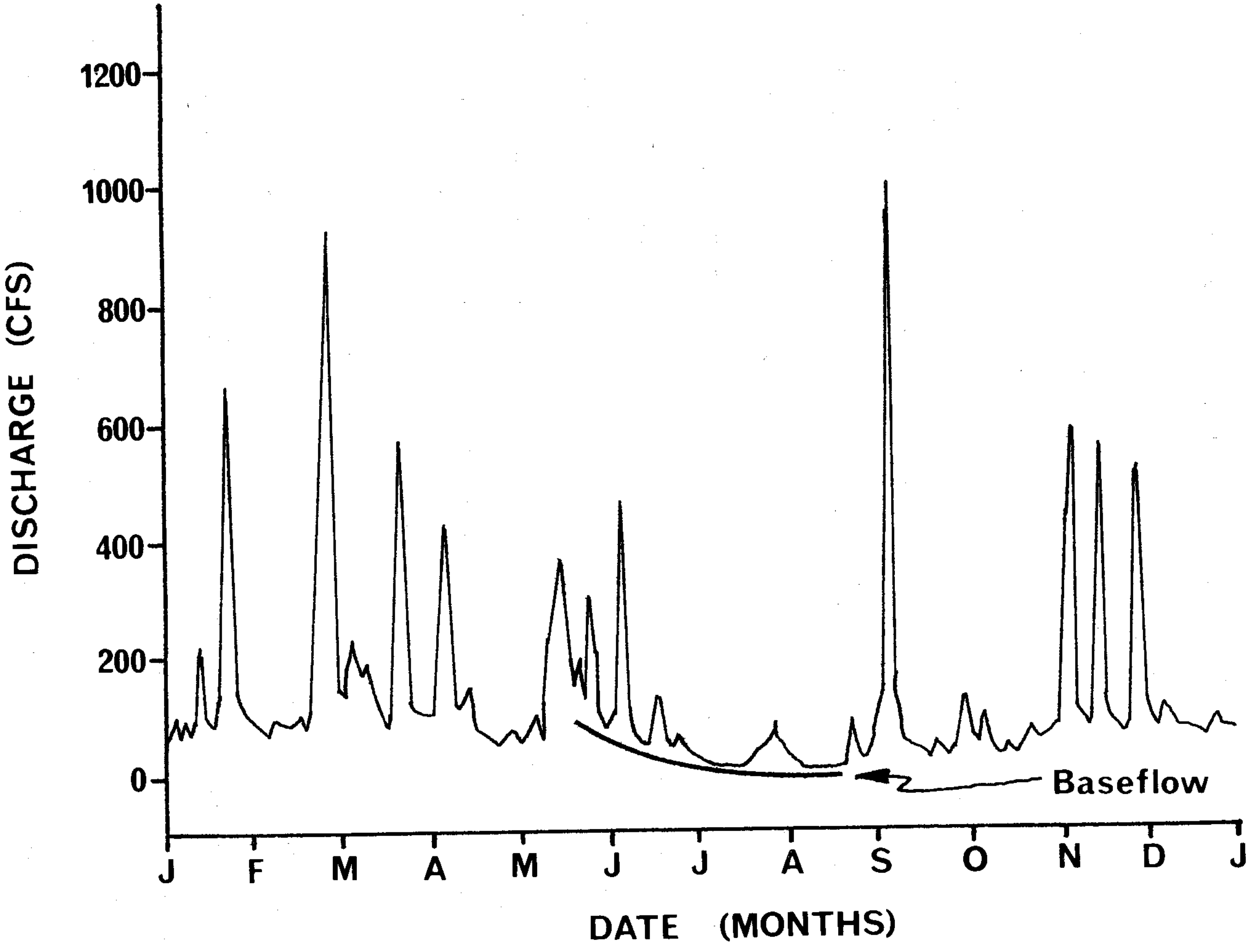
Annual Minimum Ground Water Availability

A stream hydrograph for Middle Creek at Clayton, N.C., is presented in Fig. 11 for the year 1979, a period of near-normal precipitation. The general shape of the hydrograph is typical of most years. Peak flows are most frequent during the rainy spring months, and the flows decrease through the summer to a minimum before increasing in the fall and winter as evapotranspiration decreases. An increased evapotranspiration rate in the summer months is primarily responsible for the declining stream baseflow discharge for on the long term precipitation in Wake County is distributed more or less evenly throughout the year (Table 7). This decline, or baseflow recession, is illustrated by the curved line in Figure 11 and represents the gradual decrease in ground water discharge to the stream channel during the summer.

Ground water volume available for use is approximately equal to the ground water discharge which in turn is assumed to equal recharge. If use exceeds discharge, then ground water is "mined" from storage, and the mined ground water may not be recharged in the spring. The long term result is a declining water table.

To prevent ground water mining, the peak demand for ground water in a drainage basin should not lower the water table below some critical level. For Wake County the low

FIG.11 -HYDROGRAPH OF MIDDLE CREEK, CLAYTON, NC, 1979



flow associated with the 10-year drought ($Q_{7,10}$) is considered to be the minimum stream flow required to sustain fish and wildlife habitats and to maintain the waste assimilative capacity of the stream. The portion of baseflow which exceeds the $Q_{7,10}$ value is viewed as the amount of ground water which can be used without severely mining the water table. This ground water volume is smallest during the annual drought period ($Q_{7,1}$) which usually coincides with the peak water demand period. More ground water is available during recharge periods (Table 7; Fig. 11), but the limiting volume on overdraft is the volume represented by the difference between the $Q_{7,1}$ and $Q_{7,10}$ baseflow.

If it is assumed that the difference between recharge volume based upon precipitation alone and the volume represented by the $Q_{7,10}$ volume is available for use, then during periods when recharge is lacking there will be an overdraft on the $Q_{7,10}$ volume. This overdraft must be made up during an ensuing recharge period if the long term water levels are to remain constant.

The point may be illustrated as follows. Assume a total average annual recharge of 298 gallons/acre/day (g/Ac/d); a $Q_{7,10}$ discharge volume of 63 g/Ac/d; and a $Q_{7,1}$ discharge of 277 g/Ac/d. If it is assumed that the difference between the recharge volume and the $Q_{7,10}$ baseflow volume is the usable water volume on a long term average, a total of 235 g/Ac/d is available for use. However, during the annual drought only a volume approximating 214 g/Ac/d (277-63) is available. A net deficit, or overdraft, approximating 21 g/Ac/d occurs for a period of as long as two months. The total overdraft then amounts to 1260 g/Ac for the two months, and it may be greater depending upon the length of time that the system discharges water at or near the $Q_{7,1}$ flow rate. Recharge during the ensuing winter and spring must then replace the deficit if the $Q_{7,10}$ flow volume is to be maintained, and less than 235 g/Ac/d is available for use. Although the overdraft may appear small on an annual basis, over a sufficiently long period of time it can significantly alter the ground water hydrology of a drainage basin. In the extreme case the overdraft may lead to areas of lowered water tables and associated water well failures or decreased yield.

On the other hand, if the $Q_{7,1}$ flow is taken as the basis for estimating the availability of ground water, the $Q_{7,10}$ flow volume should remain unaffected on the long term. The excess ground water, 21 g/Ac/d in the example, is available to compensate for any temporary overdraft on the $Q_{7,10}$ volume, or to be discharged through normal baseflow regimes. Risk of long term overdraft is thus reduced.

The annual minimum ground water availability ($Q_{7,1}$-$Q_{7,10}$) (Plate 6) is significant for two reasons. It reflects the hydrogeologic nature of the drainage basin, and it represents a buffer between safe consumption levels and ground water mining in a drainage basin.

Ground water availability during the annual drought is greatest in the Wake Forest-Millbrook-Bayleaf area. Relatively high ground water availability exists in the western margin of the Rolesville granite batholith along the Neuse River, although there is some evidence that other factors may restrict well yields. The volume of available ground water decreases eastward towards the center of the batholith. The Durham Basin and the Carolina Slate Belt have the lowest available volumes of ground water in the county during the annual drought.

Relation of Fractures and Geomorphic Parameters

In portions of the county where rock outcrops are poorly exposed or lacking and CWS pumping test data are unavailable, other methods must be used to evaluate the fracture systems. Because geomorphic features are influenced by fracture characteristics, drainage density (stream length ÷ drainage area) and mean well site elevation were examined.

Percolation of water into the bedrock should be enhanced by fractures. Thus, areas of high fracture frequency might be expected to have lower drainage densities because less water occurs as surface runoff. Mean values of drainage density were computed for portions of watersheds grouped by dominant lithology (Table 8). The mgs lithology shows the highest mean drainage density ($\bar{x}$=9.3 ± 1.2 mi/mi^2) and is also associated with the lowest mean yield and lowest mean fracture coefficient (Table 1). Wells drilled in the ad lithology have a relatively high mean fracture coefficient and a relatively high mean drainage density.

Table 8

MEAN DRAINAGE DENSITY (mi/mi^2) BY LITHOLOGIC CLASS

DOMINANT LITHOLOGY	NUMBER OF DRAINAGE BASINS	MEAN	STD. DEV.
mgs	6	9.3	1.2
ad	9	9.0	1.1
igs	3	8.0	1.3
fgs	6	7.6	0.5

No clear correlations are observed between drainage density and baseflows (Table 9). Apparently, the influence of other variables prevents the use of drainage density as a reliable index of fracture frequency.

If mean values of fracture coefficient provide a clue to fracture frequency, the ranking of the lithologies in order of decreasing fracture frequency is ad, fgs, igs, mgs. A lithology which is highly fractured is expected to weather at a greater rate than less fractured rock types. Thus, the mean elevation should be relatively low in the outcrop area

Table 9

LOW FLOW CHARACTERISTICS AND BASIN PARAMETERS FOR SELECTED WATERSHEDS

LOCATION		$Q_{7,10}$ (cfs/mi^2)	70%Flow (cfs/mi^2)	BASIN SLOPE (%)	DRAINAGE DENSITY (mi/mi^2)	DOMINANT LITHOLOGY*
87186	Richland, Cr, Wake Forest	.363	.433	0.6	9.54	igs
87175	Horse Cr, Wake Forest	.224	.527	0.6	9.70	fgs & mgs
87410	Poplar Cr, Knightdale	.196	.499	0.7	9.03	ad
87320	Big Br, Millbrook	.190	.432	1.3	7.46	igs
87290	Mine Cr, Millbrook	.167	.455	0.9	7.73	fgs
87080	New Light Cr, Purnell	.143	.459	0.7	9.31	mgs & um
87220	Powell Cr, Wake Crsrds.	.137	.533	0.8	9.17	ad
87160	Lower Barton Cr, Bayleaf	.115	.420	0.7	9.39	mgs & um
87370	Big Br, Garner	.103	.406	1.0	9.15	ad
87120	Upper Barton Cr, Bayleaf	.062	.351	0.8	9.43	mgs & um
87270	Hare Snipe Cr, Millbrook	.028	.227	1.1	9.55	mgs & fgs
87275	Crabtree Cr, Raleigh	.020	.135	---	7.31	fgs
88000	Middle Cr, Clayton	.011	.305	---	7.22	mgs,fgs,am,up
88380	Cedar Fk, Rolesville	.007	.221	0.8	7.22	ad
90021	Moccasin Cr, Pilot	.005	.239	---	8.16	ad

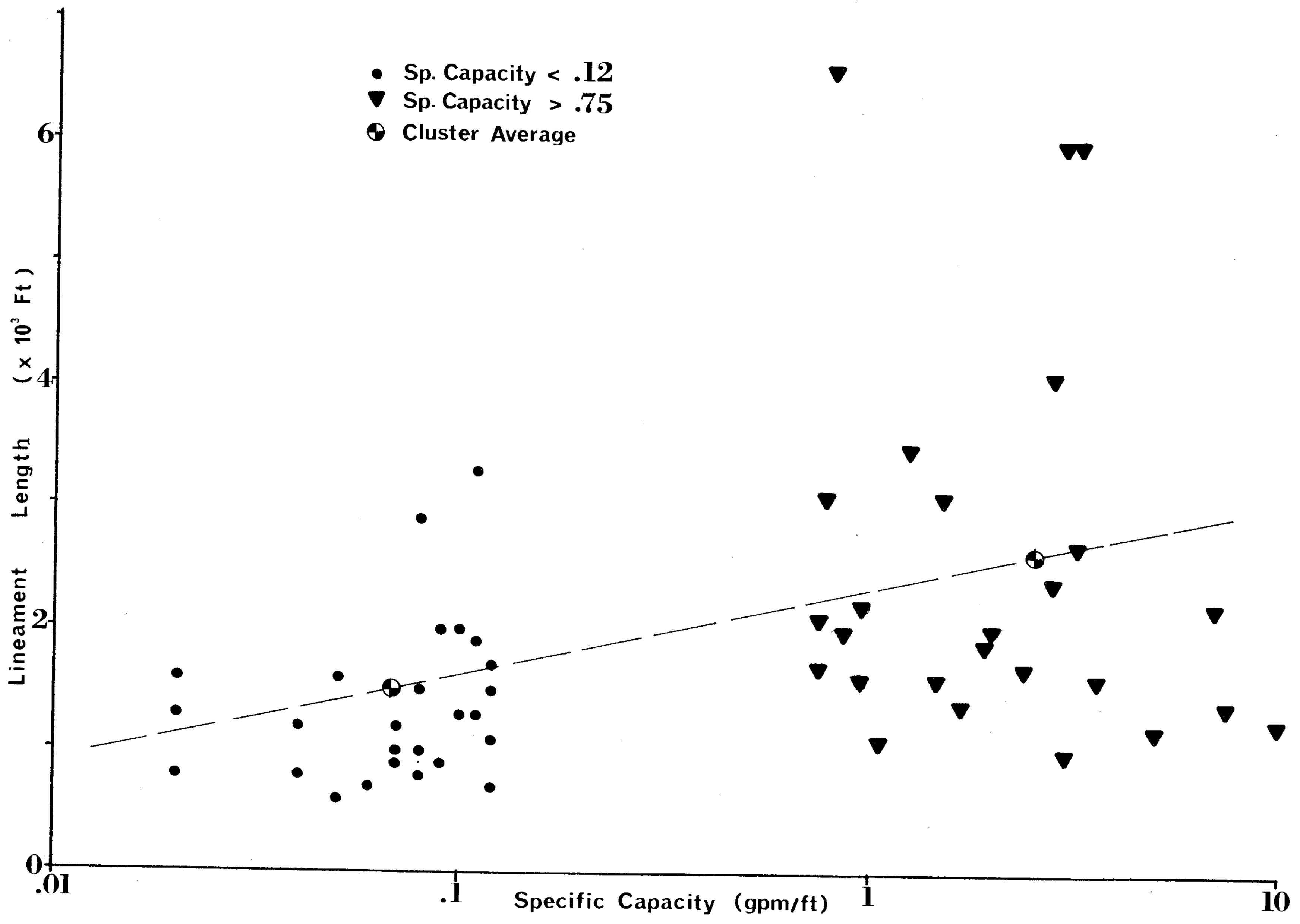
* up = unconsolidated upland deposits of gravel, sand, silt and clay
ad = granite
um = ultramafic rocks
mgs = mica and hornblende gneiss and schist
fgs = felsic gneiss and schist
igs = injected gneiss and schist
am = amphibolite

of a highly fractured lithology. However, the ad wells are associated with the highest mean elevation and the highest mean fracture coefficient (Table 1) whereas the lowest mean elevation corresponds with the relatively low fracture coefficients of the mgs wells. This suggests that mineralogy is more significant than fracture density in determining weatherability and long term erosion in Wake County.

Linear features: Length of linears and lineaments as well as their orientation with respect to potential areas of recharge bear upon ground water exploration. If a linear feature reflects a potential pathway for ground water movement, then a longer one theoretically draws upon a larger area of recharge, other conditions being equal. With this thought in mind, an analysis was made of the relationship between specific capacity of the CWS wells and the length of associated linears. In addition, consideration was given to comparison of specific yields of wells located on linears at or near a probable intersection between two or more linears and/or lineaments and the specific yields of wells not associated with a recognizable linear feature.

Because a part of the focus of the study is upon failure rates of CWS wells and incidence of low yield wells compared to the incidence of "high" yield wells, a plot of the linears associated with the upper quartile of specific capacities (> 0.75 gpm/ft) and the lower quartile (< 0.12 gpm) was

Fig.12 - Specific Capacity vs. Lineament Length



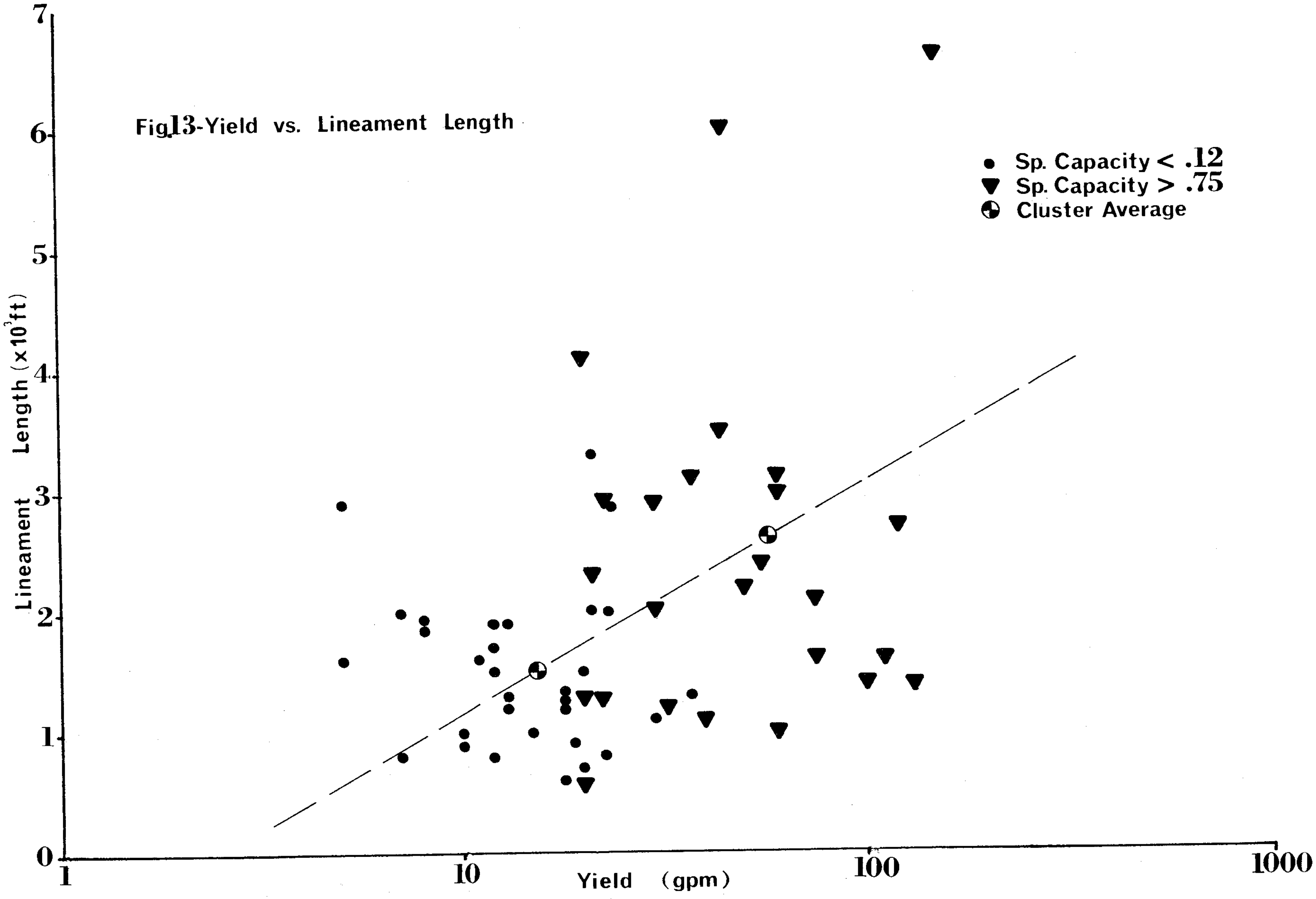


Fig.13-Yield vs. Lineament Length

prepared. In effect the central two quartiles were filtered out, and emphasis was placed upon what is believed to be the two most significant portions of the specific capacity distribution. Figure 12 is a plot of the data.

In a semi-quantitative fashion the higher specific capacities appear associated with longer linears, although, as is to be expected, considerable overlap of linear lengths from each quartile exists (Fig. 12). However, average values for specific capacities and linear lengths suggest that a generalized trend for wells with relatively higher specific capacities is to be found associated with the longer linear features. Table 10 compares capacity data from wells not

Table 10

SPECIFIC CAPACITY COMPARISON

	Specific Capacity	
	Lowest Quartile	Highest quartile
	gpm/ft	gpm/ft
Not located on linear	0.08 ± 0.02	1.67 ± 1.1
Located on or near intersection of linears	0.09 ± 0.06	2.31 ± 1.99
Average specific capacity all wells	0.06 ± 0.03	2.82 ± 2.6

associated with a recognizable linear feature with the average specific capacity values of the two quartiles. Data on linear length are summarized in Table 11.

Table 11

LENGTH OF LINEAR BY SPECIFIC CAPACITY QUARTILE

	Lowest Quartile of Specific Capacities	Highest Quartile of Specific Capacities
	Percent	Percent
Less than		
1000 ft	20	0
1000-2000 ft	33	36
2000-3000 ft	45	48
Greater than		
3000 ft	2	16

For the available data there appears to be a skewness favoring association of larger specific capacities with linear features in excess of 3000 ft in contrast to the general skewness of lower specific capacities associated with linear features of less than 1000 ft. The data suggest an equal probability of low and high specific capacities for linears between 1000 and 3000 ft in contrast to the general skewness of lower specific capacities associated with linear features of less than 1000 ft. Cast in a probability context, the probability of constructing a well of specific capacity greater than 0.75 gpm/ft is about 8 times greater than that of constructing a well with a specific capacity of less than 0.12 gpm/ft if the well site is located on a linear 3000 ft or longer.

Comparison of well yields from the two specific capacity quartiles with linear length and association with linear intersections is summarized in Table 12 and presented graphically in Figure 13. The percentage of wells exceeding the average for each quartile in relation to linear length is given in Table 13.

Table 12

WELL YIELD COMPARISON BY SPECIFIC CAPACITY

	Lowest Specific Capacity Quartile	Percentage of wells	Highest Specific Capacity Quartile	Percentage of wells
Not located on linear	19 ± 6 gpm	15	53 ± 39 gpm	13
Located on or near intersection of linears	16 ± 9 gpm	19	64 ± 41 gpm	21
Average yield all wells in quartile	15 ± 7 gpm	100	58 ± 36 gpm	100

Table 13

PERCENTAGE OF WELLS EXCEEDING AVERAGE YIELD FOR EACH QUARTILE AND LENGTH OF LINEARS

	Lowest Specific Capacity Quartile	Highest Specific Capacity Quartile
Linear less than 2000 ft	20%	13%
Linear greater than 2000 ft	10%	16%
Linear greater than 3000 ft	2%	8%

Tables 12 and 13 suggest that length of linears and presence or absence of intersections of linears have a relatively small statistical effect on expected well yields under conditions favoring well yields of less than 15 to 20 gpm. This range of yields falls in the lower portion of the interval of the yields found from the CWS well data (Table 1). In contrast, the data seem to support the concept that wells located at the intersection of linears at least one of which exceeds 2000 ft or adjacent to a single linear of this dimension potentially have a greater probability of yielding water at rates exceeding the overall average of 34 gpm (Table 1) than those located only on one linear of less than 2000 ft or not associated with a recognizable linear feature. From the quartile data the probability of finding a well yielding more than 50 to 60 gpm appears enhanced if the location is properly situated at the intersection of two or more linears exceeding about 2000 ft. In addition higher specific capacities can be anticipated from such wells by a factor estimated to be as much as 8 (Table 11).

An estimate of the probability of wells located at intersections of linears 2000 ft or more long and yielding in excess of 58 gpm can be calculated from Fig. 5 and Table 13. The estimated probability for a well yield exceeding 58 gpm when located at the intersection of linears one of which is greater than 2000 ft can be taken as the sum of the two probabilities for linear lengths and intersecting linears, 0.37 (Tables 12 and 13).

Figure 6 provides the probability for a well yield of 58 gpm by rock type. Theoretically, the potential for a given well yield should increase for a given rock type when the well site is located at the intersection of two or more fracture systems as defined by the linears. Because the well yield values used in calculating the curves of Fig. 6 include the wells used in the linear analysis, there is an unknown dependency between the rock type probabilities and probabilities for well yields based upon linear intersections. If the probability of a well yield exceeding 58 gpm is the overall probability for a given rock type increased by the percent probability associated with the intersection of linears, the net probability of equaling or exceeding 58 gpm can be estimated by adding to the rock-related probability the product of that probability and the estimated probability from the linear study, 0.37 from Tables 12 and 13. Table 14 summarizes this idea by rock type for well yields equaling or exceeding 58 gpm.

Table 14

SUMMARY OF INCREASED PROBABILITY FROM LINEAR INTERSECTIONS, YIELD = 58 gpm

Rock type	(a) Probability Fig. 5	(b) Probability Increase from Tables 12, 13	(c) Probability Sum	(d) Probability from (1-n)
igs	.28	.10	.38	.44
fgs	.23	.08	.31	.36
mgs	.06	.02	.08	.10
ad	.14	.05	.19	.22

Another way of evaluating the probability is by dividing the rock type probability by the difference between a 100 percent probability for the intersection and the estimated probability from the linear study (1-n = .63). These values are shown in Table 14 under the column (d). Columns (c) and (d) of Table 14 suggest that about one in three wells located in igs and fgs lithologies and at the intersection of two or more linears exceeding 2000 ft. will yield at least 58 gpm in contrast to about one in four to five if the well is located elsewhere. In the mgs lithology use of linear analysis should improve the chance of locating a well with a yield in excess of 58 gpm from about one in 20 to about one in 10. The risk for the mgs lithology is cut about in half if a well yield equal or greater than 58 gpm is desired. Table 15 summarizes similar calculations for a desired yield of 75 gpm. In the igs lithology the probability of a well located at the intersection of two or more linears one of which is 2000 ft or longer, producing 75 gpm or more is about 40 percent that of obtaining a yield of 58 gpm from the same circumstances.

Table 15

INCREASED PROBABILITY OF 75 GPM THROUGH USE OF LINEAR ANALYSIS

Rock type	(a) Probability (Fig. 5)	(b) Probability Increase from Tables 12, 13	(c) Probability Sum	(d) Probability from (1-n)
igs	.10	.04	.14	.16
fgs	.14	.05	.19	.22
mgs	.02	.05	.03	.05
ad	.06	.02	.08	.10

The specific capacity quartile analysis suggests that in general a trend exists for low-yield wells to possess relatively low specific capacities and high yield wells (greater than 40 to 50 gpm) to exhibit relatively higher specific capacities. This relation suggests that in those areas where low yield wells are dominant long term ground water withdrawal at even modest rates may impose a net drawdown on the regional water levels. In contrast, areas of larger individual well yields and associated higher specific capacities may cause a lesser ground water level drop for the same amount of net water withdrawal.

Well Failures

Incidence of well failure is an important consideration when planning a ground water supply system whether for local use or as part of a conjunctive use of surface water and ground water. A well failure is defined as the discontinued use of a well for drinking water at any time and for any reason. Data on failure of private domestic wells is lacking. However, because of the somewhat more stringent regulation of CWS wells by the state, some information on well failures exists.

Overall, the number of CWS well failures in Wake County represents 25.3 percent of all wells with a known history (Table 16). This percentage probably is a low estimate because many abandoned wells are not reported.

Wells drilled in the relatively more productive igs lithology have the greatest percentage of well failures, (36.8 percent). The ad wells exhibit an equally high percentage of failures (36.3 percent) whereas relatively low failure percentages characterize from fgs and mgs rock types.

Table 16

WELL FAILURES BY LITHOLOGIC CLASS

LITHOLOGY	TOTAL NUMBER OF WELLS	NUMBER OF ABANDONED WELLS	TOTAL % ABANDONED	ESTIMATED % DUE TO GEOLOGIC FACTORS
ad	91	33	36.3	18.7
fgs	57	9	15.8	7.9
mgs	62	9	14.5	7.3
igs	19	7	36.8	18.4
TOTAL	229	58	25.3	12.7

A high incidence of failures cannot be attributed solely to geologic factors. State well inspections in North Carolina reveal that approximately half of all CWS well failures may be attributed to non-geological variables such as poor maintenance, faulty equipment, or poor water quality (personal communication, Mr. Donald Williams, November, 1981). Thus, one column in Table 16 shows percentages adjusted downward by an arbitrary 50 percent to compensate for the non-geologic factors.

The locations of known abandoned wells and wells of less than 10 gpm yields are plotted on Plate 5. The relations between well failure and various hydrogeologic parameters are illustrated in Fig. 14.

No information on decreasing well yields could be extracted from the CWS well data. In most cases a pumping test is conducted shortly after the well is drilled, and no subsequent pumping tests are performed or reported.

Well Yield Patterns

To supplement information about ground water availability obtained from the CWS well systems, drillers' logs of wells drilled primarily for individual home owners or clusters of less than 10 residences from eastern Wake County were examined. The wells and their yields were plotted on Plate 5 to ascertain if any pattern or patterns existed with regard to distribution of low yield wells recorded in the CWS data and the data for the individual wells. Arbitrarily, low yield wells were defined as those yielding less than 10 gpm. Boundary lines were drawn between areas apparently characterized by wells reportedly yielding less than 10 gpm and those characterized by well yields of more than 10 gpm.

A broad band apparently more favorable for higher yield wells extends northward from the Shotwell Community to about Fowler Crossroads. The band is located in the ad lithology.

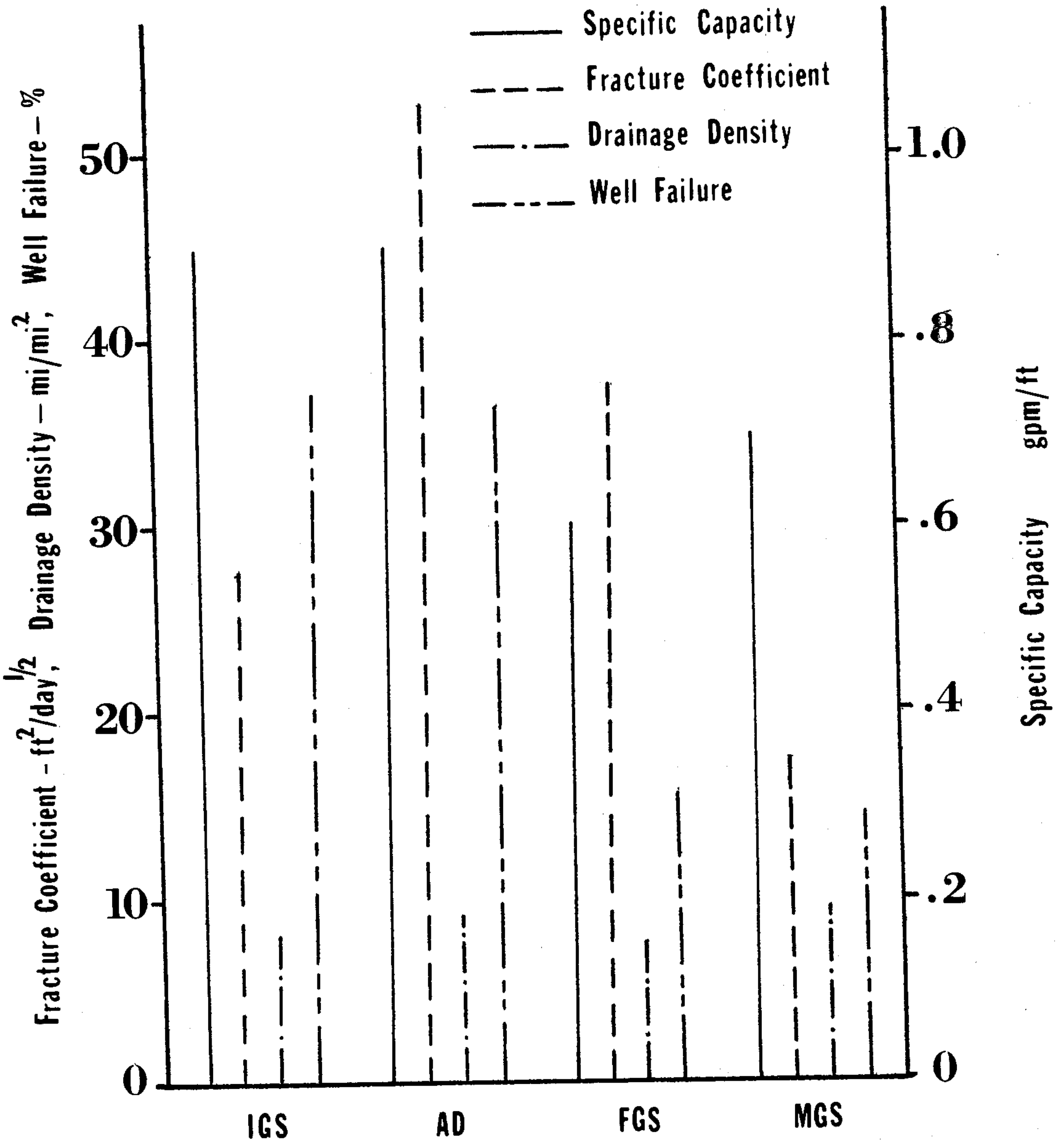


FIG. 14 - MEAN VALUES OF HYDROGEOLOGIC PARAMETERS BY LITHOLOGY

East of SR 96 another broad band favorable for higher yield wells is apparently present. It is not to be expected that all wells drilled in the high yield bands outlined will necessarily produce more than 10 gpm or that within areas apparently dominated by low yield wells that high yield wells will not be found. Rather the patterns suggest some regional trends and relative probabilities. The boundaries shown on Plate 5 must be interpreted as approximations, and they are presented only to emphasize an interpretation of the data.

Specific Capacities and Well Yields

A plot of the specific capacities and well yields of 173 CWS wells was made to ascertain if any signficiant relationship exists between the two (Fig. 15). Aside from the general increase in scatter of points with increasing yield and specific capacity, two facts emerge from the evaluation. The first is that the line connecting the points representing the average values of the specific capacities and yields in the lowest and highest quartiles of the specific capacities suggests a logrithmic relationship between the well yields and the specific capacities despite the considerable scatter of the values. The second is that a rather well defined lower limit exists for the relationship. The limiting curve indicates that with increasing yield the minimal specific capacity increases relatively more abruptly.

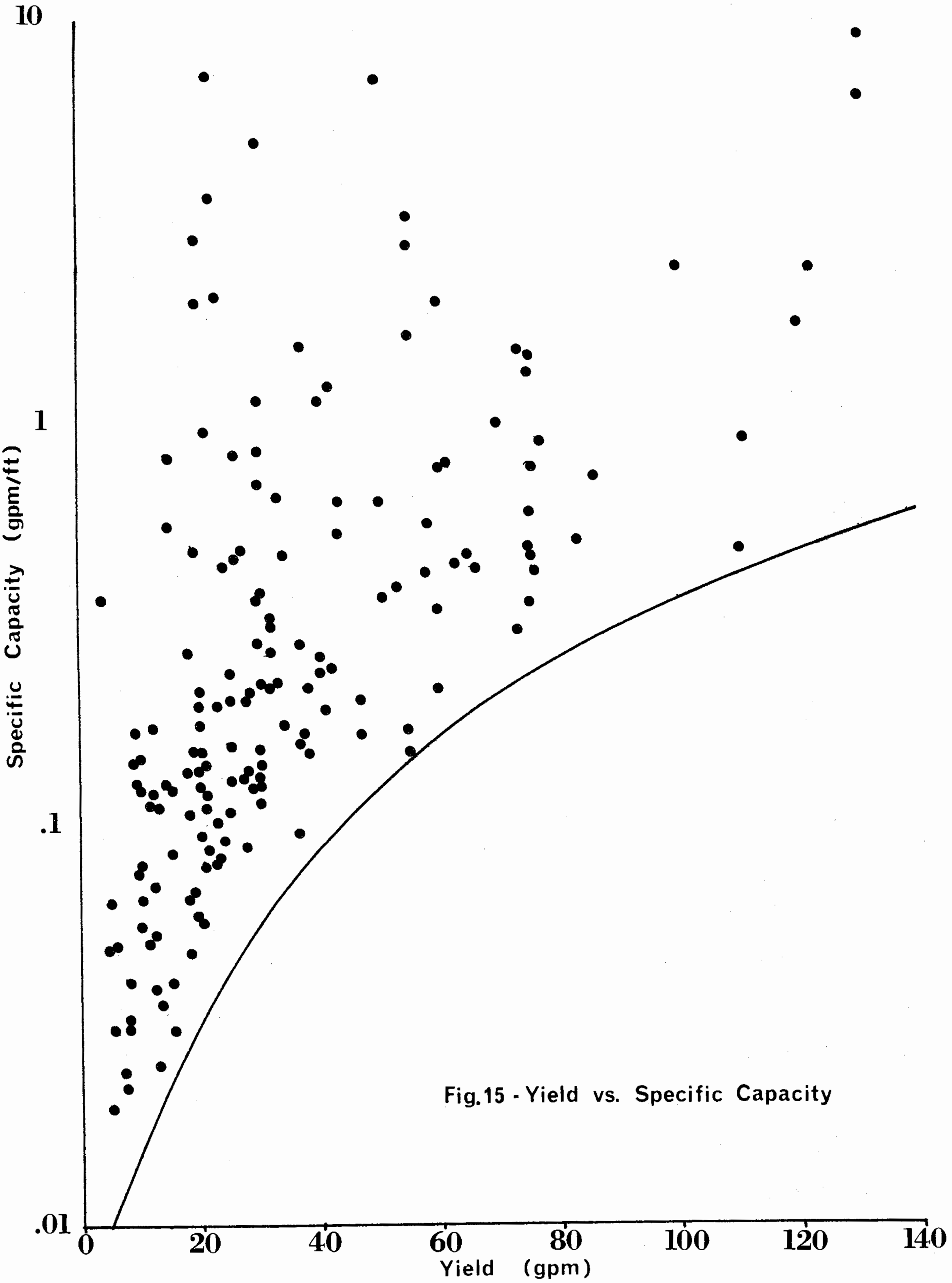


Fig. 15 - Yield vs. Specific Capacity

A tenfold increase in yield is accompanied in Wake County by a 25-fold increase in specific capacity at the lower limit.

The limiting curve provides a basis for anticipating maximum drawdown for wells in the mid-range of yields found in this study, as well as for any other part of the expected range of well yields. If one uses the mean yield for all wells to estimate the limiting drawdown (34.5 gpm; Table 1), Fig. 15 shows the limiting drawdown to be 49 ft. The actual drawdown may be less, but the geohydrology of the rocks apparently places a maximum limit on the drawdown for a given maximum well yield.

Well Yield As Function Of Well Depth

Plots of average well depth as the independent variable against the other average parameters given in Table 1 emphasize a general decrease in average values of specific capacity, well yield, and fracture coefficient with increasing well depth and consequently with rock type. Thus in a general way wells drilled in the igs lithology will tend to be shallower and to have larger yields and greater specific capacities than wells drilled in the other rock types (linear regression correlation coefficient = 0.8).

Fracture coefficient values fit the same pattern, decreasing from the ad wells to the mgs wells. If the larger mean value for the fracture coefficient of the igs wells is accepted (Table 1), the trend is for decreasing average fracture coefficients with increasing average well depths, and again the better rock type for ground water exploration and development is _igs_ lithology (linear regression correlation coefficient = 0.85).

Based on the probability information shown in Fig. 6, the _igs_ lithology has the greatest probability of providing well yields between about 20 gpm and 58 gpm. For yields above 58 gpm the greatest probability belongs to the _fgs_ rocks. If the lower fracture coefficient value for the _igs_ wells is accepted, then the change in relative probability for yields exceeding a given value between _igs_ and _fgs_ wells (Fig. 6) may be explained. The interpretation placed upon the relationship is based upon the frequency of fractures above a certain size. Larger fractures, or better interconnections, may exist in the _fgs_ lithology than in the _igs_ rocks above a set of conditions favoring well yields of 58 gpm or more.

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APPENDIX I

Probability calculations for a Log-Pearson-III distribution:

1) Compute skewness coefficient, g:

$$g = \frac{n^2 \sum x_i^3 - 3n \sum x_i \sum x_i^2 + 2(\sum x_i)^3}{n(n-1)(n-2)s^3}$$

where x_i = natural log of well yield (gpm)
s = standard deviation of x_i values

2) Find K value in Table C-2 by entering at known value of g and probability of interest

3) Compute x_i for probability of interest:

$$x_i = \overline{x_i} + Ks$$

where $\overline{x_i}$ = mean of the natural logs of yield
x_i, K and s are as previously defined

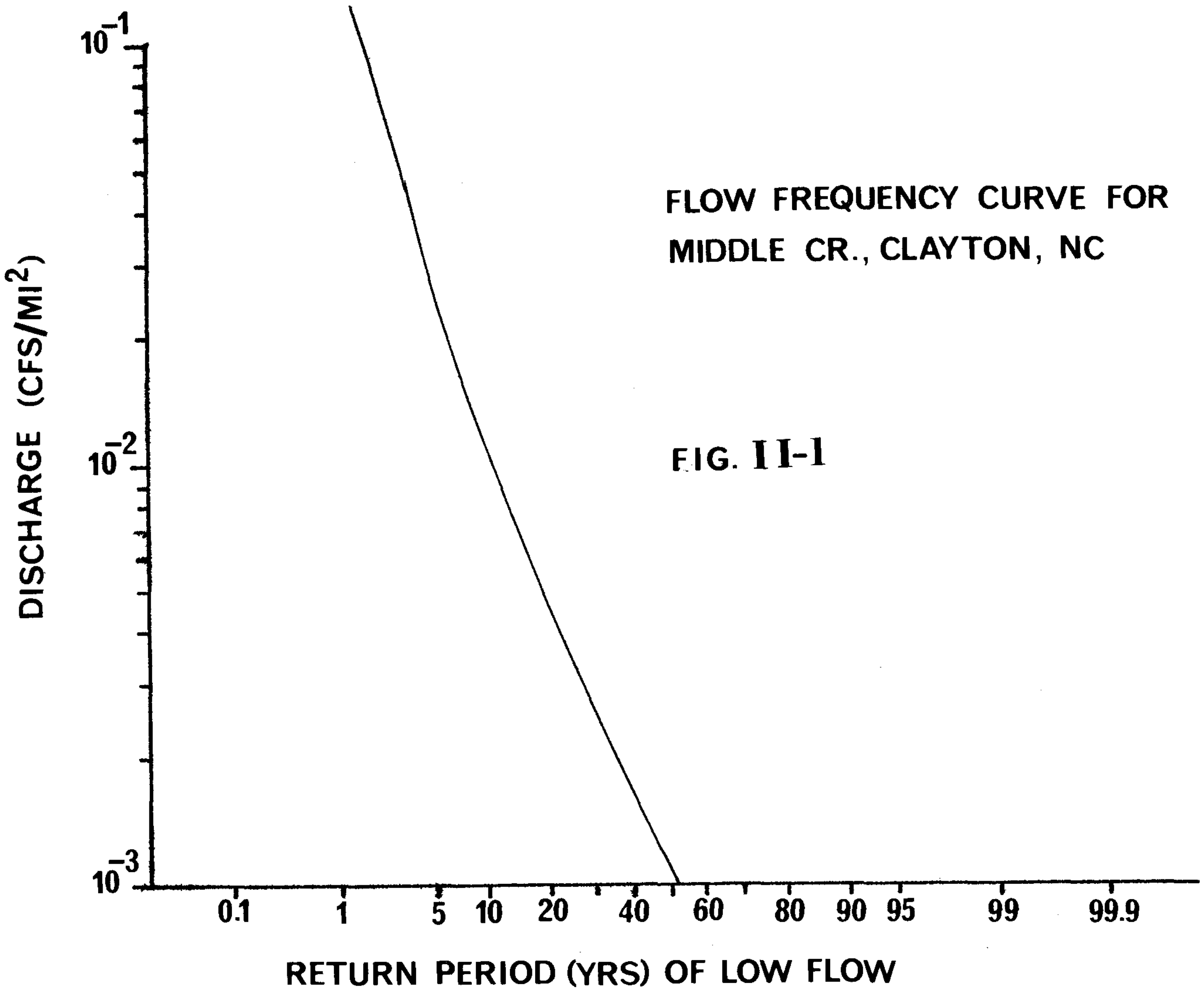
4) For probability of interest, e^{x_i} = yield in gpm

5) Plot data points on log probability paper.

(after Water Resources Council, 1967)

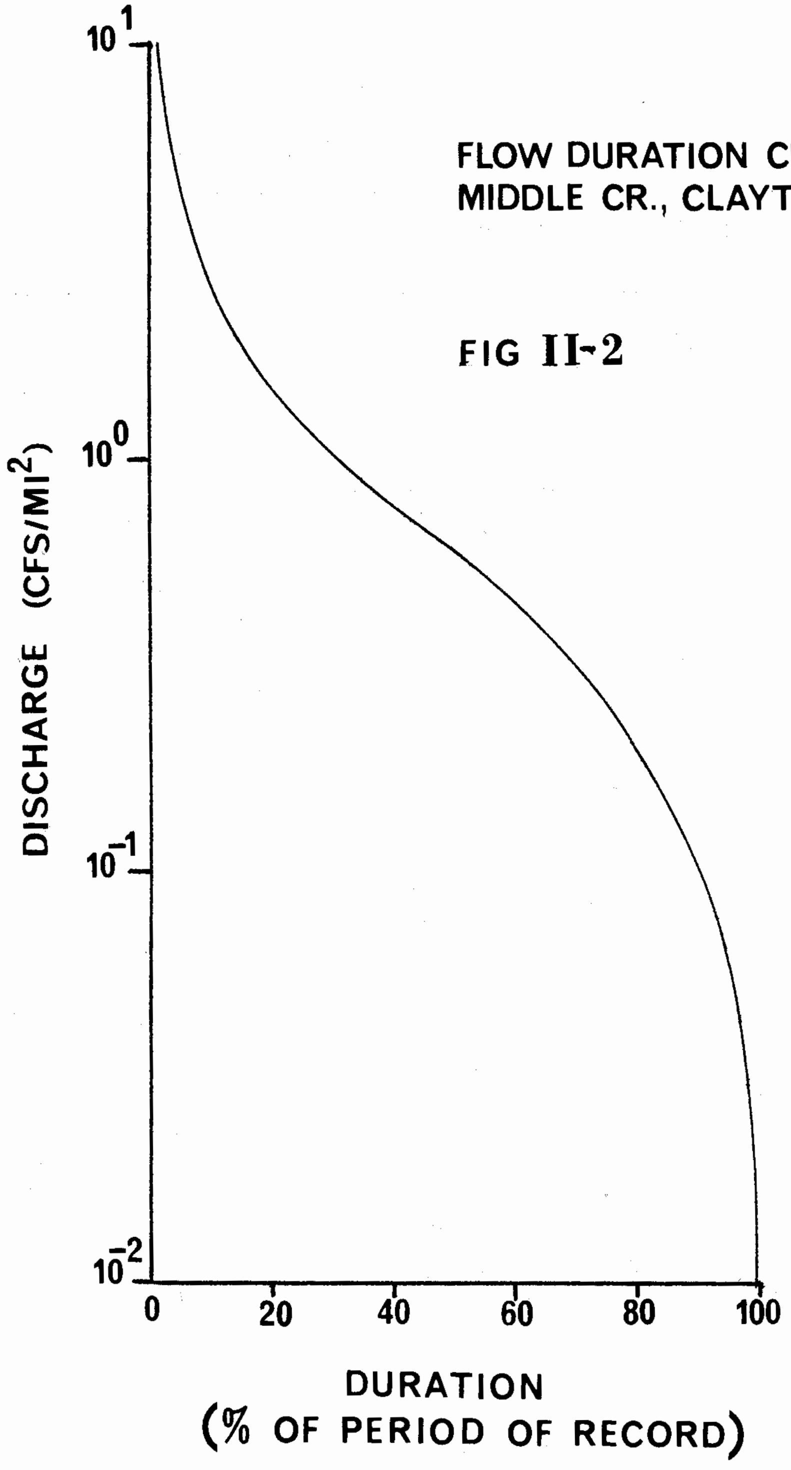
APPENDIX II

LOW FLOW CHARACTERISTICS



FLOW FREQUENCY CURVE FOR
MIDDLE CR., CLAYTON, NC

FIG. II-1



FLOW DURATION CURVE FOR MIDDLE CR., CLAYTON, NC

FIG II-2

Table II - Low Flow Frequencies

Station	Location	A_D (MI^2)	7-day low flow (cfsm) for indicated return period						
			1 yr.	2 yrs.	5 yrs.	10 yrs.	20 yrs.	50 yrs.	100 yrs.
87053	Smith Cr., Grissom	6.23	.120	.036	.009	.003	.001	0	0
87060	Beaver Dam Cr., Creedmoor	44	.005	.0	0	0	0	0	0
87080	Newlight Cr, Purnell	19.2	.393	.280	.190	.143	.108	.067	.057
87120	Upper Barton Cr., Bayleaf	12.4	.274	.166	.094	.062	.041	.020	.016
87160	Lower Barton Cr., Bayleaf	13.2	.344	.238	.156	.115	.085	.050	.042
87174	Horse Cr., Forestville	11.5	.517	.358	.235	.173	.128	.076	.064
87175	Horse Cr., Wake Forest	20.8	.465	.364	.274	.224	.183	.129	.115
87181	Honeycutt Cr., Falls	8.5	.490	.370	.267	.211	.167	.112	.098
87185	Richland Cr. Trib, Wake Forest	0.25	-	-	-	-	-	-	-
87186	Richland Cr., Wake Forest	6.3	.330	.321	.311	.303	.296	.285	.281
87188	Richland Cr., Forestville	10	.640	.515	.402	.335	.280	.206	.186
87189	RichlandCr, Wyatt	13	.436	.293	.186	.134	.097	.055	.046
87193	Smith Cr., Wake Forest	3	.169	.110	.067	.046	.033	.018	.014
87194	Austin Cr., Wake Forest	4.6	.297	.161	.080	.048	.029	.012	.009
87196	Hatters Br., Wake Forest	1.8	.308	.172	.088	.054	.033	.015	.011
87204	Smith Cr., Rolesville	23	.338	.296	.255	.228	.205	.170	.160
87206	Mill Cr., Wake Crossroads	3.6	.418	.306	.214	.165	.128	.082	.071
87208	Toms Cr., Wake Crossroads	1.25	.659	.511	.381	.308	.250	.174	.155

Table II (continued)

Station	Location	A_D (MI^2)	7-day low flow (cfsm) for indicated return period						
			1 yr.	2 yrs.	5 yrs.	10 yrs.	20 yrs.	50 yrs.	100 yrs
87220	Powell Cr., Wake Crossroads	9.9	.434	.295	.189	.137	.100	.058	.048
87246	Little Brier Cr., Nelson	8.53	.003	0	0	0	0	0	0
87249	Stirrup Iron Cr., Morrisville	25.4	.004	0	0	0	0	0	0
87251	Crabtree Cr., Cary	52.1	.019	.010	.005	.003	.002	.001	.0005
87254	Crabtree Cr., Raleigh	59.2	.033	.019	.010	.006	.004	.002	.001
87258	Sycamore Cr., Cary	10.1	.013	.002	0	0	0	0	0
87259	Sycamore Cr., Asbury	11.5	.007	0	0	0	0	0	0
87260	Turkey Cr., Leesville	4.53	.067	.019	.004	.001	.0005	0	0
87264	Richlands Cr., Asbury	6.38	.294	.135	.055	.029	.015	.005	.004
87270	Haresnipe Cr., Millbrook	7.22	.200	.103	.048	.028	.016	.006	.005
87274	House Cr., Method	2.78	.400	.236	.129	.083	.054	.025	.020
87275	Crabtree Cr., Raleigh	97.5	.103	.059	.032	.020	.013	.006	.005
87290	Mine Cr., Millbrook	8.77	.400	.299	.213	.167	.131	.087	.076
87296	Crabtree Cr., Lassiter's Mill	110	.166	.066	.023	.011	.005	.001	.0009
87308	Beaver Dam Cr., Raleigh	5.47	.192	.078	.028	.013	.006	.002	.001
87318	Big Br., Millbrook	1.13	.472	.301	.179	.123	.085	.045	.036
87320	Big Br., Millbrook	3.78	.383	.302	.231	.190	.156	.112	.100
87322	Crabtree Cr., Raleigh	121	.189	.083	.032	.016	.008	.003	.002

Table II (continued)

Station	Location	A_D (MI^2)	7-day low flow (cfsm) for indicated return period						
			1 yr.	2 yrs.	5 yrs.	10 yrs.	20 yrs.	50 yrs.	100 yrs.
87326	Pigeon House Cr., Raleigh	4.25	.534	.366	.238	.173	.127	.075	.063
87329	Marsh Cr., Raleigh	8.45	.316	.167	.080	.047	.028	.011	.008
87331	Crabtree Cr., Raleigh	140	.246	.137	.070	.043	.027	.012	.009
87334	Crabtree Cr., Raleigh	146	.233	.113	.049	.027	.015	.005	.004
87354	Wildcat Br., Raleigh	2.2	.161	.057	.018	.007	.003	.001	0
87368	Big Br. Trib, Garner	1.3	.571	.271	.115	.062	.034	.012	.008
87370	Big Br., Garner	12	.336	.226	.144	.103	.074	.043	.035
87410	Poplar Cr., Knightdale	8.7	.431	.331	.245	.196	.158	.109	.096
87590	Swift Cr., McCullers	40	.043	.012	.003	.001	0	0	0
87610	Swift Cr., McCullers	54	.152	.075	.033	.018	.010	.004	.003
87761	Little Cr., Clayton	3.84	.117	.064	.033	.020	.012	.005	.004
88380	Cedar Fk., Rolesville	5.2	.132	.050	.016	.007	.003	.001	.0005
88434	Buffalo Cr., Wendell	16	.055	.007	.001	0	0	0	0
88441	Buffalo Cr., L. Wendell	21	.325	.188	.100	.064	.041	.019	.014
90021	Moccasin Cr., Pilot	14	.137	.045	.013	.005	.002	0	0
90040	Moccasin Cr., Zebulon	28	.105	.021	.003	.001	0	0	0
102180	White Oak Cr., Holly Springs	21	0	0	0	0	0	0	0

Table II (continued)

Station	Location	A_D (MI^2)	7-day low flow (cfsm) for indicated return period						
			1 yr.	2 yrs.	5 yrs.	10 yrs.	20 yrs.	50 yrs.	100 yrs.
102337	Kenneth Cr., Fuquay Springs	5.6	.103	.024	.005	.001	0	0	0
102386	Kenneth Br., Fuquay Springs	4.0	.047	.011	.002	.001	0	0	0
102457	Kenneth Br., Chalybeate	14	.214	.111	.052	.030	.017	.007	.005

Table II-A - Low Flow Durations

Station	Location	A_D (MI^2)	Flow (cfs/mi^2) which was equaled or exceeded for indicated percent of time									
			1	10	30	50	60	70	80	90	95	99
87053	Smith Cr Grissom	6.23	-	-	-	.526	.355	.222	.129	.056	.029	-
87060	Beaverdam Cr Creedmoor	44	-	-	.406	.101	.045	.017	.006	.001	0	0
87080	New Light Cr Purnell	19.2	1.59	.98	.705	.584	.523	.459	.394	.312	.260	.145
87120	Upper Barton Cr Bayleaf	12.4	2.21	1.09	.663	.501	.426	.351	.280	.198	.152	.064
87160	Lower Barton Cr Bayleaf	13.2	1.66	.98	.676	.548	.485	.420	.354	.274	.223	.117
87174	Horse Cr Forestville	11.5	2.48	1.46	1.01	.822	.727	.630	.532	.411	.337	.177
87175	Horse Cr Wake Forest	20.8	1.31	.92	.723	.629	.580	.527	.471	.396	.347	.226
87181	Honeycutt Cr Falls	8.5	1.62	1.08	.816	.696	.634	.568	.499	.410	.352	.215
87185	Richland Cr Trib Wake Forest	0.25	-	-	-	-	-	-	-	-	-	-
87186	Richland Cr Wake Forest	6.3	.363	.350	.341	.337	.334	.331	.327	.321	.317	.303
87188	Richland Cr Forestville	10	1.56	1.15	.929	.824	.768	.706	.640	.552	.492	.339
87189	Richland Cr Wyatt	13	2.43	1.37	.917	.730	.640	.547	.455	.343	.276	.137
87193	Smith Cr Wake Forest	3	1.08	.577	.374	.292	.253	.214	.175	.129	.102	.048
87194	Austin Cr Wake Forest	4.6	3.85	1.61	.878	.623	.510	.402	.304	.199	.143	.050
87196	Hatters Br Wake Forest	1.8	3.61	1.57	.877	.631	.521	.415	.318	.212	.155	.056
87204	Smith Cr Rolesville	23	.601	.496	.434	.402	.385	.365	.344	.313	.291	.230

Table II-A (continued)

Station	Location	A_D (MI^2)	Flow (cfs/mi^2) which was equaled or exceeded for indicated percent of time									
			1	10	30	50	60	70	80	90	95	99
87206	Mill Cr W. Crsrds	3.6	1.58	1.01	.738	.618	.558	.493	.428	.344	.290	.168
87208	Toms Cr W. Crsrds	1.25	-	-	-	-	.841	.761	.677	.566	.492	.315
87220	Powell Cr Wake Crsrds	9.9	2.26	1.29	.878	.705	.620	.533	.446	.340	.276	.140
87246	Little Brier Cr Nelson	8.53	-	-	-	.100	.037	.011	.003	0	0	0
87249	Stirrup Iron Cr Morrisville	25.4	-	2.24	.225	.061	.029	.012	.004	.001	0	0
87251	Crabtree Cr Cary	52.1	.266	.108	.057	.040	.033	.026	.019	.012	.009	.003
87254	Crabtree Cr Raleigh	59.2	.399	.179	.103	.075	.062	.050	.039	.026	.017	.007
87258	Sycamore Cr Cary	10.1	-	2.08	.343	.123	.068	.034	.015	.004	.002	0
87259	Sycamore Cr Asbury	11.5	-	-	-	.237	.090	.029	.008	.001	0	0
87260	Turkey Cr Leesville	4.53	-	2.33	.655	.318	.209	.127	.071	.029	.015	.002
87264	Richlands Cr Asbury	6.38	-	-	-	.762	.590	.436	.306	.178	.117	.030
87270	Hare Snipe Cr Millbrook	7.22	3.14	1.229	.641	.443	.357	.277	.205	.130	.091	.029
87274	House Cr Method	2.78	3.77	1.766	1.043	.773	.649	.528	.415	.286	.215	.086
87275	Crabtree Cr Raleigh	97.5	1.03	.470	.273	.201	.168	.135	.105	.072	.054	.021
87290	Mine Cr Millbrook	8.77	1.32	.875	.658	.560	.509	.455	.399	.327	.280	.170
87296	Crabtree Cr Lassiters Mill	110	-	-	.849	.507	.375	.263	.173	.092	.056	.011

Table II-A (continued)

Station	Location	A_D (MI^2)	Flow (cfs/mi^2) which was equaled or exceeded for indicated percent of time									
			1	10	30	50	60	70	80	90	95	99
87308	Beaver Dam Cr. Raleigh	5.47	-	-	.943	.570	.424	.300	.199	.107	.066	.014
87318	Big Br. Millbrook	1.13	-	-	-	.820	.707	.593	.483	.353	.277	.126
87320	Big Br. Millbrook	3.78	1.03	.736	.583	.511	.473	.432	.388	.330	.290	.193
87322	Crabtree Cr. Raleigh	121	6.00	1.86	.822	.518	.395	.287	.198	.112	.072	.017
87326	Pigeon House Br. Raleigh	4.25	-	-	-	.851	.752	.649	.547	.420	.343	.178
87329	Marsh Cr. Raleigh	8.45	-	-	-	.693	.561	.438	.327	.209	.148	.049
87331	Crabtree Cr. Raleigh	140	2.84	1.237	.693	.500	.413	.329	.252	.168	.123	.045
87334	Crabtree Cr. Knightdale	146	5.11	1.800	.873	.579	.455	.343	.246	.148	.100	.028
87354	Wildcat Br. Raleigh	2.2	-	-	-	.570	.407	.273	.170	.083	.048	.008
87368	Big Br. Trib Garner	1.3	-	-	-	-	1.133	.846	.601	.357	.239	-
87370	Big Br. Garner	12	1.74	.993	.672	.538	.473	.406	.339	.258	.209	.105
87410	Poplar Cr. Knightdale	8.7	1.34	.914	.702	.604	.554	.499	.442	.367	.318	.200
87590	Swift Cr. McCullers	40	9.11	1.481	.419	.205	.135	.082	.046	.019	.010	.001
87610	Swift Cr. McCullers	54	3.00	1.092	.541	.363	.288	.218	.158	.097	.066	.019
87761	Little Cr. Clayton	3.84	1.43	.613	.340	.243	.200	.159	.121	.080	.058	-
88380	Cedar Ck. Rolesville	5.2	8.16	2.02	.769	.444	.322	.221	.141	.072	.042	.008
88434	Buffalo Cr. Wendell	16	-	-	-	.651	.337	.155	.062	.015	.005	0
88441	Buffalo Cr. L. Wendell	21	-	-	-	.637	.532	.430	.335	.229	.171	-
90021	Moccasin Cr. Pilot	14	-	-	-	.530	.368	.239	.144	.067	.037	.005

Table II-A (continued)

Station	Location	A_D (MI2)	Flow (cfs/mi^2) which was equaled or exceeded for indicated percent of time									
			1	10	30	50	60	70	80	90	95	99
90040	Moccasin Cr. Zebulon	28	-	-	1.930	.771	.451	.239	.114	.037	.015	.001
102180	White Oak Cr. Holly Springs	21	-	-	-	-	.115	.009	.001	0	0	0
102337	Kenneth Cr. Fuquay Springs	5.6	-	-	1.335	.594	.370	.211	.109	.040	.019	-
102386	Kenneth Br. Fuquay Springs	4.0	-	-	.664	.290	.178	.101	.051	.018	.008	.001
102457	Kenneth Br. Chalybeate	14	3.53	1.367	.708	.487	.392	.303	.224	.141	.099	-

APPENDIX III

INDEX OF COMMUNITY WATER SYSTEMS LOCATED ON PLATE 1

1 - Barclay Downs
2 - Bentley Woods
4 - Camelot
6 - Carriage Hills
8 - Conly Drive
9 - Country Squire Estates
11 - El Camino
12 - Emerald Village
13 - Fairview Wooded Acres
17 - Gaylee Village
18 - Greenbriar Estates
19 - Green Pine Park
20 - Green Pines
22 - Heritage Springs Acres
23 - Hidden Valley
26 - Lakeside Estates MHP
28 - MacGregor Downs
29 - McCullers Pines
30 - Martindale/Trotters Ridge
31 - Meadowlake
32 - Medfield Estates
33 - Neuse Woods MHP
34 - North Forest
35 - Northgate
39 - Pine Forest
40 - Pineview Estates MHP
41 - Ponderosa
43 - Ridge Haven
46 - Roundtree
47 - Royal Acres
49 - Springdale Estates
50 - Wakefield South
51 - Westgate Estates
52 - Heritage Point
53 - Stonehenge
55 - Glendale
56 - Kingsland Woods
60 - Springdale Gardens
61 - Rollingwood
63 - Deerfield Park
64 - Nottingham Forest
66 - Stonebridge
67 - Kensington Meadows
73 - Homestead Village
74 - Sandy Chase
76 - Ashley Hills
79 - Turner Farms
80 - Brandon Station
81 - House MHP
87 - Berkshire Downs
89 - Coachmans Trail/Trappers Creek
90 - Kilt Valley
92 - Baytree
94 - Chari Heights
96 - Crosswinds
97 - Forest Trail Estates
98 - Gatewood
99 - Lakewood Estates
100 - Legend Hills
101 - Orchard Knoll
102 - Pine Country Estates MHP
103 - Ravenwood
104 - Riverview Estates
105 - Rockwood Acres
106 - Rolling Acres
107 - Springdale Woods
108 - Swift Ridge
109 - Timberline North
110 - Willow Creek
111 - Willow Winds
112 - Woodscreek
113 - Woodstone
114 - Woodvalley
115 - All Star MHP
118 - Buffaloe MHP
119 - Burnette MHP
120 - Camelot Court MHP
121 - Countryside MHP
122 - Country Squire MHP
123 - Creekside MHP
126 - Dogwood Acres MHP
127 - Dreamland MHP
128 - Edgemont MHP
131 - Horseshoe MHP
132 - Hunts MHP
133 - Johnson and Sons MHP
134 - Jones MHP
137 - Lakeview MHP
138 - Litchford MHP
139 - Little River MHP
140 - Mead-O-View MHP
141 - Merritt MHP
142 - Mobile Hill MHP

APPENDIX III (continued)

143 - Middleton's MHP
144 - Oak Grove MHP
145 - Oak Hill MHP
146 - Oakwood MHP
147 - Plantation MHP
149 - Pleasant Grove MHP
150 - Plummer's MHP
151 - Richardson MHP
152 - Riverview MHP
154 - Rock Dell MHP
156 - Riverview North MHP
157 - Shady Acres MHP
163 - Valley Woods MHP
164 - Village Squire MHP
165 - Watkins MHP
166 - Wellington MHP
167 - Whispering Pines MHP
169 - Brookwood
170 - Cambridge Estates
171 - Crowsdale/Lynnhaven
174 - Hi House MHP
175 - Weston MHP
178 - Middle Creek Acres
180 - Oak Ridge MHP
181 - Oakmont
183 - Shady Knolls
185 - Terra MHP

MHP = Mobile Home Park

APPENDIX IV

MAPS

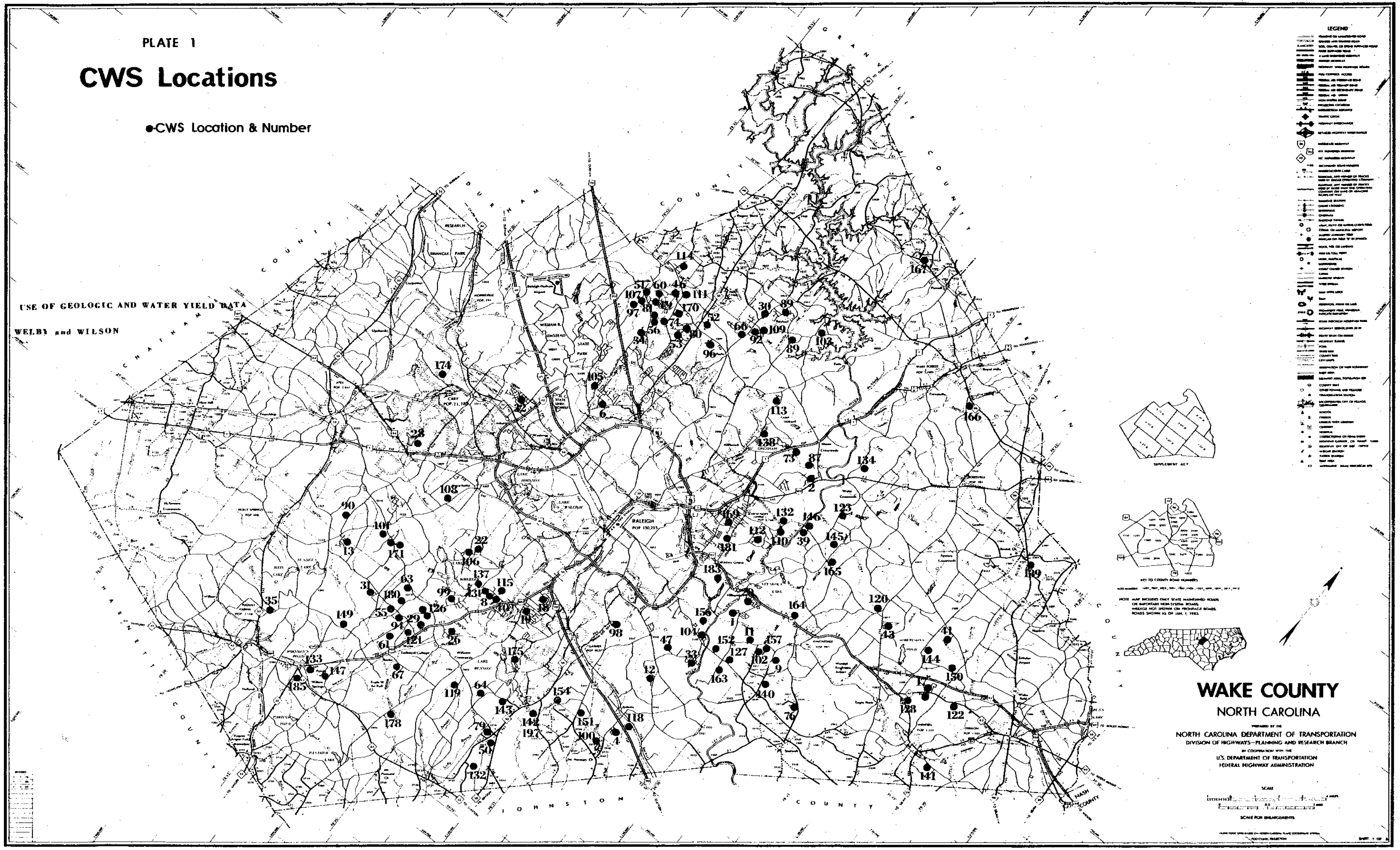
PLATE 1

CWS Locations

●CWS Location & Number

USE OF GEOLOGIC AND WATER YIELD DATA

WELBY and WILSON



2)

PLATE 2

7-DAY, 10-YEAR LOW STREAM FLOWS

(CFS/MI^2)

● USGS LOW FLOW STATION

USE OF GEOLOGIC and WATER YIELD DATA

WELBY and WILSON

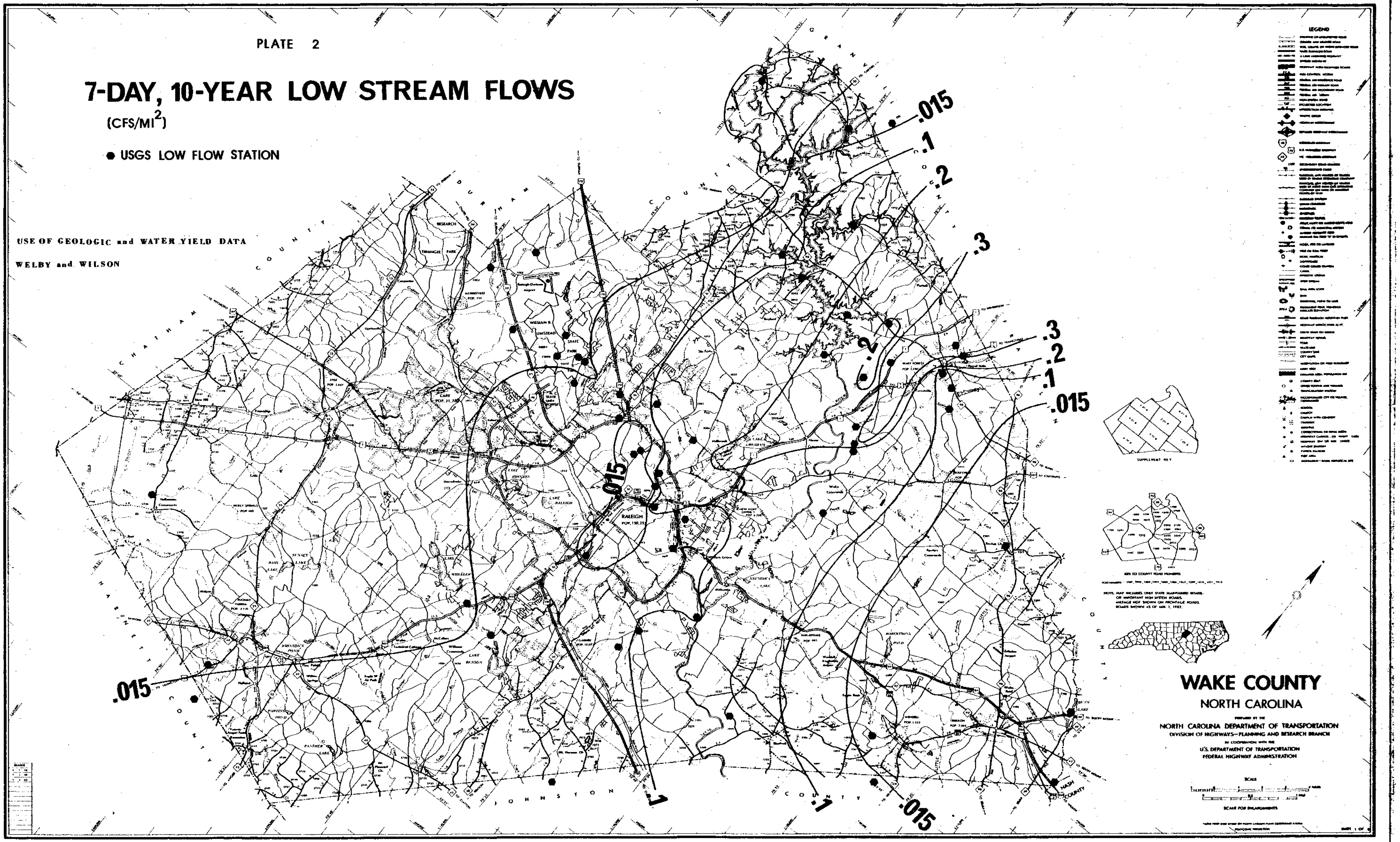
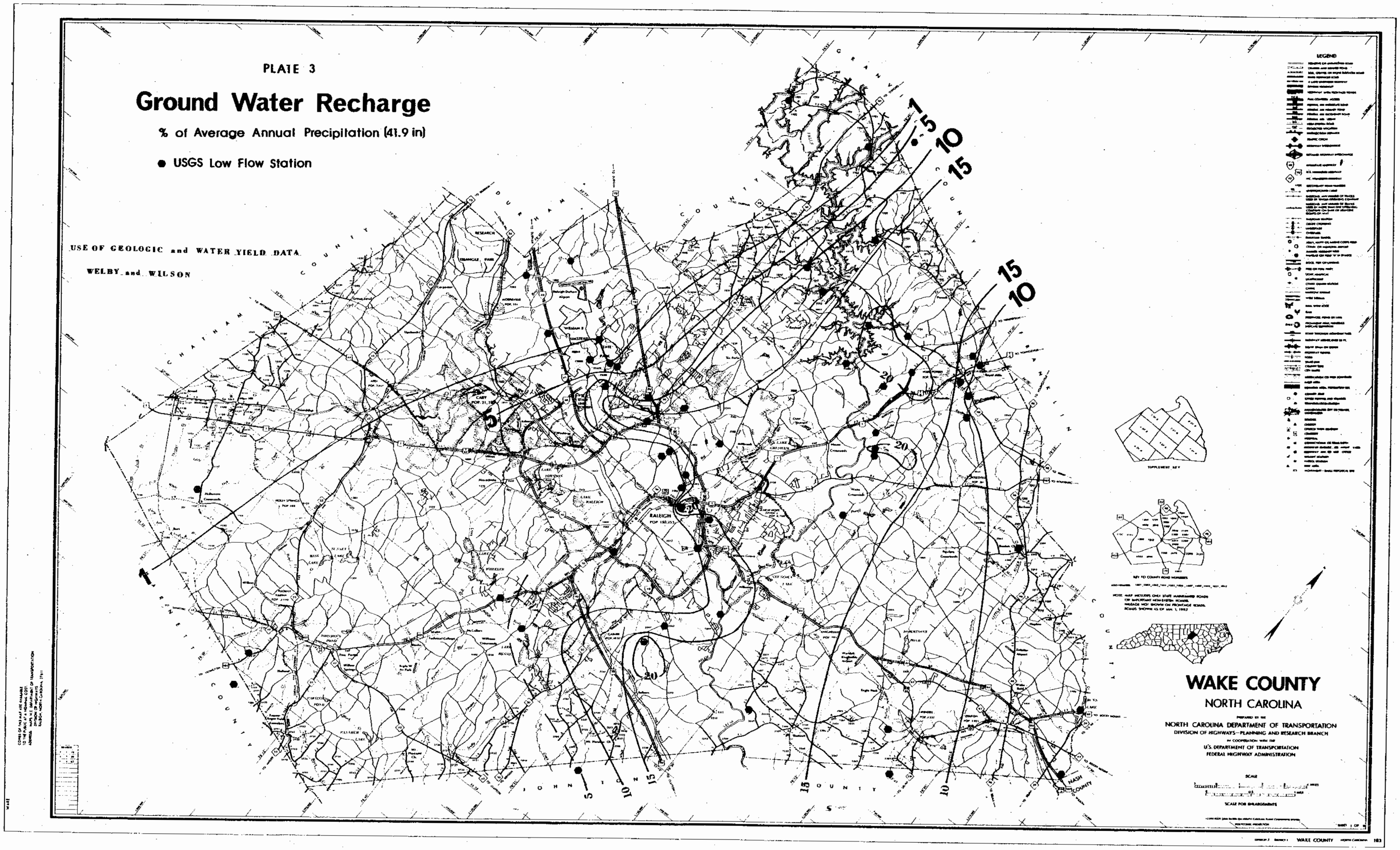


PLATE 3

Ground Water Recharge

% of Average Annual Precipitation (41.9 in)

● USGS Low Flow Station



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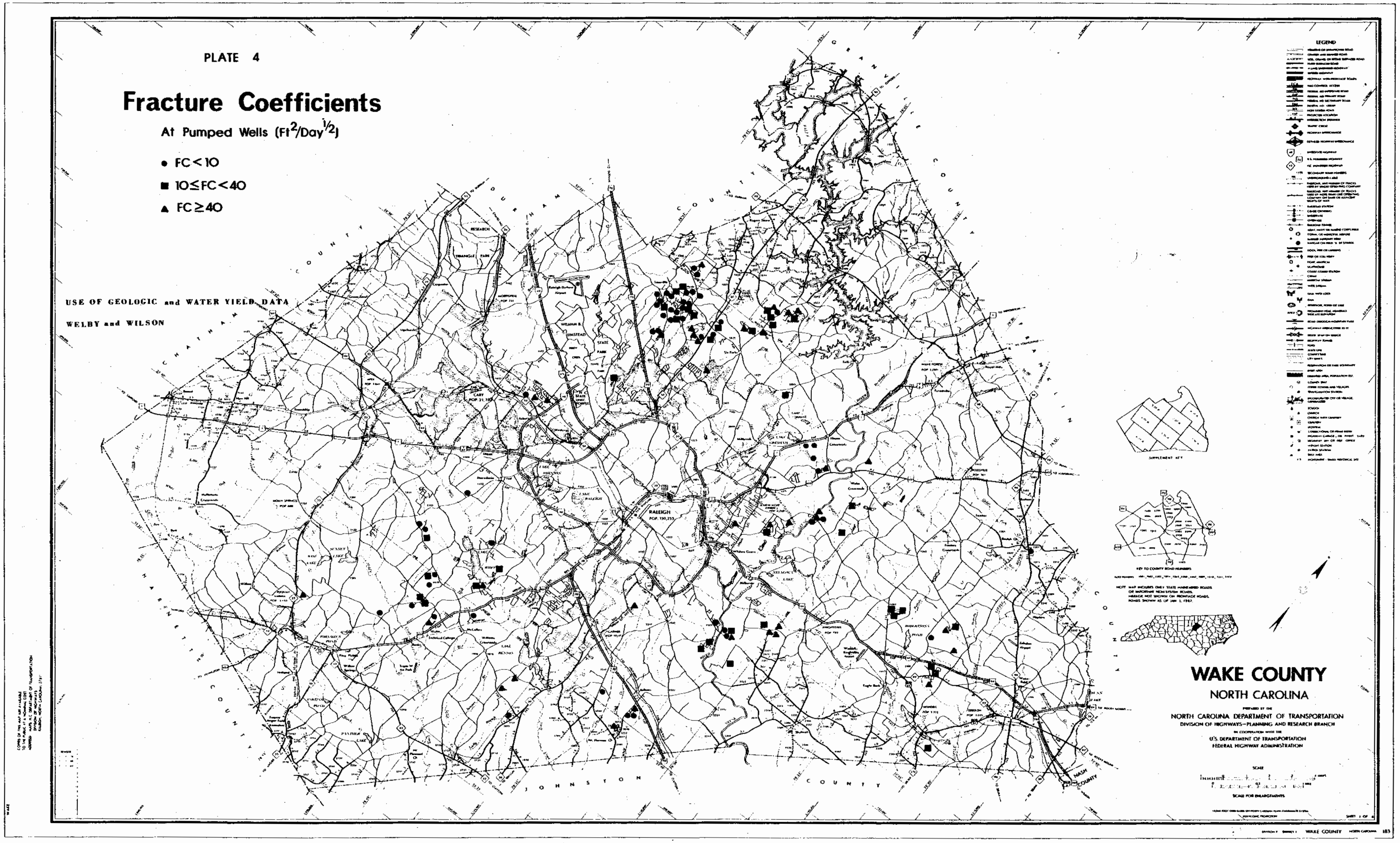


PLATE 4

Fracture Coefficients

At Pumped Wells ($Ft^2/Day^{1/2}$)

- ● $FC < 10$
- ■ $10 \le FC < 40$
- ▲ $FC \ge 40$

USE OF GEOLOGIC and WATER YIELD DATA

WELBY and WILSON

5

PLATE 5-LOW YIELD & ABANDONED WELLS

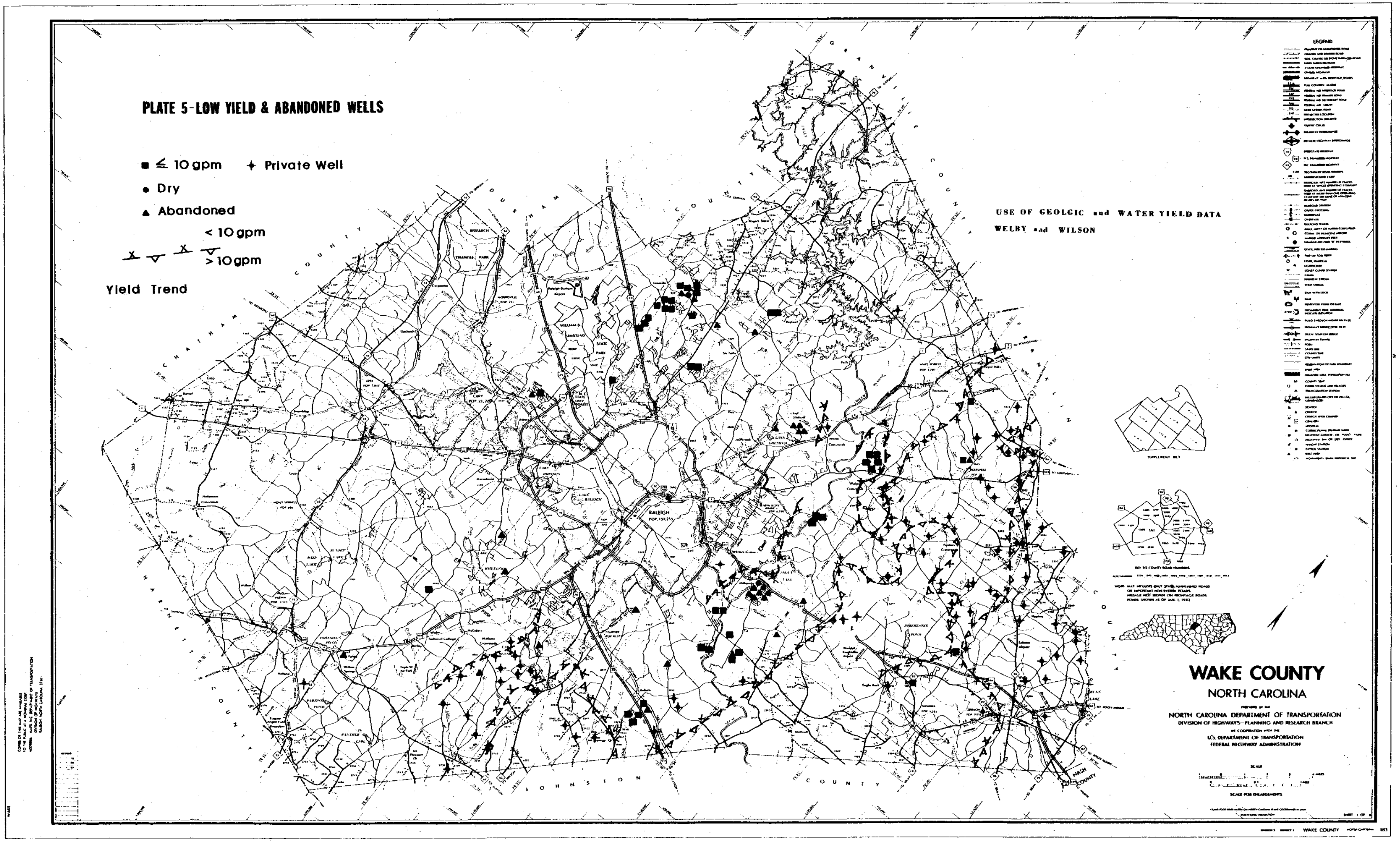


PLATE 6

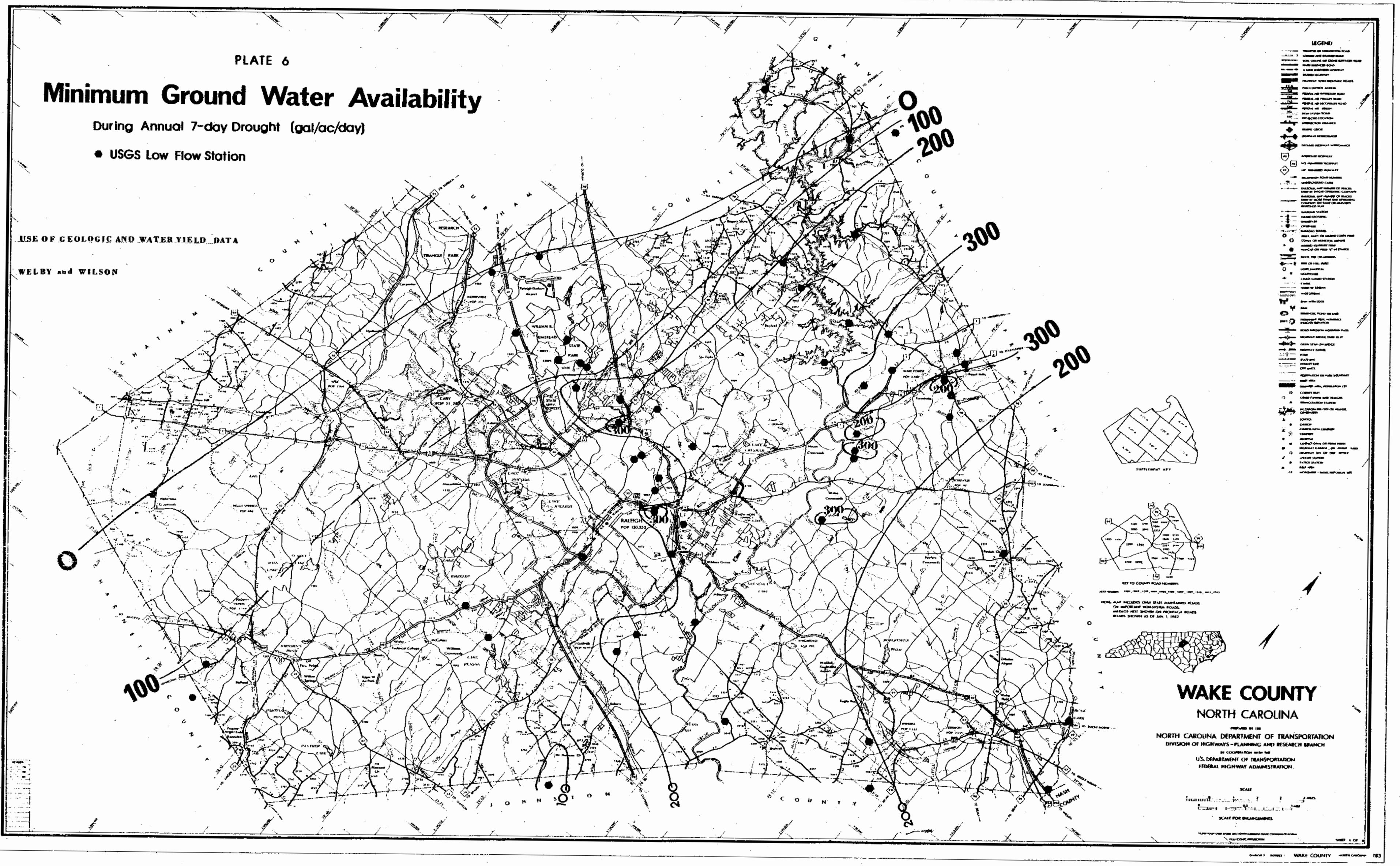
Minimum Ground Water Availability

During Annual 7-day Drought (gal/ac/day)

● USGS Low Flow Station

USE OF GEOLOGIC AND WATER YIELD DATA

WELBY and WILSON



WAKE COUNTY

NORTH CAROLINA

PREPARED BY THE

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

DIVISION OF HIGHWAYS—PLANNING AND RESEARCH BRANCH

IN COOPERATION WITH THE

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

SCALE

SCALE FOR ENLARGEMENTS

SHEET 1 OF 6