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# PREDICTING WATER WELL PRODUCTIVITY IN THE DOUGHERTY PLAIN, GEORGIA

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## ABSTRACT

Analysis of fracture trace and sinkhole characteristics near 33 wells drawing water from the Ocala Limestone aquifer beneath the Dougherty Plain of southwest Georgia, revealed that the distance from a well to the closest fracture trace (DISTL) explained 67% of the variation in well productivities. When the wells were grouped into fracture trace wells (within 25 ft of a fracture trace) and nonfracture trace wells, DISTL explained 74%, and two variables, percent area covered by sinkholes, and the distance to the closest sinkhole, explained 89% of the variation in nonfracture and fracture trace well productivities respectively.

## INTRODUCTION

In the Dougherty Plain region of southwest Georgia, covering an area of about 4,500 square miles, ground water is used extensively for agricultural irrigation and as a source of industrial, domestic, and municipal water supplies (Fig. 1).[a] Most of the water comes from the Ocala Limestone, a subaquifer of the Floridan aquifer, one of the most productive aquifers in the United States. A major problem in utilizing the Ocala aquifer is that well productivity varies widely from place to place and is extremely difficult to predict before drilling. This is a common problem in carbonate regions where ground-water flow is predominantly through interconnected solution cavities developed along lines of secondary permeability defined by faults and joints. Wells that penetrate solution cavities have high yields, those that do not, provide little water or may even be dry. Reliable methods of detecting the major ground-water-flow zones in the Dougherty Plain are needed for the most economical development of its ground water resources.

[a]The research presented in this paper utilizes English units of measurement as these are the common units of ground-water hydrology in the U.S.A.





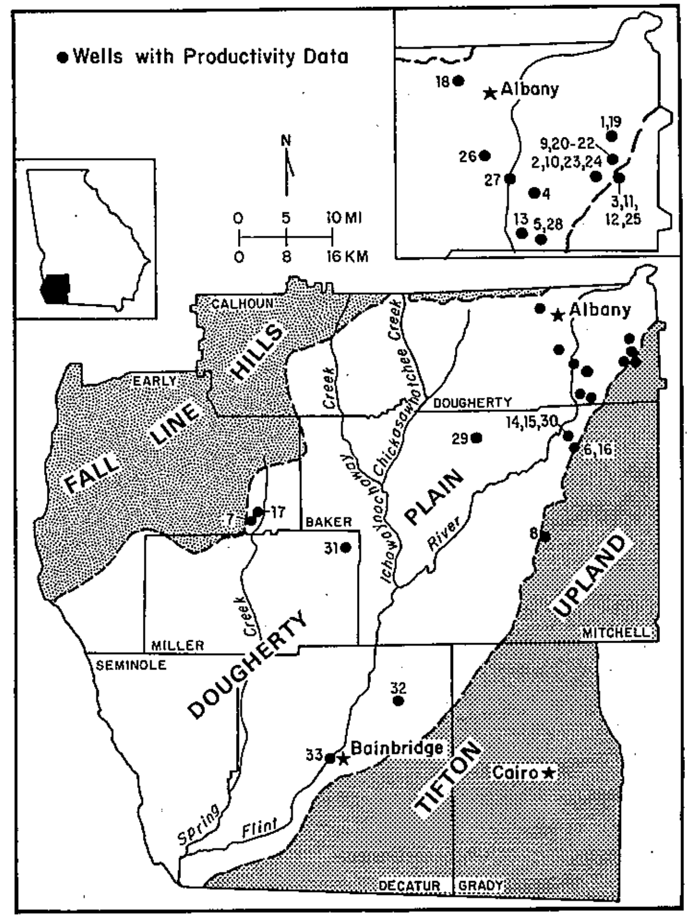


*Fig. 1 The Study Area with the Locations of Wells with Productivity Data.*

Previous studies in carbonate areas have demonstrated that wells located on lineaments or fracture traces have higher productivities than wells located in interfracture areas (1-3). Lineaments are natural linear features from one to hundreds of miles long which are visible on aerial photographs and satellite images. They are believed to be the surface manifestations of bedrock fracture zones (4). Fracture traces are lineaments less than one mile long (1, 5). Wells drilled over fracture zones have higher yields because they are more likely to encounter underground solution cavities containing water. Usually, fewer fracture traces are visible on aerial photographs of carbonate areas where the bedrock is covered by a thick layer of residuum than are visible on photographs of karst areas with only a thin soil cover. As a result, it was hypothesized that fracture

trace data alone may not be sufficient to model the productivities of wells in the Dougherty Plain. Studies by Ogden and Reger (6) in West Virginia suggest that sinkhole data may be useful in estimating the frequency and locations of subsurface cavities, which define zones of high aquifer permeability. From an examination of eleven 1.0 square mile sample areas, they obtained Spearman rank correlation coefficients of 0.86 and 0.73 between doline density and cave footage, and between percent area in dolines and cave footage, respectively.

Therefore, this study examines relationships between well productivity in gpm/ft/10 ft and the fracture trace characteristics in the area near the well, and also examines relationships between well productivity and sinkhole characteristics. The work was undertaken to obtain an understanding of the environmental factors that influence well productivity and to obtain data that might suggest a simple methodology for the location of high productivity well sites.

## THE STUDY AREA

The Dougherty Plain, bounded in the west by the Chattahoochee River and in the east by the Pelham Escarpment, is a physiographic sub-province of the Georgia Coastal Plain. Annual rainfall ranges from 46-56 inches and averages 53 inches. The Plain slopes to the southwest or south from about 300 ft above sea level (a.s.l.) in the north to about 50 ft a.s.l. in the southwest. The surficial geology consists of a residual layer of sand and clay derived from chemical weathering of the underlying Ocala Limestone. This residuum ranges from a few feet to more than 125 ft thick with an average of 50 ft. Beneath the residuum is the Ocala Limestone of late Eocene age which dips at approximately 12 ft/mile to the southeast. The Ocala ranges from a few feet thick at its updip limit in the northwest to more than 400 ft thick in the extreme southeast of the study area. The Ocala has a considerable capacity to store and transmit large quantities of water, due largely to the fractured nature of the limestone. Water moving through these fractures has produced sizeable, generally interconnected solution cavities or caves which have given the limestone an extremely high secondary permeability.

Net ground-water movement through the Ocala aquifer in the Dougherty Plain region is from northwest to southeast. However, the local direction of flow is determined by the topography, with movement towards the nearest surface water body. The Ocala is exposed along sectons of the major streams such as the Chattahoochee and Flint rivers and Spring Creek where erosion has removed the residuum. The Ocala Limestone is underlain by the Middle Eocene Lisbon Formation which consists of hard, well-cemented, sandy, clayey limestone. The Lisbon is a poor aquifer and hydraulically separates the Ocala from underlying sediments. As a result of the cavernous nature of the Ocala Limestone, the Dougherty Plain is characterized by numerous shallow sinkholes, blind stream valleys, and sinking streams. Most sinkholes were formed by subsidence of the surface residuum into solution cavities in the underlying Ocala Limestone. The Dougherty Plain is, in fact, a covered karst region, which is an area of carbonate bedrock overlain by a thick residual soil.



## DATA CHARACTERISTICS, COLLECTION, AND ANALYSIS

The yield of a well may be expressed in terms of its specific capacity, which is defined as the yield in gallons per minute per foot of drawdown (gpm/ft) for a stated pumping period. The specific capacity is affected predominantly by the hydraulic properties of the aquifer but also by the pumping period and the depth of saturated rock penetrated by the open section of the well bore. In order to compare well yields, specific capacity data must be adjusted to a common pumping period, and then divided by the depth of saturated rock pentrated to give a productivity value in gpm/ft of drawdown/unit of saturated rock penetrated.

To test for possible relationships between well productivity and fracture trace and sinkhole characteristics, data for 33 wells of similar radius, drawing water from the Ocala aquifer, were obtained from Georgia Geological Survey files (Table I). The wells ranged from 91 to 390 ft. deep and the open section of the well bore in the Ocala Limestone (wells were cased through the layer of residuum) from 41 to 240 ft. Well specific capacities, determined from pumping tests varying from 3 to 48 hours, varied from 4 to 1,040 gpm/ft. Based on data in Mitchell (7), it is apparent that water levels in most wells penetrating the Ocala Limestone beneath the Dougherty Plain tend to stabilize after one to six hours of pumping so that no standardization of well specific capacities for pumping period was necessary. Specific capacities were corrected for the depth of saturated rock pentrated by the open section of the well bore to determine productivity values in gpm/ft of drawdown/10 ft of saturated rock penetrated (Table I).

After well locations were checked in the field they were plotted on 1:24,000 scale topographic maps. Fracture traces and sinkholes were then mapped in circular sample areas 1600 ft in radius centered upon each well (Fig. 2). The size of the sample area was chosen by conducting a scree test. This revealed that an area of 1600 ft radius was the largest area in which sinkhole and fracture trace characteristics remained relatively uniform. Fracture traces and sinkholes were mapped from 1:59,000 and 1:20,000 scale black and white aerial photographs, and 1:24,000 scale color infrared images (NASA Earth Resources Project 1473). The 1:59,000 scale black and white photographs were flown in 1950. The area was flown at the 1:20,000 scale in 1948, 1964, and 1969. Color infrared images of Dougherty County were obtained in 1973. Information from the images was transferred to 1:24,000 scale topographic maps correcting for photographic distortion using a Bausch and Lomb Zoom Transfer Scope. Fracture traces were mapped largely from sinkhole shapes, from the presence of aligned sinkholes, and from tonal contrasts in soil and vegetation (1).

Eleven environmental parameters, including seven measures of the fracture trace population and four measures of the sinkhole population, were measured in the circular sample areas around the wells. These variables, their abbreviations used in the text, and their possible hydrogeological significance are shown in Table II. As sinkholes in the Dougherty Plain are formed by the migration of surface residuum into subsurface solution cavities, and as fracture traces are considered to be the surface evidence of underlying bedrock fractures, increases in the number of fracture traces (LINDEN), the number of fracture trace intersections (INTDEN), the total length of fracture traces (LENDEN), the number of sinkholes (SIKNO), and the percent area covered by sinkholes

TABLE I. FRACTURE TRACE AND NONFRACTURE TRACE WELL DATA, DOUGHERTY PLAIN, GEORGIA.

| Well* I.D. | Well Name | Depth (ft) | Depth of Open Hole (ft) | PROD (gpm/ft/10ft) | $\log_e$(PROD) | DISTL (ft) | LINDEN (no/mi2) | LENDEN (mi/mi2) | INTDEN (no/mi2) | SIKNO (no/mi2) | SIKDEN (%) | DISTIN (ft) | DISIK (ft) | LENTH (ft) | SIZSIK (mi2) | FRASI (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Firestone #1 | 265 | 70 | 148.57 | 5.00106 | 0 | 27.7 | 46386 | 27.7 | 90.1 | 19.1 | 82 | 157 | 1968 | 0.0005 | 3779 |
| 2 | Fleming Farm #10 | 290 | 220 | 34.09 | 3.52900 | 0 | 13.9 | 24557 | 6.9 | 48.5 | 5.8 | 472 | 0 | 4408 | 0.0017 | 3700 |
| 3 | Fleming Farm #12 | 310 | 235 | 21.28 | 3.05777 | 0 | 17.3 | 28923 | 10.4 | 52.0 | 11.0 | 253 | 394 | 2519 | 0.0016 | 5825 |
| 4 | Proctor & Gambell #1 | 215 | 109 | 87.71 | 4.47404 | 0 | 34.7 | 61803 | 62.4 | 93.6 | 14.1 | 33 | 0 | 1102 | 0.0001 | 2913 |
| 5 | Merck & Co. #2 | 247 | 168 | 23.81 | 3.17011 | 0 | 27.7 | 30583 | 13.9 | 79.7 | 4.7 | 197 | 118 | 1338 | 0.0005 | 6534 |
| 6 | Branch Grove #4 | 285 | 192 | 39.06 | 3.66510 | 16 | 6.9 | 20601 | 3.5 | 41.6 | 9.7 | 220 | 236 | 3700 | 0.0170 | 7951 |
| 7 | Mitchell Farms #1 | 91 | 41 | 73.17 | 4.29279 | 16 | 20.8 | 21147 | 3.5 | 38.1 | 9.3 | 197 | 94 | 1378 | 0.0002 | 3149 |
| 8 | Camilla #3 | 341 | 186 | 26.88 | 3.29138 | 10 | 17.3 | 18282 | 13.9 | 38.1 | 2.7 | 164 | 79 | 2519 | 0.0002 | 5510 |
| 9 | Fleming Farm #9 | 285 | 192 | 13.02 | 2.56649 | 82 | 24.3 | 45840 | 31.2 | 17.3 | 27.5 | 1063 | 394 | 2362 | 0.0076 | 6219 |
| 10 | Fleming Farm #7 | 290 | 200 | 9.35 | 2.23538 | 82 | 13.9 | 19919 | 10.4 | 24.3 | 9.2 | 646 | 236 | 1574 | 0.0009 | 6219 |
| 11 | Fleming Valley | 271 | 124 | 20.16 | 3.00370 | 82 | 27.7 | 28923 | 17.3 | 48.5 | 8.9 | 354 | 197 | 1417 | 0.0002 | 2125 |
| 12 | Fleming Farm #14 | 300 | 190 | 19.74 | 2.98265 | 33 | 31.2 | 39292 | 20.8 | 38.1 | 14.5 | 275 | 315 | 1338 | 0.0133 | 5274 |
| 13 | Frank Wetherbee | 234 | 124 | 17.58 | 2.86676 | 33 | 27.7 | 48569 | 27.7 | 62.4 | 3.6 | 236 | 165 | 2204 | 0.0005 | 3936 |
| 14 | Branch Grove #1 | 275 | 156 | 16.03 | 2.77446 | 33 | 17.3 | 23739 | 10.4 | 45.1 | 8.9 | 1181 | 0 | 2362 | 0.0078 | 5195 |
| 15 | Branch Grove #2 | 250 | 140 | 9.71 | 2.27316 | 66 | 6.9 | 8459 | 0.0 | 34.7 | 6.7 | 1850 | 157 | 1338 | 0.0003 | 5904 |
| 16 | Branch Grove #5 | 295 | 150 | 22.00 | 3.09104 | 66 | 6.9 | 18964 | 3.5 | 20.8 | 17.2 | 1181 | 275 | 6376 | 0.0007 | 10863 |
| 17 | Mitchell Farms #9 | 153 | 107 | 17.98 | 2.88926 | 82 | 13.9 | 21556 | 6.9 | 27.7 | 8.2 | 512 | 315 | 2755 | 0.0130 | 5904 |
| 18 | Doublegate Utility #1 | 125 | 55 | 0.73 | -0.31471 | 866 | 13.9 | 5321 | 3.5 | 17.3 | 2.3 | 1640 | 1063 | 1312 | 0.0013 | 4566 |
| 19 | Firestone #2 | 284 | 134 | 5.82 | 1.76130 | 180 | 17.3 | 18282 | 10.4 | 38.1 | 13.8 | 551 | 708 | 4959 | 0.0342 | 1732 |
| 20 | Fleming Farm #28 | 300 | 230 | 3.09 | 1.12817 | 164 | 27.7 | 30015 | 24.3 | 55.5 | 3.1 | 354 | 197 | 1338 | 0.0001 | 2204 |
| 21 | Fleming Farm #5 | 260 | 190 | 6.58 | 1.88403 | 98 | 13.9 | 20192 | 10.4 | 20.8 | 16.0 | 1023 | 472 | 4408 | 0.0167 | 6455 |
| 22 | Fleming Farm #6 | 295 | 147 | 7.28 | 1.98513 | 118 | 20.8 | 24284 | 20.8 | 62.4 | 3.9 | 394 | 354 | 1259 | 0.0002 | 2598 |
| 23 | Fleming Farm #8 | 310 | 240 | 1.87 | 0.62594 | 275 | 10.4 | 6549 | 0.0 | 48.5 | 1.7 | 708 | 275 | 866 | 0.0002 | 1653 |
| 24 | Fleming Farm #3 | 275 | 157 | 4.52 | 1.50851 | 426 | 13.9 | 26740 | 10.4 | 27.7 | 19.1 | 669 | 472 | 3267 | 0.0009 | 4881 |
| 25 | Fleming Farm #11 | 280 | 175 | 14.28 | 2.65886 | 79 | 13.9 | 20192 | 13.9 | 41.6 | 4.1 | 292 | 79 | 1141 | 0.0007 | 2676 |
| 26 | Bob's Candy Company | 190 | 108 | 2.13 | 0.75612 | 472 | 10.4 | 26058 | 6.9 | 17.3 | 2.8 | 787 | 472 | 3857 | 0.0040 | 7085 |
| 27 | Blue Springs Plant | 190 | 121 | 2.81 | 1.05318 | 410 | 10.4 | 20737 | 3.5 | 27.7 | 3.3 | 1338 | 433 | 3031 | 0.0013 | 5353 |
| 28 | Merck & Co. #6 | 240 | 125 | 3.76 | 1.32442 | 423 | 20.8 | 30015 | 13.9 | 27.7 | 3.3 | 394 | 472 | 1968 | 0.0039 | 6534 |
| 29 | Wallington #1 | 180 | 108 | 12.59 | 2.53290 | 98 | 13.9 | 14462 | 0.0 | 48.5 | 6.0 | 1968 | 315 | 1968 | 0.0040 | 3149 |
| 30 | Branch Grove #3 | 270 | 160 | 2.94 | 1.07841 | 316 | 17.3 | 25239 | 6.9 | 52.0 | 6.6 | 459 | 433 | 1929 | 0.0009 | 4644 |
| 31 | Jo-So-Li #15 | 210 | 80 | 10.50 | 2.35138 | 321 | 10.4 | 20055 | 6.9 | 31.2 | 4.3 | 512 | 394 | 2913 | 0.0044 | 5904 |
| 32 | J. C. Dollar | 200 | 100 | 17.10 | 2.83908 | 118 | 34.7 | 46113 | 34.7 | 132.0 | 6.3 | 164 | 315 | 1811 | 0.0018 | 3306 |
| 33 | Bainbridge Mills #2 | 240 | 195 | 10.26 | 2.32825 | 118 | 20.8 | 33152 | 20.8 | 101.0 | 4.8 | 197 | 118 | 3772 | 0.0002 | 5038 |

* Wells 1-8 are fracture trace wells
Wells 9-33 are nonfracture trace wells



TABLE II. ENVIRONMENTAL VARIABLES USED IN MULTIPLE REGRESSION ANALYSIS AND THEIR POSSIBLE INFLUENCE ON WELL PRODUCTIVITY.

| Variable Description | Variable Abbreviation | Hydrogeological Significance |
|---|---|---|
| Number of fracture traces (no/mi2) | LINDEN | Estimates of the average secondary permeability in the bedrock around the well bore and the degree of integration of lines of secondary permeability. Ground water movement to the well bore should increase with increases in these variables. |
| Number of fracture trace intersections (no/mi2) | INTDEN | |
| Total length of fracture traces (mi/mi2) | LENDEN | |
| Number of sinkholes (no/mi2) | SIKNO | Estimates of the average secondary permeability in the bedrock near the well bore and also of the degree of large subsurface cavity development. Ground water flow to the well bore should increase with increases in these variables. |
| Area covered by sinkholes (%) | SIKDEN | |
| Distance to the nearest fracture trace (ft) | DISTL | Estimates of the closeness of a well to possible zones of high secondary permeability. Ground water flow to a well should increase with decreases in these variables. |
| Distance to the nearest fracture trace intersection (ft) | DISTIN | |
| Distance to the nearest sinkhole (ft) | DISIK | |
| Length of the closest fracture trace (ft) | LENTH | Estimates of the magnitude of ground water flow in zones of high secondary permeability near a well. Ground water flow to a well should increase with increases in these variables. |
| Total length of fracture traces forming the closest fracture trace intersection (ft) | FRASI | |
| Size of the closest sinkhole (long axis x short axis) in mi2 | SIZSIK | |

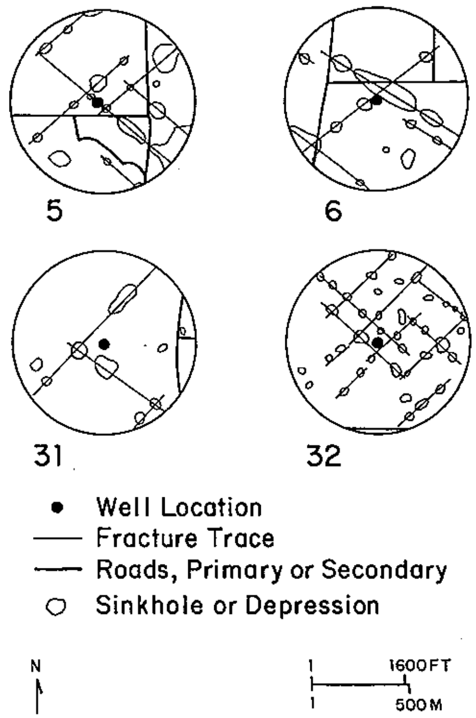


*Fig. 2 Fracture Traces and Sinkholes Mapped in Circular Sample Areas Around Wells 5, 6, 31, and 32, Dougherty Plain, Georgia.*

(SIKDEN) should all reflect an increase in aquifer secondary permeability and the magnitude of ground-water flow in the region around the well.

The distances between a well and the nearest fracture trace (DISTL), the nearest fracture trace intersection (DISTIN) and the nearest sinkhole (DISIK) are measures of the proximity of the well to possible localized zones of higher aquifer permeability. Wells on or close to such zones should have higher productivity. Ground-water flow to a well bore is also likely to increase with increases in the length of the nearest fracture trace (LENTH), the total length of fracture traces making up the nearest fracture trace intersection (FRASI), and the size of the closest sinkhole (SIZSIK). This is because fracture zones of considerable horizontal and vertical extent, which are characterized by large solution cavities, are likely to be more important ground-water-flow routes.

Bivariate and multiple linear regression analysis techniques were employed to test for possible relationships between well productivity (the dependent variable) and the fracture trace and sinkhole characteristics in the area around the well (the independent variables). As regression analysis is a basic tool in geographic research, the details of the technique are not presented here. Information on the method, governing assumptions, and problems of use with geographic data is



presented in King (8) and Silk (9). Quantitative analysis was conducted using packaged programs described in Helwig and Council (10).

## FRACTURE TRACE AND NONFRACTURE TRACE WELLS

Parizek (1) recognizes two main classes of wells — namely fracture trace wells which penetrate bedrock fracture zones (9 to 100 ft wide depending on rock type) delimited by fracture trace mapping; and nonfracture trace wells which are located in interfracture areas. Parizek has demonstrated that fracture trace wells have significantly higher productivities. To examine the possible existence of fracture trace and nonfracture trace wells in the Dougherty Plain, well productivities in gpm/ft/10 ft (abbr. as PROD) were transformed to natural logarithms to approximately linearize the relationship between PROD and DISTL and a scattergram was plotted (Fig. 3.) The scattergram showed that in the Dougherty

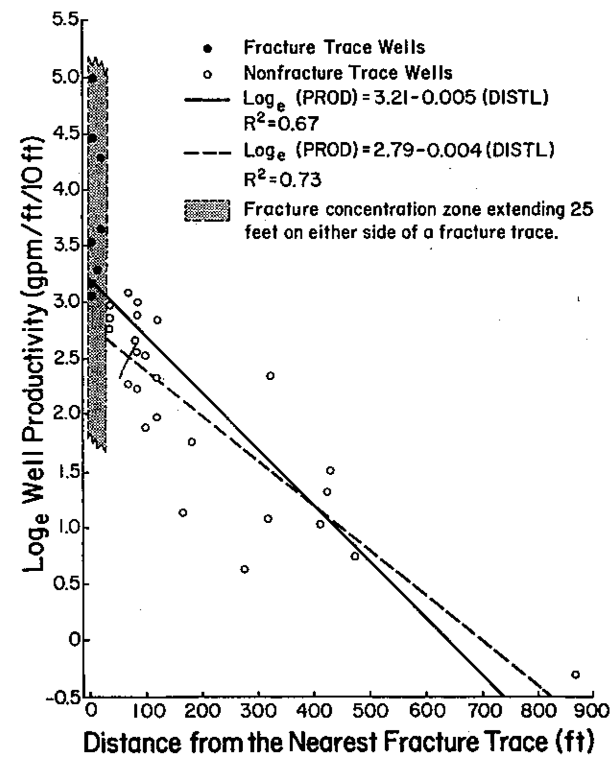


*Fig. 3 Relationship Between Well Productivity and the Distance to the Nearest Fracture Trace.*

Plain eight wells within 25 ft of a fracture trace have significantly higher productivities than the other 25 wells. Linear regression analysis revealed that although the model:

$$\log_e(\text{PROD}) = 3.21 - 0.005\ (\text{DISTL})$$

explained 67% of the initial variability in well productivities, it seriously underpredicted the productivities of wells close to fracture traces and generally overpredicted the productivities of wells between 25 and 500 ft from a fracture trace (Fig. 3, Table III). The much higher productivities of the eight wells within 25 ft of a fracture trace suggest that these are fracture trace wells which penetrate bedrock fracture zones approximately 50 ft wide. Using Parizek's (1) classification, the remaining 25 wells are considered to be nonfracture trace wells.

To determine if fracture trace and nonfracture trace well productivities are affected by proximity to a fracture trace, bivariate linear regression models were developed. The relationship:

$$\log_e\ (\text{PROD}) = 2.79 - 0.004\ (\text{DISTL})$$

was found to explain 73% of the variation in the productivities of nonfracture trace wells, while the relationship:

$$\log_e\ (\text{PROD}) = 3.81 + 0.0005\ (\text{DISTL})$$

explained only 0.003% of the variablity in fracture trace well productivity (Fig. 3, Table III). These three models indicate that well productivity is greatly increased if the well is located close to a fracture trace. For nonfracture trace wells, distance to a fracture trace explains fully 73% of well productivity variablity. However, the productivities of wells located within 50 ft-wide fracture zones are not affected significantly by distance to the center of the zone. As the productivities of these eight wells vary from 21.28 to 148.57 gpm/ft/10 ft, it is clear that additional hydrogeological factors influence the flow of water to these wells. Therefore, in subsequent analyses the two groups of wells were examined separately, as well as together, to isolate these additional environmental factors.

TABLE III. BIVARIATE LINEAR REGRESSION MODELS USING DISTL TO PREDICT WELL PRODUCTIVITY.

| MODEL NUMBER | SIGNIFICANCE OF REGRESSION PROB>F | MODEL PARAMETERS | PARAMETER VALUES | $R^2$ |
|---|---|---|---|---|
| ALL WELL DATA | | | | |
| I | 0.0001 | Intercept<br>DISTL | 3.21<br>-0.005 | 0.67 |
| FRACTURE TRACE WELL DATA | | | | |
| II | 0.9891 | Intercept<br>DISTL | 3.81<br>0.0005 | 0.00003 |
| NONFRACTURE TRACE WELL DATA | | | | |
| III | 0.0001 | Intercept<br>DISTL | 2.79<br>-0.004 | 0.73 |



## STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS

Stepwise multiple regression analysis with $\log_e$ (PROD) as the dependent variable was performed separately on all 33 wells, on the eight fracture trace wells, and on the 25 nonfracture trace wells. Models were developed using sinkhole and fracture trace variables, fracture trace variables only, and sinkhole variables only (Table IV). Only uncorrelated independent variables ($r < 0.5$) were used in the analysis. Well productivities were transformed to natural logarithms to approximately linearize data relationships. The best statistical models were chosen largely on the basis of the adjusted $R^2$ value given by :

$$\text{adjusted } R^2 = 1 - \left(\frac{n-1}{n-p-1}\ (1-R^2)\right),$$

where n is the number of observations and p the number of independent variables in the model. The adjusted $R^2$ value is appropriate for comparison of models with different numbers of independent variables developed from sample populations of different size.

Results indicate that 72% (adj. $R^2 = 0.70$) of the variation in the productivities of the 33 Dougherty Plain wells was explained by two fracture trace variables DISTL and LENDEN, and 68% (adj. $R^2 = 0.63$) of the variation by three sinkhole variables DISIK, SIKDEN, and SIKNO (Table IV, models IV and V). However, it is apparent that more accurate predictions can be achieved by using separate models to predict fracture trace and nonfracture trace well productivities. For example, 89% (adj. $R^2 = 0.85$) of the variation in fracture trace well productivity was explained by two sinkhole variables, SIKDEN and DISIK with SIKDEN providing 64% of the explanation (Fig. 4), while 76% (adj. $R^2 = 0.75$) of the variation

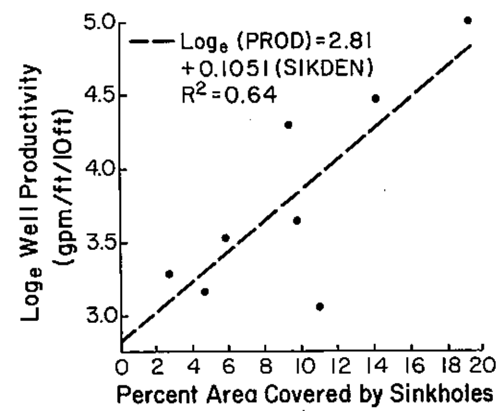


*Fig. 4 Relationship Between Fracture Trace Well Productivity and Percent Area Covered by Sinkholes.*

TABLE IV. MULTIPLE LINEAR REGRESSION MODELS USING ENVIRONMENTAL VARIABLES TO PREDICT WELL PRODUCTIVITY.

| Model Number | Data Used to Develop Model* | Significance of Regression Prob. > F | Model Parameters | Parameter Values | Significance of Parameters Prob. > F | $R^2$ | Adjusted $R^2$ | Variance Explained by Each Variable |
|---|---|---|---|---|---|---|---|---|
| FRACTURE TRACE AND NONFRACTURE TRACE WELLS | | | | | | | | |
| IV | FTS and FT | 0.0001 | Intercept<br>DISTL<br>LENDEN | 2.5695<br>-0.0045<br>0.00002 | 0.0001<br>0.0361 | 0.72 | 0.70 | 67%<br>5% |
| V | S | 0.0001 | Intercept<br>DISIK<br>SIKDEN<br>SIKND | 2.3256<br>-0.0033<br>0.0811<br>0.0086 | 0.0001<br>0.0003<br>0.0965 | 0.68 | 0.63 | 48%<br>17%<br>3% |
| FRACTURE TRACE WELLS | | | | | | | | |
| VI | FTS and S | 0.0038 | Intercept<br>SIKDEN<br>DISIK | 3.0501<br>0.1786<br>-0.0028 | 0.0018<br>0.0183 | 0.89 | 0.85 | 64%<br>25% |
| VII | FT | 0.0887 | Intercept<br>FRASI | 5.0260<br>-0.0002 | 0.0887 | 0.41 | 0.31 | 41% |
| NONFRACTURE TRACE WELLS | | | | | | | | |
| VIII | FTS and FT | 0.0001 | Intercept<br>DISTL<br>FRASI | 2.4212<br>-0.0039<br>0.00008 | 0.0001<br>0.0895 | 0.76 | 0.75 | 73%<br>3% |
| IX | S | 0.0001 | Intercept<br>DISIK<br>SIKDEN | 2.5046<br>-0.0028<br>0.0586 | 0.0001<br>0.0056 | 0.60 | 0.56 | 43%<br>17% |

* FTS = fracture trace and sinkhole data; FT = fracture trace data only; S = sinkhole data only.



TABLE V.
PREDICTIONS OF WELL PRODUCTIVITIES USING MODELS IV, VI, AND VIII.

| Well Number | Observed Productivity (gpm/ft/10ft) | Predicted Productivity (gpm/ft/10ft)[1] | |
|---|---|---|---|
| | | Model IV | Models VI and VIII[2] |
| 1 | 148.57 | 34.90 | 131.77 |
| 2 | 34.09 | 21.97 | 42.01 |
| 3 | 21.28 | 24.10 | 26.20 |
| 4 | 87.71 | 48.38 | 112.40 |
| 5 | 23.81 | 24.97 | 26.61 |
| 6 | 39.06 | 18.81 | 34.75 |
| 7 | 73.17 | 19.03 | 49.06 |
| 8 | 26.88 | 18.40 | 23.38 |
| 9 | 13.02 | 23.92 | 13.39 |
| 10 | 9.35 | 13.81 | 13.39 |
| 11 | 20.16 | 16.71 | 9.65 |
| 12 | 19.74 | 25.91 | 15.06 |
| 13 | 17.58 | 31.54 | 13.54 |
| 14 | 16.03 | 18.64 | 14.97 |
| 15 | 9.71 | 11.64 | 13.91 |
| 16 | 22.00 | 14.54 | 20.67 |
| 17 | 17.98 | 14.30 | 13.05 |
| 18 | 0.73 | 0.31 | 0.53 |
| 19 | 5.82 | 8.61 | 6.35 |
| 20 | 3.09 | 11.86 | 6.82 |
| 21 | 6.58 | 12.93 | 12.81 |
| 22 | 7.28 | 12.90 | 8.69 |
| 23 | 1.87 | 4.40 | 4.34 |
| 24 | 4.52 | 3.44 | 3.09 |
| 25 | 14.28 | 14.08 | 10.21 |
| 26 | 2.13 | 2.76 | 3.07 |
| 27 | 2.81 | 3.25 | 3.42 |
| 28 | 3.76 | 3.73 | 3.57 |
| 29 | 12.59 | 11.46 | 9.83 |
| 30 | 2.94 | 5.44 | 4.68 |
| 31 | 10.50 | 4.77 | 5.08 |
| 32 | 17.10 | 20.49 | 9.20 |
| 33 | 10.26 | 15.57 | 10.57 |

1. The best predictions are underlined

2. Fracture trace well productivities (wells 1-8) are predicted using Model VI, nonfracture trace well productivities (wells 9-33) with Model VIII.

in nonfracture trace well productivity was explained by two fracture trace variables DISTL and FRASI (Table IV, models VI and VIII). As Table V shows, models VI and VIII more accurately predicted the productivities of 21 wells and model II provided better estimates of well productivity in 12 cases. This finding appears to confirm that fracture trace and nonfracture trace wells should be treated as separate populations for the purpose of modelling well productivity. It is also apparent that both sinkhole and fracture trace data are needed to predict the productivities of Dougherty Plain wells accurately.

## CONCLUSIONS

This study has demonstrated that there is a much greater probability of obtaining a high productivity well in the Dougherty Plain covered karst region if the well is located within 25 ft of a fracture trace mapped from aerial photographs. Some 67% of the variation in well productivity is explained by one fracture trace variable, the distance between the well and the closest fracture trace (DISTL). A further finding is that sinkhole characteristics near a well can be used to estimate well productivity. Three variables: distance to the center of the nearest sinkhole (DISIK), percent area covered by sinkholes (SIKDEN), and the density of sinkholes (SIKNO) explained 68% of the variation in the productivities of the 33 wells examined in this study. In covered karst regions, therefore, subsidence sinkholes at the surface can provide important hydrogeological data about subsurface aquifers.

Based on studies of the entire well data set, it is also apparent that wells in the Dougherty Plain fall into two distinct groups with regard to their productivity values. Wells located within 25 ft of a fracture trace (fracture trace wells) shows significantly higher productivities than wells located at greater distances (nonfracture trace wells). This is taken to indicate that fracture traces are the surface manifestations of bedrock fracture zones approximately 50 ft wide (25 ft on either side of the fracture trace), that define lines of increased secondary permeability and ground-water flow. The equation: $\log_e$ (PROD) = 2.79 - 0.004 (DISTL) explained 73% of the variability in nonfracture trace well productivity. This indicates that for these wells the distance to the nearest fracture trace is the dominant control on well productivity because it defines the closest zone of concentrated ground-water flow. The equation also suggests that fracture trace wells, with DISTL ≤ 25 ft, should have productivities of at least 14.7 gpm/ft/10 ft (Fig. 3)

Fracture trace well productivity cannot be predicted accurately using the variable DISTL alone. Presumably this is because all wells in this group penetrate bedrock fracture zones, and ground-water flow need not necessarily be greatest in the centers of such zones. In fact, 64% of fracture trace well productivity can be explained by the variable SIKDEN, the percent area near the well covered by sinkholes (Fig. 4), and fully 89% of the variability can be explained by two sinkhole variables SIKDEN and DISIK. This result implies that the degree of large subsurface cavity development in the aquifer near the well (indicated by SIKDEN), and the distance between the well and the nearest large subsurface solution cavity (indicated by DISIK), are important in determining the flow of water to the fracture zone penetrated by the well bore. Fracture trace well productivity is therefore increased in areas where numerous subsidence sinkholes have developed, as these indicate a cavernous aquifer and a well integrated ground-water-flow system in the region.

Because of their simplicity, the predictive models developed in this study can be used by water resource planners and well drillers to locate high productivity wells. A greater number of such wells in the Dougherty Plain would reduce the cost of pumping ground water for agriculture and industry. Furthermore, well locations can be chosen carefully to avoid the danger of ground subsidence resulting from excessive ground water withdrawals and the development of a



cone of depression in the piezometric surface. Ground subsidences are more likely above bedrock fracture zones defined by fracture traces. By locating a well just beyond such fracture zones high productivity can be obtained without risking the danger of ground subsistence.

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## REFERENCES

1. Parizek RR: On the nature and significance of fracture traces and lineaments in carbonate and other terranes. In Karst Hydrology and Water Resources, Volume 1 (Yevjevich, Ed) Fort Collins: Water Resources Publications, 1976, 47-100.

2. LaRiccia MP and Rauch HW: Water well productivity related to photolineaments in carbonates of Frederick Valley, Maryland. In Hydrological Problems in Karst Regions (Dilamarter and Csallany, Eds) Bowling Green: Western Kentucky University, 1977, 228-234.

3. Moore GH and Hollyday EF: Prospecting for groundwater with SKYLAB photographs, central Tennessee. Remote Sens Earth Resour 4:499-519, 1975.

4. Lattman LH and Nickelson RP Photogeologic fracture trace mapping in the Appalachian Plateau. Assoc Pet Geol Bull 42:2238-2245, 1958.

5. Lattman LH: Technique of mapping geologic fracture traces and lineaments on aerial photographs. Photogramm Engng 24:568-576, 1958.

6. Ogden AW and Reger JP: Morphometric analysis of dolines for predicting ground subsidence, Monroe County, West Virginia. In Hydrologic Problems in Karst Regions (Dilamarter and Csallany, Eds), Bowling Green: Western Kentucky University, 1977, 130-139.

7. Mitchell GD: Hydrogeologic data on the Dougherty Plain and adjacent areas, southwest Georgia. Information Circular 58, Dept. of Natural Resources, Environmental Protection Division, Georgia Geol Surv, 1981, 124 pp (p. 34-44).

8. King LJ: "Statistical Analysis in Geography." Englewood Cliffs: Prentice-Hall, 1969, Chapter 6.

9. Silk J: "Statistical Concepts in Geography." London: George Allen & Unwin, 1979, Chapter 15.

10. Helwig JT and Council KA (eds): SAS User's Guide, Cary, SAS Institute Inc., 1979, 494 pp.