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GEOLOGICAL FACTORS INFLUENCING WELL PRODUCTIVITY IN THE DOUGHERTY PLAIN COVERED KARST REGION OF 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 trace and fracture trace well productivities respectively.

Introduction

In the Dougherty Plain region of southwest Georgia, covering an area of about 4,500 mi^2, groundwater is used extensively for agricultural irrigation and as a source of industrial, domestic, and municipal water supplies (Fig. 1).[1] Most of the water comes from the Ocala Limestone, a sub - aquifer of the principal artesian 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 groundwater 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 will provide little water or may even be dry. Reliable methods of detecting the major groundwater flow zones in the Dougherty Plain are needed for the most economical development of its groundwater resources.

Previous studies in carbonate areas have demonstrated that wells located on lineaments or fracture traces [2] have higher productivities than wells located in interfracture

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[1] *The research presented in this paper utilizes English units of measurement as these are the common units of groundwater hydrology in the U.S.A.*

[2] *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 (Lattman and Nickelson, 1958). Fracture traces are lineaments less than one mile long (Lattman, 1958, Parizek, 1976).*

Exhibit INT355
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areas (eg. Moore and Hollyday,1975, Parizek,1976; LaRiccia and Rauch,1977). 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 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 (1977) in West Virginia suggest that sinkhole data may also 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 mi^2 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.

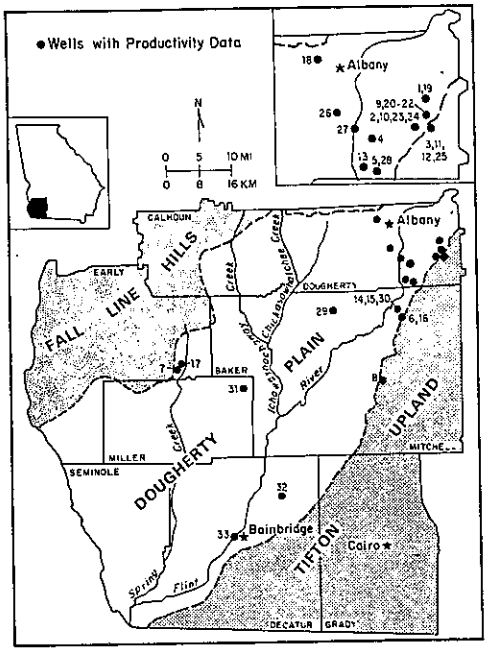

Fig. 1 – The Study Area with the Locations of Wells with Productivity Data.

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 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 then 125 ft thick with an average thickness 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 groundwater movement through the Ocala aquifer in the Dougherty Plain region is from northwest to southeast. However, local direction of flow is determined by the topography, with movement towards the nearest surface water body. The Ocala is exposed along sections 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. Because of the cavernous nature of the Ocala Limestone, the Dougherty Plain is a covered karst [3] characterized by numerous shallow sinkholes, blind stream valleys, and sinking streams. Sinkholes originated by subsidence of the surface residuum into solution cavities in the underlying Ocala Limestone.

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 penetrated 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 1). The wells ranged from 91 to 390 feet deep and the open section of the well bore in the Ocala Limestone

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[3] *A region where carbonate bedrock is covered by thick residual soil.*

Well* I.D.	Well Name	Depth (ft)	Depth of Open Hole (ft)	PROD (gpm/ft/10ft)	Log_e(PROD)	DISTL (ft)	LINDEN (no/mi^2)	LENDEN (mi/mi^2)	INTDEN (no/mi^2)	SIKNO (no/mi^2)	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 #2B	300	230	3.09	1.12817	164	27.7	30015	24.3	55.5	3.1	364	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 1 — Fracture Trace and Nonfracture Trace Well Data, Dougherty Plain, Georgia

(wells were cased through the residual layer) from 41 to 240 feet. 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 (1981, p. 34–44), it is apparent that water levels in most wells penetrating the Ocala Limestone beneath the Dougherty Plain tend to stabilize after 1 to 6 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 penetrated by the open section of the well bore the determine productivity values in gpm/ft of drawdown/10 ft of saturated rock penetrated (Table 1).

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 1,600 ft in radius centered upon each well (Fig.2).). The size of the sample area was chosen by conducting a scale test. This revealed that an area of 1,600 ft radius was the largest area in which sinkhole and fracture trace characteristics remained relatively constant. 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).[4] The information 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 (Parizek 1976).

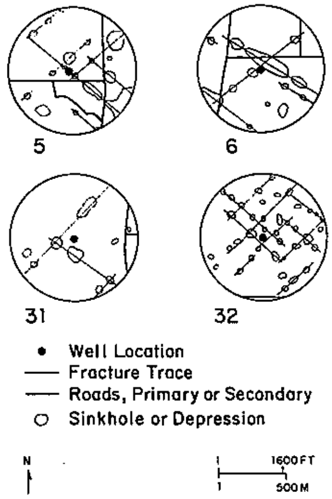

Fig. 2 – Fracture Traces and Sinkholes Mapped in Circular Sample Areas Around Wells 5, 6, 31, and 32, Dougherty Plain, Georgia.

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[4] *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.*

Eleven environmental parameters, including 7 measures of the fracture trace population and 4 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 2. 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 (SIKDEN) should all reflect an increase in aquifer secondary permeability and the magnitude of groundwater 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 productivities. Groundwater 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 groundwater flow routes.

Variable Description	Variable. Abbreviation	Hydrogeological Significance
Number of fracture traces (no/mi^2)	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/mi^2)	INTDEN	
Total length of fracture traces (mi/mi^2)	LENDEN	
Number of sinkholes (no/mi^2)	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 mi^2	SIZSIK	

Table 2— Environmental Variables Used in Multiple Regression Analysis and their Possible Influence on Well Productivity.

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). Quantitative analysis was conducted using packaged programs described in Helwig and Council (1979).

Fracture Trace and Nonfracture Trace Wells

Parizek (1976) recognized 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 well 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 shows that in the Dougherty Plain 8 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 poductivities, 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 3). The much higher productivities of the 8 wells within 35 ft of a fracture trace suggests that these are fracture trace wells which penetrate bedrock fracture zones approximately 50 ft wide. Following Parizek's (1976) differentiation, 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 variability in fracture trace well productivity (Fig. 3, Table 3). These models suggest that fracture trace and nonfracture trace well productivities are affected by different hydrogeological factors and that further analysis should examine these well groups separately as well as together.

Stepwise Multiple Linear Regression Analysis

Stepwise multiple regression analysis with well PROD as the dependent variable was performed separately on all 33 wells, on the 8 fracture trace wells, and on the 25 non-fracture trace wells. Models were developed using sinkhole and fracture trace variables, fracture trace variables only, and sinkhole and fracture trace variables, fracture trace variables only, and sinkhole variables only (Table 4). 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 indipendent variables developed from sample populations of different size.

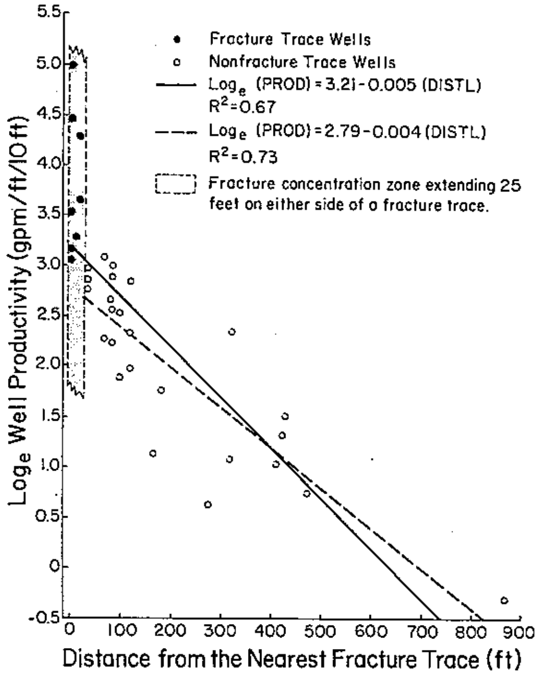

Fig. 3 – Relationship Between Well Productivity and the Distance to the Nearest Fracture Trace.

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

Table 3 — Bivariate Linear Regression Models Using DISTL 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 DISTL LENDEN	2.5695 -0.0045 0.00002	0.0001 0.0361	0.72	0.70	67% 5%
V	S	0.0001	Intercept DISIK SIKDEN SIKNO	2.3256 -0.0033 0.0811 0.0086	0.0001 0.0003 0.0965	0.68	0.63	48% 17% 3%
FRACTURE TRACE WELLS								
VI	FTS and S	0.0038	Intercept SIKDEN DISIK	3.0501 0.1186 -0.0028	0.0018 0.0183	0.89	0.85	64% 25%
VII	FT	0.0887	Intercept FRASI	5.0260 -0.0002	0.0887	0.41	0.31	41%
NONFRACTURE TRACE WELLS								
VIII	FTS and FT	0.0001	Intercept DISTL FRASI	2.4212 -0.0039 0.00008	0.0001 0.0895	0.76	0.75	73% 3%
IX	S	0.0001	Intercept DISIK SIKDEN	2.5046 -0.0028 0.0586	0.0001 0.0056	0.60	0.56	43% 17%

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

Table 4 — Multiple Linear Regression Models Using Environmental Variables to Predict Well Productivity.

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 4, 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 in nonfracture trace well productivity was explained by two fracture trace variables DISTL and FRASI (Table 4, models VI and VIII). As Table 5 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 modeling 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

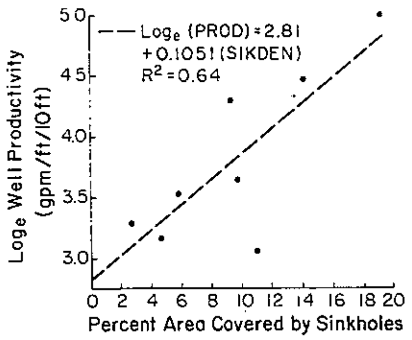

Fig. 4 – Relationship Between Fracture Trace Well Productivity and Percent Area Covered by Sinkholes.

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.

Table 5 – Predictions of Well Productivities Using Models IV, VI, and VIII.

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) show 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 groundwater flow. The equation : Log_e (PROD) = 2.79 – 0.004 (DISTL) explained 73% of the variability in nonfracture trace well productivitiy indicating 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 groundwater 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 can not be predicted accurately using the variable DISTL alone. Presumably this is because all wells in this group penetrate bedrock fracture zones, and groundwater 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 groundwater 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 groundwater for agriculture and industry. Furthermore, well locations can be chosen carefully to avoid the danger of ground subsidence resulting from excessive groundwater 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 subsidence.

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