New Jersey Geological Survey
Open File Report OFR 93-1

WELL INTERFERENCE AND EVIDENCE OF FRACTURE FLOW IN THE PASSAIC FORMATION NEAR PENNINGTON, MERCER COUNTY, NEW JERSEY

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Cover illustration: Servicing a Stevens punch-tape automatic water-level recorder. Photo by Lloyd Mullkin.

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Well Interference and Evidence of Fracture Flow in the Passaic Formation near Pennington, Mercer County, New Jersey

by
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ABSTRACT

An aquifer-stress test was conducted June 3-5, 1986, as part of the Borough of Pennington's application to increase its ground water diversion from 7.75 to 10.85 million gallons per month. The purpose was to ascertain whether borough production wells were causing interference with domestic supply wells located within the borough and in the Dublin Hills subdivision of Hopewell Township, bordering Pennington. The borough's four production wells were pumped at a combined rate of 533 gallons per minute for 48 hours and water-level measurements were recorded at 10 observation wells. All the wells tap the Passaic Formation. In Pennington the Passaic Formation is of Late Triassic age and is composed mainly of interbedded siltstones and mudstones. Ground-water occurrence and movement is controlled by joints and fractures.

Drawdown in Pennington Water Company (PWC) well 6 and in 4 observation wells, located as much as 640 feet away, showed linear flow-field characteristics, suggesting ground-water movement through fractures. Aquifer-test analysis, modeling a high-conductivity vertical fracture, yielded a transmissivity estimate of 11 to 97 feet^2/day. The strike of the modeled fracture passes through the Dublin Hills subdivision. Although interference from PWC-6 was suspected in Dublin Hills, a domestic well showed no drawdown which could be attributed to the test. Further analysis suggests that the stress test duration was too short to produce measurable drawdown in this well. Other data provide stronger evidence of interference between PWC-6 and Dublin Hills domestic wells. A statistical comparison of 1963 static-water levels in the Dublin Hills subdivision with 1987 static-water levels in northern Mercer County suggests a local lowering of the water table in the Dublin Hills area. During the period between April 1984 and December 1986, a domestic well monitored in Dublin Hills showed a seasonal water-level fluctuation of about 20 feet, far more than the 3 feet typically recorded at an observation well 1 mile north of Pennington. Cessation of pumping from PWC-6 for 2 months ending in February 1987 resulted in 15 feet of recovery in the Dublin Hills well, clearly demonstrating interference from the borough's production well.

In the northern part of the borough, the test data unquestionably show that PWC-8 is capable of causing interference with the few nearby domestic wells. A domestic well located 760 feet from PWC- 8 had about 13 feet of drawdown by the end of the test. Aquifer test analysis yielded a transmissivity of 600 ft^2/day and a storativity of 7.5×10^{-5}. Test results in the vicinity of PWC-7 and PWC-5 were inconclusive, but other data from the vicinity of PWC-7 indicate local ground-water drawdown.

INTRODUCTION

This report is a review of factors contributing to alleged well interference problems in the Dublin Hills subdivision of Hopewell Township and in the northern part of Pennington Borough (fig. 1). The work, performed by the New Jersey Geological Survey (NJGS) is a part of the Northwest Mercer County Project, funded under the New Jersey Water Bond Issue of 1981. The results of this investigation were submitted to the New Jersey Department of Environmental Protection and Energy, Bureau of Water Allocation, for consideration in the renewal of a ground-water diversion permit for the Borough of Pennington.

Acknowledgments

The author gratefully acknowledges the many thoughtful suggestions given by New Jersey Geological Survey personnel Robert Canace, Michael Serfes, and I.G. Grossman, which have greatly improved this report. He also wishes to thank Michael Pinelli, Superintendent of Public Works for the Borough of Pennington, for assistance in obtaining data used in this report. The study was funded under the Water Bond Issue of 1981.

Background

In March 1984, the Borough of Pennington petitioned the New Jersey Department of Environmental Protection, Bureau of Water Allocation (BWA), to renew its ground-water diversion permit and increase its maximum monthly pumpage from 7.75 to 10.85 million gallons per month. On July 3, 1984, a public hearing was held on the proposed diversion increase. A transcript of the hearing is on file at the Bureau of Water Allocation (Diversion Permit File No. 5276). Many Hopewell Township residents objected to the Borough's request. Four residents of the Dublin Hills subdivision, which borders Pennington Borough, reported that their wells (wells 1, 2, 3, and 4 on fig. 1) failed during the

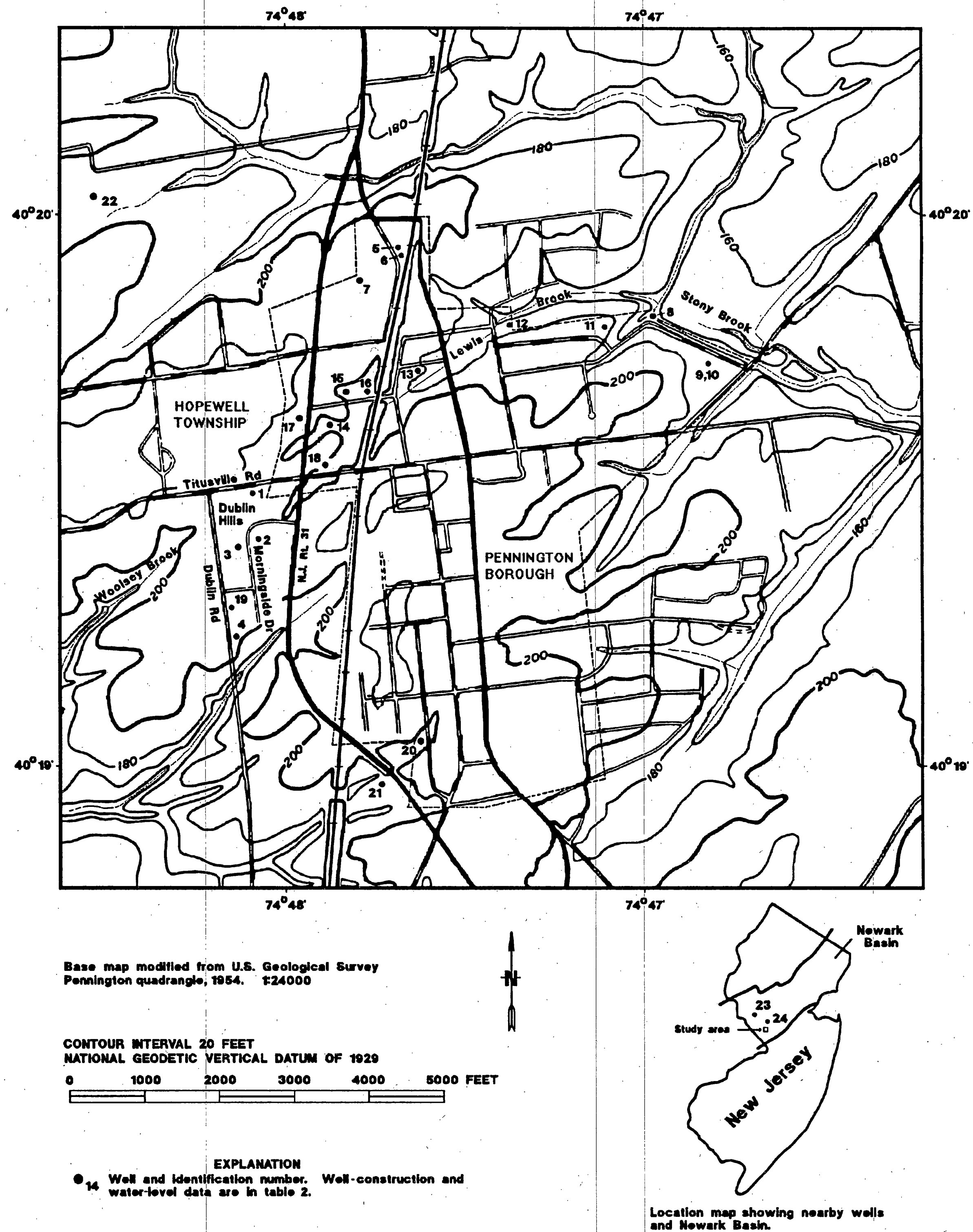


Figure 1. Maps showing location of study area, topgraphy, and wells.

Table 1. Summary of well construction and pumping-test data for wells shown on figure 1.

Well no.	Name	Water use[A]	Location		Elevation[B] (feet)	Depth (feet)	Casing		Static level		Pumping test data			Remarks[D]
			Latitude (deg. min. sec.)	Longitude (deg. min. sec.)			Depth (feet)	Diameter (in.)	(feet)	(date)[C]	Rate (gpm)	Water level (feet)	Duration (hours)	
1	Sheldon Fees	D	40 19 36	74 48 06	200 M	165	--	--	--	--/--/62	--	--	--	
2	Richard Chumney	D	40 19 29	74 48 09	200 M	152	40	6	30	06/24/68	10	100	4	Well failed; deepened to 312 feet
3	Walter Schenck	D	40 19 29	74 48 09	200 M	150	--	--	72	--/--/79	--	--	--	Well failed; deepened to 250 feet
4	Michael Arcien	D	40 19 18	74 48 10	200 M	135	22	6	70	01/01/56	7	120	3	HT-312, well failed; deepened to 215 feet in 1963.
5	Burt Phillips	D	40 20 08	74 47 51	196	--	--	--	--	--	--	--	--	
6	George Halasi-Kun	D	40 20 07	74 47 40	200 M	--	--	--	--	--	--	--	--	
7	Pennington 8	P	40 20 03	74 47 46	194	300	61	10	37	11/09/65	172	141	8	Previously Helene Fuld well.
8	Pennington 5	P	40 19 59	74 46 58	160	400	43	10	29	05/01/67	80	170	24	HT-179, NJUID 21091, yield inadequate, deepened to 400 feet in 1967
9	William Antheil 1	D	40 38 54	74 46 48	170 M	133	26	6	25	09/02/51	15	55	1	HT-159, well sealed, well water tasted like Stony Brook water.
10	William Antheil 2	D	40 38 54	74 46 48	170 M	88	50	6	30	08/01/52	12	60	5	Replacement for Wm. Antheil 1.
11	Pennington 4	U	40 19 58	74 47 06	170	512	38	10	40	11/02/46	33	136	12	HT-178, yield inadequate, used for observation well.
12	J. Neary	D	40 19 58	74 47 23	165	--	--	6	--	--	--	--	--	
13	Thomas Blackwell	U	40 19 53	74 47 37	171	180	--	4	--	--	--	--	--	
14	Pennington 6	P	40 19 47	74 47 54	185	273	43	10	83	11/12/57	201	145	264	HT-175
15	NJGS NWM-OB1	U	40 19 51	74 47 52	189	300	50	6	96	01/23/86	100	--	--	
16	NJGS NWM-OB2	U	40 19 50	74 47 48	180	300	50	6	70	01/15/86	30	--	--	
17	Mercer Mutual	C	40 19 46	74 47 57	200	--	--	6	--	--	--	--	--	
18	Pennington 3	U	40 19 45	74 47 52	180	657	57	8	38	06/--/27	45	150	48	HT-174
19	Henry Ditmars	D	40 19 21	74 48 10	207	167	22	6	75	01/01/57	15	124	4	HT-311, Deepened to 225 feet in 1963, water level below pump.
20	Pennington 7	P	40 19 04	74 47 37	195	300	81	10	10	12/12/63	300	134	24	
21	Ecklund Enterprises	C	40 19 00	74 47 46	189 A	260	63	6	120	11/01/81	15	200	2	Replacement well, old well ran dry in the summer.
22	Henry Harbat	U	40 20 18	74 48 35	186	270	50	10	--	--/--/79	--	--	--	
23	Bird Obs. well	U	40 26 44	74 56 36	342	21	--	--	--	--	--	--	--	NJUID 190002, well taps Stockton formaion.
24	Honey Branch 10	U	40 21 13	74 46 12	180	150	20	6	--	--	40	--	--	NJUID 210088

[A] Water use: **D** - domestic, **P** - public supply, **C** - commercial, **U** - unused (observation well).

[B] Elevation of land surface above sea level is based on precise leveling except those marked A (measured by altimeter), or M (estimated from topographic map). All figures rounded to nearest foot. Map contour intervals are 20 feet so that these estimates are only accurate to about 10 feet (one half a contour interval).

[C] Date of static-water level measurement is also date of well completion.

[D] Remarks: The HT-numbers are Hopewell Township well numbers used by Widmer (1965). The NJUID is a unique identifier used by the U.S. Geological Survey, Water Resources Division. All wells are in the Passaic Formation except well 23, which is in the Stockton Formation.

months of July, August, and September of 1983. They ascribed the failures to overpumping by Pennington Borough. The Pennington Water Company's quarterly reports, on file at the Bureau of Water Allocation, show that during July 1983 the Borough exceeded its permitted diversion by pumping 8.66 million gallons.

The transcript also records two domestic wells which experienced difficulties (wells 5 and 6 in Pennington Borough). This occurred during an April 1 to 4, 1981 pumping test of public supply well PWC-8 (well 7 of table 1).

In view of the local opposition to the proposed increase, a modified diversion permit was granted which called for an aquifer-stress test to enable the Bureau of Water Allocation to ascertain whether the proposed increase diversion would "not unduly interfere with other existing supplies." The test specifications called for the pumping of Pennington's four production wells (table 1) at full capacity for 48 hours while monitoring water levels in available wells in the Borough of Pennington and nearby Hopewell Township.

Hydrogeology

All of the production wells and observation wells for the stress test are finished in the Passaic Formation. This formation consists of the lower part of the former Brunswick Formation, subdivided by Olsen (1980) (table 2). Throughout this report the name Passaic is used instead of Brunswick.

In the vicinity of Pennington, the Passaic Formation is Triassic in age and consists mainly of massive-bedded, red siltstone alternating with medium- to thin-bedded mudstone and siltstone. Less abundant are gray, green, and black lake deposits of thin, interbedded calcareous and carbonaceous siltstone and impure limestone. The lake deposits contain claystone beds which weather deeply to form layers of clay having a plastic consistency. The strata strike about N44°E and dip 12°W. A dominant system of joints strikes about N23°E and dips steeply southeast at nearly 90° (Hugh Houghton, formerly N.J. Geological Survey, written communication, 1983).

Table 2. Stratigraphic nomenclature for the Newark Basin.

Kummel (1898)		Olsen (1980)
Brunswick Shale		Boonton Formation
	Third Watchung Mt.	Hook Mt. Basalt
		Towaco Formation
	Second Watchung Mt.	Preakness Basalt
		Feltville Formation
	First Watchung Mt.	Orange Mt. Basalt
		Passaic Formation
Lockatong Fm.		Lockatong Formation
Stockton Fm.		Stockton Formation

Several authors report fracture-controlled ground-water flow in the Passaic Formation. Others have noted movement parallel to bedding through fractured layers and along bedding planes. Herpers and Barksdale (1951, p. 31) reported evidence of preferential ground-water movement at Newark, New Jersey. They suggested that northeast-southwest movement was facilitated by "a dominant set of vertical cracks" and that transmission along bedding planes was unlikely.

Miller (1964) described recharge effects caused by surface-water impoundments that overlie fracture systems or faults along Honey Branch Brook, about 2.5 miles northeast of Pennington. He reported that fracture systems or faults could be identified in the Passaic by their linear topographic expression. He also observed that drill cuttings from a well penetrating a suspected fault showed brecciation, slickensides, and calcite coatings on the joint surfaces. Miller's (1964) observations on well interference in Pennington will be discussed later in this report. Widmer (1965) observed that wells in northern Mercer County situated on or near linear features, such as straight reaches of streams and swales, had higher yields than those distant from any linear topographic feature. He attributed the enhanced well productivity to open joints or minor faults. He also noted that these linear features extend across drainage divides and contribute in part to the trellis type of stream-drainage pattern in northern Mercer County.

In eastern Pennsylvania, Longwill and Wood (1965) reported that wells aligned perpendicular to the strike of the Passaic Formation generally showed less interference with each other than did wells aligned parallel to strike. In their explanation, wells aligned oblique to strike penetrate different water-bearing strata and are less likely to interfere. They pointed out that their aquifer-test data did not conform to the theoretical response predicted by a Theis (1935) curve, and that aquifer transmissivity and storage coefficients obtained using the Theis method may be unreliable for the Passiac Formation. In a similar study of the Passaic Formation in New Jersey, Vecchioli (1967) also found that standard methods for the calculation of aquifer transmissivity gave questionable results.

Vecchioli and others (1969) performed extensive aquifer tests of the Passaic Formation at a site about 1 mile north of Pennington. During the drilling of 13 wells, they found that ground water occurs in discrete zones. Drill cuttings from the more productive zones were marked by many smooth planar surfaces, interpreted as evidence of well-defined joints. The highly productive zones were traceable from well to well, and their orientation corresponded to the strike and dip of bedding. They concluded that the Passaic is a multi-layered aquifer system with the more jointed strata comprising the aquifers. They also observed that wells aligned along strike penetrate common producing zones and suggested that ground water is able to move more freely in the direction of strike than in other directions. They suggested that well interference be minimized by aligning wells in directions other than parallel to strike.

PENNINGTON AQUIFER-STRESS TEST

The aquifer-stress test was conducted June 3-5, 1986. Pennington's four production wells were pumped continuously for 48 hours at a combined rate of approximately 533 gpm. The recovery was measured for 6 hours. Water levels were monitored in 10 observation wells (6 unused wells and 4 domestic wells), and in the production wells. Water levels in the domestic wells were significantly affected by pumping for domestic use during the test. Nevertheless, the data are adequate to characterize hydrologic conditions.

Aquifer Test Analysis Methods

The methods of Theis (1935) and Jenkins and Prentice (1982) were used to estimate aquifer parameters. Aquifer transmissivity (T) and storativity (S) may be calculated by Theis' (1935) method. The method of Jenkins and Prentice (1982) allows calculation of hydraulic diffusivity (T/S); transmissivity can be calculated from hydraulic diffusivity using an estimate of storativity.

In both approaches, the aquifer is assumed to be confined, isotropic, homogeneous, of infinite lateral extent, and to be fully penetrated by the pumping and observation wells. In Theis' model, the sink is a well of infinitesimal diameter; in the Jenkins and Prentice (1982) model, the sink is a vertical fracture of infinitesimal width and infinite hydraulic conductivity.

The aquifer characteristics of the Passaic Formation contrast sharply with properties assumed in the two models. The aquifer is not confined, isotropic, or homogeneous. As noted by Longwill and Wood (1965) and Vecchioli and others (1969), the observation wells and pumping well may not tap the same zones within the aquifer. Further, the fractures and well bore are not of infinitesimal width and not all the water comes from aquifer storage, as implied by the infinitesimal dimensions. Because of the differences between the aquifer and the idealized conditions assumed by the model, the values of aquifer parameters calculated from the models are uncertain.

The fundamental difference between the Theis (1935) model and the Jenkins and Prentice (1982) model concerns the geometry of the ground-water flow field. The Theis model utilizes a radial flow field (fig. 2). The flow lines extend radially inward toward a point sink. The lines of equal hydraulic head are concentric circles about the point sink. In the Jenkins and Prentice model, there is a linear flow field. The flow lines are parallel to one another and orthogonal to the line sink and equipotential lines.

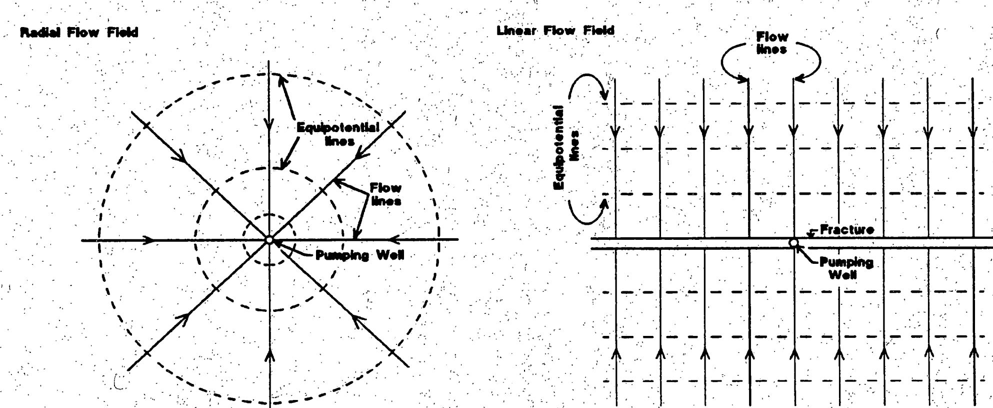


Figure 2. Diagram showing radial and linear flow fields.

Since a fracture in reality has finite length, the flow field pattern is linear only in the region close to the fracture. The pattern will change to resemble a radial flow field with increasing distance from the fracture. Just how far from a fracture it is appropriate to use the Jenkins and Price method is dependent upon the length of the fracture, the contrast between hydraulic conductivities of the fracture and the aquifer, and the length of time since pumping of the fracture began. Gringarten and Witherspoon (1972) note that radial-flow-field methods, like that of Theis, are appropriate for observation wells located at some distance from the fracture or when the time since pumping began is large.

There are fundamental differences between radial and linear flow fields. The differences result in distinct, diagnostic behavior of time-drawdown data which allow one to choose an appropriate analytic model. On log-log time-drawdown graphs, Gringarten and Witherspoon (1972) showed that straight data traces with a slope of 1/2 per log cycle are characteristic of linear flow of water from an aquifer to a high-conductivity fracture. Subsequently, straight traces with a slope of 1/4 per log cycle were shown to be diagnostic of flow to a low-conductivity fracture (Cinco-Ley and others, 1978). The presence of straight data traces was a key factor in selecting the Jenkins and Prentice (1982) model for two of the aquifer test analyses presented in this report. Other data traces were analyzed using the Theis approach or were unsuited for quantitative analysis.

TEST RESULTS AND DISCUSSION

Well 8 (Pennington Water Company Well 5)

Well 8, located close to Stony Brook at a point where the brook makes a conspicuous right-angle change in its course (fig. 1), was pumped at constant rate of about 66 gpm. Figure 3 shows a log-log time-drawdown plot of water levels for well 8. The first 10 minutes show a linear drawdown typical of borehole storage (Ramey, 1970). After about 20 minutes the drawdown stabilized at about 95-100 feet until the pump was turned off, indicating a constant-head boundary. The nearest possible recharge boundary is Stony Brook, which is less than 50 feet from the well. Induced leakage from Stony Brook to a domestic well was described by Widmer (1965, p. 32) at a site about 1,000 feet from well 8. Water quality in the domestic well was "equal to that of Stony Brook in every way: smell, color, turbidity, temperature, and algae." The well (table 1, well 9) was abandoned and a replacement well (well 10) was drilled.

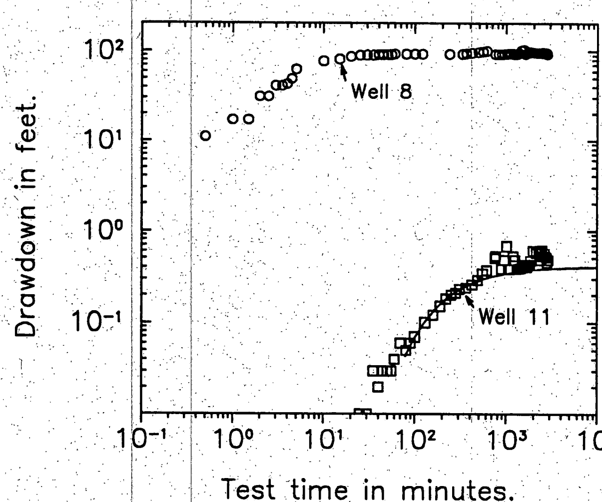


Figure 3. Log-log plot of drawdown in wells 8 and 11.

The closest observation well, well 11 (Pennington Water Company well 4), is about 750 feet west of well 8. The 0.49 feet of drawdown at well 11 (fig. 3) appears to be caused predominantly by pumping from well 8. Using Theis' model and the method of superposition to account for the constant-head boundary posed by Stony Brook, a drawdown curve was fitted to the data measured for well 11. This procedure gave a transmissivity of about 610 ft^2/day and a storativity of 5.3×10^{-4}. The transmissivity falls within the range reported by Longwill and Wood (1965) and Vecchioli (1967); the storativity, however, is slightly larger than the reported values. The larger storativity may be indicative of semi-confined conditions, as leakage from Stony Brook is clearly evident in the well 8 data.

The well 11 late-time data exhibit small fluctuations in drawdown (about 0.2 ft.). Similar fluctuations were noted in well 13 (fig. 4). These fluctuations may indicate interference from unidentified pumping.

The second-closest observation well is well 12, 1,900 feet west of well 8. Well 12 was often pumped for domestic supply during the test. Water levels did not show a trend which could be attributed to the pumping of Pennington's production wells.

The small amount of drawdown observed in well 11 and the constant-head boundary suggest that well 11's potential for causing significant well interference is minimal. Because Stony Brook appears to be augmenting ground-water storage, this may be true only when the stream is flowing. Streamflow records for Stony

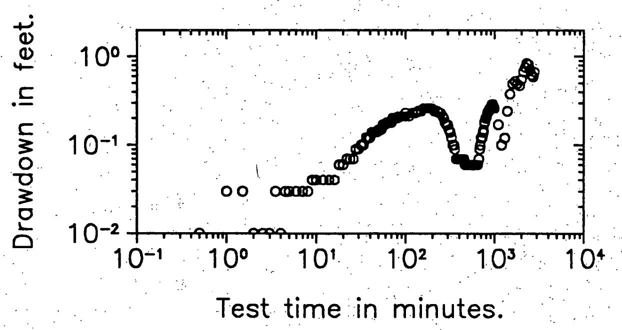


Figure 4. Log-log plot of drawdown in well 13.

Brook at Princeton typically show periods of low flow in late summer. Flow may cease altogether during droughts (United States Geological Survey, 1967).

Well 14 (Pennington Water Company Well 6)

The stress test results in the vicinity of PWC-6, are best reviewed with an understanding of the history of well problems in this area. In November 1957, during the testing of recently completed well 14, five domestic wells on Titusville Road and northern Dublin Road ceased to produce water (Miller, 1964). According to the well record, the test began November 12 and ended on November 23 or 24. The pumping rate was 201 gallons per minute (gpm). Miller attributed the well failures in the Dublin Hills area to the test pumping of well 14. He suggested that the well penetrates a minor fault or an open joint system, and proposed that the location of the structure is indicated by the alignments of Lewis Brook and the North Branch of Woolsey Brook (fig.1). The trace of the structure follows a swale passing directly through the affected area of Titusville Road and northern Dublin Road.

During the drilling of well 14, Meredith Johnson, former State Geologist, reported that its static-water level fell suddenly from 38 feet to 86 feet below land surface. The sudden drop occurred when the drill encountered a zone of dark red shale containing many "small cavities where mineral had been leached out" (permanent notes, Oct. 30, 1957, on file at the NJGS).

More recently, evidence of unusual hydraulic conditions was seen during the drilling of well 15 (an observation well drilled for the 1986 stress test by the NJGS). This well was drilled with a rotary percussion hammer using compressed air to carry the drill cuttings to the surface. While drilling was in progress, Michael Pinelli (the Pennington Water Company superintendent) and the author noted the distinct sound of air rushing up the casing of well 14. Air used to circulate the drill cuttings was evidently passing through more than 360 feet of the Passaic Formation and escaping up the casing of well 14, demonstrating a direct connection in the subsurface between the two wells.

The percussion-hammer cuttings from well 15 were mostly oblate chips about 0.25 inch across. The first zone producing significant quantities of water coincided with the arrival of calcite fracture fillings and irregularly shaped fragments as much as 2 inches long. This first producing zone was encountered at about 165 feet below land surface. Two other increases in yield also corresponded with the arrival of coarse fragments at the surface. After construction, a small volume of water issued from a seep at about 50 feet below land surface and fell in a continuous cascade to the static level, 46 feet below.

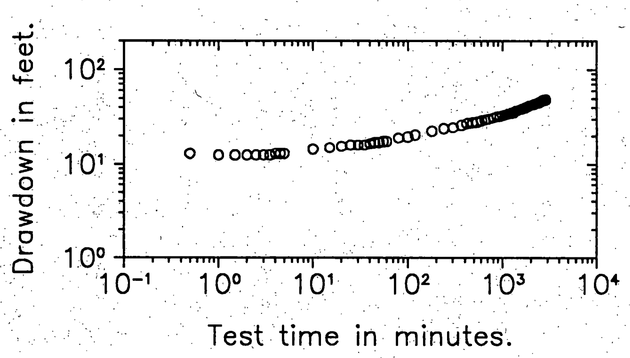


Figure 5. Log-log plot of drawdown in well 14.

In the aquifer-stress test, well 14 was pumped at a constant rate of 160 gpm. Drawdown did not stabilize; rather, it progressively increased with time (fig. 5). Similar time-drawdown data were noted for the observation wells close to well 14.

As a test for using a linear flow field model for analysis of the test data, the data were plotted in the manner recommended by Jenkins and Prentice (1982). The time-drawdown data from wells 14, 15, 16, 17, and 18 (fig. 6) form fairly straight traces. Accordingly a linear flow field model was selected. Wells 16 and 17 were selected for analysis. Well 15 was not used because, as previously discussed, it was found to be in free hydraulic connection with fractures intercepted by well 14. The data for well 18 indicate linear flow, but may be invalid. Technical difficulty with the electronic water level indicator at the start of the test affected measurements of water level and the computation of correct drawdown throughout the test. Also, for both wells 15 and 18, the intersections of the time axis by straight-line trends yield negative time-axis intercept values, which are inappropriate for the analysis.

The Jenkins and Price (1982) method provides for estimating the orientation of the vertical fracture with

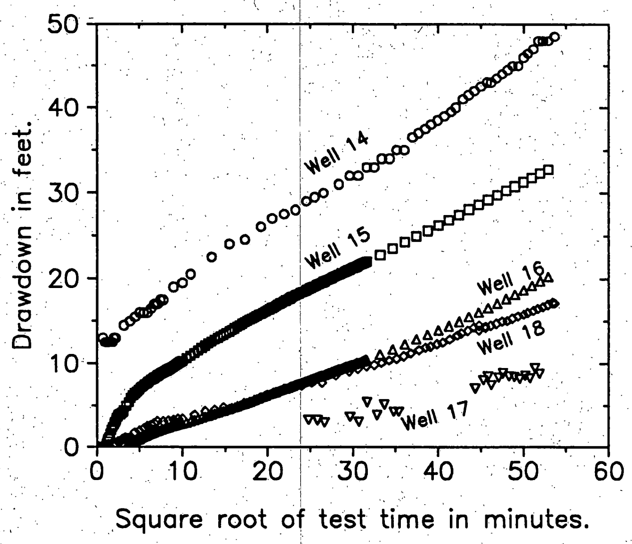


Figure 6. Specialized drawdown plot of wells 14, 15, 16, 17, and 18 based on the method of Jenkins and Prentice (1962).

respect to the observation wells. The analysis based on wells 16 and 17 is depicted in figure 7. It is assumed that the aquifer response during the stress test indicates minor faulting or an open-joint system with an extremely high hydraulic conductivity. The strike of the fault or fracture system deduced from this analysis, about N55°E, is very close to the linear topographic trend of Miller (1964), reasonably close to the N44°E strike of bedding, but distant from the principal joint strike (N23°E). The analysis supports Miller's theory of a fault or open-joint system contributing to the well failures along Titusville Road and northern Dublin Road during the 1957 test of well 14.

While the Jenkins and Prentice (1982) method enables one to calculate hydraulic diffusivity, a storativity value is needed to calculate transmissivity. Values of storativity ranging from 3.3×10^{-5} to 2.9×10^{-4} have been reported for the Passaic Formation in Pennsylvania (Longwill and Wood, 1965). Multiplication of these extreme storativities with the hydraulic diffusivity from the Jenkins and Prentice analysis results in a transmissivity between 11 and 97 ft^2/day. This transmissivity estimate is at the lower range of reported values for the Passaic Formation. Longwill and Wood (1965) reported a range of transmissivity from 13 to 24,000 ft^2/day; Vecchioli (1967) reported a range from 53 to 12,000 ft^2/day.

The low estimate for transmissivity is a result, in part, of the difference in the length of flow path assumed by the Jenkins and Prentice model as compared to that assumed by the Theis model. This difference becomes apparent when the distance from an observation well to the line sink is compared to the radial distance from the observation well to the point sink. For example, in figure 7, the distance from well 16 to the fracture trace (x_{16}) is 35 feet whereas the distance from well 16 to well 14 (r_{16}) is 510 feet. With the Jenkins and Prentice model, a much lower value of transmissivity can account for the drawdown observed in well 16.

The length of the fault or open-joint system is not known. The topographic features noted by Miller (1964) and Widmer (1965) suggest that the fault or open joint system may extend more than 5,000 feet. The minimum length necessary to produce the linear flow response predicted by the Jenkins and Prentice (1982) model is the distance between wells 16 and 17, about 1,200 feet. Extrapolation beyond this distance is speculative.

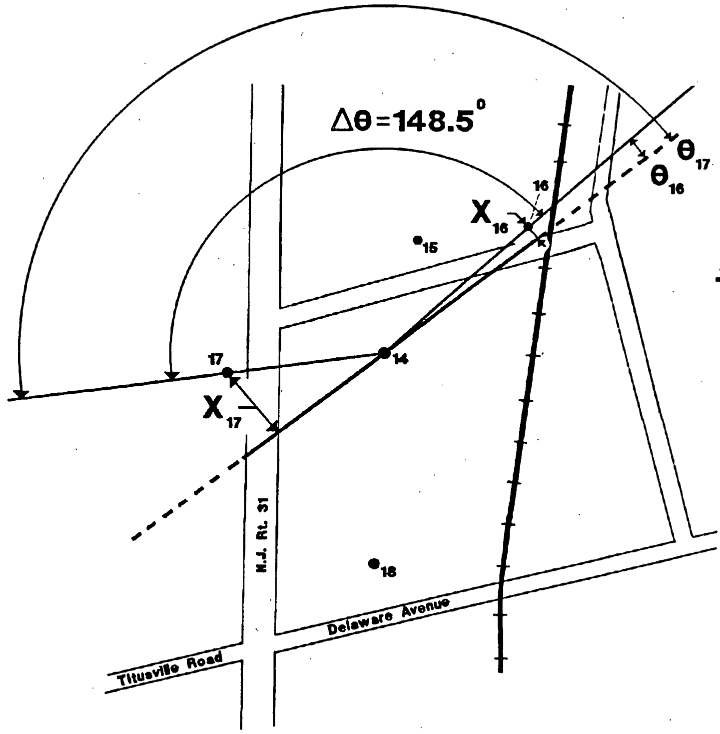
The stress test results do not unequivocally demonstrate well interference in the Dublin Hills area. In part, this may be due to observational difficulties. The sole observation well in the Dublin Hills area (well 19) was pumped for domestic supply and may have been further affected by pumping of any of the many domestic wells in the neighborhood. Also, seepage along the wellbore gave some false m-scope readings. Due to these problems, the scatter in data masks any effects attributable to interference from well 14.

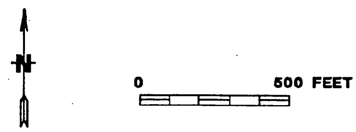
In fact, the Jenkins and Price analysis indicates that even if observational conditions had been ideal, drawdown would not have been felt at this distance in a 48-hour pumping test. The perpendicular distance (x_{19}) from well 19 to the fracture is more than 1,000 feet. The time-axis intercept (t_o), indicating when drawdown would first reach well 19 can be estimated by rearranging the variables of the diffusivity equation of Jenkins and Prentice (1982, eq. 11). Using 1000 feet for an x_{19} estimate and the hydraulic diffusivity from the analysis in figure 7,

$$t_{o_{19}} = \frac{\pi (x_{19})^2}{4\frac{T}{s}} = \frac{\pi (1{,}000\ ft.)^2}{4\left(3.35 \times 10^5 \frac{ft.^2}{day}\right)\frac{day}{24\ hr.}} = 56.2\ hr.$$

The direct hydraulic connection between wells 14 and 15, along a N17°E bearing, is not explained by the modeled fracture, but is fairly close to the principal joint strike (N23°E). This suggests that joints may be responsible for the direct hydraulic connection.

Although the fracture orientation from the Jenkins and Prentice analysis provides a plausible explanation for well interference in the Dublin Hills area, it is also





EXPLANATION

$\bullet_{14}$ Well and identification number. Well data listed in table 2. Drawdown data shown in figure 6.

——— - - - Fracture orientation based on Jenkins and Prentice (1982) method. Fracture dashed where inferred.

VARIABLES

		Well 17	Well 16
Known:	r	510 ft.	619 ft.
	t_o	197.12 min.	4.04 min.
	$\Delta\theta$	148.5°	
Unkown:		θ_{17} ; x_{17}	θ_{16} ; x_{16}

DEFINITIONS

r : radial distance to pumping well (no.14).

t_o : time-axis intercept on figure 6.

θ : angle between fracture bearing and bearing from the pumping well to the observation well.

x : perpendicular distance to fracture.

T : transmissivity

S : storativity

$$\theta_{16} = \text{ARCTAN}\left[\frac{r_{17}\sqrt{t_{o_{16}}} - \sin(\Delta\theta)}{r_{16}\sqrt{t_{o_{17}}} - r_{17}\sqrt{t_{o_{16}}}\cos(\Delta\theta)}\right] = \text{ARCTAN}\left[\frac{510\text{ ft.}\sqrt{4.04\text{ min.}} - \sin(148.5^\circ)}{619\text{ ft.}\sqrt{197.12\text{ min.}} - 510\text{ ft.}\sqrt{4.04\text{ min.}}\cos(148.5^\circ)}\right]$$

$$\theta_{16} = 3.2^\circ$$

$$\theta_{17} = \Delta\theta + \theta_{16} = 148.5^\circ + 3.2^\circ = 151.7^\circ$$

$$x_{17} = r_{17}\sin(\theta_{17}) = 510\text{ ft. }\sin(151.7^\circ) = 242\text{ ft.}$$

$$x_{16} = r_{16}\sin(\theta_{16}) = 619\text{ ft. }\sin(3.2^\circ) = 35\text{ ft.}$$

$$\frac{T}{S} = \frac{\pi (x_{17})^2}{4t_{o_{17}}} = \frac{\pi(242\text{ ft.})^2}{4(197.12\text{ min.})}\ \frac{1440\text{ min.}}{\text{day}} = 3.35 \times 10^5\ \frac{\text{ft.}^2}{\text{day}}$$

$$\frac{T}{S} = \frac{\pi (x_{16})^2}{4t_{o_{16}}} = \frac{\pi(35\text{ ft.})^2}{4(4.04\text{ min.})}\ \frac{1440\text{ min.}}{\text{day}} = 3.35 \times 10^5\ \frac{\text{ft.}^2}{\text{day}}$$

Figure 7. Analysis of vertical fracture orientation at well 14 based on the method of Jenkins and Prentice (1982).

possible to explain the interference using the producing zone concept of Vecchioli and others (1969). They suggest that the producing zones are jointed strata which comprise tabular aquifers with the same strike and dip as bedding.

To determine what bedrock strata in the Dublin Hills area are tapped by well 14, the strata intersected by the uncased interval of well 14 were projected along the N44°E strike and 12°NW dip to the Dublin Hills area (fig. 8). Several wells are shown to illustrate the potential for interference. Many other domestic wells intersect these same strata and could be affected. Further, ground-water flow from strata adjacent to those penetrated by well 14 could potentially widen the area impacted by well 14. Supporting evidence for a wider impact area comes from well 4, one of 19 wells in the Dublin Hills area (fig. 9) reported to have been deepened in the 1960's (Miller, 1964). In the cross section (fig. 8), well 4 is shown to its depth prior to deepening. Only the upper portion of well 4 intersects the same strata as well 14. Although it was deepened to 215 feet in 1963 (well below the strata intersected by well 14, but still above the elevation of the bottom of well 14), the owner reported that it failed in September 1983 (BWA, Diversion Permit File No. 5276).

While the 1986 stress test did not unequivocally demonstrate interference between well 14 and domestic wells in the Dublin Hills area, data from a protracted drought in the early to mid 1960's, and water level behavior in wells 7 and 19 between 1984 and 1987 clearly show a relationship. Figure 10 is a scattergram of well depth versus depth to water level at the time of drilling and in 1963. The data are divided into two groups, one consisting of wells which were drilled deeper because of failure, the other of wells which have not been deepened. The data were partitioned so that any effect of well deepening on static-water level might be discerned.

For both groups, water levels declined between the time the wells were drilled and 1963. All the wells which had not been deepened were drilled before 1957. The average static-water level of these wells was 58 feet at the time of drilling and 114 feet in 1963 (table 3). Wells which had been deepened show similar declines in water levels, from an average of 76 feet at the time of drilling to 122 feet in 1963. There was an average decline of 56 feet for wells which were not deepened and 46 feet for wells which were.

While some of the decline could result from the drought, wells outside the Dublin Hills area in general show much smaller seasonal and secular fluctuations. An example, the Bird observation well (well 23 on table 2), is located in Sergeantsville, about 10 miles northwest of Pennington. The Bird well has been monitored since 1965 by the U.S. Geological Survey. It has shown a maximum of about 11 feet between its highest and lowest levels between 1965 and 1986 (Bauersfeld and oth-

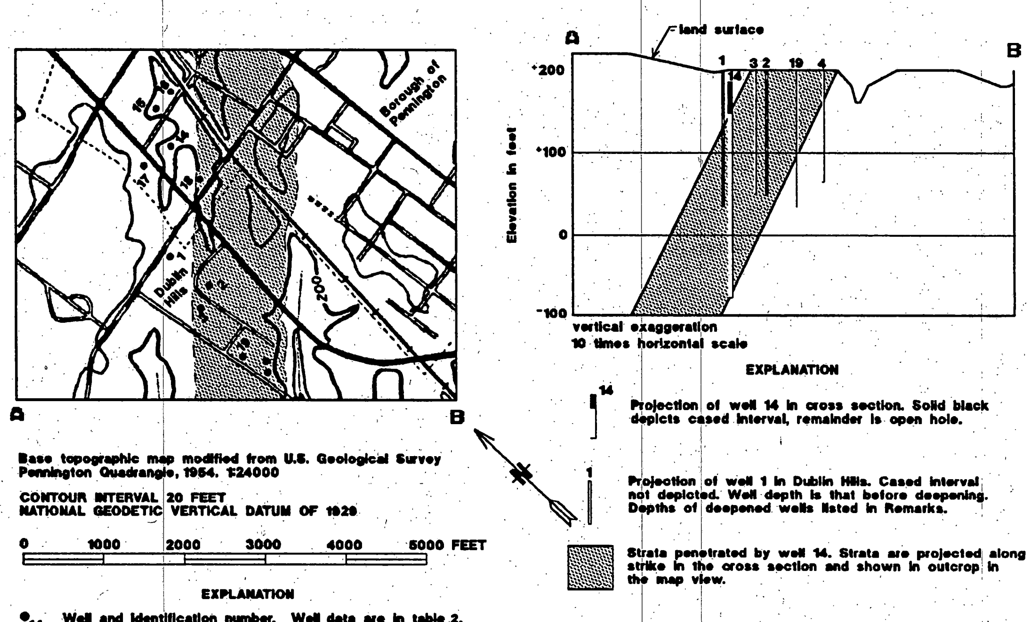


Figure 8. Diagrammatic cross section and outcrop of strata penetrated by well 14 and domestic wells in Dublin Hills.

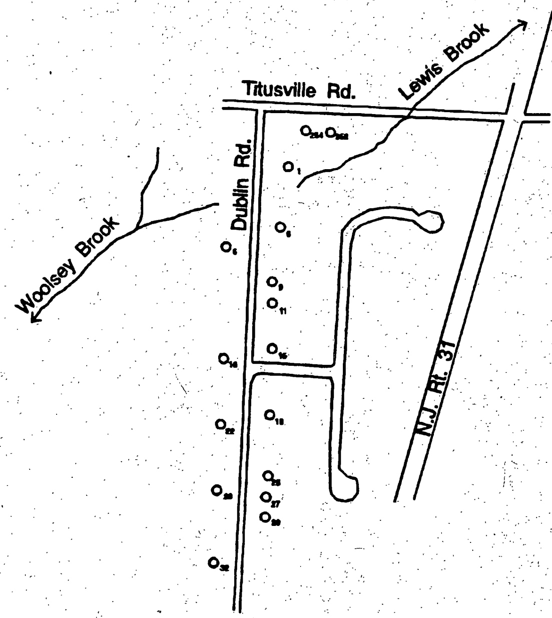


Figure 9. Locations of Dublin Road and Titusville Road wells referred to by Miller (1964, fig. 1). Numbers are street addresses shown in table 3.

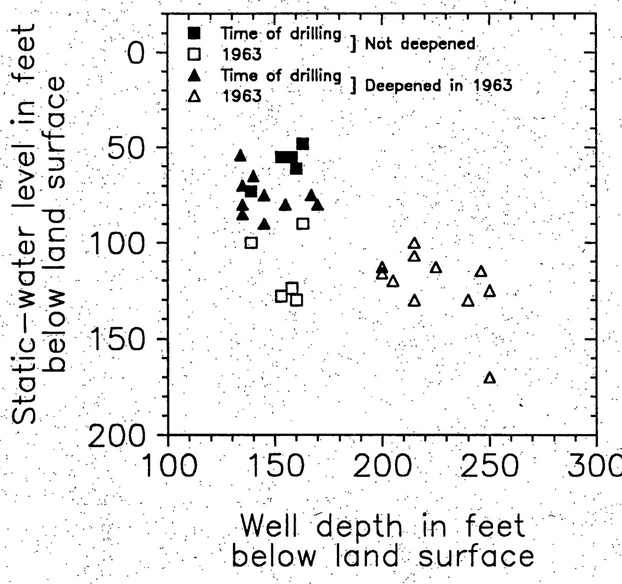


Figure 10. Scatter plot of well depth versus static-water level in the Dublin Hills area.

Table 3. Water levels in Dublin Hills from Miller (fig. 1, 1964). All depths are feet below land surface.

Wells which had not been deepened as of 1963					Wells deepened in summer and fall of 1963					
Address	Year drilled	Depth (feet)	Static-water level		Address	Year drilled	Depth (feet)		Static water level	
			Time of drilling	1963			Original	Final	At time of original drilling	After deepening
1 Dublin Rd.	1954	163	48	90	5 Dublin Rd.	1963	145	215	90	130
26 Dublin Rd.	1954	139	73	100	6 Dublin Rd.	1959	135	250	85	125
32 Dublin Rd.	1954	160	61	130	9 Dublin Rd.	1963	135	240	85	130
252 Titusville Rd.	1956	153	55	128	11 Dublin Rd.	1961	140	200	65	113
254 Titusville Rd.	1951	158	55	124	15 Dublin Rd.	1957	170	250	80	170
Average:		155	58	114	16 Dublin Rd.	1962	134	200	54	116
Minimum:		139	48	90	19 Dublin Rd.	1957	167	225	75	113
Maximum:		163	73	130	22 Dublin Rd.	1954	155	205	80	120
					25 Dublin Rd.	1956	145	246	75	115
					27 Dublin Rd.	1954	135	215	70	107
					29 Dublin Rd.	1957	135	215	80	100
					Average:		145	224	76	122
					Minimum:		134	200	54	100
					Maximum:		170	250	90	170

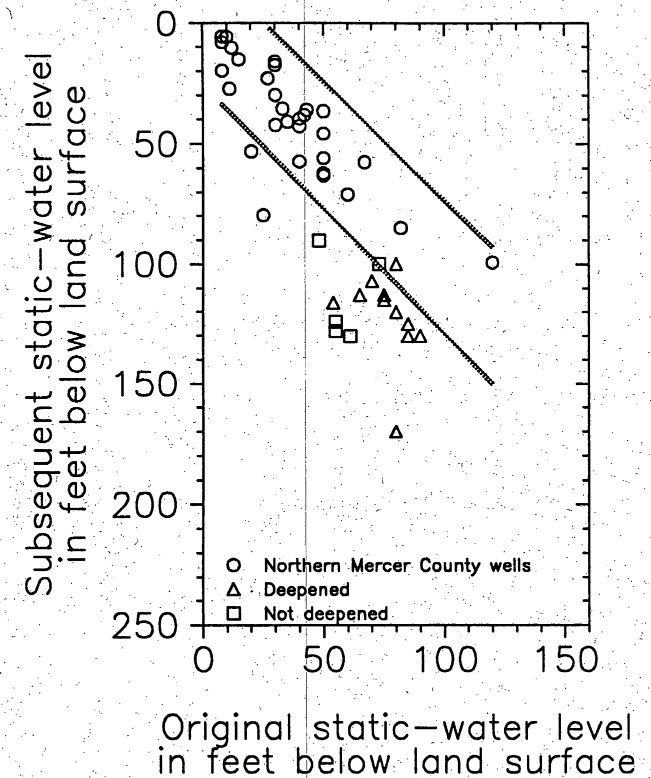


Figure 11. Scatter plot of static-water levels in the Dublin Hills area versus static-water levels in northern Mercer County.

ers, 1987). In contrast, the declines in water levels in figure 10 average 48 feet and range up to 90 feet.

In order to test whether the 1963 water levels are unusual or to be expected following drilling and residential development on the Passaic Formation in northern Mercer County, static water levels at the time of drilling and in 1963 were compared with similar data for 30 northern Mercer County wells for which data were collected in October 1987. The 1987 data were collected by the N.J. Geological Survey for the Northwest Mercer County Project. This was a fairly wet year. 54.1 inches of precipitation were recorded at Trenton (U.S. Geological Survey, 1987), but the data were collected in October, near the time of year when groundwater levels are lowest. In contrast, 30.41 inches were recorded in 1963 (National Oceanic and Atmospheric Administration, 1963). A linear regression was performed to mathematically describe the relationship between static-water levels when the wells were drilled and in October 1987. The band shown in figure 11 is the 90-percent prediction interval. Graphically, 9 out of 10 wells should plot within the band. This corresponds to a t-statistic alpha level equal to 0.1, which is commonly used in statistical analysis of geologic data (Kock and Link, 1980).

All but 2 of the Dublin Hills levels plot below the prediction band, suggesting an unusual lowering of the water table. Some of this may be a natural response of ground water to drought conditions, some the result of overpumping of well 14.

Some component of the Dublin Hills water-level decline was undoubtedly caused by drought. For a more reasonable comparison with the 1987 northern Mercer County data, the 1965 drought-related water-level drop was assumed to be equal to the 11-foot maximum difference between 1965-1986 high and low water levels of the Bird observation well, discussed above. The lowest level in the Bird well was recorded in 1965, a drought year similar in intensity to 1963. In 1965, 32.73 inches of precipitation was recorded at Trenton (National Oceanic and Atmospheric Administration, 1965). To compensate for the difference between a drought year and a wet year, the 1963 water-level data were raised by 11 feet. Still, only 4 out of the 16 Dublin Hills data points plotted within the 90-percent prediction band. It appears, thus, that the water-level declines were caused by stress other than drought.

The relationship between pumping of well 14 and water levels in the Dublin Hills area is more directly demonstrated by comparison of well 14 pumping records with hydrographs for wells 18 and 19 (fig. 12). The hydrographs are based on water levels measured at intervals of about 1 to 3 months. Both hydrographs clearly demonstrate seasonal fluctuations of 15 feet or more in 1985, 1986, and 1987. The largest fluctuations are in well 18, closest to well 14. These seasonal water-level fluctuations are unusually large. For comparison, the Honey Branch U.S. Geological Survey observation well (well 24 on table 2, 2.5 miles northeast of Pennington) is in a less developed area and not near any major ground-water diversions. It can be taken to repre-

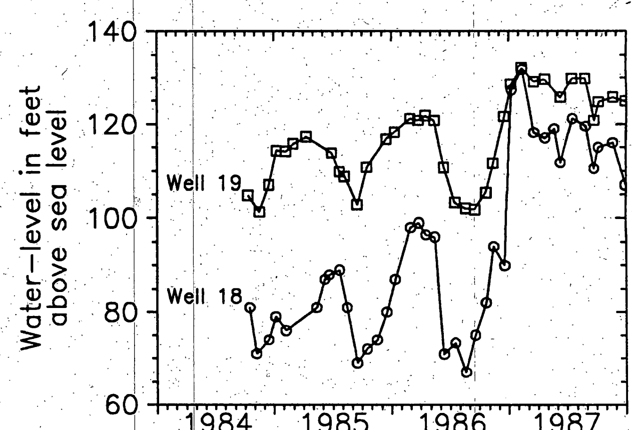


Figure 12. Hydrographs of wells 18 and 19.

sent near-natural conditions. The Honey Branch observation well shows seasonal fluctuations of only about 3 feet (Bauersfeld and others, 1984).

The pattern of large seasonal fluctuations changed dramatically in response to pumping changes in well 14. Beginning in September, 1986, well 14 was pumped at a lower rate because well 7 had gone into production. The average pumpage of well 14 from October 1984 to August 1986 was 2.57 million gallons per month (MGM). The average pumpage from August 1986 to December 1987 was 1.06 MGM, less than half the previous rate. The well was shut down from mid-December 1986 to early February 1987. This period of decreased or halted pumping correspond to pronounced recovery of water levels, with seasonal high water levels about 15 feet higher than those of 1985 or 1986, followed by a vague pattern of water-level fluctuation.

Well 20 (Pennington Water Company Well 7)

Well 20 is located in a swale similar to that near well 14 (fig. 1). Although there is no geologic evidence suggesting that this swale indicates a fault, its orientation is similar to the swale at well 14, and the stress-test data show similar drawdown characteristics. Well 20 was pumped at a constant rate of 182 gpm. On a log-log time-drawdown plot (fig. 13), the slope of the data trace progressively increases with time. After 800 minutes,

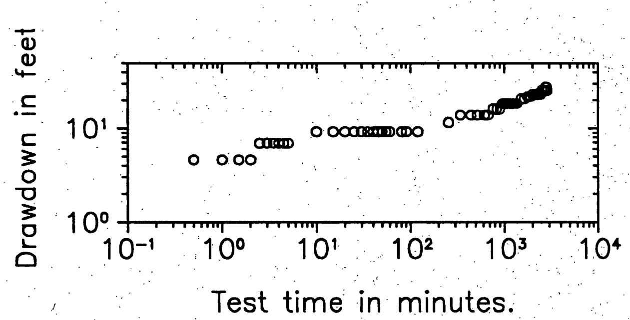


Figure 13. Log-log plot of drawdown in well 20.

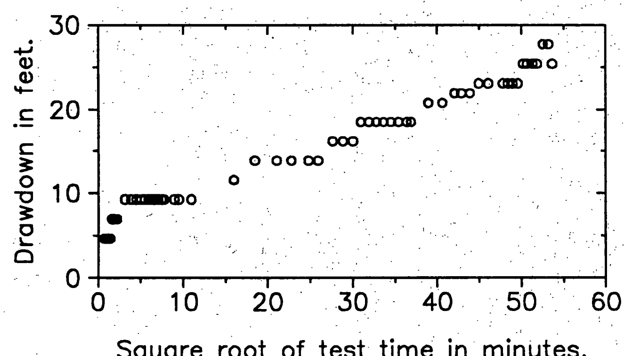


Figure 14. Drawdown plot of well 20 based on the method of Jenkins and Prentice (1982).

the slope is about 1/2 per log cycle. Accordingly, well 20 is interpreted to be connected to a high-conductivity fracture. Figure 14 is a time-drawdown plot drawn as recommended by Jenkins and Prentice (1982). The relatively straight data-trace exemplifies a linear-flow field. Further analysis by the method of Jenkins and Prentice is impossible because no nearby wells were monitored for the stress test. While there are few wells near well 20 from which to judge the potential for interference, well 21, located roughly 800 feet to the southwest of well 20, provides some basis for discussion. Well 21, which now supplies water to a day-care center, is located on the same swale as well 20 (fig. 1). Water use by the business is minimal, mainly for lavatory facilities. Well 21 was drilled by a previous business at this site to replace a well which failed occasionally, usually during the summer. The earlier business also used a minimal amount of water. A record for the earlier well is unavailable. In October 1987, the static-water level measurement for well 21 was 99 ft. below land surface, the deepest level of any domestic or commercial well measured in northern Mercer County. For comparison, the average depth to water for 30 wells tapping the Passaic Formation was about 41 ft. The deep static water level of well 21 is most easily explained as the result of drawdown from well 20.

The hydraulic gradient between wells 20 and 21 provides another indication of interference. The static-water level measured by the NJGS in October 1987 was about 74 feet above sea level for well 20 and about 94 feet for well 21. This indicates a hydraulic gradient toward well 20, uphill and towards a drainage divide.

Well 7 (Pennington Water Company Well 8)

The well 7 time-drawdown data (fig. 15) appears more complex than those of the other production wells. The plot between 2 and 300 minutes is fairly straight. At about 700 minutes the rate of drawdown begins to increase, and at about 1,300 minutes it increases rapidly.

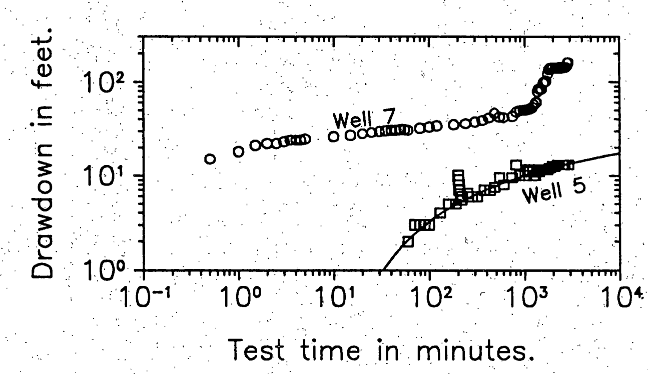


Figure 15. Log-log plot of drawdown in wells 5 and 7.

At about 1,800 minutes the rate of drawdown decreases to about the rate observed up to 700 minutes test time. A second rapid increase in drawdown occurs at about 2,850 minutes and persists until the shutdown at 2,880 minutes. The observer's notes show that both instances of rapid increase of drawdown coincided with adjustment of the pump rate to maintain an average discharge of 125 gallons per minute.

The variations in flow are explained by how ground water flows from the aquifer to the well. Under pumping conditions, ground water flows from discrete fractures, each contributing to the overall discharge. The fractures are unevenly distributed along the well bore and vary in productivity. The flow from an individual fracture initially increases as drawdown in the well bore increases the head differential between the fracture and the well. As pumping continues, storage depletion results in lower fracture pressure heads and, consequently, lower fracture productivity. The decrease in fracture productivity results in an increase in drawdown and a decrease in discharge. When the operator throttles up to maintain the pumping rate, the water level in the well drops until ground-water flow from deeper fractures has increased to match the pumping rate.

This interpretation of the fluctuation in drawdown as the result of pumping adjustments in well 7 is substantiated by the response of well 5, about 760 feet west of well 7. Well 5 is a domestic well and was used during the test. Although the time-drawdown data for the well are erratic owing to domestic use, a consistent response to the pumping of well 7 can be observed. Of particular importance, well 5 does not show steepening of the drawdown curve at 1,300 minutes. If the steepening of the curve from well 7 were the result of well interference or an impermeable boundary, similar steepening would be expected in well 5.

The data from well 5 approximates a Theis (1935) curve fairly well. Drawdown from pumping by the owner can be seen at about 200 minutes (fig. 15). Recovery from this is rapid and easy to distinguish from drawdown caused by well 7. Based on Theis approximations, the transmissivity is about 600 ft^2/day and storativity is $7.5x10^{-5}$, both within the range of values reported by Longwill and Wood (1965) and Vecchioli (1967). The maximum drawdown in well 5 attributable to pumping well 7 for 48 hours was about 13 feet.

Effects of pumping of well 7 on nearby wells have been noted previously. George Halasi-kun, reported that in April 1981 his well (table 1, no. 6) pumped water containing red silt as a result of testing of well 7. He also reported that neighboring well 5 experienced unspecified "well problems" (BWA Diversion Permit File No. 5276). In the 1981 test, well 7 was pumped at a rate of 420 gpm. Within 10 minutes the pump began "pulling air" as water levels declined 262 feet to the pump intake. Thereafter, the well was pumped at a lower rate of about 150 gpm, and drawdown stabilized at about 157 feet (BWA Diversion Permit File No. 5276). It is likely that heavy pumping during the initial period of this test mobilized fine sediment in the aquifer.

Observation well 22 is more than 3,000 feet west-northwest of well 7. Small fluctuations in its water level (about 0.2 feet) were observed, but no consistent trend attributable to the test of well 7 was apparent.

SUMMARY, RECOMMENDATION

Analysis of 1986 aquifer stress-test data from observation wells near well 14 (PWC-6) supports Miller's (1964) interpretation that this well penetrates a fracture system and that the fracture system extends through Dublin Hills. Static-water-level data from 1963 suggest a local lowering of the water table in the Dublin Hills area. A hydrograph of well 19 showed distinct responses to changes in the pumping rate of well 14. These include pronounced recovery of water level in well 19 with cessation of pumping of well 14 (mid-December 1986 to early February 1987), and a disappearance of strong seasonal fluctuation in 1987 after the pumping rate of well 14 was reduced from an average of 2.56 MGM (million gallons per month) to 1.06 MGM.

The evidence that well 14 causes well interference in Dublin Hills had a direct bearing on the borough's request for an increase in diversion. To evaluate undesirable impacts, the Pennington Water Company's monthly withdrawals from 1959 to 1987 were tabulated and analyzed for each production well. The records show that the borough's total monthly pumpage has approximately doubled from 1959 to 1987; however, the long-term average monthly pumpage of well 14 remained fairly constant. The one factor coinciding with well failures in the Dublin Hills area is short-term periods of high pumpage: 2.79 million gallons were pumped monthly from June through August 1963, when falling water levels forced deepening of numerous wells; 4.16 million gallons were pumped from well 14 during July 1983, the same month that the Dublin Hills wells failed.

A recommendation was made to the Bureau of Water Allocation to avoid excessive pumpage at well 14. The renewed diversion permit of 1988 allowed the borough to increase its withdrawal to a maximum of 10.85 MGM and established a maximum withdrawal for well 14 of 2.25 MGM, a quantity consistent with that well's average monthly pumpage from 1975 to 1987. It was further specified that the maximum volume be diverted in equal daily increments of about 72,000 gallons per day. The pumping rate was also set at 160 gpm, the same rate used during the stress test in 1986. The diversion increase and high seasonal demands were apportioned among the remaining production wells.

In northern Pennington Borough, interference from well 7 was evident in the 1986 stress test. The only requirement made in the permit is that the diversion rate be 125 gpm. Although there was a clear potential for interference near well 7, no well failures had been reported as of 1993.

No interference was conclusively demonstrated between wells 8 and 20 and domestic wells. While there are strong indications of interference between wells 20 and 21, no special conditions were placed on well 20.

The hydrogeology of the Passaic Formation is complex. It is often difficult to extract reliable estimates of aquifer parameters or to dependably forecast aquifer behavior. For example in the Dublin Hills area, well 19 showed no discernible response to pumping of well 14 during the 48-hour stress test. After the Jenkins and Prentice analysis was performed, a calculation suggested that the stress test was too short for drawdown to occur in well 19. This finding is ambiguous and inconclusive because we don't know when or how much drawdown occurred at well 19 due to the stress test. Further, it does not permit us to verify if the Jenkins and Prentice model is useful for predicting drawdown and aquifer behavior in the Dublin Hills area. The latter point is important because it would be a much finer tool for regulating withdrawals at well 14 and insuring that undesirable impacts are avoided. The clear value of long-term water-level records is demonstrated by the hydrograph for well 19. This hydrograph demonstrates that periodic water-level measurements coupled with a shutdown or reduced withdrawal rate are useful for understanding well interference problems, particularly where the hydrogeology is complex.

The application of the Jenkins and Prentice (1982) model raises some unanswered questions. The aquifer-test data do not unequivocally confirm the existence of a vertically oriented fault or fracture system near well 14. Although the Jenkins and Prentice analysis appears to confirm Miller's (1964) theory, the overall evidence is not compelling. While in fact flow characteristics of well 14 correspond to the theoretical response of a well pumping from a fracture, it still remains to be shown precisely what geologic structures are responsible for the data.

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