DIRECTIONAL HYDRAULIC BEHAVIOUR OF A FRACTURED-SHALE AQUIFER IN NEW JERSEY

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ABSTRACT

The principal source of ground water throughout a large part of central and northeastern New Jersey is the aquifer in the Brunswick Shale—the youngest unit of the Newark Group of Triassic Age. Large-diameter public-supply and industrial wells tapping the Brunswick Shale commonly yield several hundred gallons per minute each. Virtually all ground water in this aquifer occurs in interconnecting fractures; the formation has practically no effective primary porosity.

Numerous pumping tests have shown that the aquifer exhibits directional, rather than isotropic, hydraulic behavior. Water levels in wells alined along the strike of the formation show greater magnitude of interference than those in wells alined in transverse directions. Drawdown data evaluated by standard time-drawdown methods indicate computed coefficient of transmissibility in all cases is least in the direction of strike. Because of the distribution of observation wells available for the tests, distance-drawdown methods of evaluation could be used in only one instance—for just one direction; the computed coefficient compared favorably with that calculated from the time-drawdown method.

Computed values of transmissibility may be unreliable owing to the departure of the aquifer from the ideal model. It is even possible that the direction of minimum computed transmissibility is actually indicative of the alinement of fractures with greatest permeability. However, the relation of the directional behavior to the structure of the formation has practical significance when locating new wells near existing wells. Well interference can be minimized, generally, by alining wells perpendicular to the strike.

RÉSUMÉ

Comportement hydraulique directionnel d'un aquifère situé dans les schistes fissurés du New Jersey

La principale source d'approvisionnement en eaux souterraines d'une grande partie du centre et du nord-est du New Jersey est l'aquifère situé dans les schistes de Brunswick; il s'agit de l'unité la plus jeune du groupe de Newark, d'âge triasique. Des puits à grand diamètre ont été forés pour les besoins des services publics et de l'industrie dans les schistes de Brunswick; chacun débite couramment plusieurs centaines de gallons par minute (1 gallon = 3,785 l). Presque toute l'eau de cet aquifère se trouve dans des fractures reliées entre elles; la formation n'a pratiquement aucune porosité primaire réelle.

De nombreux tests de pompage ont montré que l'aquifère a un comportement hydraulique directionnel plutôt qu'isotrope. Le niveau des puits alignés suivant la direction de la formation accuse des interférences de plus forte amplitude que le niveau des puits alignés perpendiculairement à la formation. Les données relatives au rabattement de la nappe, calculées selon les méthodes habituelles de mesure de rabattement en fonction du temps, montrent dans tous les cas que c'est parallèlement à la direction des couches que le coefficient de transmissivité obtenu est le plus faible. Étant donné l'implantation des puits qu'il était possible d'utiliser pour les tests, les méthodes de mesure du rabattement de la nappe en fonction de la distance n'ont pu être appliquées qu'une seule fois, pour une seule direction; mais le coefficient obtenu se comparaît avantageusement avec celui qui avait été évalué par la méthode de mesure du rabattement en fonction du temps.

Il se peut que les valeurs ainsi obtenues de la transmissivité ne soient pas sûres en raison des différences existant entre l'aquifère réel et le schéma théorique. Il est même possible que la direction de la transmissivité minimale obtenue soit effectivement révélatrice de l'alignement des fractures de la plus forte perméabilité. Cependant, le rapport existant entre le comportement directionnel et la structure de la formation a une importance pratique lorsqu'il s'agit de forer de nouveaux puits au voisinage des puits déjà existants. Les interférences entre les puits peuvent généralement être réduites par l'alignement des puits perpendiculairement à la direction des couches.

Introduction

Throughout much of the heavily populated central and northeastern part of New Jersey, the principal source of ground water is the aquifer in the Brunswick Shale. Indeed in many places it comprises the only source. The Brunswick Shale is tapped by numerous large-diameter public-supply and industrial wells, many of which have sustained yields of several hundred gpm (gallons per minute). Most of the high-capacity wells penetrate between 200 to 500 feet of rock.

The Brunswick Shale is the youngest unit of the Newark Group which is of Late Triassic (Keuper) age. The Newark Group crops out in a broad northeast-trending belt across northern New Jersey (fig. 1). It is more than 10,000 feet thick and consists of shale, sandstone, argillite, conglomerate, and basalt. In the western part of the outcrop

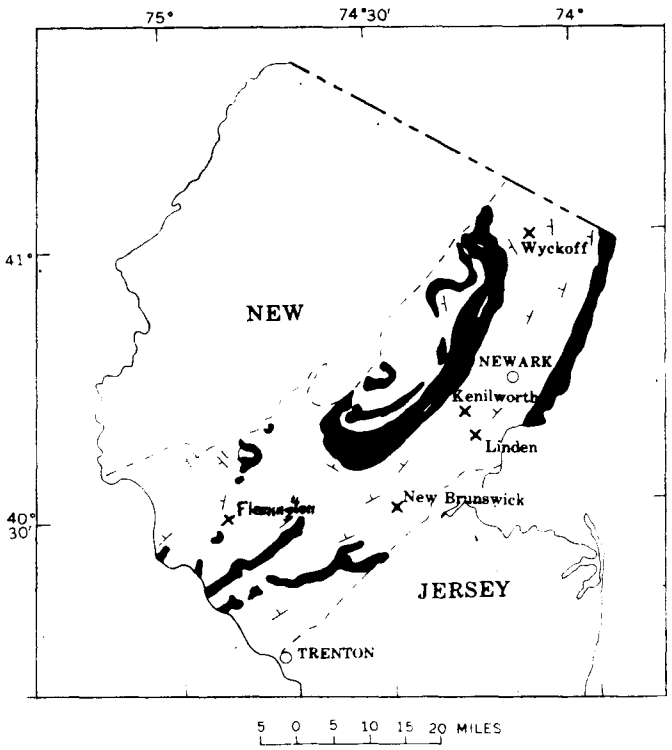


Fig. 1 — Map showing outcrop area and structure of the Newark Group in northern New Jersey (igneous rocks in black), and pumping-test sites.

area in New Jersey, the Newark Group consists, from oldest to youngest, of the following three units (Kümmel, 1897): Stockton Formation, chiefly sandstone; Lockatong Formation, mainly argillite; and Brunswick Shale. Diabase sills and dikes have intruded the Newark Group in this area. From New Brunswick northeastward, except for a narrow exposure of Stockton Formation flanking the Palisade Sill (diabase) along the State's eastern boundary, the Newark Group consists entirely of Brunswick Shale interlayered with Watchung Basalt. The Brunswick Shale is by far the thickest and

most extensive unit of the Newark Group. Deposits of till and stratified drift of the Wisconsin Stage of the Pleistocene Epoch mantle the Newark Group throughout the area northeast of New Brunswick.

Lithologically, the Brunswick Shale is mostly a soft red shale with some interbedded sandstone. The sandstone layers become more abundant and, on the whole, somewhat coarser toward the northeast, particularly near the northern State line.

The structural trend of the Newark Group is shown by the outcrop pattern of the generally concordant igneous rocks (fig. 1). The dominant strike is northeastward with dips ranging from 5° to 15° NW., but locally the strike of the sedimentary rocks differs markedly from the regional trend. Faulting has caused more complex structure locally, particularly in the western part of the belt.

Virtually all ground water in the Brunswick Shale occurs in interconnecting fractures that have resulted from jointing. This phenomena was recognized by Knapp (1904) where he states... "While our knowledge of the Newark beds is not sufficiently detailed to enable us to forecast the chances of obtaining artesian water at any given point, or even to assure us that well-defined water-bearing horizons exist, yet experience shows that a moderate supply of water can usually be obtained anywhere in these beds at depths of a few hundred feet at most. The fact that the rocks of the Newark system are thoroughly cut up by several systems of deeply penetrating joints, whose planes approach the vertical and intersect at various angles, and the further fact that in many wells the amount of water increases gradually with depth of the boring, apparently indicates that the water is present more largely in these joints and fissures than in any well-defined porous water-bearing beds. This inference is supported by observations made in several long tunnels in the red shale, where frequent streams of water were found following vertical fissures, while the bedding planes were nearly dry and no porous layers were observed."

Observations of joint set orientation made by the author at Newark and New Brunswick, by Anderson (private communication, 1963) near Linden, and by Nichols (private communication, 1964) near Flemington indicate that one set of vertical joints roughly parallels the strike of the rocks, whereas a second set is generally perpendicular to the strike. In places steeply dipping joints transverse to the aforementioned two occur. In addition, bedding plane joints are common in surface exposures. Major and minor faults also occur in the rocks of the Newark Group, with most of the faults trending largely northeastward.

Hydraulic behavior

Regionally, water-table conditions prevail in the Brunswick Shale, but artesian conditions occur locally where marked differences exist in the vertical permeability of the formation. Artesian conditions exist also in some lowland areas where the Brunswick is overlain by relatively impermeable till or lacustrine clay and silt.

Data collected during numerous pumping tests of wells throughout the outcrop area indicate that the aquifer in the Brunswick Shale possesses directional, rather than isotropic, hydraulic properties. In describing two pumping tests made in Newark, Herpers and Barksdale (1951) report that all the wells that were observed to affect one another lay along lines trending in a general northeasterly direction. Similar effects were noted by Anderson (private communication, 1961) during pumping tests conducted at Linden. He found that in an observation well one mile northeast of a pumped well the water level dropped six feet within two hours of pumping, whereas pumping at higher rates from other wells located closer to but in different directions from the observation well had less of an effect on the water level in the observation well. At both Newark and Linden, the strike of the Brunswick Shale is N 45° E—the direction of most pronounced well interference.

Similar effects have been observed in the central and western part of the outcrop area. After 24 hours of pumping of a well in New Brunswick, the water level in an observation well located 500 feet away directly along strike was lowered 87 feet, whereas that in another observation well located only 280 feet away but in a direction 30° from strike was lowered only 50 feet. Miller (private communication, 1965) reports that north of Trenton prolonged pumping of a high-capacity well adversely affected domestic wells about a mile distant along strike but other wells located equidistant in transverse directions were affected less. At the end of a 48-hour pumping test of a well near Flemington, the water level in an observation well 1,550 feet away along strike was drawn down 4.1 feet. The water level in an observation well only 1,200 feet away but in a transverse direction was lowered 3.7 feet.

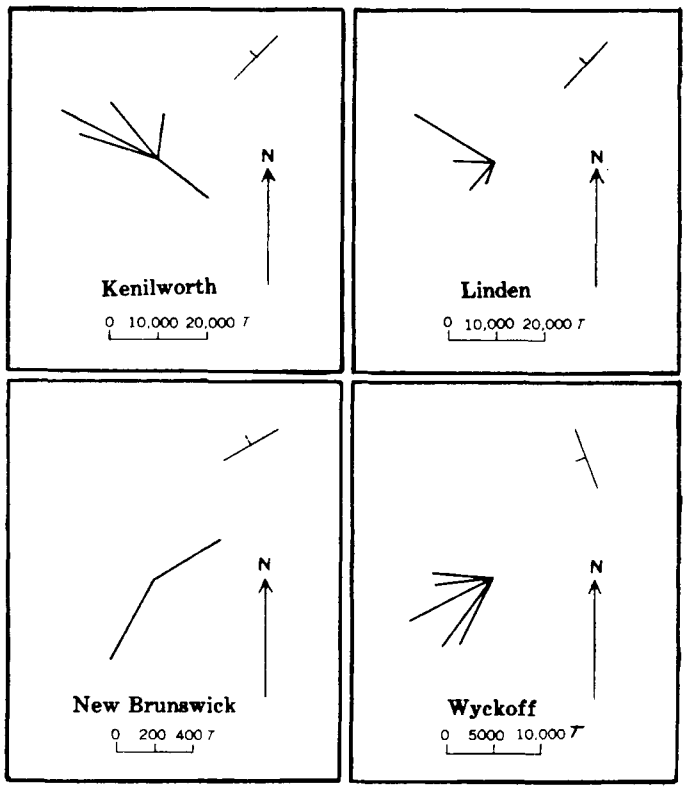


Fig. 2 — Directional transmissibilities computed from aquifer tests in the Brunswick Shale. Strike of formation shown in upper right corner for each site. Transmissibility, *T*, in gallons per day per foot, shown by ladder scale.

Hence, it is obvious that the anisotropic hydraulic behavior of the Brunswick Shale is not restricted to any particular area. Furthermore, the directional hydraulic behavior is evidently related to the structure of the formation. In all of the above tests, the wells alined parallel to the strike of the Brunswick Shale exhibited greatest mutual interference.

Because the aquifer behaves anisotropically, the hydraulic characteristics derived by analyzing pumping-test data by conventional methods are questionable. Furthermore, in all pumping tests that have been run where drawdown observations have been made in more than one direction, analysis of the data has suggested a smaller apparent coefficient of transmissibility along strike and a greater one in the perpendicular direction (fig. 2). This appears to be incongruous with what is generally believed to be the alinement of the major fracture system.

In all the tests run to date except one, the distribution of observation wells was such that the data could be evaluated only by use of time-drawdown methods of analysis, that is, if data from the pumping well are not considered. For the pumping test conducted at Flemington, it was possible to make a distance-drawdown analysis for one direction. This test will be discussed in detail.

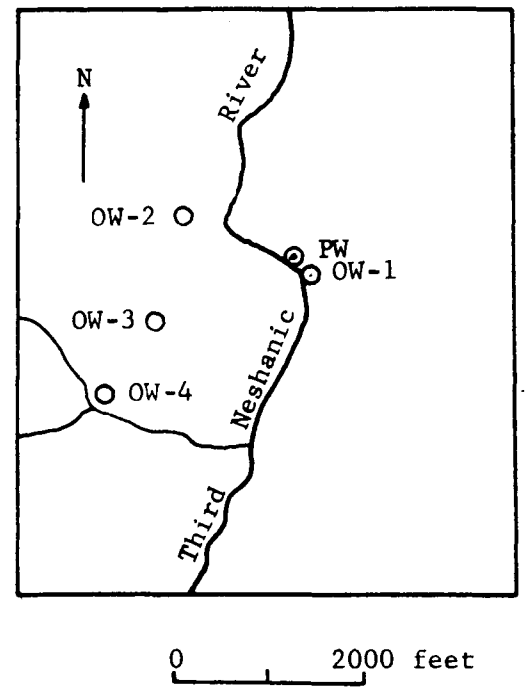


Fig. 3 — Map showing location of pumping well (PW) and observation wells (OW) used in the Flemington, N.J., pumping test.

Flemington test: The well pumped during this test consisted of a hole 10 inches in diameter and 300 feet deep of which only the upper 40 feet are cased. A pumping rate of 500 gpm was maintained continuously for a 48-hour period during which water-level observations were made on the pumping well, an unused well located 245 feet southeast of the pumping well, and three domestic wells located 1,200 feet west-northwest, 1,550 feet west-southwest, and 2,350 feet southwest, respectively, of the pumping well (fig. 3). Water-level measurements were made intermittently on the pumping well and the domestic wells with an electrical water-level indicator. A continuous record of the water level in the unused well was obtained prior to, during, and after the

pumping period with an automatic water-stage recorder. The specific capacity of the pumping well at the end of the 48-hour period was 42 gpm/ft. At the test site the Brunswick Shale strikes N 53° E and dips 25° NW. (Nichols, private communication, 1964).

The stream which traverses the test site apparently was not an effective recharge boundary. Similarly, a northly trending narrow diabase dike that cuts the Brunswick Shale about 750 feet east of the pumping well apparently was not an effective discharge boundary. However, the farthest well observed (OW-4, fig. 3) was located near a tributary stream and a large pond, and the data from this well suggest some recharge may have been occurring in this area. Two of the domestic wells were used intermittently during the test, but the quantity of water withdrawn from them is insignificantly small compared to the test rate of 500 gpm. The third well, that farthest from the pumping well, was used intermittently during the first day of the test, but the owner pumped it continuously during the second day at a rate of about 20 or 30 gpm, thus invalidating any observations at that well during the last 24 hours of the test.

If a time-drawdown analysis of the data is made (figs. 4 and 5), using the Theis nonequilibrium formula (Ferris and others, 1962), it is found that the computed coefficients of transmissibility and storage are, respectively:

Perpendicular to strike	Observation well No. 1 — 88,200 gpd per ft; 2.49×10^{-4}	
	Observation well No. 2 — 75,400 gpd per ft; 2.51×10^{-4}	
Parallel to strike	Observation well No. 3 — 57,300 gpd per ft; 2.51×10^{-4}	
	Observation well No. 4 do. do.	

If a distance-drawdown analysis of the data is made (fig. 6), using the Theim equilibrium formula (Ferris and others, 1962), it is found that in the direction perpendicular to strike, the coefficient of transmissibility is about 100,000 gpd per ft—a value which compares favorably with that given for observation well N°. 1 above. As was mentioned previously, the data from observation well N°. 4 are thought to be affected by recharge; hence, a distance-drawdown analysis in the direction of strike could not be made on the basis of observed drawdowns. However, if one uses for the drawdown in this

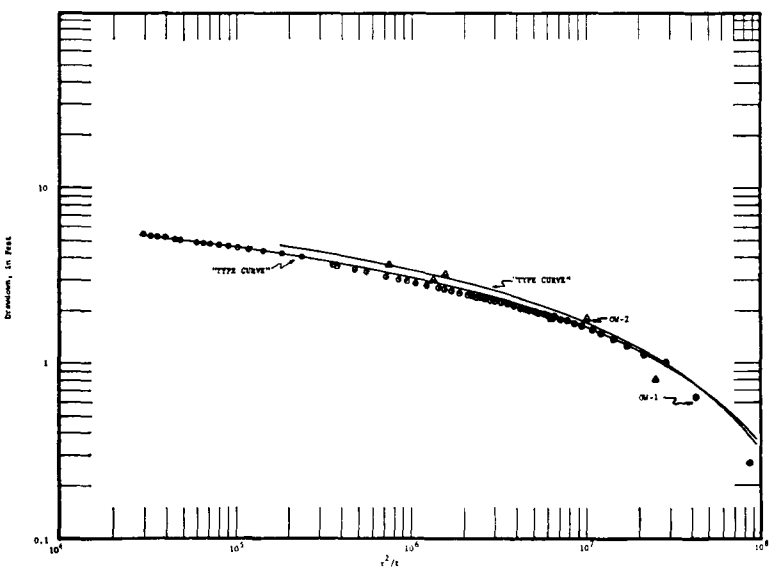


Fig. 4 — Logarithmic plot of time-drawdown data matched to the "Type Curve" for wells alined perpendicular to strike, Flemington, N.J., pumping test.

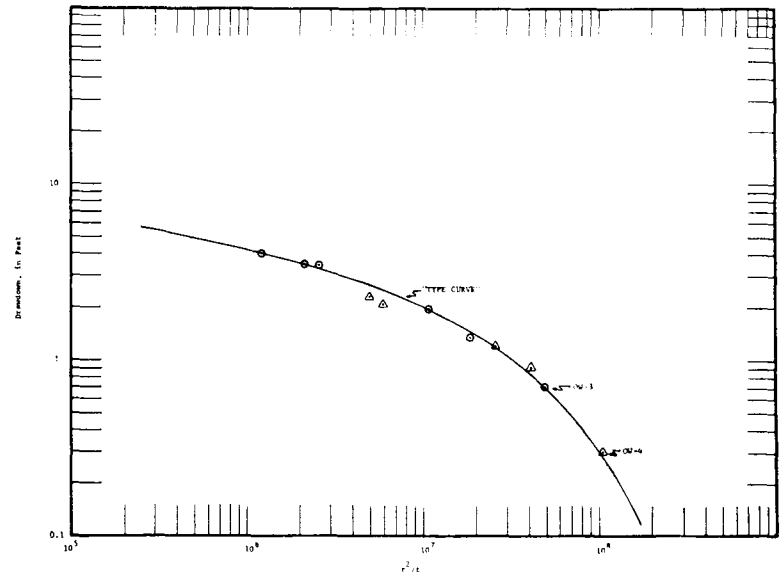


Fig. 5 — Logarithmic plot of time-drawdown data matched to the "Type Curve" for wells alined parallel to strike, Flemington, N.J., pumping test.

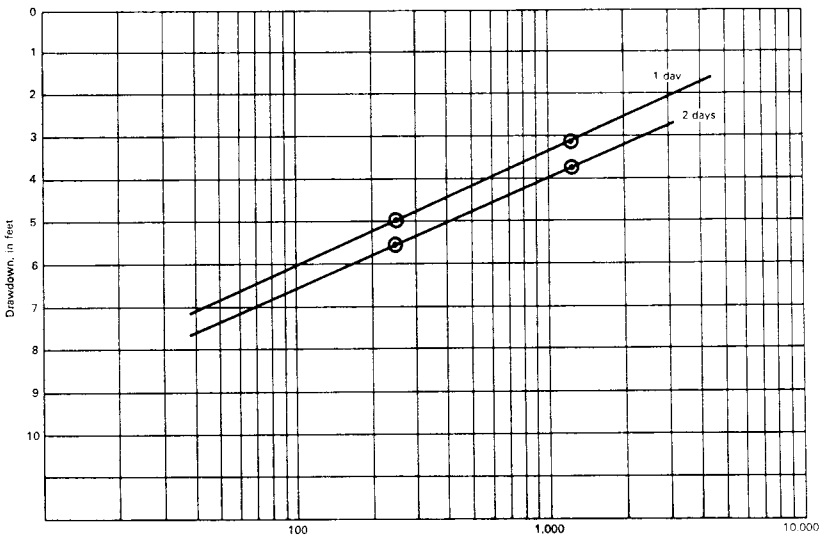
well at the end of one day the value obtained from the "Type Curve" in figure 5 and the observed drawdown value for observation well N°. 3, it is found that the computed coefficient of transmissibility is about 72,000 gpd per ft. Therefore, both methods of analyses have yielded comparable pairs of apparent values of transmissibility that are greatest perpendicular to strike and least parallel to strike.

Conclusions

That the aquifer in the Brunswick Shale exhibits directional rather than isotropic hydraulic behavior under pumping conditions is well documented. Furthermore, it has been demonstrated qualitatively for all parts of the outcrop in New Jersey that the maximum and minimum directions of anisotropy are related to the structural orientation of the Brunswick. The degree of anisotropy varies from place to place and is probably indirectly related to the productivity of the aquifer.

The validity of transmissibility values computed by standard methods are questionable, particularly where the degree of anisotropy is great. Indeed, if one takes the approach that direct interference in fracture porosity indicates that two wells tap a single fracture system whereas small drawdown indicates poor hydraulic connection between two wells, then one can conclude that the flow is not equal in all directions

and hence that the smaller values of transmissibility indicate the direction of greater permeability—or the alinement of the major fracture system. A thorough discussion on the quantitative aspects of transmissibility values computed from pumping tests in fractured rocks is beyond the scope of this paper. Suffice it to say that extreme caution must be used when analyzing quantitatively drawdown data in fractured aquifers.



Distance, in geet

Fig. 6 — Relation of drawdown with distance from pumped well in the direction perpendicular to strike, Flemington, N.J., pumping test.

Of practical significance, however, is the directional orientation of the hydraulic anisotropy exhibited by the aquifer. Owing to the apparent relation of the hydraulic anisotropy to the strike of the Brunswick Shale, it is evident that well interference can be minimized by alining wells in directions other than parallel to the strike. The local strike of the Brunswick can be determined readily from geologic maps or by an examination of outcrops in the area. Finally, it is easy to see how knowledge of the hydraulic anisotropy of an aquifer can lend considerable insight in the evaluation of existing or potential ground-water contamination and saltwater encroachment problems.

Acknowledgments

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