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NEW JERSEY GEOLOGICAL SURVEY
TECHNICAL MEMORANDUM

The Noordbergum Effect

by

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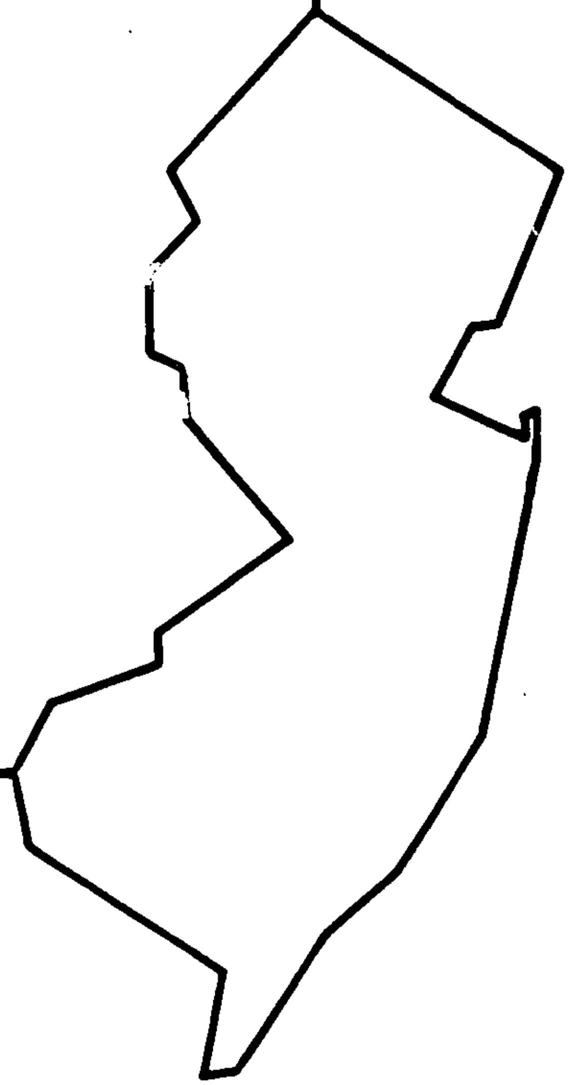

Department of Environmental Protection
Division of Water Resources

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I. Introduction

Pumping a well usually causes water levels in nearby observation wells to go down. However, the reverse of this is occasionally observed. This seemingly contradictory effect is termed the Noordbergum effect after the location in the Netherlands where it was first noticed.

As Rodrigues (1983) put it "The Noordbergum effect consists of a reverse water-level response in aquitards or in aquifers separated from the pumped aquifer by aquitards during early times of pumping and recovery tests". One of the best known examples of the Noordbergum was reported by Barksdale et al., 1936, as occurring at the Atlantic City well field. Several possible causes of this effect were postulated but none were totally satisfactory.

This report shall briefly describe the theories concerning the Noordbergum effect and then present several examples.

II. Theories

Several different theories have been formulated in an attempt to explain the Noordbergum effect. They range from an intuitive analysis of the situation to a complicated three dimensional stress analysis of pumping effects.

In order to investigate the Noordbergum effect one must first define what is being investigated. The water level in a well is actually an indication of the hydrostatic pressure (P_h). A drop or rise in P_h is indicated by a drop or rise in water level in an observation well.

The hydrostatic pressure is one component in the total pressure (P_t) at a point. The other component is the intergranular pressure (P_i). These two components sum to give the total pressure (P_t) as:

$$P_t = P_h + P_i. \tag{1}$$

In practice, the total and hydrostatic pressures are measured or calculated and the intergranular pressure is calculated by:

$$P_i = P_t - P_h. \tag{2}$$

The first theory, attributed to Barksdale, (Barksdale et al., 1936) is the most intuitive. When pumping begins, water starts moving up the casing. By Newton's third law this causes an equal and opposite force upon the pump foundation. This downward force then increases the total pressure on all aquifers and aquitards under the pump. This increase in total pressure causes an increase in both the intergranular and hydrostatic pressures. Thus the water levels in all formations will rise.

This theory is supported by the observation that placing a very heavy load on the surface (e.g. a train) causes water levels under the load to rise. Also, the cyclic rise and fall of tides creates a rise and fall in water levels near tidal waters.

The next theory, presented by Bouwer (1978), analyzes the distribution of pressure. As the hydrostatic pressure decreases (due to pumping) the intergranular pressure actually increases. This is seemingly contradictory but can be explained.

If the pumped aquifer is confined, then withdrawing water doesn't actually dewater any sediments. Thus the total weight and total pressure is unchanged. However, the hydrostatic pressure decreases.

To compensate for the decrease in hydrostatic pressure, the intergranular pressure must increase. The intergranular pressure increase is transmitted to underlying formations where it is partially transferred to the hydrostatic pressure. This causes a slight rise in head. Intuitively this makes sense. The water in the aquifer being pumped was helping to support the load of overlying sediments. As the water pressure decreases the grains in the aquifer matrix must support more and more of the load.

This theory is not entirely satisfactory in two aspects. The first is that it does not explain hydrostatic pressure increases in formations above the formation being pumped. The second is that for artesian aquifers it assumes that the total pressure doesn't change as the pressure head drops. It is known that the aquifer grains do expand slightly as the hydrostatic pressure drops, thus lowering the aquifer matrix density and thus the total pressure.

If the aquifer is unconfined a different explanation is necessary. As sediments are dewatered some water is retained in the vadose zone. This water had contributed to the hydrostatic pressure when it was part of the saturated zone but as part of the unsaturated zone does not. This causes the hydrostatic pressure to drop faster than the total pressure and results in an increase in intergranular pressure.

Example: Imagine a formation 30 meters thick with a soil density of 2.6 g/cm^3 and a porosity of 0.3. Initially the top 10 meters is unsaturated (with a water saturation of 5%) and the bottom 20 meters are saturated (a water saturation of 30%). The density of water is 1 g/cm^3.

The total pressure at the bottom of this formation is the total weight of the overlying material, or the weight of water in the unsaturated zone plus weight of water in the saturated zone plus weight of soil. Weight is equal to thickness times density times degree of saturation. The weight of water in the unsaturated zone is 10 X 1.0 X 0.05 or 0.5 $m\text{-}g/cm^3$ or 0.05 kg/cm^2. The weight of water in the saturated zone is 20 X 1 X 0.3 or 6 $m\text{-}g/cm^3$

or 0.60 kg/cm^2. The weight of soil is 30 X 2.6 X 0.7 or 54.6 $m\text{-}g/cm^3$ or 5.46 kg/cm^2. The total pressure is 0.05 + 0.60 + 5.46 or 6.11 kg/cm^2.

The hydrostatic pressure is equal to the saturated thickness times the density of water. For this example the hydrostatic pressure at a depth of 30 meters is 20 X 1 or 20 $m\text{-}g/cm^3$ or 2 kg/cm^2. From equation 2 the intergranular pressure at the bottom of the formation is 6.11 - 2.00 or 4.11 kg/cm^2.

If the water table drops 10 meters the pressure needs to be recalculated. The total pressure, following the above calculations, is 1.00 + 3.00 + 54.6 or 58.6 $m\text{-}g/cm^3$ or 5.86 kg/cm^2. The hydrostatic pressure at the bottom of the formation is 10 $m\text{-}g/cm^3$ or 1.00 kg/cm?. The intergranular pressure is thus 4.86 kg/cm^2.

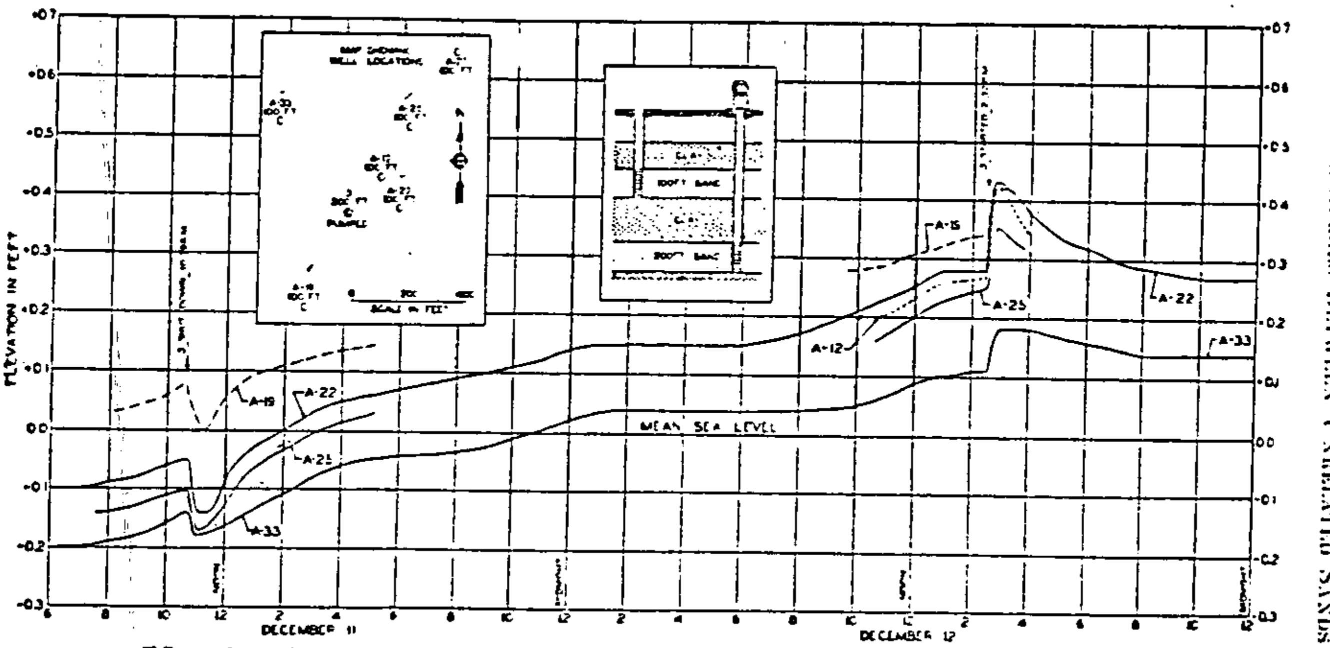
For this example a water table drop of 10 meters causes a <u>decrease</u> in total pressure but an <u>increase</u> in intergranular pressure. This increased intergranular pressure is transmitted to underlying formations where it forces a slight rise in hydrostatic pressure.

The last theory (as presented by Gambolati, 1974) results from a three-dimensional stress analysis of a pumped aquifer. After much mathematical manipulation one can show that water moving towards a pumping well exerts a force on the aquifer matrix. This force is transmitted to units above and below through formation interfaces. The force (towards the pumping well) causes an increase in total pressure, and an increase in hydrostatic pressure. In the pumped aquifer this is overshadowed by drawdown due to the pumping, but is observable in neighboring aquifers and aquitards. There is some field evidence to support this theory (Wolff, 1970) which evidence is summarized in the next section (Examples).

III. Examples

The best known example of the Noordbergum effect in the United States occurred in 1931 at the Atlantic City Water Works well field in Atlantic County, New Jersey, (Barksdale et al., 1936). In this area two sand members of the Cohansey (the 100 foot sand and the 200 foot sand) are separated by a 50 foot thick clay layer. An aquifer pumping test was conducted to determine the interaction between these two sand units.

Figure 1 summarizes the geology and results of the aquifer pumping test. Well #3, completed in the 200 foot sand, was shut down, then restarted a day later. The effect on monitoring wells in the 100 foot sand was striking. Immediately following the cessation of pumping in the lower sand, the water levels in the upper sand went down by approximately 0.1 feet, then gradually increased. When the pumping in the 200 foot sand resumed the water levels in the 100 foot sand went up and then gradually decreased. This effect was noticed only near the pumping well, in wells ranging from 165 to 400 feet from the pumping well. Well A-27, 665 feet from the pumping, showed no sign of the Noorbergum effect.



—Effect of starting and stopping a well to the 200-foot sand, at the Atlantic City Water Works, on water levels in wells to the 100-foot sand, with a map of the wells observed.

Figure 1. Geology and Hydrographs of

Atlantic City Water Works Test

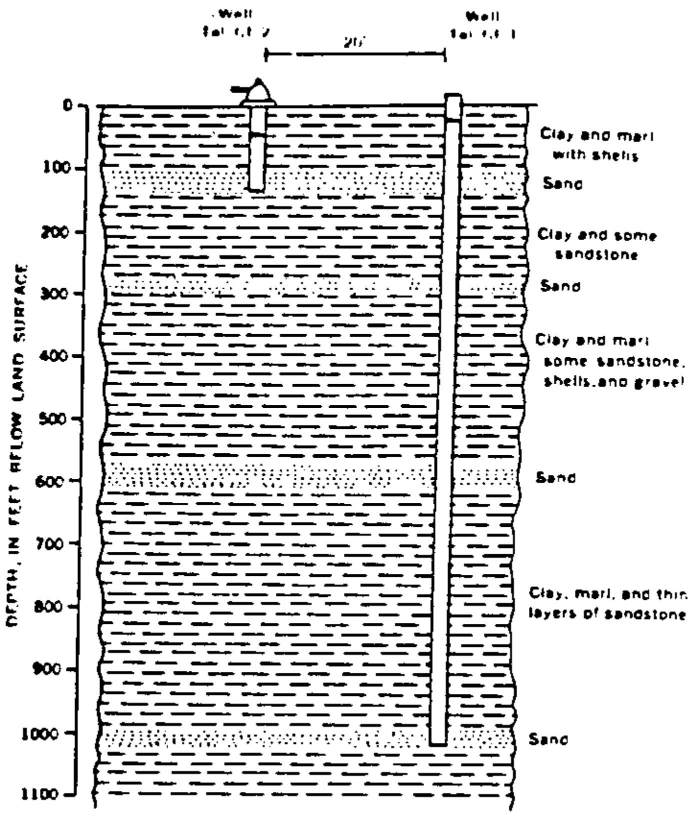
(Barksdale et. al, 1936)

Andreasen and Brookhart (1963) report an example of the Noordbergum effect at Easton, Maryland. Figure 2a shows the geology of the study area. A sand unit at a depth of approximately 100 feet below the surface was pumped while heads in a sand at 1000 feet depth were observed. These two sand units are separated by three clay/marl units and two other sand units. Figures 2b and 2c show hydrographs from the deeper well (Tal - C E1) while the shallow well (Tal - CE 2) was being pumped. The magnitude of the effect was slight, only 0.05 feet, but it was consistent throughout the test.

During this aquifer pumping test an effort was made to see if the stresses placed by the pump on its foundations caused the underlying aquifers to consolidate slightly. The results showed that the surface elevation of the pumping well did not change during the pump test.

Another example was reported by Rodriques (1983) in Portugal. A confined sand unit was pumped and heads in the overlying clay unit displayed the Noordbergum effect. Figure 3a shows the geology of the site while figure 3b displays the hydrograph from well PC5/1 when B4 was pumped. The Noordbergum effect was about 4 cm (0.2 inches) at its maximum.

The next example, from Wolff (1970), shows results from Salisbury, Maryland. Wolff also measured surface movement. A well in a aquifer was pumped and heads in an underlying clay unit measured.



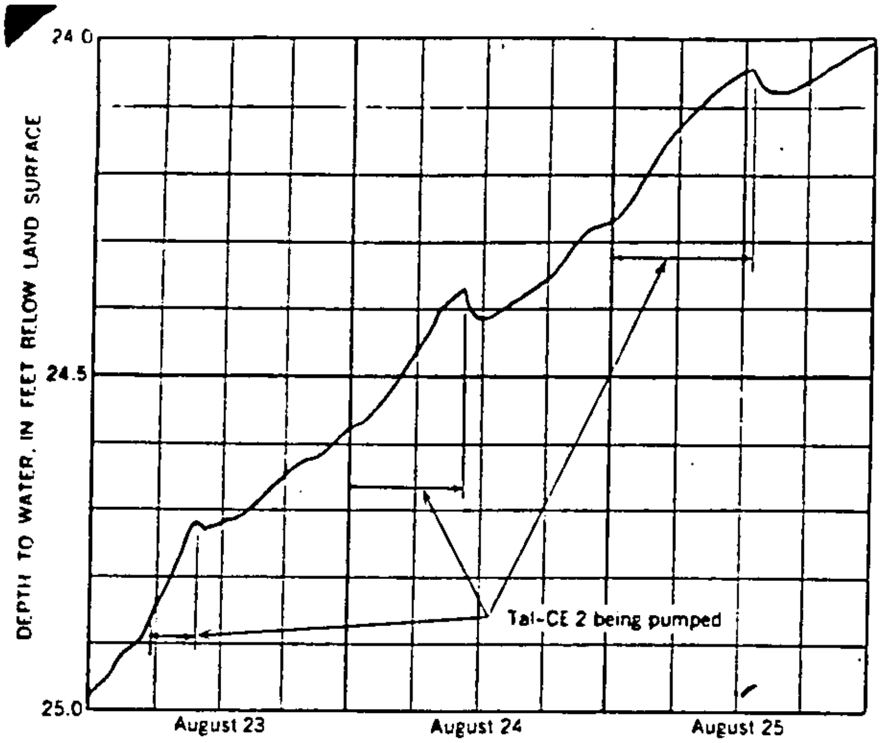
—Generalized geologic section at Easton, Talbot County, Md

Figure 2a

Figure 2. Geology and Hydrographs of

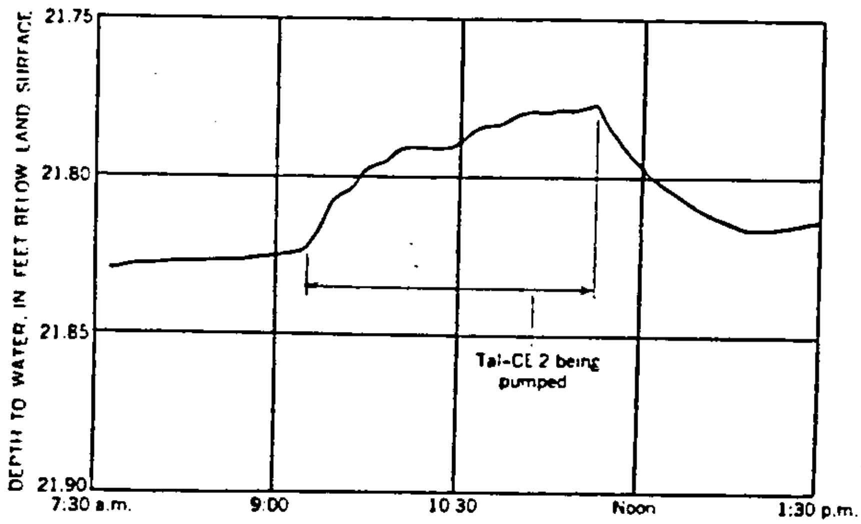
Easton, Maryland Test

(Andreasen and Brookhart, 1963)



—Hydrograph showing reverse water-level fluctuations in well Tal-Ce 1, Aug. 23-25, 1950

Figure 2b



—Hydrograph showing reverse water-level fluctuations in well Tal-Ce 1 on Sept. 15, 1950.

Figure 2c

Figure 2. (continued)

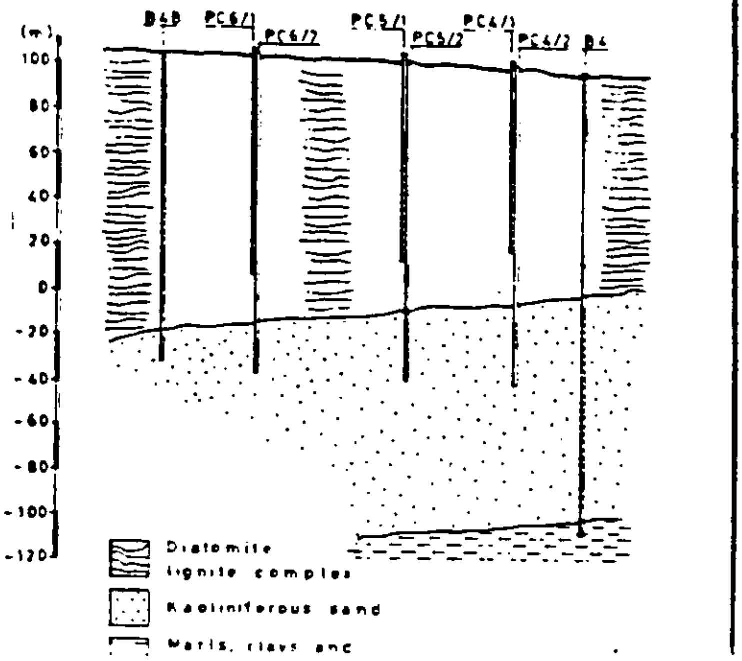
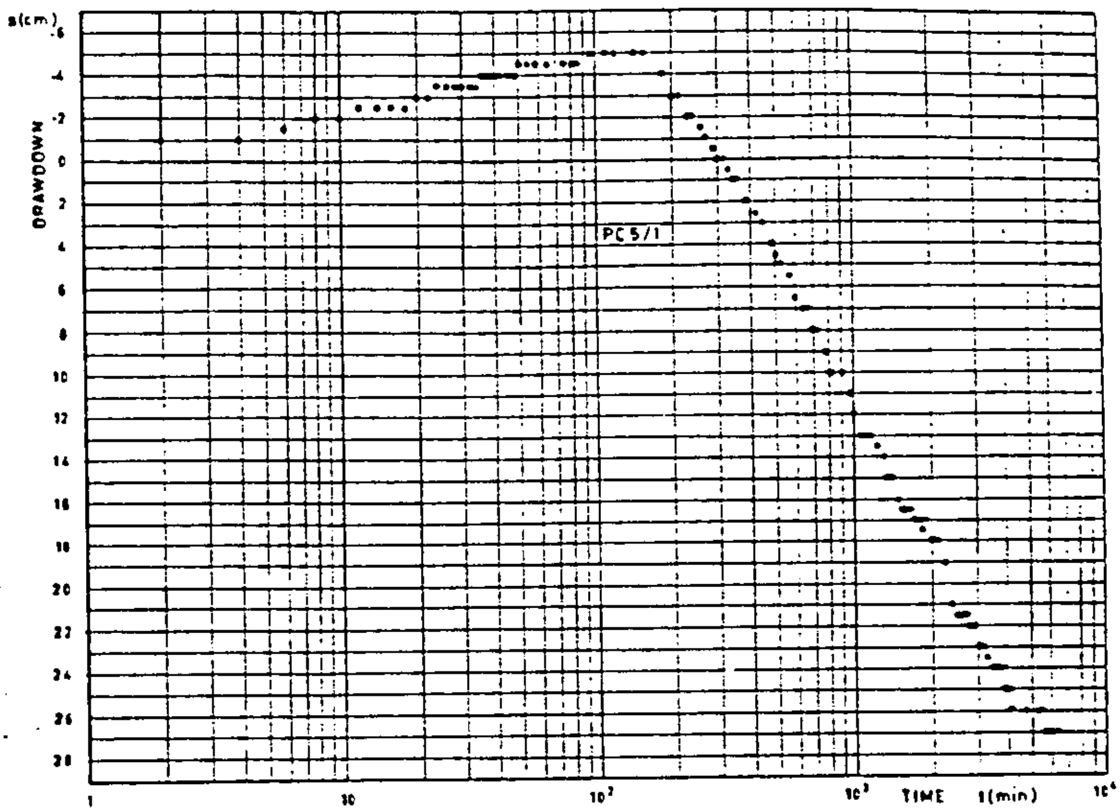


Figure 3a



3b

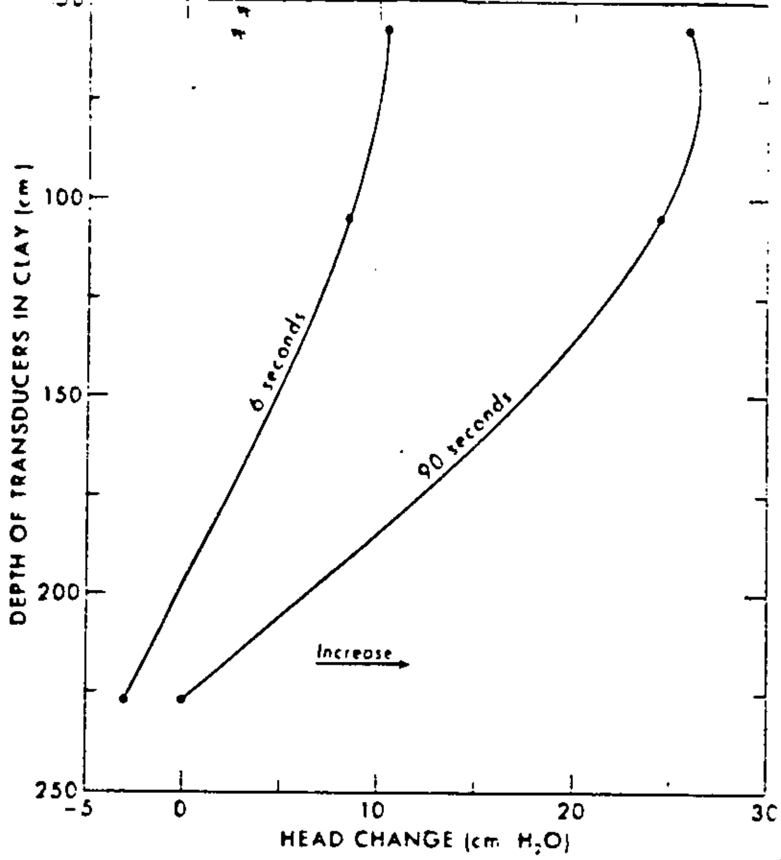
Noordbergum effect at PC5/1; B4 pumping well taps the sand aquifer and the observation well is screened in the aquitard.

Figure 3. Geology and Hydrograph of Portugal Test

(Rodrigues, 1983)

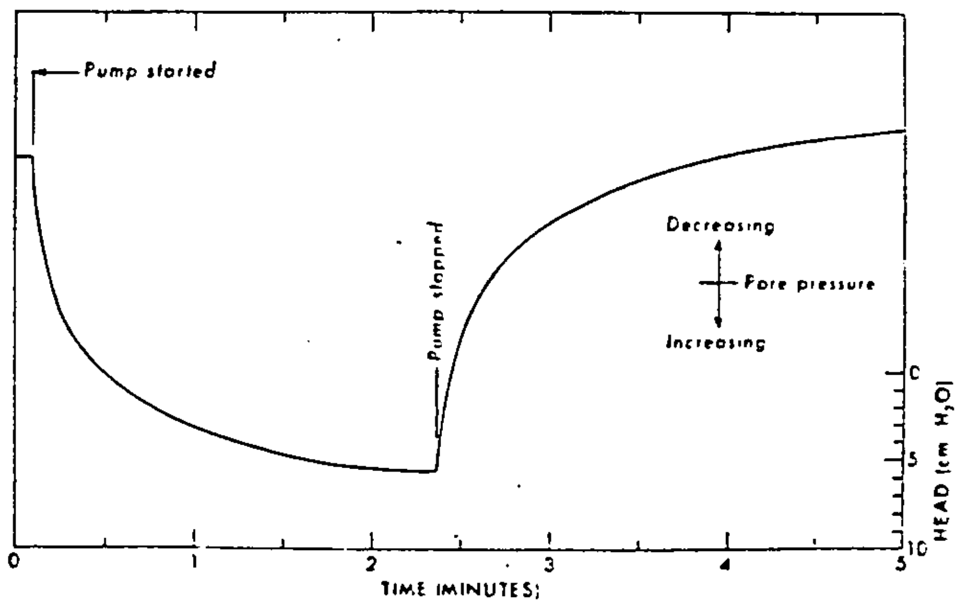
Figure 4a shows how heads at 3 different locations in the clay at 2 different times. Starting the pump increased the hydrostatic pressure in the clay, an example of the Noordbergum effect. Figure 4b displays a hydrograph from a piezometer in the clay 3.05 meters from the pumping well. Pumping caused a head increase of about 20 centimeters at this point.

Wolff's most startling work entailed measuring surface movement caused by pumping. Figure 5a displays a typical setup used to measure strain. Figure 5b shows the areal results of the strain measurements. Near the pumping well the ground moved towards the well, while away from the well it moved away from the pumping source. Figure 5c shows strain at one surface location. Maximum surface movement was approximately 13 microns (0.00004 feet). Figure 5d shows how well theoretically calculated strain values matched observed values. The match is relatively good thus lending credence to the theory that pumping creates a physical stress on the aquifer which forces water levels to go up.



4a

Observed pore pressure changes at three different depths in a clay bed underlying the pumped aquifer. The time represents the elapsed time since pumping started.

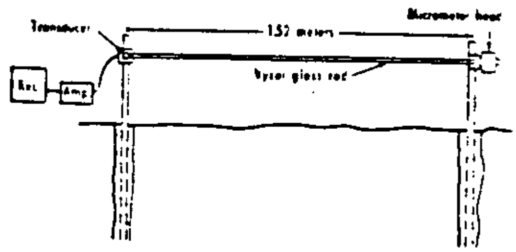


4b

Tracing of a strip chart recording for a piezometer located 0.64 meter below the pumped aquifer–clay interface and at a radial distance of 3.05 meters from the pumped well. The tracing shows the instantaneous effect of starting and stopping the pump.

Figure 4. Hydrographs of Salisbury, Maryland Test

(Wolff, 1970)



Diagrammatic sketch of setup used for strain measurements.

Figure 5a

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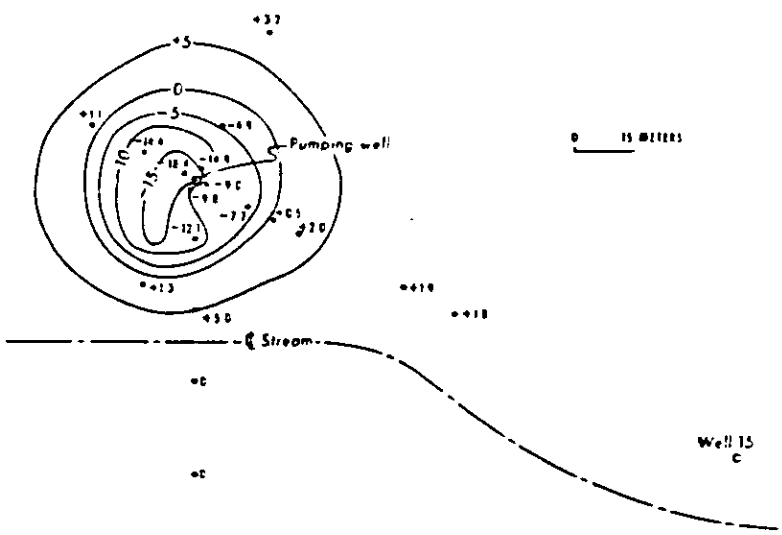


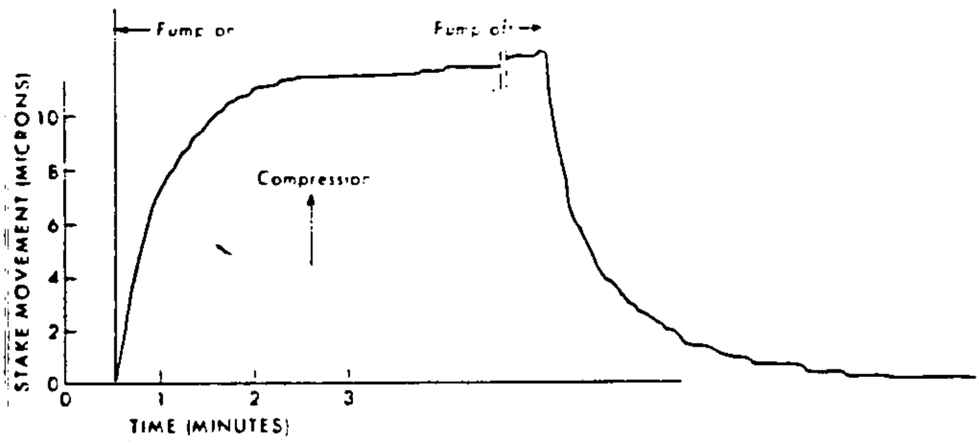
Contour map of radial strains, measured at the surface, as a result of starting pumping. —, posts moving together; +, posts moving apart; contours, strain × 10^{-6}.

Figure 5b

Figure 5. Strain Measurements of Salisbury, Maryland Test

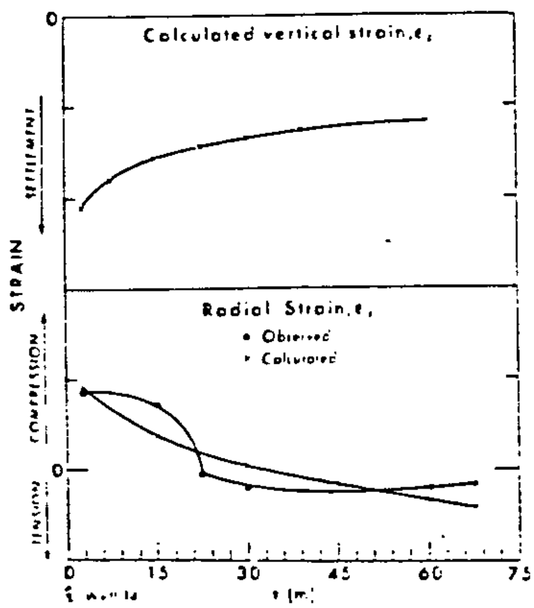
(Wolff, 1970)

Strain Due to Pumping



Tracing of a strip chart recording showing typical relative movement of the stakes to one cycle of starting and stopping the pump.

Figure 5c



Plot of strain versus distance from the pumping well along a straight line connecting wells 14 and 15 (Figure 5).

Figure 5d

Figure 5 (continued)

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