A Comparative Study of Specific Yield Determinations for a Shallow Sand Aquifer

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ABSTRACT

Using the type-curve methods of Boulton (1963) and Neuman (1972), and comparisons, at various times, of the cumulative volume of water pumped to the volume of the water-table drawdown cone (volume-balance method), values of specific yield were obtained from pumping test data from numerous piezometers in an unconfined sand aquifer. The long-term value of specific yield for the aquifer was determined from measurements of the laboratory drainage curve of the aquifer material.

The volume-balance method gave specific yield values of 0.02, 0.05, 0.12, 0.20, 0.23, and 0.25 at times of 0.25, 0.66, 10, 26, 45, and 65 hours, respectively, indicating a gradual increase in specific yield and an asymptotic approach to the long-term value of 0.30 determined from the laboratory method. The type-curve methods provided values of 0.07 and 0.08, which correspond to the volume-balance values at early times, but which are less than one-third of the value obtained from the laboratory method and from the volume-balance method applied at the end of the pumping test (2.7 days). The type-curve procedures therefore provide unrealistically low values of specific yield for application to problems concerning the long-term yield characteristics of the aquifer.

The observed trend towards increasing values of specific yield with increasing duration of pumping, and the vertical hydraulic head profiles that were measured during the pumping test indicate that both delayed drainage from above the water table and downward hydraulic gradients in the saturated zone can be important hydraulic effects contributing to the delayed-drawdown segment that is characteristic of time-drawdown graphs for unconfined aquifers.

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INTRODUCTION

It is common practice to determine the specific yield of unconfined aquifers by analyzing pumping test data using the type curves developed by Boulton (1963) and Neuman (1972). In these methods, drawdown versus time data from pumping tests, which are normally less than a few days in duration, are matched to type curves. Much less commonly, specific yield is determined from the ratio of the cumulative volume of water pumped, to the volume of the water-table drawdown cone. In this paper, this is referred to as the *volume-balance* method.

Pumping test analyses for sand and gravel aquifers based on the type-curve methods of Boulton and Neuman have provided published values of specific yield that are, almost without exception, between 0.03 and 0.13. For example, Boulton (1963) used type curves to analyze pumping test data from an unconfined sand-gravel aquifer which, though of glacial origin, was known to contain no distinct interbedding of till lenses. He obtained values of specific yield ranging between 0.02 and 0.09. Using Boulton's type-curve method, Prickett (1965) obtained specific yield values between 0.03 and 0.13 for some unconfined glaciofluvial sand aquifers. Neuman's type-curve method gave specific yield values ranging between 0.03 and 0.04 for a fine to medium-grained sand aguifer (Neuman, 1975). Rushton and Howard (1982) used the type-curve methods and obtained specific yield values between 0.0004 and 0.01 for an unconfined, fine-medium-grained sandstone aguifer. These authors stated that these values were much lower than the "known long-term specific yield" of between 0.10 and 0.15 for this aquifer.

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Remson and Lang (1955) used the volumebalance method to obtain a specific yield of 0.10 at the end of a 24-hour pumping test in an unconfined sand-gravel aquifer. In a more detailed application of the volume-balance method in a very fine-medium sand and gravel aquifer, Wenzel et al. (1946) computed specific yield values at times of 4, 8, and 15 hours, and obtained specific yield values of 0.01, 0.014, and 0.018, respectively. From a similar study in a glaciofluvial sand-gravel aguifer, Wenzel (1942) found specific yield to increase from 0.09 after six hours of pumping through 0.16, 0.18, to 0.20 after 24, 36, and 48 hours, respectively. For pumping tests of normal duration, these examples suggest that specific yield commonly increases with duration of pumping, and is higher when obtained by the volume-balance method than by the type-curve methods.

In the normal context of aquifer evaluation and management, specific yield is a measure of the volume of water that an aquifer can yield when it is pumped for a sufficiently long time for the water to fully drain by gravity from above the water table. Thus, although pumping tests are usually short in duration, aquifer yield is normally evaluated over much longer periods of time that are relevant to water usage. Long time periods provide for full gravity drainage of the zone above the declining water table. On the basis of studies on time-drainage relations in long columns of silt, clean sand and gravel materials (Johnson et al., 1963), a time scale that would be required to reach equilibrium in sand-sized materials, and thus provide for the attainment of maximum specific yield in long-term pumping situations, has been estimated by Prill et al. (1965), as cited by Johnson (1967), to be in the order of 2 to 12 months. Johnson (1967) and Stallman (1971) have studied the dependence of time of drainage, and hence specific yield, on the average grain size. These studies indicate that the time required to attain a given value of specific yield increases considerably with decreasing mean grain size. Stallman further concluded that for a clean sand with a typical water-table drawdown, less than 70% of the ultimate specific yield will be attained after two days. Thus, to the extent that the types of laboratory-tested sands apply in field situations, the duration of many pumping tests may be less than the time necessary for drainage from above the water table to be complete.

Comparison of the results of the various types of specific yield studies of sand reported in the literature suggests that specific yield values depend

on the type of test, the time scale of the test, and the method of data analysis. In the investigation described in this paper, the specific yield of an unconfined sand aquifer was determined by pumping tests using type-curve and volume-balance methods, and by laboratory drainage tests. The influence of delayed drainage from above the water table is assessed by comparison of specific yield values obtained at various times in one of the pumping tests and by laboratory observations.

The field study was conducted in an unconfined sand aquifer at the Canadian Forces Base at Borden, Ontario. The hydrogeology of this aquifer is described by MacFarlane et al. (1983). The aquifer material is a clean, well-sorted, and predominantly medium-grained sand of glaciofluvial origin. However, as a result of small-scale bedding, texture varies from fine to coarse sand (Sudicky et al., 1983). Although the aquifer has bedding features, it is relatively homogeneous when compared to many aquifers of glaciofluvial or alluvial origin. The textural changes are subtle to the extent that undisturbed cores are generally necessary in order to detect the bedding.

The sand deposit is 9 m thick and is underlain by a thick deposit of clayey silt. The water table, which is relatively flat, was about 2.3 m below ground surface before and after the pumping tests.

The important hydrogeologic characteristics of the study site thus include a relatively homogeneous and laterally extensive aquifer of near-uniform thickness, and a horizontal water table overlain by a flat topography.

METHODS OF INVESTIGATION

The pumping well and piezometer network at the study site were designed to provide data from which specific yield could be determined using volume-balance and type-curve methods. The fullypenetrating pumping well was installed by cable tool drilling, and has a Johnson 13-cm telescopic screen about 4 m long. The pumping well casing has an inner diameter of 15 cm. The piezometer network includes three groups of piezometers, a deep group (P series), a very shallow group (WS series), and an intermediate group (WD series), as shown in Figures 1 and 2. The piezometers were made from 3.5 cm I.D. PVC pipes perforated over the bottom 0.35 m and screened with nylon cloth (NITEX 3). The deep piezometers were installed through a temporary casing jetted to a depth equivalent to that of the mid-section of the pumping well screen. These piezometers provided time-drawdown data most suitable for type-curve

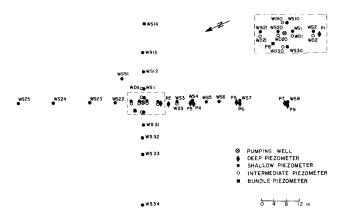


Fig. 1. Plan view of pumping well and piezometers.

methods of analysis. They also were used for slug tests for hydraulic conductivity determinations. The shallowest group of piezometers were handaugered to 0.35 m below the static water table. These provided water-table data from which the volume of the water-table drawdown cone was calculated. It was anticipated that after about one day of pumping, the water-table drawdown near the pumping well would exceed 0.35 m. The piezometers in the WD series were therefore installed to a depth of 0.35 m below the WS series. This made it possible to monitor the water-table drawdown cone at all times. In addition to these piezometers, a bundle of seven narrow-diameter piezometers was jetted in at a distance of 3.5 m from the pumping well. These narrow-diameter piezometers were distributed at intervals of about 1 m between the water table and the bottom of the aquifer, and provided hydraulic head profiles across the aquifer.

A short-term pumping test of about four hours duration, and a long-term test lasting 65 hours were conducted. The discharge rate, which was measured periodically by noting the time taken to fill a container of known volume, was consistently within 60 ± 1 l/min⁻¹ during the longterm test, and $36 \pm 1 \text{ l/min}^{-1}$ throughout the duration of the short test. Water levels in the piezometers and pumping well were measured to within 0.5 cm using electric sounders. In each of the two tests, specific yield was determined at several time intervals using the volume-balance method. The long-term test provided late timedrawdown data, thus permitting the use of type curves to obtain specific yield. Aguifer transmissivity was also determined using the type curves.

The laboratory study of the drainage characteristics, and hence specific yield, of the aquifer material was accomplished using an experimental arrangement adapted from Day et al. (1967) as described by Wilson (1980), to obtain water content versus pressure-head data. An ovendried sample of the aguifer material taken from within the cone of water-table drawdown was packed into a filter funnel to a bulk density of 1.6 gm/cm⁻³, a value typical of clean sands (Wilson, 1980). The Borden aquifer material is a clean fine-medium sand. The sample was then saturated from the bottom with deaired water by allowing the water to flow in from a burette during a stepwise lowering of the filter funnel. The saturated volumetric water content was 0.37. The time required to reach equilibrium varied from tens of minutes at high values of water content to one to

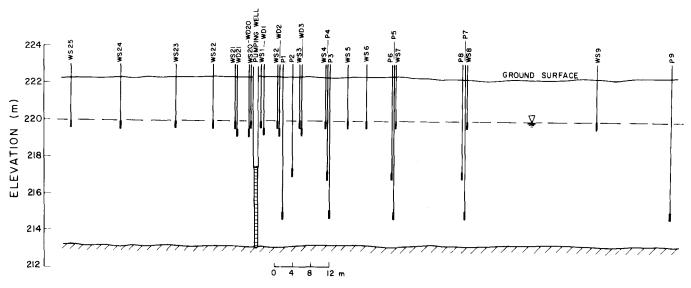
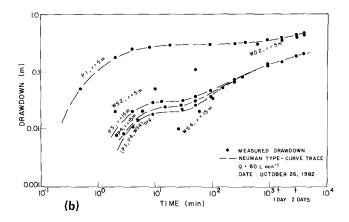


Fig. 2. Vertical cross section showing pumping well and piezometers.



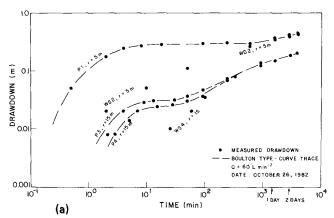


Fig. 3. Time-drawdown data: (a) Boulton type-curve traces: r/B = 0.6 (P1), r/B = 1.5 (P3), r/B = 2.0 (P4); and (b) Neuman type-curve traces: $\beta = 0.1$ (P1), $0.4 < \beta < 1.0$ (P3), $\beta = 1.0$ (P4), $\beta = 2.5$ (P3, P4, WS4)_{avg}.

two days at low values of water content. The saturated soil column was then adjusted in steps down to a negative pressure head of 150 cm. The volume outflow from the sample was measured for each increment in pressure head, from which a graph of water content versus pressure head was constructed. As noted in McWhorter and Sunada (1977), specific yield is equal to the saturated water content (θ s) minus the residual water content (θ r). In that the curve is obtained under equilibrium conditions, the resulting specific yield is the maximum long-term value. Because the aquifer sand in the drawdown-cone area is relatively uniform, the specific yield value obtained from the laboratory drainage-curve data should be reasonably representative of the field conditions.

RESULTS AND DATA ANALYSIS

Double logarithmic plots of the time-draw-down data from piezometers P1, WS2, WD2, P3, P4, and WS4 for the long-term pumping test are shown in Figure 3. The average drawdown across the aquifer thickness as determined by taking the arithmetic mean of the drawdown values from P₃,

P₄, and WS₄ is also shown. Piezometers P1 and P3 show how the time-drawdown curves vary with radial distance at the bottom of the aquifer, and piezometers P3, P4, and WS4 illustrate the variation of time-drawdown curves with depth at a fixed radial distance of 15 m. The observed trends are consistent with the type curves of both Boulton (1963) and Neuman (1972). The deep piezometers exhibit the delayed response in the mid-time period that is characteristic of unconfined aquifers.

Figure 3a shows the best-fit traces of the Boulton type curves, and Figure 3b shows those of Neuman. The type curves of Neuman were applied to both the vertically averaged and depth-specificdrawdown data. It is evident from these figures that there is a close match between the data points and the type curves. The late time-drawdown data for P3 are coincident with those of P4. Consequently, the same match point was used in the type-curve analyses for both piezometers. From late time-drawdown data, Boulton's type-curve method gave a specific yield value of 0.08 from piezometers P3-P4, and a transmissivity value of 1.53×10^{-3} m²/sec⁻¹. For the same piezometers, the Neuman method gave a specific yield value of 0.07 and a transmissivity of 1.47×10^{-3} m²/sec⁻¹. Applying the Neuman type-curve method to the late time-average-drawdown data gave a specific yield value of 0.05 and a transmissivity of 1.32×10^{-3} m²/sec⁻¹. These values are close to those obtained by using depth-specific or "point" drawdowns that were measured in individual piezometers. Using the early time-drawdown data from piezometer P3, Boulton and Neuman type curves gave similar transmissivity values of 1.2 × 10⁻³ m²/sec⁻¹ and 1×10^{-3} m²/sec⁻¹, respectively. Identical values were obtained from piezometer P4, also using the early time data.

The specific yield and transmissivity values determined using the Boulton method for piezometer P1 were 1.30 and 4 × 10⁻⁴ m²/sec⁻¹, respectively. The Neuman method gave identical values of specific yield and transmissivity. These specific yield and transmissivity values are not realistic. Although the pumping well is fully penetrating, it has a screened length equivalent to about 60% of the initial saturated thickness of the aquifer. This partial screening of the aquifer causes a distortion in the drawdown pattern near the pumping well due to strong vertical flow components. Piezometer P1 is at a radial distance of only 5 m, which is less than the initial saturated thickness of the aquifer. Analyses of drawdown data

from so close to the pumping well using the type curves commonly result in anomalous values of aquifer parameters (Kruseman and de Ridder, 1970).

Excluding the data from P1, transmissivity values determined using the type curves range between 1×10^{-3} m²/sec⁻¹ and 1.53×10^{-3} m²/sec⁻¹. The saturated thickness of the aquifer is about 7 m. Dividing the transmissivity by this thickness provides hydraulic conductivity values ranging from $1.43 \times 10^{-4} \text{ m/sec}^{-1}$ to $2.18 \times 10^{-4} \text{ m/sec}^{-1}$. Slug and bail-test data from the deep piezometers were analyzed using the methods of Hvorslev (1951) and Papadopulos et al. (1973), and gave hydraulic conductivity values ranging from $3.0 \times 10^{-5} \text{ m/sec}^{-1} \text{ to } 6.0 \times 10^{-5} \text{ m/sec}^{-1}$. Hydraulic conductivity values ranging between 6.0×10^{-5} m/sec⁻¹ and 1.0×10^{-4} m/sec⁻¹ were determined from grain-size data (MacFarlane et al., 1983). Thus the transmissivity, and hence the hydraulic conductivity, predicted by the type curves are consistent with the results obtained from grainsize data, and are somewhat larger than the values obtained from slug tests.

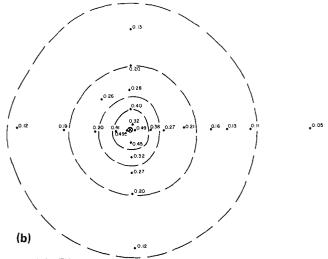
Specific yield values using the volume-balance method were obtained from the relation.

$$Sy = Vw/Vc \tag{1.1}$$

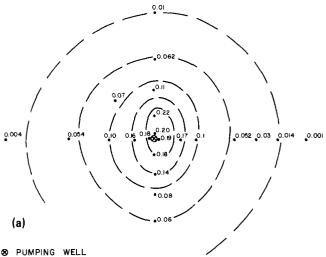
where Sy is the specific yield, Vw is the cumulative volume of water discharged, and Vc is the volume of the cone of water-table drawdown. Specific yield determinations were made at 0.25, 0.66, 10, 26, 45, and 65 hours after pumping started. The volume of water discharged within these time intervals was 0.9, 2.4, 36, 93.6, 158.5, and 232.2 m³, respectively. Figures 4a and b are water-table drawdown maps 160 minutes into the short test, and 3,800 minutes into the long test, respectively. These maps indicate radial symmetry of the watertable drawdown about the pumping well. The measured water-table drawdown at the various time intervals during the long test is shown in Figure 5. Based on the radial symmetry, the volumes of the respective cones of water-table drawdown were determined using the trapezoidal rule of numerical integration to evaluate the integral expression,

$$Vc = 2\pi \int_{x}^{\infty} (sr) dr$$
 (1.2)

where x, the lower limit of integration, is the effective radius of the pumping well; and s is the water-table drawdown at a given radial distance, r, from the pumping well. Following the method of



⊗ PUMPING WELL *0.21 MEASURED DRAWDOWN CONTOUR INTERVAL ~ 0.5 m TIME ~ 3800 min PUMPING RATE ~ 60L min⁻¹



•0.19 MEASURED DRAWDOWN
CONTOUR INTERVAL - 0.04 m
TIME - 160 min
PUMPING RATE - 36 L min -1

Fig. 4. Water-table drawdown contour map: (a) short test and (b) long test.

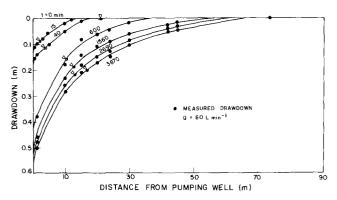


Fig. 5. Water-table drawdown cones along a section from north to south.

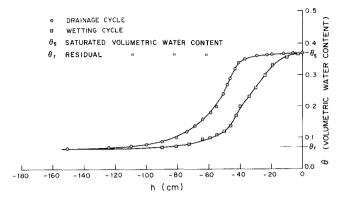


Fig. 6. Drainage curve for a sample of aquifer sand.

McWhorter and Sunada (1977), and replacing the upper limit of integration with y, the radial distance at which water-table drawdown is zero, expression (1.2) was evaluated graphically by calculating, in segments, the volumes of elemental cylinders taken about the pumping well in the form,

$$2\pi \int_{x}^{y} (sr) dr = 2\pi \left[\left\{ \Delta r_{1} \left(\frac{(rs)_{1}}{2} + (rs)_{2} - \dots + (rs)_{m-1} + \frac{(rs)_{m}}{2} \right) \right\} + \left\{ \Delta r_{2} \left(\frac{(rs)_{1}}{2} + \dots + \frac{(rs)_{m}}{2} \right) \right\} + \dots + \left\{ \Delta r_{n} \left(\frac{(rs)_{1}}{2} + \dots + \frac{(rs)_{m}}{2} \right) \right\} \right]$$
(1.3)

where Δr is constant for each segment and represents the elemental cylinder thickness, n is the number of segments, and m refers to the number of elements in each segment. The volumes of individual segments were summed to obtain Vc. There was some uncertainty as to the exact radial distance where the water-table drawdown is zero. Vc was determined for the estimated minimum and maximum radial limits of each of the water-table drawdown cones. At the times given previously, the volumes of the cones of water-table drawdown were 35, 50, 288, 472, 695, and 935 m3. Errors attributable to the uncertainty concerning the exact position of zero water-table drawdown range between $\pm 3 \text{ m}^3$ during early times and $\pm 9 \text{ m}^3$ at late time. Compared to the mean value of Vc, these errors are negligible. Substituting the corresponding values of Vw and Vc into (1.1) gives values of specific yield of 0.02 at 0.25 hr, 0.05 at 0.66 hr, 0.12 at 10 hrs, 0.20 at 26 hrs, 0.23 at 45 hrs, and 0.25 at 65 hrs, respectively. A similar calculation procedure was used to analyze the short-test drawdown data, and specific yield values of 0.03, 0.06, and 0.07 were obtained at times of 0.30, 1.5, and 3 hours, respectively. These values are very

Table 1. Values of Specific Yield Obtained in This Study

Method of evaluation	Specific yield	Remarks
Neuman's type curve	0.07	t = 120-3870 min; r = 15 m
Boulton's type curve	80.0	t = 120-3870 min; r = 15 m
Volume-balance (long test)	0.02	t = 15 minutes
	0.05	t = 40 minutes
	0.12	t = 600 minutes
	0.20	t = 1560 minutes
	0.23	t = 2690 minutes
	0.25	t = 3870 minutes
Volume-balance (short test)	0.03	t = 18 minutes
	0.06	t = 90 minutes
	0.07	t = 180 minutes
Laboratory study	0.30	

close to those obtained from the long test at corresponding values of time.

The water content/pressure head relation for the sample of aquifer material from the drawdown-cone area is shown in Figure 6. The characteristic curve shows the saturated and residual volumetric water contents to be 0.37 and 0.07, respectively, thus giving a specific yield of 0.30. This value is within the range expected for a clean, unconsolidated sand (Johnson, 1967).

DISCUSSION

The values of specific yield obtained in this study range from 0.02 to 0.30 (Table 1). Figure 7 shows the values of specific yield obtained from the volume-balance method plotted against time. Also shown in the figure are the values of specific yield determined from the laboratory measurement of the drainage curve and the type-curve methods of Boulton (1963) and Neuman (1975). Most published values obtained using the type-curve

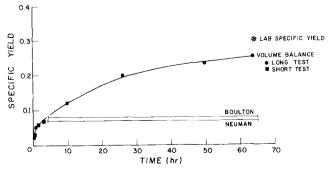


Fig. 7. Specific yield versus time relationship as shown by the volume-balance and type-curve methods.

methods for sand aquifers are within the range obtained in this study. The specific yield values obtained from the type-curve methods are represented on Figure 7 at the times within which the type curves were fitted to the drawdown data, a period of 0.07 days to 2.8 days.

The laboratory drainage experiment gave a specific yield value of 0.30. This is typical of values obtained by other investigations for sand materials using similar methods. Because of the equilibrium approach, and the homogeneous nature of the aquifer, it is considered to represent the long-term specific yield for this aquifer. It is the highest value obtained in this investigation, and it is about three times as large as the values obtained from the type curves. Figure 7 shows that the values of specific yield determined using the volume-balance method are similar, at early time, to those obtained from the type curves, but at late time, approach the laboratory value.

The increasing value of specific yield obtained from the volume-balance method is consistent with the results of laboratory experiments involving drainage from long columns referred to previously (Johnson et al., 1963; and Prill et al., 1965). It is recognized that in field situations, unlike the column experiments, flow in the expanding drawdown cone is two-dimensional. However, because of the vertical component of gradient that is particularly strong during the early stage of pumping and which is similar to that in laboratory column experiments, it is reasonable to conclude that the flow conditions that result in the long times required for development of the maximum specific yield during column drainage are the same conditions that give rise to the increasing specific yield with time of pumping as shown by the volume-balance data of Figure 7.

In the field situation, strong vertical gradient exists during early times and near the pumping well. It is thus probable that, at early time, the water table declines very rapidly near the well, and because of the time required for drainage from above the water table to occur, the volume-balance method would give low values of specific yield. At later times, the water table declines much more slowly, allowing drainage from above the water table to catch up and to approach an equilibrium water-content distribution. At progressively later times, a larger proportion of the water is coming from progressively greater distances from the pumping well, in areas where the rate of decline in the water table is much slower. Because of the slow rate in decline, the water content profiles above

the water table would approach equilibrium values. The net effect would be large departures from the equilibrium drainage profile near the well at early times resulting in very low specific yield values, and a gradual approach towards equilibrium conditions resulting in higher specific yield values at late times. These trends are represented in Figure 7.

The type curves provide values of specific yield that are much below the values relevant to long-term aquifer yield. They are based on mathematical models developed on particular assumptions of drainage and flow conditions in the zones above and below the water table. The Boulton (1963) model attributes the delayed-drawdown region of the type curves to a lag in drainage from above the declining water table, and includes an empirical delayed-yield factor to account for this process. Laboratory and field data that are available in the literature, as well as the data of this study indicate that there is indeed delayed drainage from above the water table during pumping of sand aquifers. Although this supports the conceptual basis of the Boulton model, the unreasonably low values of specific yield obtained from the type curves indicate this to be an inadequate basis for representing the overall behaviour of the aquifer.

Neuman (1972) assumed that the release of water from storage at the water table is instantaneous and complete as the water table declines during pumping. He attributed the apparent delayed-drawdown region of the type curves to flow caused by vertical hydraulic gradients below the water table. Figure 8 shows the hydraulic head profiles in the bundle piezometer at 10 and 100

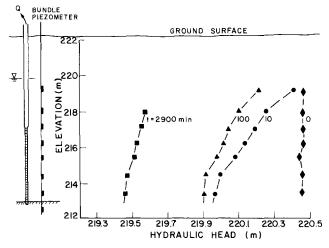


Fig. 8. Hydraulic head profiles during the short test at the bundle piezometer located 3.5 m from the pumping well.

minutes into the short test, and at 2,900 minutes into the long-term test. Although these two sets of profiles were obtained for two different pumping rates, and the magnitudes of the hydraulic head declines are therefore different, the qualitative changes of the profiles with time are expected to be similar. Comparing the time-drawdown data of P1 and WS2-WD2, and P3, P4 and WS4 (Figure 3), and from the hydraulic head profiles of Figure 8, it is evident that at the onset of pumping, the decline in hydraulic head at the bottom part of the aquifer is greater than in the upper part, and that the vertical gradients decrease with time. Thus, particularly at early time, a measurement of hydraulic head that is integrated across the entire aquifer, or indeed any measurement that is made at a point other than at the water table, would not give an accurate measure of the drawdown of the water table. At later times, as flow tends to become more horizontal, these measurements would more closely indicate the position of the water table. Thus, in the Neuman model, the delayed-drawdown region of the type curves represents the transition from shallow vertical and deeper radial flow at early time to more complete radial flow at later times. The hydraulic head data from below the water table supports the conceptual basis of aquifer flow inherent in the Neuman model, but the unreasonably low values of specific yield show the model to be an inadequate representation of the water release processes associated with water-table decline.

It is interesting that although the Neuman and Boulton type-curve sets are based on substantially different conceptual models, they give almost identical and characteristic S-shaped drawdown versus time curves; they both give what appear to be accurate values of the aquifer transmissivity and they give similar, although unrealistically low values of specific yield. In that parts of the conceptual basis of both models are supported by the field data, one is led to speculate that the problems pertaining to both models are those associated with incompleteness. It follows that a model that includes the effects of both vertical hydraulic gradients in the saturated zone and delayed drainage from above the water table would probably yield improved estimates of specific yield from type curves.

SUMMARY AND CONCLUSIONS

The values of specific yield obtained from the late drawdown data using type curves and volume balances and from the laboratory soil-water

drainage curve show large differences. The laboratory drainage curve indicates that the long-term specific yield of the aquifer is about 0.30. The volume-balance method, using early time-drawdown data, provided values of specific yield that are much lower than the long-term value. However, the values increase with increasing duration of pumping, and closely approach the laboratory-determined value after two and one-half days. This trend indicates that delayed drainage from above the water table is an important process influencing the response of the aquifer system.

The Boulton and Neuman type-curve methods give almost identical results, and although the computed values of transmissivity are reasonable, the values of specific yield are about one-third the late time values obtained from the volume-balance and laboratory methods. It appears, therefore, that the type-curve models provide values of specific yield that are not suitable for use in the context of long-term aquifer yield analysis, and that using the volume-balance method at late time or the laboratory method provides a more reasonable estimate of the long-term specific yield of this aquifer.

Although the Boulton and Neuman methods are based on substantially different conceptual models of unconfined aquifer response, they have nearly identically-shaped type curves and both have type curves that fit the field data quite closely. However, each of these models is lacking an apparently important process, either vertical flow in the saturated zone which is not included in the Boulton model, or delayed drainage from above the water table, which is not accounted for in the Neuman model. The results of this study suggest that a more appropriate model would be one that includes both of these effects.

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