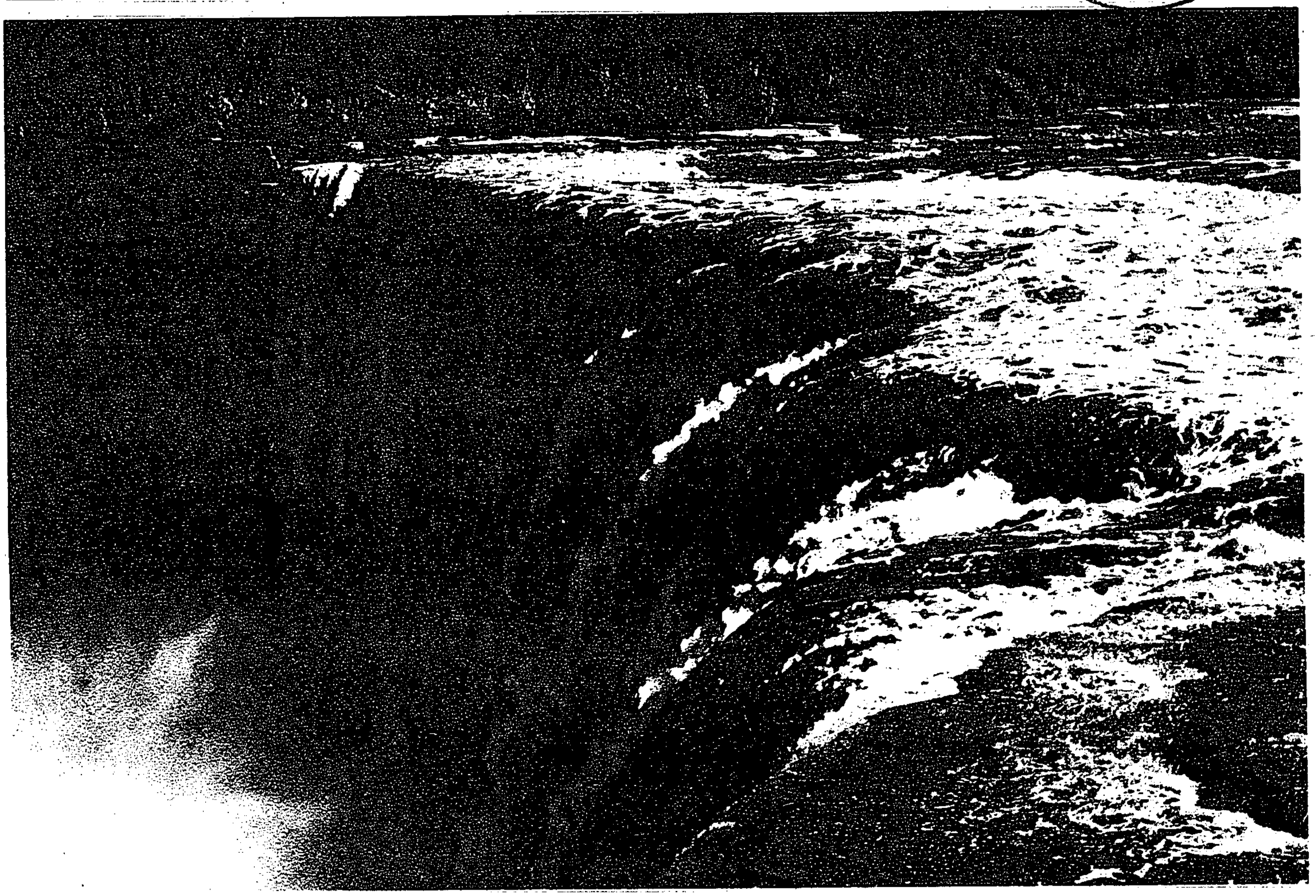
An Unusual Pump Test Near Esterhazy, Saskatchewan

A. Vandenberg



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INLAND WATERS DIRECTORATE
WATER RESOURCES BRANCH
OTTAWA, CANADA

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(Résumé en français)

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Abstract

As part of a program to study possible contamination of the environment by leaching of waste brine from storage basins at a potash mine near Esterhazy, Saskatchewan, a series of pump tests was conducted in March 1971. A pump test of approximately 20 hours duration was run on each of seven test wells and the piezometric head recorded simultaneously in the other six wells; the length of the intervening nonpumping periods was between 27 and 75 h.

The aquifer in which the observation wells were completed can be described as a semiconfined, buried bedrock-channel aquifer, with sand and gravel channel fill forming the aquifer body, and till forming the overlying, semiconfining bed. The location and thickness of the aquifer in the vicinity of the wells have been defined by the drilling of 91 stratigraphic test holes.

To analyze the pump-test data and to obtain estimates of transmissivity, storativity and leakage the recorded raw piezometric data had to be separated into (1) seasonal trend; (2) residual drawdown from previous pump tests and (3) the drawdown caused by the well being pumped at the instant of observation.

For most well pairs the distance between wells was large compared to the width of the channel; as a consequence, analysis by the Theis or Hantush method was excluded, and a method of analysis consistent with the geometry of a parallel strip aquifer was developed and has been reported (Vandenberg, 1976a, 1977a).

From the pump-test analysis the following ranges of the aquifer parameters were obtained:

Transmissivity	1.12 to 1.94 m^2/min
Storativity	3.8×10^{-4} to 1.2×10^{-3}
Leakage factor	1600 to 3900 m

As a test of the validity of the aquifer model thus obtained, the complete series of pump tests was simulated (1) by using the analytical expression for drawdown in a homogeneous leaky, parallel-strip aquifer and (2) by using a finite difference model in which the inhomogeneous aquifer parameters and the irregular boundaries of the aquifer could be more truthfully represented.

The results of the comparison show that there is a large range of uncertainty in the expected drawdown after a prolonged period of pumping. Real drawdown in the test holes exhibited a sustained downward trend which was much stronger than in the model solutions. Reasons for this trend could be (1) a seasonal downward trend owing to causes extraneous to the pumping, or (2) strongly reduced permeability or absence of the buried valley deposits to the east of the study site or (3) less leakage than was assumed on the basis of the pump-test analyses.

Résumé

Au cours d'un programme d'études de la contamination éventuelle de l'environnement par les saumures de rejet qui pourraient s'infiltrer à travers les parois des bassins de retenue d'une mine de potasse près d'Esterhazy (Saskatchewan), on a procédé à une série de pompages expérimentaux en mars 1971. Un pompage d'une durée d'environ vingt heures a été fait à chacun de sept puits pendant que le niveau piézométrique était mesuré simultanément dans les six autres. L'intervalle entre les pompages variait de 27 à 75 heures.

La couche dans laquelle les puits d'observation se terminaient peut être décrite comme une nappe aquifère captive à toit semi-imperméable sur roche de fond compacte, avec une couche de sable et de gravier formant la couche aquifère et une couche d'argile glaciaire formant le toit semi-imperméable. La localisation exacte de l'aquifère et son épaisseur aux alentours des puits ont été déterminées au moyen de 91 forages stratigraphiques.

Pour analyser les données des pompages expérimentaux et obtenir une évaluation de la transmissivité, du coefficient d'emmagasinement et du facteur de drainance, les données piézométriques brutes ont dû être divisées en (1) tendances saisonnières, (2) dépression du niveau de la nappe due aux pompages précédents, et (3) dépression du niveau de la nappe causée par le pompage au moment des observations.

Pour la plupart des paires de puits, la distance de puits à puits était grande comparée à la largeur du gîte; en conséquence, il a fallu exclure la méthode de Theis et celle de Hantush et développer une méthode d'analyse conforme à la géométrie d'un aquifère à limites étanches parallèles, méthode décrite ailleurs (Vandenberg, 1976a, 1977a).

L'éventail des paramètres de l'aquifère obtenus au cours de l'analyse des pompages expérimentaux est le suivant:

Transmissivité	de 1.12 à 1.94 m^2/ min
Coeff. d'emmagasinement	de 3.8×10^{-4} à 1.2×10^{-3}
Facteur de drainance	de 1600 à 3900 m

Pour vérifier la validité du modèle d'aquifère ainsi obtenu, la série complète des pompages expérimentaux a été simulée (1) en utilisant l'expression analytique pour la dépression du niveau de la nappe dans un aquifère semi-captif homogène à limites étanches parallèles, et (2) en utilisant un modèle à variations données dans lequel les paramètres d'un aquifère non homogène et les limites irrégulières de l'aquifère pouvaient être plus exactement représentées.

Les résultats de cette comparaison démontrent bien qu'il existe une incertitude très prononcée dans la dépression du niveau prévu après une période de pompage prolongée. La dépression réelle du niveau des puits d'essai indiquait une tendance très nette vers un niveau beaucoup plus bas que celui du modèle. Les raisons de cette tendance pourraient être fonction (1) d'une baisse saisonnière due à des causes étrangères au pompage, ou (2) d'une perméabilité fortement réduite, ou peut-être même de l'absence de sédiments préglaciaires à l'est de la zone des essais, ou bien (3) du facteur de drainance moins élevé que prévu sur la base des analyses des essais de pompage.

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INTRODUCTION

Groundwater Aspects of Waste Disposal near Potash Mines in Saskatchewan

The large amounts of liquid and solid waste (mostly NaCl) generated by the potash industry in Saskatchewan, and commonly disposed of or stored at the surface near the plants in artificially constructed lagoons, have caused concern because of their potential to contaminate groundwater resources near the mines. Except for one mine west of Regina, all mines are located near major undeveloped freshwater aquifers, mostly Pleistocene deposits of sand and gravel.

A major hydrogeological study was therefore undertaken to assess the severity of the problem and to obtain sufficient data on the disposition of the geological strata near one of the waste disposal sites in order to design effective monitoring systems and to assess various possible methods of waste containment. The selected study area was adjacent to the waste disposal ponds at the International Minerals and Chemical Corporation (Canada) Ltd. K2 plant, approximately 14 km east of Esterhazy, in southeastern Saskatchewan. The cooperation and assistance of the management and officials of IMCC during the course of these investigations is gratefully acknowledged.

Previous Investigations and Scope of This Report

For the ultimate purpose of the study - the simulation and assessment of brine movement in the subsurface and in a buried bedrock-channel aquifer in particular - the determination of the dimensions and hydrologic characteristics of the aquifers was of paramount importance. The dimensions of the aquifer underlying the waste disposal pond at the K2 plant have been determined as part of the program and are described in detail by Vonhof (1975b); a contour map and geological cross sections from his publication are reproduced in Figure 1 and in Figures 2 and 3, respectively.

Preliminary analysis of the drawdown data was done by Bourne (1976), who estimated transmissivity and storativity using Jacob's method, the Theis recovery method, grain-size distributions and electric-log characteristics. Vonhof (1975a) reported transmissivity values derived from slug tests (Hvorslev [1951] piezometer tests).

The purpose of this publication is to report on a detailed analysis of the pump-test data, using a new development in aquifer-test analysis that is particularly suited to the buried bedrock-channel aquifer. This technique was not available to Bourne (1976), who correctly remarks (p. 35): "At Esterhazy, none of these assumptions [inherent to the Theis and Jacob methods of analysis] is satisfied, so these are limitations on the direct application of the methods to the data. The first assumption [infinite areal extent of the aquifer] restricted the analysis to very early drawdown data... Noticeable deviations from the type curve for large times due to leakage and boundary effects makes this data unsuitable for direct calculation."

The technique used in this report permits the use of data from later in the pump test as well as the calculation of the leakage from the overlying till and is technically no more complicated or time-consuming than the Theis non-equilibrium method.

Description of the Aquifer

Dimensions

The thickness and areal extent of the buried bedrock aquifer has been investigated in detail by drilling and logging of 91 test holes during 1968 and 1971.

Figure 1, reproduced from Vonhof (1975b), shows the extent and thickness of the buried channel aquifer near the pump-test site; the cross sections shown in Figure 2 (after Vonhof, 1975b) indicate the depths of the sand and gravel deposits and the thicknesses of the two overlying till sheets. Figure 3 is a longitudinal cross section shown to direct attention to the observed facies change in the northeast-trending branch of the channel. This indicates little or no hydrological connection with the valley of the Cutarm Creek; the aquifer does, however, continue in a southeastely direction, as indicated on Figure 1, although the valley till becomes highly variable, with the till content increasing drastically.

Description of Buried Valley Fluvial Deposits and Overlying Till Formations

The fluvial deposits forming the aquifer consist of silt, sand, polymictic gravel and shale-pebble gravel derived from the underlying Riding Mountain Formation. Their maximum thickness is about 75 m (Fig. 1).

The overlying till consists of two distinct units: the Floral Formation, directly overlying the bedrock or the fluvial deposits, and the Battleford Formation. The Battleford Formation is described by Christiansen (1968) as a gray to light olive gray, friable, oxidized calcareous, sandy and silty till; the Floral Formation is an oxidized to unoxidized, calcareous pebbly till, featuring near vertical fractures commonly extending from the top to about 9 m deep (Grisak *et al.*, 1976).

Description of Pump Test

Figure 4 shows the location of the test wells in relation to the boundaries of the aquifer. All wells were completed with 11.6 cm diameter stainless-steel screens of various lengths (2.4 to 4.2 m). Six wells were completed in the upper part of the aquifer and one well in the lower part of the aquifer (Well G, Figure 4).

Table 1 gives the complete pumping schedule. The average pumping period was 20 h, and the recovery periods between tests varied from 1 to 4 days.

Except for the periods during which the pump was being installed or removed, regular observations of piezometric head were obtained for all wells using continuous automatic recording equipment (piezometric head scale 1:1, time scale 1 cm: 1 h) for the observation wells and an electric tape in the pumped well.

Outline of Pump-Test Analysis Procedure

In the next two chapters the story of the complete analysis will be told in detail. A brief outline of the procedure is given here:

1. The water level changes indicated by the recorded piezometric head data were used to estimate the drawdown caused by the pumped well by separating out the estimated effects of barometric pressure changes, seasonal trend and residual drawdown from previous pumping periods.
2. Out of the 42 time-drawdown curves, 29 were analyzed using a recently developed technique for the analysis of pump tests in leaky parallel-strip aquifers.
3. The results were used to simulate the complete test (a) with an analytical solution based on an idealized homogeneous linear strip aquifer and (b) with a finite-difference model.

HYDROGRAPH ANALYSIS

Separation of Drawdown and Extraneous Effects

Before the piezometric head data could be used to determine aquifer characteristics it was necessary to separate the drawdown owing to the well being pumped

Table 1. Pumping Schedule of Composite Pump Test, March 9-25, 1971

Well No.	Date and time pump started		Date and time pump stopped		Duration of test (minutes)	Duration of recovery period (minutes)	Pumping rate m^3/minute
C	9-3-71	17:30	10-3-71	14:05	1235		.076
						1640	
B	11-3-71	17:25	12-3-71	14:10	1245		.038
						4510	
D	15-3-71	17:20	16-3-71	10:50	1050		.076
						3250	
E	18-3-71	17:00	19-3-71	14:55	1315		.227
						1505	
F	20-3-71	16:00	21-3-71	10:30	1110		.189
						1775	
G	22-3-71	16:05	23-3-71	10:30	1105		.227
						1815	
A	24-3-71	16:45	25-3-71	10:30	1065		.227

at the instant of observation from head changes owing to other effects: (1) barometric response, (2) seasonal trend and (3) residual drawdown from previous pumping. Comparison of barometric pressure records and piezometric head levels during selected periods after the test were used to compute the barometric efficiency of the wells, which was applied as a correction factor. However, barometric effects during the pump tests were small in comparison with the uncertainties in the combined seasonal and residual drawdown trend, and had therefore little influence on the computed values of the aquifer characteristics.

Removal of the combined effect of the seasonal and residual-drawdown trends was achieved by extrapolation of the trend during the prepumping period (Fig. 5). As a consequence, the drawdown values obtained for the latter part of each test are somewhat in doubt, not only because the absolute error in the extrapolated value increases with increasing length of the interval of extrapolation, but also because of the decrease with time of the incremental drawdown. Thus, the relative error increases even faster than the absolute error.

Computation of Transmissivity, Storativity and Leakage

The analysis of the time-drawdown data is based on the following assumptions:

1. The aquifer is homogeneous.
2. The aquifer is shaped as an infinitely long, permeable tube, of constant cross-sectional area, receiving leakage from an overlying bed, but elsewhere bounded by impermeable beds.

With these assumptions, the drawdown s caused by a well pumped at constant rate Q is given by (Vandenberg, 1976a, 1977a)

$$s = (Qx/2TD)F(u,x/B) \qquad (1)$$

where

- x = the distance from the pumped well;
- T = the transmissivity;
- D = the width of the channel;
- F = the well function for leaky channel aquifers,

$$(1/2\pi^{1/2}) \int_u^\infty \exp\left\{-y-x^2/(4B^2y)\right\} y^{-3/2}\, dy;$$

- u = $x^2S/(4tT)$;
- S = the storage coefficient;
- t = the time since pumping started;
- B = the leakage factor = $(T/L)^{1/2}$;
- L = the leakance = K^1/b^1;
- K' = the vertical hydraulic conductivity of the confining bed;
- b' = the thickness of the confining bed.

Equation 1 is an approximation based on the assumption that flow in the aquifer is parallel to the axis of the channel. The error resulting from the approximation is negligible for all $x \geq D$. For $x < D$ the function F should be replaced by the proper summation of Hantush's leaky-aquifer curve (Vandenberg, 1976a).

The aquifer characteristics T, S and B can be determined from the time-drawdown data plotted on full logarithmic paper by matching the drawdown curve with published type curves. An example of the procedure is presented in Figure 6.

Of the 42 available sets of drawdown data, 13 were not analyzed for various reasons: for the combination, well F pumped, G observed and vice versa, for example, the wells were too close to one another and were, furthermore, completed in different sections of the aquifer. Another example is provided by the pumping of well A, during which period recovery was still very strong in all other wells and extrapolation of the residual drawdown trends was considered to be subject to too much error. A somewhat different situation is associated with the responses of wells F and G to pumping from any of the other five wells. These responses were so similar that only the drawdown curves of one of the two - well F - had to be analyzed.

Of the remaining 29 combinations of pumped well and observation well, 24 satisfied the condition for application of Equation 1,

$$x < D,$$

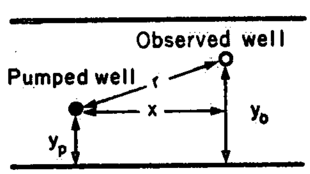
and could thus be analyzed with the aid of the published type curves. For the other four combinations, special sets of type curves were prepared as indicated by Vandenberg (1976a); an example of these is given in Figure 7.

Discussion of Results

Table 2 summarizes the results of the analyses. For most cases, the duration of the test was insufficient for the

Table 2. Summary of Results of the Pump-Test Analyses

Pumped well	Observation well	Coordinates defining well geometry (m) (see diagram)				Transmissivity (m^2/min)	Storativity	Leakage factor (m)
		x	y_o	y_p	r			
B	A	191	0	172	257	0.70	1.1×10^{-3}	1700
B	C	300	353	205	334	0.70	1.1×10^{-3}	1700
B	D	1202				1.32	5.9×10^{-4}	–
B	E	1121				1.10	3.9×10^{-4}	2800
B	F	582				1.12	7.1×10^{-4}	2900
C	A	467				0.96	6.9×10^{-4}	2300
C	B	300	205	353	334	0.76	6.4×10^{-4}	1700
C	D	1503				2.50	8.4×10^{-4}	–
C	F	890				1.38	7.5×10^{-4}	3000
D	A	992				1.39	7.9×10^{-4}	–
D	B	1202				1.42	9.0×10^{-4}	–
D	C	1503				1.79	9.5×10^{-4}	–
D	E	2337				2.07	9.1×10^{-4}	–
D	F	615				1.05	6.6×10^{-4}	–
E	A	1274				1.79	6.2×10^{-4}	–
E	B	1121				1.78	4.9×10^{-4}	–
E	C	835				1.22	4.9×10^{-4}	–
E	D	2337				2.20	8.1×10^{-4}	–
E	F	1680				2.46	8.2×10^{-4}	–
F	A	377	0	138	400	1.35	7.1×10^{-4}	2000
F	B	582				1.24	8.5×10^{-4}	1700
F	C	890				1.67	1.1×10^{-3}	3000
F	D	615				2.11	7.1×10^{-4}	–
F	E	1680				2.38	9.3×10^{-4}	–
G	A	377	0	138	400	1.01	5.2×10^{-4}	1600
G	B	582				1.51	6.7×10^{-4}	3900
G	C	890				1.31	7.5×10^{-4}	3000
G	D	615				1.39	6.5×10^{-4}	–
G	E	1680				1.93	6.1×10^{-4}	–
						$\Sigma T/n = 1.50$	$\Sigma S/n = 7.5 \times 10^{-4}$	



y_o, y_p and r only needed when x < D

determination of leakage and, besides, the uncertainty in the observed drawdown at later times renders the significance of the calculated leakage values doubtful. There is a clear positive correlation between the distance x from pumped well to observation well and the calculated transmissivity (Fig. 8) and a lack of correlation between x and the storativity. A similar situation was found by Vandenberg (1977b) for simulated drawdown caused by a well pumping from a randomly nonuniform aquifer. In this case of actual field data the randomness or uncertainty of the aquifer is composed of a variety of terms: uncertainties in the thickness, width, and hydrologic parameters of the aquifer, as well as uncertainties in the correction for seasonal and recovery trend.

Figure 9 further demonstrates the amount of uncertainty in the use of the computed values of the parameters T and S as a predictive tool in the calculation of drawdown. Values of s/Qx have been plotted against t/x^2. From Equation 1 it can be shown that all these points would fall on a single curve if (1) there were no leakage, (2) all x > D, (3) the aquifer were a perfect parallel strip and (4) the aquifer were homogeneous.

In Figure 9 the only data plotted were from tests in which condition 2 was satisfied. Condition 1 will give only minor deviations and these only for the larger values of t/x^2; thus the spread in the data is clearly an indication that, apart from possible uncertainties in the data measurement, conditions 3 and 4 are not satisfied. Figure 9 can also be used to determine the range of expected drawdown at any values of Q, t, and x. For example, for

$$x = 1000 \text{ m}$$
$$t = 1000 \text{ min}$$
$$Q = 1 \text{ m}^3/\text{min}$$

$t/x^2 = 10^{-3}$ min/m^2 and the range of s/Qx is given by the line segment AB in Figure 9; thus the range of s will be between 0.4 and 1 m.

The limiting curves of the set of points in Figure 9 are traces of the well function for nonleaky parallel-strip aquifers and define limiting values of T and S; the dashed centre line represents a fit of the type curve to the densest part of the curve and defines most likely values of drawdown and most likely values of T and S. These values (Table 3), combined with limiting values for B, can be used to predict limiting and most likely values of drawdown for any combination of Q, x and t. It should be kept in mind, however, that for extrapolation to large values of t/x^2 an accurate value of the leakage coefficient is required. Figure 10 shows ranges of expected unit drawdown (min/m^2) for distance x = 100, 1000 and 10 000 m, and a time span of 10 min to 20 yr (10^7 min); the ranges for x = 100 m are approximate, since they were calculated by Equation 1, although in this case $x < D$.

Table 3. Limiting and Most Likely Values of Transmissivity, Storativity and Leakage Factor

Parameters	Transmissivity (m^2/min)	Storativity	Leakage factor (m)
Parameters defining lower limit of drawdown	1.94	1.2×10^{-3}	1600
Parameters defining most likely value of drawdown	1.32	6.8×10^{-4}	2400* 3000†
Parameters defining upper limit of drawdown	1.12	3.8×10^{-4}	3900

*Average from those tests in which B could be determined.
†Value giving the best fit in the simulation study; the actual value may be even higher if the aquifer extends to quasi-infinity to the west of the test site.

SIMULATION OF COMPOSITE PUMP TEST

Since the purpose of a pump test and the ensuing calculation of aquifer parameters is the prediction of the behaviour of the piezometric surface under long-term pumping conditions, an appropriate test of the parameters derived in the preceding section (Tables 2 and 3, Fig. 9) would be the simulation of the drawdown in each of the wells during the complete period of the test—March 9-25, 1971—and a comparison between simulated and observed water levels. Such a simulation can be achieved in either of two ways:

(a) By considering the aquifer as a perfect infinite and homogeneous parallel-strip aquifer and calculating drawdown as the appropriate sum of terms of the form of Equation 1, taking into account the rates and pumping periods of each well.

(b) By using a numerical mathematical model in which the actual shape of the aquifer as well as its inhomogeneity can be taken into account. A difficulty presents itself, however, in the specification of the values of the aquifer parameters throughout the aquifer: values obtained in pump tests cannot be considered as actual values at any specified point or region in the aquifer but rather reflect an average condition over a wide range in the aquifer (Vandenberg, 1977b). Thus, trying to simulate drawdown in an inhomogeneous aquifer would necessitate a considerable amount of trial and error, the value of which is rather doubtful in view of the uncertainty in the calculated true drawdown - i.e., in the difference between observed water level and estimated seasonal trend - with which the simulated results would have to be compared.

The uncertainty in the calculated true drawdown arises because the observed water levels are the sum of the real drawdown and a seasonal variation. The latter component cannot be estimated with sufficient accuracy; simulation of water level response to rainfall, evapotranspiration, frost and thaw would be a major study in itself and beyond the scope of this report. With the exclusion of this possibility, three possible ways to estimate seasonal, nonpumping trend remain:

(1) Backward extrapolation of water level records obtained after the testing period (water-level data for the period immediately preceding the test were inadequate for a forward extrapolation); in this case a reasonable period of recovery should be allowed as being part of the pump test, decreasing the reliability of the extrapolation.

(2) Adjustment of the observed water levels to the simulated data. Insofar as testing the reliability of the calculated aquifer parameters is concerned, this is putting the cart before the horse; Figure 11 shows that a fit can be obtained on the assumption that the seasonal trend in the ith well can be expressed as a quadratic in time,

$$\Delta s_i = a_i t + b_i t^2$$

where the coefficients a_i and b_i, $i = 1, \ldots 6$, are chosen such that observed and simulated water levels coincide at two instants.

(3) The seasonal trend is observed under the same climatic conditions as those of the test, but with water levels undisturbed by pumping. Inspection of water level records of the test wells for the period of December 29, 1971, to March 23, 1972, shows an almost uniform decline in water level for all the wells of 3 mm per day. This value was therefore used as a reasonable estimate of the seasonal trend during the same period of the previous year, i.e. the period of the pump test, and observed water levels were adjusted accordingly to obtain adjusted drawdown values for all the wells.

After this report was completed, it was learned that in 1972 the level of the brine in the waste disposal pond was either constant or slightly declining. In March 1971, however, the level of the brine pond was still rising at an average rate of about 2 mm per day. Since the level of the pond has a loading effect on the water levels in the wells – a rising brine level causing rising levels in the wells – the applied correction may have been too large. As a consequence, drawdown owing to pumping would have been underestimated and the leakance overestimated.

Analytical Solution: the Idealized Homogeneous Buried-Channel Aquifer

Figure 12 compares the simulated drawdowns in wells A, B, C, D, E and F throughout the period of the test, for the limiting and most likely values of T, S and B (Table 3), with the observed drawdowns adjusted for seasonal trend. Real drawdown in the pumped wells, consisting for a large part of well loss, cannot be duplicated by the model and must be ignored in the comparison. The remainder of the drawdown lies within the expected limits but rather near the maximum expected drawdown, indicating either an underestimation of the downward seasonal trend or overestimation of leakage (underestimation of the leakage factor).

Numerical Model Solution: the Homogeneous Buried-Channel Aquifer

For the simulation of the pump test by numerical modelling, program ESOPH (Vandenberg, 1976b), with a capability to simulate piezometric head response to pumping in an inhomogeneous, leaky aquifer, was used. Figure 13 shows the finite-difference model (aquifer I). The model spacings were designed to ensure that all wells fell on grid nodes and that a large part of the aquifer was included in the model. The southern end of the model was initially modelled as a line of constant head; to the west the aquifer was extended 4000 m beyond well E, where it was also terminated by a constant-head boundary.

Figure 14 shows computed drawdowns for the sets of parameters resulting in the maximum, minimum and most likely drawdowns. The fourth computed hydrograph given in the figure is for an inhomogeneous aquifer with transmissivity and storativity distributed in accordance with the results from the individual pump tests. The uncertainty inherent in the assignment of parameters obtained from pump tests to specific sections of the aquifer model has already been discussed at the beginning of this chapter.

As was observed for the analytical solutions, the numerical solutions do not reflect the overall downward trend of the real adjusted water levels. Furthermore, the water levels calculated with the numerical model are generally shallower than those calculated by the analytical model; this discrepancy may well be due to the widening of the aquifer to the west. The effect of the constant-head boundaries of the model, although also giving rise to shallower water levels than expected, cannot be very significant in view of the large distance between these boundaries and the wells. Nevertheless, the effect of the boundary was ascertained by comparison with a second model - aquifer II—in which the boundaries were moved much closer to the wells (Fig. 15) and the condition of constant head on the boundaries was changed to that of an impermeable boundary. Drawdowns for this aquifer of limited extent are shown in Figure 16, as compared to the drawdown in the quasi-infinite aquifer. The aquifer parameters used were those for the most likely case.

As could be expected, the boundaries of aquifer II result in lower water levels, but the resulting hydrograph still lies well above the corrected observed water levels.

Figure 17 shows the result of varying the model leakage factor; aquifer II was modelled using values of T and S of 1.32 m^2/min and 0.00068, respectively, and four different values of B: 2400, 3000, 3600 and 5000 m. It appears that with B = 3000 m a reasonable simulation of the adjusted observed drawdown is obtained. Obviously, an equally good fit could have been obtained with the model of aquifer I and a higher value of B.

CONCLUSION

Although the analysis of the pump-test data and the subsequent simulation of the 16 days of composite pumping have resulted in a reasonably accurate fit of simulated and adjusted observed drawdowns in the six wells, there are a number of uncertainties about the aquifer model which should be resolved before the model can be used to predict the long-term behaviour of the groundwater system, especially if the model is ever to be used for the calculation of the rate of contaminant movement.

Although transmissivity and storativity are subject to variation, their ranges are known and can therefore be used to establish limits on, and a most likely behaviour of, the system. Leakage, on the other hand, which has an important bearing on the response of the system, is poorly defined by the test; similarly, the extent of the aquifer, especially in a westerly direction where it is not defined by test drilling, influences the long-term behaviour of the aquifer, although to a lesser extent than the leakage.

The main reason for the poor definition of leakage is clearly the short duration - approximately one day - of the individual test possibly coupled with the uncertainty in the extrapolation of the recovery. From this point of view, the test would have yielded better information if only one well had been pumped for a week or so, using the other wells exclusively as observation wells.

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Figures 1 to 17

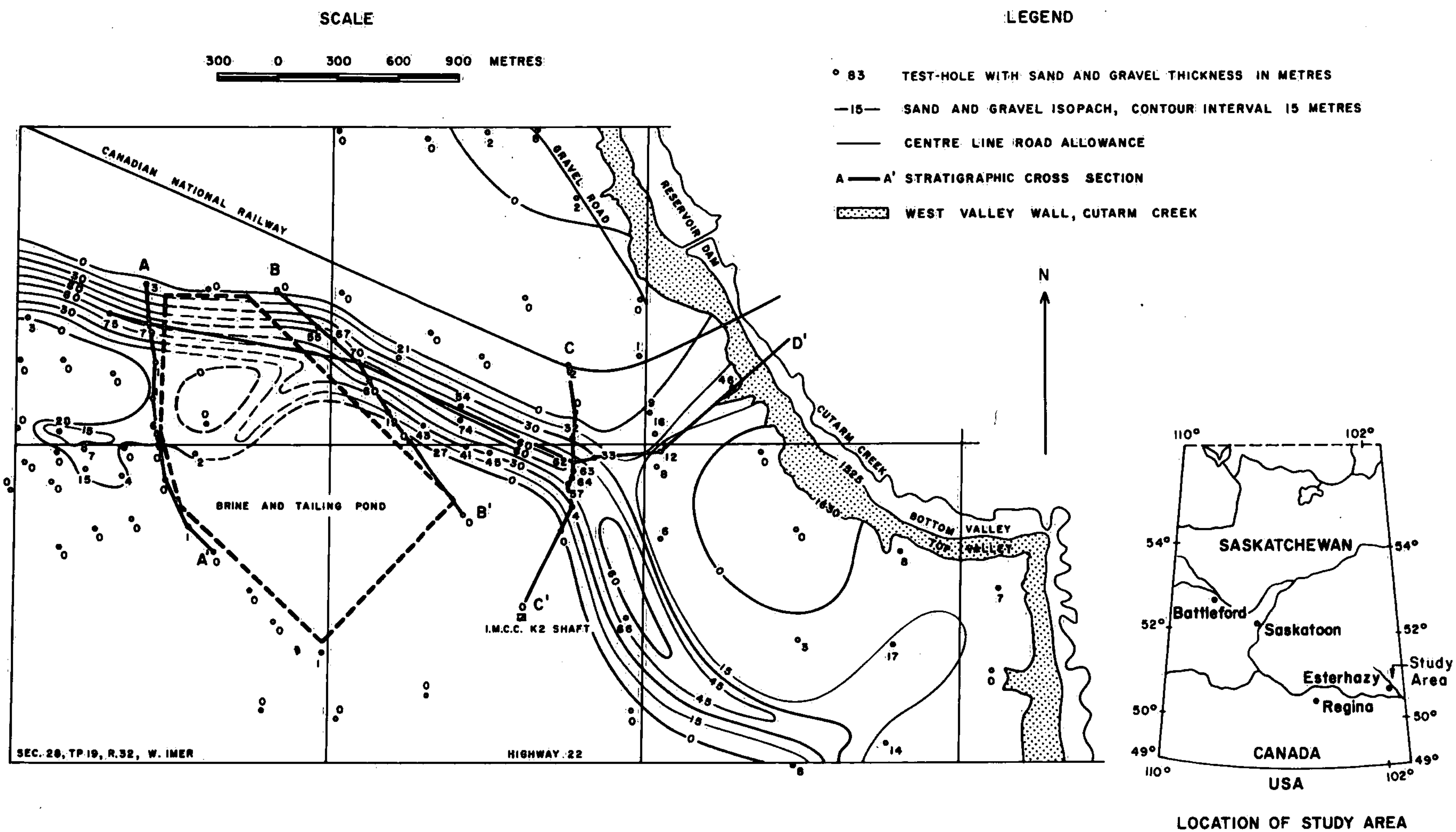

Figure 1. Isopach map of buried-channel aquifer (after Vonhof 1975b).

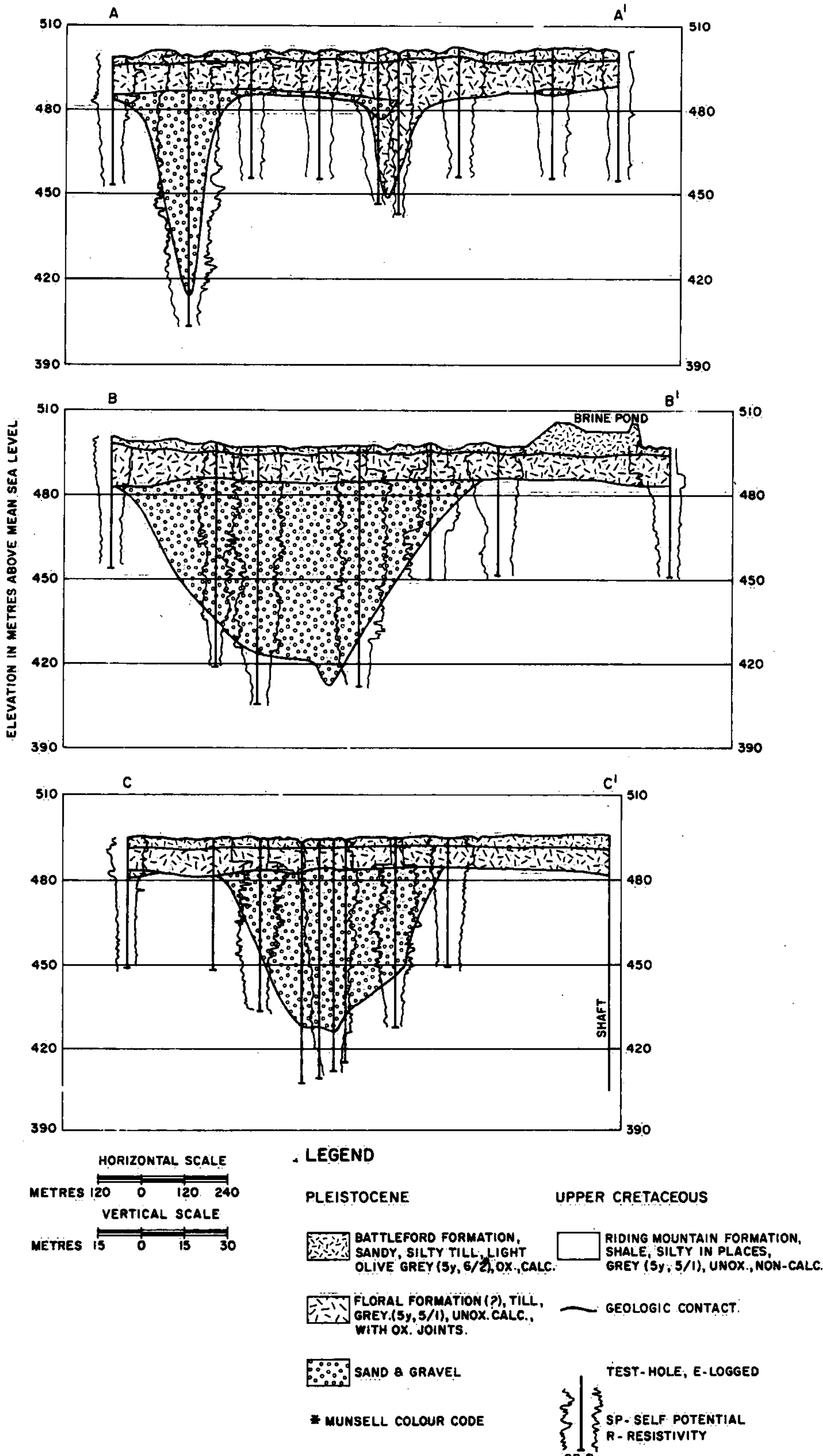

Figure 2. Transverse cross sections through buried-channel aquifer (after Vonhof, 1975b).

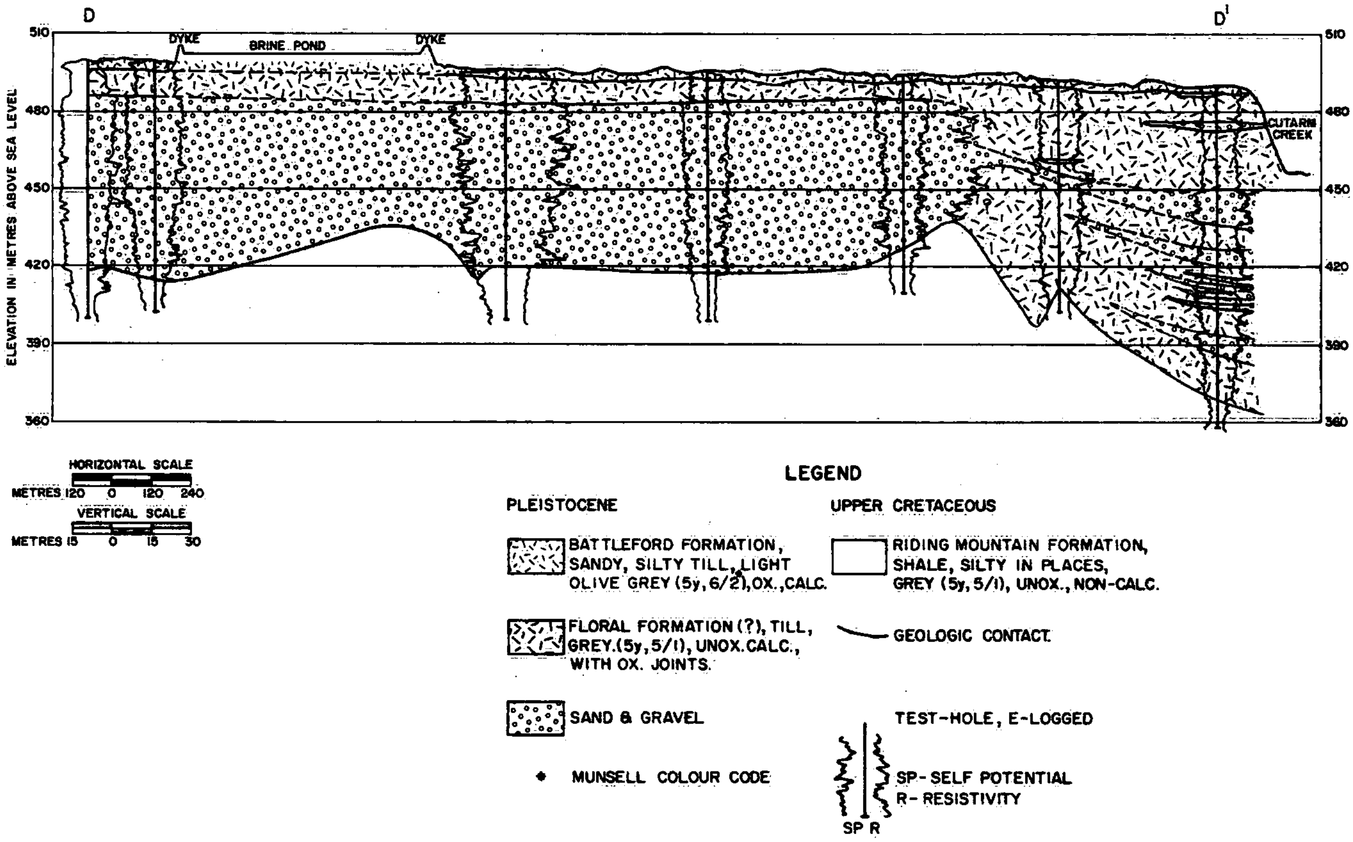

Figure 3. Longitudinal cross section through buried-channel aquifer (after Vonhof, 1975b).

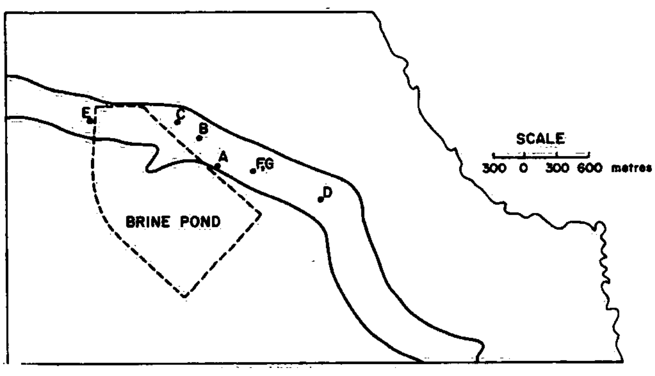

Figure 4. Location of test wells.

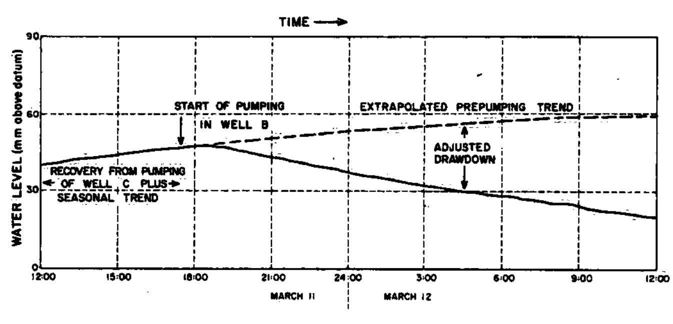

Figure 5. 24-hour record of Well E: example of extrapolation of prepumping trend to correct drawdown data for seasonal variation and recovery.

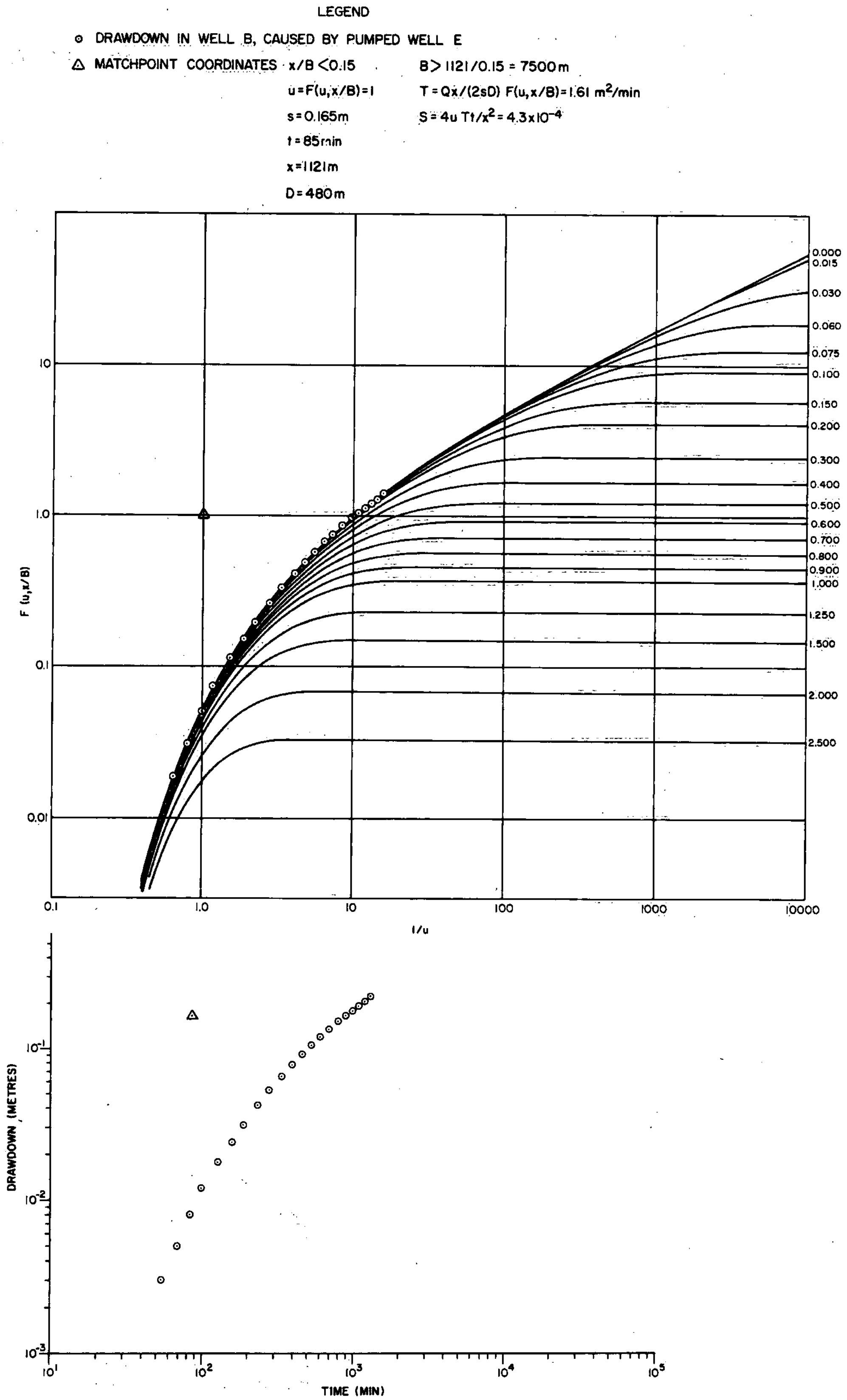

Figure 6. Example of pump-test analysis by matching the drawdown curve with type curves of the well function for leaky parallel-channel aquifers.

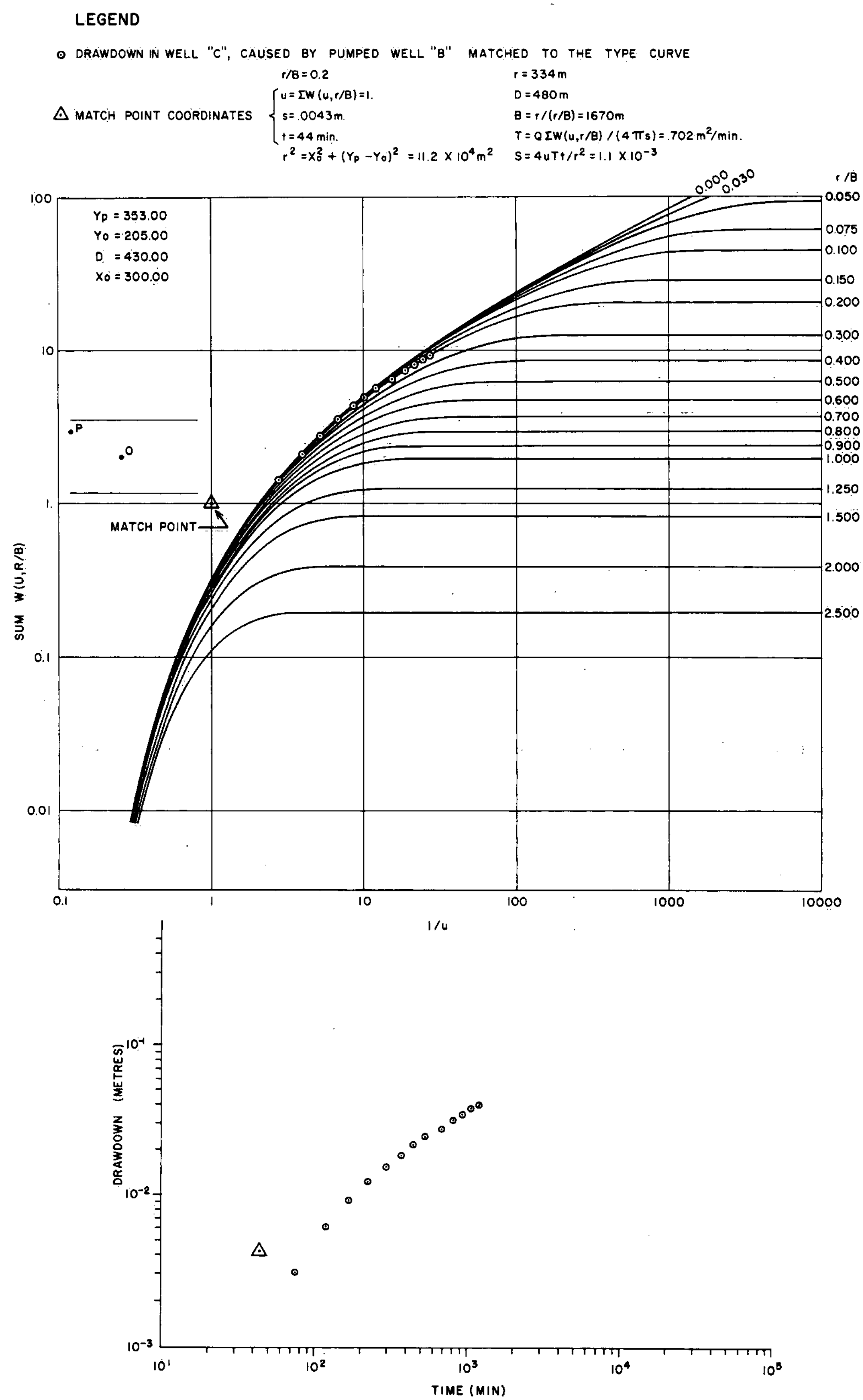

Figure 7. Example of pump-test analysis by matching the drawdown curve with precomputed type curves for well configurations for which $x < D$.

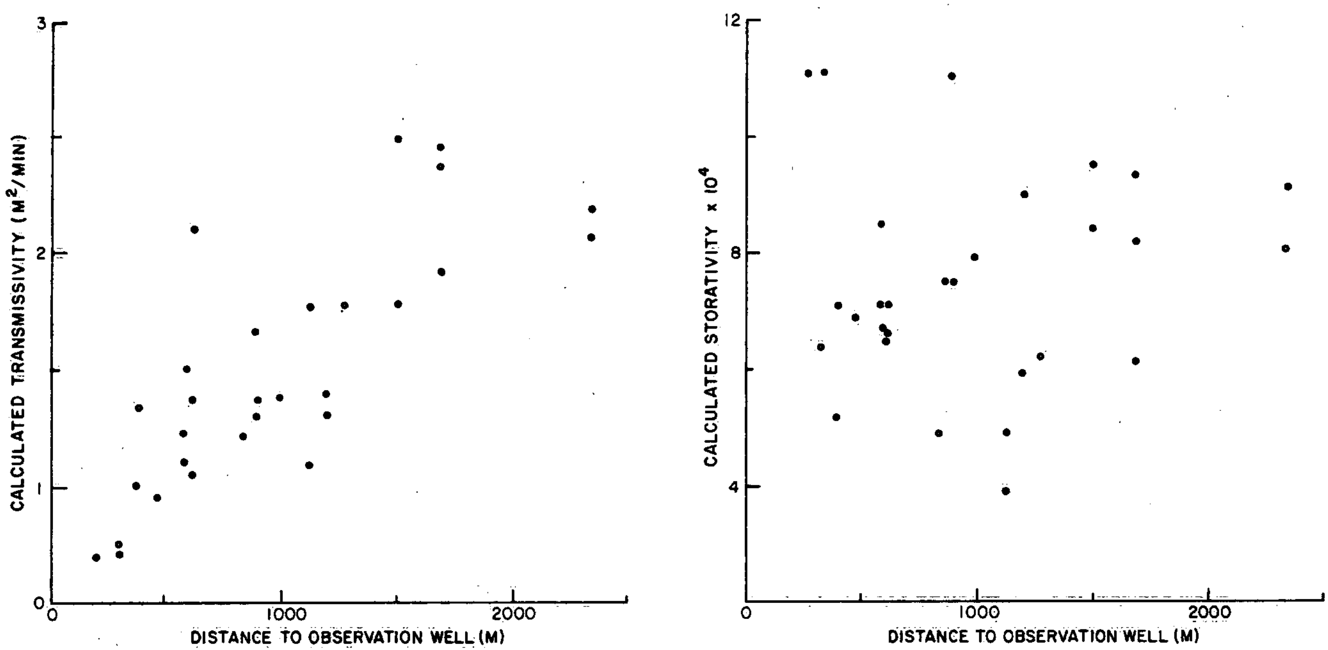

Figure 8. Calculated transmissivity and storativity as functions of distance to observation well.

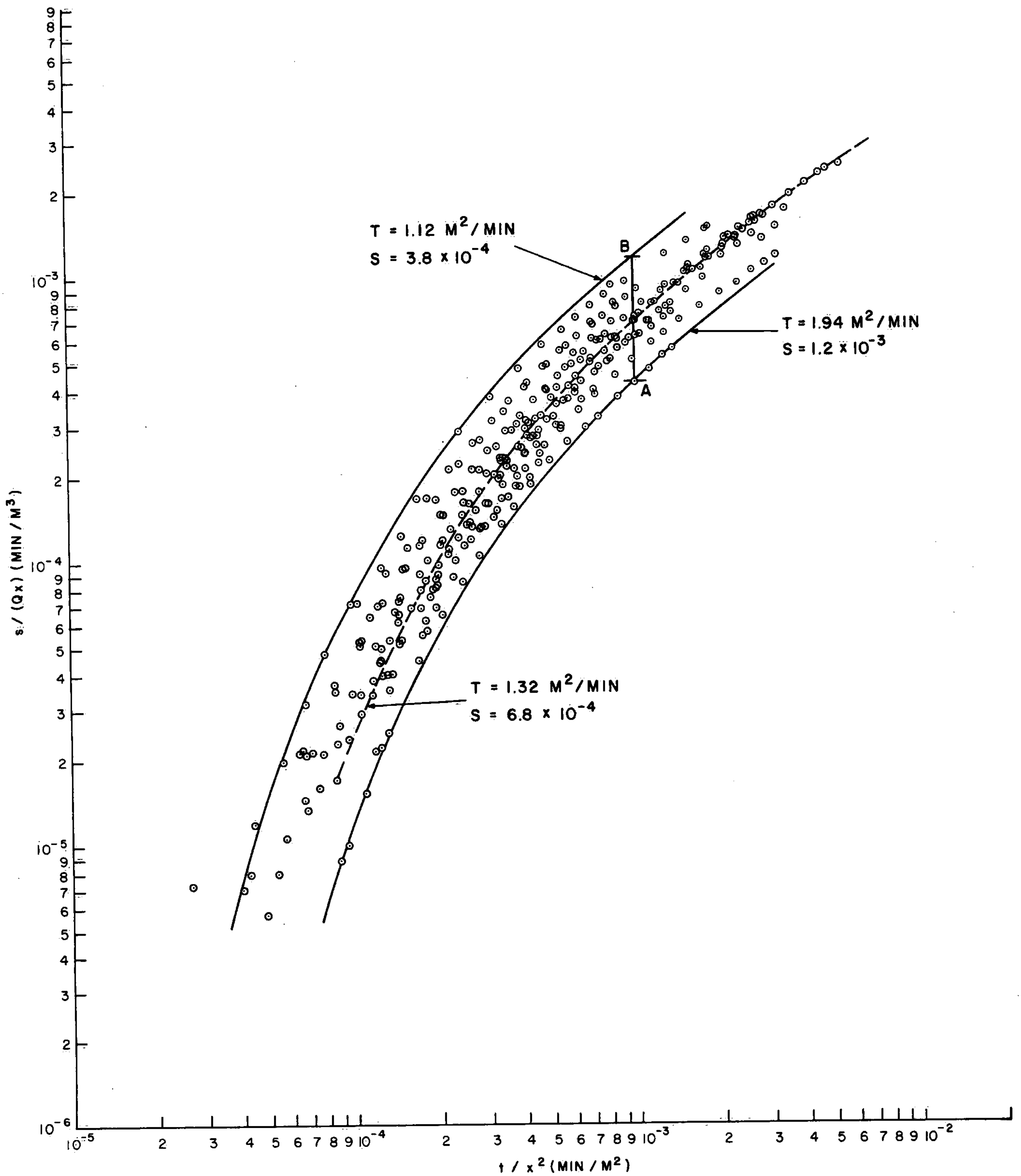

Figure 9. Plot of s/Qx against t/x^2, for all tests for which x > D.

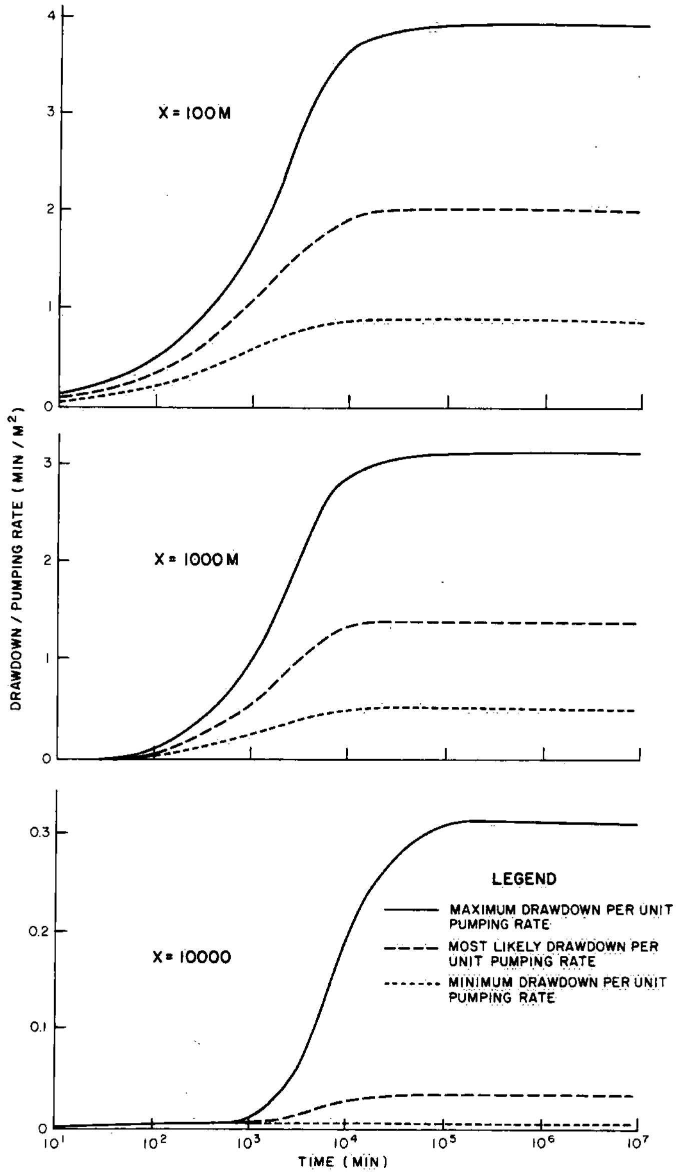

Figure 10. **Ranges and most likely values of expected drawdown per unit pumping rate for x = 100, 1000 and 10 000 m and a time span for 10 min to 20 years (10^7 min).**

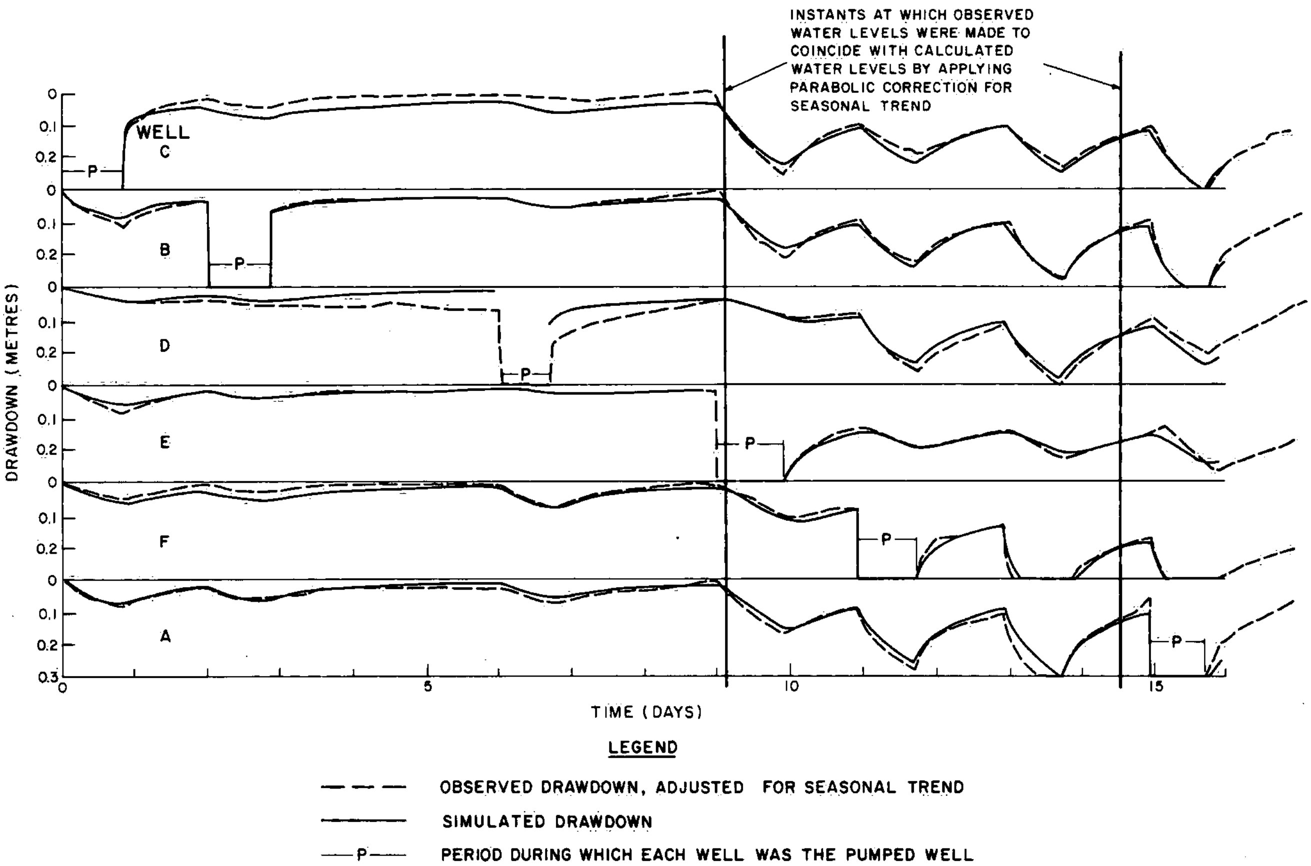

Figure 11. Simulated drawdowns (analytical solution) and observed drawdown, adjusted for seasonal trend by parabolic trend equations.

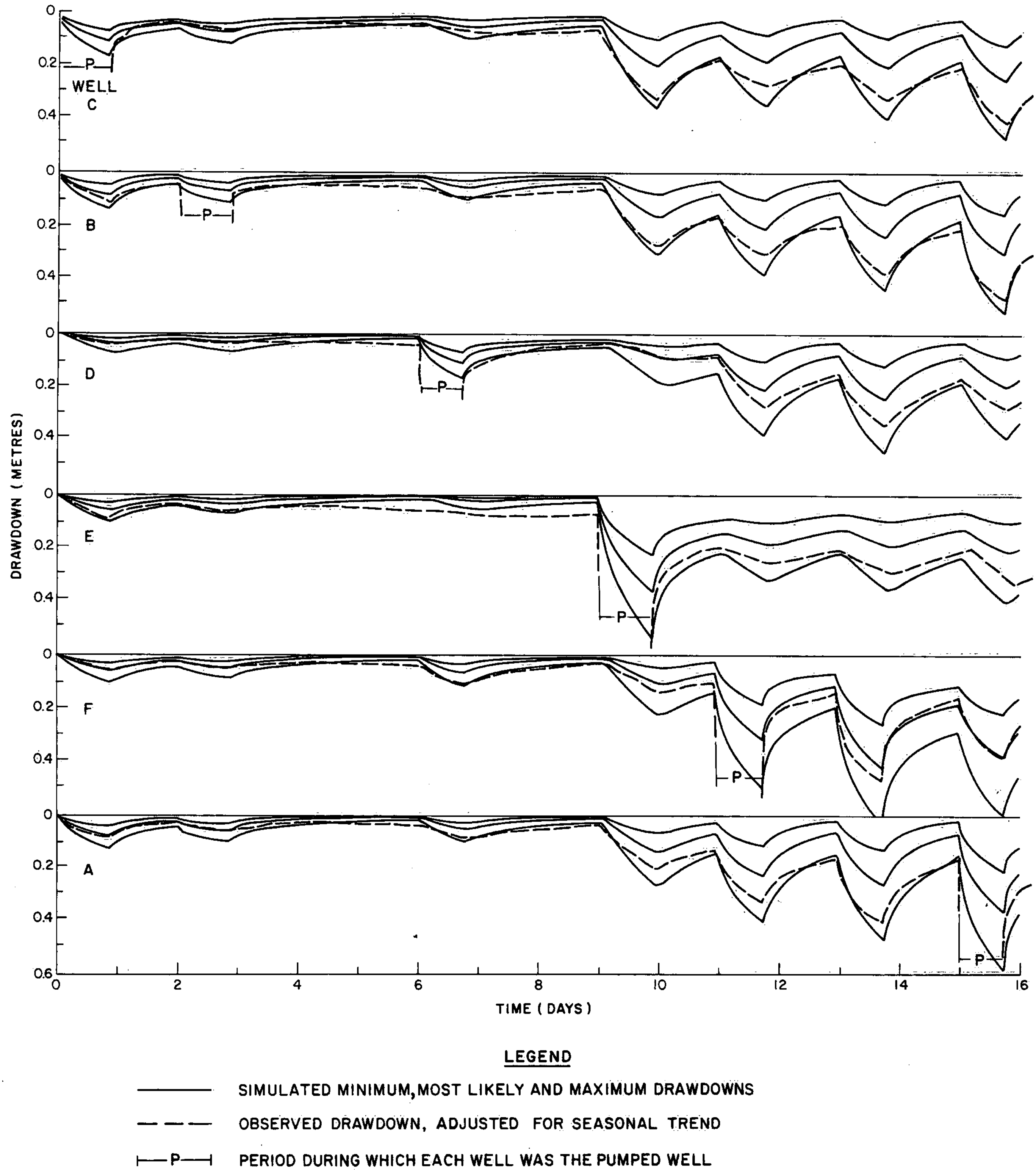

Figure 12. Simulated maximum, minimum and most likely drawdowns (analytical solution) compared with adjusted observed drawdowns.

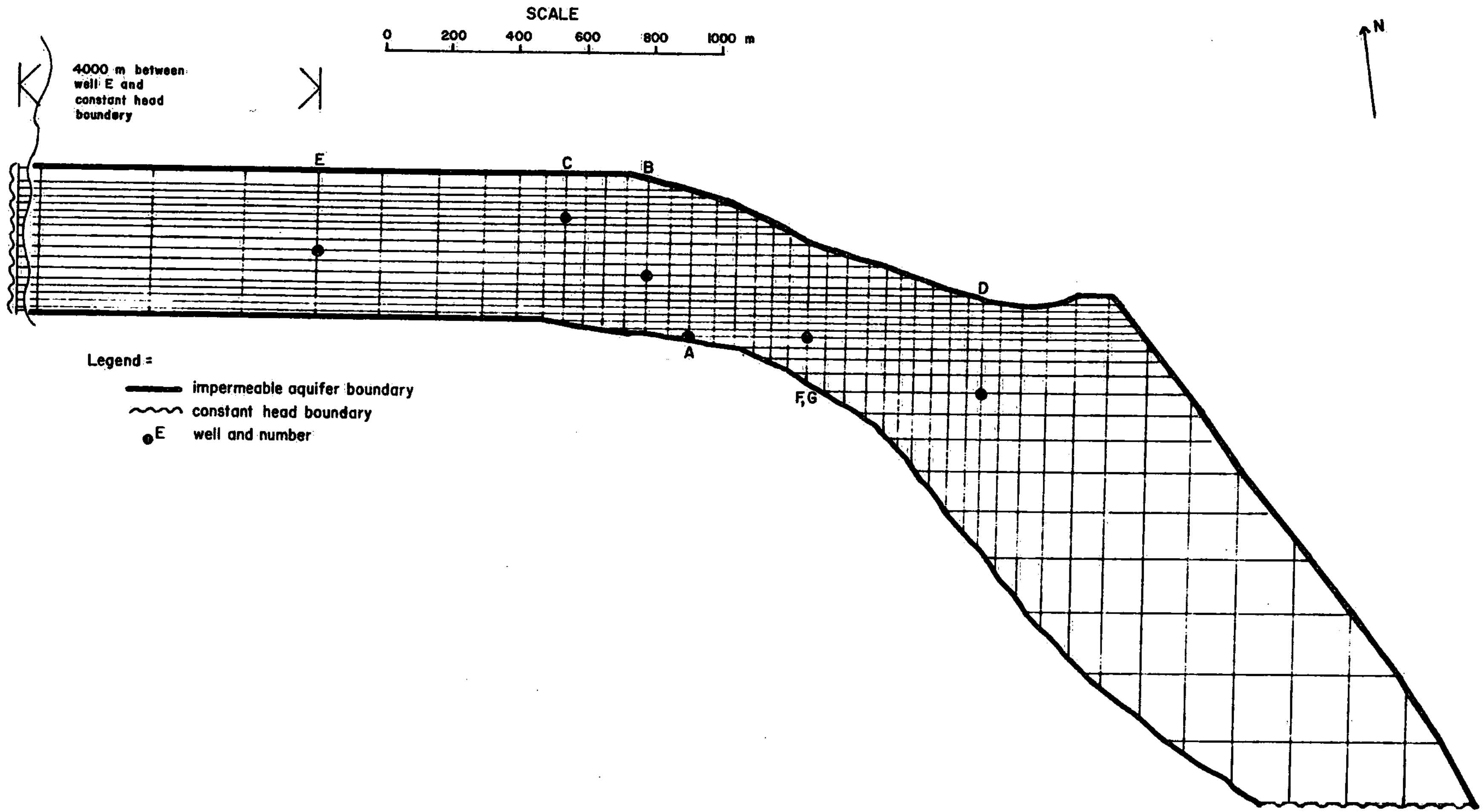

Figure 13. Model aquifer I and finite-difference grid for the simulation of drawdown by program ESOPH.

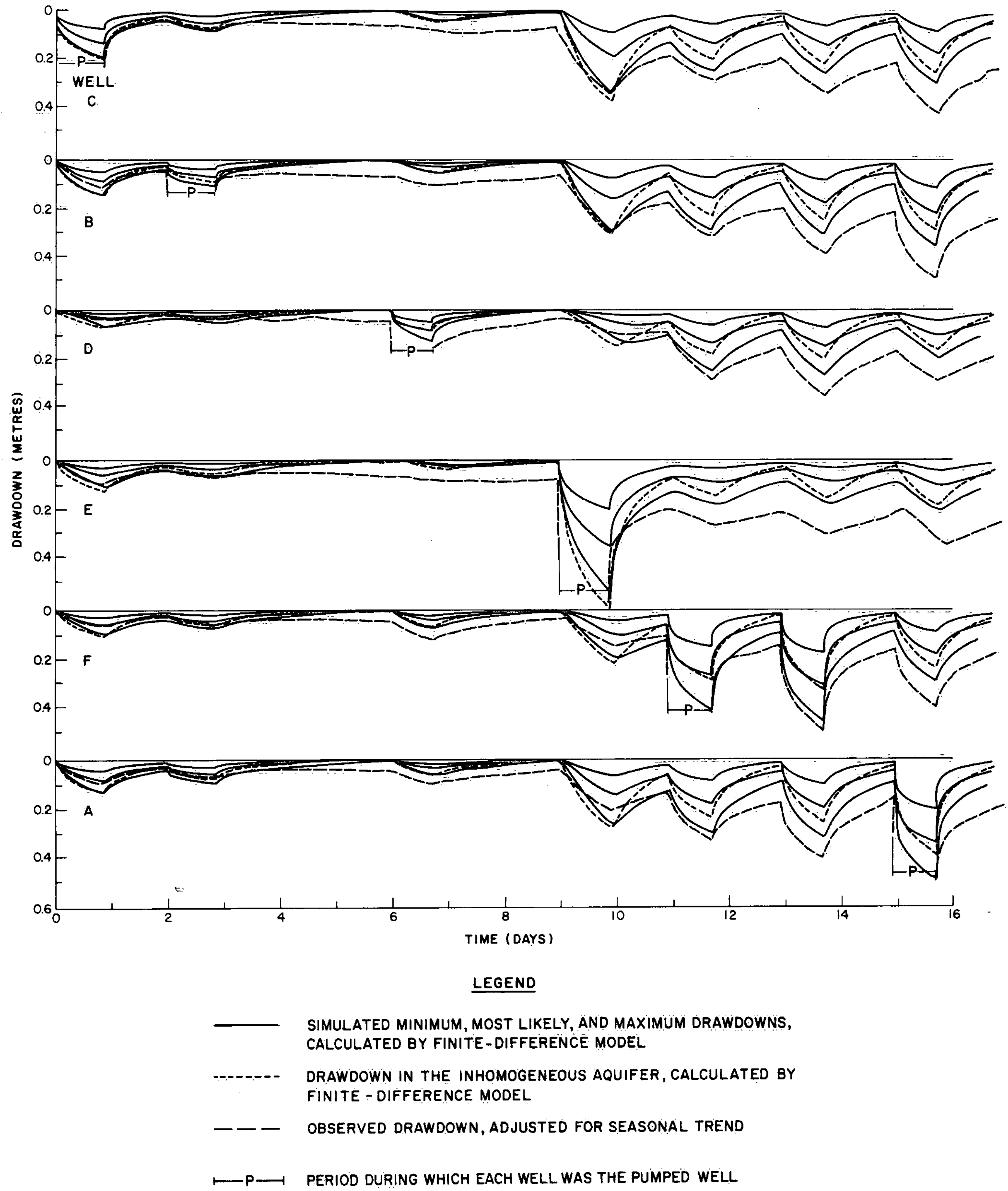

Figure 14. Simulated maximum, minimum and most likely drawdowns (numerical solution) compared with adjusted observed drawdown.

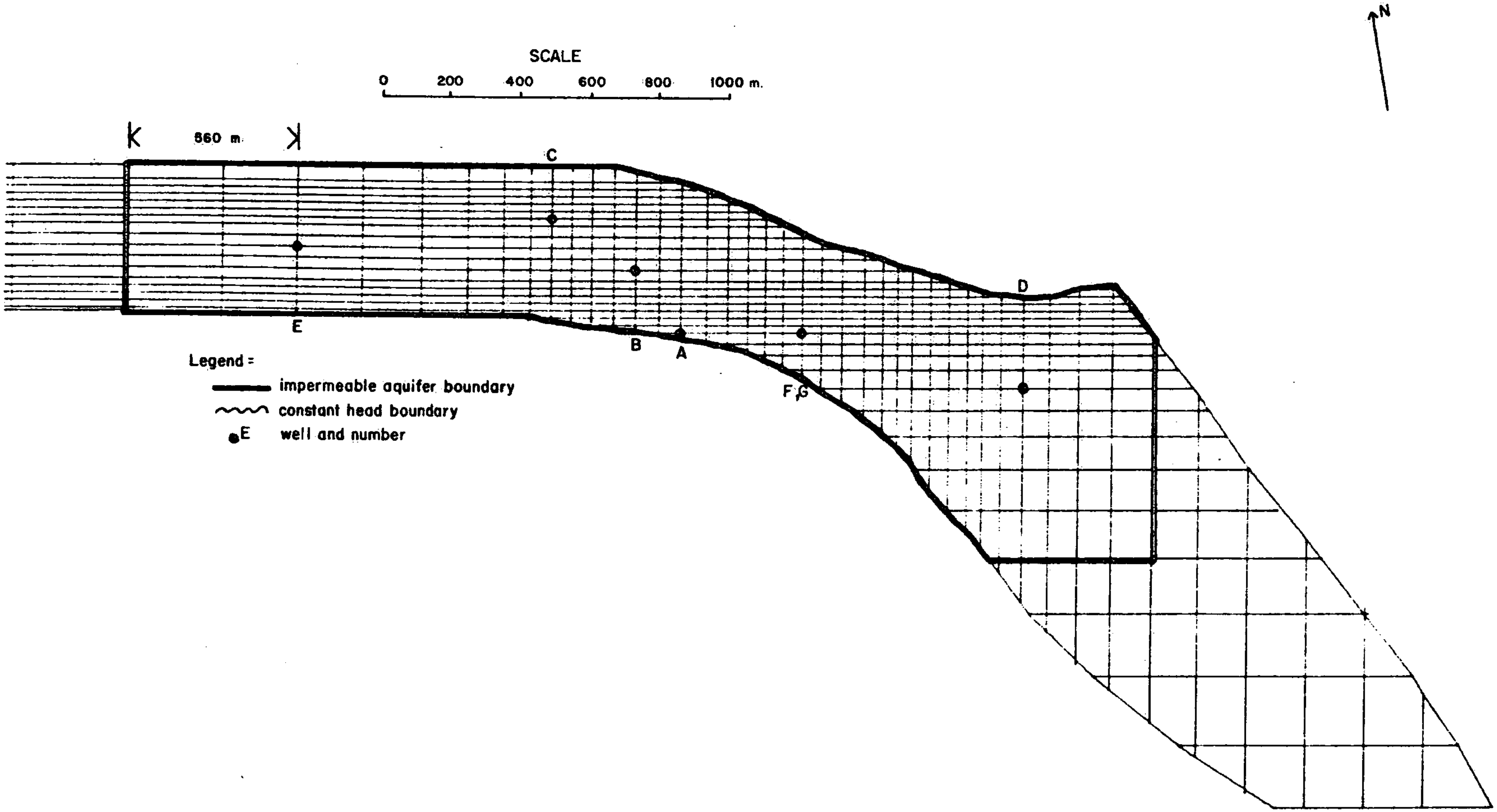

Figure 15. Model aquifer II with reduced areal extent and impermeable boundaries.

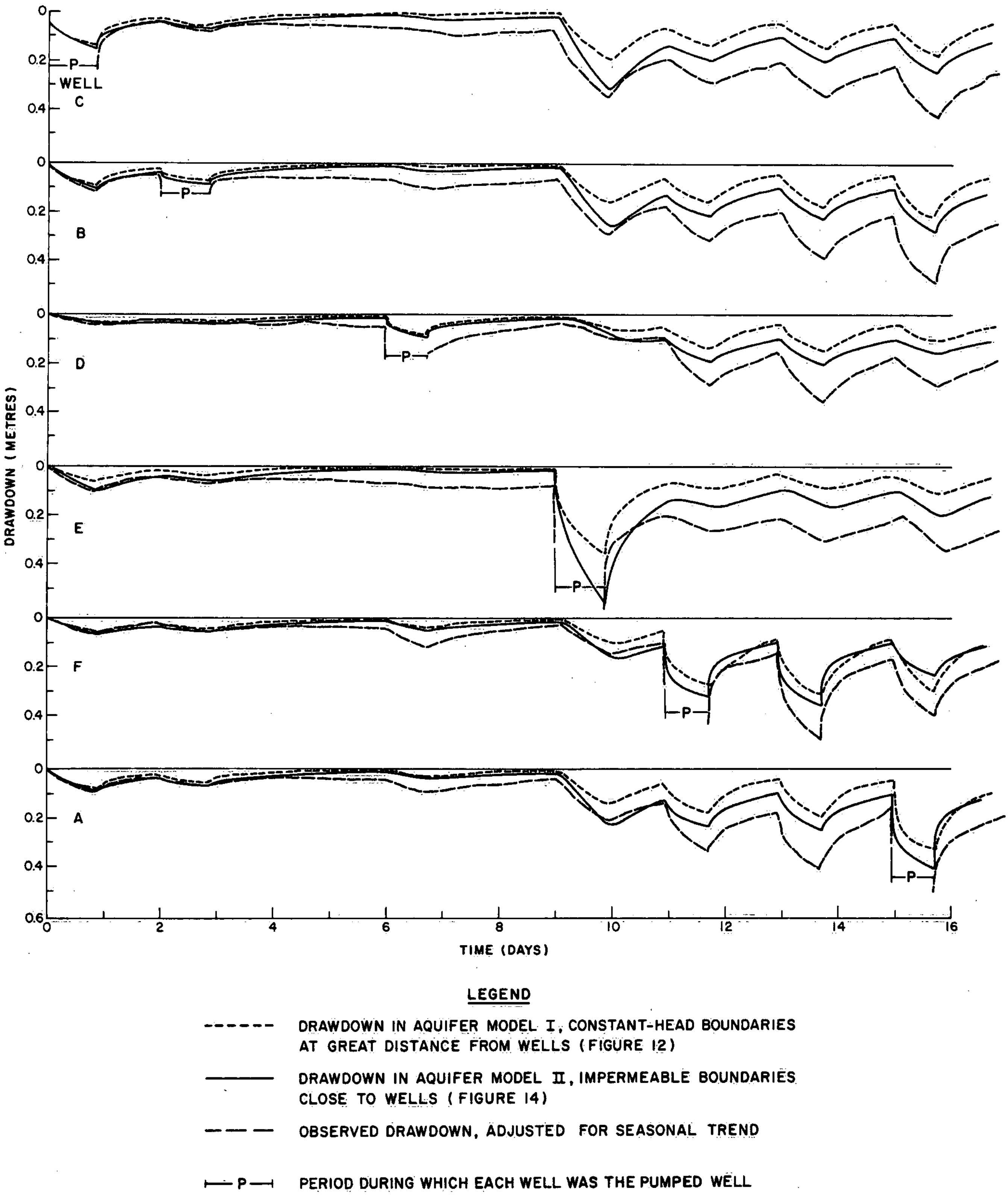

Figure 16. Drawdowns in aquifers I and II: $T = 1.32\ m^2/min$, $S = 0.00068$, $B = 2400\ m$.

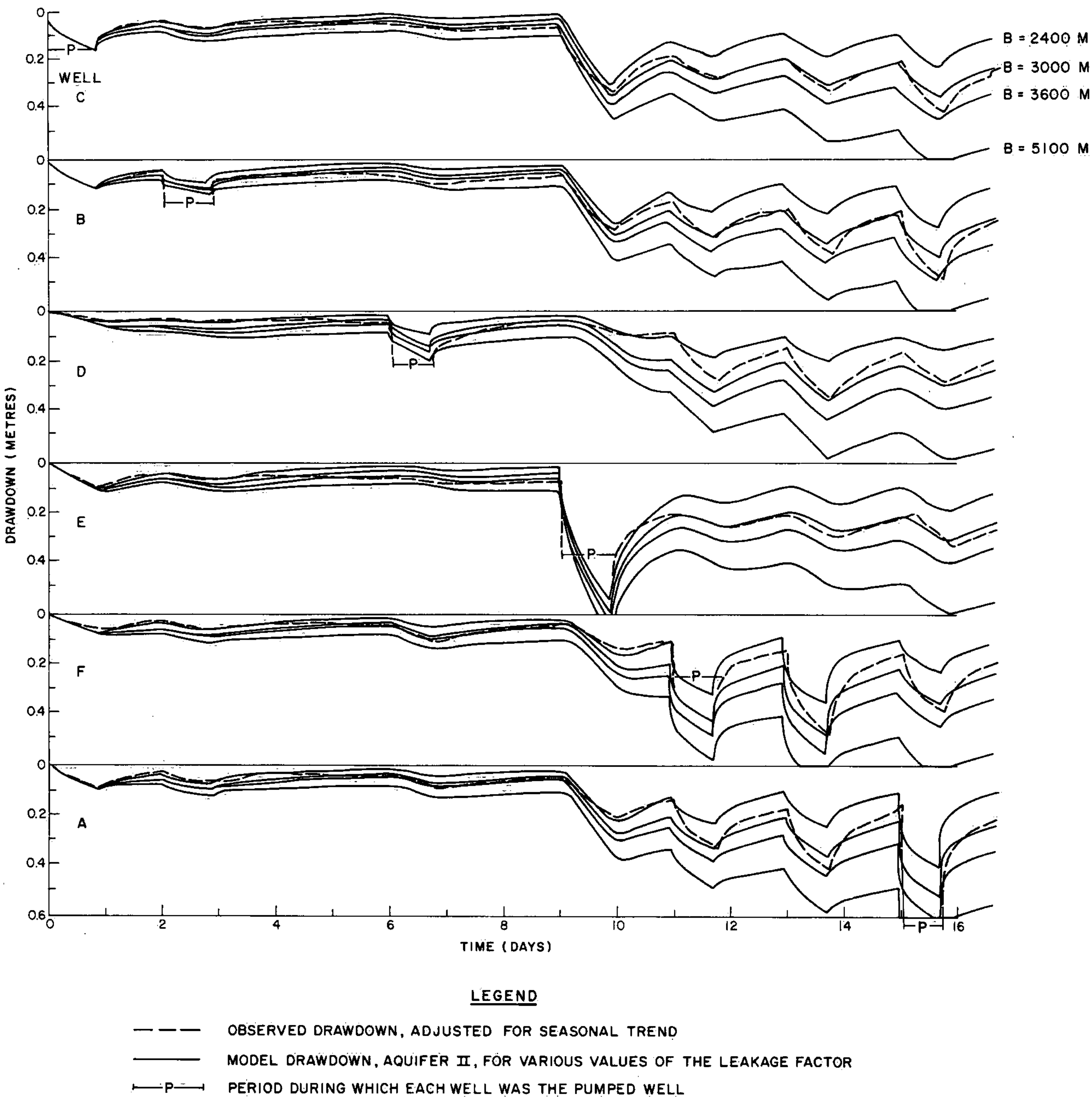

Figure 17. Drawdowns in aquifer II, for various values of the leakage factor.

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