SODA ASH BOTSWANA PTY LTD

SUA PAN PROJECT

Phase III Investigations

Memorandum No. 1
COMPUTER MODELLING

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GLOSSARY

Aquifer — A saturated stratum capable of yielding water to wells or springs at a sufficient rate to provide a practical source of supply. It must consequently be of high permeability.

Aquitard — A geological formation of low permeability.It may itself contain a large quantity of water, but it gives it up too slowly to be considered as an aquifer.

Types of Aquifer

) Confined Aquifers

A confined aquifer is a completely saturated aquifer whose upper and lower boundaries are impervious layers. Completely impervious layers rarely exist in nature and hence confined aquifers are less common than is often recognised. In confined aquifers the pressure of the water is usually higher than that of the atmosphere and the water in wells stands above the top of the aquifer.

ii) Semi-Confined Aquifers

A semi-confined or leaky aquifer is a completely saturated aquifer that is bounded above by a semi-pervious layer and below by a layer that is either impervious or semi-pervious. A semi-pervious layer is defined as a layer which has a low, though measurable, permeability. Lowering of the piezometric head in a leaky aquifer, for example by pumping, will generate a vertical flow of water from the semi-pervious layer into the pumped aquifer. Since the permeability of the covering layer is usually very small, the horizontal flow component in this layer can be neglected. In general, the drawdown of the phreatic level in the semi-pervious layer is very small compared with the lowering of the piezometric level of the aquifer.

iii) Unconfined Aquifers

An unconfined aquifer is a permeable bed only partly filled with water and overlying a relatively impervious layer. Its upper boundary is formed by a free water table or phreatic level under atmospheric pressure. Water in a well penetrating an unconfined aquifer does not, in general, rise above the phreatic level, except when there is vertical flow.

Hydraulic Properties

) Transmissivity

The transmissivity is the product of the average horizontal permeability and the thickness of the aquifer. Consequently, transmissivity is the rate of flow under a hydraulic gradient equal to unity through a cross-section of unit width over the whole thickness of the aquifer. It is designated by the symbol KD and is expressed in m^2/day.

ii) Storage Coefficient and Specific Yield

The storage coefficient (or storativity) and the specific yield are both defined as the volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface. Both are designated by the symbol S and are dimensionless.

The storage coefficient refers only to the confined parts of an aquifer and depends on the elasticity of the aquifer material and the fluid.

The specific yield refers to the unconfined parts of an aquifer. In practice, it may be considered to equal the effective porosity or drainable pore space because in unconfined aquifers the effects of the elasticity of aquifer material and fluid are generally negligible. It should be kept in mind that small pores do not contribute to the effective pore space because they retain water due to capillary forces.

iii) Leakage

Leakage is the vertical flow of water from a low permeability confining layer into a pumped aquifer. The leakage factor, L, is used to determine the distribution of leakage into a semi-confined aquifer and is equal to $\sqrt{\frac{KD.D'}{K_v}}$ where KD is the aquifer transmissivity, D' is the thickness of the aquitard and K_v is the vertical permeability of the aquitard. High values of L indicate a great resistance to flow within the confining layers as compared with the resistance of the aquifer itself. In this case the influence of leakage will be small. The factor L is expressed in metres.

1. INTRODUCTION

In August 1983 WLPU carried out preliminary hydrological modelling of the Sua Pan aquifer using the computer facilities available at the Institute of Hydrology. The model employed was crude, but nevertheless provided useful indications of the controls that the transmissivity of the aquifer and the vertical permeability and specific yield of the aquitard could be expected to exercise upon drawdowns. These preliminary simulations were limited to a duration of one year, so that only short term effects were considered. The effect of storage depletion on long term drawdowns could only be estimated roughly. Also, the results of the twinwell and maxiwell pumping tests were not incorporated into the model. These results subsequently provided a new understanding of the aquifer.

Therefore, an improved model has been developed to meet the following objectives:

a) To enable more accurate estimates of well drawdowns to be made.

b) To investigate further the sensitivity of drawdowns to the vertical permeability and specific yield of the aquitard horizons.

c) To observe the effects of storage depletion on the long term performance of the aquifer.

d) To ascertain the effect of recharge.

e) To establish viable long term wellfield yields (l/s/km^2).

2. DESCRIPTION OF THE MODEL

The model uses a finite difference method to solve the partial differential equation describing unsteady flow in the aquifer system. It is based on a programme developed by the Institute of Land Reclamation and Improvement, Holland. A manual for users has been prepared by Boonstra and de Ridder (1981). The method requires that the area to be modelled is split into small but finite elements. Each sub-area thus formed has a node which is considered to be representative of that nodal area and at which all recharge and abstractions are assumed to occur. Each node is assigned a particular storage coefficient or specific yield. A certain permeability is assumed for each boundary between adjacent nodal spaces. Every node is connected mathematically to its neighbours enabling an approximate representation to be obtained of the unsteady flow system.

The following features and restrictions are incorporated into the model:

a) The aquifer is treated as a two-dimensional flow system.

b) The value of storage coefficient input to the model for each nodal area is considered to be constant through the depth of the aquifer.

) The aquifer is bounded at the bottom by an impermeable layer.

d) Darcy's law (linear resistance to laminar flow) and Dupuit's assumptions (vertical flow can be neglected) are applicable in the aquifer.

e) In the low permeability top layer of a semi-confined aquifer the model adjusts the saturated thickness according to the calculated water table elevation. The water table in this layer may vary according to recharge and seepage rates or can be kept constant. Horizontal flow in the top layer is neglected.

f) The processes of the infiltration and percolation of rain and surface water and of capillary rise and evapotranspiration, taking place in the unsaturated zone of an aquifer (above the water table), cannot be simulated. The net recharge to the aquifer must be calculated manually and prescribed to the model.

g) The model cannot simulate spatial and time variations of groundwater quality.

3. SELECTION OF MODEL PARAMETERS

3.1 Boundary Conditions

The locations of the boundaries are shown on Fig.1. The reasoning behind the choice of boundaries is set out below:

a) The Western Boundary

In the previous model the boundary was taken parallel to the edge of the Pan. Bailleul (1979) has suggested the presence of a fault separating the Sua and Ntwetwe Pans. A notional alignment for the fault hypothesized by Bailleul was drawn along the Pan's western shoreline to pass alongside M6. This boundary was assumed impermeable since very little is known concerning the hydraulic interconnection of the Sua and Ntwetwe Pans.

b) The Eastern Boundary

An impermeable boundary closely following the Pan shoreline has been drawn because wells drilled to locate freshwater supplies off the Pan during Phase I investigations have exhibited low yields.

c) The Northern Boundary

This boundary approximately follows the line of the Nata-Maun road. Borehole records for the area to the north of the road indicate low well yields, generally less than 2 l/s. Therefore, it is conservative to consider the boundary as impermeable.

d) The Southern Boundary

No data is available concerning the southern part of the Pan. A boundary was arbitrarily selected running from the root of Sua Spit in the east to a point about 10 km south of the projected line of the Spit at the western shore. This boundary was also taken as impermeable.

3.2 The Finite Difference Mesh

The finite difference mesh developed for use in the model is shown on Fig.1, together with the boundaries. It was decided that nodes should be spaced at 2km centres in the proposed wellfield area and in the immediate surrounds which might prove suitable for relocating wells. However, having regard to the constraint of data availability, there was considered to be little merit in using a fine mesh throughout, since this merely increases computing time and hence cost, without enhancing the accuracy of the results. Therefore, the mesh becomes progressively coarser away from the wellfield.

A total of 221 internal nodes have been used to cover the Pan area. A further 60 external nodes were required to define the boundaries. By comparison, the previous model employed only 40 internal nodes, with 27 external nodes describing its boundaries.

The mesh was constructed using the Thiessen method. The nodal centres form the vertices of a system of triangles in which no internal angle may exceed 90 degrees. Perpendicular bisectors were drawn to all the sides of the triangles, thereby forming the edges of the nodal spaces.

3.3 Aquifer Type

The model gives only three options from which to select the aquifer type. These are (i) confined, (ii) semi-confined and (iii) unconfined. The model does not have the facility for a confined aquifer to become unconfined during prolonged pumping.

It is believed that the semi-confined aquifer option is the most suitable to idealize the field conditions. This conclusion is based upon the following observations:

a) A slight artesian pressure has been observed in the wells immediately after they have been drilled, although this is subsequently removed by pumping. In none of the pump tests carried out to date has the aquifer behaved as though it were unconfined. The storage coefficient calculated from these tests is about 0.001, a typical value for an artesian aquifer. On the basis of these observations it was concluded that the unconfined aquifer option would not be appropriate.

b) The vertical permeabilities measured in the laboratory using samples from the cored holes indicate layers with high permeabilities interspersed with semi-pervious layers having lower, though significant permeabilities.

Geophysical logging suggests that the sediments of Sua Pan consist of stratified sands, silts and clays. Although there appears to be a predominance of fine grained deposits over the top 30m, the occurrence of sand layers has also been noted.

During long term pumping at maxiwell MX58 there were indications of partial dewatering of the aquifer at the well itself. For dewatering to take place, the phreatic surface must be drawn down through an aquifer horizon. This can occur in an unconfined aquifer, or in an artesian aquifer that becomes unconfined during prolonged pumping.

On the basis of these observations the confined aquifer option was considered unsuitable.

c) Piezometers P5U and P5L are situated at varying depths at the same distance from well W1. Monitoring these piezometers during pump testing has indicated the occurrence of vertical leakage. Observations at miniwell M3 during pump testing of T1S have also suggested that leakage is taking place.

After removal of the initial artesian pressure by pumping, approximately hydrostatic conditions are indicated. For this situation any further reduction of pressure in the aquifer, brought about by pumping, will produce a hydraulic gradient between the aquifer and its bounding aquitard horizons such that a vertical flow is induced across those boundaries.

Vertical flow, or 'leakage', from a semi-pervious layer to an aquifer is characteristic of semi-confined conditions.

3.4 Aquifer Geometry

The idealized section used in modelling the Sua Pan aquifer system is presented in Fig.2.

The ground elevation was assumed constant for the whole Pan area. It was decided to ignore the initial artesian condition of the groundwater, since this disappears with pumping, and to take no account of seasonal fluctuations in the groundwater table elevation. Since the water table has been observed at varying depths between 0.5 - 1.5m, the groundwater elevation was assumed to occur 1.0m below the ground surface throughout.

The parameters used to describe the aquifer geometry have been selected on the basis of the logs of the cored holes, the miniwell cuttings logs, the geophysical logs, the results of the laboratory testing and petrographic analyses. Consideration was also given to the response of the twinwells and maxiwells to pumping. This material has previously been presented in the reports on the Phase I and Phase II investigations, but is summarised here for convenience.

Generally, the logs indicate a succession of stratified deposits in which sand layers are interspersed with silts and clays. At greater than 30m depth the sand layers are cemented to a varying extent. The particle size distributions suggest that two main types of deposit occur in the Pan basin.

Over the upper 25m there occur mostly widely graded deposits. Narrowly graded deposits predominate at greater than 25m depth.

Transmissivities calculated from pump tests conducted on the shallow twinwells were approximately 90% of the corresponding values obtained from the adjacent maxiwells. The yields from the deep twinwells were consisently low. Therefore, it was decided that all deposits at greater than 30m depth should be ignored.

In order to locate the aquifer horizons within the 30m below the ground surface all the logs were examined closely. The thicknesses of sand layers, excluding the surface sands, were noted. The mean combined thickness of the sand layers was found to be approximately 10m and these layers were assumed to be the aquifer horizons. Laboratory testing on samples from the remaining 20m have indicated that the strata have a measurable permeability, and these were assumed to be aquitard layers.

The model requires that a single aquitard overlies one aquifer. Therefore, the aquifer is assumed to be situated between elevations 0m and 10m, with the top of the aquitard at elevation 30m.

3.5 Consequences of the Simplifying Assumptions

The present understanding of the aquifer is that it comprises several separate horizons. Initially the phreatic surface occurs above all of the aquifer layers. Under this condition the volume of brine which can be released from storage is indicated by the storage coefficient which has a value of about 0.001. However, under prolonged pumping it may be possible to draw the phreatic surface down into a shallow aquifer horizon and to begin to dewater the layer. The mechanism through which the brine is released from storage then begins to change. The volume which can be relased is indicated by specific yield which might be of the order of 0.1, but, as the layer is dewatered, its saturated thickness will decrease and its transmissivity will be reduced accordingly.

Once the phreatic surface has passed below this stratum it will be subject to a constant head and hence it will not be possible to increase the flow from it. Since the model requires the aquifer to occupy a single band beneath the aquitard it is not possible to investigate the effects of partial dewatering of aquifer horizons.

The location of the aquifer horizons within the 30m below the ground surface has a direct influence on the maximum length of the flow path through the aquitard. In the model the maximum flow path is 20m, whereas in the field it might be only 5m. In order that the leakage in the model is equal to that in the field for this case the value of vertical permeability for the model must be about four times that in the field.

The aquitard occurring below 30m depth is omitted from the model because the base of the aquifer is assumed impermeable. Moreover, these layers cannot physically be dewatered, since they are beneath the aquifer. The storage coefficient for this aquitard might be 0.0005 (at W2, a value of 0.0002 was indicated by pump testing), which is very low in comparison to the specific yield of the upper aquitard. Since the extractable volume of water is insignificant, the error involved in its omission from the model is small.

3.6 Aquifer Properties

3.6.1 Transmissivity and Horizontal Permeability

The values of transmissivity calculated for each well have previously been presented in the Phase II report. They are reproduced here for ease of reference, together with the values used in the model.

Miniwell KD(m^2/day)	Twinwell KD(m^2/day)		Maxiwell KD(m^2/day)		Phase I Well KD(m^2/day)	Value Used in Model
M1					W1	
250					280	280
M2					W2	
160					2	160
M3	T1S	T1D				
145	100	40				145
M4						
80						80
M5	T2S	T2D	MX5M	MX5B		
300	350	50	-	380		300
M6/6A						<50
M7						
135						135
M8						
170						170
M9						
145						145
M10	T3S	T3D	MX10M	MX10B		
360	400	60	400	-		360
M11						
160						160

Note: KD = Transmissivity

The well locations, together with their corresponding transmissivities, were plotted onto a map of the Pan on which the impermeable boundaries had been marked. The boundaries were assumed to denote a contour of zero transmissivity. Contours of transmissivity were interpolated between the wells and the impermeable boundaries for the western side of the Pan. The contours were distorted between M2 and M7 to facilitate modelling. It was then assumed that the contours for the eastern part of the Pan would mirror those of the western area, apart from local adjustments so that the contours follow the shape of the eastern boundary. The assumption is considered reasonable because the Pan comprises a sedimentary basin. The resulting transmissivity contours are presented on Fig.3.

The finite difference nodal mesh was overlain upon the contours of transmissivity and the value for each nodal edge computed. The transmissivity (KD) was divided by the aquifer thickness (D = 10m) to determine the mean horizontal permeability of the aquifer, which was input directly to the model.

3.6.2 Storage Coefficient

The value of the aquifer storage coefficient as calculated from pump testing during the Phase II investigations was found to vary in the range 0.0004 - 0.0015. For the model it was assumed to be 0.001 throughout. In order to approximate dewatering of the aquifer the storage coefficient was replaced by a specific yield of 0.1 in one run. The corresponding reduction in transmissivity was not taken into account. This is a valid approximation as long as the reduction in the saturated aquifer thickness remains small.

3.7 Aquitard Properties

3.7.1 Vertical Permeability

A review of vertical permeabilities indicated for the first 25m below ground surface was carried out as part of the Phase II investigations and the results were presented in Fig.9 of the Phase II report. The majority of the results were obtained from laboratory testing of core samples recovered during the Phase I investigations. Indications were that the vertical permeability lay in the range 0.002 to 0.2m/day. It was decided to carry out a sensitivity analysis within the above range to facilitate rapid interpretation of results from future investigations.

3.7.2 Specific Yield

In view of the lack of field data and the dearth of published information on storage depletion in alternating aquifer/aquitard horizons it was considered prudent to examine a range of values for the specific yield of the aquitard. Kruseman and de Ridder (1979) note that the specific yield for sands may be in the range 0.1 to 0.2. However,the specific yield may be considered to equal the effective porosity; that is the drainable pore space. For loose sand the porosity can be as high as 0.5. Therefore, a sensitivity analysis was conducted with specific yield varied from 0.05 to 0.5.

3.8 Abstraction Rates

A continuous abstraction rate of 950 l/s has been assumed in the model on the basis of information on brine demand provided by S.A.B.

Since the model uses a regular grid in the wellfield region, the wellfield nodal spaces have equal areas. Thus, the abstraction from a particular well was taken as being proportional to the transmissivity at that point. This method was used so that, ignoring storage depletion and interference effects, the drawdown would be approximately equal at all the wells. A total of 50 wells were used and the mean abstraction corresponded to 5.1 $l/s/km^2$ of wellfield area.

In order to ascertain the effect of wellfield layout on drawdowns the flows were redistributed in some cases in an attempt to produce a constant total drawdown, including storage depletion and interference effects, throughout the wellfield. Also, the size of the wellfield was increased to determine whether this would reduce drawdowns significantly.

3.9 Recharge

There is relatively little information available on the water balance of the Sua Pan, but a hydrological study of the area is currently in hand.

Three possible sources of recharge have been identified:

i) Groundwater Flow: The Sua Pan is a basin of inland drainage but there is very little data available on groundwater movements.

ii) Surface Water Flow: Monthly discharges are available for the Nata and Mosetse Rivers which flow into the Pan. The equivalent mean annual inflow from the Nata River on the basis of 8 years of record (1969-77) is $8m^3/s$. However, it has not been established that the proposed wellfield area could be recharged by river inflows at the north-eastern corner of the Pan.

iii) Rainfall: The average annual rainfall at Sua Pan is about 440mm per annum, but it is not known how much of the direct precipitation penetrates to the groundwater table.

In view of the uncertainties concerning the sources of recharge it was decided to use a range of values. Recharge was input to the model as a depth per unit time over the nodal area and was varied from 0 - 440mm per annum.

4. COMPUTER RUNS

Using the input data discussed in the foregoing sections a total of 30 computer runs have been carried out on a mainframe computer accessed through S.I.A.Ltd of London. The parameters input for each run have been tabulated and are presented in Appendix A together with a brief description of the objectives of the runs.

4.1 Choice of Timestep

Three runs were initially carried out to determine a suitable timestep for the analysis. It is desirable to use as large a value as possible to reduce computing time. However,if the timestep is too large the accuracy of the results is impaired. The effect of the choice of timestep upon the result is demonstrated on Fig.4. It was concluded that a timestep of a fortnight was suitable for short runs of a few months duration, but that a two month time-step was appropriate for runs of one year.

The timestep was increased to four months in long term studies on the basis of a comparison of results for the end of the fifth year of pumping between a 5 year run with 2 month timestep and a 10 year run with 4 month timestep.

4.2 Effective Radius of a Node

Theoretical solutions assume that flow occurs through a continuum, whereas the model considers the flow taking place through a system of small, inter-connected elements. This simplification creates discretization errors such that the drawdown estimated by the programme for a node at which abstraction takes place does not correspond to that which would occur at a pumped well. Prickett (1967) and Rushton and Herbert (1966) have considered this problem and it can be shown that, if steady state conditions exist, the effective radius of a node is 0.208 dx for a square mesh, where dx is the mesh spacing. However, for a semi-confined aquifer modelled by an irregular mesh in which unsteady state conditions exist, together with storage depletion and well interaction effects, it is not possible to calculate the effective radius. Therefore, a run was carried out in which abstraction occurred at only one well and the aquitard water table was maintained at a constant level. Having thus eliminated the effects of storage depletion and well interaction, the drawdown indicated by the computer was compared to those calculated using Walton's method, which is discussed in greater detail in Kruseman & de Ridder, op.cit. The effective radius of a node was found to be about 650m, (see Fig.5).

In the following discussion of the results, the drawdowns quoted are those given by the computer for the aquifer (unless otherwise specified), that is, remote from the well. For nodal areas in which abstraction takes place the aquifer drawdown represents the value at a radius of 650m from the well and includes the effects of storage depletion and well interaction. A correction must be added in order to establish the drawdown at the well itself .

5. RESULTS

5.1 Short Term Performance

A series of runs was carried out in which vertical permeability of the aquitard was varied from 0.002 - 0.2 m/day and the aquitard specific yield from 0.05 to 0.5. All runs simulated 1 year of pumping and used a 2 month timestep. The results are shown on Fig.6. The upper two graphs illustrate the effect of specific yield upon drawdowns for a given vertical permeability at both the edge and the centre of the wellfield, of which nodes 59 and 104 respectively are representative. It is evident that a value of specific yield greater than 0.1 is required if storage depletion is not to have a significant effect on drawdowns. The lower graphs demonstrate the dependence of drawdowns on vertical permeability for a set value of specific yield. If vertical leakage from the aquitard is to proceed at a sufficient rate to prevent excessive drawdowns the permeability must exceed 0.01 m/day. K_v

The effects of storage depletion and well interaction were also investigated using runs of short duration. A one year simulation without storage depletion (i.e. a run in which the aquitard water level was kept constant) indicated drawdowns at the edge of the wellfield of 0.299m, and drawdowns of 0.575m at the centre. Since the simulated well abstractions were calculated so that, ignoring interference and depletion effects, the drawdowns would be about equal in all wells, this difference is the result of interference and boundary reflection effects. Fig.7 illustrates how storage depletion and interference effects increase the drawdown at Node 71 (MX5). It is concluded that well interaction is limited and that, whilst it produces a measurable increase in drawdowns,it is not a critical consideration for the satisfactory performance of the wellfield in the long term. However,storage depletion may have a dramatic effect on the projected life of the wellfield. The greater volume of water comes out of the aquitard, evidence of which can be observed on Fig.8, which indicates that the reduction in head within the aquitard is only marginally less than that in the aquifer.

5.2 Long Term Performance

A vertical permeability of 0.02 m/day was considered appropriate for use in runs investigating the long term performance of the aquifer for the following reasons:

) The short term runs suggest that a value greater than 0.01 m/day is required for the wellfield to operate satisfactorily on a long term basis.

ii) Laboratory permeability tests suggest a field value of 0.007 m/day. However, this figure is possibly an under-estimate because it is easier to obtain samples from the less permeable strata.

iii) The Sua Pan aquifer horizons are interbedded with the aquitard layers, so that the real flow path is much shorter than that used in the model. This can be overcome by assuming a higher value of vertical permeability for the model than exists in the field.

It was decided to vary the aquitard specific yield between 0.125 and 0.25 for two reasons:

a) The runs of 1 year duration suggested that a specific yield in excess of 0.1 would be necessary if storage depletion was not to be a problem in the long term.

b) A specific yield of 0.25 is considered to be an optimistic value on the basis of the observation of Kruseman and de Ridder, op.cit., that the specific yield of sands is generally 0.1 0.2. Also, whilst the effective porosity of loose sands is about 0.5, laboratory testing has indicated that porosities of the Pan sediments are typically 0.3 - 0.4. The effective porosity, which represents the drainable pore space of the material, will be smaller than the porosity because of effects such as capillary suction.

It is stressed that there are at present no data from the field to substantiate the lower bound figure of 0.125 adopted for specific yield.

Long term runs were carried out using the above parameters. An initial run simulating 5 years of pumping showed that drawdowns were acceptable, so the duration was increased to 10 years for subsequent runs. The results showed that:

I Drawdowns are controlled to a large extent by storage depletion, as illustrated by Fig.9. If drawdowns are not to become excessive during prolonged pumping,the values of the aquitard specific yield and vertical permeability must be sufficiently high. It is apparent that a pumped well located at Node 104 would be exhausted after about 8 years for a vertical permeability of 0.02 m/day and a specific yield of 0.125. If the specific yield were 0.25, however, the useful life of the well would almost double.

II The vertical leakiness of the aquitard is such that drawdowns are limited to the wellfield area only, as shown on Figs.10A and 10B. This has several implications:

1) Once drawdowns become excessive within the original wellfield it will be possible to relocate the wellfield elsewhere on the Pan. Thus, the brine is effectively 'mined' from the immediate vicinity of the wellfield, a new source area being opened up once the initial supply nears exhaustion.

An alternative to relocation would be to drill many wells at the outset. By abstracting less flow from each well the drawdowns would be limited, thus prolonging the life of the wellfield. Many of the wells would probably be placed in poorer transmissivity areas, so that the size of the wellfield would be large. The large initial capital outlay involved makes this option unattractive.

2) Locating the wellfield at sufficient distance from the solar ponds (about 4 km) restricts drawdowns at the ponds to less than 1m after 10 years (see Figs.10A & B).The consequences of increased drawdowns on solar pond seepage losses are discussed elsewhere.

3) The Nata River flows into the north-eastern area of the Pan where drawdowns indicated by the model after 10 years are effectively zero. Therefore,the annual floodwaters may not infiltrate to beneath the level at which recharge is balanced by the combined effects of capillary rise and evaporation, and hence will be lost as evaporation. However,the hydraulic gradient between this north-eastern corner and the wellfield might be sufficient to produce a groundwater flow to recharge the wellfield and reduce drawdowns.

III Although the constraints of the model do not permit a confined aquifer to become unconfined during pumping it was possible to approximate the effect of aquifer dewatering by increasing the aquifer storage coefficient of 0.001 to a specific yield of 0.1. The resulting effect on drawdowns can be gauged from Fig.11. It should be borne in mind that this is a very approximate method. The aquifer does not dewater from the commencement of pumping and no account is taken of the corresponding decrease in transmissivity which accompanies dewatering. Although this effect is small initially, dewatering of the aquifer horizons in the long term is likely to outweigh the benefit of increased specific yield arising from the development of unconfined behaviour.

5.3 Wellfield Management

A total of 48 wells were assumed for the purposes of cost estimating at the end of the Phase I investigations. On the basis of the Phase II results a wellfield comprising 43 wells was considered appropriate. Therefore,for convenience, a wellfield having 50 wells at 2 km centres was assumed for use in the computer model. The well abstractions were chosen so that the drawdowns, ignoring the effects of storage depletion and interaction, would be about equal.

The results of the long term runs suggest that after 10 years drawdowns are becoming excessive at the centre of the wellfield; mainly because of the effects of storage depletion, although there is also some contribution from well interaction. The drawdowns in the wellfield are highest in the centre, as shown on Fig.12. Therefore, the possibility of restricting the central drawdowns was examined using the following methods:

) The number of wells was increased to 70. The area of the wellfield increased correspondingly from 187 km^2 to 262 km^2. However, the expansion necessitated the positioning of wells in poorer transmissivity areas. Thus,the increase of 40% in wellfield area produced only a 20% decrease in drawdowns.

ii) The effects of redistributing the well abstractions were investigated. Perimeter wells had their flows increased by 15%, and then 20%, with corresponding reductions in flow from the central wells. The results are indicated by Fig.13. It was concluded that a more even distribution of drawdown could be obtained in this way. A reduction of 10% could be achieved on maximum drawdowns, enabling the wellfield life to be prolonged.

The long term runs also indicated that drawdowns were limited to the wellfield itself, thus raising the possibilty of relocation of the wellfield. A run was carried out in which the central wells, assumed to be exhausted, were not pumped. The flows from the perimeter wells were reduced to about 60% of the rate abstracted during the first 10 years. A total of 35 new wells were incorporated into the model in order to maintain a flowrate of 950 l/s. The run simulated 10 years of pumping and demonstrated the viability of relocation. Although drawdowns developed beyond the circumference of the wellfield, there was a small recovery of storage in the central region where pumping had been stopped (see Fig.14). However,relocation might require the use of regions of poorer transmissivity, so that well spacings would increase.

5.4 Recharge

The effect of recharge was not considered in any of the runs discussed thus far. It is evident, however, that a larger wellfield than that envisaged to date will be necessary if it is to operate for more than 20 years without recharge.

The annual volume of recharge and its distribution through the year is unknown. Typical annual rainfall of 440mm per annum over the wellfield area alone is equivalent to a continuous flow of 2.5m^3/s. The equivalent mean annual flow in the Nata is 8m^3/s, based on 8 years of record. Since the required abstraction is only about 1m^3/s, the possibility exists that recharge may be sufficient to facilitate pumping indefinitely, assuming that the brine maintains a sufficiently high specific gravity. If the recharge does not pick up the required specific gravity but rests above the original groundwater by virtue of its lower specific gravity, then it may still provide the necessary head to cause the underlying groundwater to leak into the aquifer.

Therefore, a series of runs was carried out to examine the sensitivity of drawdowns to recharge. The recharge to the wellfield region was increased from 0 to 440mm per year and the results have been plotted on Fig.15. (Recharge is input to the model as a depth per unit time for a nodal area.) It will be observed that if the effective recharge exceeds 100mm per annum the drawdown at the edge of the wellfield will be reduced to about zero, whilst a recharge of 210mm per annum would replenish storage throughout the wellfield. *Effective recharge* has been used in this context to denote that recharge which infiltrates below the zone of capillary rise and hence cannot subsequently be lost by evaporation.

Finally, because effective recharge is unlikely to be a continuous process, and may occur during perhaps only 2 months of the year, a run was carried out to simulate this condition. Fig.16 shows the effect on drawdowns.

6. CONCLUSIONS

6.1 Aquifer Behaviour

The following general conclusions on aquifer behaviour have been drawn from the computer modelling:

a) The drawdown at the well itself is dependent primarily upon transmissivity, especially in the short term.

b) Short term drawdowns remote from the well are controlled primarily by vertical permeability of the aquitard.

c) Long term drawdowns away from the well depend upon the storage coefficient or specific yield of the aquifer, the specific yield of the aquitard and the effects of recharge.

d) Well interaction will increase drawdowns everywhere, but the effect is small at the well spacings currently under consideration.

The data on transmissivities gathered during Phases I and II of the site investigations covers the western part of the exploration area. Additional information is required on transmissivities both to optimise the location of the initial wellfield and to cover the areas available for expansion in the longer term.

Data on vertical permeability of the aquitard is limited. The model suggests that a value of at least 0.01m/day is required to ensure that vertical leakage from the aquitard will keep pace with pumping.

For the wellfield to maintain the specified yield in the long term, the model suggests that a high aquitard specific yield and/or recharge will be required.

If zero recharge is assumed, it is apparent that an aquitard specific yield of at least 0.125 is required for sustained wellfield performance, even taking account of future expansion of the wellfield to prolong its effective life. The long term field values of specific yield for the aquifer and the aquitard are not known at present, but the possibility must be recognised that the aquitard specific yield may be below 0.125. If this is so, the satisfactory long term performance of the wellfield will depend upon recharge which may arise from surface and groundwater inflows to the Pan and/or from direct surface precipitation.

6.2 Long Term Yields

To investigate long term performance, the operation of a wellfield 187 km^2 in extent was simulated under continuous pumping at $0.95 m^3/s$ for 10 years.

A maximum drawdown of 27.4m was indicated at a pumped well at the centre of the wellfield. The corresponding drawdown for a well at the edge of the wellfield was 19.6m. The central wells were assumed to be exhausted at this time. This condition would be manifested in practice by reducing well yields as the aquifer horizons became dewatered. It was assumed that after 10 years of pumping from the initial wellfield an additional area of 175 kms^2 would be developed. Pumping at the original central wells would be discontinued and pumping at the original perimeter wells would be continued at a reduced rate. Under these conditions a further 10 years of pumping would be possible. The mean wellfield yield over 20 years of pumping would be 2.6 $l/s/km^2$, based on an aquitard specific yield of 0.125, a vertical permeability of 0.02 m/day and zero recharge.

It is emphasized that the enlarged wellfield after 10 years extends into an area where transmissivity values are at present conjectural. Confirmation of transmissivity values and aquitard properties would be required before the indicated wellfield yield for the assumed configuration could be viewed with confidence.

6.3 Location of Aquifer Horizons

If the specific yield of the aquitard proves to be low and there is little or no recharge then drawdowns will become large. In practice this condition may lead to dewatering of aquifer horizons occurring at shallow depth and a corresponding decrease in transmissivity values. It is therefore important that the aquifer horizons are identified in the Phase III exploratory wells so that estimates of allowable drawdowns may be refined for wellfield design.

6.4 Solar Ponds

Although drawdowns indicated in the solar ponds area are small, they would exert a significant effect on seepage losses.During monitoring of performance of the pilot solar ponds the average head difference between the ponds and the surrounding brine table was about 0.6m and seepage losses of approximately 1.7 l/s per km of wall were estimated. A drawdown of 1.0m in the brine table beneath the ponds could increase the head difference to 1.6m, so that seepage losses might increase to about 4.5 l/s per km. Seepage losses may be maintained at acceptable levels either by managing the wellfield so as to minimise drawdowns in the solar ponds area or by partially lining the ponds to reduce losses.

6.5 Wellfield Management

The modelling has confirmed that the choice of wellfield size and arrangement and the distribution of abstractions have a large influence on the drawdowns, and hence wellfield life.

A choice currently exists between using a relatively small group of wells initially, placed in the higher transmissivity areas, with a phased introduction of new wells as the original wells are exhausted,or using a sufficiently large wellfield at the outset so that drawdowns will not become excessive during the projected wellfield life.

6.6 Recharge

All analysis to date has been carried forward on the basis of zero recharge, on the grounds that it is difficult to quantify and that, if it could be demonstrated that the resource would provide the required long term yield without recharge, then it would not be necessary to address the problem in detail.

The model has demonstrated the need to investigate recharge and to establish with confidence the extent to which this effect may be relied upon in the long term.

If it can be established that effective recharge makes a substantial and reliable contribution to the brine resource in the long term it is probable that a relatively compact wellfield will function indefinitely, possibly with a higher wellfield yield than has been indicated hitherto.

If, on the other hand, recharge is found to be an insignificant effect and aquitard specific yield proves to be low, it is likely that a very large wellfield area, possibly extending beyond the boundaries used in the computer model, will need to be developed progressively to maintain the required yield in the long term.

In either case, the final extent of the wellfield will depend upon aquitard specific yield and vertical permeability.

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* Base taken as impermeable. In effect there could be upward leakage from the lower sequence. A 3-layered model would be more representative.

* Drawdowns of 15m plus occur, i.e. equivalent to a 50% loss in T with equal distribution of layers. The inability of the model to accomodate this is a serious constraint on model representativeness.

* S range 4×10^{-4} to 1.5×10^{-3}. Value of 1×10^{-3} adopted seems rather high and runs should have been made with, say, 1×10^{-4} or 5×10^{-4} for comparison.

* Lowest K_v would be main constraint on vertical movement. More test data required

* Specific yield only applicable to aquitard as this is dewatered and becomes unconfined. The top 20m is taken as the aquitard – i.e. fine grained sediments – ~~with~~ which would have a low specific yield. The 'Sy' value adopted relates to sands and a much lower value should be used, say 1%, whereas 0.125 (12.5%) is needed. This is most unlikely.

* Where will the additional wellfield area for secondary abstraction come from?

Model Study

* Impermeable boundaries provide conservative results. A fixed head boundary to the south probably more representative.

* Faulting may not affect the top 30m. The occurrence of coarser grained deposits should be more frequent to the east, north east and ? south which provide the sediment input.

* Generally > 250mm required to trigger direct recharge. The area is probably in a steady-state situation with inputs being lost by shallow groundwater evaporation. Lowering of the water table with decrease Eg and recharge may then occur in greater quantities. Main recharge inputs from the Nata and Semowane rivers

Initial zero hydraulic gradient.

Suspect that single layer of high K may produce yields and that this layer (s) may be either in upper or lower sequence at different sites. Were T values computed by the same methods for all Ph II wells for valid comparison and why were drawdowns so large at the twin shallow wells if this is the most productive zone with high T? Why do the upper, less cemented sands stand open - particularly with vertical flow down the annulus?

TABULATION OF COMPUTER RUNS

APPENDIX A

Object of Investigation	Run Identification	S	S'	K_v (m/day)	Recharge	Duration	Timestep (months)	Comment
Selection of Timestep	SGMP000A	0.001	0.05	0.002		1 yr	0.5	
	SGMP000B	0.001	0.05	0.002		1 yr	1.0	
	SGMP000[1]	0.001	0.05	0.002		1 yr	2.0	Timestep of 2 months suitable for 1 yr runs.
Effective Radius	SGMP028	0.001	(0.125)	0.02		2 mths	0.5	No storage depletion. Single well pumped. r = 650m
Short Term Effects	SGMP000[1]	0.001	0.05	0.002		1 yr	2.0	
	SGMP020	0.001	0.125	0.002		1 yr	2.0	
	SGMP003	0.001	0.25	0.002		1 yr	2.0	
	SGMP002	0.001	0.50	0.002		1 yr	2.0	
	SGMP026	0.001	0.125	0.007		1 yr	2.0	
	SGMP004	0.001	0.05	0.02		1 yr	2.0	K_v = 0.007m/day estimated from lab. permeability tests
	SGMP010	0.001	0.125	0.02		1 yr	2.0	Sensitivity study for both K_v and S'
	SGMP005	0.001	0.25	0.02		1 yr	2.0	
	SGMP006	0.001	0.5	0.02		1 yr	2.0	
	SGMP007	0.001	0.05	0.2		1 yr	2.0	
	SGMP021	0.001	0.125	0.2		1 yr	2.0	
	SGMP008	0.001	0.25	0.2		1 yr	2.0	
	SGMP009	0.001	0.5	0.2		1 yr	2.0	
Wellfield Management	SGMP005	0.001	0.25	0.02		1 yr	2.0	Standard wellfield layout: 50 wells at 2km c/cs
	SGMP011	0.001	0.25	0.02		1 yr	2.0	Wellfield enlarged to 70 wells
	SGMP022	0.001	0.25	0.02		1 yr	2.0	50 Wells: 15% redistribution of flow to perimeter
	SGMP012	0.001	0.25	0.02		1 yr	2.0	50 Wells: 20% redistribution of flow to perimeter
	SGMP023	0.001	0.125	0.02		10 yrs	4.0	Examination of relocating wellfield after 10 yrs
	SGMP025	0.001	0.125	0.02		10 yrs	4.0	and pumping for additional 10 yrs
Long Term Effects	SGMP013	0.001	0.25	0.02		5 yrs	2.0	Establishing effect of storage depletion. Showed
	SGMP014	0.001	0.25	0.02		10 yrs	4.0	that Δt = 4 mths suitable for long term runs
	SGMP023	0.001	0.125	0.02		10 yrs	4.0	Investigate effect of aquitard specific yield
Aquifer Dewatering	SGMP016	0.10	0.25	0.02		1 yr	2.0	Check run
	SGMP014	0.001	0.25	0.02		10 yrs	4.0	Runs compared to determine effect of aquifer
	SGMP017	0.10	0.25	0.02		5 yrs	4.0	dewatering
Recharge	SGMP015	0.001	0.25	0.02	✓	1 yr	2.0	37mm/month effective recharge to wellfield only.
	SGMP018	0.001	0.125	0.02	✓	1 yr	2.0	Effect of specific yield on storage replenishment
	SGMP010	0.001	0.125	0.02	-	10 mths	2.0	Wells pumped continuously through year with 150mm/
	SGMP024	0.001	0.125	0.02	✓	2 mths	0.5	month effective recharge during final 2 months
Storage Depletion & Well Interaction Effects	SGMP027	0.001	(0.125)	0.02		1 yr	2.0	No storage depletion. Wellfield pumped.
	SGMP028	0.001	(0.125)	0.02		2 mths	0.5	No storage depletion. Only MX5 (Node 71) pumped.
	SGMP019	0.001(MX5) 0.0004(W1)	(0.25)	0.02		4 mths	0.5	No storage depletion. MX5 and W1 pumped.

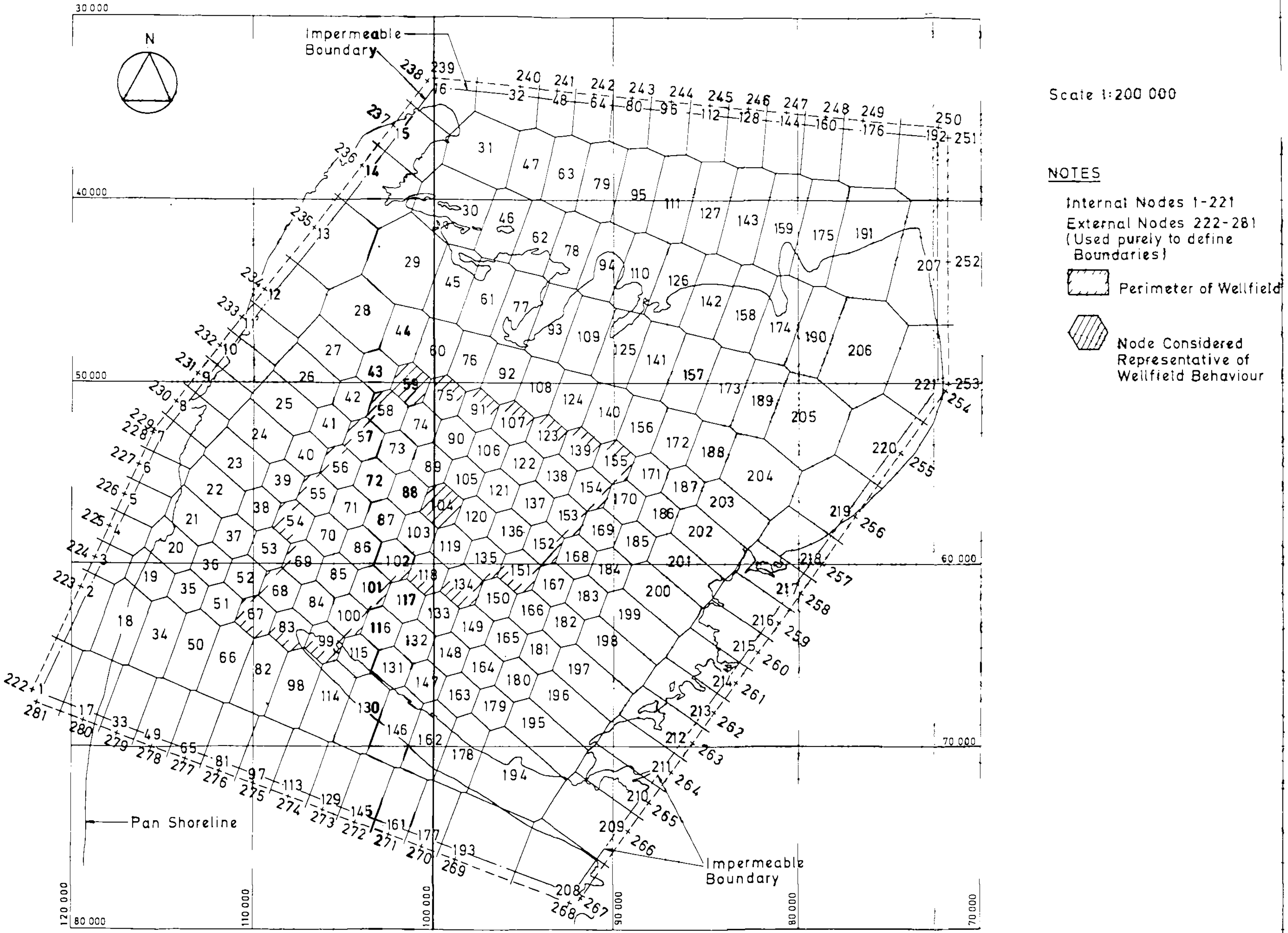
NOTES

1. Explanation of symbols used: S = Aquifer storage coefficient S' = Aquitard specific yield K_v = Vertical permeability of aquitard Δt = Timestep r = Effective radius of node

2. For runs which use the zero storage depletion option the model maintains the aquitard water table at a constant level by means of artificial infiltration and the allocated aquifer specific yield is ignored. The specific yield has been included in the table between brackets for runs employing this option.

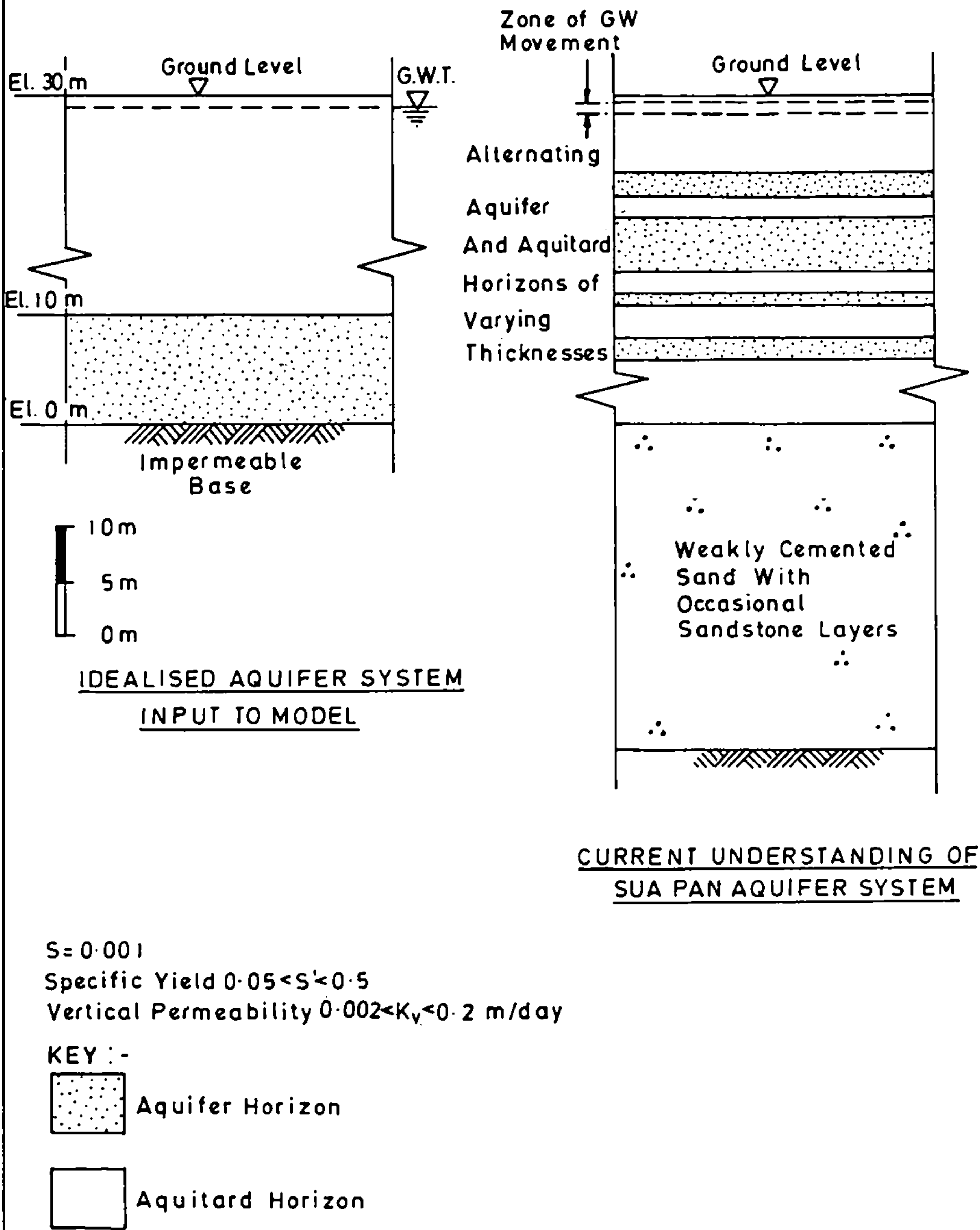
3. Runs have sometimes been used to investigate more than one effect. Where this has occurred, the run description has been entered into all appropriate sections of the table.

FIGURE .1



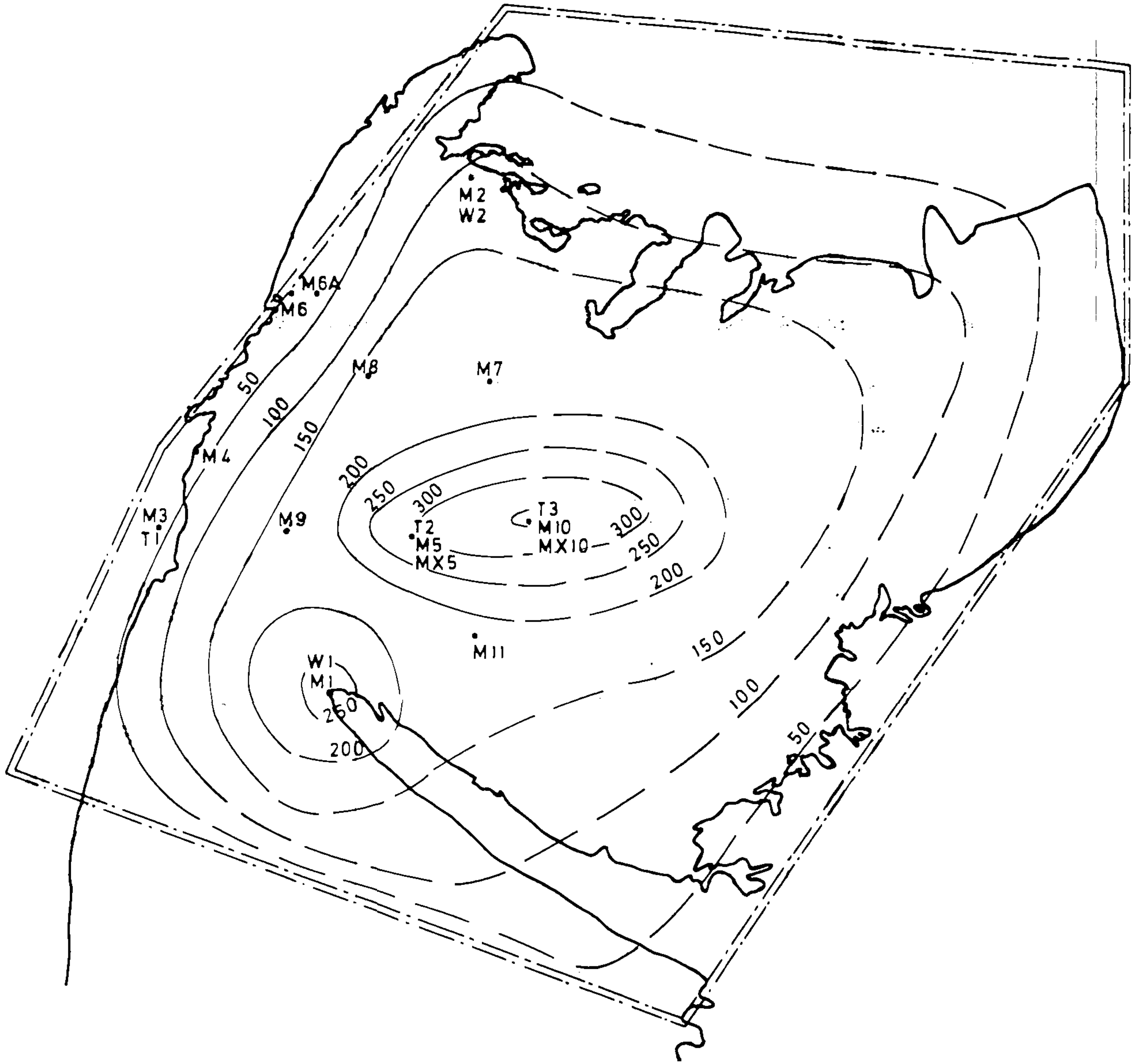
THE FINITE DIFFERENCE MESH

FIGURE 2



AQUIFER GEOMETRY

FIGURE 3

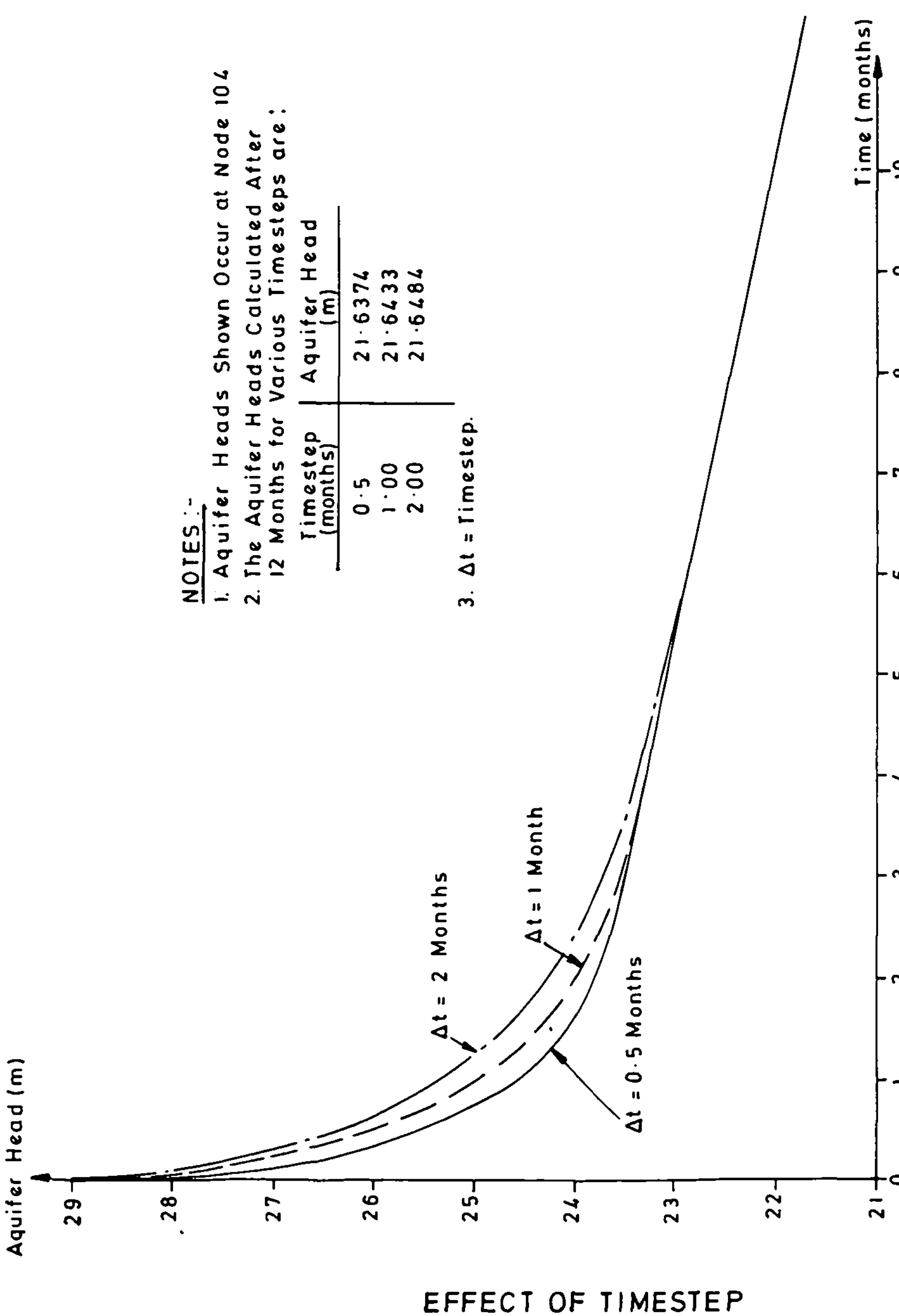


NOTES

1. Impermeable Boundary Assumed to be a Contour of Zero Transmissivity.
2. ______ Contours Interpolated Between Points of Known Transmissivity.
3. — — — Contours Extrapolated for Areas of Unknown Transmissivity.
4. Transmissivities Given in m^2/day.

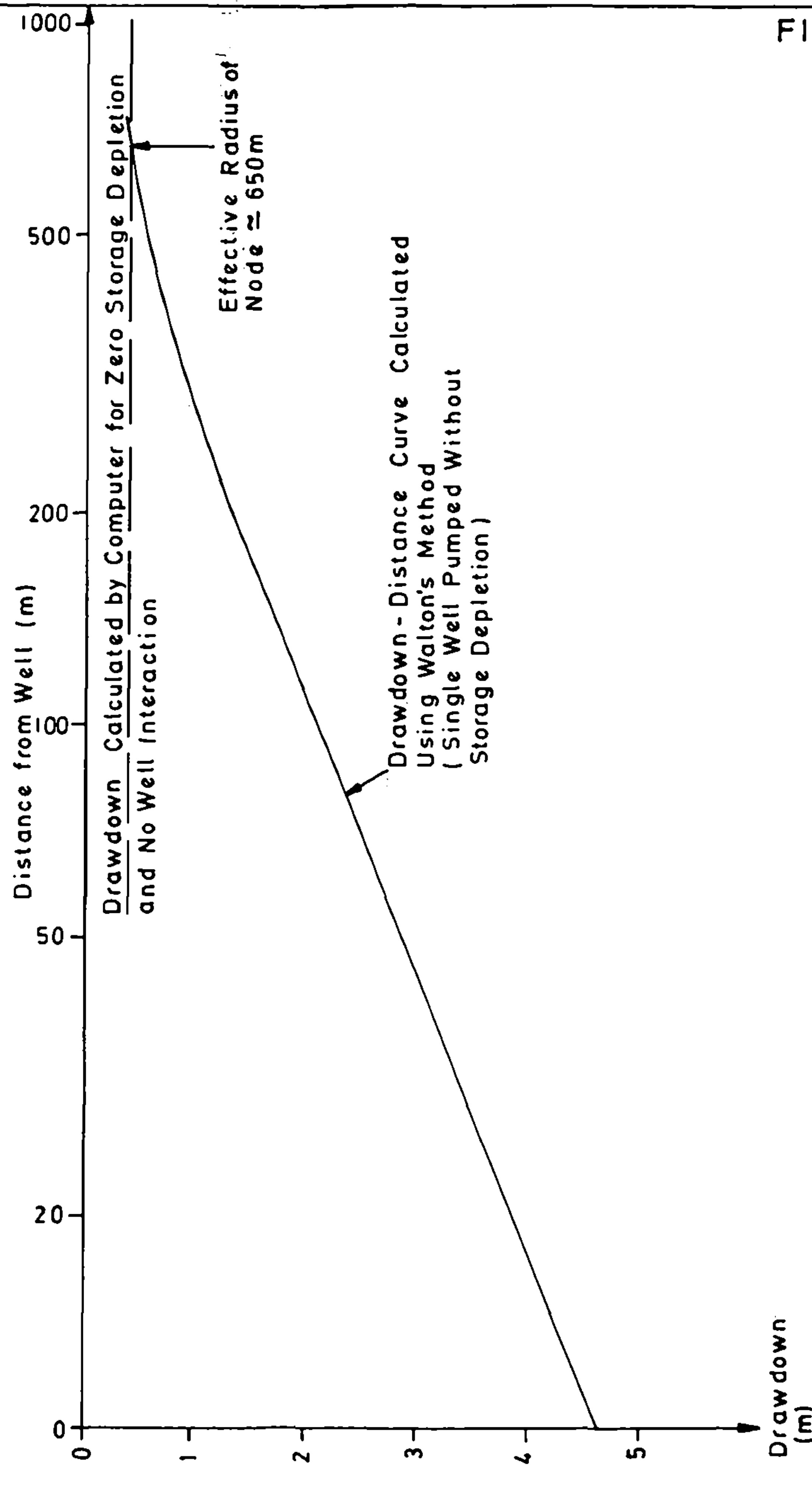
CONTOURS OF TRANSMISSIVITY

FIGURE 4



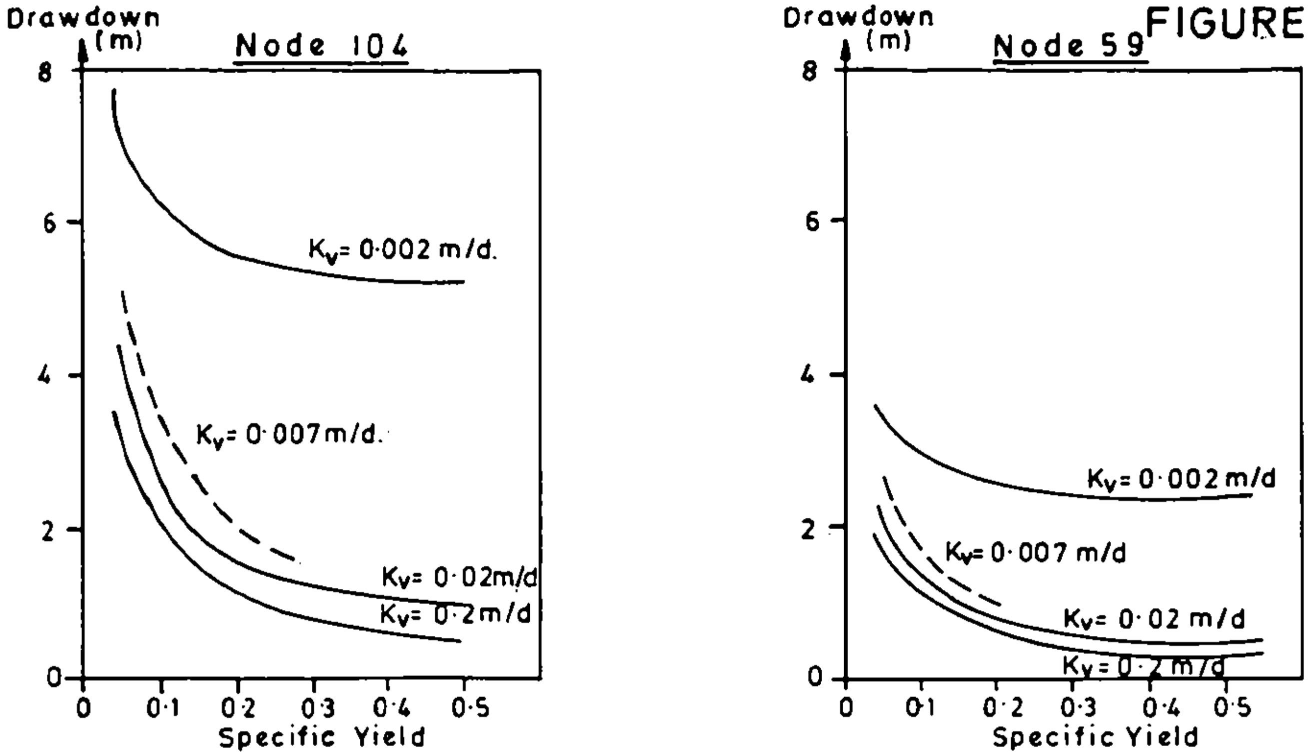
EFFECT OF TIMESTEP
ON COMPUTED AQUIFER HEAD

FIGURE 5



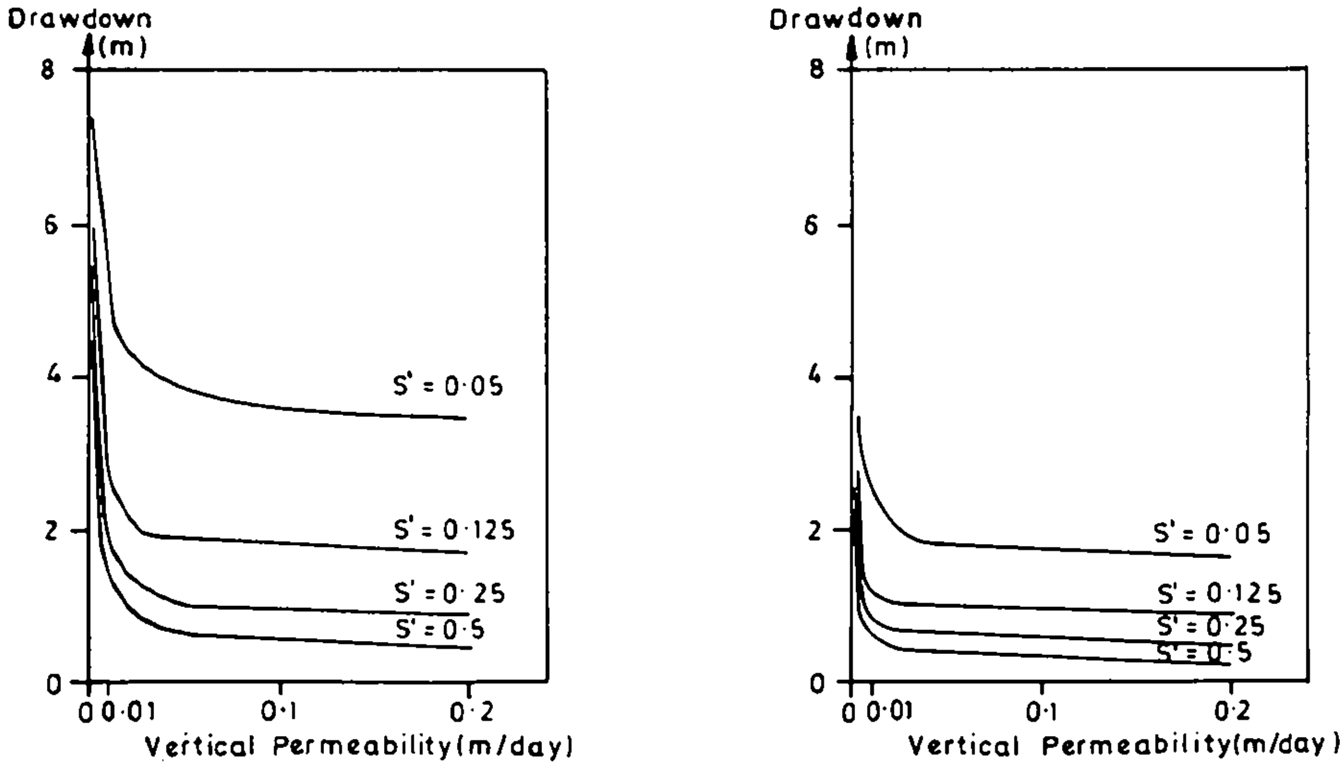
EFFECTIVE RADIUS OF A NODE

FIGURE 6



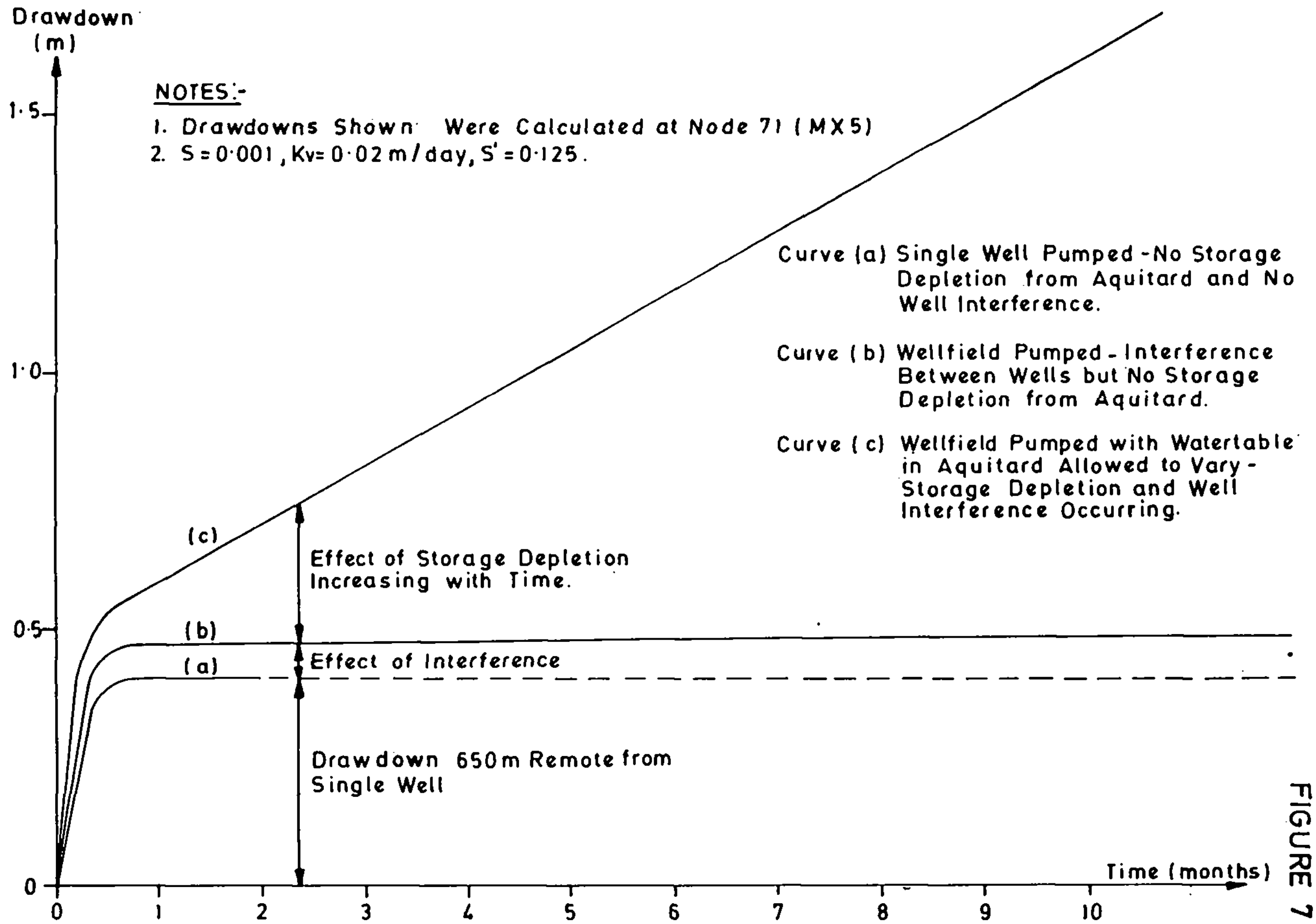
NOTES:-

1. All Drawdowns Apply After 1 Year.
2. S' = Specific Yield
   Kv= Vertical Permeability



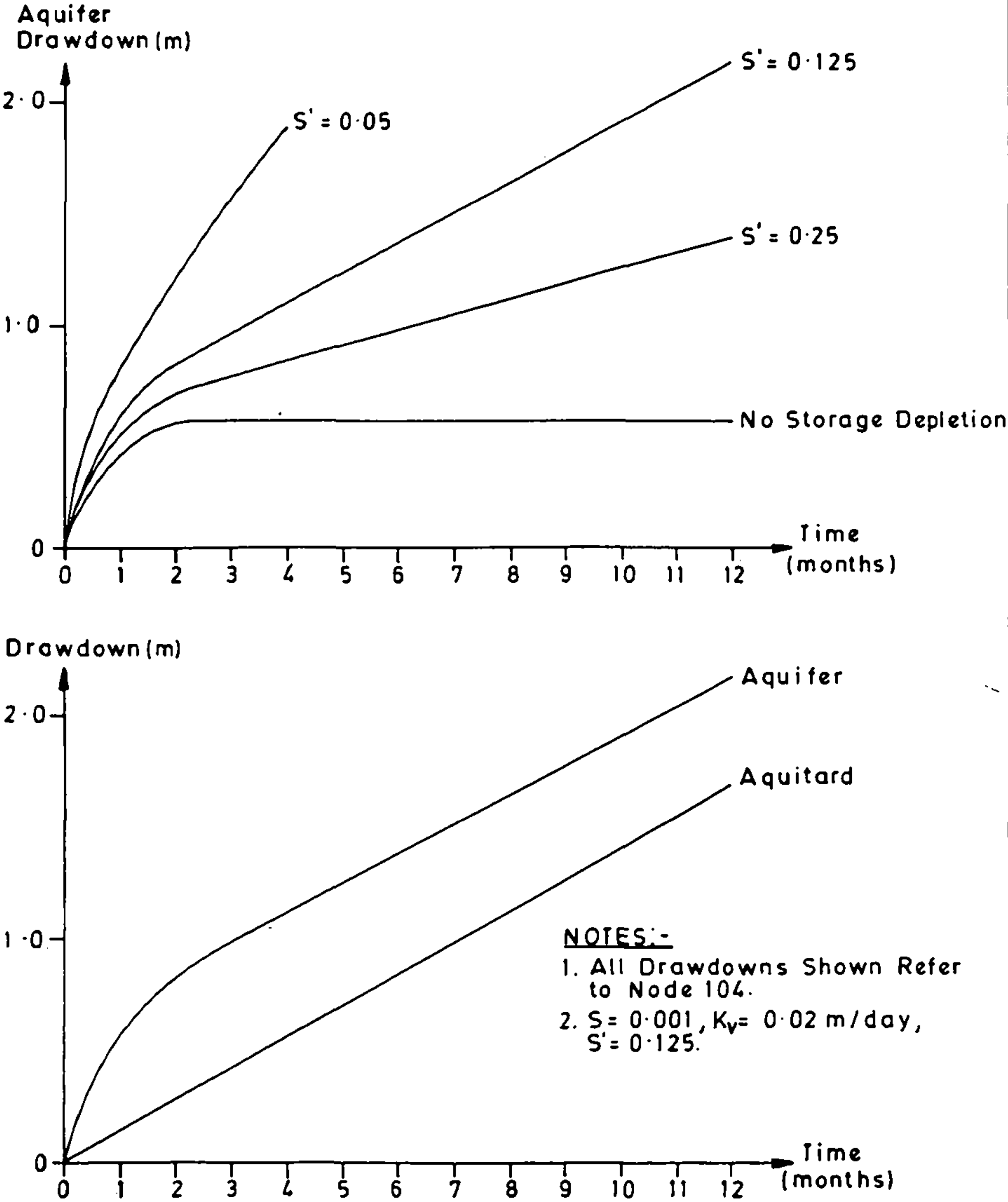
THE EFFECT OF SPECIFIC YIELD AND VERTICAL PERMEABILITY OF THE AQUITARD ON SHORT TERM DRAWDOWNS

FIGURE 7



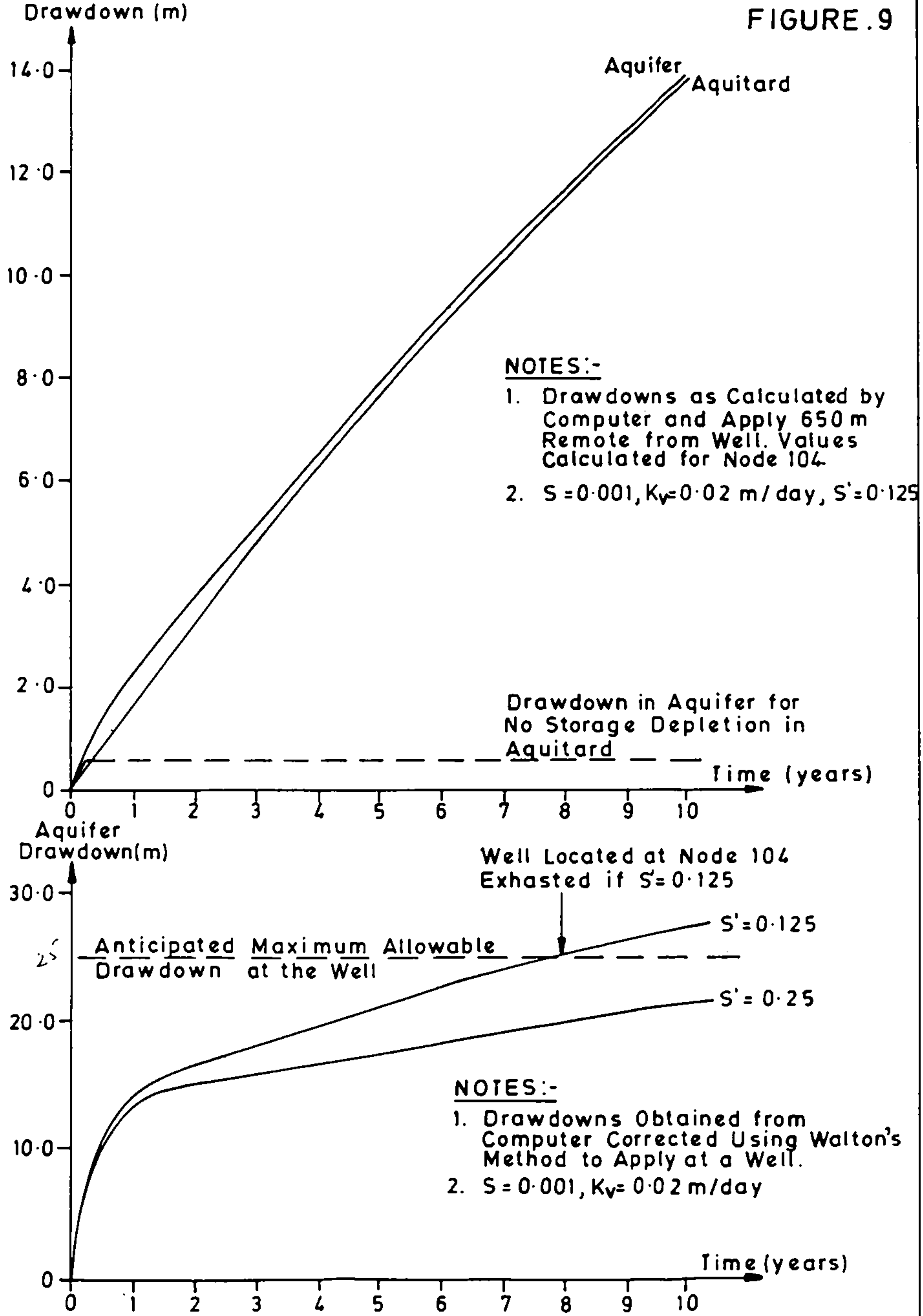
CONSTITUENTS OF NODAL DRAWDOWN

FIGURE.8



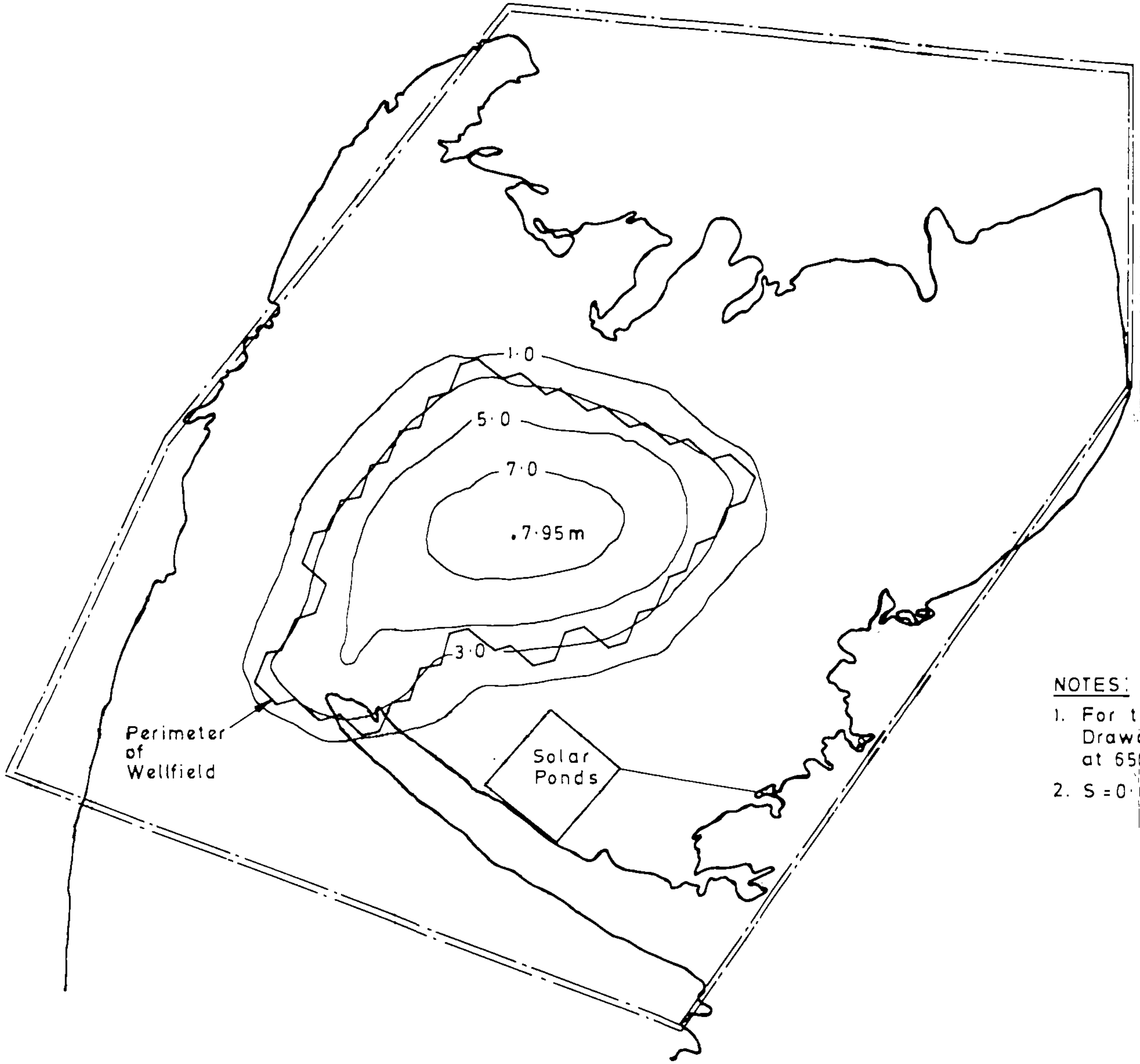
EFFECT OF AQUITARD SPECIFIC YIELD ON AQUIFER DRAWDOWNS AND THE RELATIONSHIP BETWEEN AQUIFER AND AQUITARD DRAWDOWNS

FIGURE.9



LONG TERM IMPLICATIONS OF AQUITARD SPECIFIC YIELD

FIGURE 10 A

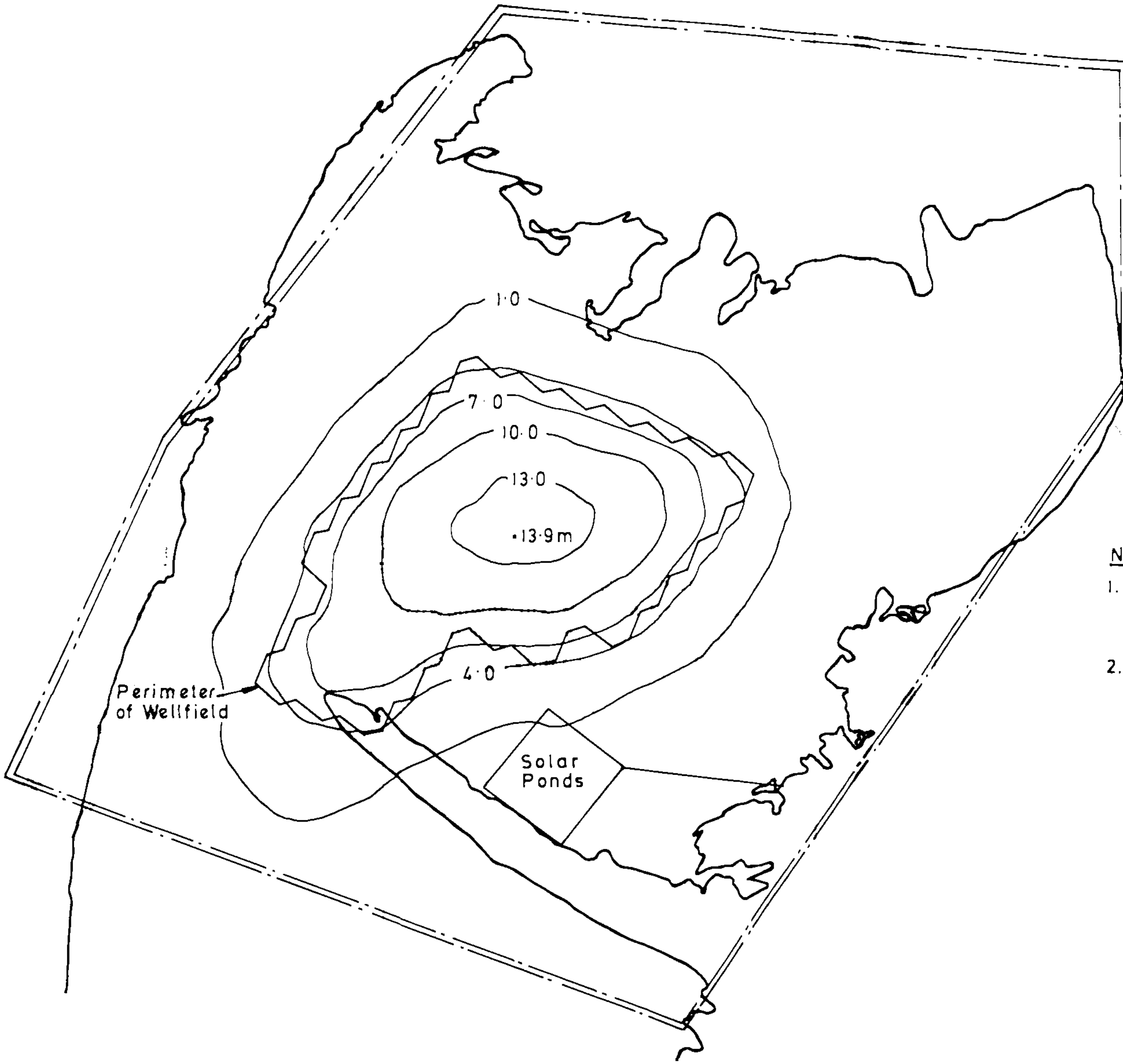


NOTES:

1. For the Wellfield Area, Indicated Drawdowns are Remote from the Well at 650m Radius.
2. S = 0·001, K_v = 0·02 m/day.

LONG TERM PERFORMANCE:
DRAWDOWNS AFTER 10 YRS
FOR S' = 0·25

FIGURE 10B



NOTES:

1. For the Wellfield Area, Indicated Drawdowns are Remote from the Well at 650m Radius.
2. S=0·001 K_v=0·02 m/day.

LONG TERM PERFORMANCE
DRAWDOWNS AFTER 10 YRS
FOR S'= 0·125.

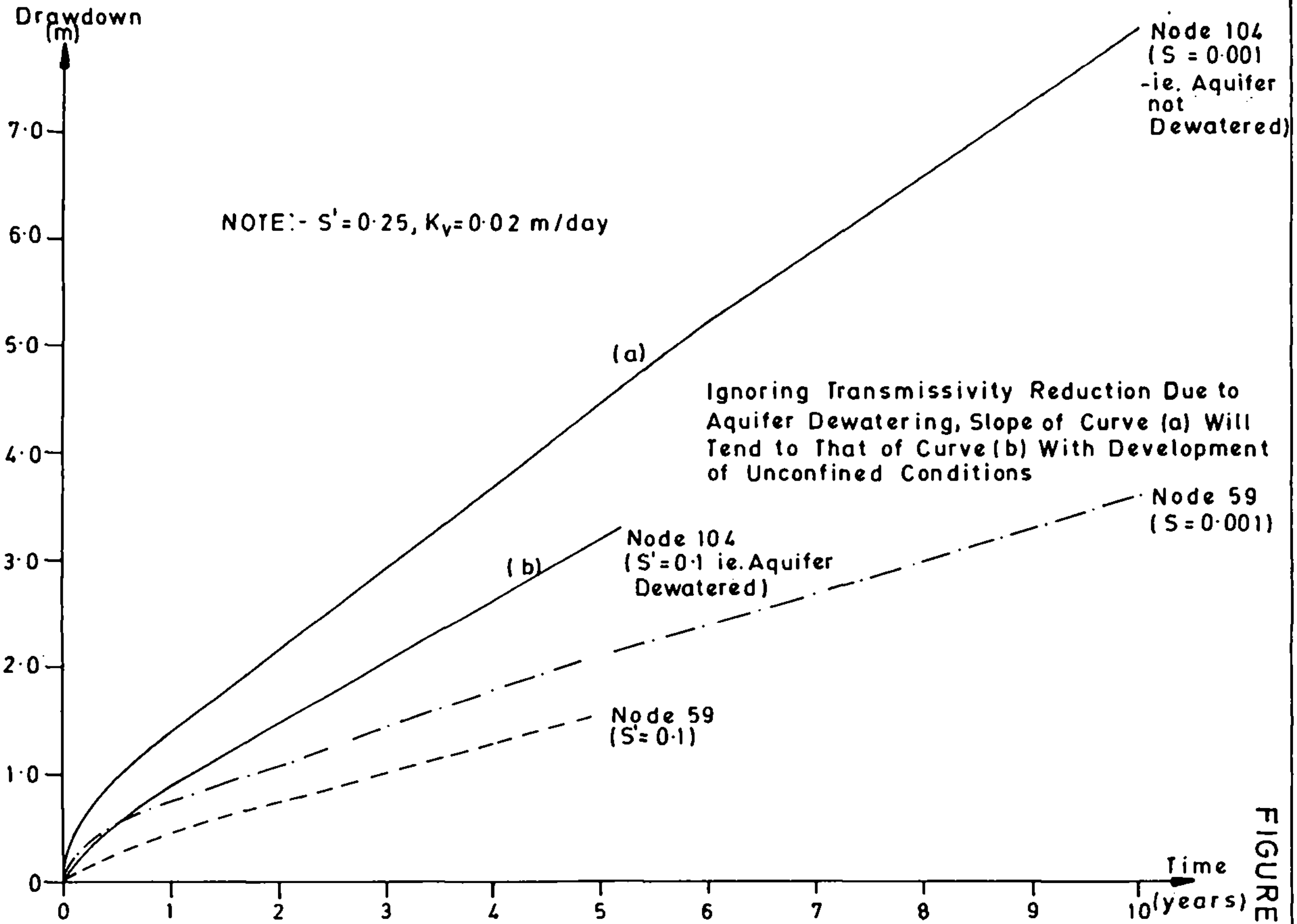
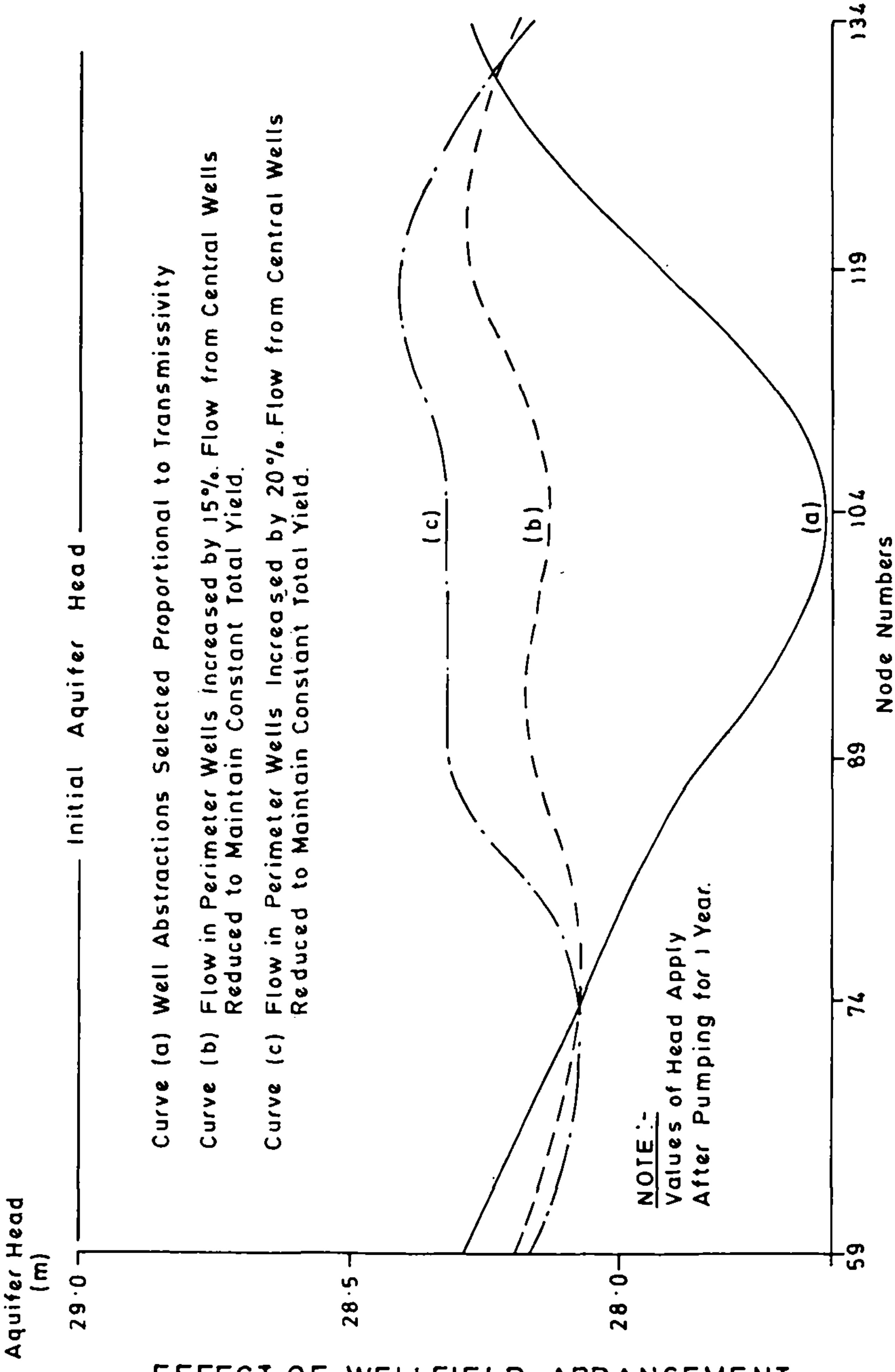


FIGURE.11

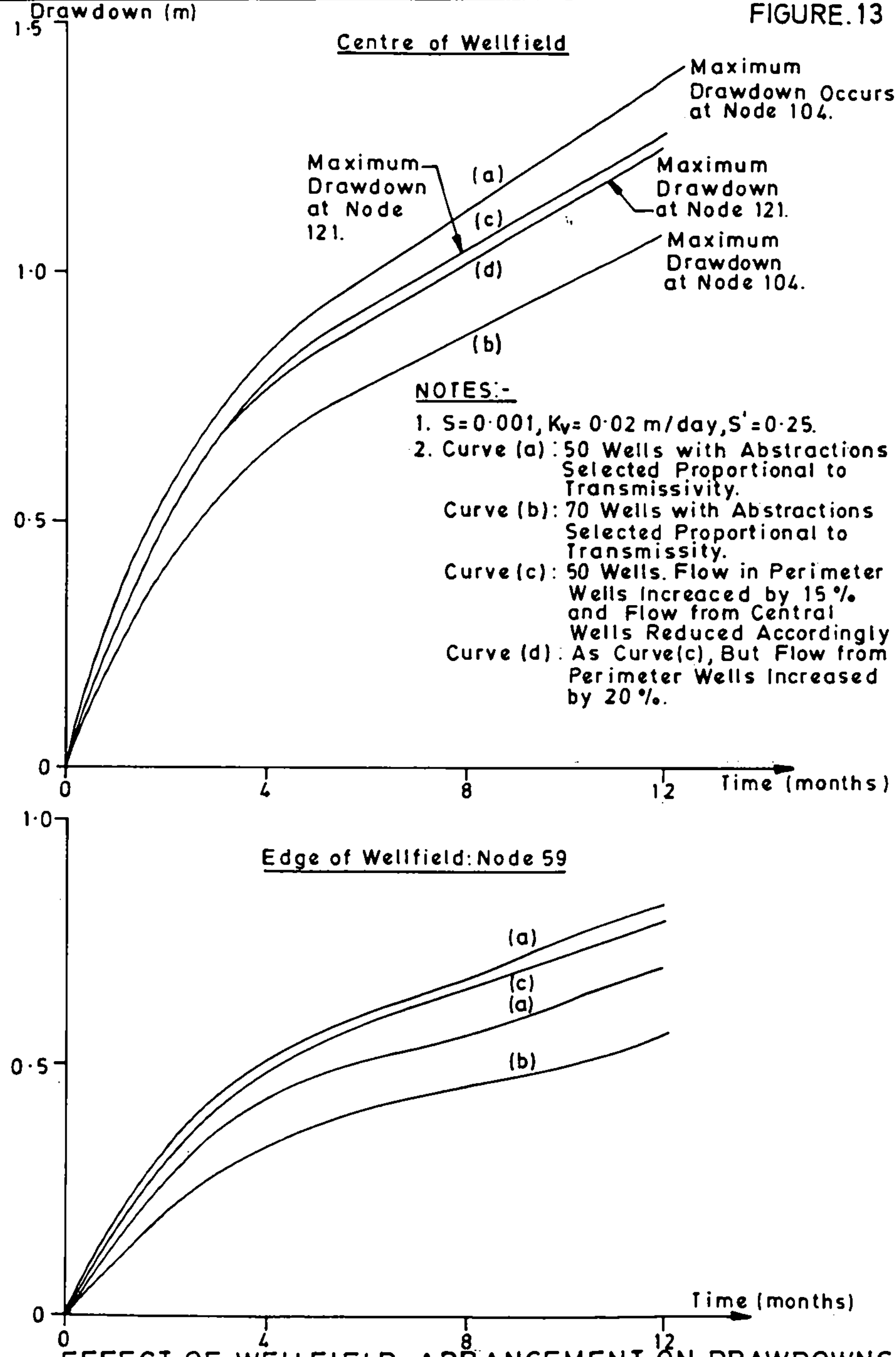
EFFECT OF DEWATERING ON AQUIFER DRAWDOWNS

FIGURE 12



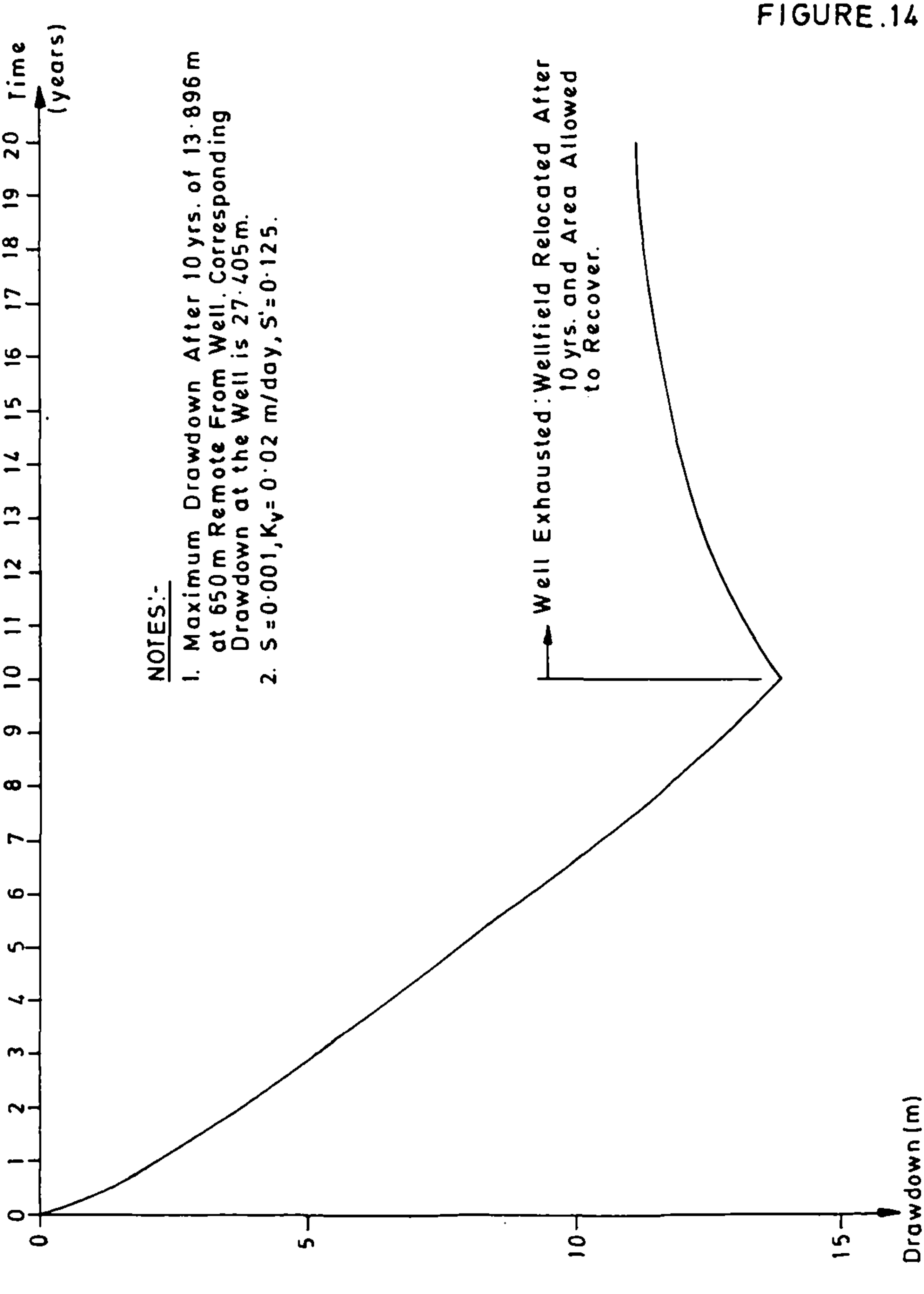
EFFECT OF WELLFIELD ARRANGEMENT
ON AQUIFER HEADS THROUGH THE WELLFIELD

FIGURE. 13



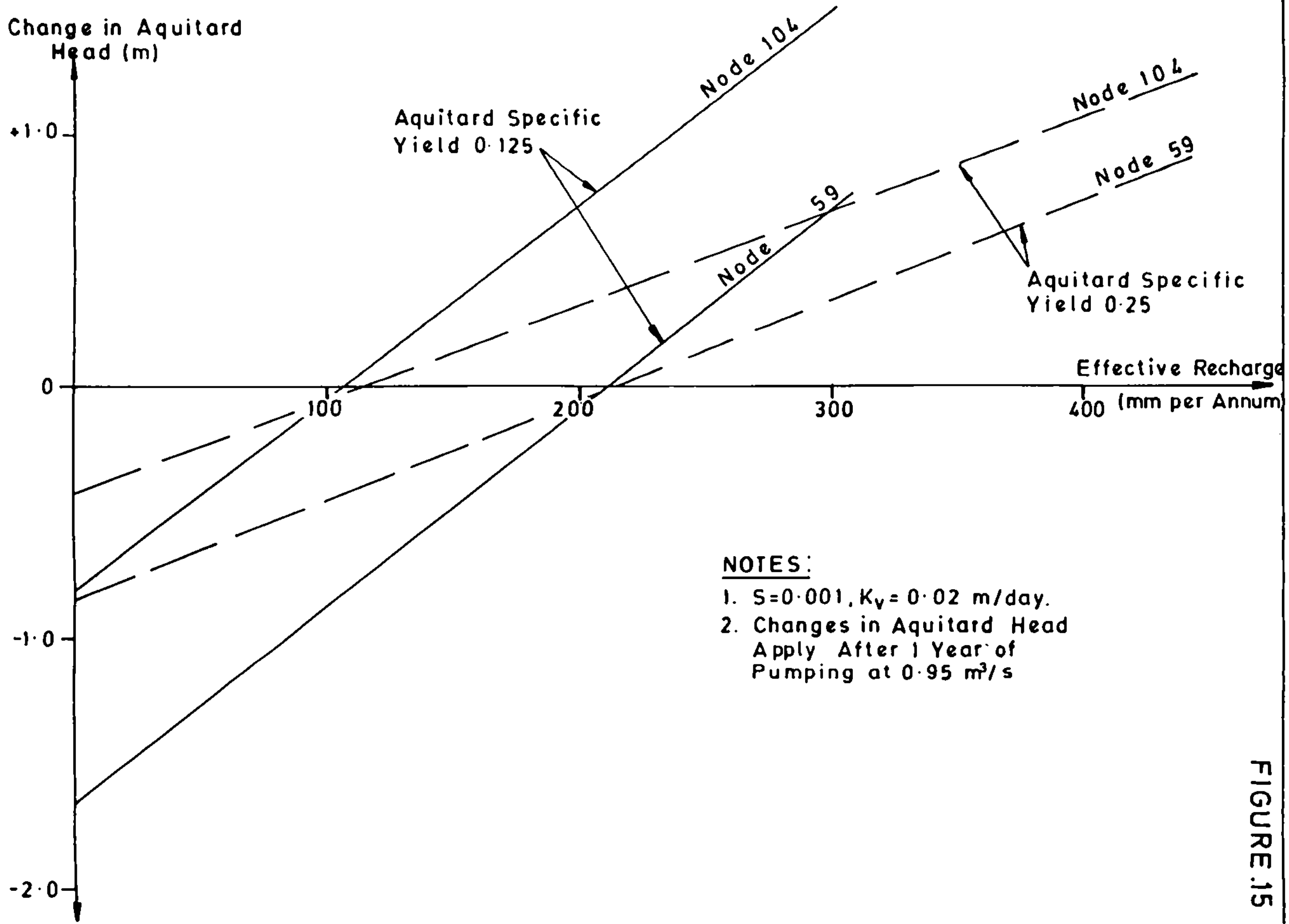
EFFECT OF WELLFIELD ARRANGEMENT ON DRAWDOWNS

FIGURE.14



TIME - DRAWDOWN CURVE FOR CENTRE OF WELLFIELD DURING PUMPING AND THE SUBSEQUENT RECOVERY AFTER RELOCATION OF THE WELLFIELD.

FIGURE.15



THE EFFECT OF RECHARGE ON AQUITARD DRAWDOWNS

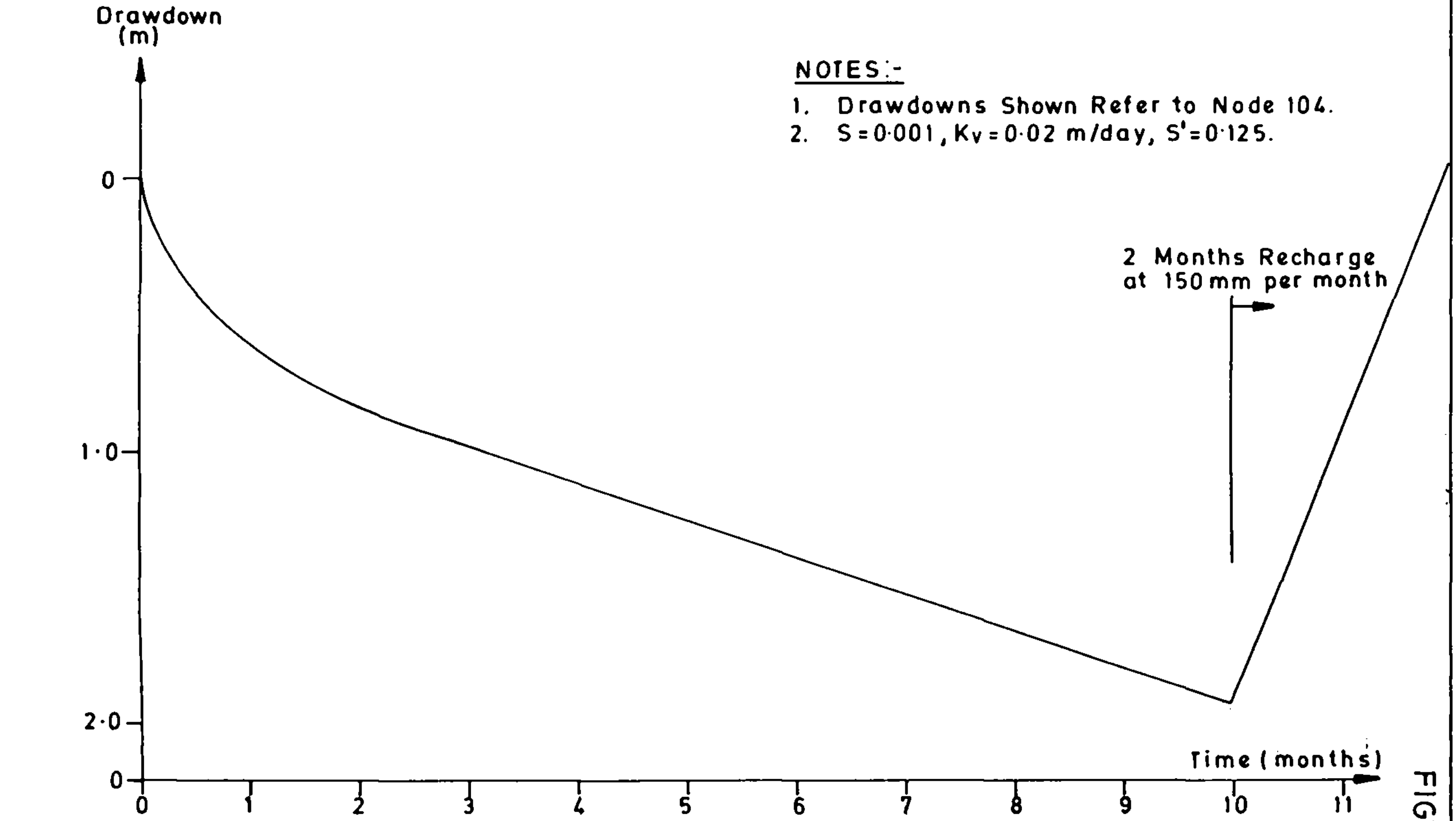


FIGURE.16

EFFECT OF VARIABLE
RECHARGE ON DRAWDOWNS

wlpu
CONSULTANTS
Watermeyer, Legge, Piësold & Uhlmann