SIMULATION OF AN INLAND DELTA AQUIFER SYSTEM TO EVOLVE PRE-DEVELOPMENT MANAGEMENT SCHEMES: A CASE STUDY IN OKAVANGO DELTA, BOTSWANA

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ABSTRACT

Development of groundwater resources to meet the increase demand for drinking, industries, irrigation and other purposes is ever growing in developed and developing countries. The over development of groundwater resources leads to the decline of water level causing socio-economic and environmental degradation. It is, thus, imperative to manage the groundwater resources in an optimal manner. Management schemes can be evolved, only if the groundwater potential is assessed in more realistic manner. Mathematical modelling in conjunction with detailed field investigations have been proved to be a potential tool for this purpose. Evolving pre-development management schemes is still works out to be better choice. One such study was carried out in Kunyere River valley, Okavango Delta, Botswana. Kunyere River valley has three tributaries viz. Marophe, Xudum and Matsibe Rivers. The valley falls in the southeastern fringe of Kalahari Desert (Botswana) which tends along the Kunyere fault in a northeast to southwest direction. The materials in the valley system are saturated below a depth of 7 to 9 m below ground level (bgl), where a fresh potable groundwater reserve is present to a maximum depth of 50 to 70 m (bgl) and below this depth, groundwater is brackish one. The groundwater resource in the valley has been quantified through exploratory drilling, test pumping, and hydro-chemical analysis of groundwater samples by the Department of Water Affairs, Govt. of Botswana.

A model with six layers flow regime was conceptualised by making use of available data. Fourth layer of the model is the main fresh water bearing aquifer and the bottom layer is brackish one. Long duration pumping test carried out in this area indicated the leaky nature of the aquifer system. Mathematical model of the basin was constructed and calibrated for steady state condition by using Visual Modflow computer software. Two prognostic runs were made and an optimal one was identified which will ensure minimum upward leakage from the bottom saline unit to the pumping aquifer. This simulation study indicates that substantial development of groundwater potential is possible in this area.

1.0 INTRODUCTION

The Kunyere River valley is located in Okavango Delta (Fig. 1), Botswana (Southern Africa). The Okavango River which originates in Angolan highlands reaches in north western Botswana and terminates as a huge inland delta, namely the Okavango Delta. The Kunyere River valley runs along the Kunyere Fault and drains the basin to Lake Ngami (Fig. 2). Maun a small Town, which is located on the bank of river Thamalaknae is emerging as a famous wild life tourist centre in Botswana and the demand for more wate is ever increasing. The demand during the year 1997 was about 3540m^3/day and it is likely to increase to about 4200m^3/day during the year 2000. The present demand is met from the well fields located in the valleys of Shashe and Thamalakane and the future demand has to be met from new resources. Therefore, Government of Botswana formulated a Project in the year 1996 to explore and assess the new groundwater structures through integrated geophysical and geohydrological studies in the neighbourhood of Maun. The Kunyere River valley (Fig. 2) covering an area about 120 km^2 is one such system wherein geohydrological, geophysical and chemical quality studies was combined to find suitable structures for exploiting groundwater. The data collected under this project was used to conceptualise the groundwater flow regime and a preliminary mathematical model was developed to study the aquifer response and thereby to evolve pre- developmental management schemes. The model was constructed and calibrated for steady state condition. The model calibration has clearly indicated that upper and middle aquifers are semi-confined in nature. The calibrated model was then used to study the aquifer response under two possible scenarios for evolving optimal well field locations in the upper semi-confined aquifer.

2.0 HYDROGEOLOGICAL SETTING

The aquifer system belongs to Kalahari beds. Three exploration boreholes and one water-level observation borehole have been drilled within the Kunyere valley. The vertical subsurface geological section along the valley is shown in Fig. 3. The lithology encountered during the drilling of these boreholes indicates a thin surficial cover of silts ranging in thickness from less than one meter in the south west (BH8275) to about seven metres in the northeast at the location of BH8255/BH8257. These silts are underlain by clayey fine sands and silty fine sands with a thickness ranging from 15 to 20 m. The unit is in turn underlain by medium sand and fine to medium sand with a thickness between 11 to 19 meters. The medium sand and fine to medium sand is underlain by sandy to silty clay and silty fine sand with a thickness varying between 8 to 15 m. This unit is underlain by fine to medium sand interbedded with clay lenses (BH8275) which has a thickness varying from 7 to 21 meters. The fine to medium sand increases in thickness from the northeast to southwest down the Kunyere Valley and is underlain by fine silty sand. There are two main aquifer systems in the river valley (Fig. 3). The top zone (surface soil) is the low permeable zone with average thickness of 10 m. The top two aquifers are fresh water bearing units and the bottom one is saline. An outline of the hydrogeological conditions in each of these units is given below.

Upper Semi-confined Aquifer (Layer 2)

The upper semi-confined aquifer consists of fine to medium grained sand. The upper aquifer has a more or less uniform thickness throughout the reach of the valley between BH8255 and

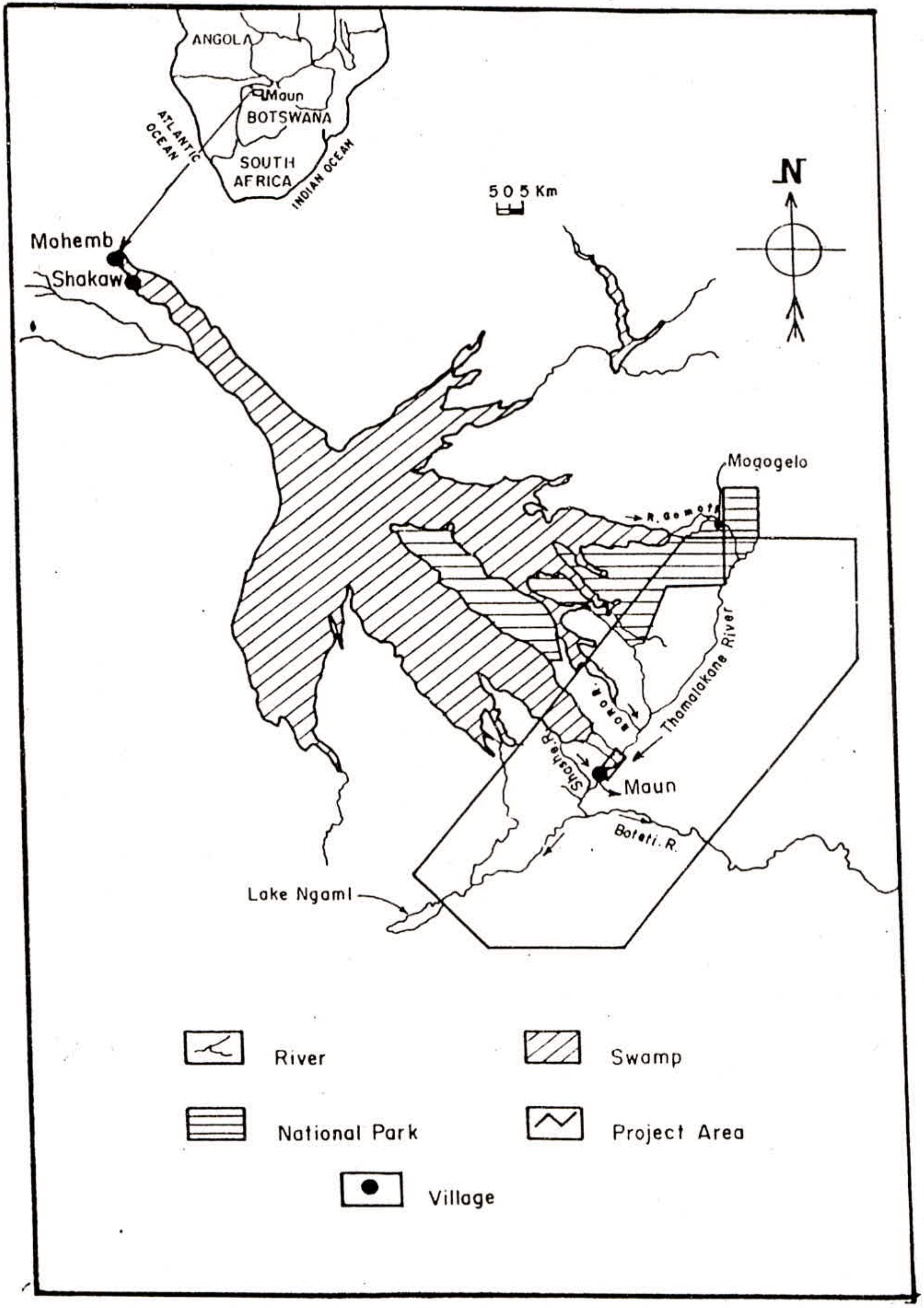


Figure 1: Location Map of Okavango Delta

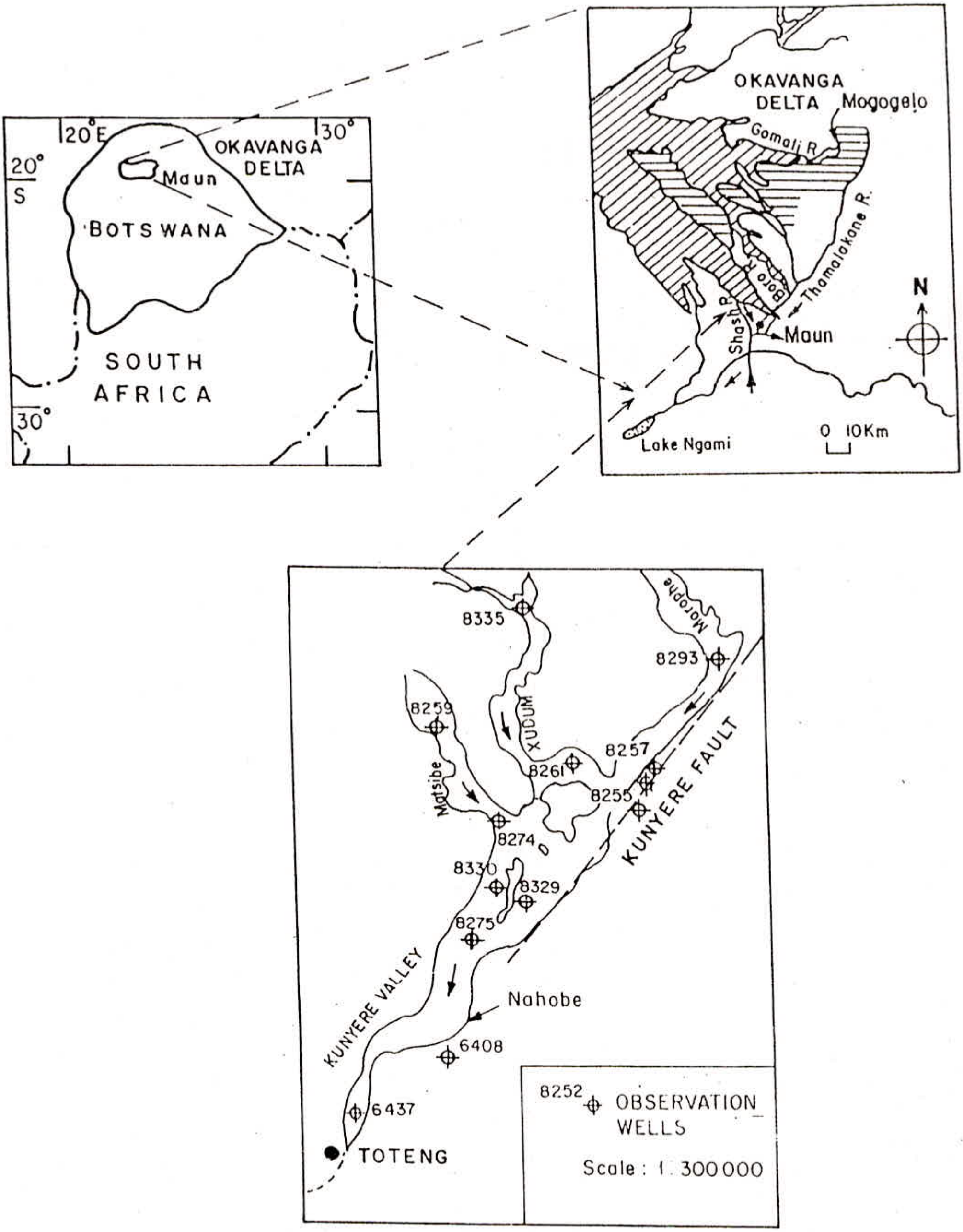


Figure 2: Location Map of Kunyere River Valley

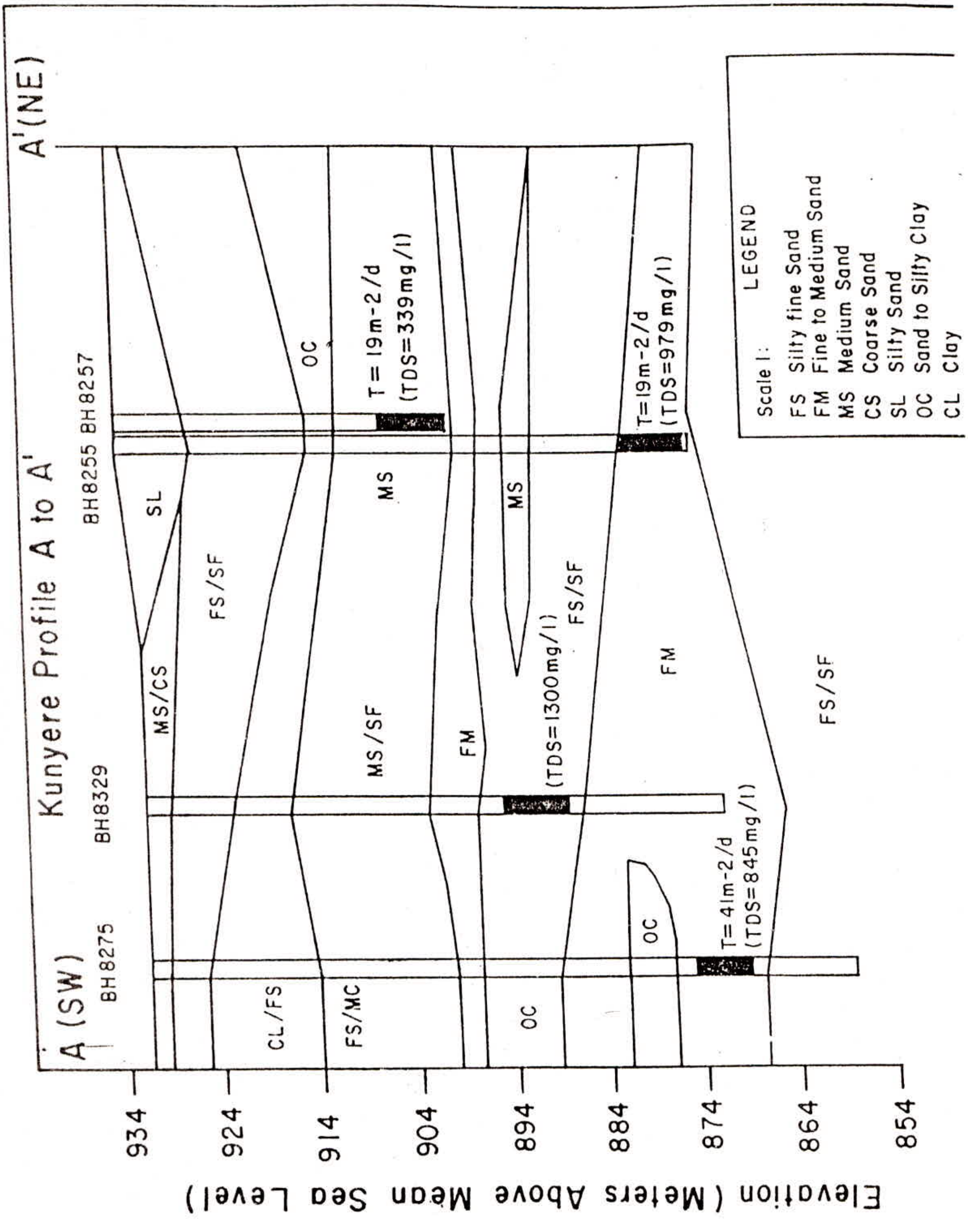


Figure 3: Vertical Geological Section along Kunyere River Valley

BH8275. This upper aquifer unit occurs at approximately 20 m below ground surface (approximately 910 m (amsl)) and the bottom occurs at around 36 m below ground surface (approximately 895 m (amsl)). The thickness of this aquifer is about 16 m. Recharge to the semi-confined aquifer has been predominantly from river water infiltration as downward leakage. Major rainfall events also recharges the top aquifer to a limited extent and it is derived from model calibration as 1.8 mm per annum. This is well with in the range of value recommended by the recharge committee of Botswana. The mean annual rainfall for 1986-1996 from the Maun airport weather station is about 380 mm. Presently the main discharge from this aquifer is that the evapotranspiration.

Lower Semi-confined Aquifer (Layer 4)

The lower aquifer occurs between 45 and 68 m below ground surface (approximately 890 m (amsl) to 880 m (amsl)) and appears to thicken in a southwesterly direction. In general this aquifer has lenses of finer grained material (silts and silty clays) in the south near the Matsibe junction. The average thickness of this aquifer is about 24 m. The lateral extent or boundaries of the fresh water aquifer in the Kunyere Valley have been delineated on the basis of an air-borne Electro-magnetic survey flown over the area as well as transient Electro-magnetic (TEM) soundings. This survey indicates that the lateral extent of the fresh water within the Kunyere valley varies from 5.5 km in the southwest near the Kunyere/Matsibe junction to approximately 3 km in the northeast near the Kunyere/Marophe junction. This reach of the Kunyere valley covers a total length of approximately 30 km. The average area of the fresh water aquifer covered by this stretch of the Kunyere Valley is approximately 127 km^2. The depth of fresh water in the Kunyere Valley was delineated on the basis of TEM soundings conducted in the valley. A contoured depth to interpreted fresh water/saline water interface based on TEM soundings indicates that fresh water occurs to a maximum depth of 70 m and minimum depth of approximately 50 m.

The transmissivity (T) values were estimated through single well pumping tests in the upper and lower semi-confined aquifers. T value of 19 m^2/day was estimated in layer 2 and 41 m^2/day in layer 4. The storativity values were inferred and not estimated.

Bottom Aquifer (Brackish, Layer 6)

The aquifer, which occurs approximately between 70 and 75 m below the ground level, comprised of fine to medium sands and contains brackish to saline water. There is not much information available as regards hydraulic characteristics of this unit. The hydraulic conductivity value is assumed of 7 m/d and its storativity value as 2.9 x 10-4. The bottom aquifer is hydraulically connected with the overlying middle semi-confined aquifer.

3.0 MODEL DESIGN

Methodology

Groundwater models are the simplified representations of the subsurface aquifer systems. The calibrated and validated models may be used to predict aquifer response to pumping stresses.

Groundwater flow in three dimensions in a porous media of constant density can be expressed by the following partial differential equation (Rushton and Redshaw, 1979):

$$\frac{\delta}{\delta x}\left(K_{xx}\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\left(K_{yy}\frac{\delta h}{\delta y}\right)+\frac{\delta}{\delta z}\left(K_{zz}\frac{\delta h}{\delta z}\right)=S_{s}\frac{\delta h}{\delta t}\pm W \ldots\ldots\ldots\ldots(1)$$

Where,

Kxx, Kyy, Kzz = the hydraulic conductivity along x, y, and z co-ordinates which are assumed to be parallel to the major axes of hydraulic conductivity (LT^{-1})
h = potentiometric head (L)
W = volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1})
Ss = the specific storage of the porous material (L^{-1}), and
t = time (T)

Equation (1) describes groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the x-y Cartesian co-ordinate axes. The groundwater flow equation together with specification of flow and/or initial head conditions at the boundaries constitute a mathematical representation of the aquifer system. Numerical methods are used in general to solve the groundwater flow equation.

The computer software program Modflow developed by the United States Geological Survey (USGS, 1988) was used for the present study. In this program, groundwater flow equation is solved by using the Block Centred Finite Difference Approach. A pre-and post-model processor viz. Visual-Modflow developed by Nilson Guigner and Thomas Franz of Waterloo Hydrologic Software Inc., Waterloo, Ontario, Canada (1996) was used for graphical data input, and for analysis and presentation of the output data.

Conceptual Model

The Kunyere River valley aquifer system was conceptualised as a six-layer system with three aquifers separated by two confining layers (confining/semi-confining) as follows:

Top soil with low permeable zone
Upper semi-confined aquifer
Upper confining unit
Lower semi-confined aquifer
Lower semi-confining unit,
Bottom brackish/saline aquifer

The confluence points of three tributaries viz. Matsibe, Xudum and Morphe were taken as the inflow boundaries. The lateral boundary represents the fresh water zone in the upper semi-confined and lower semi-confined aquifers. This delineation is approximate one and based on available data. The lateral boundaries were delineated based on the lithology of recently drilled lateral boundary definition boreholes, the airborne EM survey and TEM sounding data. The area considered for this model study is 130 km^2. The study area was divided in to square grids and the map is shown in Fig. 4.

Initial Condition and Boundary Conditions of the Model

The confluence points of three tributaries were taken as the inflow boundaries in the upper and lower semi-confined aquifers. The quantum of inflow flux was calculated by using transmissivity values and the hydraulic gradient. It was estimated that about 1100 m^3/d is received in the upper aquifer and lower aquifer. Layers 3 and 5 (silty sands & clays) were taken as aquitards. Since bottom aquifer (saline unit) is laterally extended, the northeast and southwest boundaries were assumed as inflow and outflow boundaries respectively. The eastern and western lateral boundaries were treated as no flow boundaries as the flow is predominantly from north -east to south -west. The subsurface out flow towards the southwestern direction was simulated as fixed heads near Toteng. The water levels monitored in the presently drilled bore wells are very useful in fixing the boundary heads in all the three layers.

The aquifer parameters hydraulic conductivity (K (m/day)), Specific yield (Sy) and Specific storage (Ss (L-1)) were assigned in zone wise for each layer. Storativity value of 0.00029 was uniformly assumed for the upper and lower semi-confined aquifers. The vertical permeability for each layer is assigned as one tenth of horizontal conductivity. The upper semi-confining unit and lower confining unit were assumed to have storativity value of 0.001. The hydraulic conductivity value of 0.052 m/day was set for both the upper confining and lower confining units.

Model Calibration

Steady State Calibration

The aquifer condition of March 1997 was assumed to be the initial condition for the steady state model calibration. The model could not be initialised to an early date due to the non-availability of water level data before January 1997. Minimising the difference between the computed and the field water level for each observation point started the steady state model calibration. Number of trial runs were made by varying the input / output stresses and the hydraulic conductivity values of the top and middle aquifers in order to keep the root mean square (RMS) error below 0.2 m and mean error below 0.1 m. The computed versus observed head for selected observation points are shown in Fig. 5. This figure indicates that there is a fairly good agreement between the calculated and observed water levels. The computed water level contours in layer 4 and 6 are shown in Figures 6 and 7 respectively. The calibrated zonal hydraulic conductivity (K) values for the upper, lower and bottom aquifers and upper aquitard are shown Table 1. Due to non- availability of historical water level data, transient state calibration could not be initiated in the present study. The calibrated steady state model was then used to progonose the aquifer response.

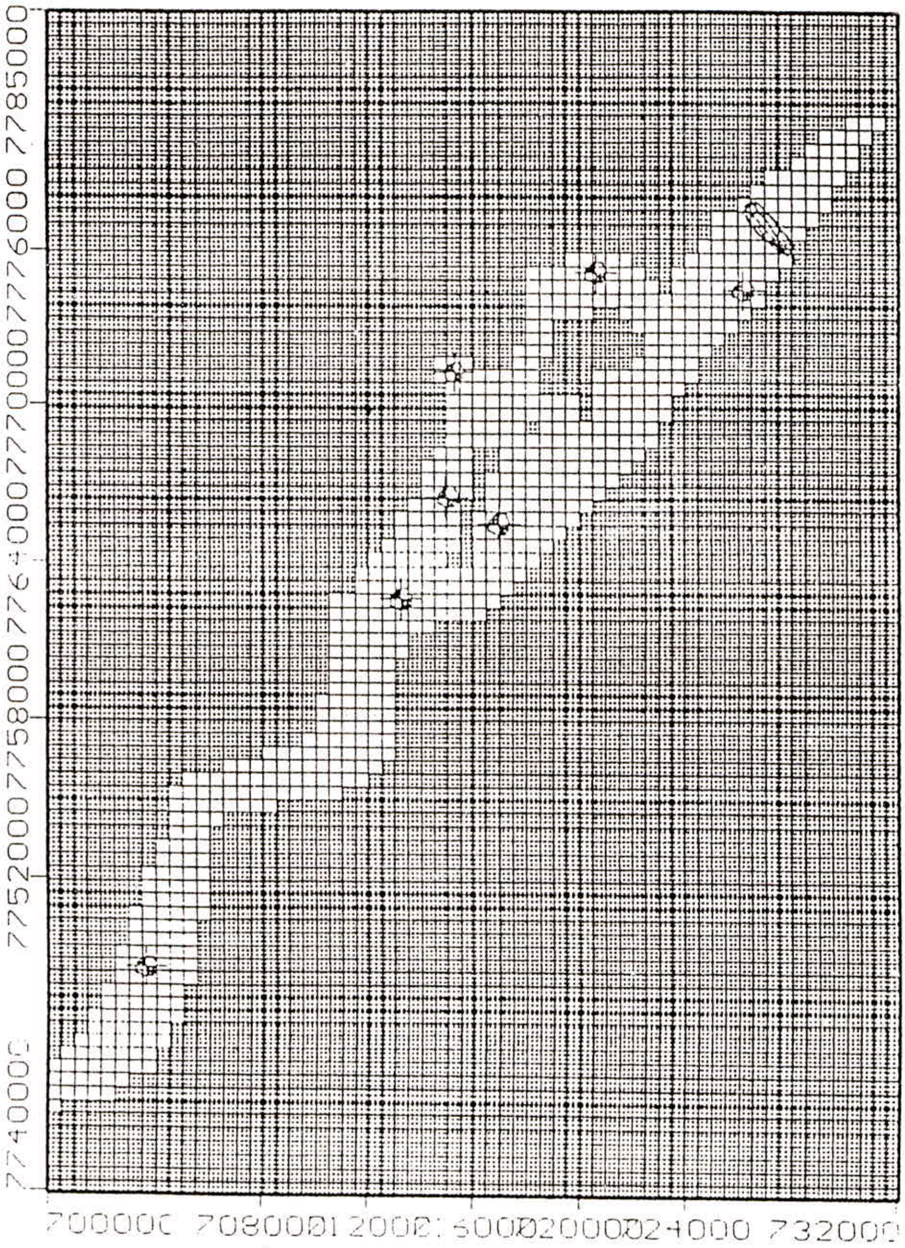
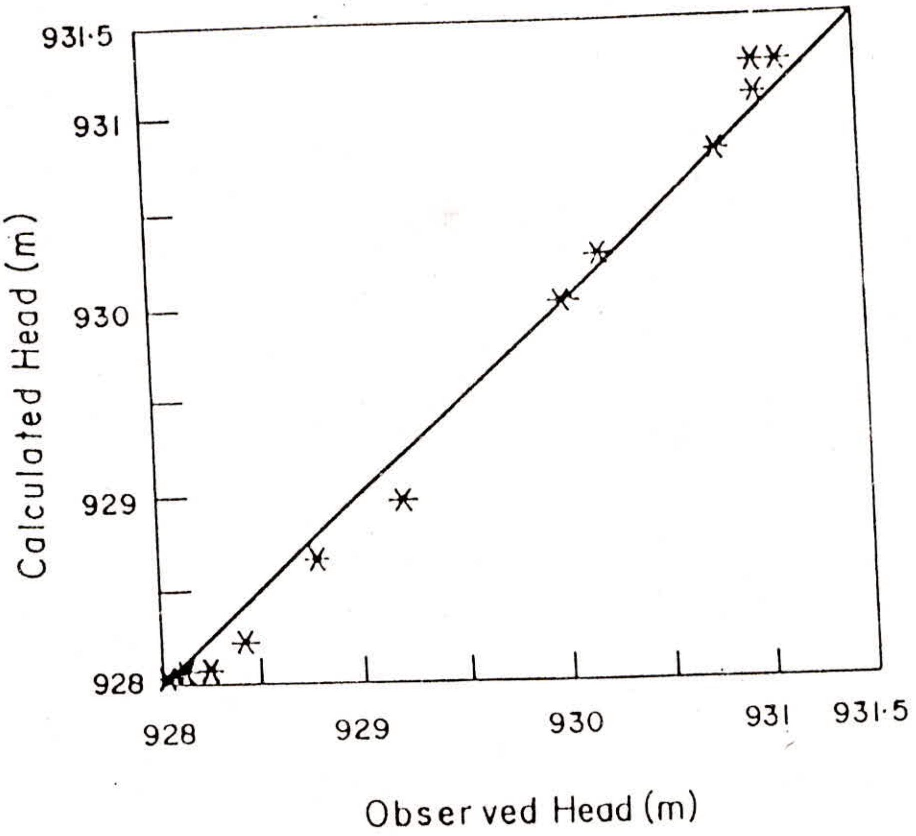


Figure 4: Grid Map of the Study area



Mean error :— 0·02598

Mean error :— 0·11495

RMS error :— 0·13980

Figure 5: Comparison of Computed Vs Observed Heads (Steady State Model)

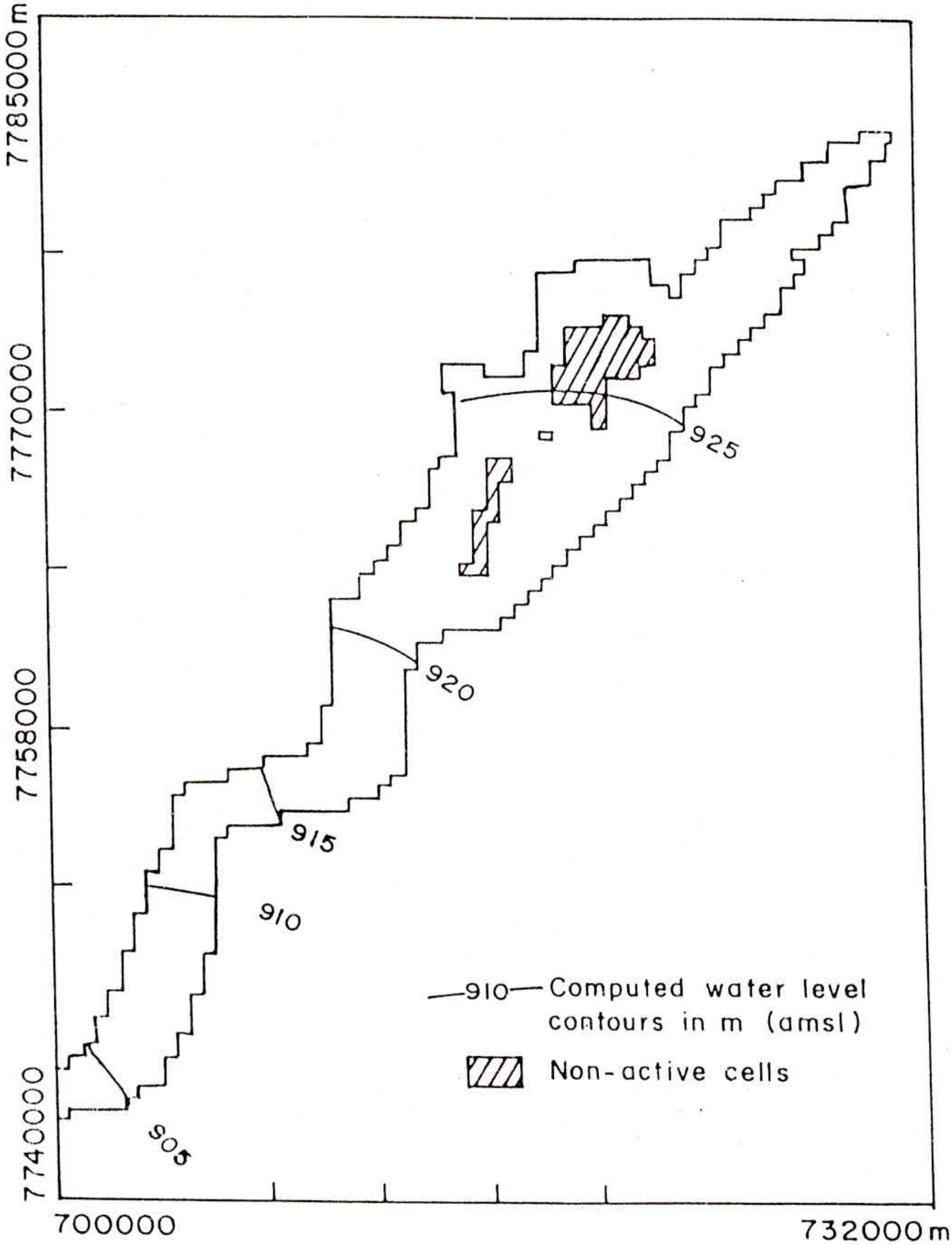


Figure 6: Computed Water Level Contours in layer 4 (Lower semi-confined aquifer) (Steady State, January 1997)

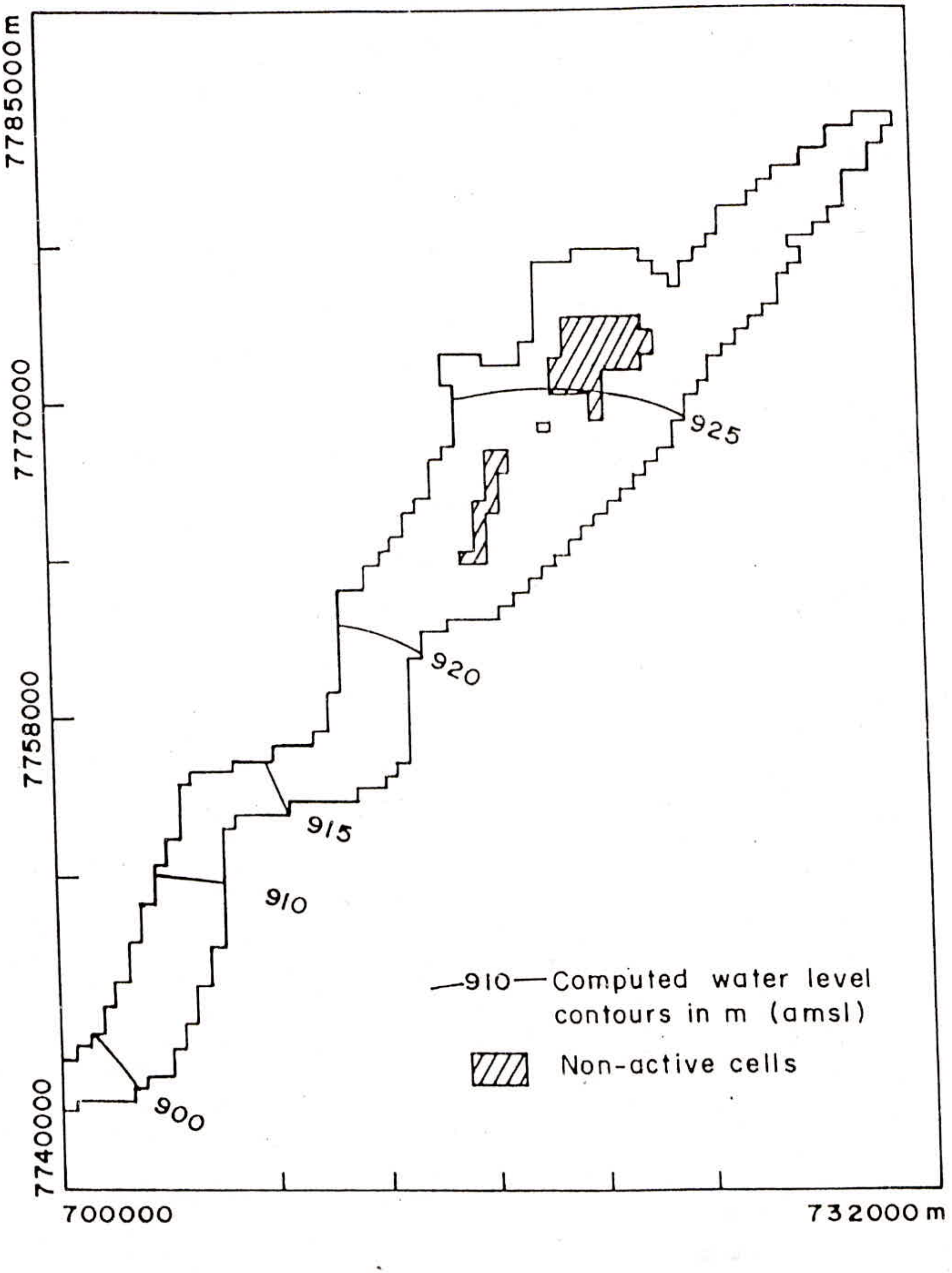


Figure 7: Computed Water Level Contours in layer 6 (lower semi-confined aquifer) (Steady state, January 1997)

Table 1: Model parameters - Steady State Condition

LAYER	UNIT DESCRIPTION	AVERAGE	FIELD DERIVED HYDRAULIC CONDUCTIVITY (K in m/d)	MODEL CALIBRATED HORIZONTAL HYDRAULIC CONDUCTIVITY (K_x in m/d)	STORATIVITY
1	Semi-Confining Unit	20	NA	0.052	0.001
2	Semi-Confined Fresh Water Aquifer	15	$K_x = 3.2$	2.1 to 3.2	0.00029
3	Semi-Confining Unit	7	NA	0.052	0.001
4	Semi-Confined Fresh Water Aquifer	24	K_x = 3.2 to 7	3.5 to 9.5	0.00029
5	Semi-Confining Unit	2	$K_x = 0.0055$	0.052	0.001
6	Semi-Confined Brackish Aquifer	50	NA	7	0.00029

K_x = *Horizontal Hydraulic Conductivity.*
K_x = *Vertical Hydraulic Conductivity, Assumed to be 0.1 of* K_x.

4.0 PREDICTION SCENARIO RUNS

Two preliminary model prediction scenarios were run utilising simulated production boreholes completed in the lower semi-confined aquifer.

Prediction Scenario -1

In Scenario 1, 10 simulated production boreholes (Fig. 8) were placed over an area of 93 km^2 (3-km spacing) in the lower semi-confined aquifer, each pumping at a rate of 480 m3/d over a 10-year period. Table 2 summarises the computed inflows and outflows to the lower semi-confined aquifer. The bulk of inflow to the lower semi-confined aquifer is through downward vertical leakage from the upper semi-confining unit and the upper semi-confined aquifer (Column 6 on Table 1). Contribution to pumping from aquifer storage in the lower semi-confined aquifer is insignificant (Column 8). There is a net vertical downward leakage to the lower brackish/saline aquifer from the lower fresh water semi-confined aquifer up until Year 8 in the simulation (Column 9) After Year 8, there is an 8 to 9 percent contribution to pumping in the lower semi-confined aquifer due to upconing of water from the brackish/saline aquifer (Column 12). Calculated water quality impact due to this upconing in Year 10 of the simulation is an increase in TDS from a baseline of 800 mg/l to 1,147 mg/l.

Figures 8, 9 and 10 show predicted water-level contours in the top surface layer (Layer 1), lower semi-confined aquifer (Layer 4) and bottom brackish (Layer 6) aquifer for January 1998 (First year); Figures 11, 12 and 13 show the same for January 2007 (Tenth year). These figures indicate that the dewatering of the top surface layer progresses northeastward over the simulation period. The water-level contours indicate an approximate 5 m decline over the 10-year simulation.

Figures 14 and 15 are computed water-level hydrographs for boreholes 8255, 8257 and 8274, 8275 respectively. Except one borehole 8255, all other boreholes are completed in the lower semi-confined aquifer (Layer 4) and the first one in the upper semi-confined aquifer (Layer 2). Water levels in the lower semi-confined aquifer appear to drawdown by 7 m at BH8255 (northeastern portion of the valley) and at BH8275 (southwestern portion of valley) after 10 years in this abstraction scenario. Also, there appear to be 7 m of drawdown within the upper semi-confined aquifer (Layer 2) at BH8257. The top layer (Layer 1) becomes dewatered from the Nhabe/Kunyere confluence to the lower end of the wellfield. The correlation of drawdown in the upper and lower aquifer systems implies significant leakage between these two units.

Prediction Scenario -2

In Prediction Scenario 2, the number of production boreholes placed in the lower semi-confined aquifer within the 93 km^2 area was doubled to 20 boreholes (1.5 km spacing), each pumping at 480 m^3/d over the 10 year simulated period (Figure 16). The inflows and outflows from the semi-confined aquifer for this scenario are summarised on Table 3. As in Scenario 1, the bulk of the water supplied to pumping is via vertical downward leakage from the upper semi-confining layer and upper semi-confined aquifer (Column 6 on Table 3). The contribution from aquifer storage in the semi-confined aquifer is still insignificant (Column 8). Contribution from horizontal inflow to the lower semi-confined aquifer increases in this scenario due to lowering the hydraulic head as a result of the higher rates of pumping (Column 7). There is a net downward leakage from the lower semi-confined aquifer to the brackish/saline aquifer in Year 8 of the simulation period (Column 9). After Year 8, there is a 5 to 6 percent contribution to pumping in the lower semi-confined aquifer due to upcoming of water from the lower brackish/saline aquifer (Column 12). The calculated water quality impact due to this upcoming in Year 10 of the simulation is similar to that in Scenario 1.

Figures 16, 17, and 18 show predicted water-level contours in the top low permeable aquifer (Layer 1), lower semi-confined aquifer (Layer 4), and brackish aquifer (Layer 6) for January 1998 (Year 1). Figures 19, 20, and 21 show the same for January 2007 (Year 10). The entire length of top layer was de-watered after 10 years of pumping. Water-level declines in the lower semi-confined aquifer appear to be on the order of 10 to 15 m.

Figures 22 and 23 are computed water-level hydrographs for BH8255, 8257 and BH8274, 8275. Water levels in these boreholes declined by 12 to 13 m after 10 years in this abstraction scenario.

Table 2: Model Prediction Scenario 1: Pumpage of 4800 m3/d from Lower Semi-Confined Aquifer with no River Recharge

Year	Pumping Rate from Lower Semi-Confined Aquifer (m^3/d)	Horizontal Outflow (m^3/d)	Downward Leakage between lower semi-confined aquifer and brackish/saline aquifer (m^3/d)	Total Outflow from the lower Semi-Confined aquifer (m^3/d)	Inflow from Downward Leakage from Upper Semi-Confining Layers and Upper Semi-Confined Aquifer (m^3/d)	Horizontal inflow (m^3/d)	Contribution from Aquifer Storage in the Semi-Confined Aquifer (m^3/d)	Upward leakage Between lower Semi-Confined Aquifer and Brackish/ Saline Aquifer (m^3/d)	Total inflow to the Lower Semi-Confined Aquifer (m^3/d)	Percent Contribution to Pumping from Lower Semi-Confined Aquifer Storage	Percent Contribution to Pumping from Upcoming
1	4800	2288	3397	10,485	6179	1147	95	0	10,485	2	0
2	4800	2754	3578	11,132	6944	1310	108	0	11,132	2	0
4	4800	3169	1602	9571	6744	1535	94	0	9571	2	0
8	4800	4465	0	9265	6138	1852	68	394	9265	1	8
10	4800	4394	0	9194	5528	1974	50	431	9194	1	9

Table 3: model prediction scenario 2: Pumpage of 9600 m^3/d from Lower Semi-Confined Aquifer with no river recharge

Year	Pumping Rate from Lower Semi-Confined Aquifer (m^3/d)	Horizontal Outflow (m^3/d)	Downward Leakage between lower semi-confined aquifer and brackish/saline aquifer (m^3/d)	Total Outflow from the lower Semi-Confined aquifer (m^3/d)	Inflow from Downward Leakage from Upper Semi-Confining Layers and Upper Semi-Confined Aquifer (m^3/d)	Horizontal inflow (m^3/d)	Contribution from Aquifer Storage in the Semi-Confined Aquifer (m^3/d)	Upward leakage Between lower Semi-Confined Aquifer and Brackish/ Saline Aquifer (m^3/d)	Total inflow to the Lower Semi-Confined Aquifer (m^3/d)	Percent Contribution to Pumping from Lower Semi-Confined Aquifer Storage	Percent Contribution to Pumping from Upcoming
1	9600	2286	33125	15,011	9877	4948	186	0	15,011	1	0
2	9600	2735	3339	15,674	10,194	5295	185	0	15,674	1	0
4	9600	3153	1420	14,173	9342	4674	157	0	14,173	1	0
8	9600	4417	0	14,017	7925	5454	105	533	14,017	1	5.5
10	9600	4326	0	13,926	7060	6214	79	573	13,926	1	6

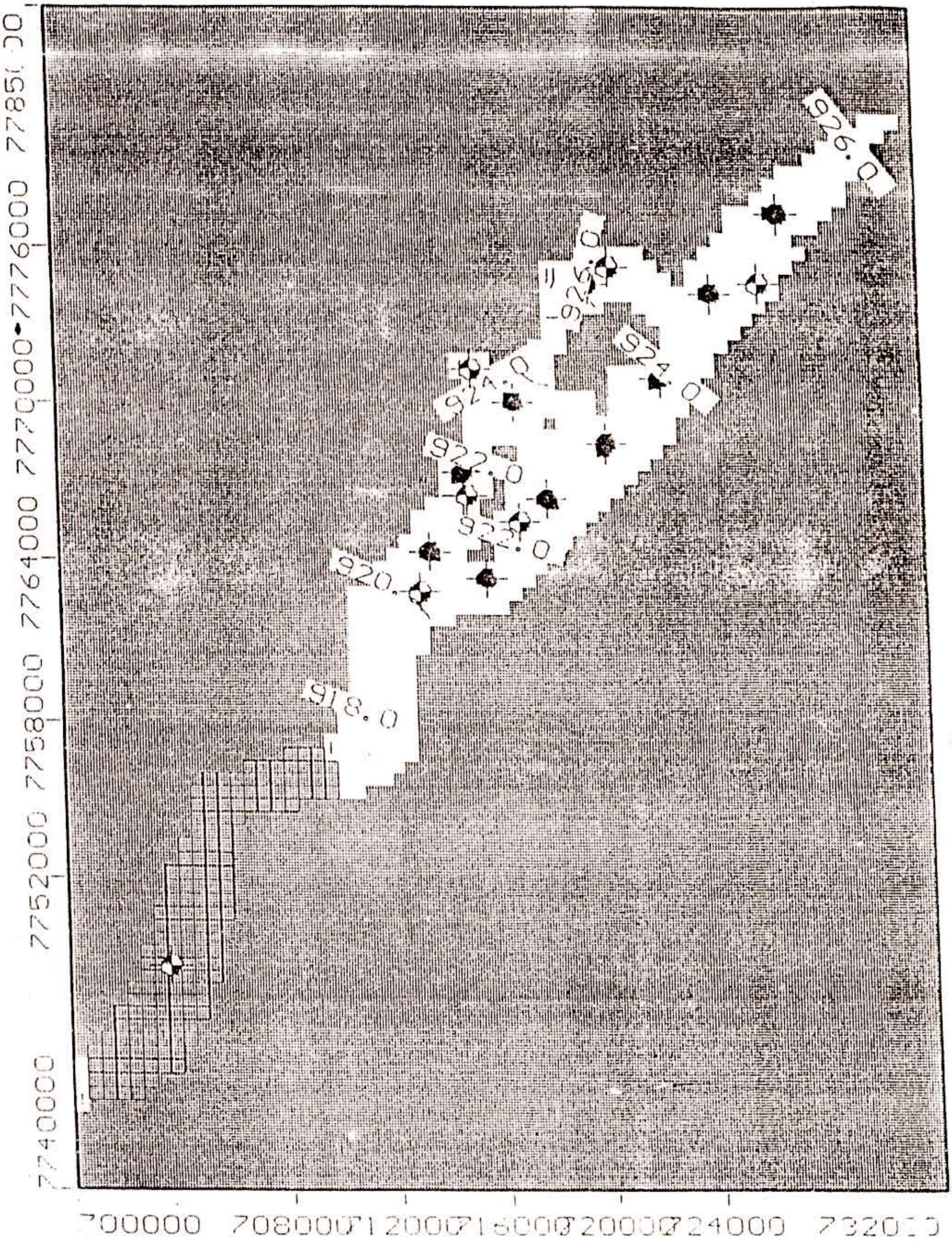


Figure 8: Predicted Water Level Contours in layer 1 (Top layer) for January 1998 (Prediction Scenario-1)

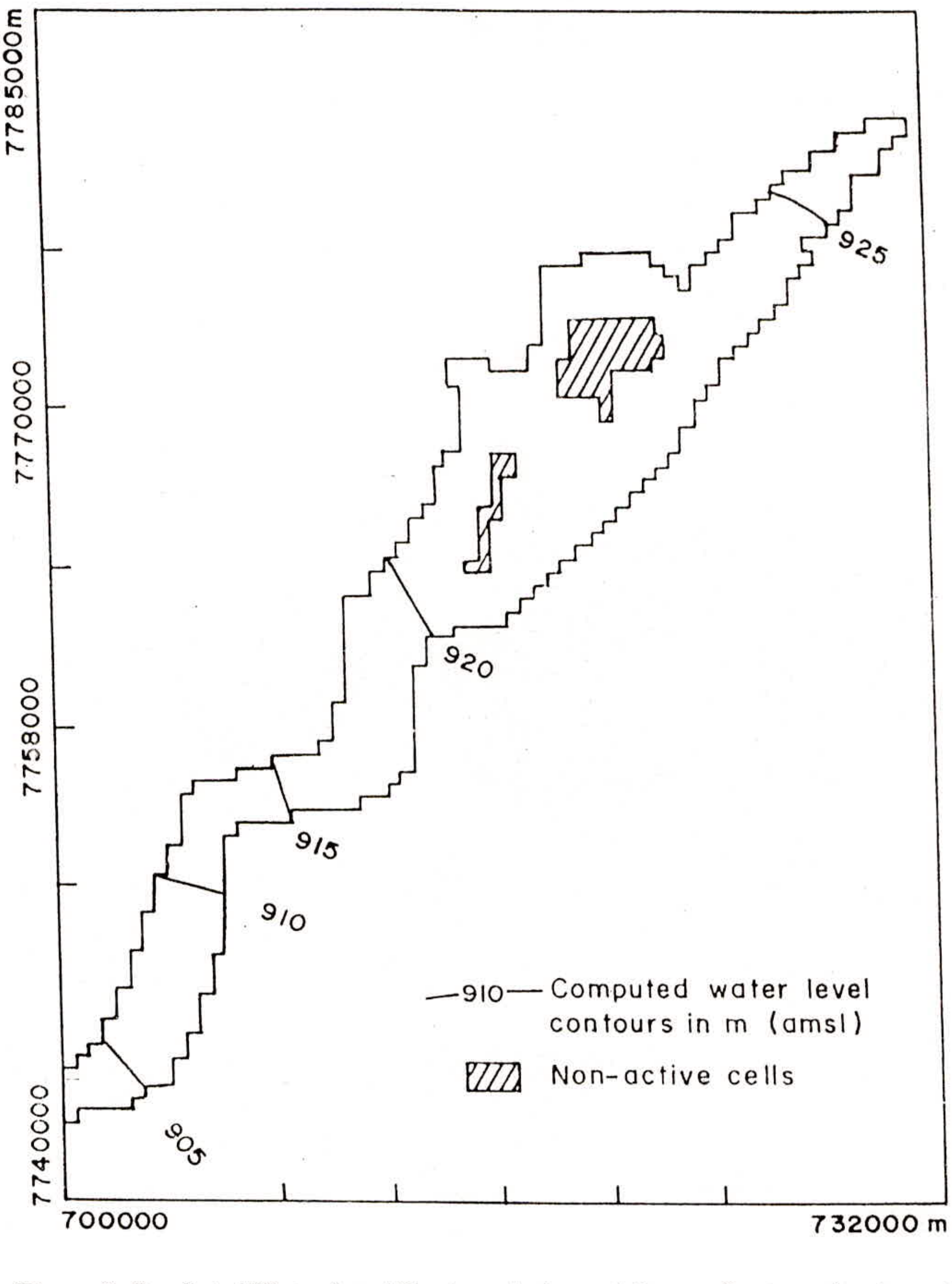


Figure 9: Predicted Water Level Contours in layer 4 (Lower Semi-confined aquifer) for January 1998 (Prediction Scenario-1)

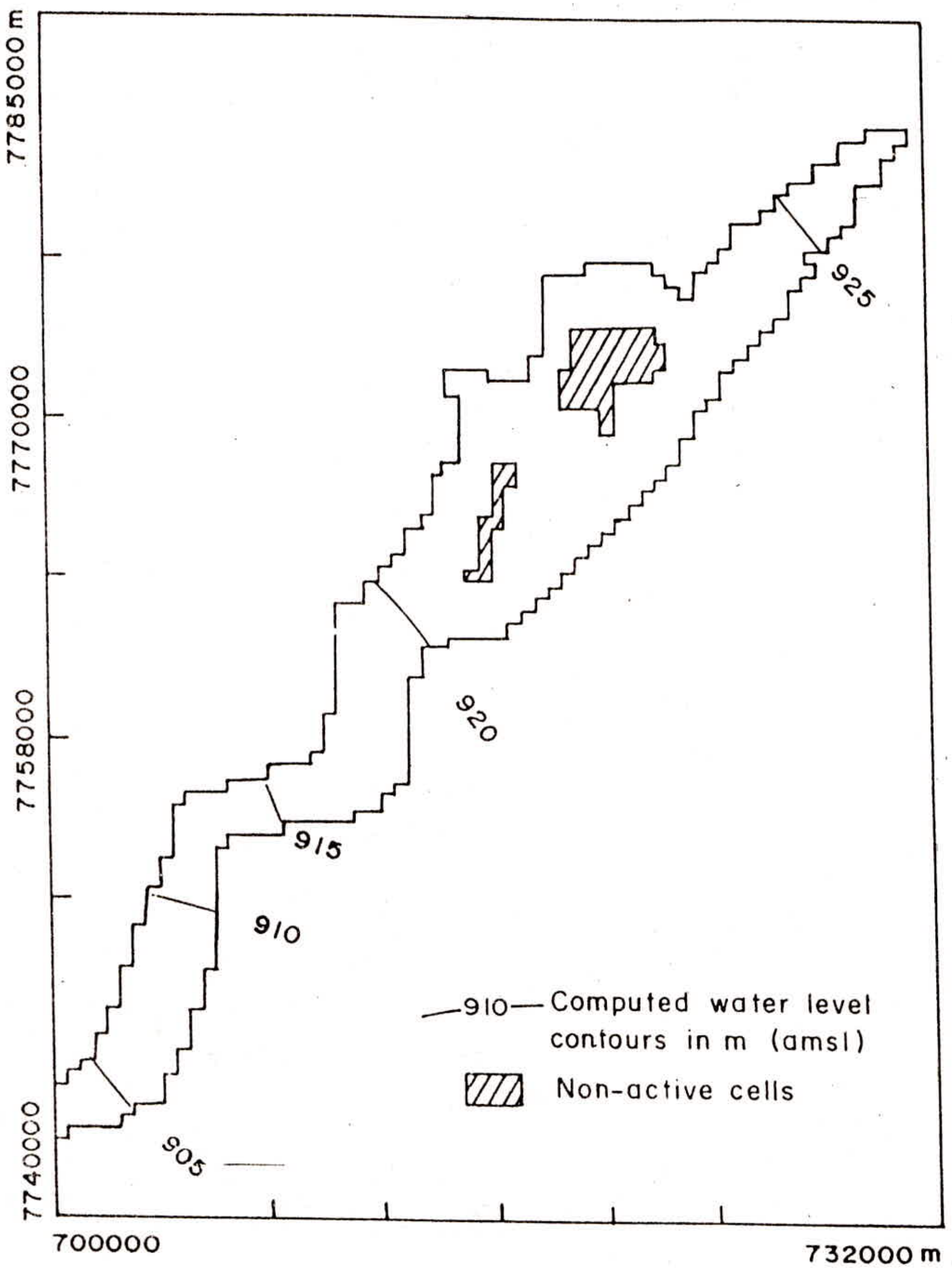


Figure 10 : Predicted Water Level Contours in layer 6 (Brackish aquifer) for January 1998 (Prediction Scenario-1)

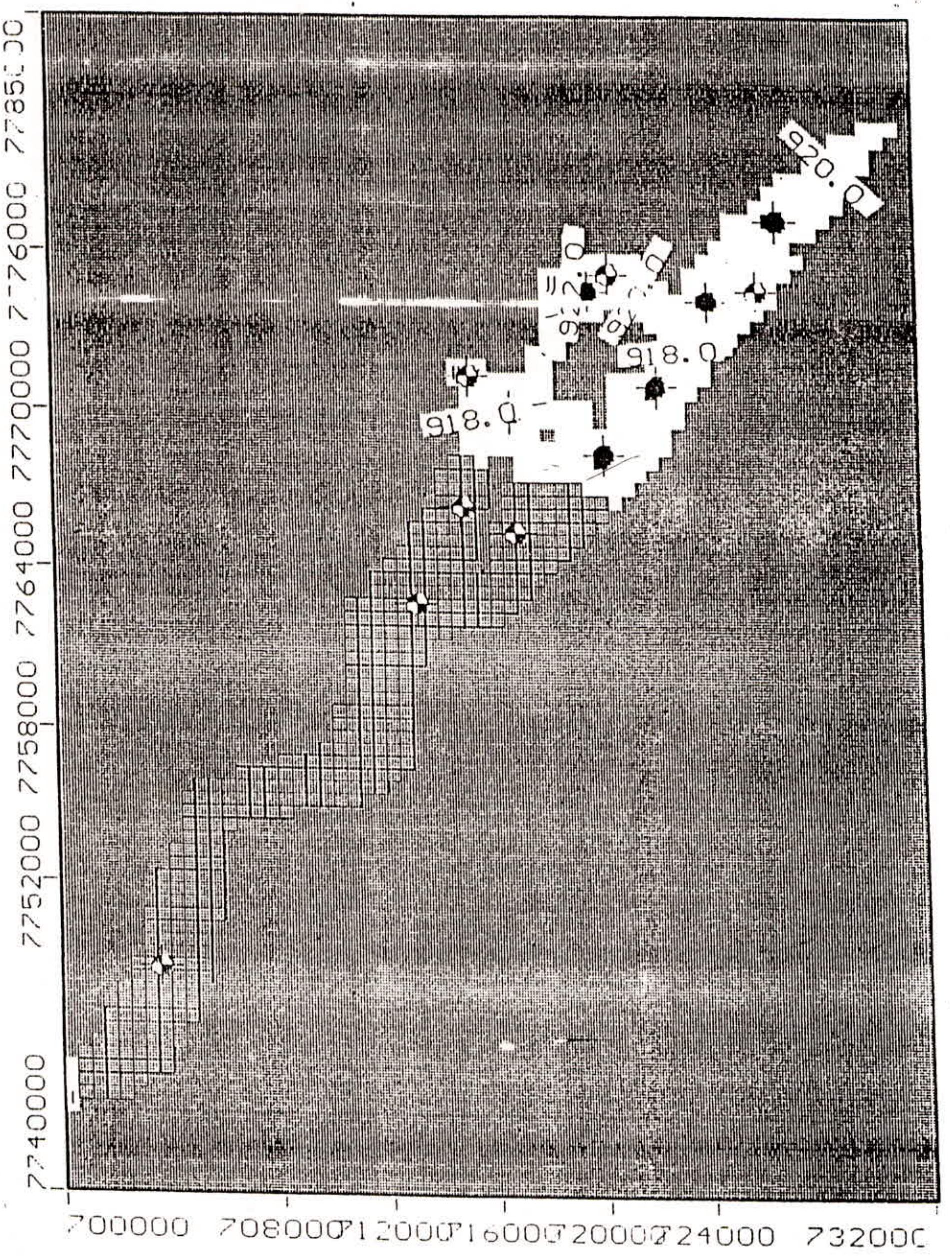


Figure 11: Predicted Water Level Contours in layer 1 (Top Layer) For January 2007 (Prediction Scenario-1)

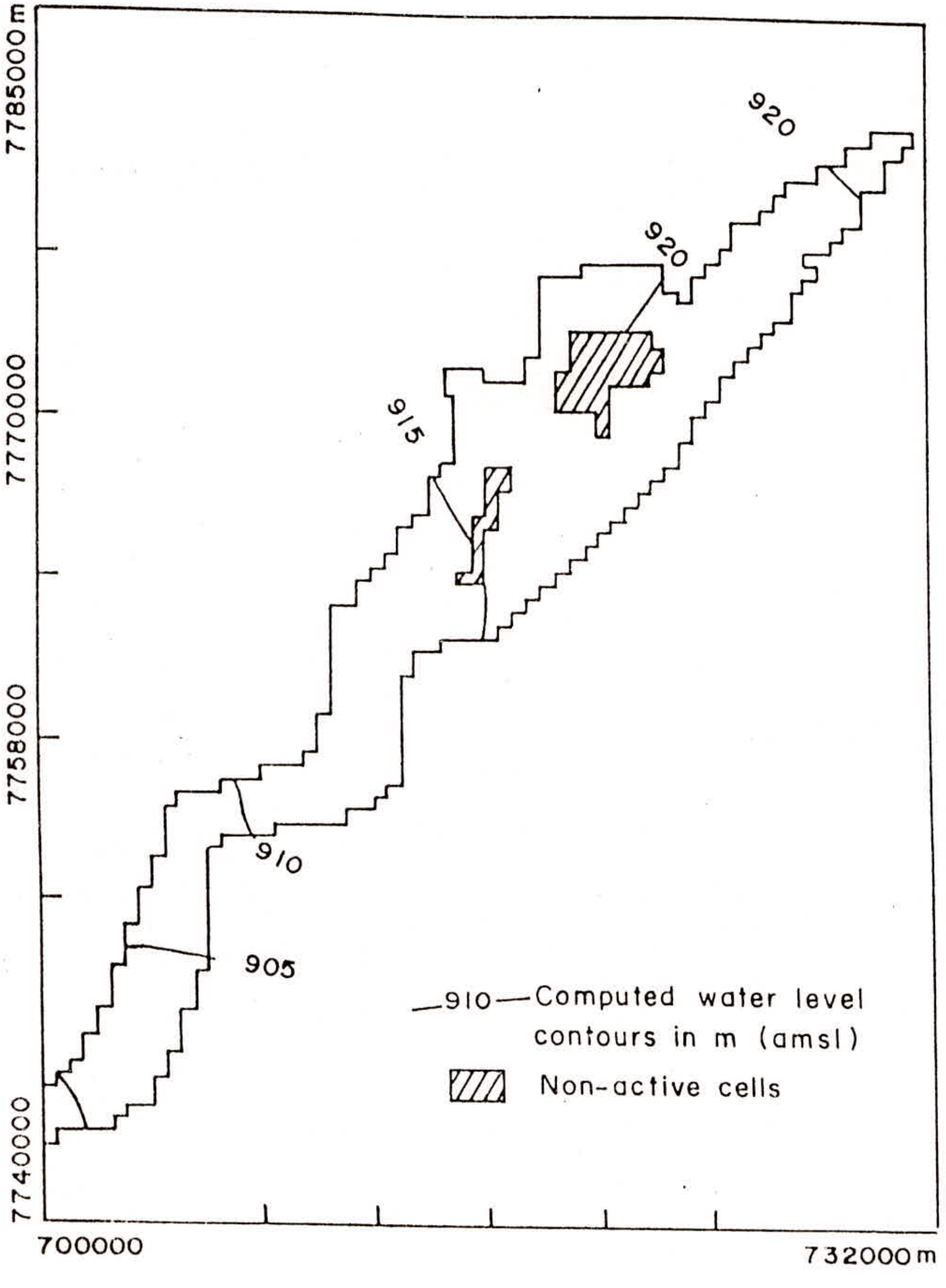


Figure 12: Predicted Water Level Contours in layer 4 (Lower Semi-confined aquifer) for January 2007 (Prediction Scenario-1)

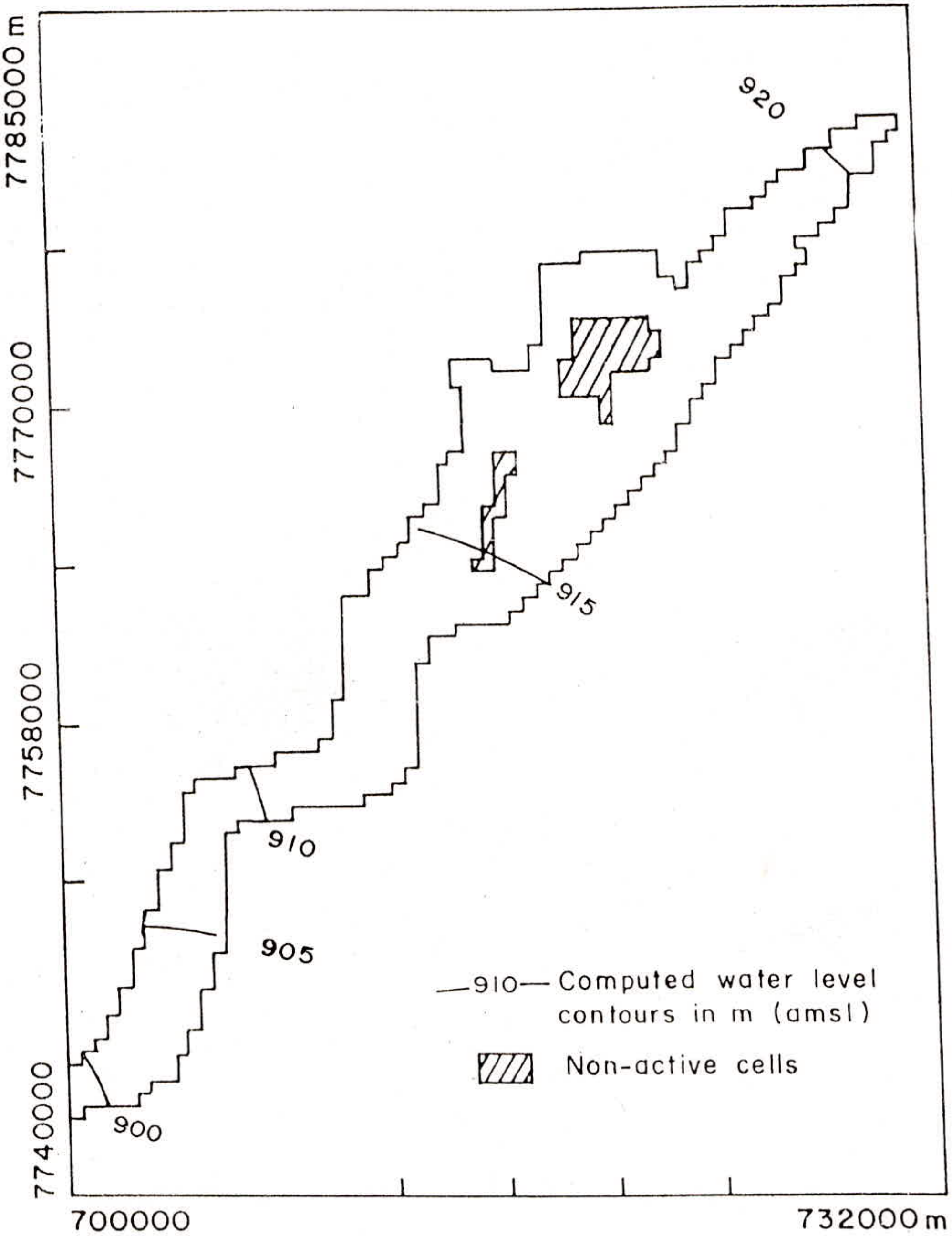
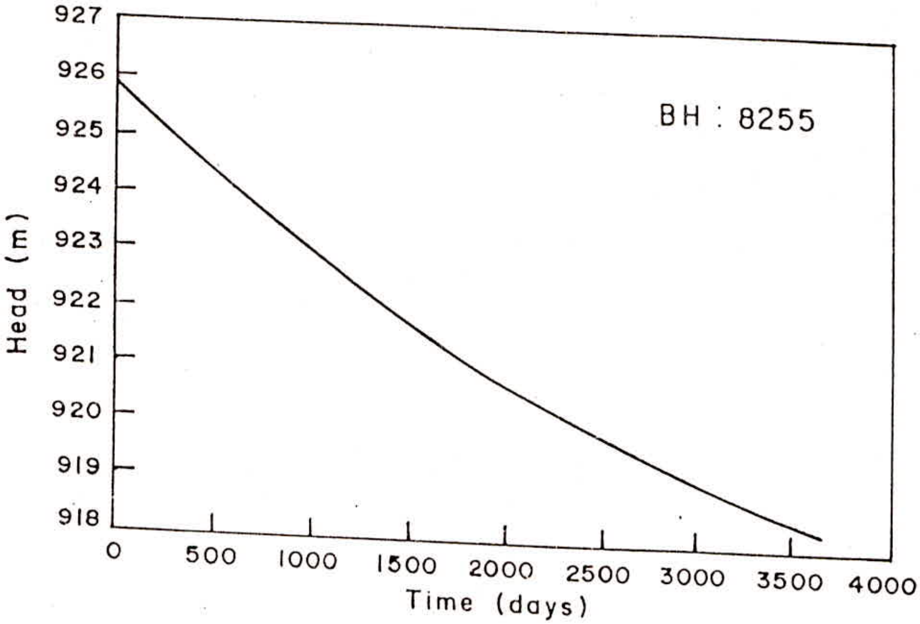


Figure 13: Predicted Water Level Contours in layer 6 (Brackish aquifer) for January 2007 (Prediction Scenario-1)



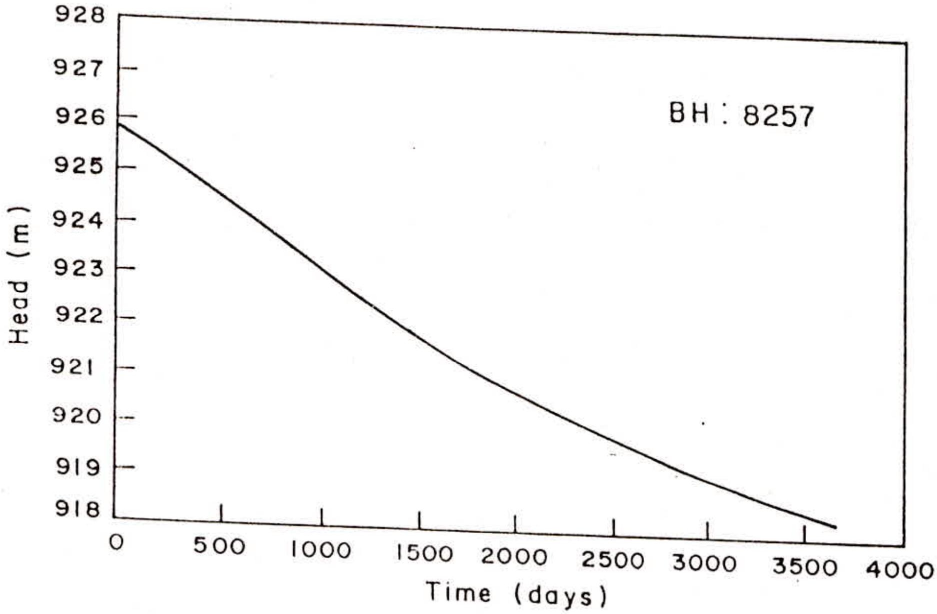
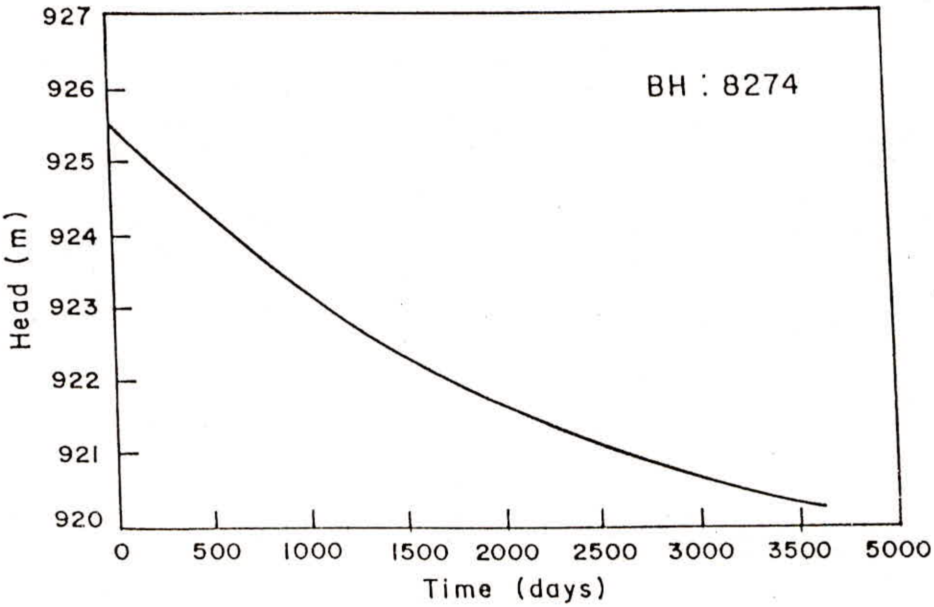


Figure 14: Predicted Well Hydrographs for Observation Wells 8255 and 8257 (Prediction Scenario-1)



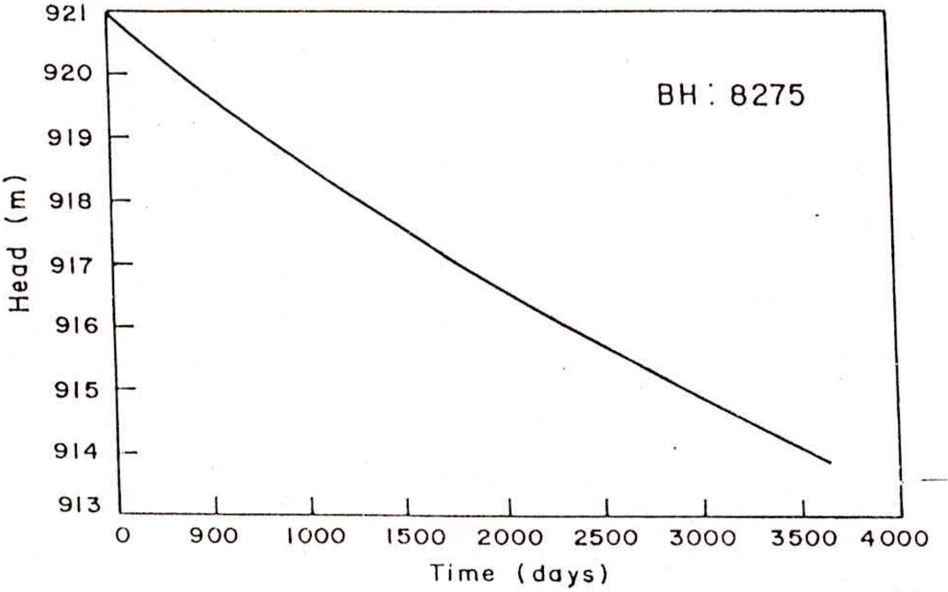


Figure 15: Predicted Well Hydrographs for Observation Wells 8274 and 8275 *(Prediction Scenario-1)*

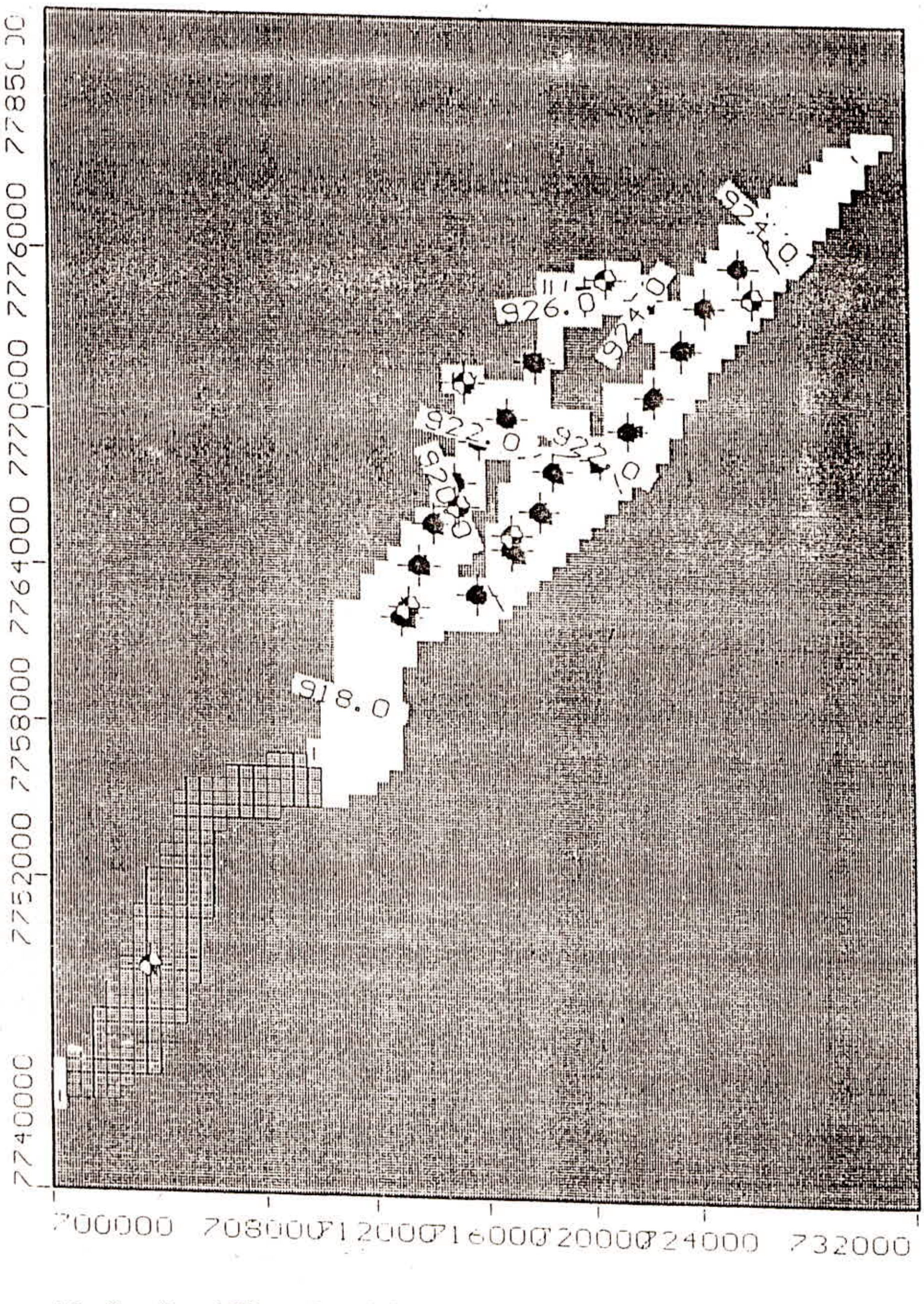


Figure 16 : Predicted Water Level Contours in layer 1 (Top Layer) for January 1998 (Prediction Scenario-2)

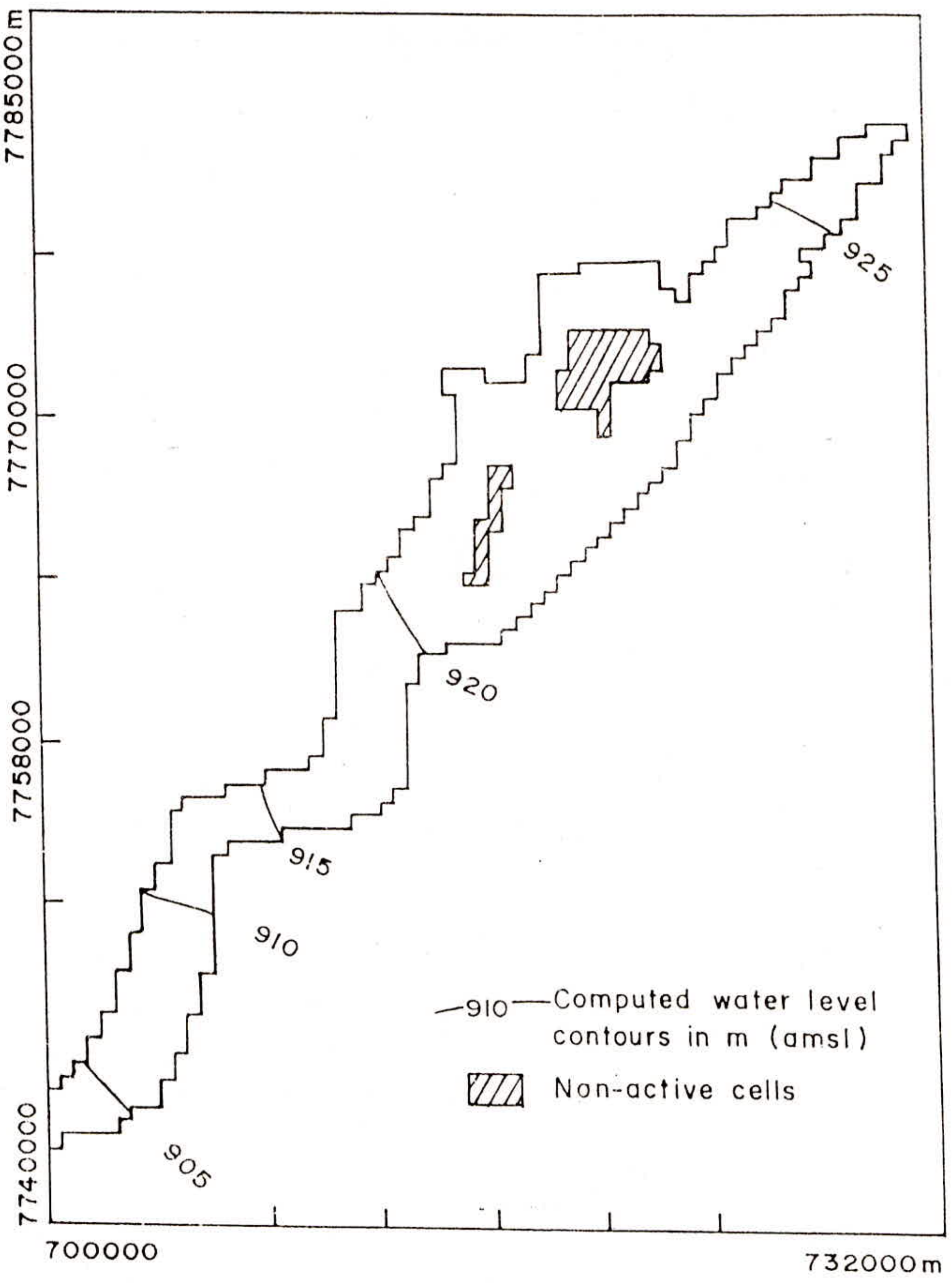


Figure 17: Predicted Water Level Contours in layer 4 (Lower Semi-confined aquifer) for January 1998 (Prediction Scenario-2)

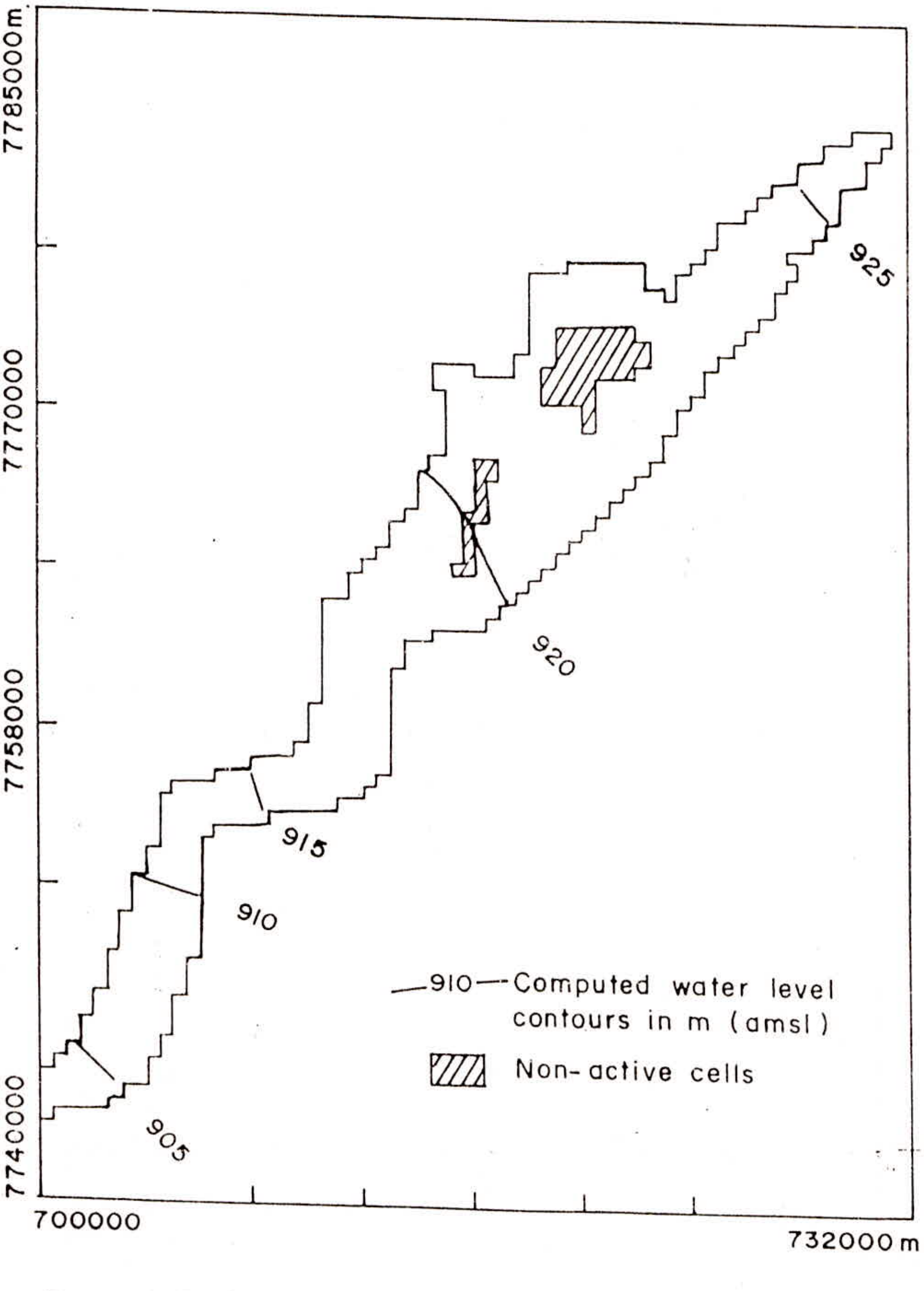


Figure 18 : Predicted Water Level Contours in layer 6 (Brackish aquifer) for January 1998 (Prediction Scenario-2)

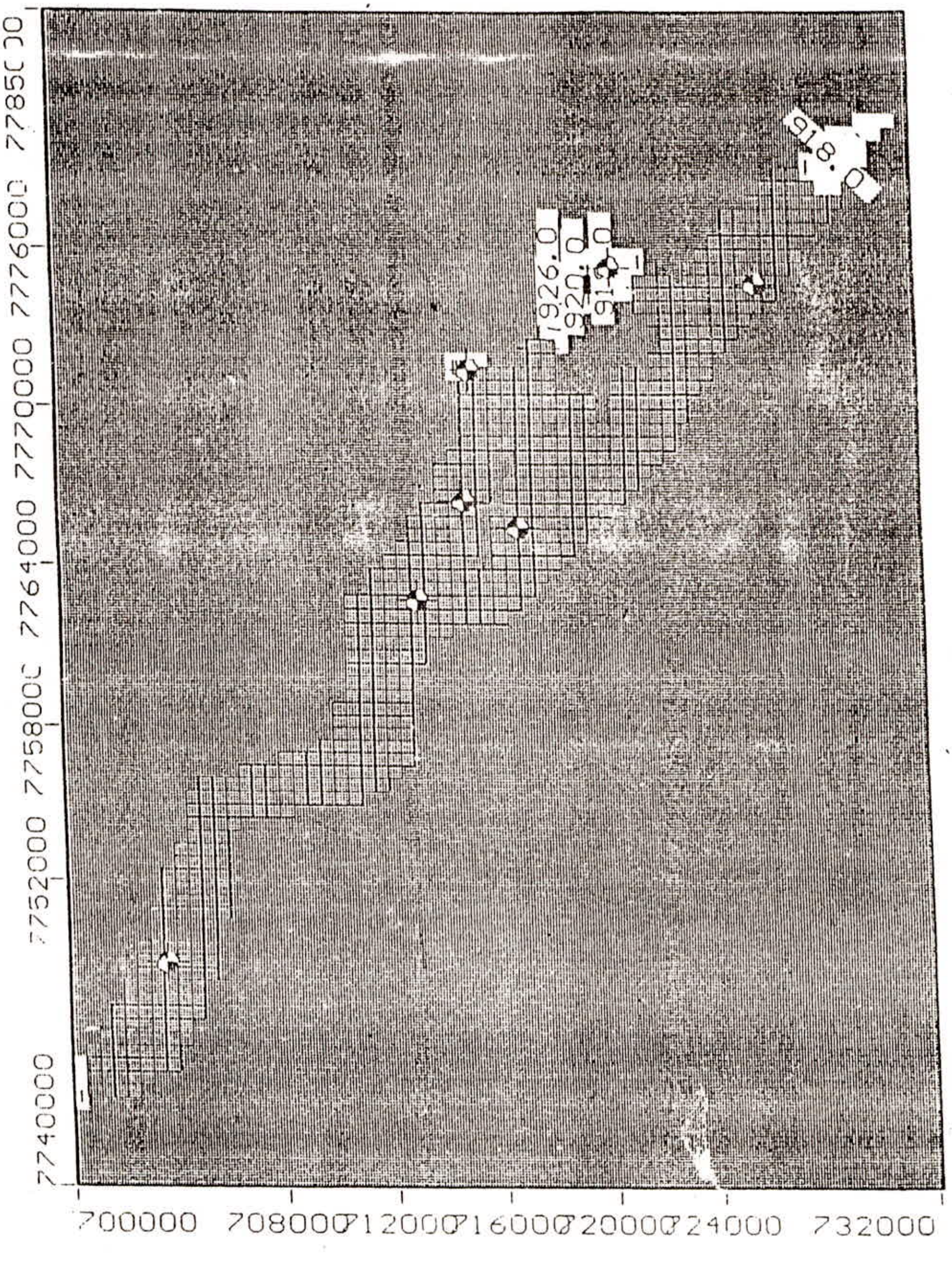


Figure 19: Predicted Water Level Contours in layer 1 (Top Layer) for January 2007 (Prediction Scenario-2)

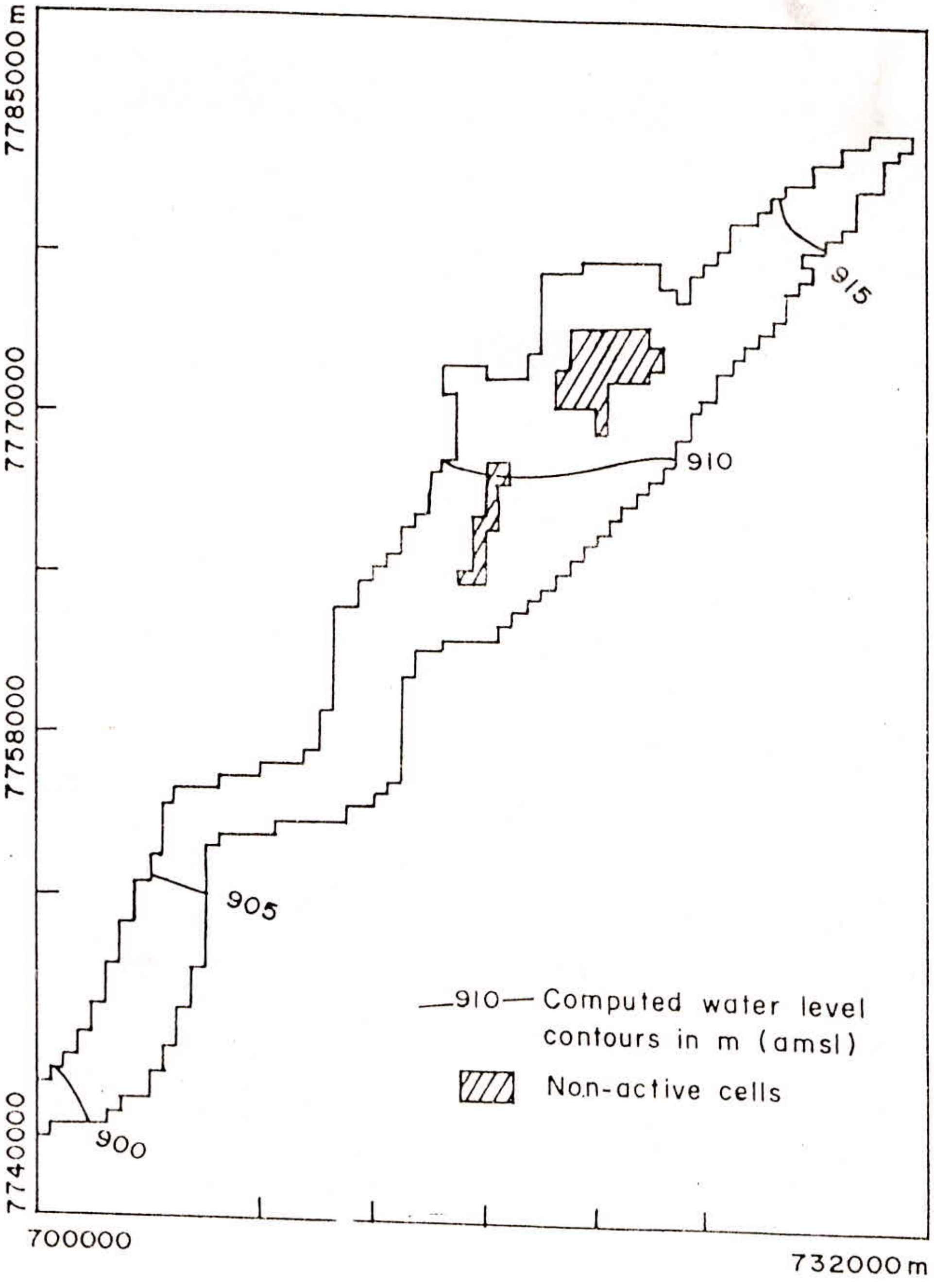


Figure 20 : Predicted Water Level Contours in layer 4 (Lower Semi-confined aquifer) for January 2007 (Prediction Scenario-2)

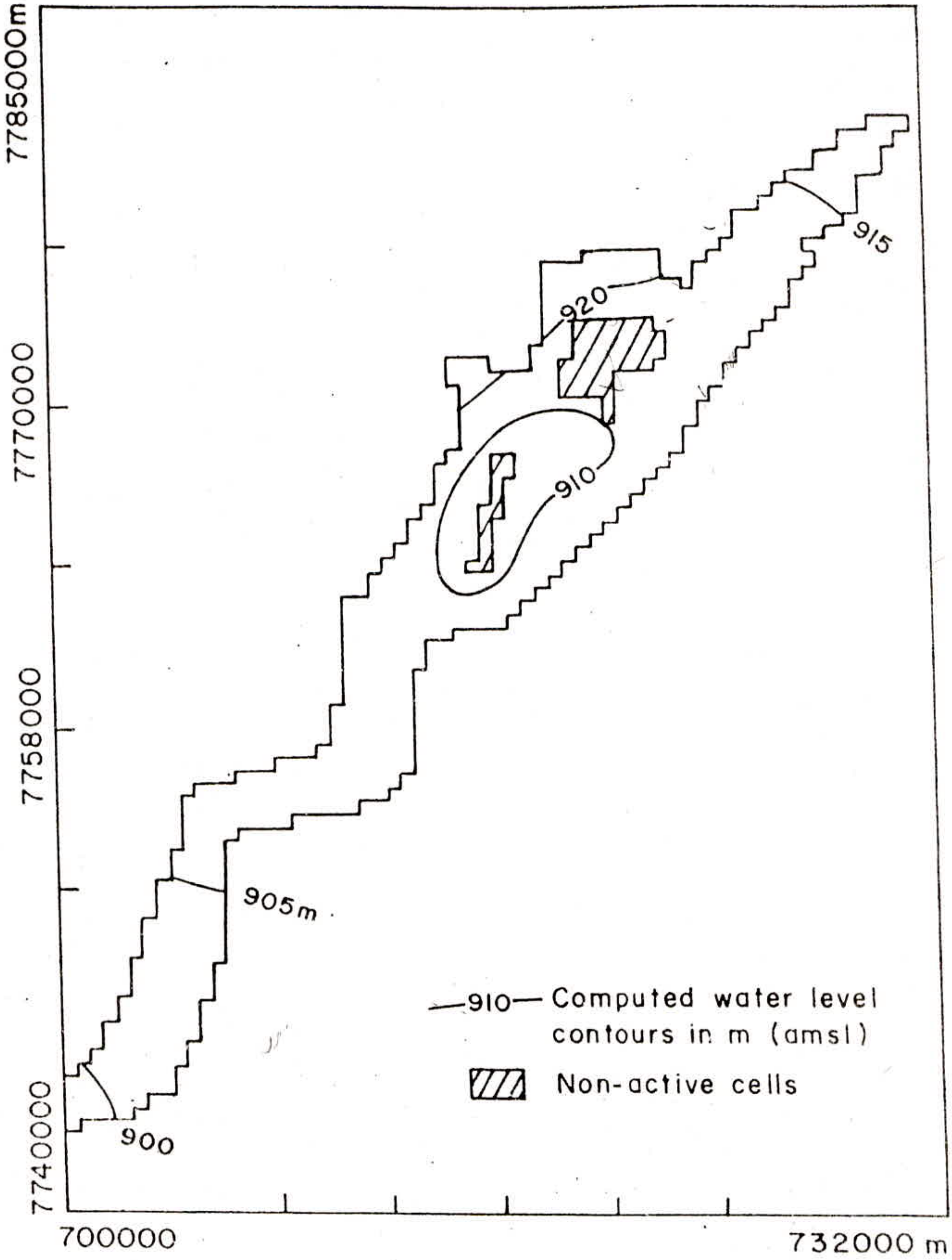
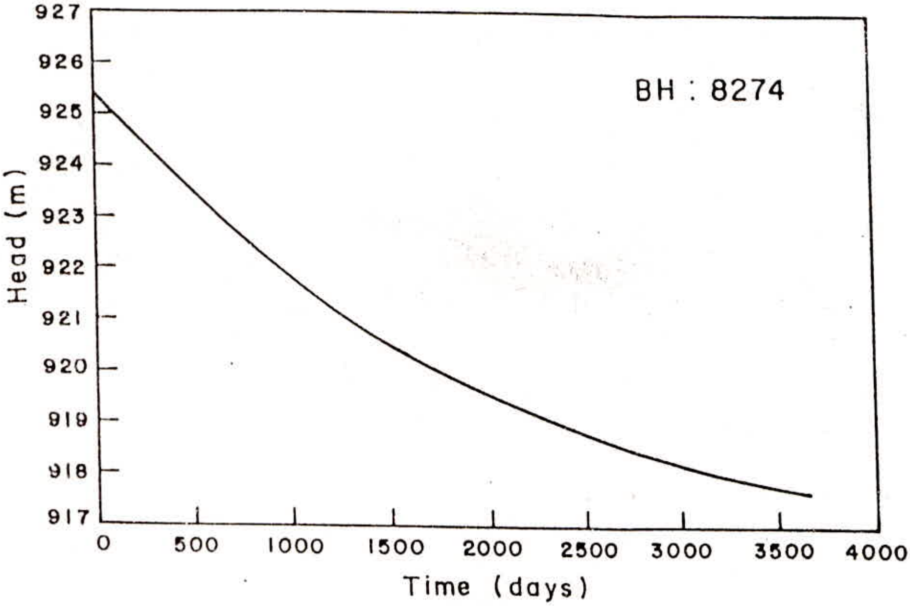


Figure 21: Predicted Water Level Contours in layer 6 (Brackish aquifer) for January 2007 (Prediction Scenario-2)



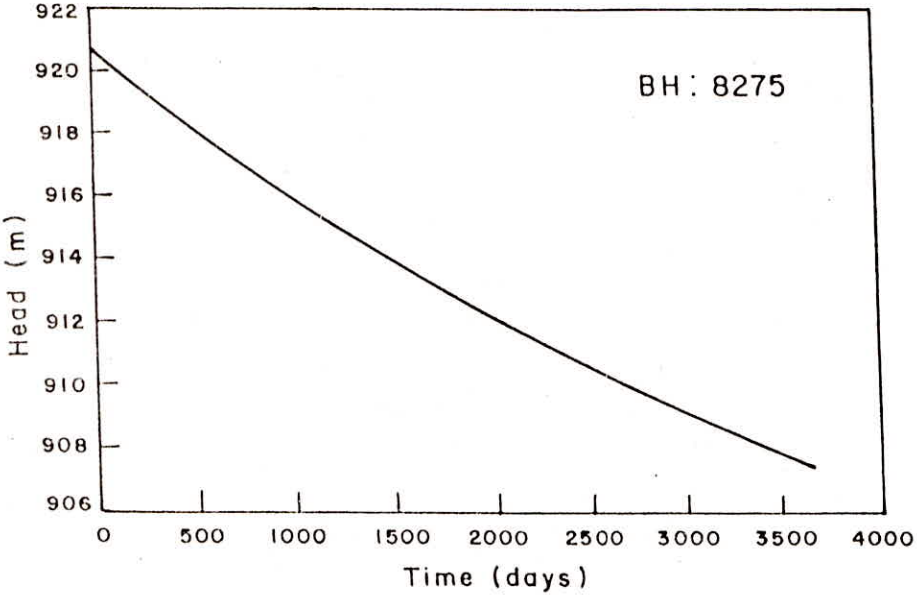
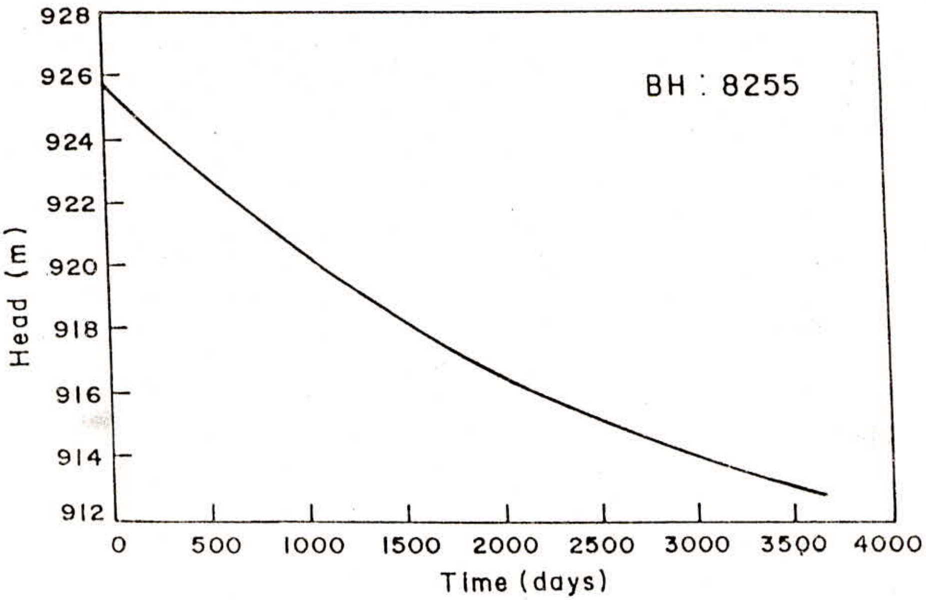


Figure 22: Predicted Well Hydrographs for Observation Wells 8255 and 8257 (Prediction Scenario-2)



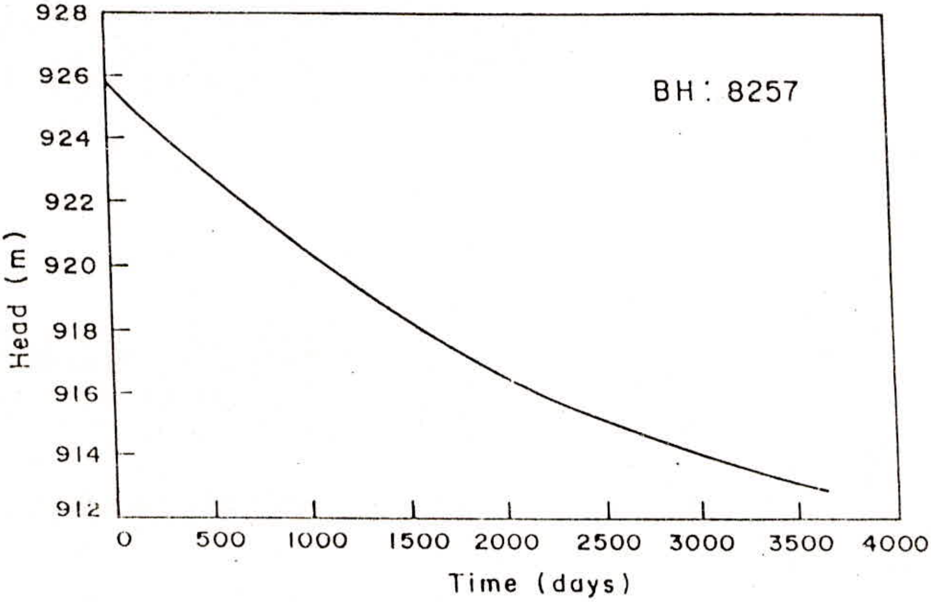


Figure 23: Predicted Well Hydrographs for Observation Wells 8274 and 8275 (Prediction Scenario-2)

5.0 DISCUSSIONS

The preliminary modelling supports the future consideration of this area for development. It appears that the area can support a considerable amount of freshwater withdrawal without significant water quality changes as a result of upconing. As with most of the explored area, the hydraulic conductivity of the geologic materials that separate the fresh and brackish groundwater is an uncertainty of the model and needs to be investigated in more detail.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The present modelling study is very preliminary and subject to many assumptions and assumed hydraulic parameters. The infiltration due to river flow is not considered in this study, as there was no regular flow for the last three years. The preliminary modelling for this area indicates substantial development potential over a portion of this exploration area. Simulations at pumping 4,800 and 9,600 m3/day, while producing impacts to the top layer in terms of de-watering, were sustainable if this area receives regular river flow in the future.

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