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ARTIFICIAL RECHARGING OF AN UNCONFINED AQUIFER WITH AN INJECTING WELL (KARNATAKA)

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PREFACE

As there are increased constraints on the development of surface water resources as a result of saturation and environmental stresses, more and more attention is being paid to the development of the groundwater resources in various parts of the globe. The increased dependence and utilisation of groundwater has also caused environmental hazards and depletion of many aquifers. Many regions of our country also experience receding water tables due to over exploitation and ill-management of the resources. Artificial recharge methods using percolation tanks, injection wells, spreading basins, rainwater harvesting etc. have been proposed and being implemented in order to recharge the depleting groundwater resources to certain extent. Various aspects demand attention in the planning, design and location of such artificial storage-recharge schemes, particularly in a complex aquifer system. Among those, geohydrological and flow aspects deserve special attention as those are the factors that determine how an artificial recharge scheme can be effective. Besides, it is essential to examine the hydraulic response of an aquifer system to recharge. Modelling studies are powerful tools in the investigation and implementation of potential artificial recharge schemes. Presented in this report is one such kind of study, wherein the groundwater flow characteristics in Hukkeri taluk has been investigated and feasible artificial recharge measures have been evaluated through a mathematical modelling technique. Hukkeri taluk in the Ghataprabha sub-basin of Krishna basin has been experiencing highly fluctuating groundwater tables leading to depletion of aquifer for a few years. The report is expected to provide useful information on the methodology of using modelling applications to artificial recharge studies including evaluation of various options.

This work has been carried out and reported by Mr. Mathew K. Jose with the guidance of Mr. P.K. Majumdar under the work programme of the Groundwater Modelling and Conjunctive Division of the institute for the year 1999-2000.

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ABSTRACT

The increased dependence and utilisation of groundwater has caused depletion of aquifers in many parts of our country. Artificial recharge methods using percolation tanks, injection wells, spreading basins etc. have been proposed and implemented to certain extent in order to resuscitate the depleting groundwater resources. The important issues associated with artificial recharge are the nature of the rechargeable water source, the system of recharge to be used, the expected injection rates, the hydraulic response of the system to injection and the management of the injected water as part of the total water resources system. Mathematical modelling is a powerful tool in the investigation of artificial recharge processes and evaluation of viable strategies.

Most of the river basins of peninsular India, have been facing groundwater development problems varying in nature and severity. Being no exception, Ghataprabha sub-basin of Krishna river basin too has its own problems. It has got a wide spectrum of issues such as cases of failure of wells at several places on the one hand, while some areas becoming unfertile due to waterlogging. Hukkeri taluk in the Ghataprabha sub-basin has been experiencing depletion its aquifers for a number of years. The problem has been investigated through mathematical modelling techniques and plausible measures for recharging the aquifers have been evolved.

In order to address local-scale groundwater issues a calibrated three dimensional regional finite difference model, based upon the USGS modular three dimensional finite difference ground water flow model MODFLOW, generated for the Ghataprabha sub-basin has been used as a basis for the local-scale modelling of the Hukkeri region, which has been experiencing drying of open and bore-wells in recent times. The generated microscopic model with finer mesh is calibrated and validated using the existing USGS code MODFLOW. Various options of artificial recharge measures have been tried out with the calibrated model and results analysed. Analysis of the results shows that maintaining a higher water-level in the Ghataprabha river reach in downstream of Hidkal Dam and in Hiranyakeshi tributary is the best option for maintaining a reasonable water table depth in the area.

1.0 INTRODUCTION

As development of surface water resources approaching saturation levels, more attention is being paid to the development of the groundwater resources in various parts of the globe. The increased dependence and utilisation of groundwater has caused depletion of aquifers too. Many parts of our country also experience receding water tables due to various reasons including over exploitation. Artificial recharge methods using percolation tanks, injection wells, spreading basins etc. have been proposed and implemented to certain extent in order to revamp the depleting groundwater resources. Artificial recharge is the process by which the groundwater reservoir is augmented at a rate exceeding that under natural conditions of replenishment. Various aspects demand attention in the planning, design and location of such artificial storage-recharge schemes, particularly in a complex aquifer system. Among those, geohydrological and flow aspects deserve special attention as those are the factors that determine how an artificial recharge scheme can be effective. Besides, it is essential to examine the hydraulic response of an aquifer system to recharge. The important issues associated with artificial recharge are the nature of the rechargeable water source, the system of recharge to be used, the expected injection rates, the hydraulic response of the system to injection and the management of the injected water as part of the total water resources system. Mathematical modelling is a powerful tool in the investigation of artificial recharge processes and subsequent formulation of viable strategies/ methods.

A survey of the literature shows that mathematical modelling of artificial recharge processes have been carried out extensively in the past. Nutbrown (1976) presents some simple guide lines for assessing the response of groundwater to artificial recharge. Chowdhury et. al. (*1978*) carried out a theoretical analysis of the flow through a recharge well in a leaky aquifer system. Latinopoulos (*1981*) presented analytical solutions for the groundwater flow in an unconfined aquifer under seasonal artificial recharge schemes of variable duration. A generalised analytical solution for the formation of groundwater mound in response to recharge from rectangular areas to finite aquifers is available *(Rao and Sharma, 1981)*. Finite Fourier Transforms method was used by Rao and Sharma (*1984*) to develop an analytical solution for the profile of a groundwater mound due to localised recharge from a strip basin to a finite aquifer with mixed boundaries. Hunt (*1985*) provides classification for the various streamline patterns that can occur when an abstraction well and recharge well placed along the same streamline in uniform seepage. Warner et.al. (*1989*) presented several analytical solutions that describe artificial recharge from basins. Zomorodi (*1990*) presented a methodology for maximisation of recharge volume using optimal intermittent operation and a multi-basin system. Methods are available to evaluate the response of a water-table to artificial recharge (*Zomorodi, 1991*). Sorman et.al. (*1993*) carried out a study to evaluate the flow process under arid and extremely arid conditions. Shamsai and Marino (*1992*) gives a numerical investigation of artificial recharge in multilayered, an isotropic unconfined porous media for radial flow configuration. Allam et.al. (*1997*) carried out numerical simulation of artificial recharge of groundwater through spreading basin in West Nile Delta region using MODFLOW.

Most of the river basins of peninsular India, have been facing groundwater development problems varying in nature and severity. Being no exception, Ghataprabha sub-basin of Krishna river basin too has its own problems. It has got a wide spectrum of issues such as cases of failure of open and dug wells at several places on the one hand, while some areas becoming unfertile due to waterlogging (*Majumdar et al, 1996*). The reported failure of wells in Hukkeri taluk and waterlogging in the nearby area of Gokak taluk, both in Belgaum district, can be perceived as indispensable consequences of unsustainable development of groundwater in the Ghataprabha sub-basin, rather than an issue of local origin. Obviously, it is necessary to adopt appropriate scientific approaches to investigate the causes and formulate remedial action plans. In order to investigate the groundwater scenario of the Ghataprabha sub-basin, a three dimensional two layered finite difference model has been generated and calibrated for Ghataprabha sub-basin (*Majumdar et al, 1997*) with the aid of the USGS modular three dimensional finite difference ground water flow model, MODFLOW. Using the regional model developed, various groundwater development scenarios on the regional scale have been discussed.

2.0 OBJECTIVES

As mentioned before, Hukkeri taluk in the Ghataprabha sub-basin has been experiencing highly fluctuating groundwater tables and depletion of aquifer for a number of years. Hence, it is intended to examine the problem in terms of the flow aspects and to evolve any plausible measures. Thus the objective is to investigate the groundwater flow characteristics in the area and also to evaluate feasible artificial recharge measures, through mathematical modelling technique. A three dimensional groundwater flow modelling software MODFLOW originally developed by the USGS has been used for the simulation of the aquifer. The regional scale model already developed (*Majumdar et al, 1997*) would be used as a basis for the telescopic mesh refinement modelling of the Hukkeri region in order to address microscopic groundwater issues.

3.0 DESCRIPTION OF THE SUB-BASIN

3.1 General

Ghataprabha is one of the sub-basins of Krishna basin. River Krishna is the second largest river in peninsular India, rises in the Mahadev ranges of the Western Ghats near Mahabaleshwar at an altitude of about 1337 m above MSL. After traversing a distance of about 1400 km, the river joins the Bay of Bengal. The principal tributaries of the river are Ghataprabha, Malaprabha, Bhima, Tungabhadra, Musi, Palleru and Munneru. The basin consists of twelve sub-basins, including the Ghataprabha catchment. This catchment lies approximately between the latitudes of 15° 45′N and 16° 25′N and longitudes 74° 00′E and 75° 55′E as indicated in the index map (Fig.1). River Ghataprabha rises from the western ghats in Maharashtra at an altitude of 884 m above MSL, flows eastward for 60 km through Sindhudurg and Kolhapur districts of Maharashtra, forms the border between Maharashtra and Karnataka for 8 km and then enters Karnataka. In Karnataka, the river flows 216 km through Belgaum district past Bagalkot. After a run of 283 km the river joins the Krishna on the right bank at Kudli sangam at an elevation of 500 m, about 16 km from Almatti. Its principal tributaries are the Tamraparni, the Hiranyakeshi and the Markandeya. River Tamraparni rises in Maharashtra, flows in Maharashtra for 26 km and then joins the Ghataprabha after another 26 km run in Karnataka. Hiranyakeshi rises at Aamboli in Maharashtra flows 6 km there and 19 km in Karnataka, joins the Ghataprabha on the left bank. Markandeya rises and flowing 8 km in Maharashtra joins the Ghataprabha on the right bank after a run of 66 km in Karnataka. Total catchment area of the sub-basin is 8829 sq.km., of which 77% belongs to Karnataka and rest falls in Maharashtra. Belgaum and Bijapur of Karnataka and Kolhapur and Sindhudurg of Maharashtra, respectively lie in the sub-basin. Most of the sub-basin is flat to gently undulating except for isolated hillocks and valleys. The climate of the sub-basin is marked by hot summers and a mild winters. The winter is from November to mid-February and summer is from mid-February to end of May. April used to be the hottest month while December is generally the coldest month. The sub-basin experiences only the south-west monsoon for the period June to October.

3.2 Land Use and Soil

Land use particulars of Ghataprabha sub-basin with respect to geographical area of the sub-basin are: Net area sown (63.7 %), Forests (12.6 %), Current fallow (8.7 %), Non agricultural use (4.0 %), Barren land (3.9 %), Culturable waste (2.7 %), Permanent pastures and other grazing land (2.3 %), Other fallow (1.8 %), and Land under miscellaneous crops and trees (0.3 %) (*Source: NWDA Technical study No.17, 1991*).

North and north-west parts of the districts of Belgaum and Kolhapur, in the sub-basin, occupy coarse shallow black soils with depths less than a foot. These soils are well drained and have moderate permeabilities. The crops grown under rainfed conditions are jowar, bajra, millet and pulses. However, the yield is low due to shallow rooting depths and scanty rainfall. Medium black soils is in parts of Belgaum, Hukkeri, Bailhongal, Mudhol and Bilagi taluks. The medium black soils are also found to some extent on the peninsular gneiss areas. These soils are moderately deep (25-90 cm) with low permeabilities. The crops grown in theses soils under rainfed conditions are jowar, wheat, millets , cotton , safflower, tobacco, groundnut, ginger, linseed, chillies, tur, gram and other pulses. Deep black soils occur on very gently sloping to nearly level or flat topography in the low lands of Deccan trap and limestone regions, in parts of Hukkeri, Gokak, Ramdurg, Mudhol and Bagalkot taluks. These are deep soils (more than 90 cm) with clayey texture. The crops grown under rainfed and irrigated conditions are the same as that for the medium black soils. Mixed red and black soils usually occur on gently undulating plain or complex geological material comprising gneiss dharwar schistose and sedimentary rock formations and occupy areas in parts of Ramdurg and Bailhongal taluks in the sub-basin. The red soils are comparatively of coarser texture and have moderate drainage and low permeability. The crops grown under rainfed conditions are jowar, cotton, groundnut, chillies, wheat and pulses. The crops grown under irrigation are cotton, pulses, paddy, sugarcane maize, wheat and tobacco. Lateritic soils are found on undulating, rolling plain to gently sloping topography of the peninsular gneiss regions occupying areas in parts of Kolhapur district coming under the dry agro-climatic region. These soils are deep to very deep, and are well drained with moderate to high permeabilities. The depth of these soils in the sub-basin varies from 15 cm to 100 cm. The crops grown in these soils under rainfed conditions fare jowar, groundnut, pulses, safflower, linseed and other millets. Under irrigation the crops grown are paddy, sugarcane, chillies, wheat, turmeric and vegetables.

3.3 Hydrogeology

The geological formations within the sub-basin are i) Deccan trap of tertiary age, ii) sedimentary formations known as "kaladagi group" comprising lime stone, shale and quartzites, iii) schistose, gneiss and other crystalline rocks and iv)laterite rocks. Borelogs and lithologs at various locations summarises to five zones namely, soil cover, weathered, partially weathered, fractured and sound rock. Also, transmissivities and storage coefficients of these hard rocks are given in Table 1.

Table 1. Flow properties of hard rocks. *(Source: DANIDA report,1995)*

Rock type	Transmissivity in m^2/day	Storage coefficient
Greywake	17.6-467.7	0.0046-0.0062
Basalt	90.9-545.7	0.0019-0.0057
Limestone	131.8-227.9	0.039
Granitic gneiss	164.1-180.7	7.8×10^{-7}-2.3×10^{-3}
Charnockite	98.3-135.4	2.1×10^{-4}-6.0×10^{-3}
Granite	535.1	7.8×10^{-7}

The two types of aquifers, based on the subsurface geology, are i) the top weathered zone which extends down to 30.0m. and forms the shallow or the phreatic aquifers tapped mostly by dug wells and dug-cum-bores, shallow bore wells and filter point wells and ii) the fractured aquifer which lie below the shallow zone and extend down to 80 m. and beyond, the maximum drilled depth being 200m (*CGWB,1997*). Accordingly, permeability values in shallow aquifer zone varies from less than 1 m/day to 5 m/day, and transmissivity of second aquifer zone varies from a few sq.m/day to more than 100 sq.m/day. Investigations reveal that groundwater occurs in the sub-basin under phreatic to semi-confined conditions in all gneiss, quartizites and alluvial deposits. The occurrence and movement of groundwater in these rocks are controlled by the nature and extent of weathering and the presence of joints and fractures in them. The groundwater development in the sub-basin is from open wells and dug-cum bore wells. The taluk-wise groundwater level fluctuation in Ghataprabha sub-basin is given in Table 2.

Table 2. Ground water level fluctuation in Ghataprabha sub basin.

Location	District	State	Period	Gwl fluctuation [m]		
				Max	Min	Average
Karve	Kolhapur	Maharashtra	1974-1995	8.20	1.73	5.35
Nesri	Kolhapur	Maharashtra	1989-1995	3.00	0.55	1.64
Kalavikatti	Kolhapur	Maharashtra	1976-1995	11.08	1.06	6.29
Sambra	Belgaum	Karnataka	1977-1996	14.15	3.95	9.96
Hukkeri	Belgaum	Karnataka	1987-1996	10.72	1.17	4.62
Chikkandi	Belgaum	Karnataka	1972-1996	7.95	0.90	3.59
Bailhongal	Belgaum	Karnataka	1973-1996	10.93	0.65	3.53
Muragod	Belgaum	Karnataka	1973-1996	6.30	0.96	2.92
Lokapur	Bijapur	Karnataka	1973-1996	6.05	0.70	2.41
Bilgi	Bijapur	Karnataka	1973-1996	7.99	0.95	3.30
Bagalkot	Bijapur	Karnataka	1973-1995	23.00	1.00	5.05
Guledgudda	Bijapur	Karnataka	1973-1996	6.30	0.73	2.77

Overall ground water flow in the sub-basin follows the ground level profile, except some local disturbances due to geological, geophysical variations in the weathered and fractured mass and changes in the water levels of surface water bodies. Water table gradients vary areally with a maximum value of 2 m/km in the upper reaches and with a minimum value of 0.5 m/km in the lower reaches of the basin after Hukkeri. Seasonal fluctuations in subsurface water levels are mainly affected by the respective seasonal precipitation. In command areas it is being added by the seepage from canals and irrigation return flows.

3.4 Study Area

Hukkeri taluk which is located in the north-western part of Belgaum district, covers an area of 990.25 sq km and lies between longitude : 74° 19'30"E and 74° 46'10"E and latitude : 15° 57'40"N and 16° 21'45"N (Fig.1). Topographically the area is much undulating consisting of extensive flat topped plateau and rounded hills with intermittent valleys. The region forms a transition between the hilly western ghats and greater plains to the east. The average elevation of the ground varies from 615m to 840 m above MSL. Ghataprabha river with its major tributaries Hirenyakeshi and Markandeya forms the chief drainage for the area. Ghataprabha river enters the taluk at the south - western part of the taluk and flows northeast taking its course over quartzite valleys in the west and over-trap in the north-eastern part. Hirenyakeshi river flows in the central part of the taluk in the direction of east and drains into Ghataprabha near Ingli village. Markandeya river forming the south-eastern boundary of the taluk flows from southwest to north-east and ultimately drains into Ghataprabha in Gokak taluk.

Meteorological data indicates that this area experiences hot summers and mild winters. The summer temperature during April - May can reach as high as 42° C while the minimum can be as low as 8° C in December. South-west monsoon sets in June and lasts till September end. The heaviest rainfall generally occurs in the month of July. There are six raingauge stations in the region (vide Fig.1). Average rainfall over the region is in the range of 600 mm to 700 mm. Average annual evaporation is 2301.06 mm which is more than the average precipitation values.

Major part of the Hukkeri taluk is covered by black to red soils. The thickness of soil cover varies from 0.5 m to 1.5 m. Red loamy/ sandy soils are mainly seen in the southern part of the taluk. Groundnut, tobacco and jowar are the major crops. There is not much variation either in the land use or cropping pattern over the years. Sandy loam soils are widely distributed in and around Hidkal. Black soils exhibit variety in grain size ranging from clay to pebble. Clayey soils may act as a flow barrier in aquifers. Average rate of infiltration in the taluk (based on tests conducted around Hidkal dam site) is 3 cm/hour in the agriculture land.

Geologically the area can be divided into two units, the northern part consisting of mostly Deccan traps and the southern portion consisting of sandstone and quartzite of Kaladgis. Laterites capping the traps are exposed on hill top near Hidkal. Basaltic lava flows which cover major northern part of the taluk are grey to black in colour and are hard, massive, compact with very few blow holes. This variety of trap is crisscrossed by vertical as well as horizontal joints. Vertical joints which are prominently developed at shallow depths have produced columnar structures. Weathering in this variety of trap is very rare. Spheroidal weathering of traps is noticed at Sankeshwar, Chikalgud and other neighboring areas.

There are no irrigation tanks existing in the area. A few percolation tanks are constructed at the initial catchment zones near Nerli, Shirahatti, Kudur etc. which are very minor and possess water only for few months in a year. It was expected that these tanks might help in raising the water table in the wells by percolation and prevent heavy surface run off. Previously, a number of lift irrigation wells were sunk along the nalla course of Kapurdhahalla which was reported to be once perennial. But, subsequently, this nalla with its tributaries were completely dried up due to severe droughts in recent years and heavy lifting of water and sinking of innumerable wells along the nalla course. Lift irrigation is being attempted to irrigate about 800 to 1000 hectares of land by utilising the water of Hirenyakeshi river near Sankeshwar and under this scheme only sugarcane is being grown. The river Hirayanakeshi becomes dry for at least 4 to 6 months of the year. Hidkal dam was constructed across the river Ghataprabha near Hidkal covering an extent of about 13,032 hectares of land. It was expected that this dam would have considerable influence on the wells.

The main source of recharge to groundwater body is rainfall. Infiltration of water from the streams during floods and return flow from irrigated fields supplement a little towards recharging. Nearly 70% of the total rainfall occurs during the southwest monsoon period of June to September. Excess rainfall is available during the month of June, July and August, which being used in all other months when evaporation exceeds rainfall. Hukkeri Taluk has 121 villages which rely upon open wells for irrigation and upon bore wells for drinking purposes. Depth of open wells ranges from 6m to 25 m while depth of bore wells ranges from 40m to 110m. Various details and yearly fluctuations of some selected wells are given in Table 3. In open wells water table starts declining from February onwards and reaches the deepest by end of May, thereafter it is being replenished through monsoon rainfall recharge. In bore wells no specific trend is available as it depends entirely on recharge and discharge through out the year. Most of the bore wells have been used for rural water supply only. Only a few among these wells are fitted with motors. As per the available information, there are about 3000 dug wells of which two-thirds are energised with electric pump sets. Average annual draft is about 25 MCM (*CGWB,1980*). On the basis of survey conducted by the Department of Mines and Geology, 15 villages have been detected where open wells have failed. Depth of these wells ranges from 9 m to 15 m. One of the presumed reasons for the failure of open wells is over exploitation of groundwater through bore wells.

Table 3. Characteristics of some of the wells in the region.

Village	Well Type	Depth [m] (SWL)	Size [m]	Sp. Yield	Water Max. [m]	Level Min. [m]	Fluctuation [m] (Average)
Hukkeri	Dug	8.14	---	0.02	6.05 (1991)	1.30 (1990)	3.70 (1986-93)
Yadgud	Dug	21.80	3.78 (Dia)	0.02	14.70 (1991)	0.66 (1987)	5.26 (1986-93)
Hebbal	Bore	45.00 8.00	0.1143 (Dia)	25 gph	5.65 (1989)	2.14 (1989)	3.97 (1986-93)
Hattargi	Bore	42.00 10.00	0.1143 (Dia)	50 gph	8.5 (1986)	1.6 (1990)	5.13 (1986-90) (Collapsed)
Hanchinal	Bore	106.00 15.00	0.1143 (Dia)	75 gph	7.64 (1988)	3.06 (1986)	4.95 (1986-88) Collapsed
Nerli	Bore	45.00 NA	0.1143 (Dia)	---	10.30 (1988)	2.52 (1986)	6.41 (1986-88) Collapsed

The groundwater balance of the Ghataprabha basin, taluk-wise, is estimated and are given in Table 4 alongwith the average annual rainfall of each taluk; for easier comparison, these are abstracted in Table 5.

Pump tests were carried out in Gajbarwadi, adjacent to Hukkeri town where cases of failed wells have been found frequently. Areas of these wells are ranging from 29.16 sqm. to 134.55sqm. and depth from 2.35m to 16.0m. Rockmass permeability values range between 0.08 m/hr. to 0.35 m/hr. Maximum inflow capacity of these wells comes out to be between 1.543 cu.m/hr and 13.42 cu.m/hr. Estimated maximum time taken for 99 % of recuperation varies from 60hrs. to 300hrs. for individual wells.

Table 4. Talukwise Yearly Groundwater Recharge in MCM and Rainfall in m.

Year	Chickodi	Gokak	Hukkeri	Raibag	Jamakhandi	Mudhol	Bilgi	Bagalkot
1986 GWR	97.96	42.22	31.25	11.05	49.89	29.8	18.06	23.44
Rf (m)	0.57	0.42	0.58	0.16	0.728	0.50	0.43	0.44
1987 GWR	38.19	61.76	34.15	30.94	77.56	37.02	45.33	54.87
Rf(m)	0.519	0.414	0.384	0.446	0.634	0.674	0.673	0.711
1988 GWR	93.42	122.9	134.5	93.91	19.9	82.01	33.2	45.13
Rf(m)	0.636	0.594	0.630	0.758	0.597	0.591	0.407	0.453
1989 GWR	74.48	132.0	56.34	44.37	99.68	69.85	23.12	49.42
Rf (m)	0.576	0.458	0.685	0.415	0.607	0.586	0.492	0.606
1990 GWR	48.02	51.61	1.74	33.97	18.75	27.5	19.6	17.99
Rf (m)	0.479	0.572	0.416	0.339	0.227	0.227	0.138	0.266
1991 GWR	134.6	26.95	67.88	68.65	51.23	27.93	15.3	47.58
Rf (m)	1.054	0.528	0.851	0.650	0.482	0.157	0.695	0.525
1992 GWR	81.25	86.03	22.98	41.19	33.06	16.35	15.3	15.68
Rf (m)	0.717	0.977	0.361	0.543	0.300	0.193	0.159	0.157
1993 GWR	96.04	32.13	58.00	26.98	46.08	31.34	21.47	36.54
Rf (m)	0.977	0.404	0.702	0.486	0.552	0.403	0.487	0.584

Table 5. Comparative Hydrological condition in Hukkeri Taluk.

Year	Ghataprabha Basin Average in m.			Hukkeri Taluk Average in m.		
	Rainfall	GWR	Ratio	Rainfall	GWR	Ratio
1986	0.480	0.035	7.29 %	0.580	0.032	5.52 %
1987	0.555	0.044	7.92 %	0.384	0.034	8.85 %
1988	0.580	0.082	14.13 %	0.630	0.136	21.59 %
1989	0.555	0.063	11.35 %	0.685	0.057	8.32 %
1990	0.330	0.026	7.88 %	0.416	0.011	2.64 %
1991	0.430	0.051	11.86 %	0.650	0.069	10.61 %
1992	0.620	0.036	5.81 %	0.361	0.023	6.37 %
1993	0.570	0.040	7.02 %	0.584	0.059	10.10 %

4.0 MODEL DESCRIPTION

The three dimensional groundwater flow equation for an anisotropic and heterogeneous porous medium is given by:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right] - W = S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where,

K_{xx}, K_{yy}, K_{zz} : hydraulic conductivity along major axes [LT^{-1}],
h : potentiometric head [L],
W : volumetric flux per unit volume (sources and/or sinks) [T^{-1}],
S_s : specific storage of the porous material [L^{-1}] and,
t : time [T]

In general, S_s, K_{xx}, K_{yy} and K_{zz} are function of space, for example; $S_s=S_s(x,y,z)$, $K_{xx}=K_{xx}(x,y,z)$, etc. whereas W and h are functions of space and time i.e $W=W(x,y,z)$ and $h=h(x,y,z)$. Equation (1) together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions, constitutes a mathematical model of ground water flow (*McDonald and Harbaugh, 1984*). Analytical solutions of equation (1) are rarely possible. So, various numerical methods are employed to obtain an approximate solution of the above equation. One such approach is the ***finite-difference*** method. The continuous system described by equation (1) is replaced by a finite set of discrete elements in space and time, and the set of finite difference equations are solved numerically which yields *values of head* at specific points and times. Possible inflow/outflow term (W) includes recharge from rainfall, artificial recharge through wells, pumping through wells, evapotranspiration losses, recharge from river/canal cells, outflow into a river/canal cell, inflow/outflow across boundaries, outflow through drains and spring flow.

5.0 NUMERICAL SIMULATION

Before trying out artificial recharge measures in Hukkeri area, it was necessary to carry out regional simulation of the sub-basin having natural boundary conditions, to ascertain the situation in totality. The details of this regional model may be found elsewhere (*Majumdar et.al.,1997*). Subsequently, a local scale model for the area around Hukkeri has been formulated with finer mesh design in order to go in for detailed analyses. The basic properties and the boundary conditions for the local scale model is derived from the regional scale model.

Generalised subsurface geology existing beneath the Ghataprabha sub-basin are soil cover, weathered zone, partially weathered zone, jointed and fractured zone underlain by sound rock. Lateral continuity of these hydrostratiographic layer varies throughout the flow domain. Surface elevations and the levels of the bottom of both the layers were extracted from the regional model and krigged through krigging model GEOPACK for 150x150 grids. The contour plots of ground level, bottom level of first layer and bottom level of second layer are shown in Fig. 2a, 2b and 2c respectively.

Groundwater flow for the local domain was investigated by subdividing the spatial domain into 45,000 finite difference grid blocks in two layers as shown in Fig 3. The descretisation consist of 150 grid blocks in each direction having lateral dimension of 704 mts in X-direction and 501 mts in Y-direction. Conforming to the regional model, the local model is also conceptualised in two distinct layers, namely, layer-1 comprised of soil cover and weathered zone and layer-2 incorporating the remaining formations. Spatial extent of rivers, drains and reservoir are incorporated according to the topographic maps. Areal recharge to the flow system is spatially variable. Contributing factor to this spatial variability is flow system heterogeneity which is guided by soil types in layer 1 and geological classification in layer 2. Six zones have been introduced for conductivity ranges and five zones for storage coefficient. These demarcations are shown in Fig 4a, 4b and Fig. 5. Layer 2 is having the same storage coefficient through out the horizontal descretisations. Zone-wise transmissivity and storativity values are depicted in Table 6 and Table 7, respectively. First layer is set to behave within unconfined conditions and second layer in a semi-confined fashion with transmissivity values varying according to the saturated thickness of the layer. The value of storage coefficient may alternate between confined and unconfined values. Vertical leakage from above is limited if the aquifer desaturates.

Table 6. Calibrated Hydraulic Conductivity values for the model.

Property No.	Layer No.	Layer Type	Kx(m/sec)	Ky(m/sec)	Kz(m/sec)
1	1	Deep Black Cotton Soil	2.350e-10	2.350e-10	2.350e-11
2	2	Basalt	3.100e-9	3.100e-9	3.100e-10
3	2	Schist and Gneiss	7.000e-7	7.000e-7	7.000e-8
4	1	Medium Black Soil	5.500e-10	5.500e-10	5.500e-11
5	1	Coarse Black Soil	1.000e-8	1.000e-8	1.000e-9
6	2	Limestone & Sandstone	3.000e-8	3.000e-8	3.000e-9

Table 7. Storage Property values used for the simulations

Property No.	Layer No.	Layer Type	Storage coefficient	Specific yield	Porosity
1	1	Deep Black Cotton Soil	0.01	0.05	0.35
2	2	Rock Formation	1.00e-6	0.14	0.35
3	1	Medium Black Soil	0.001	0.10	0.35
4	1	Mixed Red and Black soil	0.001	0.10	0.35
5	1	Coarse Black Soil	0.001	0.20	0.40
6	1	Lateritic soil	0.001	0.12	0.30

Physical characteristics of the four river/ stream systems are delivered by two parameters i.e. river bottom elevation and conductance. Conductance value includes actual stream width, length of the cell, hydraulic conductivity of the bed material and thickness of the transmitting layer. These rivers are expected to interact with the aquifer system depending upon the stages in the river and the water table in the aquifer. Like-wise, the four major drains existing have also been incorporated into the model to represent the drainage pattern.

Calibrated regional scale parameters are validated for the steady state condition in the local scale model. A transient run was then executed for a selected season in the year 1982-83. Number of stress periods are 6, each containing 30 days, starting from May 1982 to November 1982. Initial condition for both the layers are supplied through surfer-grid generated for May, 1982 as shown in Figure 6a and 6b. Post monsoon scenario is depicted in Figure 7a and 7b. For steady state validation no additional recharge blocks are provided except water is presumed to be standing at an highest elevation throughout the study domain in each layer. In transient run recharge values have been provided in 7 zones based on the Theissen polygon analysis as shown in Figure 8. The estimated recharge values for the seven zones are provided in Table 8.

Table 8. Recharge estimates for transient run for the season 1982-83.

Sr. No.	Zone No.	Station Name	State	Annual Rainfall	Annual Recharge
1	1	Chandgad	Maharashtra	2814 mm	422 mm
2	2	Gadinglaz	Maharashtra	644 mm	97 mm
3	3	Belgaum	Karnataka	877 mm	131 mm
4	4	Bailahongal	Karnataka	382 mm	57 mm
5	5	Chikodi	Karnataka	365 mm	55 mm
6	6	Gokak	Karnataka	353 mm	53 mm
7	7	Hukkeri	Karnataka	391 mm	59 mm

Effect of the following artificial recharge measures have been evaluated using the simulation model for the Hukkeri region.

i. Recharge through a set of injection wells in the Hukkeri region.
ii. Raising of water level in the Ghataprabha river, in the downstream of Hidkal dam through appropriate structural measures or by other means.
iii. Raising of water level in the Hiranyakeshi river by suitable means.
iv. Construction of underground check dam all along the existing Chikodi branch canal.
v. Raising the recharge in adjacent the Chikodi zone

6.0 RESULTS AND DISCUSSION

Results of the steady-state validation is shown in Figure 9a and Figure 9b, for layer 1 and layer 2, respectively. The mass balances for the steady state validation is also computed in cubic meters as follows:

Components			In	Out	
River Leakage	=		114.24	18.68	
Drains	=		0.0	95.61	
Total	=		114.24	114.29	
In - Out	=	-0.05	Discrepancy	=	-0.04%

It can be observed that water-level contours follow the local topography, in general. Results of transient-run is shown in Figure 10a and 10b for sample water-level contours in layers 1 and 2. Mass-balance results (in cubic meters) have been acquired as shown in Table-9. Simulated water-level contours for the stress-period 6 almost follow the observed post-monsoon scenario of contours shown in Figures 7a and 7b.There is no appreciable increase in total mass-balance over the period.

On the simulated model, various options of artificial recharge have been evaluated. For the well-injection strategy, one well has been selected in Hukeri and various rates of injection were carried out putting the well-screen in layers 1 and 2 alternatively. There is no appreciable change in the water-level contours. In mass-balance analysis, the total amount of water being injected is getting adjusted in the quantity of water going out of the storage term. As such there is no big difference found in the groundwater balance estimates with and without injection well even with a higher value of 40,000 cubic meters per day. Subsequently, a network of wells have been conceptually installed in the model and simulated for various injection rates. The resulting mass balances and equipotentials did not exhibit any significant improvement in the situation. It has been inferred that though the water retaining capacity of the aquifer material is good, the severe topographic undulations with alternating trough and crusts cause draining of recharged water faster. That is the reason why in the net mass balance there is no substantial increase in the storage of the aquifer for a particular stress period.

Table 9. Mass balance results for various stress periods obtained from the transient simulation.

Stress-Period	Components	In (m^3/day)	Out (m^3/day)
I	Storage	57168648	14947793
	Drain	0	31801664
	Recharge	15540431	0
	Riv. Leakage	288589	26248542
	Total	72997664	72998000
II	Storage	103528906	29941904
	Drain	0	31801664
	Recharge	31042910	0
	Riv. Leakage	640823	26248542
	Total	135211824	72998000
III	Storage	143311408	45721532
	Drain	0	82625784
	Recharge	46504860	0
	River Leakage	1774340	63240532
	Total	191590608	191587840
IV	Storage	178681488	61333548
	Drain	0	103871200
	Recharge	61941660	0
	River Leakage	2743226	78157080
	Total	243366384	243361824
V	Storage	210304672	76752216
	Drain	0	123024392
	Recharge	77345464	0
	River Leakage	3523490	91390512
	Total	291173632	291164104
VI	Storage	238954512	92168392
	Drain	0	140464944
	Recharge	92730752	0
	River Leakage	4303673	103346440
	Total	33598892	335979776

Table 10. Zonal mass balances for the first stress period before activating injection wells

Zones	Components	In (m^3/day)	Out (m^3/day)
I (Region outside Hukkeri Taluk)	Storage	1597600	442190
	Drain	0	976310
	Recharge	463760	0
	Riv. Leakage	4208	647150
	Zonal exchange	4.8	11.5
	Total	2065500	2065700
II (Hukkeri Taluk)	Storage	130490	54998
	Drain	0	3681
	Recharge	54017	0
	Riv. Leakage	4716	130550
	Zonal exchange	11.5	4.8
	Total	189240	189230

The zonal mass balances for the Hukkeri region and rest of the study domain have been computed separately to examine any zonal exchanges between the two before activating the injecting wells and also after activating the injection wells for artificial recharging. The results did not show any improvement in the aquifer condition as compared from the zonal mass balances given in Table 10 and Table 11. The comparison of head distribution in the two cases for stress period 6 in layer 1 are shown in Fig. 12a and 12b.

Another option tried out was maintaining higher water-levels in the Ghataprabha river downstream of Hidkal Dam and also in the adjoining tributary called Hiranyakeshi. With the increase in the water-levels, the groundwater table in Hukeri area has shown an increasing trend. This can be seen in Figure 11a and 11b, where water level contours for the top layer are plotted for two selected stress periods. This result appears to be significant as it supports the general notion that construction of the dam might have been one of the causes that resulted in the depletion of the aquifer in the Hukkeri region.

Table 11. Zonal mass balances for the first stress period after activating injection wells.

Zones	Components	In (m^3/day)	Out (m^3/day)
I (Region outside Hukkeri Taluk)	Storage	1597600	442190
	Drain	0	976310
	Recharge	463760	0
	Riv. Leakage	4208	647150
	Zonal exchange	4.8	11.5
	Total	2065500	2065700
II (Hukkeri Taluk)	Storage	130490	54998
	Drain	0	3681
	Recharge	54017	0
	Riv. Leakage	4716	130550
	Wells	1000	0
	Zonal exchange	11.5	4.8
	Total	190240	190230

In yet another trial an underground check-dam all along the Chikodi branch-canal was envisaged in the model and transient simulation was carried out to examine whether that will improve the condition of the aquifer. However, no significant rise in the water-level of the region is observed. Further, no appreciable changes in the water-balance have also been noticed. This clearly indicates that the leakages are not localised, but are taking place in the domain as a whole owing to gravity drainage which is controlled by the downstream water levels.

Another scenario looked into was a possible increase in the recharging from the adjacent Chikodi zone. The hypothetical recharges from the Chikodi was then assumed to be four times higher than the existing recharge from that zone. Transient simulation were carried out and mass balances computed zone-wise. The results of the mass balances can be seen in Table 12. Also, the head distribution for stress period 6 in layer 1 and layer 2 respectively are shown in Fig. 13a and 13b.

Table 12. Zonal mass balances for the first stress period with augmented recharge in the adjacent Chikodi area

Zones	Components	In (m^3/day)	Out (m^3/day)
I (Region outside Hukkeri Taluk)	Storage	159550	497900
	Drain	0	976710
	Recharge	521930	0
	Riv. Leakage	4208	647150
	Zonal exchange	4.8	11.5
	Total	2121600	2121800
II (Hukkeri Taluk)	Storage	130490	59195
	Drain	0	3681
	Recharge	57213	0
	Riv. Leakage	4716	130550
	Wells	0	0
	Zonal exchange	11.5	4.8
	Total	193430	193430

7.0 CONCLUSIONS

Evaluation of a few artificial recharge measures in the Hukeri region have been carried out by the application of mathematical modelling. A local scale flow model has been conceptualised and formulated, based on a regional scale model of the sub-basin, for the purpose. The evolved model performed well both in steady-state and transient conditions. It has been observed that flow in the study domain is mostly influenced by the local topography. Of the various artificial recharging measures tried out, only one option deemed suitable; others being found little effective. The best option, according to simulation results, is to maintain higher water-levels in the Ghataprabha river reach downstream of Hidkal Dam site and also in Hiranyakeshi river which is an adjoining tributary of the Ghataprabha river. However, the feasibility of this option was not subjected to analysis as it is beyond the scope of the present report. Other efforts towards artificial recharging of the dwindling aquifers of Hukkeri, such as ponding or injecting wells found to be of not much effective as the flow domain is strongly influenced by the undulating geology of the region. Similar investigations may be carried out to evaluate various options for artificial recharging in any region so that appropriate methods can be adopted for optimum benefit.

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APPENDIX

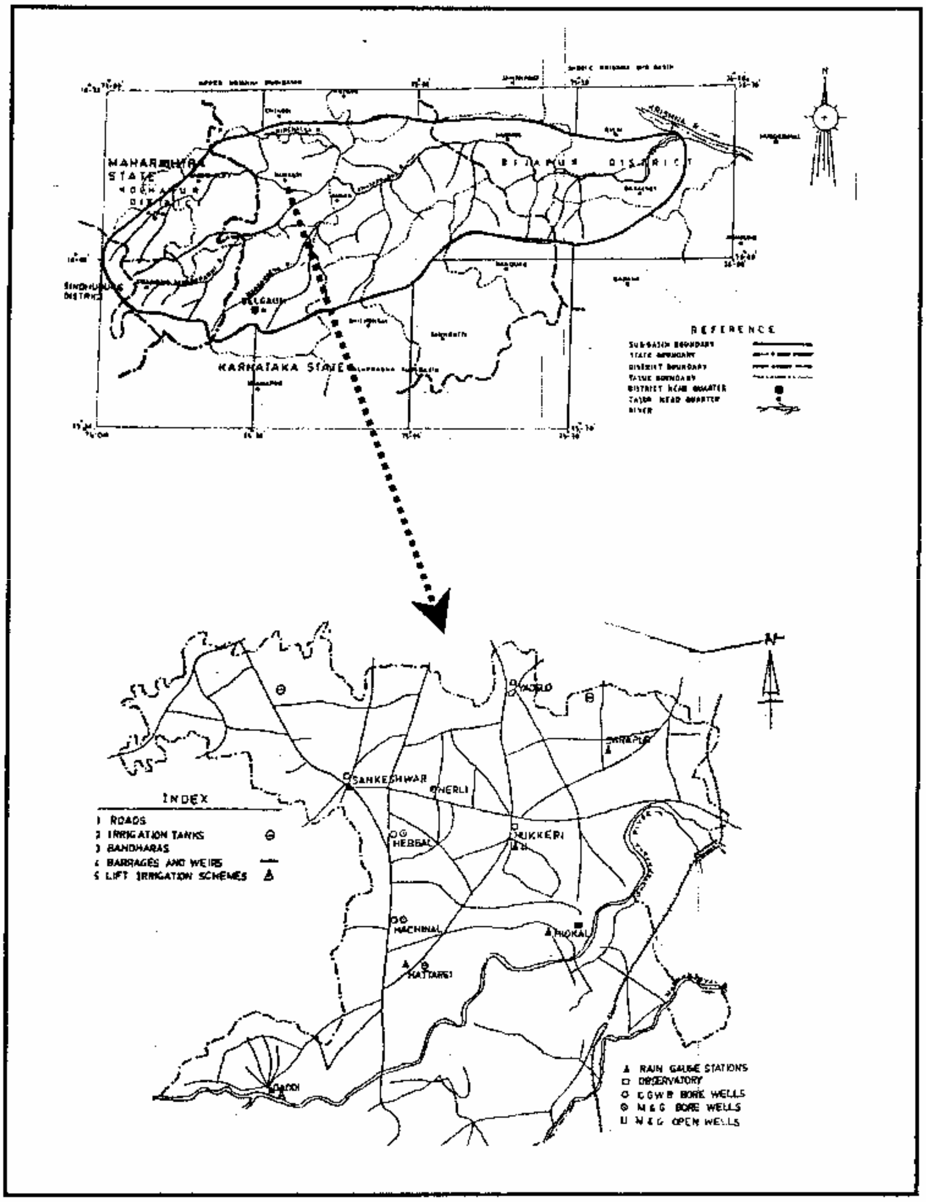

Fig. 1 Location map of the study area in the Ghataprabha sub-basin

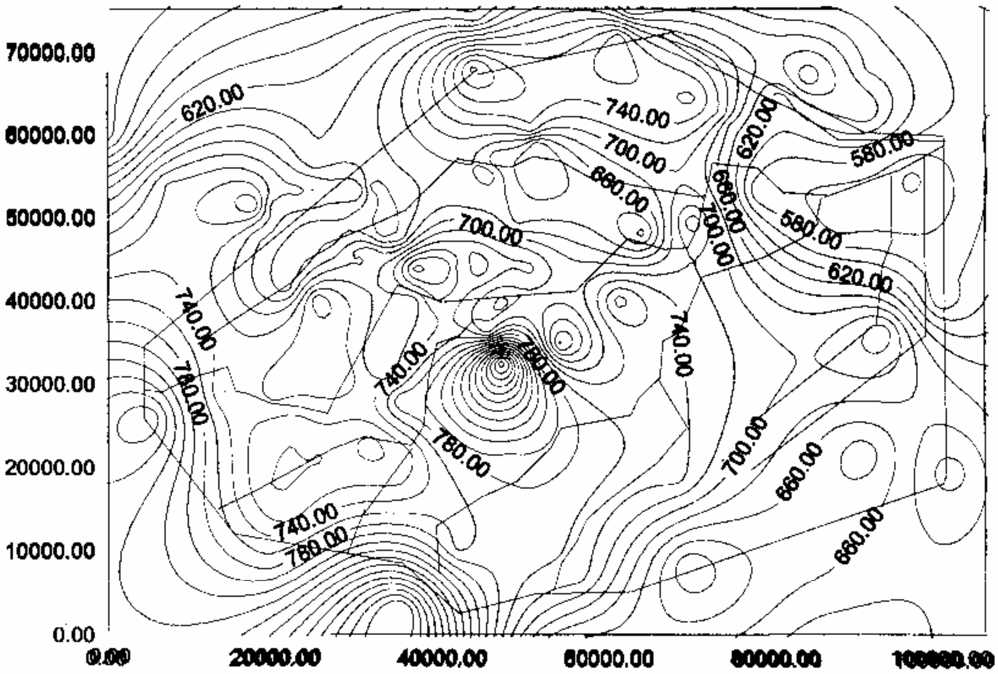

Fig.2a Ground level contours of he study domain

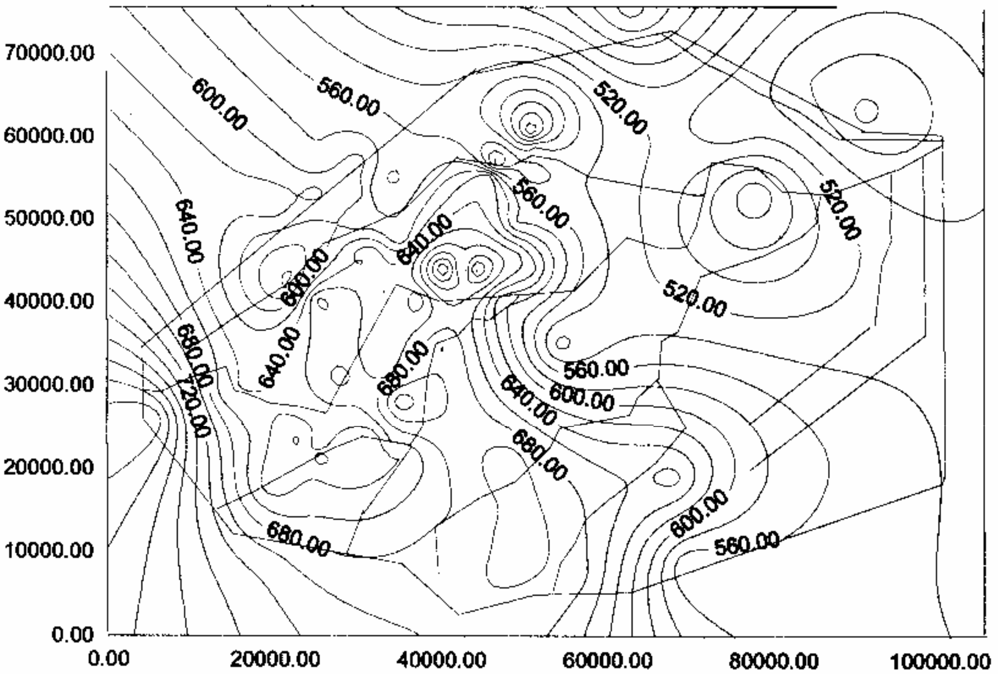

Fig.2b Bottom elevation contours in layer 1 of the study domain

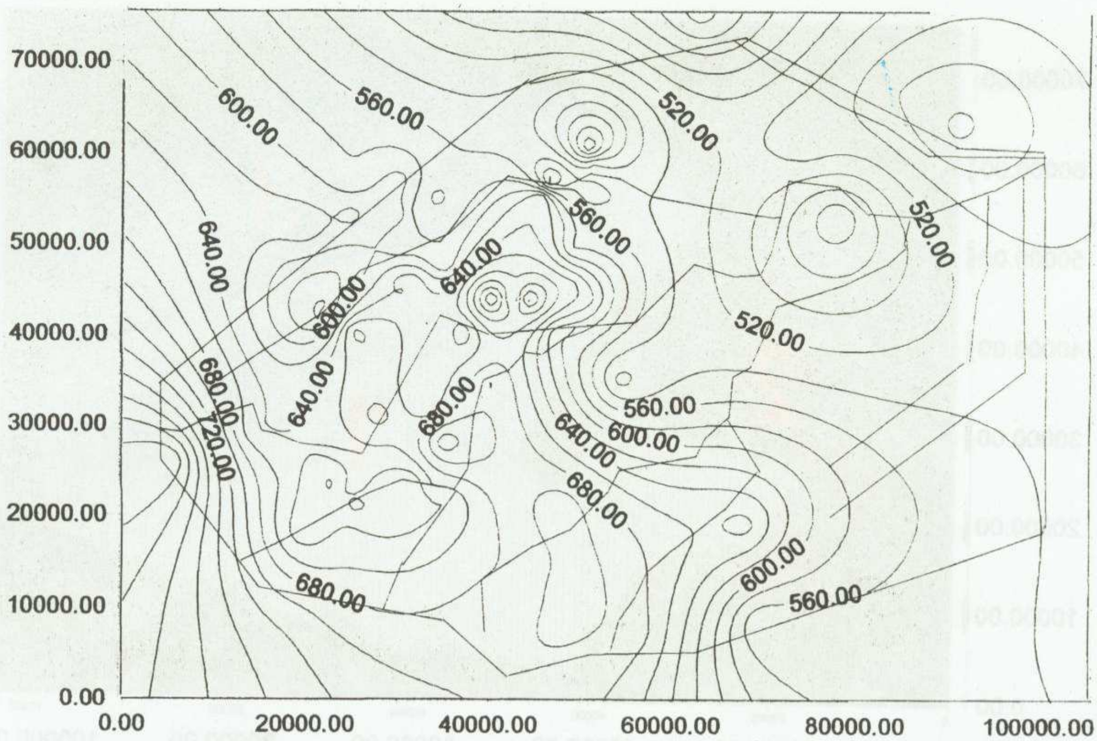

Fig. 2c Bottom-elevation contours in layer 2 of the study domain

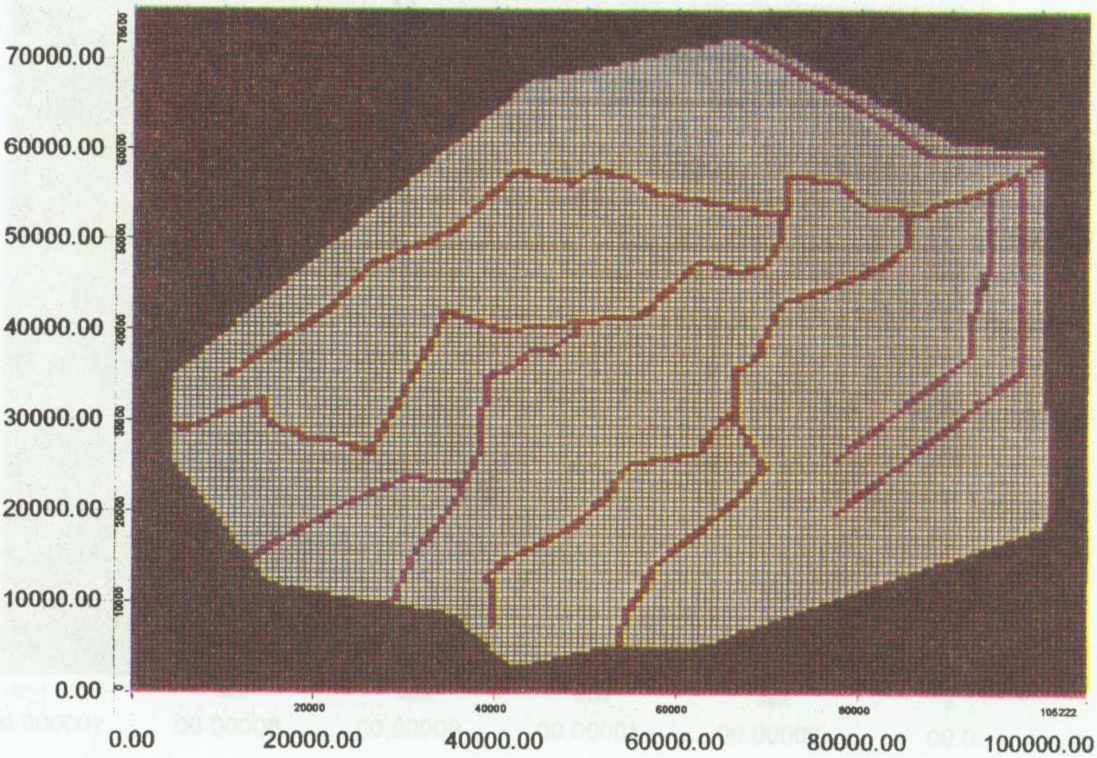

Fig. 3 Finite difference discretisation of the study domain

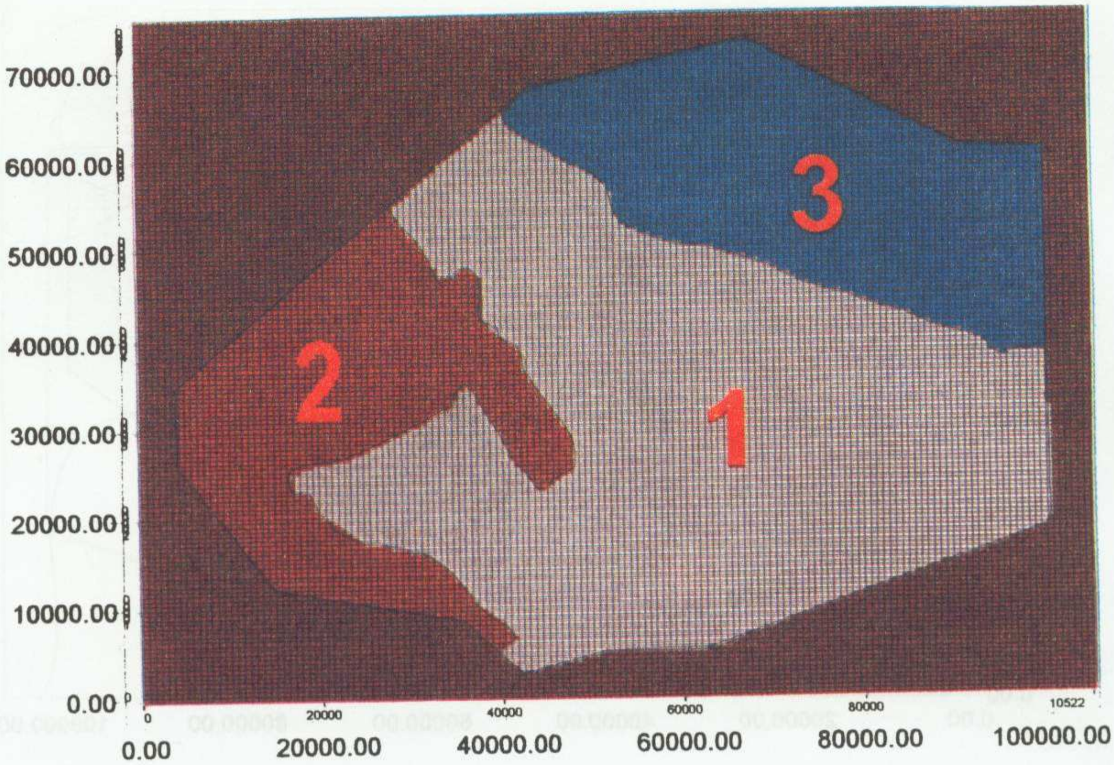

Fig. 4a Hydraulic conductivity zones in layer 1

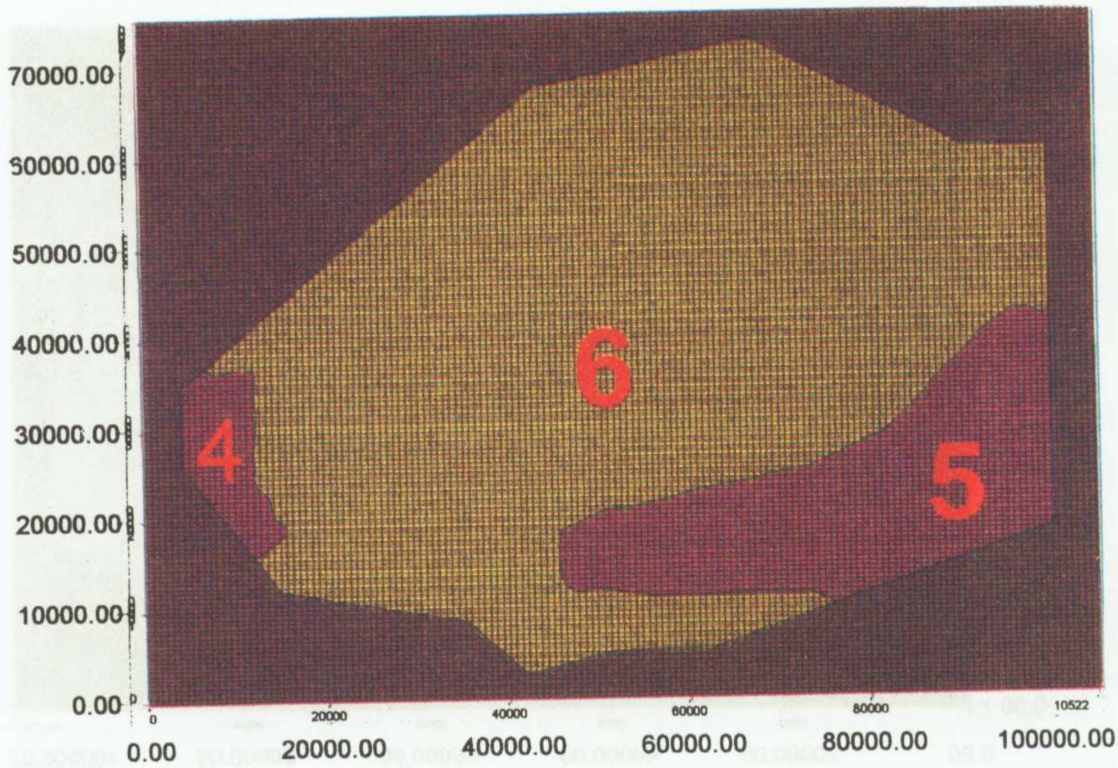

Fig. 4b Hydraulic conductivity zones in layer 2

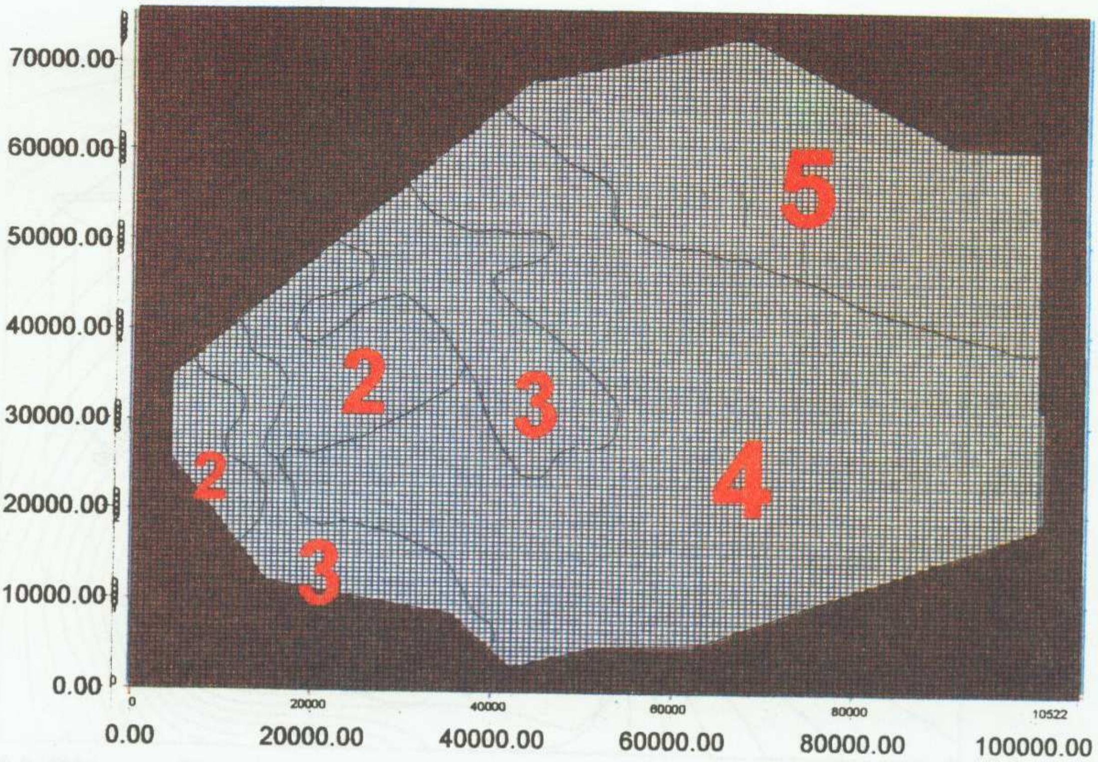

Fig. 5 Storage coefficient zones in layer 1

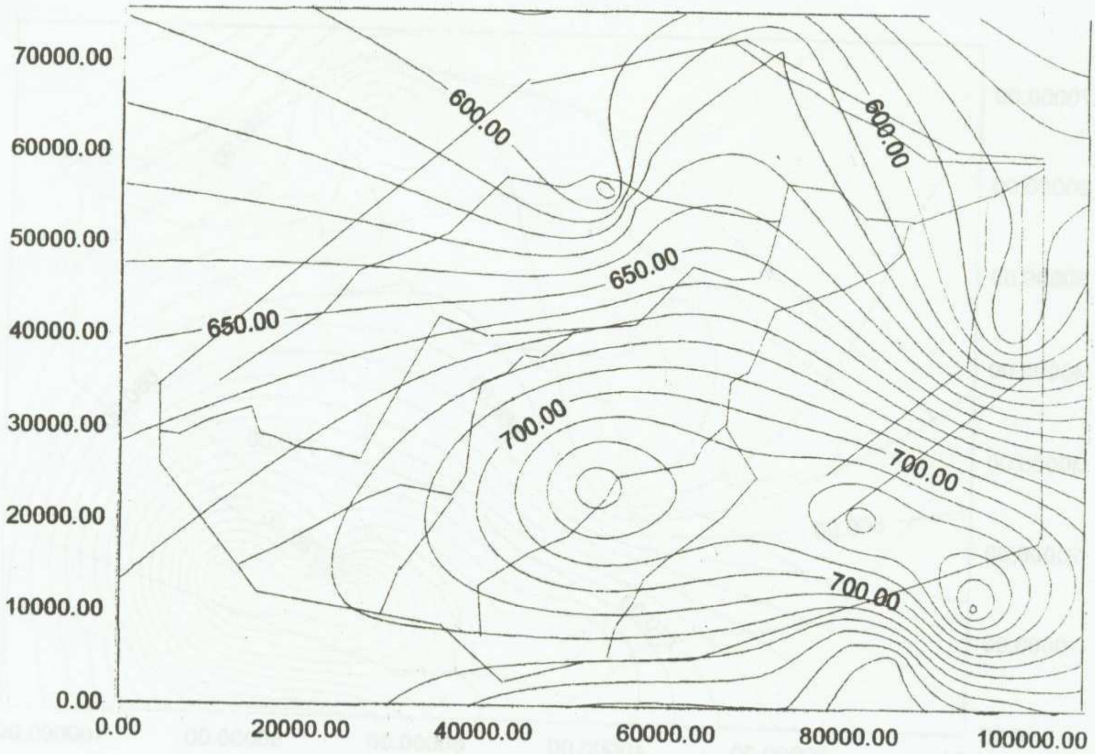

Fig. 6a Pre-Monsoon water level contours in layer 1

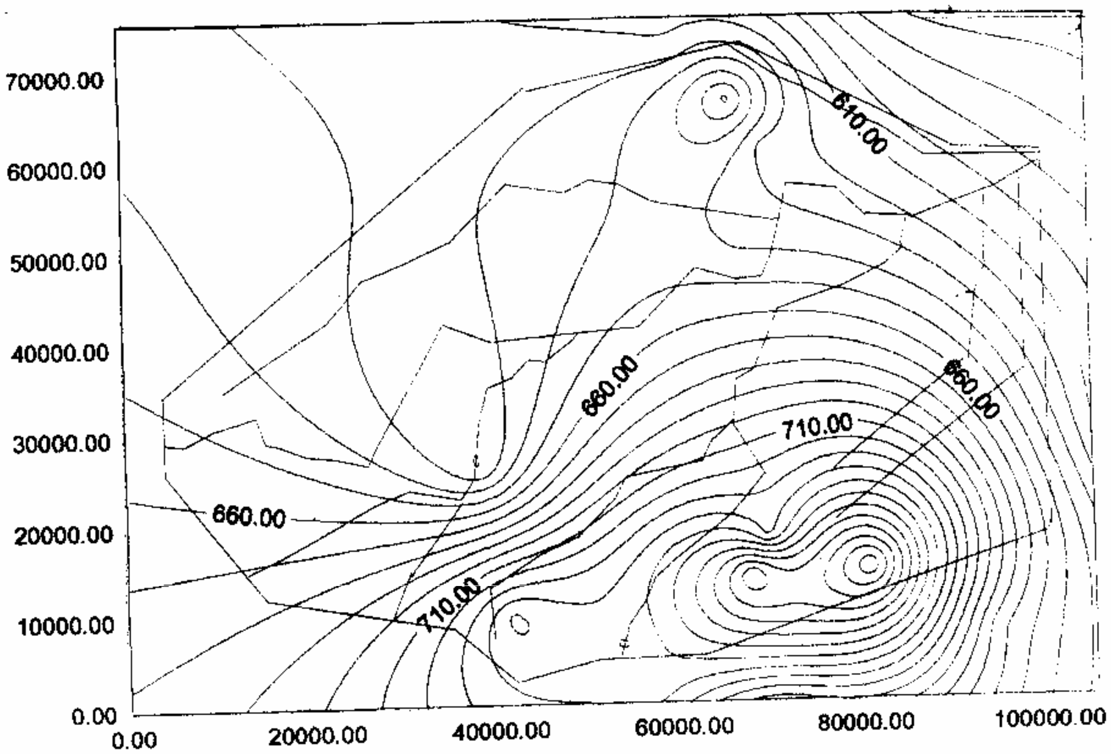

Fig. 6b Pre-Monsoon water level contours in layer 2

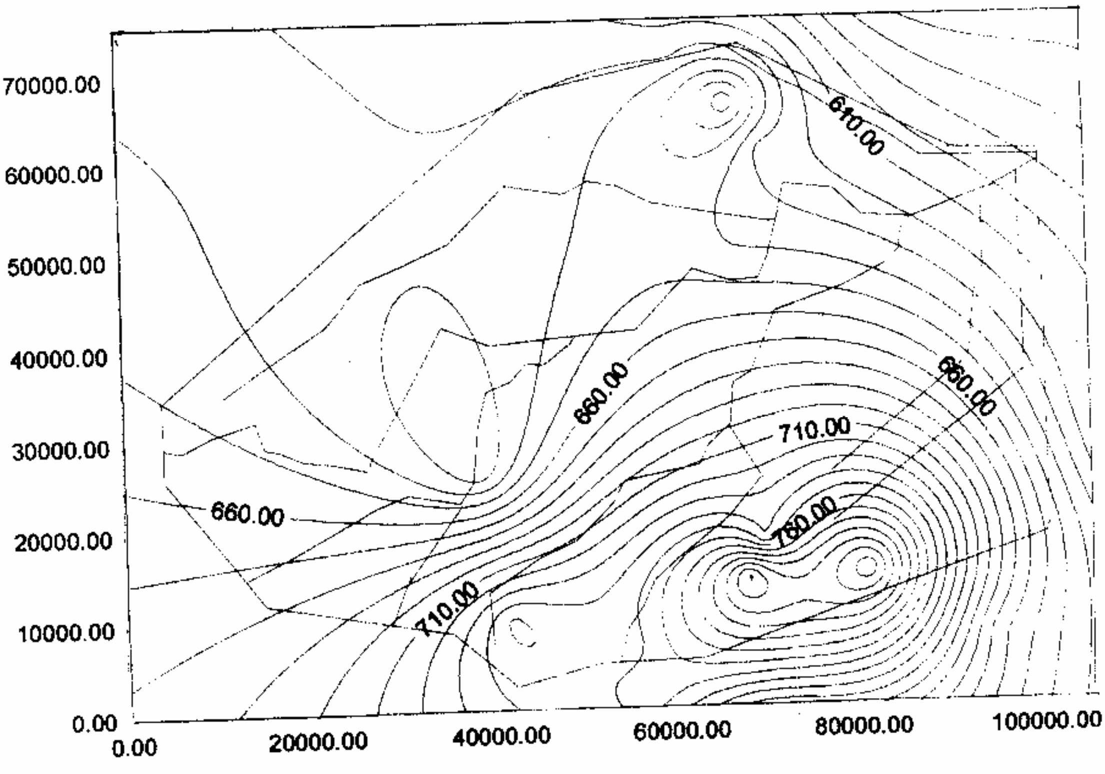

Fig. 7a Post-Monsoon water level contours in layer 1

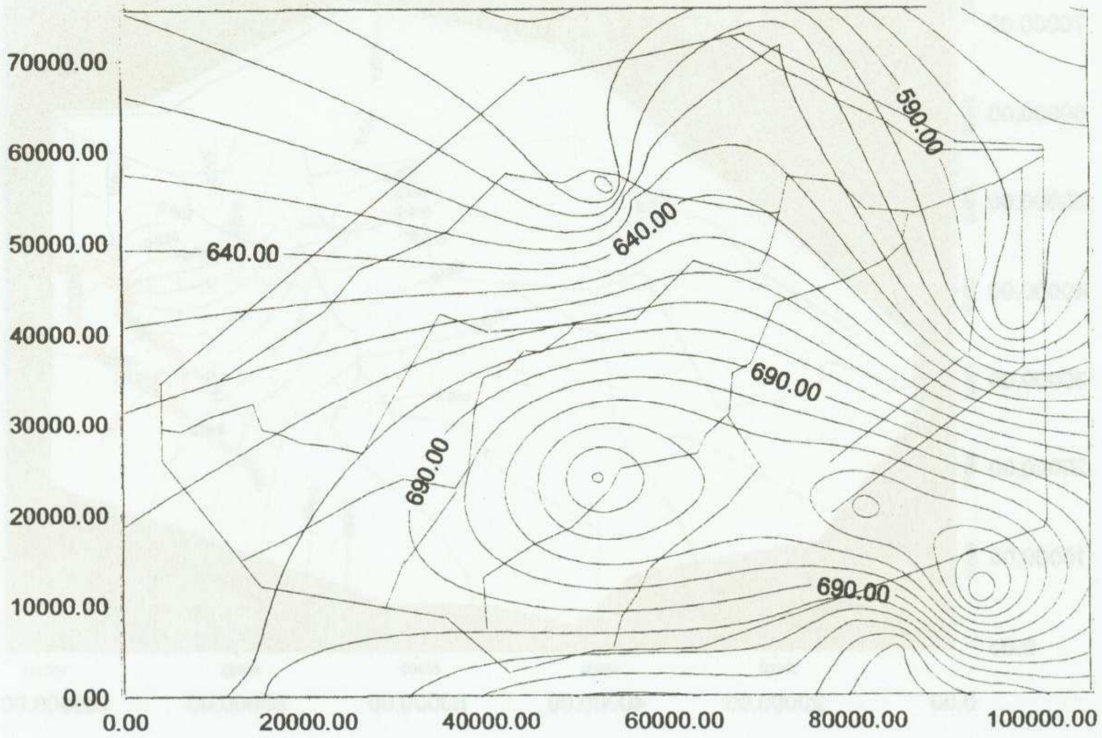

Fig. 7b Post-Monsoon water level contours in layer 2

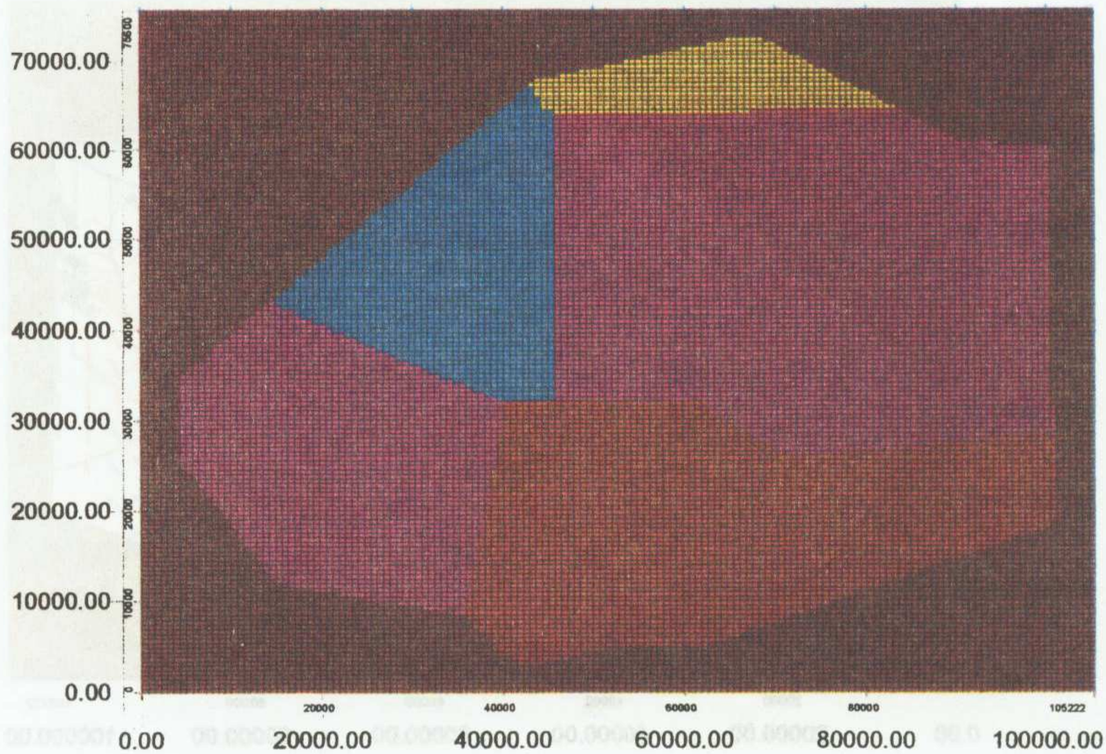

Fig. 8 Recharge zones of the study domain

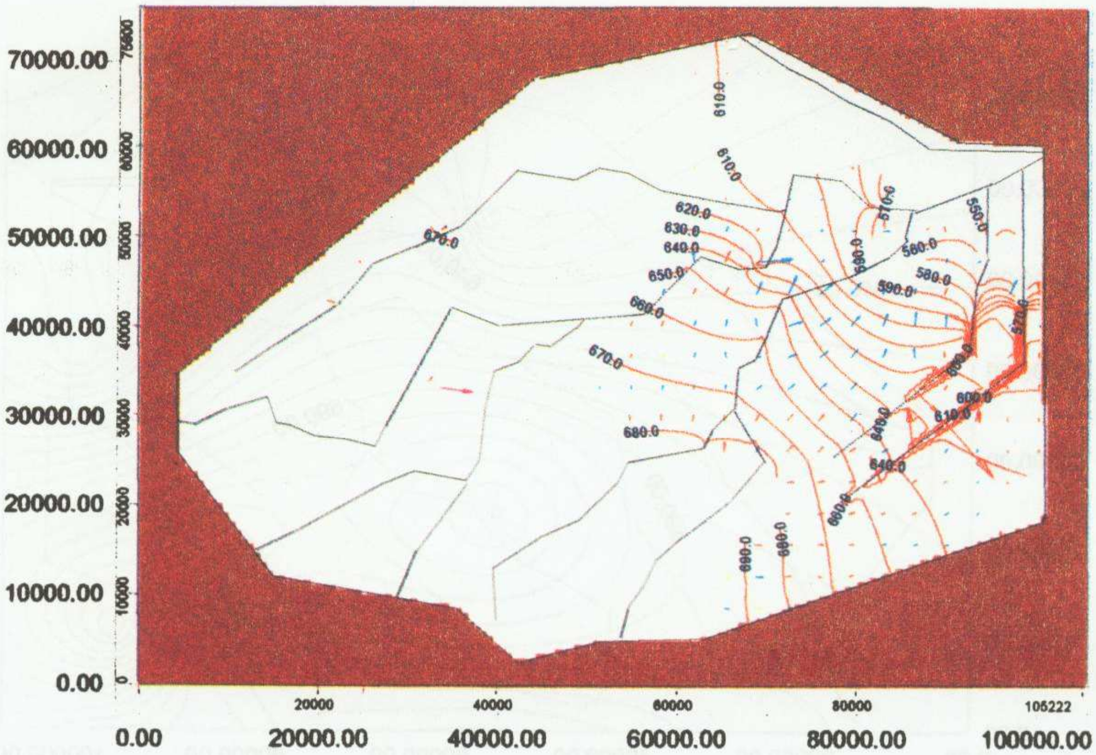

Fig. 9a Water levels in layer 1 with steady state simulation

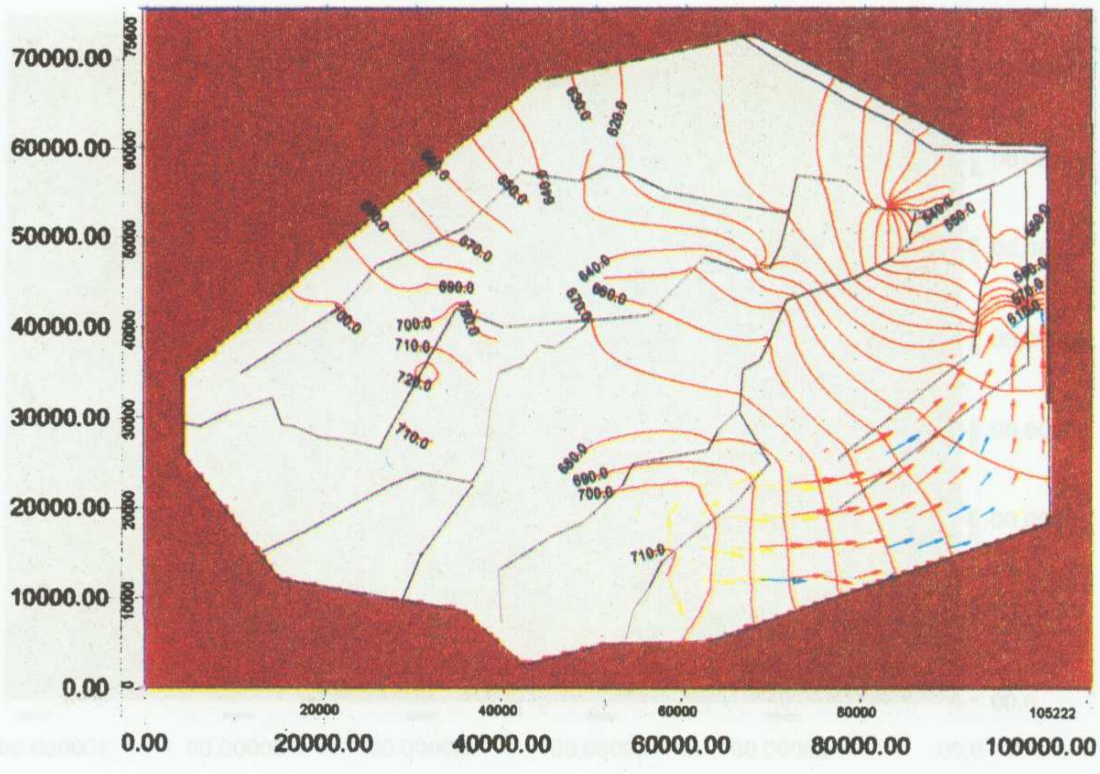

Fig. 9b Water levels in layer 2 with steady state simulation

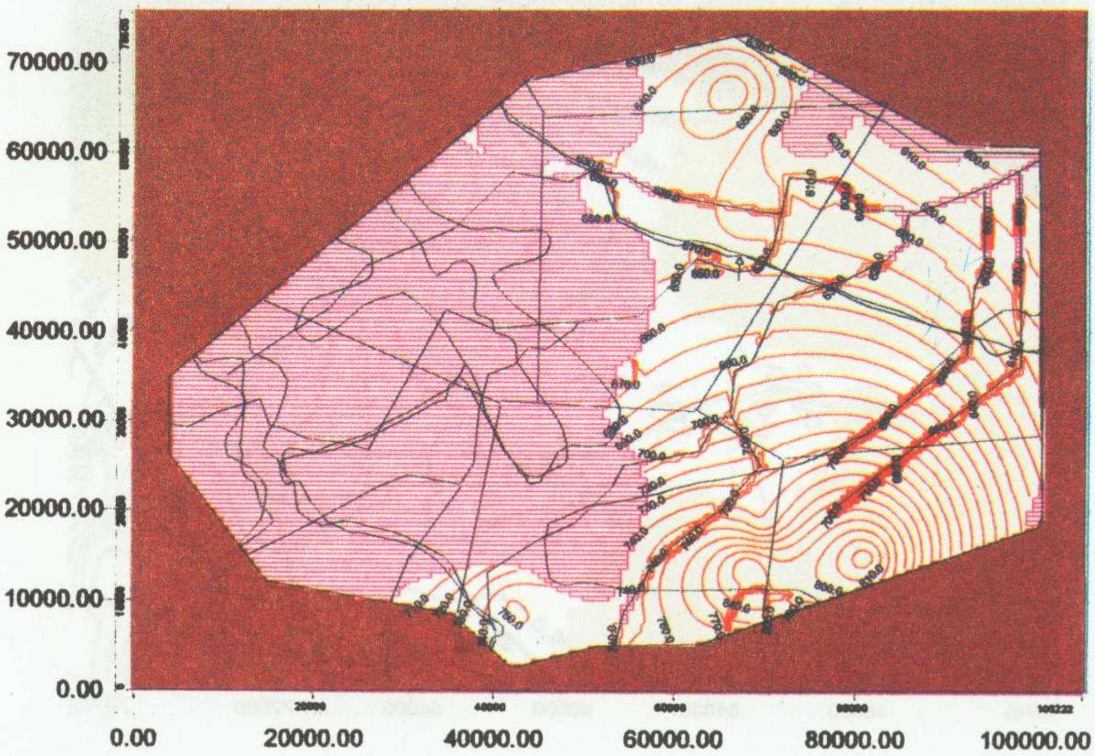

Fig. 10a Water levels in layer 1 with transient simulation

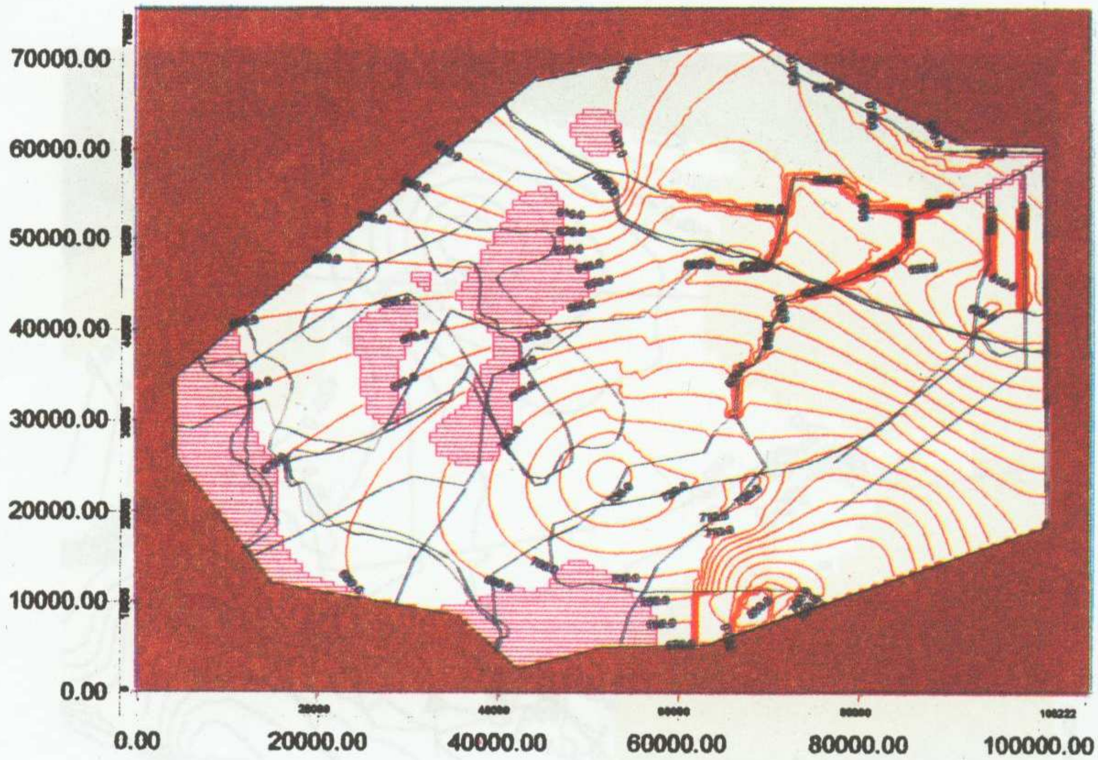

Fig. 10b Water levels in layer 2 with transient simulation

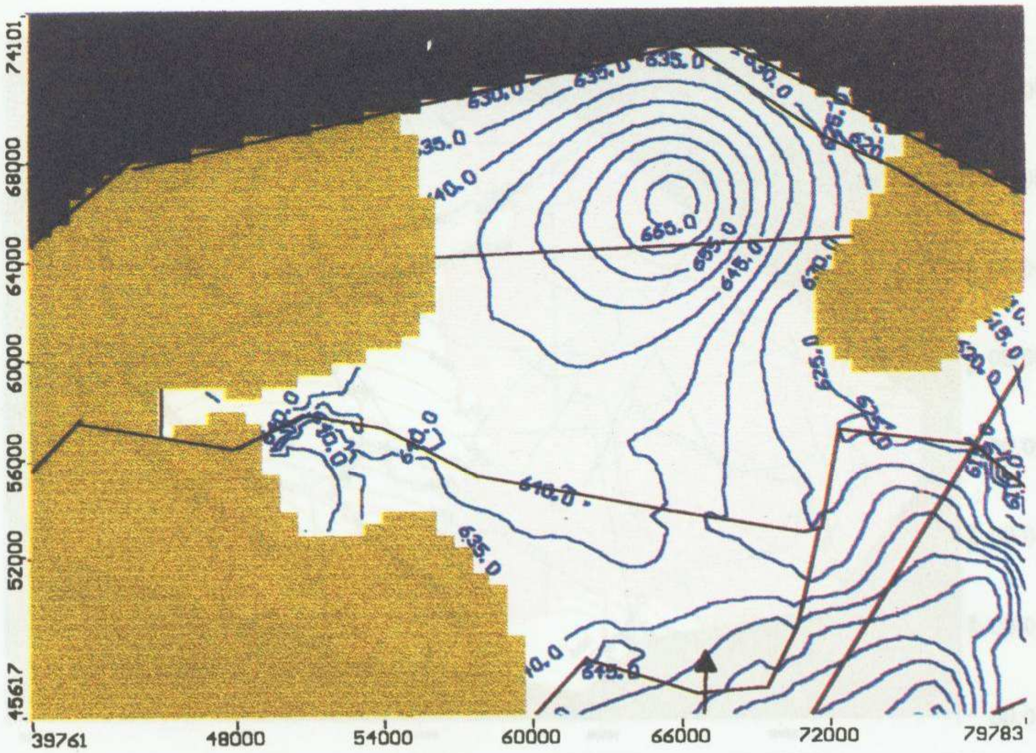

Fig 11a Waterlevel contours with artificial measure for stress period 1

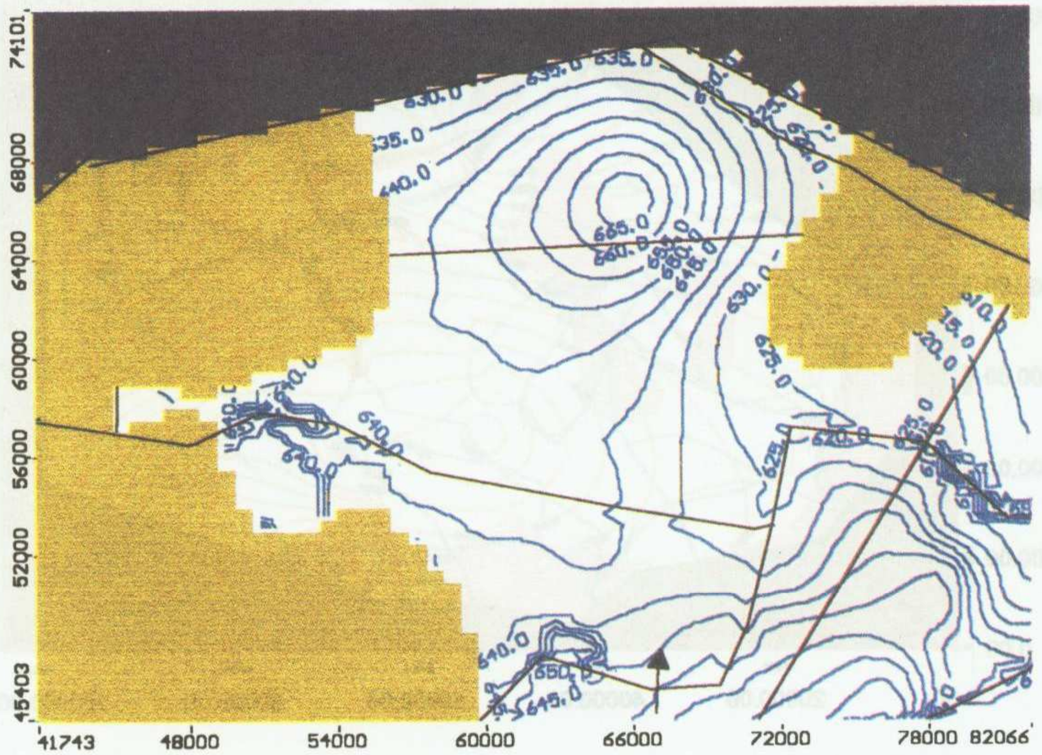

Fig. 11b Waterlevel contours with artificial measure for stress period 4

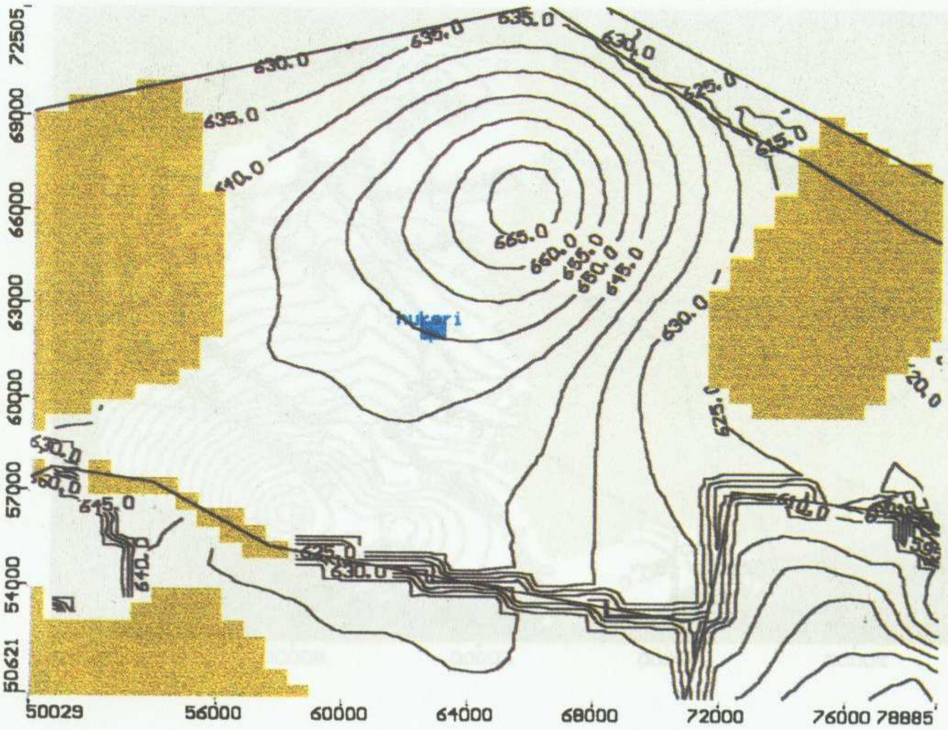

Fig. 12a Water level contours for stress period 6 without injecting wells

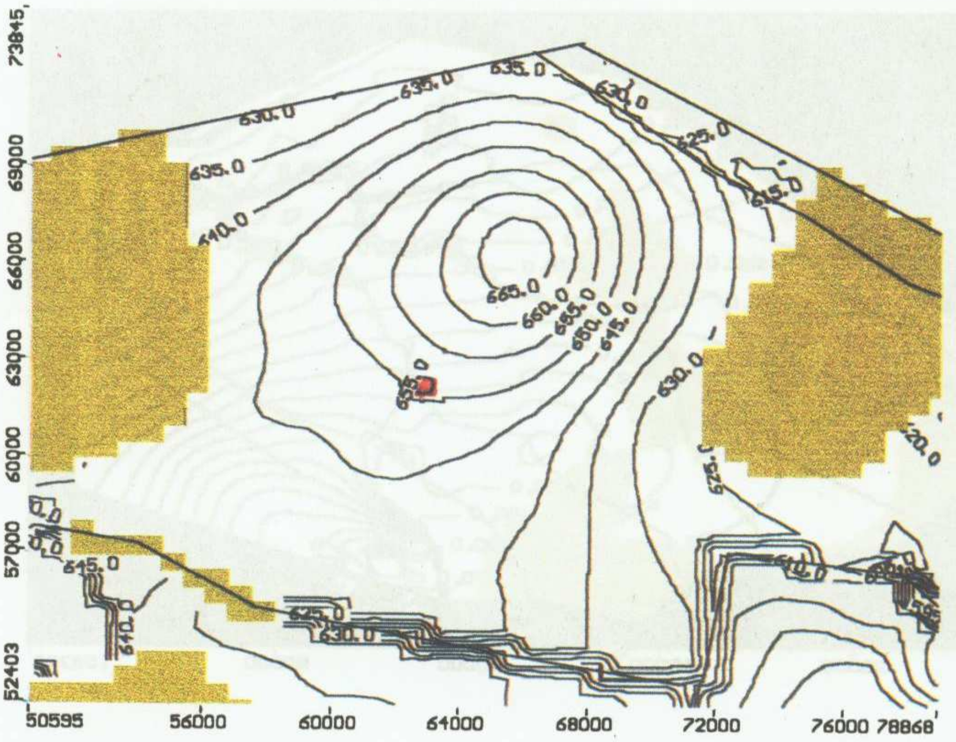

Fig. 12b Water level contours for stress period 6 with injecting wells

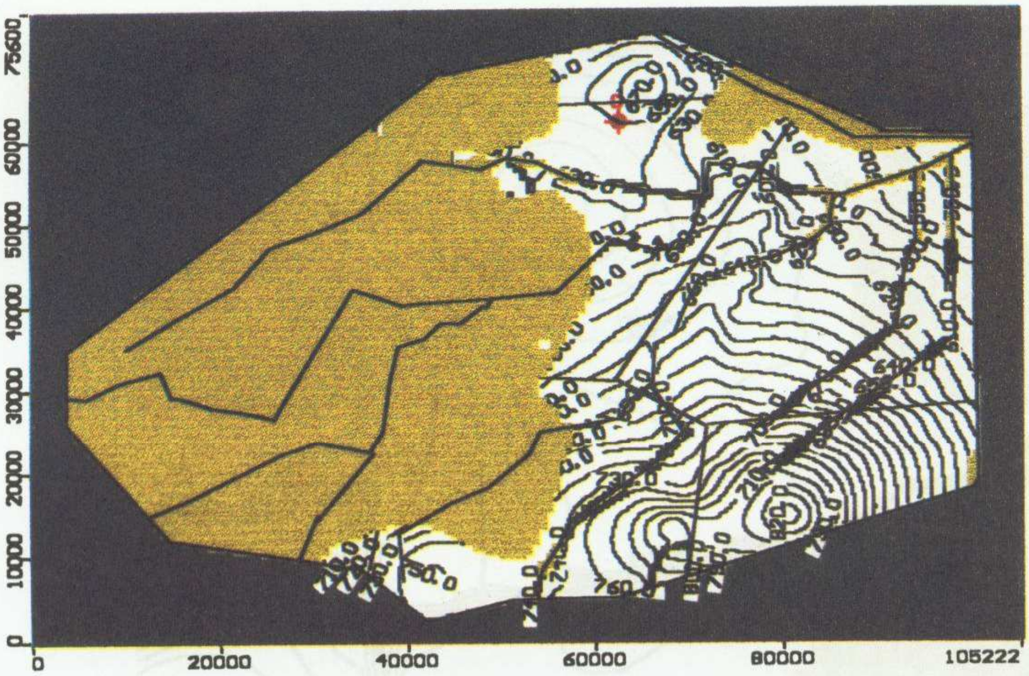

Fig. 13a Waterlevel contours in layer 1 with augmented recharge

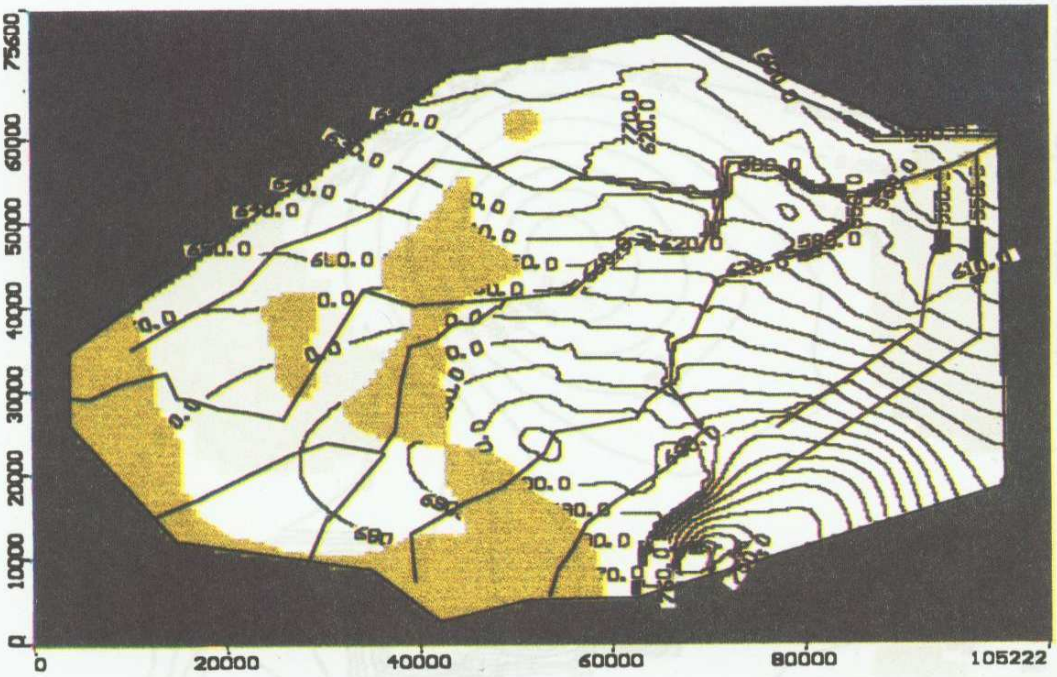

Fig. 13b Waterlevel contours in layer 2 with augmented recharge

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