A Case Study Illustration on Rising Groundwater Table in Jodhpur City, Rajasthan

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This lecture note presents an illustration of various data analyses and results obtained from the study carried out on "Rising groundwater table in Jodhpur City, and evolving a management plan for containing the rising trend" by the Ground Water Hydrology Division of the Institute.

BACKGROUND

The rise of groundwater table near to the ground surface in some parts of the Jodhpur city has resulted in a hazard to the people living in the affected areas. Controlling the rising trend of groundwater level in the urban area of Jodhpur city has emerged as a challenging task to find the cause and an immediate problem resolving scientific solution for the Public Health Department and Ground Water Department of the Government of Rajasthan. In order to find the exact source and causes of groundwater table rise and to develop an appropriate management plan to revert back the rising trend to contain the groundwater at a safe level, the problem was referred to the National Institute of Hydrology, Roorkee.

For addressing the issues and to reach to logical conclusions and solution, a systematic in depth analysis of the data/information related to topography, demography, geological formations, hydrometeorology-hydrology and hydrogeology, groundwater quantity and quality, sewage flows, inflows and outflows of waters to/from the Jodhpur city and from the Kailana-Takhatsagar Reservoir have been carried out. To analyze the data, all spatially varying databases have been geo-referenced with reference to the geographic coordinate system (WGS-1984) by their latitudes and longitudes. Therefore, the analyzed data and results presented in this report can be verified with the in situ field truth.

The Study Area

The study area (Figure 1) comprising of 76 sq. km. encompasses the old and the sprawled Jodhpur city area including the waterlogged area. The Kailana and the Takhatsagar Reservoirs, which are two naturally formed cascading type geological faults and are the source of water supply to the city area, are located outside the boundary of the study area as they are located in a different geological entity. The topography of the Jodhpur city area (Figure 2), which has been analyzed making use of surveyed data supplied by the GWD, Jodhpur in conjunction with the ASTER data, showed a general slope of the Jodhpur city towards south-west, south, and south-east directions, except for the hilly terrain in the north-western side. The southern terrain has flatter slope than that of the south-west, and south-east terrain. The topography level of the city area varies between 202 m and 360 m above MSL (Mean Sea Level) with a small stretch near to the fort area having higher elevation of 310 m, whereas most of the area in the city is largely flat terrain having elevation below 250 m above MSL.

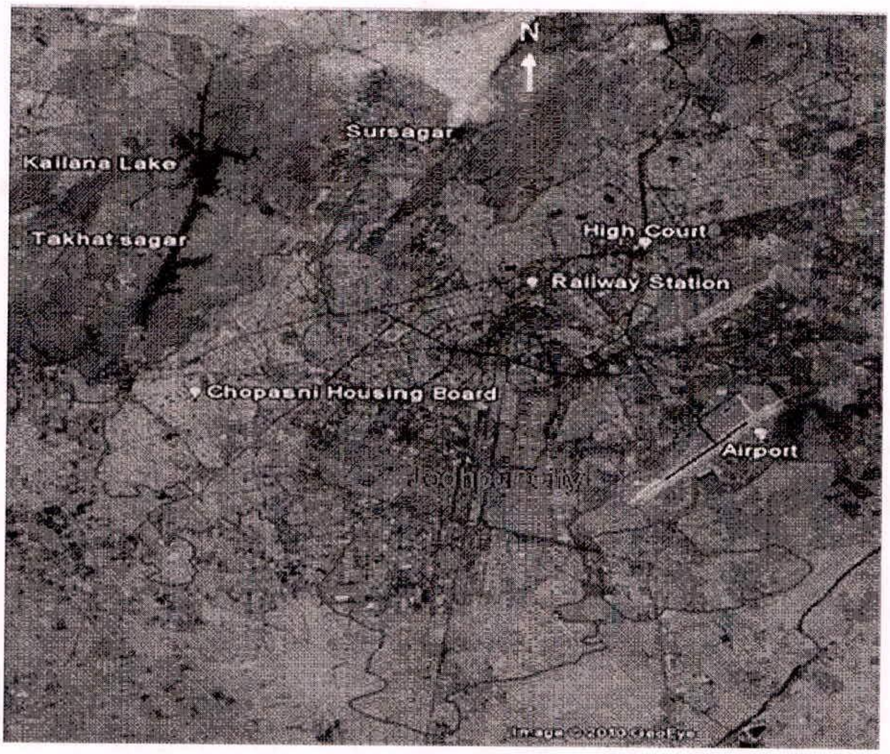

Fig. 1 A geo-referenced map of the Jodhpur city showing its sprawled area and water bodies in and around the city.

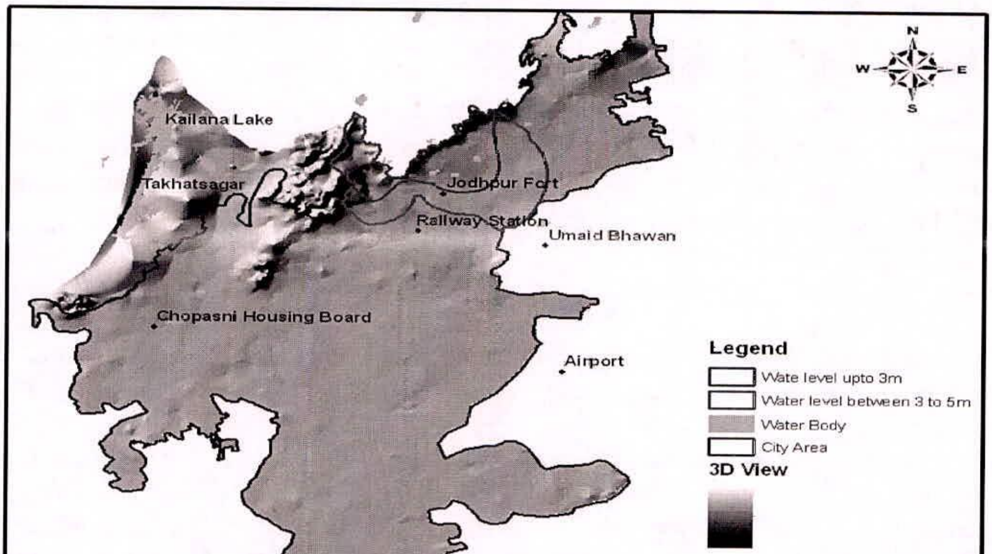

Fig. 2 A 3-D Digital Elevation Map (DEM) of the Jodhpur area showing location of Kailana and Takhatsagar and area in which water table lies up to 3 m and 5 m below ground surface.

Geological Setups and Formations

Geologically, Jodhpur area is comprised of the rocks of Pre-Cambrian, Paleozoic periods and Quaternary sediments (Figure 3). The geological formations of the Jodhpur city area have been analyzed making use of the bore logs data of 93 locations supplied by the GWD, Jodhpur in 'ROCKWORKS' software. Based on the analysis one could infer that the Kailana and Takhatsagar area is located on the Rhyolite formation, whereas Jodhpur city is mainly located on the sandstone and shale formation (Figure 4) . These two formations have different hydro-geological properties and cannot be considered as a single system. The geological formations of the Jodhpur city area are primarily composed of Shales, Sandstones and Rhyolites with the Quaternary alluvium formations at the top particularly in the plain areas. The Quaternary alluvium formations vary in thickness from few centimeters to about 75 m and form an unconfined aquifer.

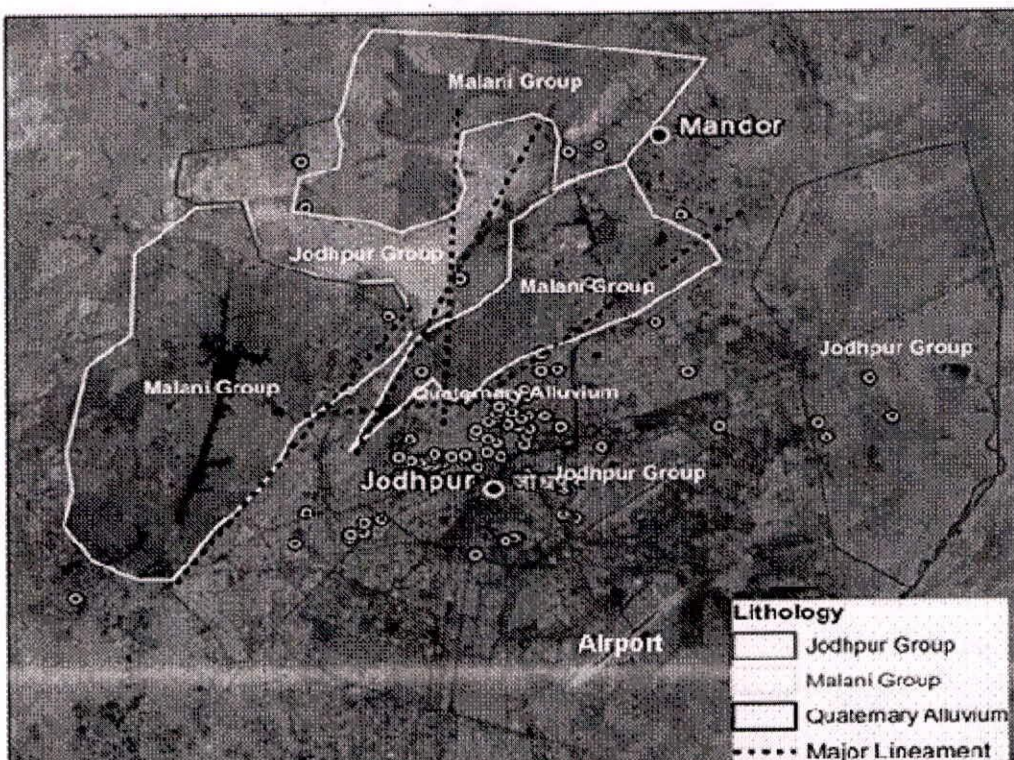

Fig. 3 Geological groups of the geological formations of Jodhpur area as observed from the satellite imageries.

Rainfall and Demography

Analysis of thirty six years (1971-2006) daily rainfall data of the Jodhpur city indicated that about 68% and 86% of the annual rainfall occurred respectively during July-August and during the monsoon months (June through September) with average annual rainfall of 378 mm. The maximum water surface evaporation is observed to be in the month of May (14.127 mm/day) followed by June (13 mm/day), and minimum is in the month of December (4.059 mm/day) followed by January (4.255 mm/day) every year.

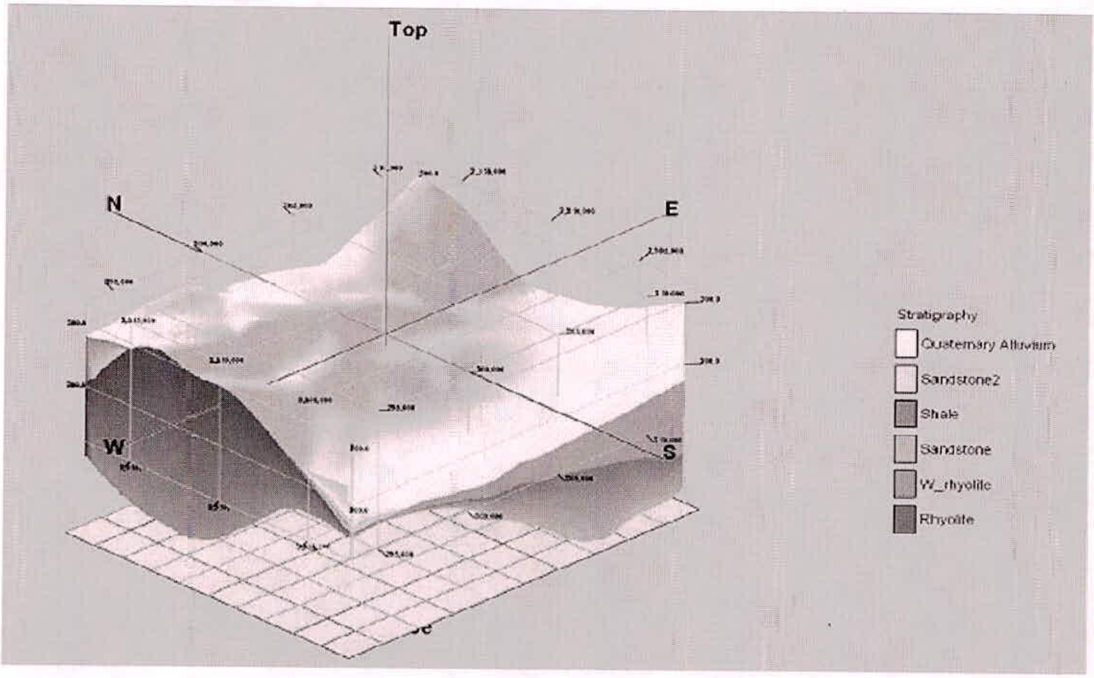

Fig. 4 Stratigraphic model of the geological formations of the Jodhpur city.

The demographic data analysis showed a population of 11, 08,950 in the Jodhpur city area by the year 2010. The population censuses of previous four decades indicated a growth rate of 3.21% per year. The projected population by the year 2015 is 12, 74,830.

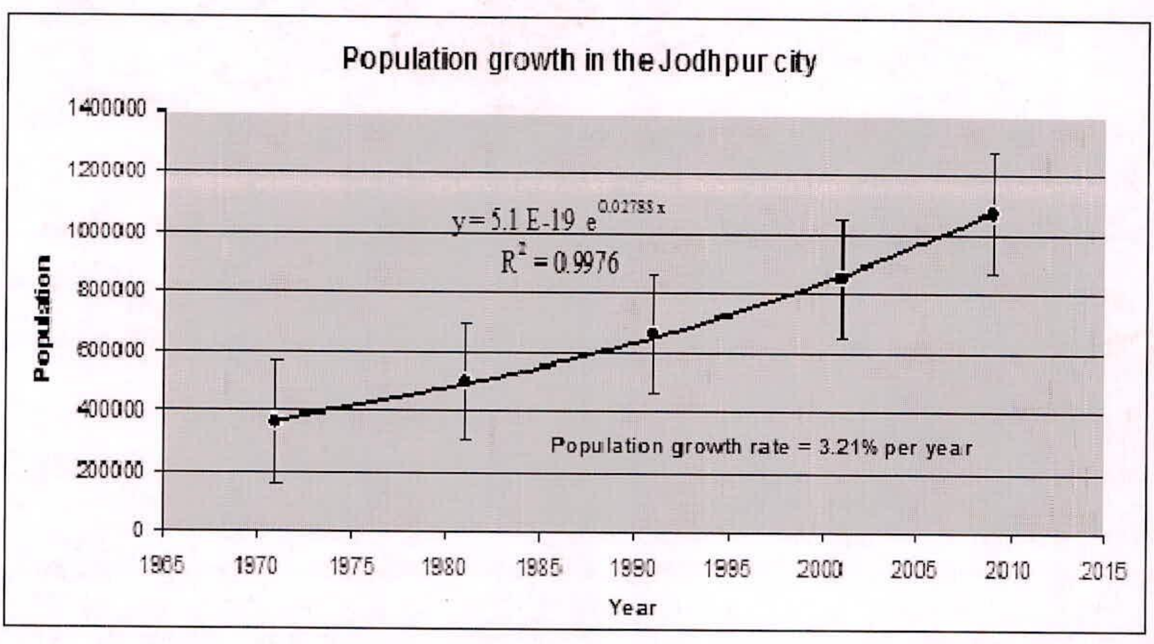

Fig. 5 Variation of Population growth in the Jodhpur

The water supply to the population in the city area has been made on the basis of a thumb rule in accordance to the supply-demand norm. The quantities of water supplied per capita per day to the population in the city area from the Kailana-Takhatsagar Reservoir in different years were 17% to 60% higher than the quantity of 140 lcpd prescribed by the Ministry of Welfare and Housing (MoWH), Govt. of India .

The Stage-Area-Capacity Analysis

The Stage-Area-Capacity relationships for the Kailana, Takhatsagar and Umaid Sagar Reservoirs have been formulated which provide functional relationships of the water spread areas and the reservoir capacities with depths of water in the respective reservoirs.

The functional relationships that hold good to estimate the capacities for varying stages and capacities for different wetted areas of the Kailana Lake are as follows:

(a) *Stage-Capacity relationship:*

$$V = 0.001\,h^3 - 0.004\,h^2 + 0.05\,h - 0.049 \quad (1)$$

(b) *Area-Capacity relationship*

$$V = 2.585\,A^2 + 3.791\,A - 0.102 \quad (2)$$

or,

$$A = 0.0064\,V^3 - 0.0496\,V^2 + 0.2756\,V + 0.0224 \quad (3)$$

The functional relationships that hold good to estimate the capacities for varying stages and capacities for different wetted areas of the Takhatsagar Reservoir are as follow:

(a) *Stage-Capacity relationship:*

$$V = 0.019\,h^{1.89} \quad (4)$$

(b) *Area-Capacity relationship*

$$V = 14.75\,A^2 + 1.673\,A - 0.12 \quad (5)$$

or,

$$A = -\,0.006\,V^2 + 0.129\,V + 0.0972 \quad (6)$$

V is the storage capacity in MCM (million cubic m); h is the stage of water measured above the bottom of the Lake in meter, and A is the water spread area of the in sq. km.

Inflow and outflow of Kailana and Takhatsagar Reservoir

The inflow-outflow components of the Kailana-Takhatsagar Reservoir and their independent water balance analyses considering seepage losses from the reservoirs could provide information as to how the water supplies pattern varied in different years and also within a year. The Kailana-Takhatsagar Reservoir receives its inflow from the Indira Gandhi Canal through Rajiv Gandhi Lift Canal by pumping at PS-8 pumping station. A line diagram of Canal-Lake-Reservoir-City water supply management practice is shown in Figure 6.

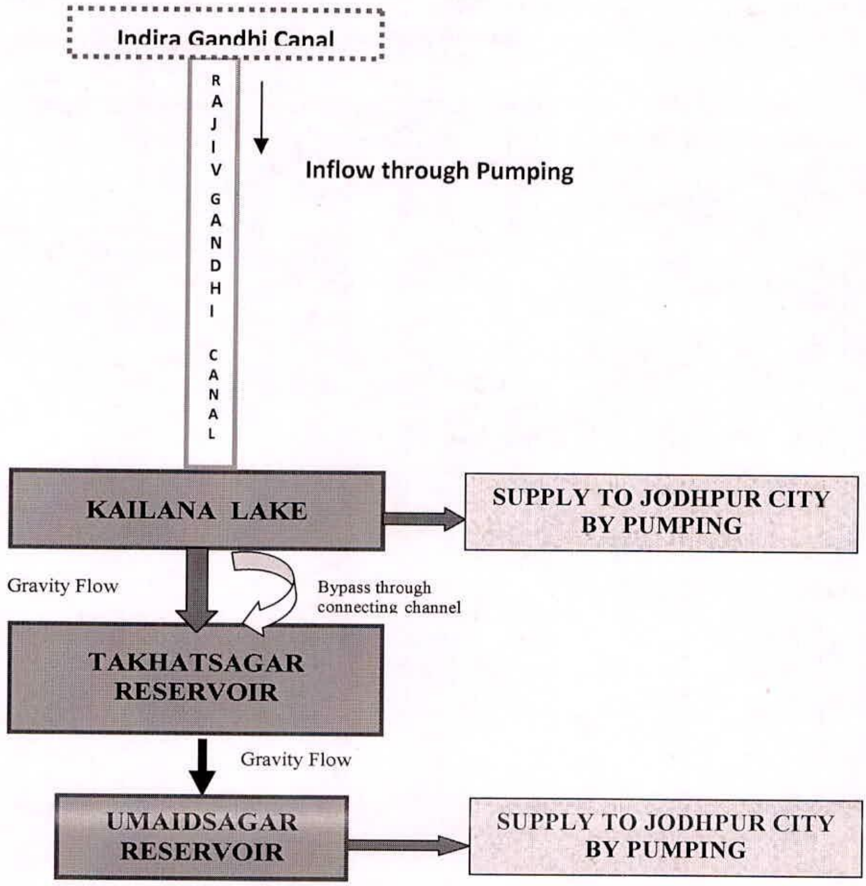

Fig. 6 Line diagram of Canal-Lake-Reservoir-City water supply system.

Groundwater Scenarios

Reservoirs are prone to seepage depending upon the hydraulic conductivity of the underlying geologic formation. The Kailana and the Takhatsagar Reservoirs, which approximately conform to a rectangular strip of long length, may be prone to seepage. The hydraulic conductivity of the hard rock geologic formation near the reservoirs is estimated to be $0.058 \text{m} / \text{day}$ Corresponding to the hydraulic conductivity value, k = 0.058 m/day, the probable quantities of seepage from the Kailana and Takhatsagar Reservoirs have been estimated for varying heads of water in the reservoirs . As the reservoirs conform to a long strip, a water ridge, i.e. a line contour for the maximum water table height under the reservoirs aligned along the reservoir axses, is likely to be formed below the reservoirs resulting from seepage. The other contours lines will be parallel to the ridge in the vicinity of the reservoir.

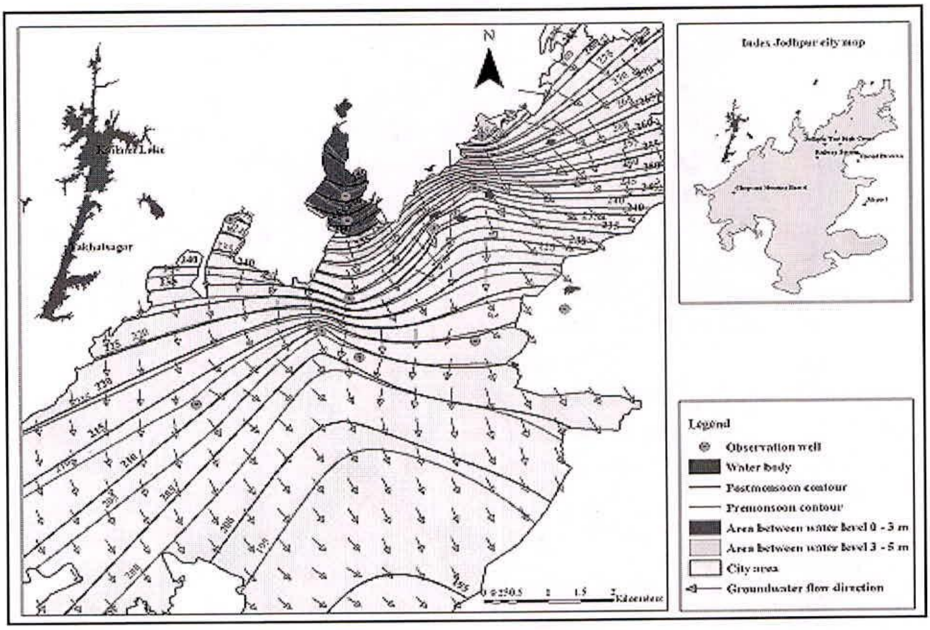

Fig. 7 Pre (red color) and post (black color) monsoon groundwater table contour map for 1996 with the assumption that the Kailana-Takhatsagar is hydraulically connected to the aquifer below the Jodhpur city (→ Indicates groundwater flow direction).

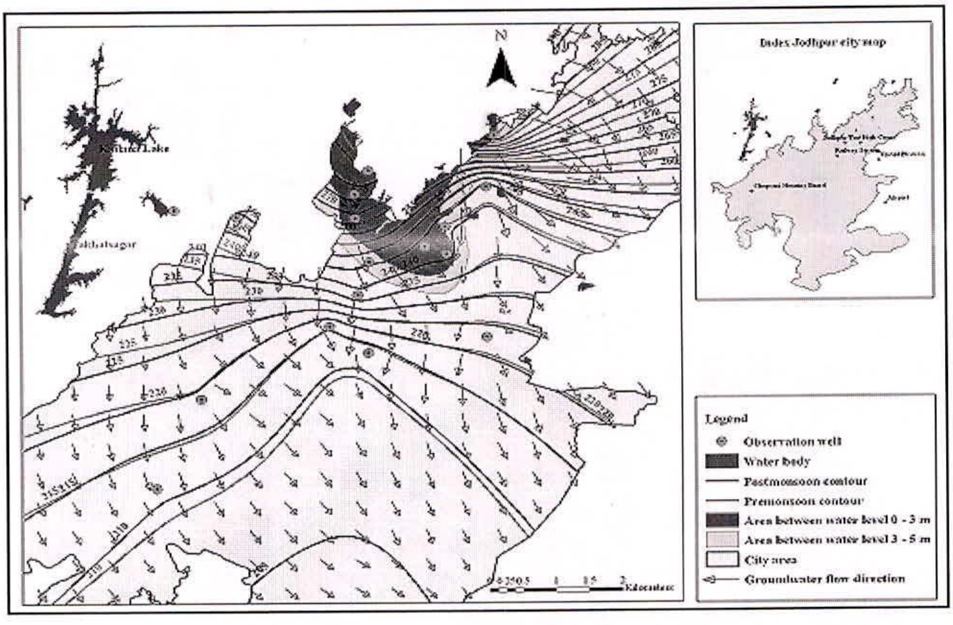

Fig. 8 Pre (red color) and post (black color) monsoon groundwater table contour map for 2000 with the assumption that the Kailana-Takhatsagar is hydraulically connected to the aquifer below the Jodhpur city (→ Indicates groundwater flow direction).

The groundwater level contours prepared for the pre- and post monsoon of the years 1996 to 2008 indicated that groundwater flow from the Kailana-Takhatsagar side is not causing water logging in the waterlogged area as the flow direction is not towards the water logged area. The source of water causing water logging is generated locally.

Seepage and Drainage Data Analysis

Before the year 1996-'97, the water supply of the Jodhpur city for domestic and municipal water including drinking water used to meet partly from about 1962 numbers of hand pumps, 109 numbers of tube wells/open wells, 4 numbers of step wells & baories, surface water bodies in the city and from the monsoon storage available in the Kailana-Takhatsagar Reservoir. After the year 1996-'97, all the groundwater based supplies have been put into hold, and the water supply to the city has been fully switched over to meet from the Kailana Lake and Takhatsagar Reservoir through continuous feeding from the IGNP linked Rajiv Gandhi Lift canal by partly pumping and partly by gravity flow, after treatment. Water from the Kailana-Takhatsagar Reservoir to the city area is transported through large diameter pipes. The quantity of water supplied from the Kailana-Takhatsagar Reservoir in different years during the period 1991-2009 is shown in Figure 9. It can be seen from Figure 9 that, the supplies of water from the Kailana-Takhatsagar Reservoir to the city have increased gradually over the years from 228 lacs gallon per day in the year 1996 to 522 lacs gallon per day by the year 2009 to meet the rising demands for water by the growing population and their allied activities.

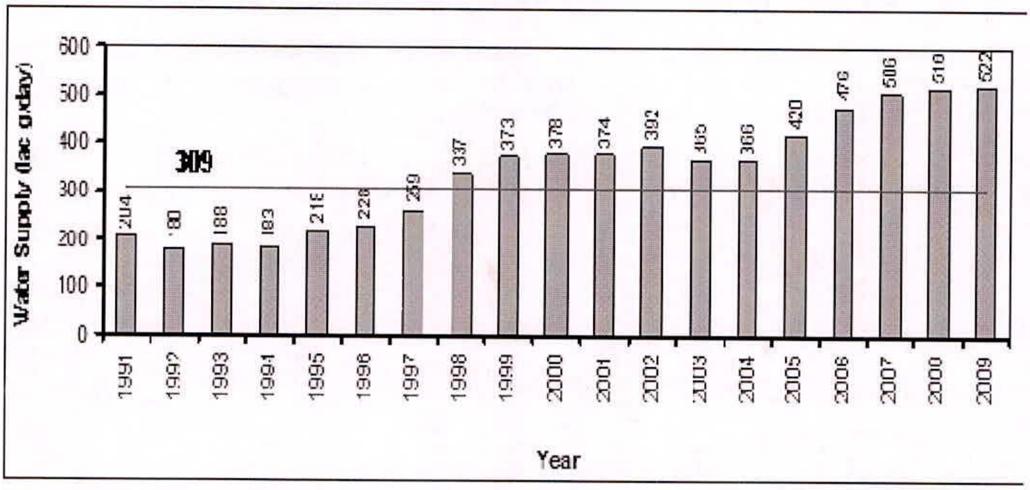

Fig. 9 Water supplied from the Kailana-Takhatsagar Reservoir to the Jodhpur city in different years during 1991-2009.

To assess the daily sewages outflow from the city area, field investigations and measurements have been carried out in the three sewerages drains; the one near to the Jodhpur Airport, the second one near to the Jodhpur Polytechnic Institute, and the third one at the Nandri sewage treatment site. Based on the measured velocities of flows, sectional geometries, and depths of flows; the time varying discharges of sewage flows have been computed. Averaging the 7 days flows, the generalized graphs of time-varying discharges of flows for 24 hours for each of the three sites has been developed. Figure 10 shows the graph for the sewerage drain near the Jodhpur Airport area. The analyses of the measured sewages data show that the total discharge of sewages from the city areas through these three sewerage systems is 37% of the daily water supplied. The wastewater generated is approximately 65% of the water supplied during a year. Thus about 28% of the water supplied is joining the unconfined aquifer below the city.

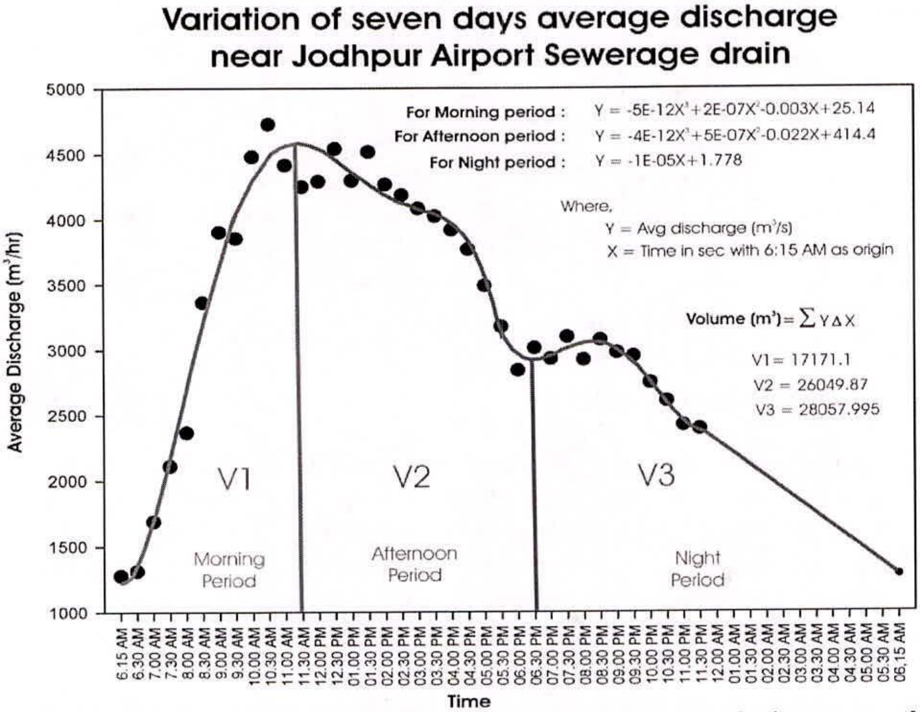

Fig. 10 Generalized rating curve of the sewage flows in the sewerage drain near to the Jodhpur Airport area; developed based on the continuous 7 days field measurements from 6:00 A.M to 11:00 P.M. (April, 2010).

Aquifer Parameters Estimation

To ascertain the aquifer parameters, namely; Transmissivity and Storage coefficient, pumping/recovery tests have been conducted at four different locations in the study area, and the aquifer parameters have been estimated using tested advanced algorithms. For the aquifer test conducted in the wells with small radii, the inverse problem has been solved using the Theis' basic solution treating the aquifer to be confined. For the tests conducted in large diameter wells, Hantush' basic solution for well with finite radius has been used considering well storage effect on drawdown data. Table 1 gives the iterative values of the estimated transmissivity and storage coefficient.

Groundwater Quality Data Analysis

The groundwater quality data have been analyzed to ascertain spatial variation of the parameters pH, Cl_2, TDS, NO_3 and SAR. The analyzed results showed that the source of water logging and rise in groundwater level in the problematic area are due to the return flow of water from water supply system and from the source other than the sewage waters originating from domestic supply. In some pockets, the seepage from sewage system cannot be ruled out. The quality of groundwater showed that the groundwater can safely be used for irrigation purposes.

Table 1. Transmissivity and storage coefficient as obtained through successive iteration

Iteration no	T^*	ϕ^*	ΔT	$\Delta\phi$	Error: C(1)	Error: C(2)
1	0.024	0.01	-0.0518	0.117059	5.70E-06	3.44E-06
2	0.024	0.127059	-0.03277	0.418365	-7.69E-06	-6.00E-07
3	0.024	0.127059	-0.03485	0.423725	-7.69E-06	-6.00E-07
4	0.024	0.127059	-0.03485	0.423725	-7.69E-06	-6.00E-07

- Iterated Transmissivity, T= 0 .024 m^2 / min =24.56 m^2 / day
- Iterated Storage Coefficient, ϕ = 0.127

Groundwater Simulation Modelling

The groundwater simulation modeling has been carried out using visual MODFLOW software. The responses of the aquifer for different stress periods have been simulated setting transient state model. Based on the analyses of data and modeling, different management options have been analyzed, and the best one of those has been recommended accordingly. The study area of about 76 sq. km. has been discretized into 107 x 113 grids (along x direction = 107 nos; along y direction = 113 nos) of each grid size 100 m x 100 m. Vertically along z-direction, the maximum aquifer thickness of about 78.6 m which varies from location to location has been divided into 6 layers in accordance with the variation of geological formations and their hydraulic properties. Each layer has different thickness. A schematic view of the discretized study area and its sectional view indicating the vertical discretization prepared using the Visual MODFLOW software (version 9.1) is shown in Figs. 11 and 12.

Initial and boundary conditions

The status of groundwater condition in the year 2004 during the pre-monsoon period is considered as the initial condition. Two types of boundary conditions are considered; one is General Head Boundary (GHB) and the other one is No Flow Boundary (NFB). The GHB is the one through which cells just adjacent to the boundary can exchange flow in either side of the boundary depending upon the gradient of heads in the cells. The NFB is the one through which no flows are allowed get in or out of the boundary. The aquifer is considered to be unconfined, i.e., under water table condition. The hydraulic properties of the geological formations are initially considered as given in Table 2.

Input stresses

The inflow and outflow stresses are those based on which the responses of the aquifer are to be ascertained. The inflows to the study are: return flow from the accumulated wastewaters, rainfall recharge to groundwater, seepage from water bodies, and the inflows through boundaries; while the outflows from the study area are: evapotranspiration, withdrawal from the groundwater, and outflows through the boundaries.

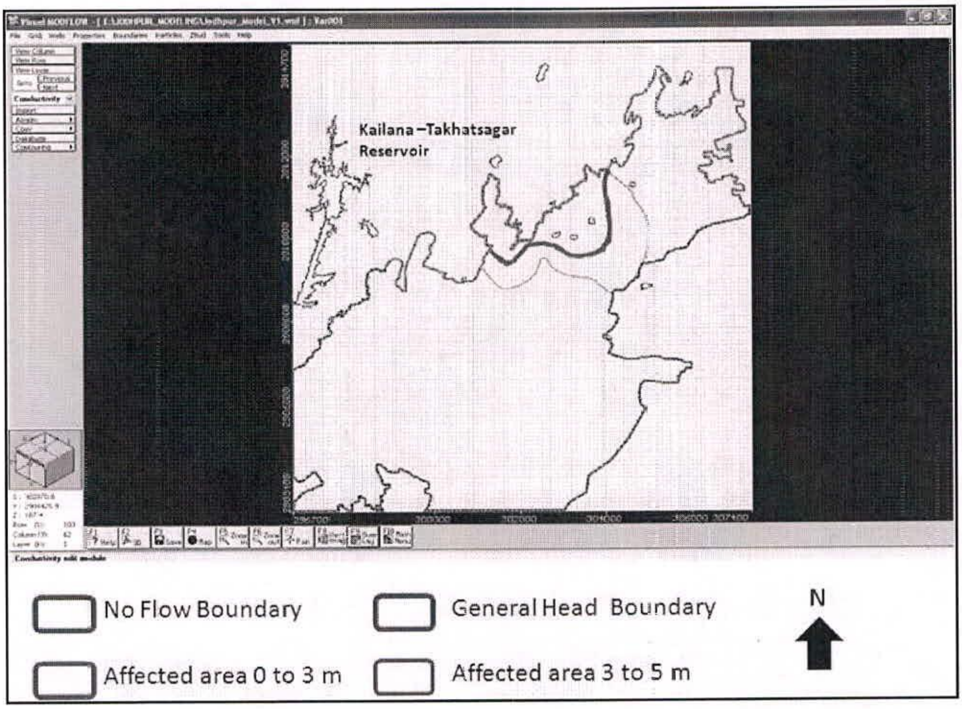

Fig.11 Discretized view of the study area including the water bodies and the affected area within the Jodhpur city (Number of grid along X direction = 107; Number of grid along Y direction = 113; size of each grid = 100 m x 100m).

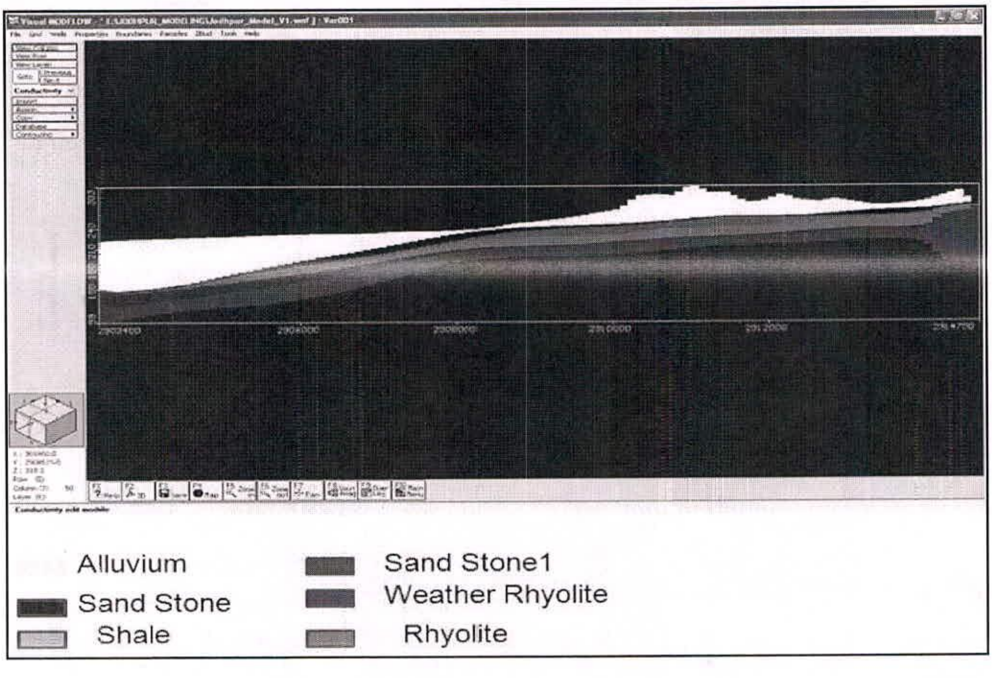

Fig. 12 Vertical section of the study area indicating discretized view of the geological formations (Number of layers = 6 each of different thickness).

Table 2. Hydraulic properties of the geological formations, considered as the initial guess values.

Geological formations	Values of the parameters		
	Porosity (dimensionless)	**Transmissivity** (m^2/day)	**Storativity** (dimensionless)
Quaternary Alluvium	0.30	50 - 245	$2.71 \times 10^{-4} - 2.337 \times 10^{-1}$
Sandstone	0.27	4.32	3×10^{-4}
Rhyolite weathered	0.02	3.0	3×10^{-5}
Rhyolite	0.015	2.25	3×10^{-6}
Shale	0.06	10	2×10^{-5}

The magnitude of spatial variation of inflow and outflow components for different years, and in different period in a year have been calculated and assigned to each grid accordingly. A scheme of the input stresses which have been assigned zone wise is shown in Figure 13.

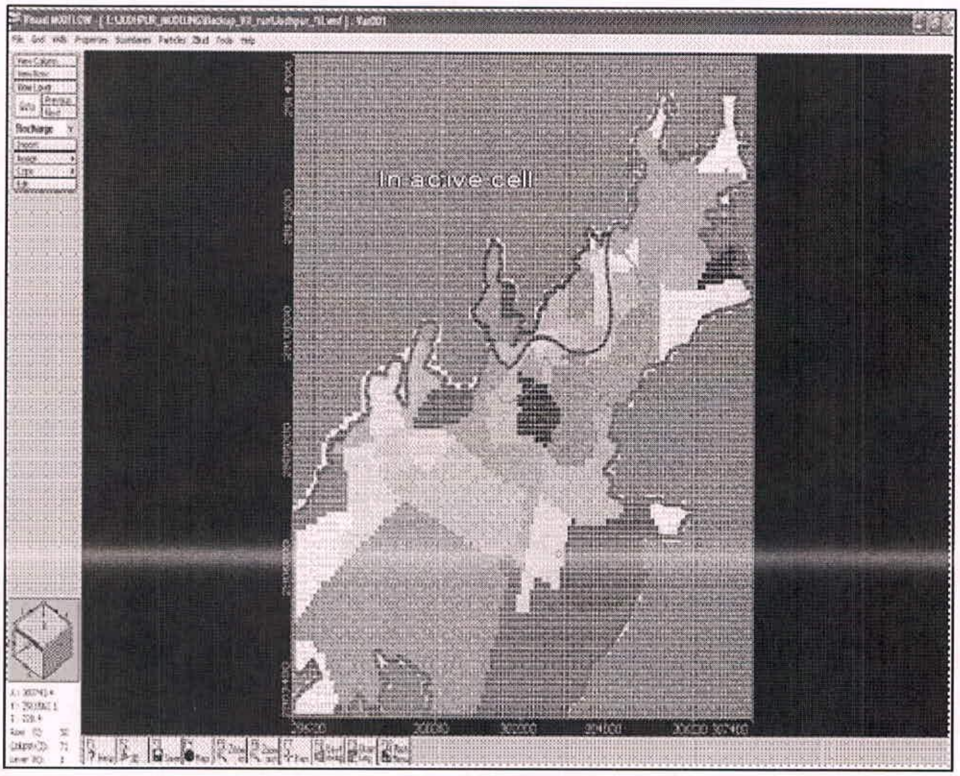

Fig. 13 A scheme of the input stresses assigned zone wise to the modelling area.

Time Step Size and Simulation Period

The time step size for simulation of the groundwater levels is considered 1 day. This will constitute 365 time intervals in a year. The time step size of 1 day indicates that all input and output stresses are to be assigned on per day basis with time step size, $\Delta t = 1$ day. The simulation is carried out setting a transient-state model considering uniform stresses between pre-monsoon to post monsoon and post monsoon to pre-monsoon, and so on.

With the above inputs data, values of the parameters and variables; the mathematical model has been set to ascertain the responses of the aquifer using the visual MODFLOW software (version 9.0 pre.) developed by the USGS.

Simulation Results

Making use of the inputs stresses and boundary conditions, the model has been calibrated for steady state scenario employing the pre-monsoon groundwater profile of the year 2004. The model parameters were calibrated by comparing the computed and the observed water table. Figure 14 shows the comparison between the pre-monsoon computed water table and the observed water table for the year 2004.

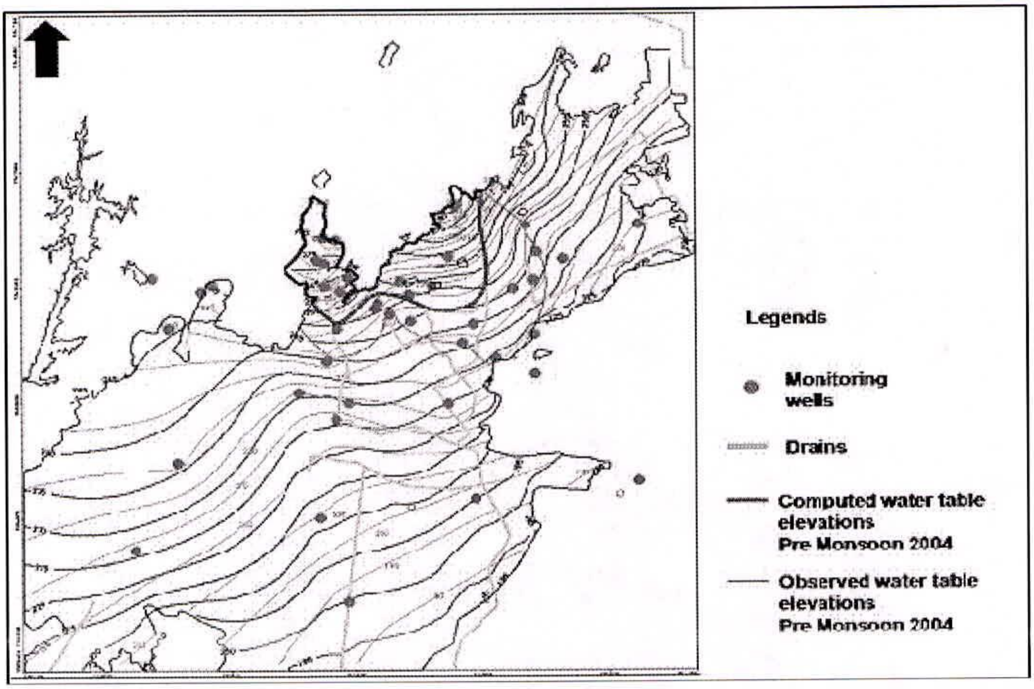

Fig. 14 Comparison of the steady-state simulated and observed groundwater table for the pre-monsoon period of the year 2004.

Concluding Remarks

A comprehensive analysis of meteorological, hydrological, hydrogeological, groundwater contours, water quality, etc has been done bringing all spatially varying data into ArcGIS framework. Groundwater flow modelling has also been carried out using spatially varying data.

The ArcGIS environment framework has provided the necessary tool for data analysis, and input databases preparation for groundwater modelling including developing groundwater contour maps and groundwater direction.

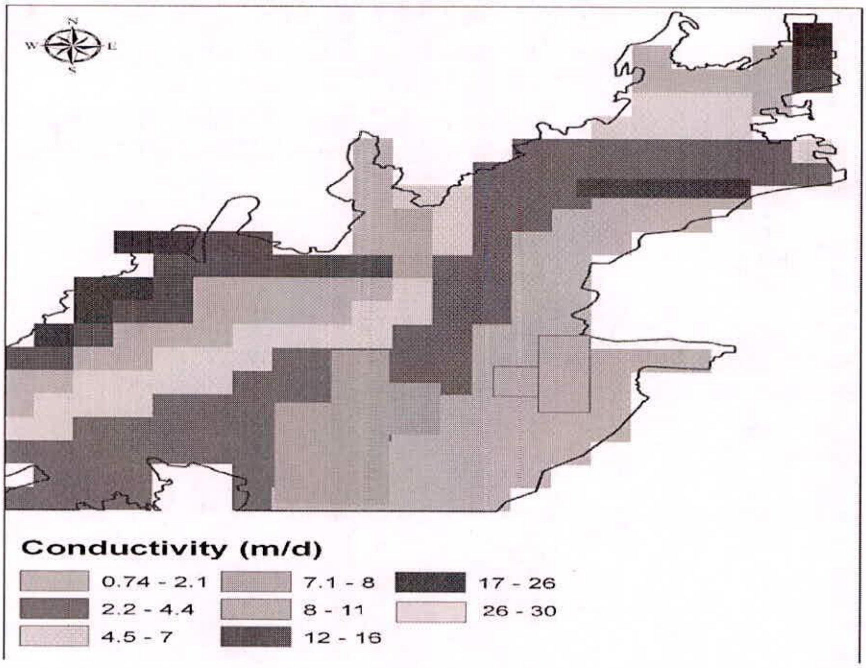

Fig. 15 Calibrated hydraulic conductivity (m/day) zones of the aquifer.

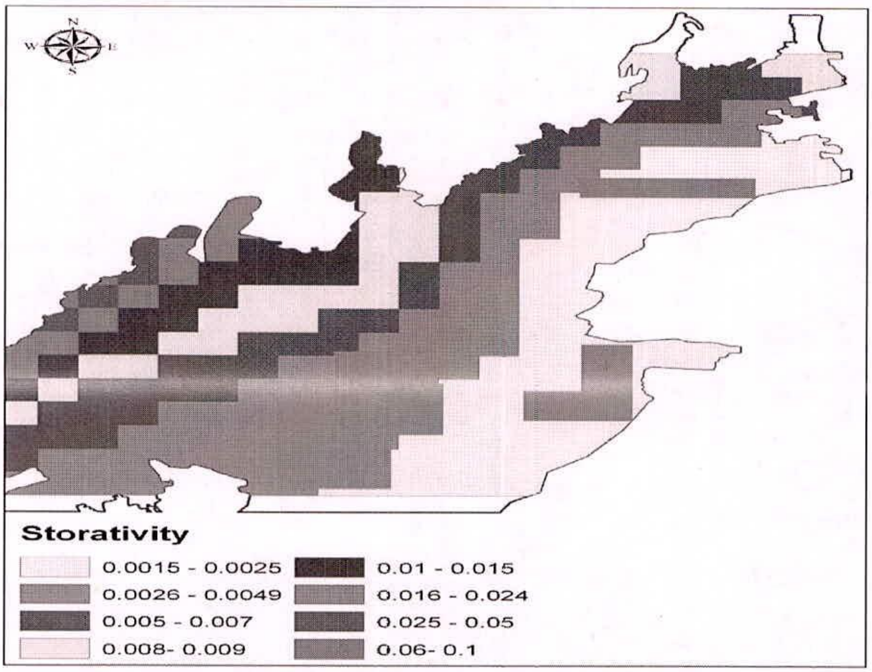

Fig. 16 Calibrated storativity (dimensionless) zones of the aquifer.

The ArcGIS can effectively be used for analyzing field data, preparation of thematic maps and resolving many groundwater related problems including preparation of databases for groundwater modelling using MODFLOW.

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Acknowledgements

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