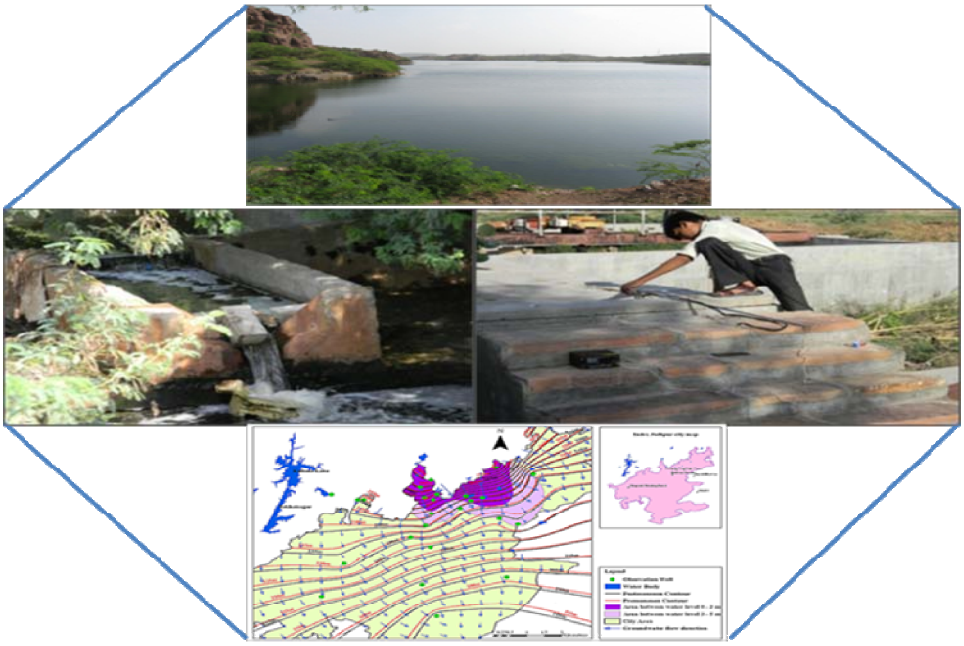
Study on Rising Groundwater Table in Jodhpur City, and to Evolve a Management Plan for Containing the Rising Trend

FINAL REPORT



Sponsored by:

Ground Water Department
Government of Rajasthan
Jodhpur

Studied By:

National Institute of Hydrology,
Roorkee – 247 667
May, 2011

Project Data

Title of the Study	: Study on rising groundwater table in Jodhpur City, and to evolve a management plan for containing the rising trend.
Sponsoring Agency	**:** Ground Water Department, Jodhpur Government of Rajasthan.
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Executing Agency	**:** National Institute of Hydrology, Roorkee

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Foreword

The problem of rising groundwater level in some parts of the Jodhpur city located in the Thar Desert of the western Rajasthan that is known for a water scarce region is not only a matter of concern but also an eye opening issue from the hydrology point of view. As such, groundwater is a hidden resource; the fact findings from the study of such resource for a problem that has been originated from the human interventions into the associated hydrological and hydro-geological components are, in fact, a challenging task.

In order to find the source and causes of groundwater table rise and to develop an appropriate management plan to revert back the rising trend and to contain the groundwater at a safe level, the project entitled "Study on rising groundwater table in Jodhpur City, and to evolve a management plan for containing the rising trend" has been entrusted to the National Institute of Hydrology, Roorkee. I put on records my thanks to Government of Rajasthan, particularly to the Ground Water Department, Jodhpur for considering NIH capable for this challenging task.

To accomplish the envisaged objectives, the comprehensive study involving analyses related to hydrological and hydro-geological components has been carried out using the data supplied by the Ground water Department, Public Health Engineering Department, Jodhpur and also collected from the field investigations and experimentations during the course of the study. Based on the analyses and modeling exercises, specific conclusions outlining the reasons of the problem and suggesting the possible options as to how the problem can be resolved have been brought out. I believe that the findings and recommendations outlined in this report will help the Government of Rajasthan for resolving the problem.

The study has been carried out by the group of scientists and scientific staff of NIH under the coordination of Dr. N. C. Ghosh, Scientist-F and Principal Investigator of the study. The study team deserves appreciation and thanks for their sincere and commendable efforts. I put on record my appreciation to Prof. (Retd.) G. C. Mishra, consultant of this project, for his contribution.

Date : 20th May, 2011

(Raj Deva Singh)
Director, NIH

Acknowledgement

Groundwater is a hidden resource. To identify the cause(s) of a problem that has been originated from the groundwater hazards and to find the scientific solution of it requires a huge database and analyses. If the causes of the problem are because of the human interventions to the hydrologic and hydro-geologic regimes; then the tasks to attain the logical solution to the problem become more cumbersome and tedious. The problem of the rising groundwater level in Jodhpur city has been the tasks of such category. The data support and the help extended by different organizations and individuals to achieve the goal are thankfully acknowledged.

On behalf of the National Institute of Hydrology (NIH), I convey my sincere thanks to the Ground Water Department, Jodhpur, Government of Rajasthan for considering NIH to entrust this challenging task.

I thankfully acknowledge the help and data support provided by the officials of the Ground Water Department and Public Health Engineering Department, Jodhpur in general, and particularly to Shri K. N. Mathur then Chief Engineer, PHED; Shri U. K. Mathur then Chief Engineer, GWD; Shri C. S. Sekhawat, Chief Engineer, GWD; Shri G. S. Marwaha, Superintending Hydrogeologist; Shri G. L. Bora, Senior Hydrogeologist; Shri Niranjan Mathur, TA–Hydrogeologist; Dr. P. S. Rathore, TA-Hydrogeologist for their keen interest to the study and constant support as and when requested during the course of the study. Thanks are due to the members of the 'Task Force' for their keen interest and critical review of the activities from time to time. The data support provided by the SRRSC, RRSC, and CGWB are also duly acknowledged.

I convey my sincere gratitude to Prof. (Retd.) G. C. Mishra, IIT Roorkee for working as a think tank to this scientifically challenged problem. The laboratory analysis support given by the Environmental Hydrology Division and the Soil-Water Laboratory of NIH is also thankfully acknowledged. The efforts given by all the study teammates are earnestly acknowledged. Special thanks to my young colleagues Shri Dinesh Kumar, Shri Vikrant Vijay Singh, and Dr. K. Servanan, all are project staff, for their untiring efforts.

Last but not the least, the assistance provided by Shri Avdesh Sharma, PA and Shri Haridas, Messanger-Sr. Gr. is also duly acknowledged.

Date : 20th May, 2011

(N. C. Ghosh)
Scientist-F & Principal Investigator

Executive Summary

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 emersed 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 present study had been entrusted to the National Institute of Hydrology, Roorkee, with the following objectives:

(i) Identification of cause(s) of rising ground water levels in Jodhpur city.

(ii) Development of an effective and sustainable management plan for maintaining the water table of the area at a safe level to avoid any adverse impact on the civil structures and population of the area.

To facilitate and accomplish the above objectives, a number of terms of references (TORs) have been attached to the sponsored study. Those TORs were emphasized primarily to ensure the attainment of the above goals.

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. The data have mostly been supplied by the Ground Water Department (GWD) and the Public Health Engineering Department (PHED) of Jodhpur; and some data have been collected by the executing agency from the field investigations/surveys and from the other sources (IMD, NRSC, local agencies) during course of the study.

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 data analyses and results have been reported in 17 Sections. The Section-1 presents an introduction to the problem; Section-2 elaborates geography and topographic of the study area; Section-3 describes the geological formations of the area; Section-4 illustrates hydro-meteorological data analyses; Section-5 explains demography and water usages and requirements; Section-6 brings out the Stage-Area-Capacity analyses and curves for the Kailana-Takhatsagar and Umaid Sagar Reservoirs; Section-7 provides analyses of Inflows-outflows data of the Kailana-Takhatsagar Reservoir and their water balances; Section-8 contains analyses of the groundwater data; Section-9 illustrates sewages flow measurements and data analyses; Section-10 describes the surface water balance of the study area; Section-11 elaborates analyses of aquifer parameters estimation; Section-12 focusses on groundwater quality data and scenario analyses; Section-13 demonstrates the inputs data preparation for groundwater modelling of the study area; Section-14 provides description of the modelling aspects and analyses of results obtained from the modelling of water table evolution in the study area; Section-15 illustrates the possible management strategies to remediate the problem; Section-16 brings out the summary and conclusions of the study; and finally Section-17 states the recommendations as to what actions would be necessary to resolve the problem.

The study area 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, 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.

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**.** 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.

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.

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.

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 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 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 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.

To assess the daily sewages outflow from the city area, field investigations and measurements have been carried out in the three sewerages drains; one near to the Jodhpur Airport, other one near to the Jodhpur Polytechnic Institute, and the third one at the Nandri sewage treatment site. 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.

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.

The groundwater quality data supplied by the PHED, Jodhpur have been analyzed The spatial variation of the parameters pH, Cl_2, TDS, NO_3 and SAR in the study area indicated 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.

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.

(i) Identification of Cause of Rising Ground Water Levels in Jodhpur City

Based on the analysis of satellite imageries, it is found that Jodhpur city is mainly located on the sandstone and shale formations, which are relatively pervious. Kailana and Takhatsagar area is located on the Rhyolite formation. As Rhyolite formation exhibits low permeability (0.058 m/day), the seepage losses from the lake would be very small.

Considering two extreme situations (i.e. in the first situation, the reservoirs are hydraulically connected with the under lying aquifer implying that a rise in water table position in the aquifer in the vicinity of the reservoir boundary would reduce the seepage from the reservoir, and in such situation the water level in the reservoir forms as a known water level contour line; in the second situation, in which any change in water level in the aquifer near the reservoirs do not affect the seepage from the reservoir, and water level in the reservoir is not linked to the water level in the aquifer), contours are drawn and flow directions ascertained. As seen from the water level contours maps, the flow directions are not converging towards the water logged area. Therefore, the seepage from the reservoir irrespective of its quantity is not entering to the water logged area. The flow directions are towards the south-east region only; and in the south east region, the water table contours are having less value than those in the waterlogged area. From the consideration of hydraulic principle, and from the consideration of the direction of flow, it is evident that the seepage from the reservoirs is not entering to the waterlogged areas.

The contours of pH of groundwater in the study area exhibit three concentration peaks, two in the water logged area, and another in the south west region. The contours around each peak show evidence of mechanical dispersion. Mechanical dispersion is caused by groundwater flow. The two peaks in water logged area indicate that the high concentration of pH is caused locally as the contours nearer to each peak are mostly circular. The gradient directions of the contours and decreasing trend around the peak exhibited in the south west region indicate that groundwater is not entering to the water logged area from the West or South-West.

Besides three peaks, there are two troughs one towards North and the other in South East. The contours around each trough show evidence of dispersion. From the gradient direction of the contours and decreasing trend of pH towards North in the northern trough, it could be argued that no ground water flow is occurring from north to the waterlogged area.

There is only one lineament, which is oriented towards the waterlogged area. The Lineament analysis survey and the geological and geophysical study conducted independently by the National Geophysical Research Institute (NGRI), Hederabad (2010) surrounding the Kailana-Takhatsagar Reservoir indicated that the lineaments are oriented in NNE-SSW to NE-SW directions with no connectivity to the city areas. A few lineaments with ESE-WNW directions are present but these are small and do not have connectivity to the city areas. The findings of the NGRI thus corroborate the present finding based on hydraulic principle. The chances of seepage from the Kailana-Takhatsagar Reservoir to the waterlogged areas through lineaments are, therefore, very less.

As water is not entering to the part of the aquifer below the water logged area from any side, it is evident that water logging is caused because of vertical infiltration of sewage and return flow of domestic supply.

(ii) Remedial Measures

1. As the first and foremost remedial measure, it is suggested to regulate the quantity of water being supplied to the city area at the source itself, i.e., regulation of water from the Kailana-Takhatsagar Reservoir. The regulation needs to be based on per capita per day water requirement basis. The Jodhpur city being located in the arid and water scarce region, about 110 liters per capita per day could be taken as the guideline. The break up of 110 liters is as follows: 70 liter (drinking & toilet flushing) + 20 liter (commercial uses) + 20% conveyance losses. Industrial water requirements are to be included separately. For 110 lpcd supply, the quantity of water requirement for the estimated population of 11,08,950 in the Jodhpur city for the year 2010 is worked out to be 268.69 lac gallon per day. To meet water requirement for domestic animals, and kitchen gardens, swimming pools, and public parks 1/3 of the requirement for the population i.e., about 100 lac gallon per day extra water be supplied, which will reduce the quantity by about 30% over the quantity supplied (521.7 lac gpd) in the year 2009.

2. In the affected area, the water supply lines need to be thoroughly checked to find the locations of leakages, and suitable remedial measures to stop the leakages need to be taken up. The sewages/drainage lines in the affected area need to be properly sealed to stop seepage, if any.

3. The topography of the city area in the northern and middle part is of undulating type. The thickness of the alluvium formation varies from about 2.0 m to 13.0 m in that part. Therefore, a single generalized safe ground water level is incorrect to suggest. In general, considering the possibility of capillary rise in alluvium, groundwater table should be at least 0.5m below the foundation level. In areas where building basement floors are located, assuming that basement level is 3.5m, and capillary rise is 0.5m, the groundwater table should be at 4.0 m below the ground surface. The groundwater level in the affected area thus has to be lowered down below 4.0 m from the respective ground surface elevation.

4. The terrain being undulating , the area being an urban area, the requirement of lowering the water table by 4m, minimum depth of alluvium being 2m in some places, all these aspects do not promote provision of a usual horizontal sub surface drainage system. However random sub surface drainage trench of 4m depth, filled with coarse sand and gravel, where possible, can be constructed to control the rising water. The water entering into such trenches can be led to a collector caisson, from where water can be pumped out. Construction of such trenches to control water table rise would depend upon the local terrain and building locations.

5. Provision of vertical drainage system i.e. by pumping the water from the aquifer in the problematic area looks feasible, as drainage wells can be constructed with least interference with the urbanized area. The pumping rate and schedule can be controlled, the number drainage wells can be increased in a locality as required, and already such practice has been initiated in the area, all these factors favor provision of vertical drainage. In region of low transmissivity area i.e. transmissivity $< 30 m^2/day$ large diameter wells of 0.5m can be constructed. However vertical drainage system would require electrical energy, and would cause noise pollution.

6. There are three large ponds, namely; Baiji Ka Talab, Fateh Sagar, and Gulab Sagar, located near to the problematic area. The pond beds are more or less impervious, or if necessary these can be lined. The pumped water can be discharged to these ponds through conveyance pipe. From these ponds surface channel can be constructed to convey the water stored in the pond to the existing surface drainage system through gravity.

7. A Bentonite clay grout curtain across the lineament which is terminating before but directing towards the water logged area can be constructed proximity to the reservoir site to check the groundwater flow, if any, from the reservoirs to the water logged area.

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Section - 1.0: INTRODUCTION

The Jodhpur city (also known as Sun City), that had spread in an area of about 14.5 sq. km. in the year 1972 (Survey of India map, 1972), is presently sprawled over 76 sq. km. between latitudes $26^0$15’ N to 26^0 20’ N and longitudes 73^0 $0^'$ E to 73^0 $4^'$ E in the Thar Dessert in Western Rajasthan. Being a city of historical importance and the second largest in the state having progressive infra-structural urban facilities, the city is expanding very rapidly, mainly towards south-east, south and south-west directions despite the area located in the arid region having sparse rainfall, hot and dry climatic conditions. In order to facilitate human activities and their aspirations, administratively the Jodhpur area has been categorized into 60 wards based on the households and population. Domestic and other needs of water for the people living in those wards of the city are mainly supplied by the Jodhpur Municipal Corporation; while the availability of water from the source to the City is facilitated by the Public Health Engineering Department (PHED), Jodhpur. The city has a network of organized water supply distribution lines (not connected to every household) of which, some distribution lines, mainly in the old city areas, had been developed long back, and some others have been constructed with the passage of the progression of city’s extension. As the city and its human habitations are expanding, the demands of water supply and networking of distribution lines are also increasing, connecting more people and human activities to the water supply system of the city. These are resulting towards more and more usages of supplied water to the city. Waters supplied to the city areas are used for domestic uses for the purposes of drinking, bathing, laundering, car washing, lawn watering, gardening, etc., and in some areas for supporting minor to medium commercial activities. As such, waters supplied to the city areas are not used for any major agricultural irrigation activities. Whatever quantity of water is supplied for the domestic and other activities to the city area, some fraction of the applied water in excess of the consumptive uses of water, will be returned back in the form of wastewater from each household and from water users after their usages. The wastewaters of different qualities, which depend on the uses of water, are normally to be drained out from the city area to avoid accumulation, water logging or water quality hazards in the city area. For draining out wastewaters both domestic and municipal, the city has a network of underground sewerage lines; some of which, mainly in the old city area, had been constructed long back not connecting to every house developed within the area; even some of the areas developed at a later states have also not been fully brought into the network of city's sewerage connection. The wastewaters generated from the city areas have the following disposal patterns: large fraction is through network of sewerage drains, partially flows to the Talabs located within the city through local nalas/drains, and the remaining infiltrates in the form of return flow to join the underneath groundwater system

To support the water supply requirement to the city area for domestic, commercial and industrial purposes, since the year 1997 the PHED had switched over from the earlier mixed supply pattern of surface water and groundwater to the present completely canal water based supply system through storages in the Kailna-Takhatsagar Reservoir. According to the data of PHED, Jodhpur (GWD et al., 1999), the supplies of water to the city were about 183.5 lacs gpd (i.e.,117 lpcd) in the year 1994, 278.6 lacs gpd (i.e., 164.8 lpcd) in the year 1998, 341.7 lacs gpd(i.e., 185.1 lpcd) in the year 2000, 462.4 lacs gpd (i.e, 211.9 lpcd) in the year 2006, and 521.7 lacs gpd (i.e., 220 lpcd) in the year 2009. The waters supplied to the city areas in the respective years were liable to generate wastewaters. To maintain a perfect balance between water supply-disposal of wastewaters of such quantities, and resulting shallow water table position, a fitting water supply and drainage systems would be necessary. The conveyance losses during transportation due to leakage/seepage or otherwise would cause accumulation of water in the subsurface system.

The city is devoid of any perennial natural drainage system. The Jojri River, which routes through the outer periphery about 10 km away from the city, is the only natural ephemeral stream that flows intermittently during the monsoon. There are number of small water bodies inside the city, some of those are manmade, constructed long back to store monsoon water; while others are formed by the natural topographic depressions.

In addition to those small water bodies, there are two cascading type naturally formed large depression storages, locally known by Kailana lake, and Takhatsagar Reservoir, which are located about 5 km. away from the city towards the western side. The monsoon runoffs that generate from the city's catchment partially flow out through the storm water drainage system and partially get accumulated in the water bodies located within the city.

Prior to the current arrangement of water supply from the transit storage in the Kailana lake, Takhatsagar Reservoir and Umaid sagar Reservoir , which are fed from the IGNP linked Rajiv Gandhi Lift canal, the domestic and municipal water supply including drinking water was met from hand-pumps, tube-wells, step-wells, baories, and from surface water storage in the city. After the existing arrangement of the water supply scheme to the city in the year 1996-'97, i.e., feeding the Kailana Lake and Takhatsagar Reservoir from the IGNP linked Rajiv Gandhi Lift canal and transferring the water from the Kailana and Takhatsagar Reservoir largely by pumping and partially by gravity flow for treatment of water and then supplying to the city, almost all the previous provisions of water supply from the groundwater storages have been put into hold. The enhanced-urban-water-supply-return-flows and the seepage from the water bodies would cause rise in ground water level. The existing hydrogeological condition and water usages transformation have consequently given rise to the problem of groundwater level increase. The resulting impact of rise in groundwater level over the years was such that a number of pockets and stretches in the city area have been experiencing waterlogged conditions. The rising trend of groundwater level was noticed since the year 1997, and over the years the situation had continued to be so aggravated that considerable area, mainly in the old city area had come under the grim of water logging conditions. Many depressed land surfaces along the built up groundwater flow direction had also experienced the surface water logging conditions. To cope up with the situation of rising groundwater levels and water logging conditions, the State Groundwater Department has made several pumping stations to lower the groundwater levels in a number of affected areas. Even people having basement floors in the affected areas have also regularly drained out the accumulated groundwater in the basement floors. Pumping out of accumulated groundwater through network of bore wells, from baories and from the basement floors in the affected areas is being carried out on daily basis. It has been reported that with the progression of time, the waterlogged areas are gradually spreading towards southeasterly along the direction of built up groundwater flow.

To find the sources and causes of groundwater rise in the Jodhpur city, a number of organizations investigated the problem; these organizations are: GWD, Jodhpur (1998), joint study by GWD, PHED, MBM Engineering College, and RRSSC, Jodhpur (1999); BARC, Mumbai (2000); GSI, Western Region (2001); CGWB, Western Region (2001); GWD, Jodhpur (2006); RRSSC, Jodhpur (2007), etc. Different and mixed opinions have been stated regarding the causes of groundwater rise in the above investigations. For example, GWD et al., (1999) indicated the cause of groundwater rise is due to seepage from the used water and the Kailana-Takhatsagar Reservoir ; BARC (2000) indicated the reason to be direct seepage from the Kailana-Takhatsagar Reservoir through rock fractured aligned to the city areas or seepage from pipelines carrying lake water; CGWB (2001) explained the reasons as the seepage from the open drains and sewerage lines, RRSSC (2007) strongly expressed the source as the Kailana-Takhatsagar Reservoir and the cause of rise is due to seepage through lineaments/joints present in the rocks. Different investigators had suggested several remedial measures to contain the rise in groundwater level. However, the problem resolving issues are yet to be focused.

In order to find the exact source and causes of groundwater level rise in the Jodhpur city and to develop an appropriate management plan to revert back the rising trend or containing the groundwater at a safe level, the task has been entrusted to the National Institute of Hydrology, Roorkee with the following objectives:

(i) Identification of cause(s) of rising ground water levels in Jodhpur city.

(ii) Development of an effective and sustainable management plan for maintaining the water table of the area at a safe level to avoid any adverse impact on the civil structures and population of the area.

It was emphasized by the sponsoring agency, i.e., GWD-Jodhpur that a rigorous investigation and analysis be made to fulfill the requirements of the above two objectives.

Thus, the framework of activities to attain the objectives is envisaged as: diagnosis survey, field experimentation, rigorous data analysis, hydrologic analysis of different components linked to the water balance of the area, and simulation of water table by groundwater modeling.

Based on the preliminary analyses of the pertinent data supplied by GWD, PHED, Jodhpur and collected till December, 2009, an interim report with the following prima-facie observations had been provided in the month of April, 2010:

- *The Kailana-Takhatsagar Reservoir and Jodhpur city are located in two different geologic formations. The geological formation on which Kailana-Takhatsagar Reservoir is located is of Malani group having low hydraulic conductivity. Therefore, the seepage loss from the lake will not be very significant.*

- *The source of water causing water logging is getting originated locally in the problematic area.*

- *The seepage from the Kailana-Takhatsagar Reservoir does not enter to the waterlogged area.*

- *A lineament is noted orienting towards the waterlogged area. Near to the Kailana Lake the connection of this lineament with the lake is not clear. If at all the flow from the Kaikana Lake to the waterlogged area is occurring through this lineament, it can be prevented by intercepting wells.*

To cope up with the situation of rising groundwater level, the following recommendations had been made in the interim report with the riders that the observations are subjected to further verification and refinement by detailed analysis of different hydrological components and groundwater modeling.

- *The subsurface flow entering to the waterlogged area can be prevented constructing intercepting vertical drainage wells along an equipotential boundary which is located upstream of the problematic area.*

- *Two to three lines of drainage wells each line consisting of few staggered drainage wells along equipotential lines will be required to restrict water logging.*

- *The pumping rates and number of wells can only be ascertained using groundwater modelling.*

- *A grout curtain of Bentonite clay across the lineament directing towards the waterlogged area needs to be constructed to check the possible seepage from the Kailana-Takhatsagar Reservoir .*

This report is the final outcome of the detailed analysis of different hydrologic and hydro-geologic components and groundwater flow modeling. In order to analyze the data, all spatially varying databases, such as locations, have been first geo-referenced with reference to the geographic coordinate system (WGS-1984) by their latitudes and longitudes. Therefore, the analyzed data and results can easily be verified with the field conditions.

The report brings out the results of different remedial options, and suggests the suitable one, fitting to the field conditions. The analyses in the report primarily deal with the following:

(i) Detailed description of the problematic and the study area.
(ii) Geological formations and aquifer characterization.
(iii) Hydro-meteorological data and analysis.
(iv) Demography and water requirement,
(v) Stage-area-capacity data of the Kailana-Takhatsagar Reservoir.
(vi) Inflow-outflow data analysis of the Kailana-Takhatsagar Reservoir.
(vii) Groundwater data analysis.
(viii) Sewerage and city’s drainage data analysis.
(ix) Water balance of the study area.
(x) Aquifer parameters estimation.
(xi) Groundwater quality data and analysis.
(xii) Discritization of the study area, and input data for groundwater modeling.
(xiii) Modeling scenario for different remedial options.
(xiv) Remedial options and groundwater management plan.

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2.1 Geography

The Jodhpur city located in the Thar Desert is the second largest and one of the fastest growing urban areas in the state of Rajasthan even though it has the characteristics of arid, hot and dry climatic conditions. Presently, the city is on an area of about 76 sq. km located between latitudes $26^0$15’ N to 26^0 20’ N and longitudes 73^0 0' E to 73^0 4' E, and it is sprawled mainly towards south-east, south and south-west directions **(Figure 2.1**). The old walled city area, which is thickly populated, is located on the hill slope area and on the base of the fort hill ridge, whose surface topography is of undulating type. The sloping area gradually turns to plain alluvial terrain towards south, east and south-west sides. The north-western side of the city is largely comprised of hillocks covered with shale and sandstone. The city area has been sprawled partially on the Malani group of rock formations, mainly the old city area and the major part has been expanded on the Quaternary Alluvium formations. As such, there is no river/stream passing through the city except the ephemeral Jojri River, that routes through the outer periphery about 10 km away from the city. There are number of small water bodies inside the city, some of those are man-made, constructed long back to store monsoon water; while others are formed by the natural topographic depressions. The Kailana and Takhatsagar Reservoir , which are two naturally formed cascading type geological faults providing large storage volume aligned towards north-south west direction, are located about 5 km away in the western side of the city. The Kailana and the Takhatsagar Reservoir are located in a single geological unit and form one continuous depression storage. For operational benefits, these have been divided into two separate storage units by constructing an embankment in-between them. The upper part is known as the Kailana Lake and the lower part is named as Takhatsagar Reservoir. The Kailana Lake has larger water spread area than the Takhatsagar Reservoir. The Takhatsagar Reservoir has been connected to the Kailana Lake through gate operated pipes concealed inside the embankment at different operating depths of water in the Kailana Lake. The flow from the Kailana Lake is also diverted through open channel constructed at a particular height on the right bank of the Kailana Lake. The Takhatsagar Reservoir storage has been created by constructing a dam across the natural depression. The Kailana water level is maintained at higher level than the Takhatsagar Reservoir level so as to enable the Kailana water to flow to Takhatsagar Reservoir by gravity flow. The storage capacity of the Kailana Lake is 4.814MCM at its maximum elevation level of 273.7 m, and that of the Takhatsagar Reservoir is 6.524

MCM at its maximum elevation level of 269.75 m. Both have a specific drainage area, which is inadequate to fill their highest level from the monsoon runoff. The overall land-use and land cover of the city area are urbanized area having less scope of infiltration and percolation of water to the sub-surface formations. There is not much area in and around the city having agricultural activity; however, the city has a good coverage of greenery, mainly in the area located on the alluvium formations. The water supply requirements in the city area for different uses since the year 1997 have been meeting from the Kailana Lake and Takhatsagar Reservoir, which are fed from the IGNP linked Rajiv Gandhi Lift canal. Prior to the existing arrangement of water supply from the transit storage in the Kailana lake, Takhatsagar Reservoir and Umaid sagar Reservoir, the domestic and municipal water supply including drinking water was from hand-pumps, tube-wells, step-wells, baories, and from surface water storage in the city.

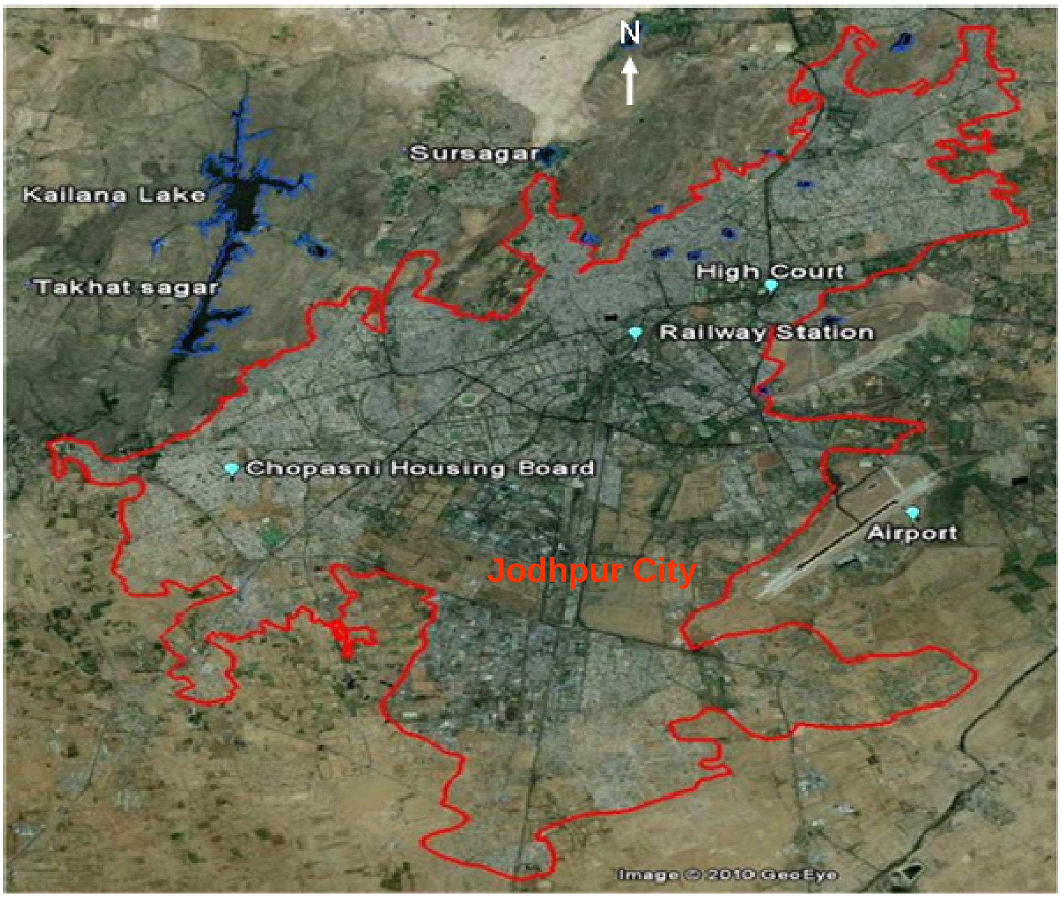

Figure 2.1: A geo-referenced map of the Jodhpur city showing its sprawled area and water bodies in and around the city.

2.2 Topography

In general, the topographic slope of the Jodhpur city is towards south-west, south, and south-east directions. Except, the hilly terrain in the north-western side, the slopes of the city along the south-west, south, and south-east directions vary. The southern terrain has flatter slope than the south-west, and south-east terrain. Based on the topographic data supplied by the PHED, Jodhpur, that contained ground level elevations at 5m x 5 m interval, a geo-referenced ground level contour map and a 3-Dimensional digital elevation map (DEM) have been generated. Locations, where surveyed data were not available, particularly in the western side of the city, ASTER data available at 30 m x 30 m grid interval were used to develop the DEM applying an interpretation technique. The geo-referenced ground level contour map and the DEM are shown in **Figures 2.2, 2.3 and 2.4.** The DEM **(Figures 2.3 and 2.4)** showing general topographic features clearly depicts that topographic slopes of the Jodhpur city are towards south-east, south and south-west directions.

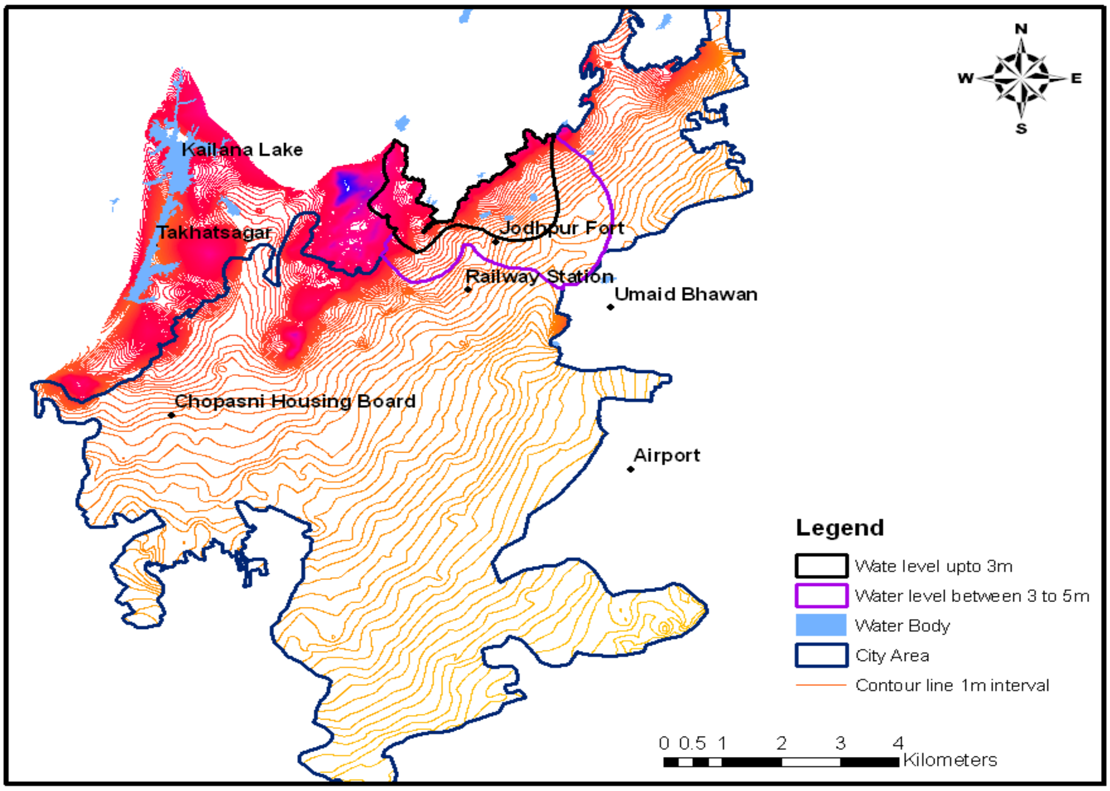

Figure 2.2: Topographic map of Jodhpur city showing topographical contour lines, Kailana & Takhatsagar Reservoirs including locations of some of the important places, and contours of water table up to a depth of 3m and 5 m below the ground surface.

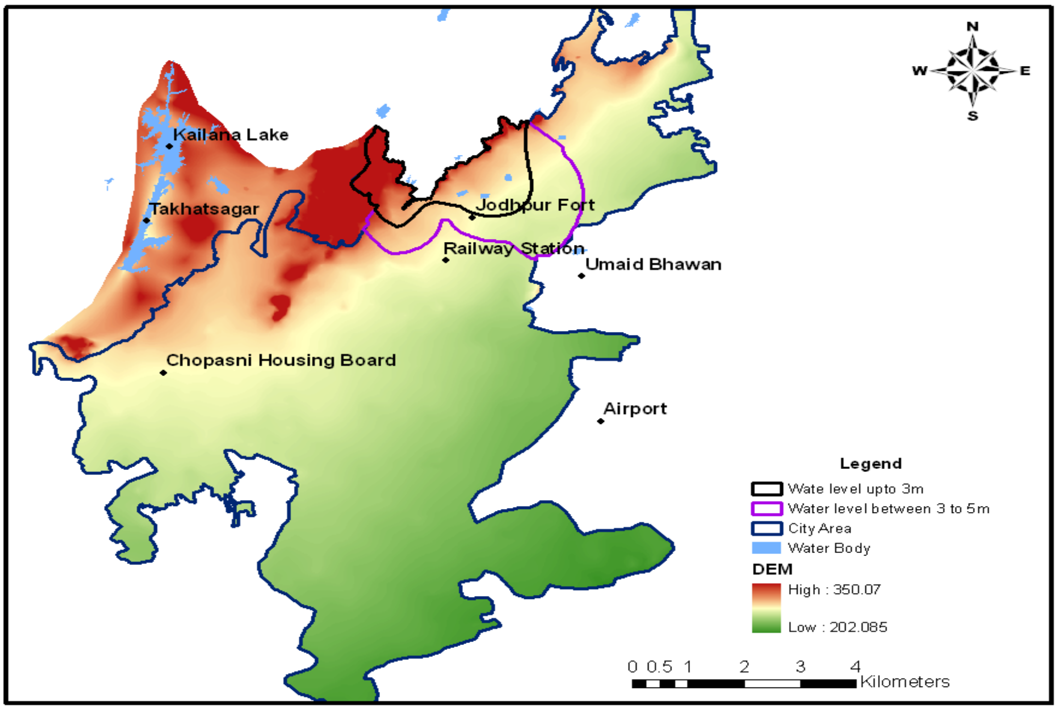

Figure 2.3 : 2-D Digital Elevation Map (DEM) for Jodhpur area showing locations of Kailana & Takhatsagar, small water bodies and two contour lines along which water table lies at 3 m and 5 m depth below ground surface.

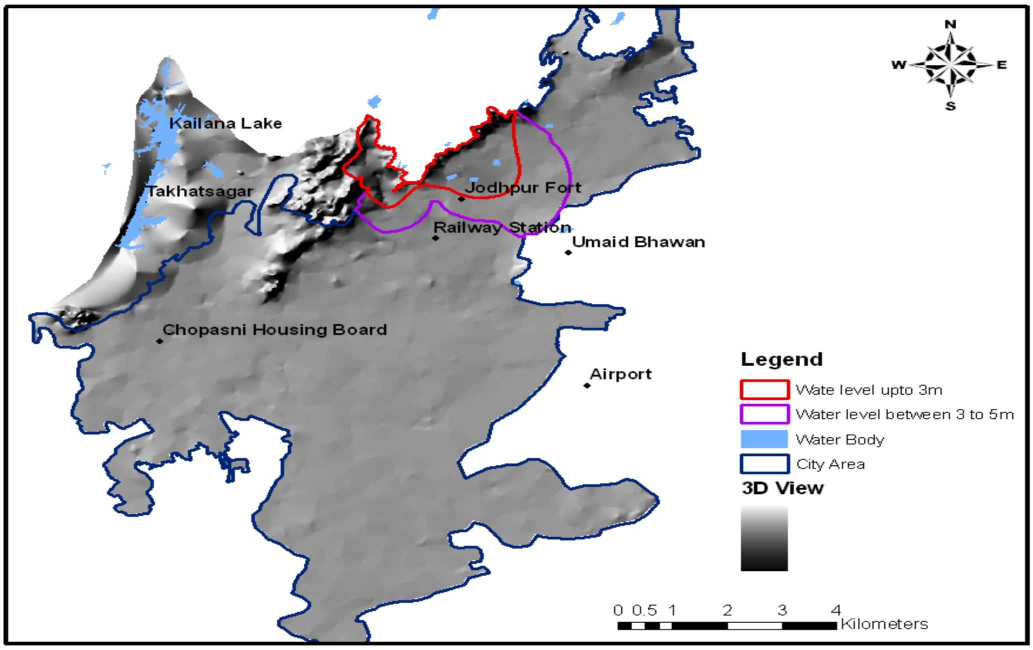

Figure 2.4: 3-D Digital Elevation Map (DEM) of the Jodhpur area showing location of Kailana and Takhatsagar and area in which water table lies up to 3 m and 5 m below ground surface.

The level of topography within the city area varies between 202 m and 360 m above msl with a small stretch near to the fort area having higher elevation with peak value of 310 m, whereas most of the area in the city is largely flat terrain having elevation below 250 m above msl. The Kailana Lake and the Takhatsagar Reservoir, which have the minimum bottom elevation of 254 m and 251 m above msl, have the maximum water elevation level of 273.7 m and 269.75 m respectively, above msl. Grossly, the bottom elevations of the Kailana Lake and the Takhatsagar Reservoir are above the elevation of the most part of the Jodhpur city. The storage conditions in the the Kailana Lake and the Takhatsagar Reservoir, apparently indicate that the Kailana Lake and the Takhatsagar Reservoir have the potential of groundwater flow movement to the city area provided the areas are hydraulically connected. However, the rising groundwater level and the waterlogged conditions in the city were observed along the extreme northern side in the old city area down below the Jodhpur fort area where the area has ground elevation between 230m and 310m, and the problematic area has an alignment almost at the same horizontal line if drawn from the Kailana and Takhatsagar Reservoir, which are separated by two distinct watersheds divider by a distance of about 5 km from the city area **(Figures 2.2, 2.3, and 2.4).** In Figures 2.2, 2.3 and 2.4, two contour lines of groundwater table; one indicating depth at 3 m below ground level (bgl) and other one indicating depth at 5m bgl have been shown. The orientation of the groundwater contour lines in the problematic area, which have been developed from the groundwater level data, indicates sprawling tendency towards south-easterly and south-westerly direction. The positional setups of the Kailana and Takhatsagar Reservoir, and the problematic area do not show any signature of homogeneous hydraulic connectivity rather has disjointed formations. If at all, both the setups have any linkage between them; that may be possible by sub-surface conduit created by rock fractures and lineaments.

Question then arises;

(i) Whether the Kailana Lake and the Takhatsagar Reservoir could be the source for cause of rise in groundwater level in the area facing the water logging conditions?

(ii) If yes, how? And if no, then what are other possible causes of such rise in groundwater level?

(iii) What are the remedies, and how to contain the rising groundwater level in a sustainable manner?

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Section - 3.0 : GEOLOGICAL FORMATIONS AND AQUIFER CHARACTERIZATION

3.1 Geological Formations

Geologically, Jodhpur area is comprised of the rocks of Pre-Cambrian, Paleozoic periods and Quaternary sediments. General stratigraphy of the Jodhpur area is given in Table-3.1:

Table 3.1 : Stratigraphy of the Jodhpur area

Era	Formation	Group	Lithology
Quaternary	Recent to Sub Recent		Wind blown sand and alluvium
Unconformity			
Paleozoic	Marwar Super Group	Jodhpur Group	Sandstone and Shale
Unconformity			
Pre-Cambrian	Malani Igneous suite		Rhyolite with tuffs and Granite

The Malani suite of Igneous rocks is comprised of grey, buff and brown colored volcanic flows of Rhyolite. These rocks constitute the basement rocks in the area. The volcanic rocks are exposed as bold ridges with respect to regional ground level and separate Jodhpur group of rocks into two distinct outcrops. These rocks are exposed mainly in the western and northern part of the area.

The Jodhpur group of rocks is deposited over these moderately undulating basement rocks (volcanic). The Paleozoic formations of the Jodhpur area are categorized as upper and lower Vindhyans in the east and Marwar in the west, which are primarily comprised of thick series of sedimentary rocks consisting of sandstone, limestone and shales. These rocks are exposed in the central, eastern and north western part of the study area. Quaternary alluvium comprising of sand, clay, silt and kankars, overlies the Jodhpur group or Rhyolites in the southern part of the area **(Figure 3.1).**

From the analysis of satellite imageries, it is noted that Kailana and Takhatsagar area is located on the Rhyolite formation, whereas Jodhpur city is mainly located on the sandstone and shale formation **(Figure 3.1).** These two formations have different hydro- and cannot be considered as a single system. Rhyolite is relatively impervious, whereas sandstone is reasonably pervious.

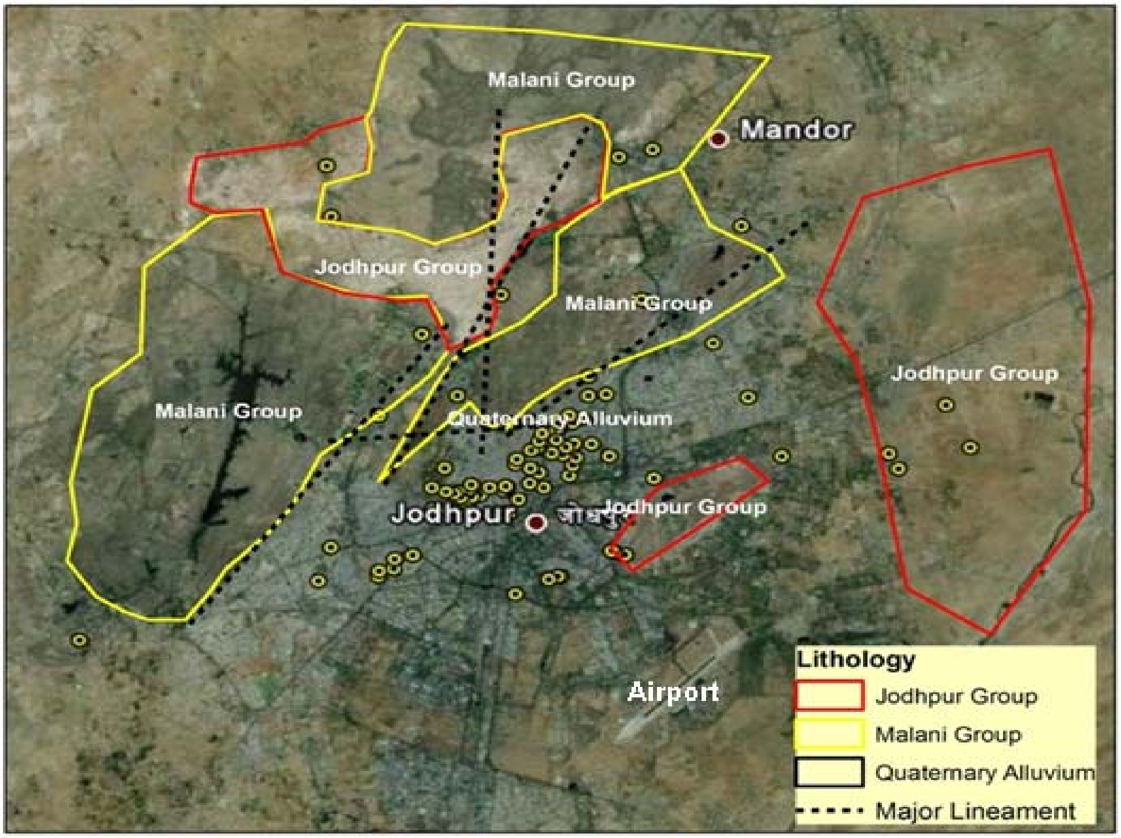

Figure 3.1 : Geological groups of the geological formations of Jodhpur area as observed from the satellite imageries.

3.2 Aquifer Characterization

The litholog data of 93 bore wells (details are given in **Table-A3.1** in the Annexure), supplied by the Groundwater Department, Jodhpur, have been analyzed using ROCKWORKS 2006 software. The geo-referenced locations of the borelogs are shown in **Figure 3.2.** From the analysis of the lithologs data, it is observed that the Jodhpur city area is characterized by a number of flat-topped hills trending in N-S or NE –NW direction and are primarily composed of Shales, Sandstones and Rhyolites (**Figure 3.3),** while the plain terrain represents the Quaternary alluvium formations at the top, which is formed by weathering of Rhyolites and Sandstones. The Quaternary alluvium formation varies in thickness from few centimeters to about 75 m in depth. The alluvium formation is underlain mainly by the Sandstone and Shale of Jodhpur group **(Figure 3.4)**, which is further underlain by the Rhyolites.

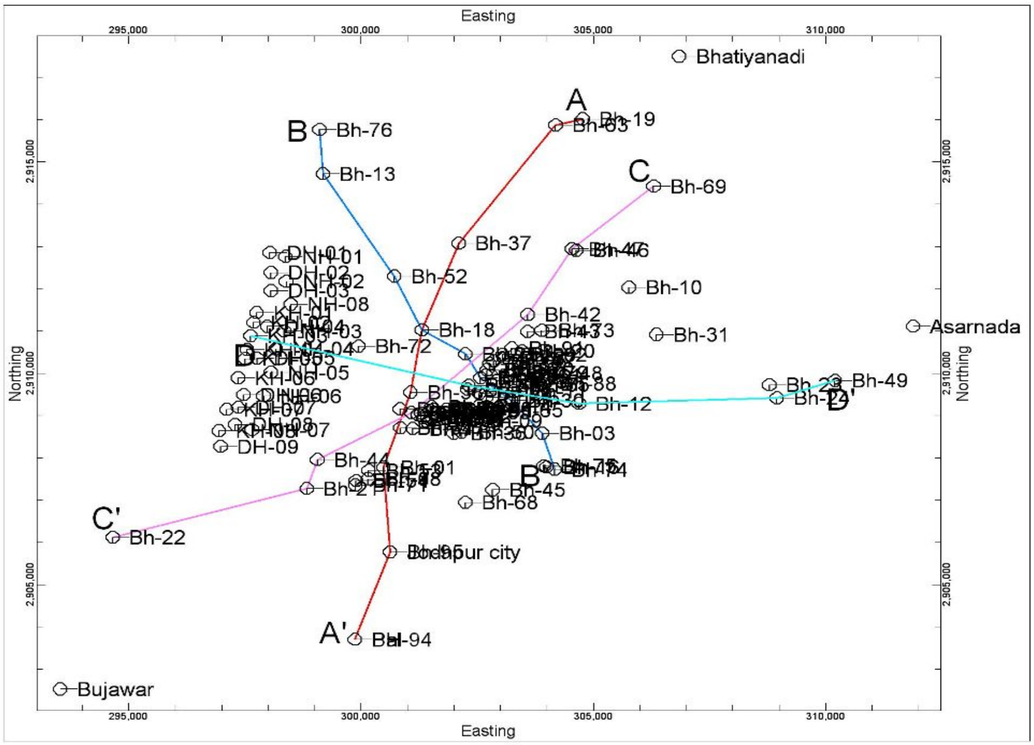

Figure 3.2: Map showing locations of 93 bore logs and their sectional lines along which geological formations are shown.

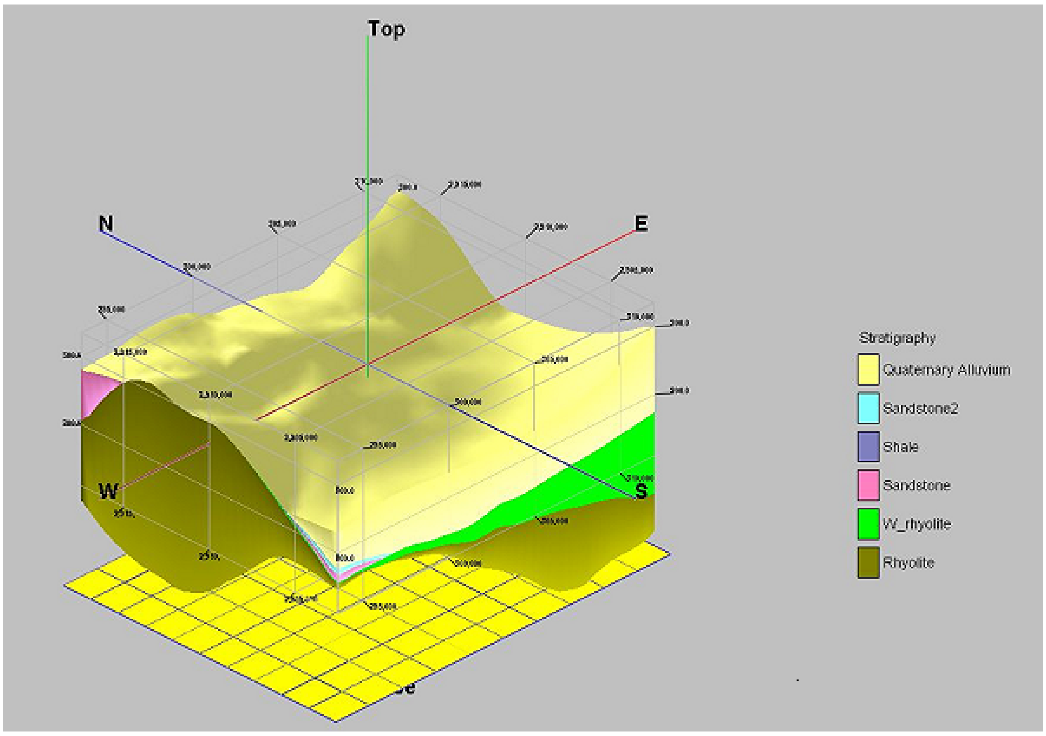

Figure 3.3 : Stratigraphic model of the geological formations of the Jodhpur city.

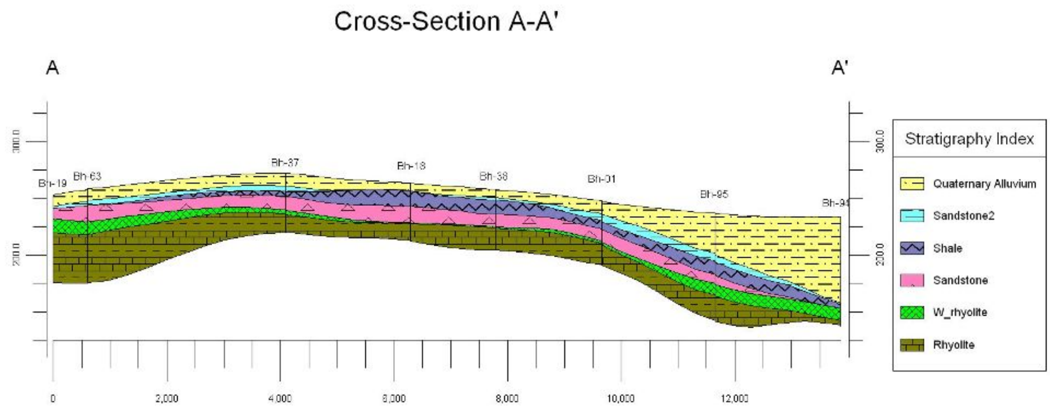

Figure 3.4: Geological formations of Jodhpur area along line A-A’ of Figure-3.2.

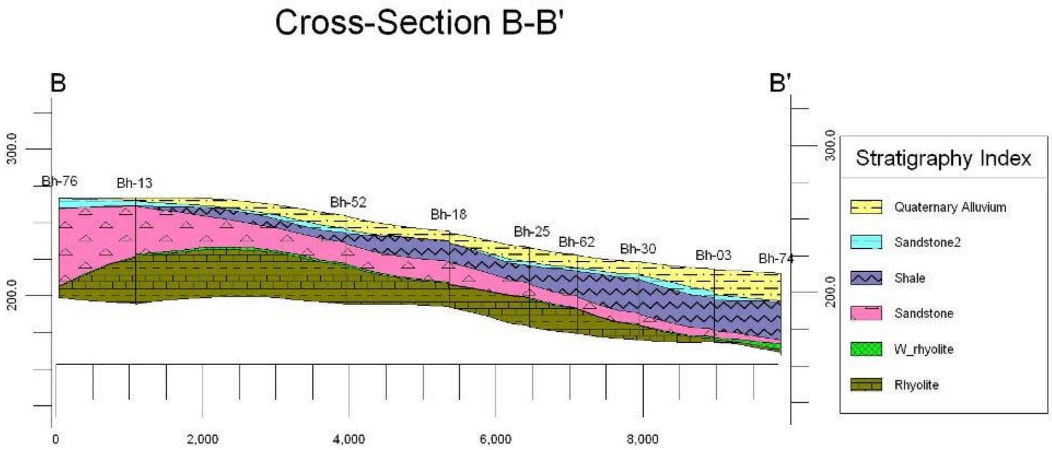

Figure 3.5: Geological formations of Jodhpur area along line B-B’ of Figure-3.2.

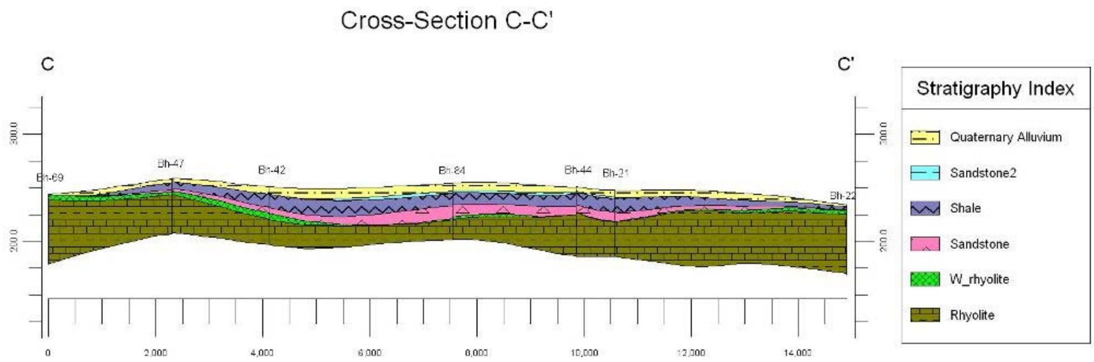

Figure 3.6: Geological formations of Jodhpur area along lines C-C’ of Figure-3.2.

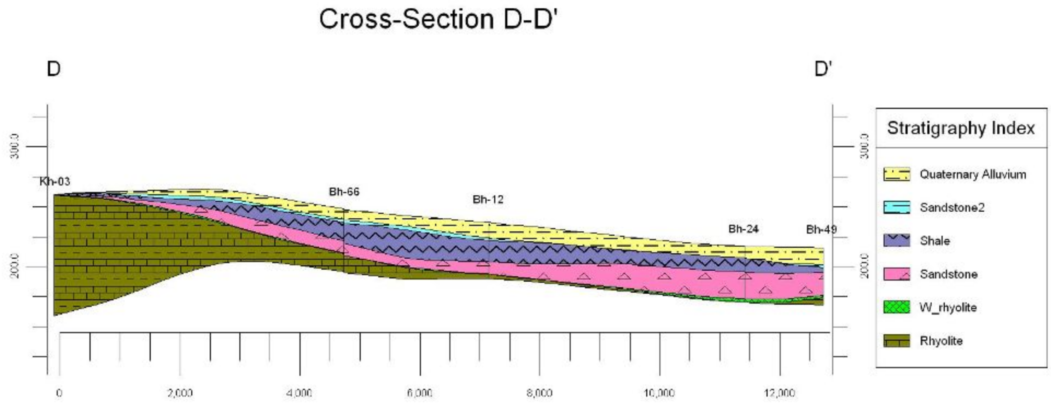

Figure 3.7: Geological formations of Jodhpur area along line D-D' of Figure-3.2.

It can be seen from Figure 3.1 that, there are number of faults and lineaments mostly oriented towards N-E to S-W direction and few from North to south direction. There is only one fault and lineament that is aligned in west to east direction perpendicular to the Kailana-Takhatsagar Reservoir and extended to the Jodhpur city close to the problematic area, apparently showing not exactly connected near to the proximity of the Kailana-Takhatsagar Reservoir, but are separated by two distinct geological formations; one is comprised of Malani Group of rocks on which Kailana-Takhatsagar Reservoir is situated, and the other one is Quaternary alluvium formation encompassing the problematic area. However, whether these two formations are connected to each other through fractures can be studied by hydraulic analysis of flow in addition to the geophysical survey.

The geological formations underneath the Jodhpur city can be seen in details from the cross-sectional views along different directions. The cross-sectional view along A-A' direction of **Figure 3.2**, that indicates formations along N-S direction, is shown in **Figure 3.4.** It can be seen from Figure 3.4 that the top formation is of Quaternary alluvium having thickness varying from about 7 m along northern side to a maximum of about 75 m as one move along south direction. The Quaternary alluvium formation is underlain by a thin layer of Sandstone formation, which is further underlain respectively by; Shale, Sandstone, and finally by Rhyolite of varying thickness. As such, the borelogs data representing formations up to a depth of 75 m below ground surface do not represent existence of any other aquifer at larger depth except the one at the top comprised of Quaternary alluvium formation. The general slope of the alluvium formation is towards southern direction.

The cross-sectional view along B-B’ direction of Figure 3.2**,** that indicates formations along NW towards SE direction, is shown in **Figure 3.5**. It can be seen from Figure 3.5 that the top formation is of Quaternary alluvium having thickness varying from zero near the NW side to a maximum of about 21 m as one move to the SE direction. The Quaternary alluvium formation is underlain by a thin layer of Sandstone formation, which is further underlain respectively by; Shale, Sandstone, and finally by Rhyolite of varying thickness. The general slope of the alluvium and Shale formations are towards south-east direction; whereas the thickness of the Sandstone formation gradually reduces in the south-east direction. The formations along this direction also do not indicate presence of any deeper aquifer underneath the Rhyolite formation.

The cross-sectional view along C-C’ direction of Figure 3.2, that indicates formations along NE towards SW direction, is shown in **Figure 3.6**. It can be seen from Figure 3.6 that the top formation is of Quaternary alluvium having by and large relatively less thickness varying from zero along NE direction to a maximum of about 6 m towards the SW direction. The Quaternary alluvium formation is underlain by a thin layer of Shale formation, which is further underlain respectively by; Sandstone, and finally by Rhyolite of varying thickness. The general slope of the alluvium and Rhyolite formations are towards south-east; whose thickness varies from location to location. The formations along this direction also do not indicate presence of any deeper aquifer underneath the Rhyolite formation.

The cross-sectional view along D-D’ direction of Figure 3.2, that indicates formations along W to E direction, is shown in **Figure 3.7.** It can be seen from Figure 3.7 that the top formation is of Quaternary alluvium formation having zero thickness near to the western side and gradually increases to a large thickness of about 22 m as one move towards east direction. The Quaternary alluvium formation is underlain by a very thin layer of Sandstone formation that disappears in many locations, which is further underlain respectively by; Share, Sandstone, and finally by Rhyolite of varying thickness. Thickness of the bottom Rhyolite formation increases to a large extent as the formation approaches towards Kailana-Takhatsagar Reservoir. The general slope of the alluvium formation is towards eastern direction; whose thickness gradually increases from west to east direction. The formations along this direction also do not indicate presence of any deeper aquifer underneath the Rhyolite formation.

Largely, the geological formations of the Jodhpur city indicate presence of an unconfined aquifer comprised of Quaternary alluvium formation having thickness varying from zero around the NW and NE direction, which increased gradually to a large depth ranging from 6 and 75 m, as one moves from SW to SE direction, having slope primarily towards south-easterly direction. The shape of the unconfined aquifer can be categorized as Pan-shaped. The unconfined aquifer is underlain respectively by Shale, Sandstone and finally by Rhyolite formation of different thickness varying from location to location. As such, there is no existence of any deeper aquifer below the Jodhpur city up to a depth of 75 m, below the ground surface.

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Section – 4.0 : HYDRO-METEOROLOGICAL DATA AND ANALYSIS

4.1 Rainfall

Thirty six years (1971-2006) daily rainfall data of the Jodhpur city obtained from the IMD showed that average annual rainfall of the city is 378 mm with minimum of 91 mm in the year 2002 and maximum of 821 mm in the year 1990 **(Figure 4.1),** while the last 25 years (1982-2006) annual rainfall data indicate an average annual rainfall of 357 mm **(Figure 4.2).** The main rainfall months are July and August. July is the most wetted month, followed by August. About 68% and 86% of the annual rainfall occurs respectively during July and August during the monsoon months (June through September). The number of intensified rainy days in a year is reported to be about 15 days. Distribution of daily rainfall pattern in a year, analyzed based on the data of last 36 years (1971-2006) is shown in **Figure 4.3.** The variation of annual rainfalls in the Jodhpur city during the year 1978-2006 is shown in Figure 4.3**.**

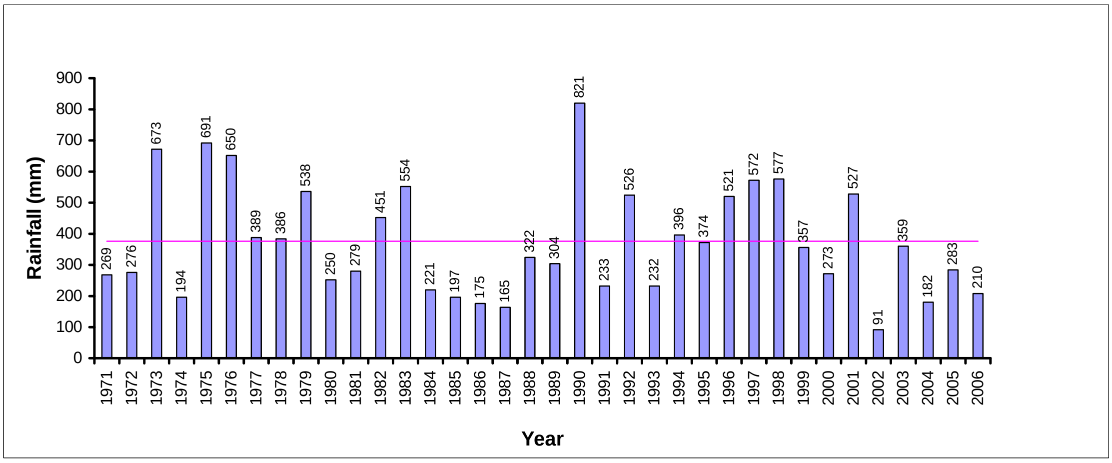

Figure 4.1: Annual variation of rainfall in Jodhpur area during the last 36 years for the period 1971-2006.

The average maximum temperature and the average minimum temperature during summer are reported to be 42.2°C, and 27.3°C respectively, and during winter the average maximum temperature is 27.5°C and the average minimum temperature is 9.5°C.

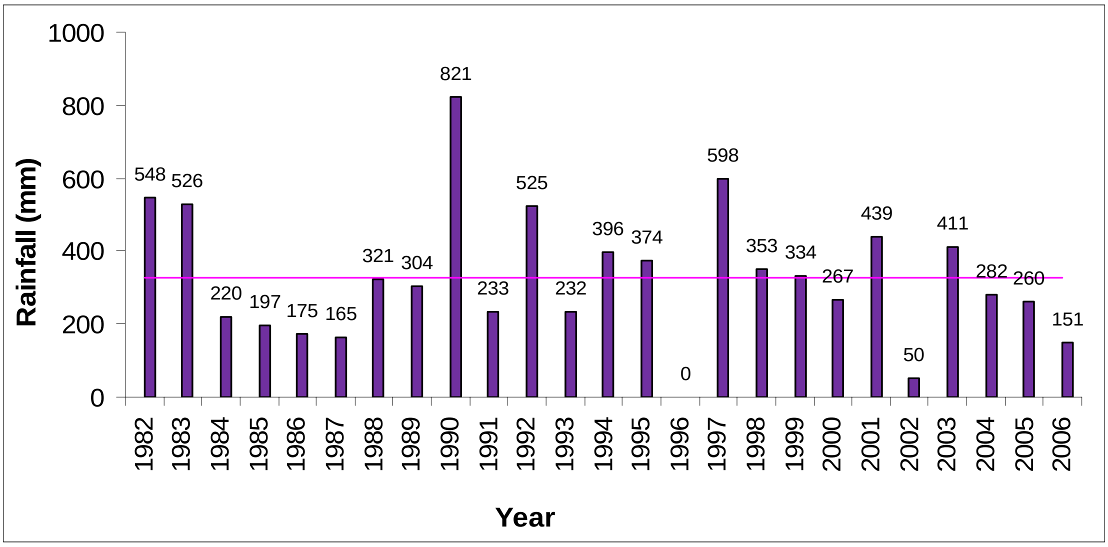

Figure 4.2: Annual variation of rainfall in Jodhpur area during the last 25 years for the period 1982-2006

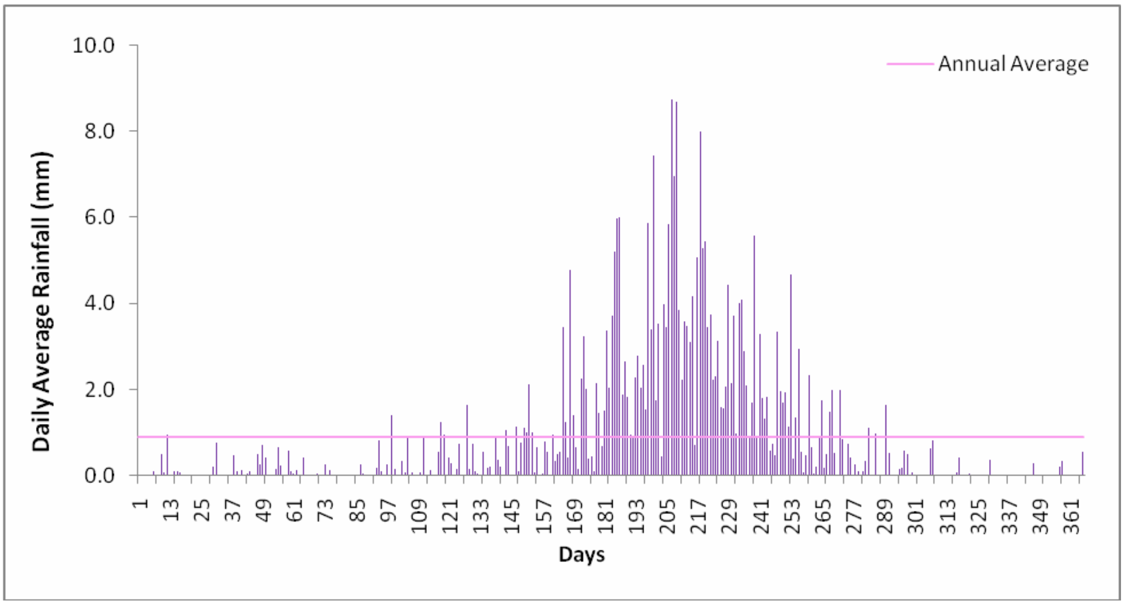

Figure 4.3: Distribution of daily rainfall pattern in Jodhpur area during the last 28 years for the period 1978-2006

4.2 Evaporation

Twenty five years (1978-2002) monthly Pan-A evaporation data of the Jodhpur station (station no. 42339) obtained from IMD shown in **Table-4.1** and **Figure 4.4** indicate that the maximum water surface evaporation is 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. The evaporation data of the Jodhpur city indicate that the total evaporation losses from the 19 water bodies of surface area about 1.66 sq. km, if the water bodies contain water over the year, would be about 48,015,219 m^3.

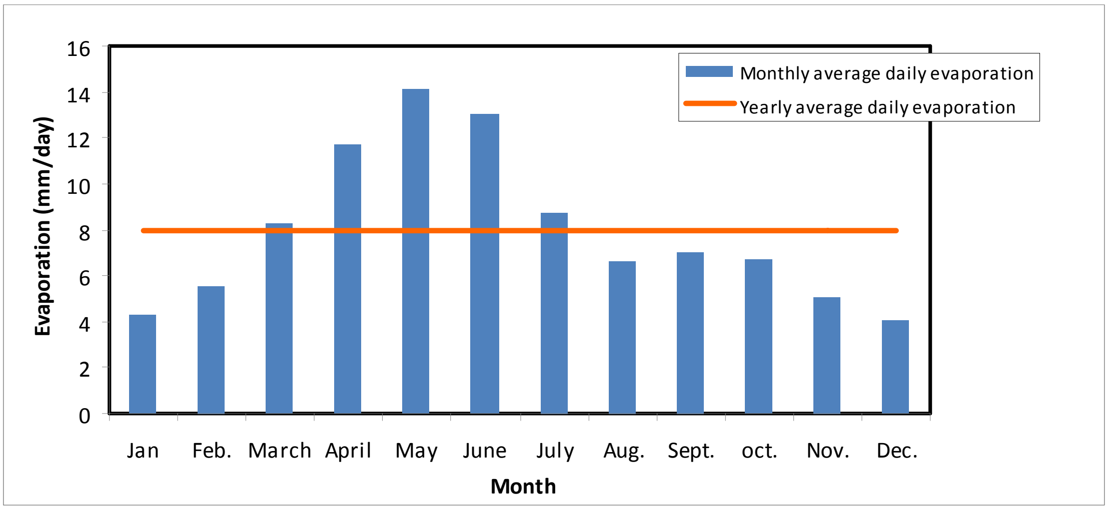

Figure 4.4: Average monthly variation of water surface evaporation in the Jodhpur area.

Table-4.1: Average monthly evaporation from Class 'A' Pan considering 25 years (1978-2002) IMD data for Jodhpur city

Month	Average	Standard Deviation
	Evaporation (mm/day)	
January	4.255	0.7139
February	5.573	0.7034
March	8.300	0.8421
April	11.673	1.1576
May	14.127	1.7027
June	13.000	1.4340
July	8.709	2.0309
August	6.618	1.5349
September	7.045	1.6163
October	6.718	1.0928
November	5.036	0.8647
December	4.059	0.6998

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Section – 5.0: DEMOGRAPHY AND WATER REQUIREMENT

5.1 Demography

Because of its historical and commercial importance, strategic location and infrastructural facilities, Jodhpur city has grown very fast in the past and is also growing continuously. It being the Headquarters of the Western Air Command, it has a strategic importance for the country. The Aerodrome is located in the city in the south-eastern side. The city is known to be the second largest city in Rajasthan after Jaipur.

The city that had a population of about 3,65,000 in the year 1971, was expected to have a population of 11,00,000 by the year 2010. According to the censuses of the years 1981, 1991, and 2001, the population of the Jodhpur city had been reported to be 5,05,000; 6,66,280 and 8,51,051, respectively. The population censuses of previous four decades indicated a growth rate of 3.21% per year. The growth rate of 3.21% per year gives the projected population of about 11,08,950 at the end of the year 2010, and 12,74,830 by the year 2015. The variation of population growth over different years since the year 1971 is shown in **Figure 5.1**. The fitted population data give an exponential rise satisfying the following equation:

$$P = 5.1\, x\, 10^{-19}\, Exp\,(0.02788\, X) \qquad \text{................ (5.1)}$$

in which, P is the population in a particular calendar year; X is the calendar year in its full term, e.g.,1990, for which population is to be calculated. Equation (5.1) fits to the data with a correlation coefficient, $R^2 = 0.9976$.

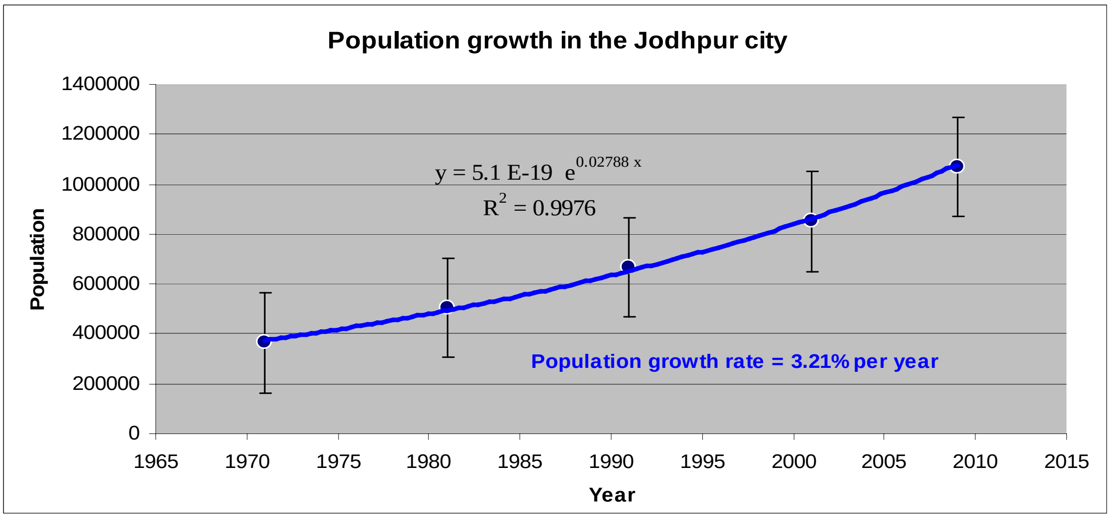

Figure 5.1 : Variation of Population growth in the Jodhpur

In order to facilitate human activities and their aspirations, administratively the Jodhpur area has been categorized into 60 wards based on the households and population. All these wards do not appear within the study area. Nearly, 34 wards fully and 17 wards partially encompassed by the study area. The wards, encompassed within the study area including their identification details, area, and population as of the year 2001, are given in **Figure 5.2 and Table-5.1.** Considering a uniform growth rate of 3.21% per year on the population of the year 2001 in each ward, the ward-wise projected population for different years has been estimated and given in **Table-5.2**.

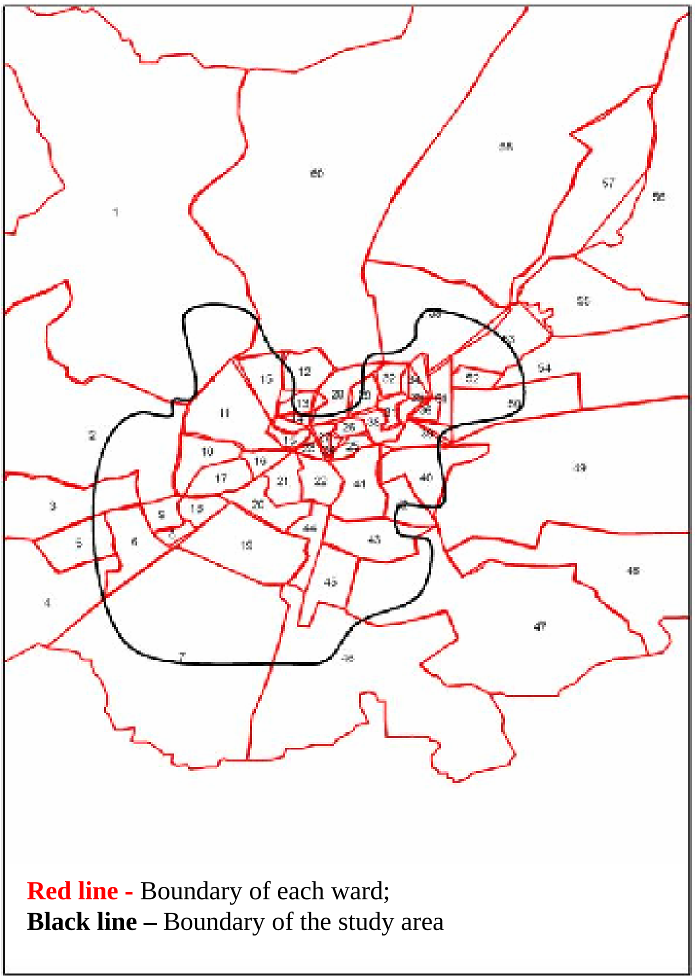

Figure 5.2 : Municipal wards encompassed in the study area in the Jodhpur city

Table 5.1: Wards encompassed in the study area including their population by the year 2001, total area & area covered within the study area

Wards No.	Position in study area	Population (2001)	Total area (sq.km)	Approx. area within study area (sq. km)	Estimated Population in the area encompassed by study area (2001)
1	Partially	11,857	39.79	3.75	1117
2	Partially	21,231	20.90	4.81	4883
3	Partially	22,339	3.43	0.79	5138
4	Outside	40,590	17.23	0.00	
5	Partially	17,153	1.38	0.32	3945
6	Fully	12,905	1.60	1.60	12905
7	Partially	22,410	15.98	8.75	12268
8	Fully	14,313	0.30	0.30	14313
9	Fully	10,791	0.60	0.60	10791
10	Fully	15,842	1.10	1.10	15801
11	Fully	16,941	2.55	2.55	16910
12	Partially	9,556	0.85	0.20	2198
13	Partially	8,669	0.39	0.20	4437
14	Fully	11,756	0.12	0.12	11935
15	Fully	13,488	1.14	1.14	13519
16	Fully	8,841	0.39	0.39	8783
17	Fully	21,734	0.86	0.86	21732
18	Fully	11,012	0.50	0.50	10941
19	Fully	10,513	2.94	2.94	10498
20	Fully	12,586	1.00	1.00	12552
21	Fully	8,021	0.73	0.73	8015
22	Fully	11,555	0.80	0.80	11564
23	Fully	10,579	0.19	0.19	10447
24	Fully	9,063	0.16	0.16	9019
25	Fully	11,969	0.26	0.26	11816
26	Fully	13,117	0.23	0.23	13178
27	Fully	10,623	0.20	0.20	10497
28	Partially	11,702	0.91	0.25	3230
29	Partially	12,061	0.38	0.22	6935
30	Partially	7,115	0.40	0.35	6240
31	Fully	9,289	0.26	0.26	9115
32	Fully	8,104	0.36	0.36	8076
33	Fully	12,297	0.40	0.40	12326
34	Fully	8,161	0.49	0.49	8233
35	Fully	10,995	0.39	0.39	10863
36	Fully	12,492	0.66	0.66	12411
37	Fully	12,970	0.07	0.07	12251
38	Fully	10,282	0.40	0.40	10306
39	Fully	7,065	0.66	0.66	7014
40	Partially	10,499	1.74	1.55	9362

41	Fully	7,081	1.52	1.52	7076
42	Partially	11,341	0.78	0.40	5799
43	Fully	13,116	1.62	1.62	13123
44	Fully	10,949	0.79	0.79	10961
45	Fully	13,652	1.27	1.27	13604
46	Partially	23,074	14.77	1.95	3047
47	Partially	22,605	13.35	1.45	2456
48	Outside	13,125	8.26	0.00	
49	Outside	26,083	20.14	0.00	
50	Partially	14,211	2.53	1.25	7031
51	Fully	8,722	0.75	0.75	8749
52	Fully	10,119	0.41	0.41	10200
53	Partially	17,435	2.03	1.05	9002
54	Outside	29,391	12.07	0.00	
55	Outside	27,035	3.94	0.00	
56	Outside	21,969	27.94	0.00	
57	Outside	13,063	5.35	0.00	
58	Outside	16,894	26.68	0.00	
59	Partially	11,993	4.84	2.55	6313
60	Outside	16,707	31.82	0.00	
	TOTAL	**8,41,505**	**303.44**	**55.55**	**4,80,731**

Table 5.2: Projected population of each ward encompassed by the study area; calculated on pro-rata basis with growth rate of 3.21% per year.

Wards No.	Population in the ward encompassed by study area in 2001	Population in the ward encompassed by study area in 2005	Population in the ward encompassed by study area in 2010	Population in the ward encompassed by study area in 2015
1	1117	1261	1440	1620
2	4883	5510	6294	7078
3	5138	5798	6622	7447
5	3945	4452	5085	5718
6	12905	14562	16633	18705
7	12268	13844	15813	17782
8	14313	16151	18448	20745
9	10791	12177	13909	15640
10	15801	17830	20366	22902
11	16910	19081	21795	24509
12	2198	2480	2833	3186
13	4437	5007	5719	6431
14	11935	13467	15383	17298
15	13519	15255	17425	19595
16	8783	9911	11321	12730

17	21732	24523	28011	31499
18	10941	12346	14102	15858
19	10498	11846	13531	15216
20	12552	14163	16178	18192
21	8015	9044	10331	11617
22	11564	13048	14904	16760
23	10447	11789	13465	15142
24	9019	10178	11625	13073
25	11816	13333	15229	17126
26	13178	14870	16985	19100
27	10497	11845	13530	15215
28	3230	3645	4163	4682
29	6935	7826	8939	10052
30	6240	7042	8043	9045
31	9115	10286	11749	13212
32	8076	9113	10409	11705
33	12326	13909	15887	17866
34	8233	9290	10611	11933
35	10863	12258	14001	15745
36	12411	14004	15996	17988
37	12251	13824	15791	17757
38	10306	11630	13284	14938
39	7014	7915	9040	10166
40	9362	10564	12066	13569
41	7076	7984	9120	10256
42	5799	6544	7475	8405
43	13123	14808	16914	19020
44	10961	12368	14128	15887
45	13604	15351	17535	19718
46	3047	3438	3927	4416
47	2456	2771	3165	3560
50	7031	7934	9063	10191
51	8749	9872	11276	12681
52	10200	11510	13147	14784
53	9002	10158	11602	13047
59	6313	7124	8137	9150
TOTAL	**4,80,731**	**5,42,457**	**6,19,615**	**6,96,772**

Out of the total area of 303.44 sq. km of 60 wards covered by the Jodhpur city, the area encompassed by 51 wards (34 fully, and 17 partially) within the study area is nearly 55.55 sq. km. The total population in the 60 wards as per the year 2001 was about 8,41,505, out of which nearly 4,80,731 (estimated on pro-rata basis in accordance with the proportion of area of each ward encompassed by the study area) is estimated to be the population in the study area. The ward-wise details of area and population can be seen in

Table 5.1. Based on the population growth rate of 3.21% per year, the projected population of each ward for the year 2005, 2010, and 2015 have been calculated and given in **Table 5.2.** It can be seen from Table 5.2, the population in the study area, which was about 4,80,731, might had gone up to the tune of 5,42,457 by the year 2005, and 6,19,615 by the year 2010, and expected to increase to the order 6,96,772 by the year 2015 with the growth rate remaining same at 3.21% per year.

5.2 Water Requirement and Distribution

The water supply requirements to the population in the city area for their various designated uses are primarily met by the Jodhpur Municipality through water supply & distribution systems managed by the Public Health Engineering Department (PHED), Jodhpur. As such, no specific guidelines towards quantity of water being supplied are followed; it is based on thumb rule in accordance to the supply-demand norm. As the city has expanded over the years, more areas and more number of people have been brought under the coverage of the water supply distribution; and the water supply from the intake has been increased accordingly on pro-rata basis. The city, by and large, has a large network of water supply distribution lines not connecting to all households. In some areas, the distribution lines are very old, constructed long back, and in some parts people/houses are not connected to organized water supply lines, use water from the hydrants constructed along the roadsides or from the nearby water supply points. Owing to the unregulated and uncontrolled supply of water, people in the city area practice water uses round the clock without understanding to its far reaching consequences.

As per the Ministry of Works and Housing (MOWH,1999) norms of water requirement @ 140 litres per capita per day (lpcd), the water supply requirement of the people living in the whole Jodhpur area was about 218.6 lacs gallon per day (gpd) in the year 1994, 244.4 lacs gpd in the year 1998, 258.4 lacs gpd in the year 2000, 305.5 lacs gpd in the year 2006, and about 332.1 lacs gpd in the year 2009, excluding the industrial requirements in those years in the city area. According to the data of the PHED, Jodhpur

(GWD et al., 1999), the supplies of water to the city were about 183.5 lacs gpd (i.e.,117 lpcd) in the year 1994; 278.6 lacs gpd (i.e., 164.8 lpcd) in the year 1998; 341.7 lacs gpd (i.e., 185.1 lpcd) in the year 2000; 462.4 lacs gpd (i.e, 211.9 lpcd) in the year 2006; and 521.7 lacs gpd (i.e., 220 lpcd) in the year 2009; that showed average yearly rate of increase about 6.1 lcpd since the year 1994. The percent increase of per capita water supplied to the city area during the year 1998 to 2009 varied between 17% - 60% with respect to the standard norms of 140 lcpd. Year-wise variations of water supply requirements as per the MOWH norms and the water supplied by the PHED to the city area have been given in Figure 5.3 and Table 5.3. It can be seen from Figure 5.3 and Table 5.3 that the quantities of water supplied to the city from the Kailana-Takhatsagar Reservoir in different years are much higher than the quantity actually required as per the MOWH norms. Even, the water supply norm of MOWH of 140 lcpd is also very much on higher side particularly, for the arid and semi-arid regions where water is scarcely available.

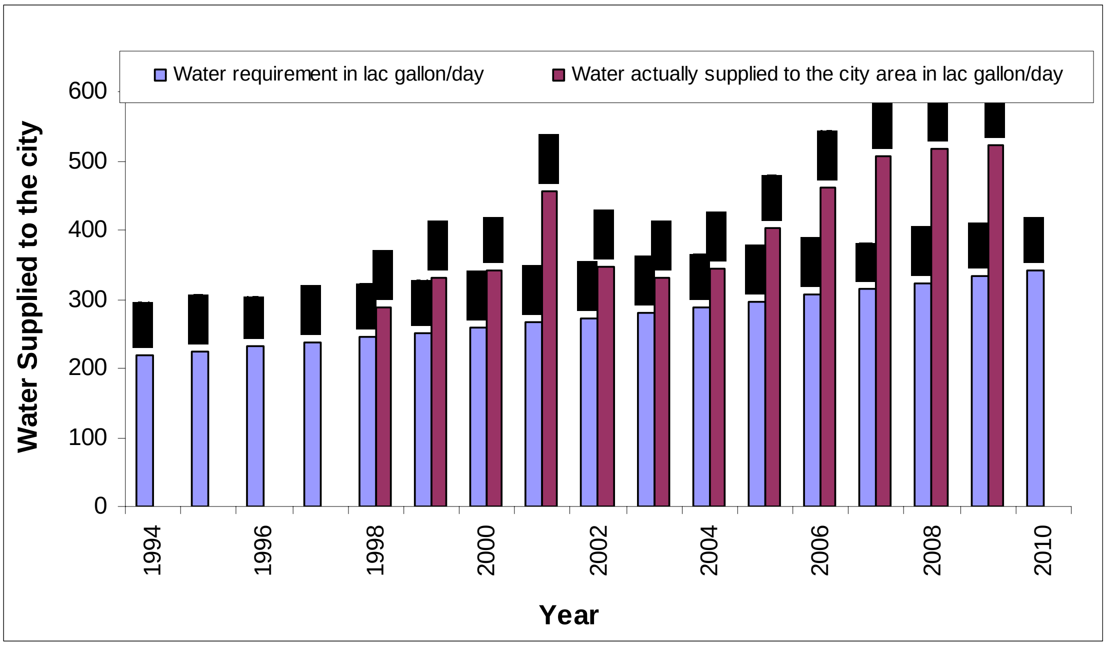

Figure 5.3 : Water requirements as per MOWH norms and actually supplied per day to the Jodhpur city in different years

Table 5.3 : Water requirements as per MoWH norms and actually supplied from the Kailana-Takhatsagar Reservoir in different years

Year	Population	Water required in lac gallon/day	Water actually supplied to the city in lac gallon/day
1994	709875	218.62	
1995	729944	224.80	
1996	750582	231.15	
1997	771802	237.69	
1998	793623	244.41	287.64
1999	816060	251.32	330.99
2000	839132	258.42	341.66
2001	862857	265.73	455.83
2002	887252	273.24	346.82
2003	912336	280.97	330.76
2004	938130	288.91	343.52
2005	964653	297.08	401.70
2006	991926	305.48	462.35
2007	1019970	314.11	505.95
2008	1048807	322.99	516.47
2009	1078459	332.13	521.67
2010	1108950	341.52	

As such, no specific data were available on the area-wise water supplied to the different locations in the city. Based on the ward-wise population and their projections in different years, a conservative estimate of water requirement (MOWH norm) and water supplied in different years on pro-rata basis has been made, and the estimated values are given in Table- 5.4. For projection of ward-wise population, the criterion of uniform growth rate of 3.21% per year on the basic data of population (year, 2001) in the respective ward has been considered. The quantities of water supplied in different years to the respective wards are also considered for further analysis. As the sum total of water distribution in the different wards satisfies the total quantity of water supplied in the city area, hence, it assures the overall water balance.

Table 5.4 : Ward-wise water requirements and actually supplied in different years.

Wards No.	Year	Population	Water requirement as per MOWH norm (1999) (gallon/day)	Water actually supplied on pro-rata basis (gallon/day)
1	2001	1117	34399	59009
	2005	1261	38834	52510
	2009	1437	44254	69510
	2015	1620	49890	
2	2001	4883	150378	257959
	2005	5510	169688	229447
	2009	6291	193740	304307
	2015	7078	217976	
3	2001	5138	158231	271430
	2005	5798	178557	241440
	2009	6619	203841	320173
	2015	7447	229340	
5	2001	3945	121491	208406
	2005	4452	137105	185390
	2009	5082	156507	245825
	2015	5718	176093	
6	2001	12905	397426	681745
	2005	14562	448456	606390
	2009	16630	512143	804423
	2015	18705	576045	
7	2001	12268	377809	648094
	2005	13844	426344	576491
	2009	15810	486890	764758
	2015	17782	547620	
8	2001	14313	440788	756127
	2005	16151	497391	672559
	2009	18445	568038	892218
	2015	20745	638869	
9	2001	10791	332323	570067
	2005	12177	375007	507074
	2009	13906	428253	672658
	2015	15640	481654	
10	2001	15801	486612	834735
	2005	17830	549098	742475
	2009	20363	627105	984995
	2015	22902	705297	
11	2001	16910	520766	893321
	2005	19081	587624	794569
	2009	21792	671113	1054118
	2015	24509	754787	
12	2001	2198	67690	116116
	2005	2480	76375	103272

	2009	2830	87154	136892
	2015	3186	98117	
13	2001	4437	136643	234398
	2005	5007	154197	208501
	2009	5716	176032	276493
	2015	6431	198051	
14	2001	11935	367554	630502
	2005	13467	414734	560792
	2009	15380	473647	743958
	2015	17298	532714	
15	2001	13519	416335	714182
	2005	15255	469798	635247
	2009	17422	536533	842733
	2015	19595	603454	
16	2001	8783	270484	463988
	2005	9911	305222	412713
	2009	11318	348553	547472
	2015	12730	392037	
17	2001	21732	669265	1148058
	2005	24523	755218	1021185
	2009	28008	862543	1354797
	2015	31499	970053	
18	2001	10941	336942	577991
	2005	12346	380211	514111
	2009	14099	434197	681994
	2015	15858	488368	
19	2001	10498	323300	554588
	2005	11846	364813	493290
	2009	13528	416612	654374
	2015	15216	468597	
20	2001	12552	386555	663097
	2005	14163	436168	589774
	2009	16175	498130	782414
	2015	18192	560246	
21	2001	8015	246832	423416
	2005	9044	278522	376609
	2009	10328	318064	499584
	2015	11617	357761	
22	2001	11564	356128	610903
	2005	13048	401830	543344
	2009	14901	458896	720788
	2015	16760	516146	
23	2001	10447	321729	551894
	2005	11789	363058	490917
	2009	13462	414580	651181
	2015	15142	466318	
24	2001	9019	277752	476456
	2005	10178	313445	423831

	2009	11622	357915	562177
	2015	13073	402600	
25	2001	11816	363889	624216
	2005	13333	410607	555212
	2009	15226	468905	736509
	2015	17126	527418	
26	2001	13178	405834	696167
	2005	14870	457941	619215
	2009	16982	522983	821450
	2015	19100	588209	
27	2001	10497	323269	554535
	2005	11845	364782	493249
	2009	13527	416582	654325
	2015	15215	468566	
28	2001	3230	99472	170634
	2005	3645	112253	151785
	2009	4160	128113	201227
	2015	4682	144188	
29	2001	6935	213572	366362
	2005	7826	241012	325890
	2009	8936	275196	432250
	2015	10052	309564	
30	2001	6240	192169	329647
	2005	7042	216868	293242
	2009	8040	247602	388909
	2015	9045	278553	
31	2001	9115	280708	481527
	2005	10286	316771	428329
	2009	11746	361733	568175
	2015	13212	406881	
32	2001	8076	248711	426639
	2005	9113	280647	379483
	2009	10406	320466	503357
	2015	11705	360471	
33	2001	12326	379595	651158
	2005	13909	428346	579197
	2009	15884	489168	768338
	2015	17866	550207	
34	2001	8233	253546	434933
	2005	9290	286098	386853
	2009	10608	326687	513128
	2015	11933	367492	
35	2001	10863	334540	573870
	2005	12258	377501	510447
	2009	13998	431087	677108
	2015	15745	484888	
36	2001	12411	382213	655648
	2005	14004	431271	583153

	2009	15993	492525	773610
	2015	17988	553964	
37	2001	12251	377286	647196
	2005	13824	425728	575658
	2009	15788	486212	763694
	2015	17757	546850	
38	2001	10306	317387	544445
	2005	11630	358161	484295
	2009	13281	409006	642426
	2015	14938	460035	
39	2001	7014	216005	370536
	2005	7915	243753	329596
	2009	9037	278306	437136
	2015	10166	313075	
40	2001	9362	288315	494576
	2005	10564	325332	439905
	2009	12063	371496	583509
	2015	13569	417875	
41	2001	7076	217915	373811
	2005	7984	245878	332469
	2009	9117	280770	441006
	2015	10256	315847	
42	2001	5799	178588	306350
	2005	6544	201531	272505
	2009	7472	230110	361434
	2015	8405	258843	
43	2001	13123	404140	693262
	2005	14808	456032	616634
	2009	16911	520796	818015
	2015	19020	585746	
44	2001	10961	337558	579048
	2005	12368	380889	515027
	2009	14125	434998	683252
	2015	15887	489261	
45	2001	13604	418953	718672
	2005	15351	472754	639245
	2009	17532	539921	848054
	2015	19718	607242	
46	2001	3047	93836	160967
	2005	3438	105878	143165
	2009	3924	120845	189811
	2015	4416	135996	
47	2001	2456	75636	129746
	2005	2771	85337	115390
	2009	3162	97378	152952
	2015	3560	109635	
50	2001	7031	216529	371434
	2005	7934	244338	330387

	2009	9060	279015	438248
	2015	10191	313845	
51	2001	8749	269437	462192
	2005	9872	304021	411089
	2009	11273	347167	545295
	2015	12681	390528	
52	2001	10200	314122	538845
	2005	11510	354465	479298
	2009	13144	404787	635799
	2015	14784	455293	
53	2001	9002	277228	475558
	2005	10158	312829	422999
	2009	11599	357206	561064
	2015	13047	401799	
59	2001	6313	194417	333503
	2005	7124	219393	296657
	2009	8134	250497	393456
	2015	9150	281786	

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6.1 The Kailana Lake

The Kailana lake is situated at an altitude of 256 m above m.s.l. between the latitudes from 26° 17′ 58″ N to 26° 19′ 21″ N and longitudes from 72° 58′ 01″ E to 72° 58′ 50″ E. The full level of the Kailana Lake is 273.7 m above msl. The water spread area and the capacity of the Kailana Lake at its full level are 0.88 sq. km and 4.814 mcm, respectively. The stage-capacity and area-capacity curve of the Kailana lake including their functional relationships developed based on the surveyed data supplied by the PHED are given in Figures 6.1, 6.2 and 6.3, respectively, and the stage-area-capacity table indicating the numerical values is given in **Table-A6.1** in the annexure. The Kailana Lake is fed directly by the Rajiv Gandhi lift canal, locally known as Hathi canal. It also receives some quantities of water during monsoon period through surface runoffs from the catchments encompassing the lake. The Rajiv Gandhi Lift canal, that travels a total of 650 kilometers in Rajasthan and ends at Ramgarh, near Jaisalmer, takes water from the Indira Gandhi Canal. The Indira Gandhi Canal is one of the biggest canal projects in India. It starts from the Harike Barrage at Sultanpur, a few kilometers below the confluence of the Sutlej and Beas rivers in Punjab state. The supply of water to the Kailana Lake, being linked to the Indira Gandhi Canal, has an ensured inflow, unless otherwise the canal supply is disrupted.

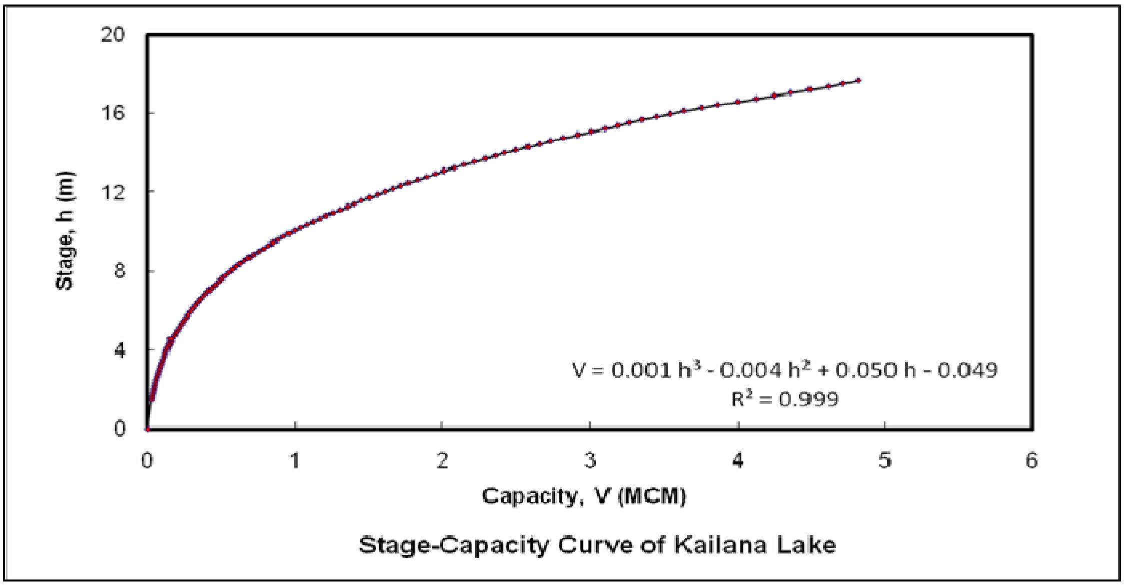

Figure 6.1 : Stage – Capacity curve of the Kailana Lake

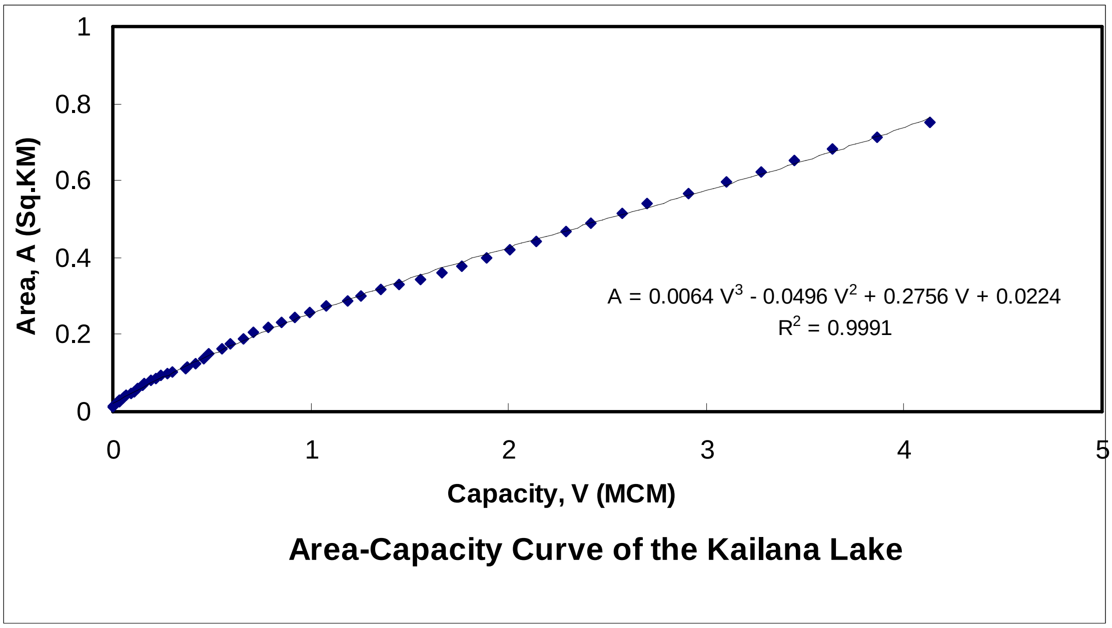

Figure 6.2 : Area-Capacity curve of the Kailana Lake

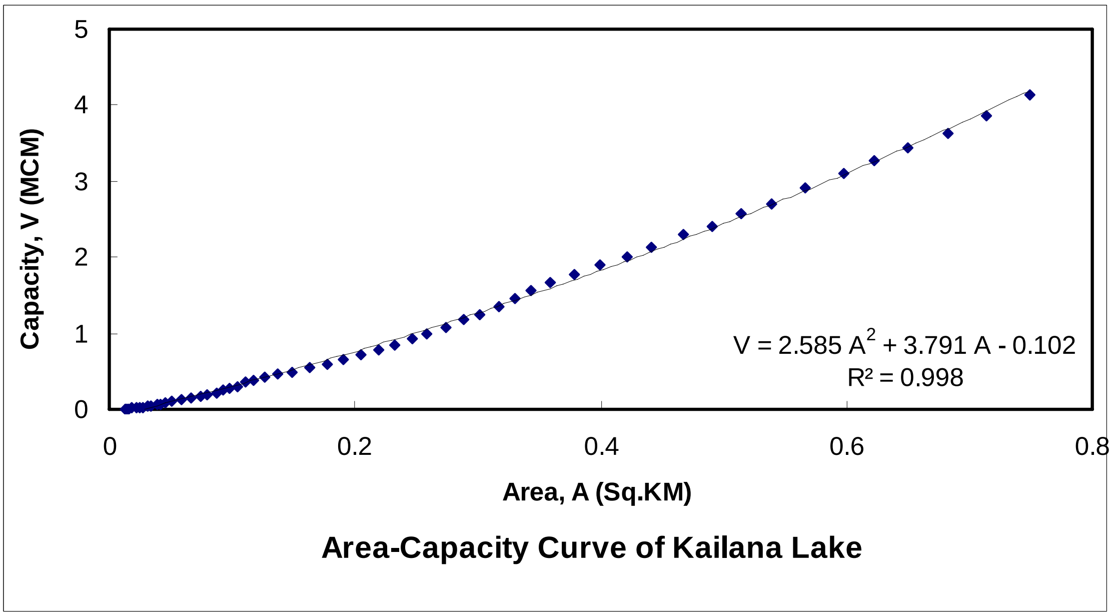

Figure 6.3 : Area-Capacity curve of the Kailana Lake

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 follow:

(a) Stage-Capacity relationship:

$$V = 0.001\,h^3 - 0.004\,h^2 + 0.05\,h - 0.049 \quad \text{……………..} \quad (6.1)$$

(b) Area-Capacity relationship

$$V = 2.585\,A^2 + 3.791\,A - 0.102 \quad \text{.....………….} \quad (6.2)$$

or

$$A = 0.0064\,V^3 - 0.0496\,V^2 + 0.2756\,V + 0.0224 \quad \text{………………} \quad (6.3)$$

V is the storage capacity of the Kailana Lake 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 Lake in sq. km. The above three equations fitted to the field data have the correlation coefficients , $R^2 > 0.998$, and hence can satisfactorily be used for estimation of storage capacity of the Kailana Lake from known stage or water spread area. Alternately, when the storage capacity of the Lake is known from the measurement of stages, the corresponding water spread area can be computed using equation (6.3).

6.2 The Takhatsagar Reservoir

The Takhatsagar Reservoir , which is fed by the Kailana Lake through regulated gates, is situated at an altitude of 241 m above msl between the latitude ranges from 26° 16′ 51″ N to 26° 17′ 58″ N and longitude ranges from 72° 57′ 51″ E to 72° 58′ 25″E . The Takhatsagar Reservoir has been created by constructing a masonry dam across the depressed valley formed by natural geological faults. In fact, the Kailana-Takhatsagar Reservoir is situated on the same geological faults, but separated by a man-made earthen dam in between. The bed levels as well as the water surface levels of the Kailana and Takhatsagar Reservoirs are different, and the bed level and water surface level of the Kailana Lake are at considerably higher elevation than those of the Takhatsagar Reservoir. The full level of the Takhatsagar Reservoir is 269.75 m above msl. The area and capacity of the Takhatsagar Reservoir at its full level are estimated to be 0.601 sq. km and 6.523 mcm, respectively. The stage-capacity and the area-capacity curve of the including their functional relationships are given in **Figures 6.4, 6.5 and 6.6,** respectively and the stage-area-capacity table is given in **Table-A6.2** in the annexure. The water is supplied to the Jodhpur city from both the Kailana and Takhatsagar Reservoirs after treatment.

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:

$$V = 0.019\, h^{1.89} \quad \text{.............................. (6.4)}$$

(c) Area-Capacity relationship

$$V = 14.75\, A^2 + 1.673\, A - 0.12 \quad \text{................. (6.5)}$$

or

$$A = -\,0.006\, V^2 + 0.129\, V + 0.0972 \quad \text{................. (6.6)}$$

V is the storage capacity of the Takhatsagar Reservoir 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.

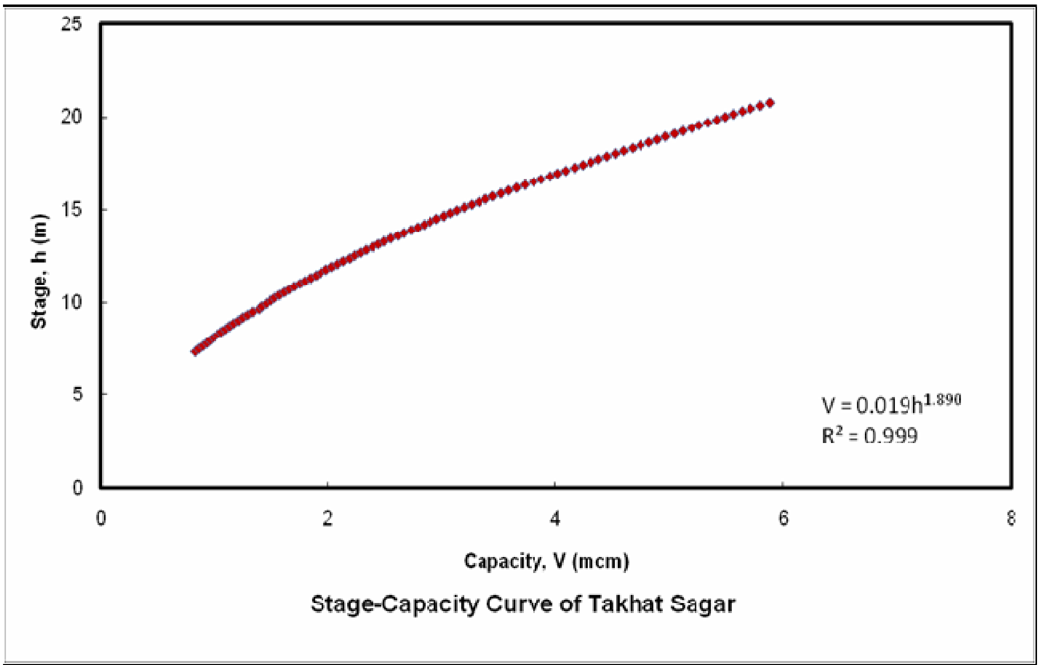

Figure 6.4 : Stage –Capacity curve of the Takhatsagar Reservoir.

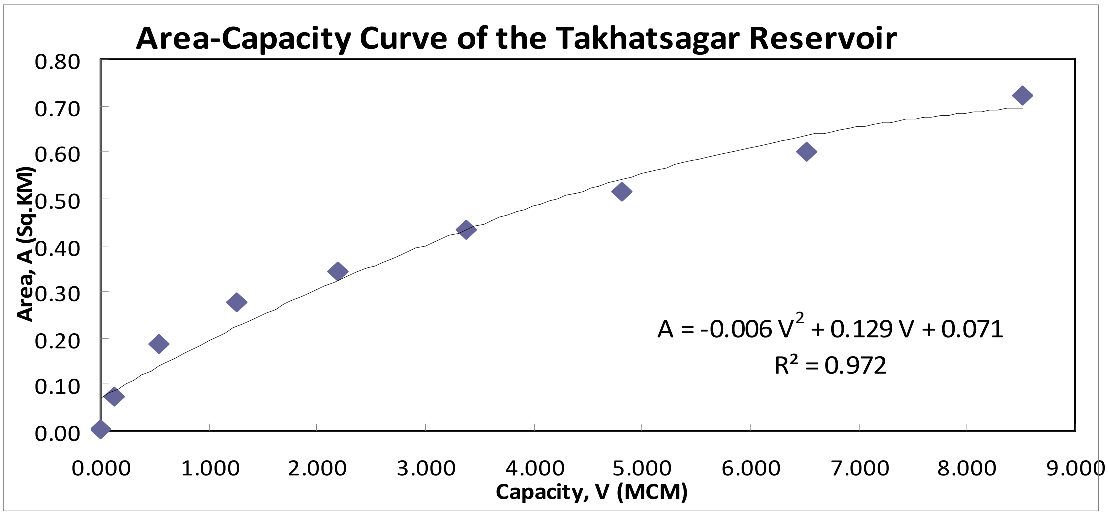

Figure 6.5 : Area-Storage Capacity curve of the Takhatsagar Reservoir.

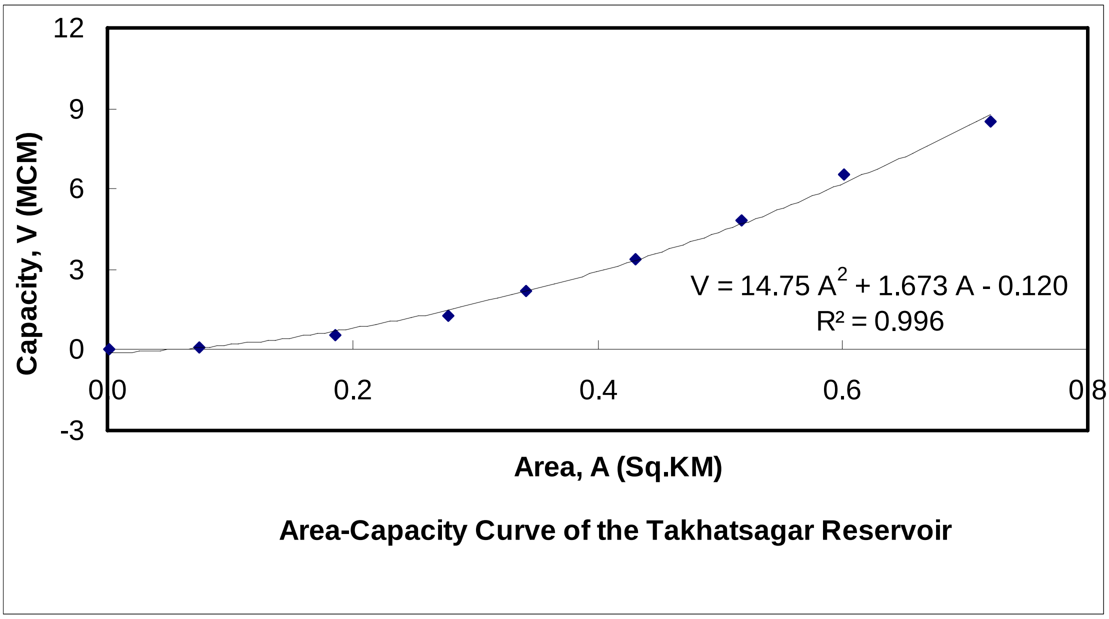

Figure 6.6 : Area-Storage capacity curve of the Takhatsagar.

All three equations fitted to the field data have correlation coefficients, $R^2 > 0.972$, and hence can satisfactorily be used for estimation of storage capacity of the Takhatsagar Reservoir from known stage or water spread area. Alternately, when the storage capacity of the Reservoir is known from the measurement of stages, the corresponding water spread area can be computed using equation (6.6).

6.3 The Umaid Sagar Reservoir

The Umaid Sagar Reservoir, which is fed by the Takhatsagar Reservoir by gravity flow, is situated between latitudes 26° 17′ 07″ N and 26° 17′ 13″ N and between longitudes 73° 02′ 40″ E to 73° 02′ 53″E. The full depth of water in the Umaid Sagar Reservoir is 11.58 m above its bed level. The capacity of the Umaid Sagar Reservoir is 9.854 mcm at full level. The stage-capacity curve of the lake is given in **Figure 6.7** and the stage- capacity table of the lake is given in **Table-A6.3** in the annexure.

The functional relationships that hold good to estimate the capacities for varying stages of the Umaidsagar are as follow:

(a) Stage-Capacity relationship:

$$V = 0.015\, h^{2.262} \qquad \text{.....} \quad (6.7)$$

in which, V is the storage capacity of the Umaidsagar in MCM; h is the stage of water measured above bottom of the in meter.

Equation (6.7) fitted to the field data has the correlation coefficient, R^2 = 0.998, and hence can satisfactorily be used for estimation of storage capacity of the Umaidsagar corresponding to a known stage.

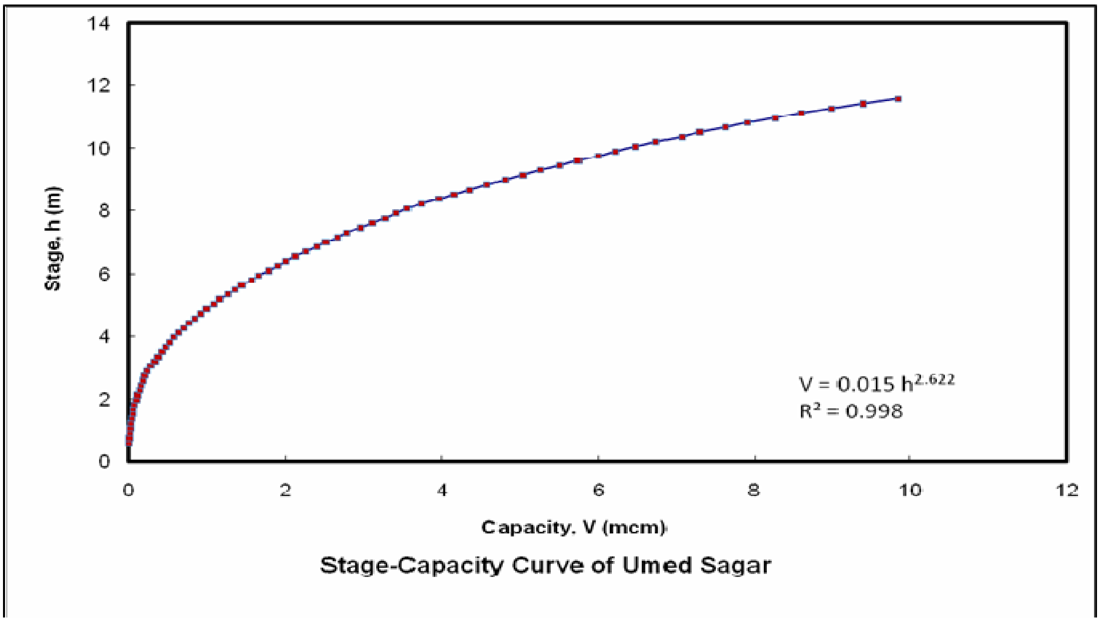

Figure 6.7: Stage–Capacity curve of the Umaid Sagar .

Section - 7.0 : INFLOW-OUTFLOW OF THE KAILANA-TAKHATSAGAR RESERVOIR

The Kailana-Takhatsagar Reservoir receives its inflow from the Indira Gandhi Canal through Rajiv Gandhi Lift Canal by pumping at PS-8 pumping station. There are six pumps to lift water from the Indira Gandhi canal; out of which normally, 3-4 pumps operate almost round the clock. There is no gate that regulates the flow between the pumped out water till it reaches to the Kailana Lake. The regulation of flow is based on some pre-decided thumb rules, which are based on the supply of water to the city area and to the downstream reservoirs, namely Takhatsagar and Umaidsagar; i.e., a constant rate of inflow is maintained, and as and when the water level in the Kailana Lake goes down below a specific level, the inflow rate is increased by operating more number of pump. A line diagram of Canal-Lake-Reservoir-City water supply management practice is shown in **Figure 7.1.**

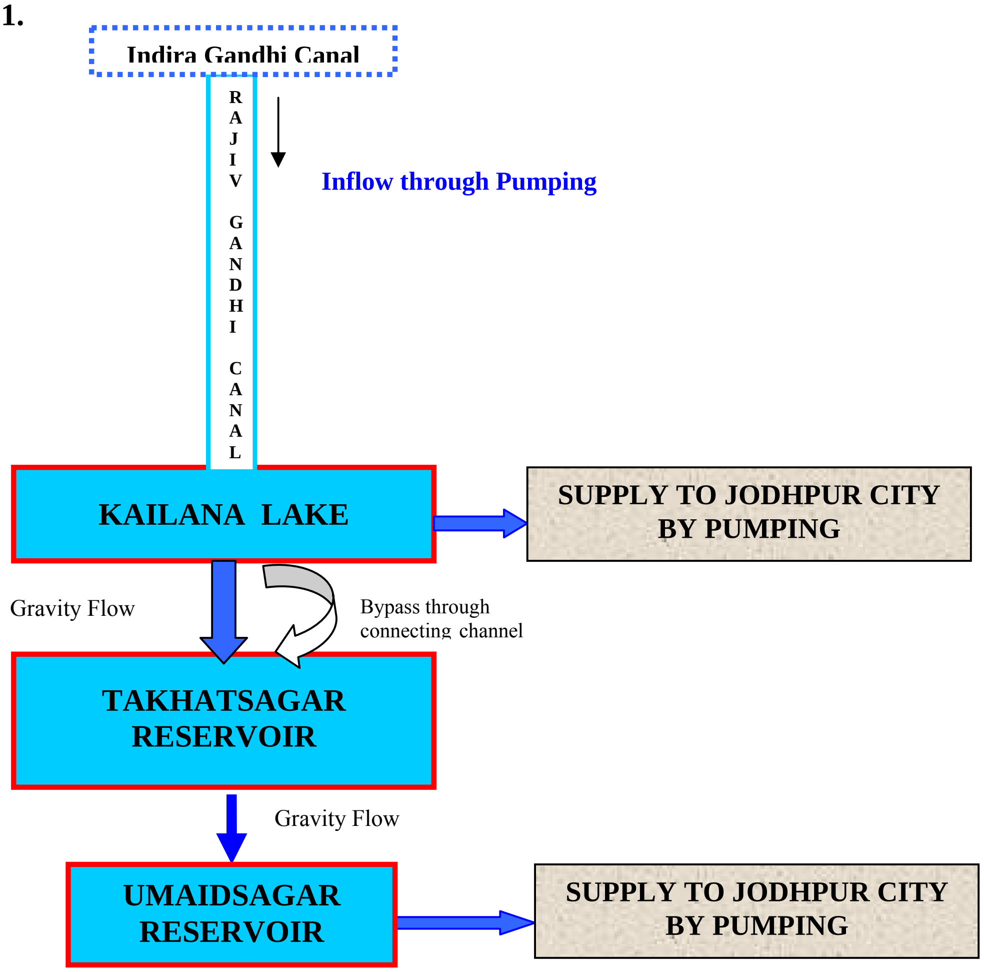

Figure 7.1 : Line diagram of Canal-Lake-Reservoir-City water supply system.

The quantities of flow of water supplied to the Kailana Lake through the Rajiv Gandhi Link canal during the period year 2002 through 2009, which are obtained from the PHED- Jodhpur, are shown in **Figure 7.2.** It can be seen from **Figure 7.2** that during the period from the year 2002 to 2009, the supply of water from the intake to the Kailana Lake had increased exponentially satisfying the following equation:

$$y = 58.802 \exp(0.0997\, X) \qquad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (7.1)$$

in which, y is the inflow to the Kailana Lake in MCM/day (million cubic meter/day) during a year; X is the calendar year. Equation (7.1) fits to the yearly variation of inflow with a correlation coefficient, $R^2 = 0.9318$.

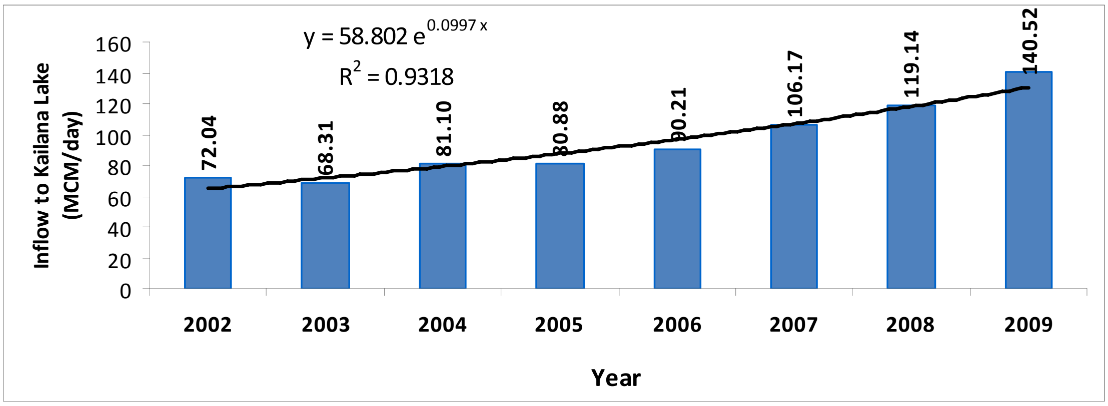

Figure 7.2 : Variation of average inflow per day in different years to the Kailana Lake from the Rajiv Gandhi Lift Canal

7.1 Water Balance of the Kailana Lake

After the inflow of water to the Kailana Lake through the Rajiv Gandhi Lift canal, locally known as Hathi canal, some part of water is, thereafter, pumped to the nearby treatment plant for preliminary treatment before supply to the city through water supply system; and some part is diverted to the Takhatsagar Reservoir through gate operated pipes and regulated diversion canal, which flow under gravity. The regulation of flow to the Takhatsagar Reservoir depends on the downstream requirement, which is decided based on the gauge height in the Takhatsagar Reservoir. The Kailana Lake has a small catchment encompassed by its surrounding sloping topography. Whatever rainfall occurs on its catchment area, some fraction of it in the form of runoff, in addition to the direct rainfall on the water surface area also accumulates in the Kailana Lake as its storage water. During the course of accumulation of water in the Kailana Lake, a component of accumulated water is lost in the form of water surface evaporation, and another component has the opportunity to seep/infiltrate-percolate below the Kailana Lake bed to the underneath aquifer/groundwater whose rate depends on the potential head, lake bed material, geological formations and their hydraulic properties. Higher the potential head and the values of hydraulic properties, larger is the rate of seeping through the Lake bed. A schematic diagram showing the different components, involved in the water balance of the Lake, is given in **Figure 7.3.**

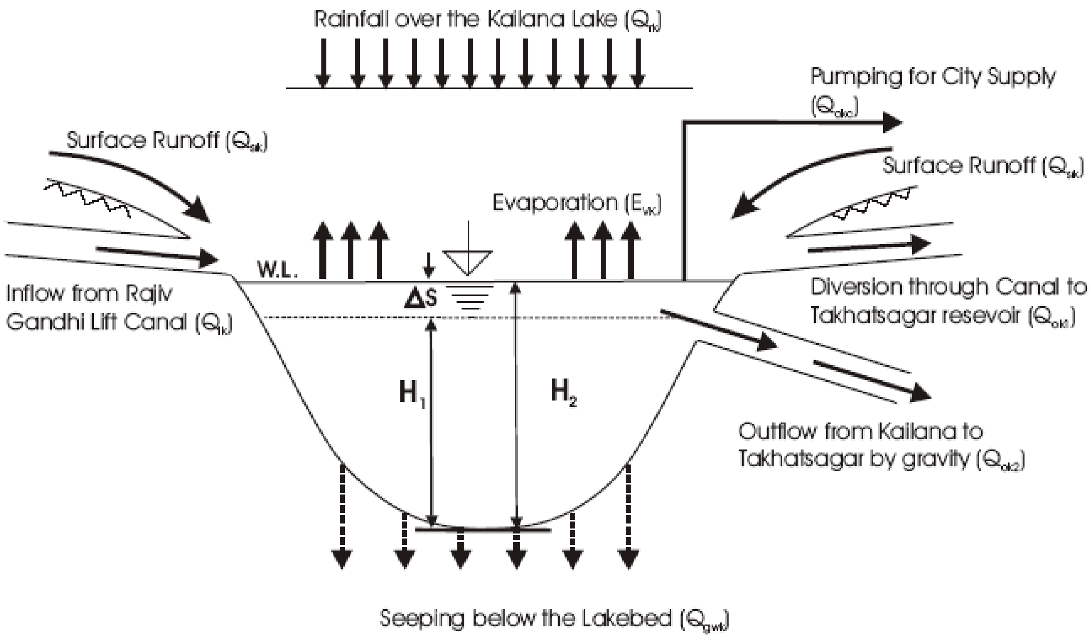

Fig 7.3 : Schematic of Water Balance components of the Kailana Lake

The water balance equation connecting the hydrological components involved in the Kailana Lake shown in **Figure 7.3** can be written as:

$$\lfloor \left(Q_{ik} + Q_{rk} + Q_{srk} \right) - \left(Q_{ok1} + Q_{ok2} + Q_{evk} + Q_{gwk} + Q_{0kc} \right) \rfloor \Delta t = A(H)\,\Delta H \qquad .. (7.2)$$

in which, Q_{ik} is the quantity of inflow from the Rajiv Gandhi lift canal to the Kailana Lake in L^3T^{-1}; Q_{rk} is the quantity of rainfall over the Kailana Lake in L^3T^{-1}; Q_{srk} is the quantity of surface runoff from the Kailana catchment in L^3T^{-1}; Q_{ok1} is the quantity of outflow from the Kailana Lake to the Reservoir through regulated pipe flow in L^3T^{-1}; Q_{ok2} is the quantity of outflow from the Kailana Lake to the Takhatsagar Reservoir through regulated canal diversion in L^3T^{-1}; Q_{evk} is the quantity of water surface evaporation from the Kailana Lake in L^3T^{-1}; Q_{gwk} is the quantity of groundwater seeping (recharge) through the Kailana Lake bed in L^3T^{-1}; Q_{okc} is the quantity of water pumped from the Kailana Lake to the city area which is supplied after treatment in L^3T^{-1}; Δt is the time step in unit of time(T); and Δh is the change in water level in the Kailana Lake in unit of length (L); $A(H)$ is the lake area which is a function of lake stage H .

The components, Q_{ik} is known from the daily inflow data of the Kailana Lake obtained from the PHED; Q_rk is known from the daily rainfall data obtained from the IMD as shown in **Figures 4.1, 4.2 & 4.3** in section 4; Q_{srk} can be estimated from the rainfall data using suitable rainfall-runoff relationship; Q_{ok1} and Q_{ok2} although are regulated flow, however, are not known in exact quantities as to how these are regulated and hence are to be ascertained; Q_{evk} can be estimated externally from the evaporation rate data given in **Figure 4.4** and **Table 4.1** in section 4.0 for the corresponding water spread area at a particular head of water above the lake bottom; Q_{gwk} can be estimated for a particular head of water above the lake bottom using seepage theory; Δt can be chosen suitably for which the water balance is to be performed; and ΔH is known from the measurement of heads of water in the lake = $H_2 - H_1$, in which H_1 is the head of water at time T_1, and H_2 is the head of water at time T_2; and $\Delta t = T_2 - T_1$.

To compute the evaporation component,(Q_{evk}) for a particular water spread area of the Lake, the water spread area has been estimated using the relationships given by Eqs.(6.1)-6.3) and **Figs.(6.1)-(6.3)** in section 6.0 for the corresponding head of water in the Lake. The groundwater seepage component, (Q_{gwk}) has been calculated for two situations: (i) the lake has a permeable bed through which water is continuously seeping to the underneath formation in which water table lies at a large depth, (ii) the lake bed is impermeable that seepage is very much negligible. To compute the seepage when water table lies at a large depth, Kozeny's equation (vide Harr, 1962) has been used.

$$q = k\,(B + 2H)) \qquad \ldots\ldots\ldots\ldots\ldots (7.3)$$

in which, q = the seepage per unit length of the Lake , L^2T^{-1}; B = representative width of the Lake at the water surface, L; H = the depth of water in the Lake, L; k = the hydraulic conductivity of the lake bed material, LT^{-1}. The representative width *B* has been computed from the water spread area and longitudinal length of the lake.

The parameter, k of the Lakebed materials, which represent Rhyolite formation, is suitably chosen from literature, and k is taken to be 0.058 m/day. Making use of the measured data, such as; inflow to Kailana Lake, rainfall, outflow to city, depth of water in the Lake, the water balance components, namely; Q_{ik}, Q_{rk}, Q_{srk}, Q_{okc}, and Q_{evk} have been estimated on daily basis for different years. Using the estimated values of these components in Eq.(7.2) along with other known component , namely ΔS; the unknown component the sum of diverted flow from Kailana to Takhatsagar Reservoir, Q_{ok1} and Q_{ok2}, has been estimated on daily basis (i.e., Δt = 1 day) by inclusion and without inclusion of groundwater seeping component. The variations of the diverted flow from the Kailana to the Takhatsagar Reservoir for the years 2003, 2005, 2008 and 2009 are shown in **Figures 7.4-7.7,** respectively.

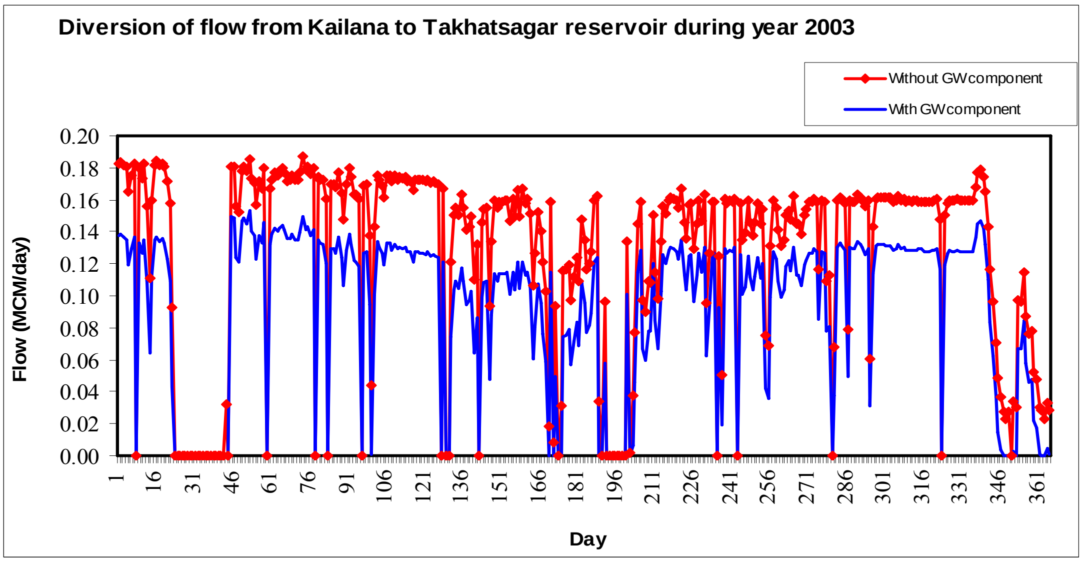

Figure 7.4 : Variation of supply of water from Kailana Lake to Takhatsagar Reservoir during the year 2003 staring from January,1 –December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

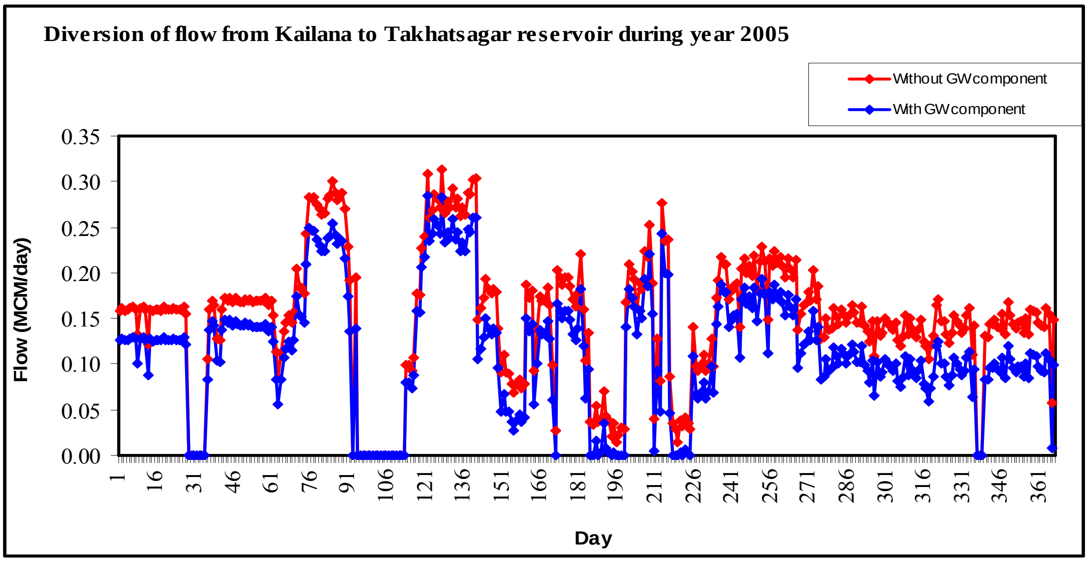

Figure 7.5 : Variation of supply of water from Kailana Lake to Takhatsagar Reservoir during the year 2005 staring from January,1 –December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

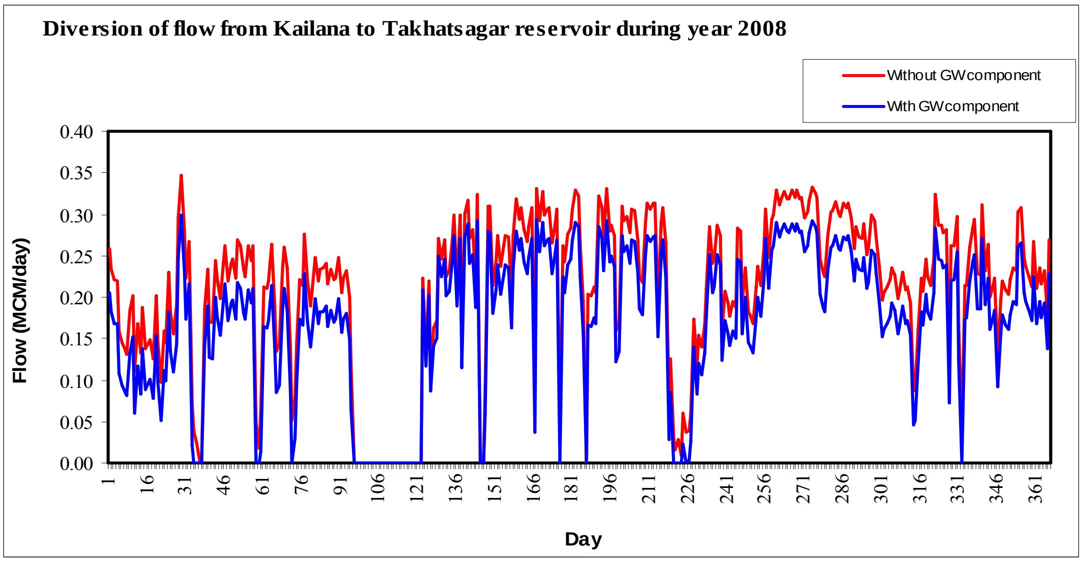

Figure 7.6 : Variation of supply of water from Kailana Lake to Takhatsagar Reservoir during the year 2008 staring from January,1 –December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

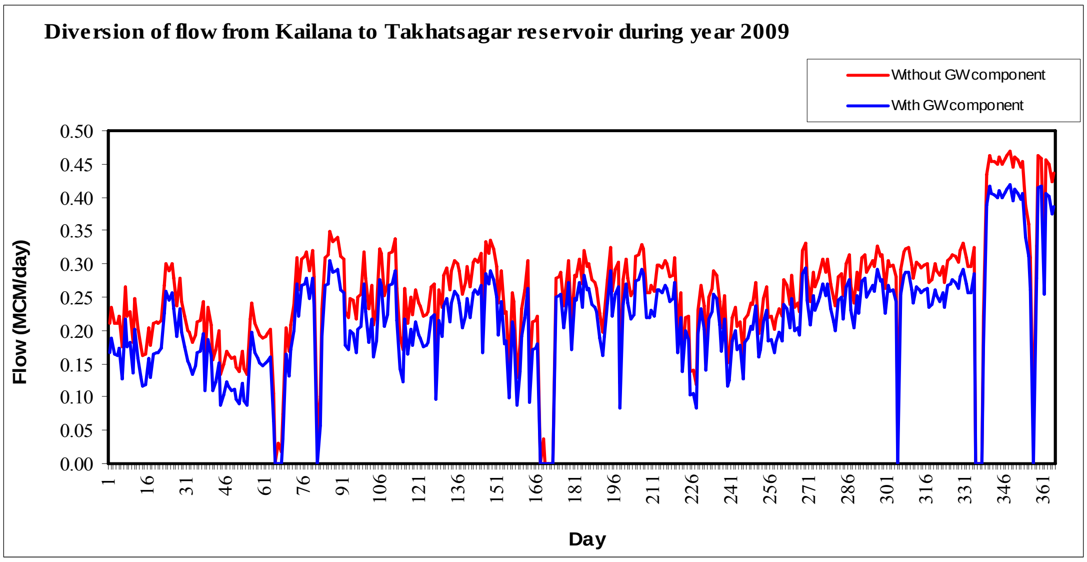

Figure 7.7 : Variation of supply of water from Kailana Lake to Takhatsagar Reservoir during the year 2009 staring from January,1 –December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

It can be seen from **Figs. 7.4-7.7** that, the supplies of water from the Kailana to the Takhatsagar Reservoir varied during a year, and even year to year. In some of the days in a year, virtually there was no supply of water from the Kailana to the Takhatsagar Reservoir. The variation of seepage below the lakebed has been estimated to be varied very marginally following the same trend as that of the outflow pattern from the Kailana Lake, i.e., higher the rate of outflow from the Kailana Lake to the Takhatsagar Reservoir, larger is the rate of seepage below the lakebed. It can, in other way, be explained in the following way: large inflow to the Takhatsagar Reservoir means increased outflows from the accumulated storages in the Kailana Lake; larger storages designate higher potential of head, and thereby more seepage through the lakebed. Moreover, larger the inflow rates from the Rajiv Gandhi lift canal to the Kailana Lake, higher is the outflows from the Kailana to the Takhatsagar Reservoir, which can be seen from **Figs.7.8-7.11.** Figs. 7.8-7.11 show year-wise variation of inflows to the Kailana Lake from the Rajiv Gandhi lift canal, supply of water from the Kailana Lake to the city, and the outflows from the Kailana Lake to the Takhatsagar Reservoir. It can be seen from Figs.7.8-7.11 that, the inflows to and outflows from the Kailana followed almost a similar trend except during certain period, while the supply to the city area remained largely uniform in a year. The inflows to the Kailana Lake from the Rajiv Gandhi lift canal have also found to be varied over the year, as well as, from year to year. The flow diverted from the Kailana to the Takhatsagar Reservoir formed the inflow to the Takhatsagar Reservoir.

The year-wise sum of each water balance component which is involved in the water balance equation of the Kailana Lake is given in Table-7.1. It can be seen from Table-7.1 that the differences between the change in storage estimated from the inflow-outflow balance and the change in storage calculated independently are very minor. These minor differences may be due to the errors in the fitting of the rating curve.

Table 7.1 : Water balance components of the Kailana Lake in different years.

Year	**Inflow Components (MCM)**		**Outflow Components (MCM)**					Change in storage = $\sum Inflow - \sum Outflow$ **(MCM)**	Change in storage Calculated **(MCM)**
	Inflow to Kailana	Rainfall Volume	Pumping from Kailana to City	Diversion from Kailana to Takhatsagar without GW Component	Diversion from Kailana to Takhatsagar with GW Component	Ground water Component	Evaporation		
2003	69.31	0.38	25.03	45.86	34.27	11.56	1.48	- 2.68 (- 2.65)*	-1.57
2005	85.46	0.24	32.49	54.16	40.91	12.20	1.40	- 2.35 (- 2.30)*	-1.70
2008	125.94	0.10	49.13	78.26	64.78	13.50	1.47	- 2.82 (- 2.84)*	-1.07
2009	144.15	0.00	46.23	96.02	81.75	14.25	1.66	0.24 (0.26)*	0.00

(*) indicates change in storage with ground water component.

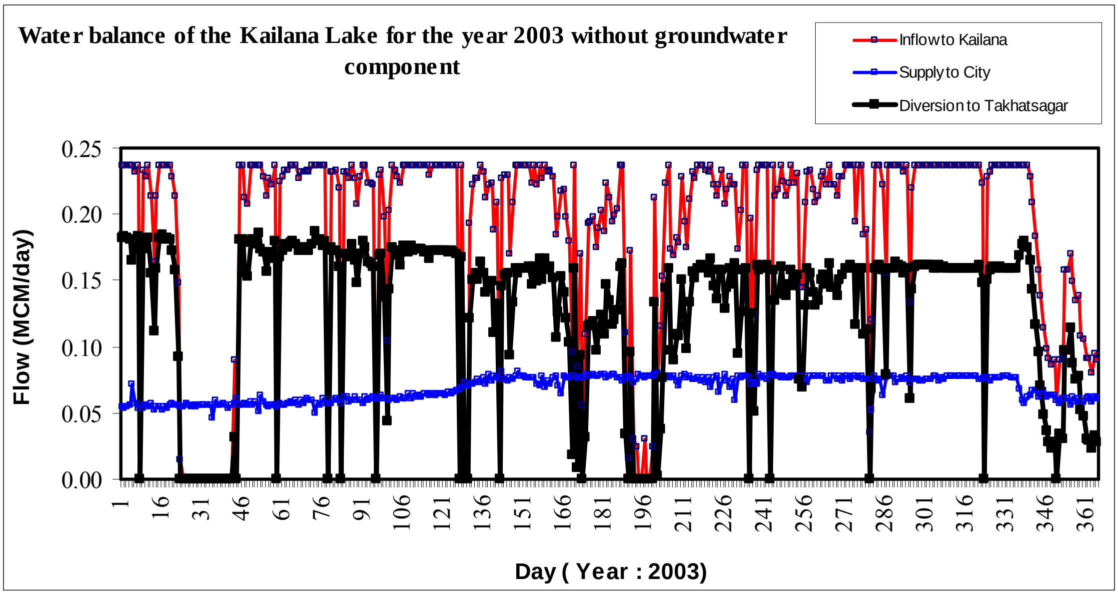

Figure 7.8 : Variation of water balance components of the Kailana Lake during the year 2003 staring from January,1 –December, 31.

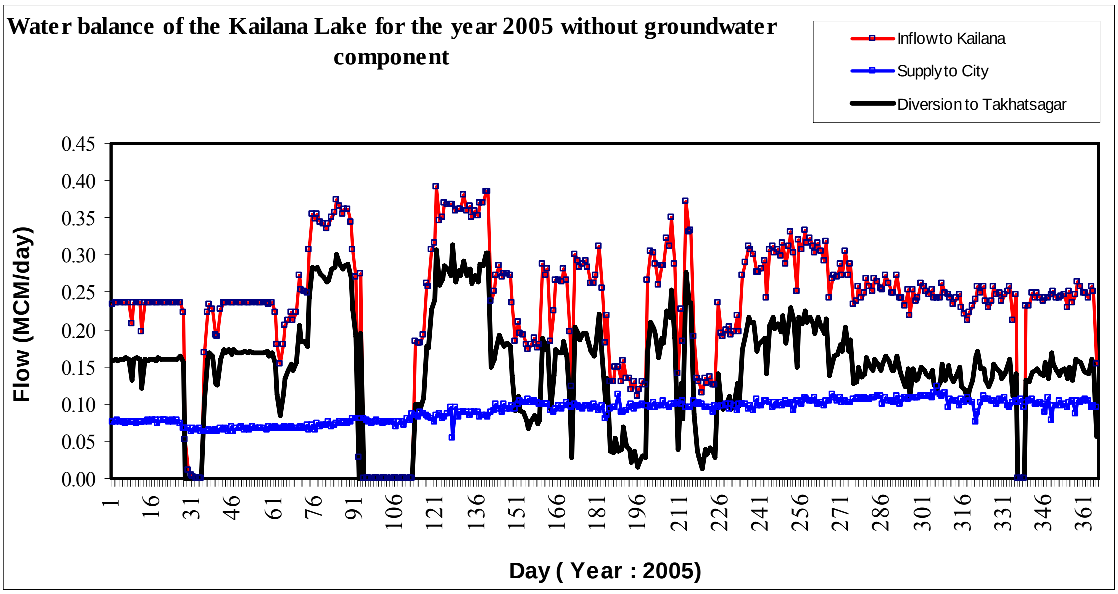

Figure 7.9 : Variation of water balance components of the Kailana Lake during the year 2005 staring from January,1 –December, 31.

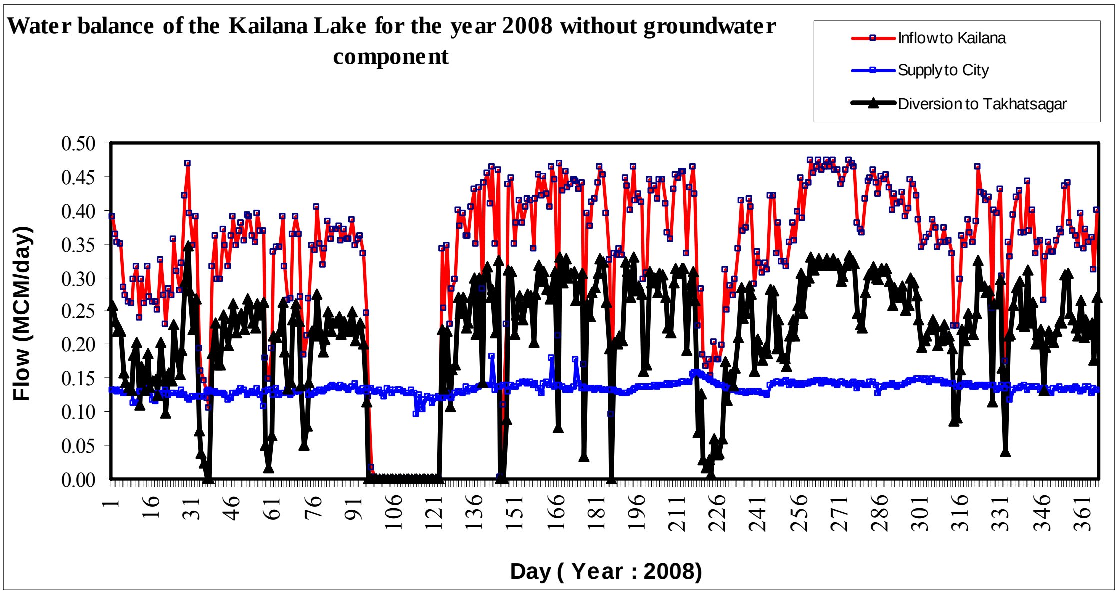

Figure 7.10 : Variation of water balance components of the Kailana Lake during the year 2008 staring from January,1 –December, 31.

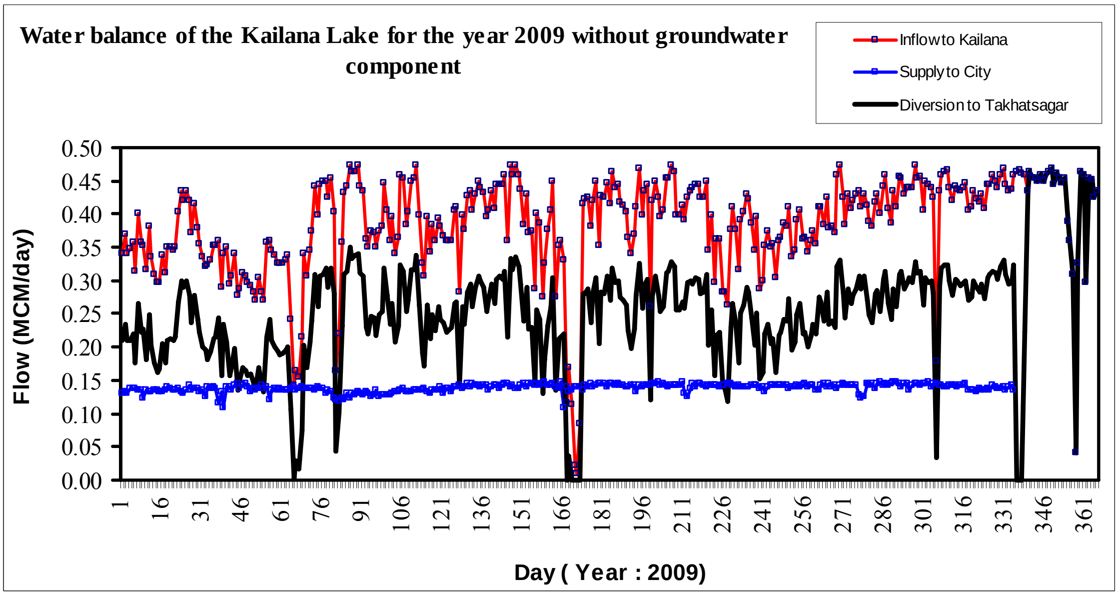

Figure 7.11 : Variation of water balance components of the Kailana Lake during the year 2009 staring from January,1 –December, 31.

7.2 Water Balance of the Takhatsagar Reservoir

The diverted outflow from the Kailana Lake to the Takhatsagar Reservoir through gate operated pipes and regulated diversion canal, which flow under gravity, form the inflow to the Takhatsagar Reservoir. The stored water in the Takhatsagar reservoir is further diverted to the downstream Chopasni Filter House by gravity flow for supply to some of the areas in the city after necessary treatment. The regulation of the flow from the Takhatsagar Reservoir depends on the downstream requirement, which is decided based on the gauge height in the reservoir. The Takhatsagar Reservoir has a small catchment encompassed by its surrounding sloping topography. Whatever rainfall occurs on its catchment area, some fraction of it in the form of runoff, in addition to the direct rainfall on the water surface area also accumulates in the reservoir as its storage water. During the course of accumulation of water in the Takhatsagar Reservoir, a component of the accumulated water is lost as water surface evaporation, and another component may seep/infiltrate-percolate below the Takhatsagar Reservoir bed to the underneath aquifer/groundwater whose rate depends on the potential head, reservoir bed material; geological formations & their hydraulic properties. A schematic diagram showing the components involved in the water balance of the reservoir is given in **Figure 7.12.**

The water balance equation for the Takhatsagar reservoir can be written as:

$$\left\lfloor \left(Q_{it} + Q_{rt} + Q_{srt} \right) - \left(Q_{ot} + Q_{evt} + Q_{gwt} \right) \right\rfloor \Delta t \quad = \quad A(H)\,\Delta H \text{ .... (7.4)}$$

in which, Q_{it} is the quantity of inflow from the Kailana Lake to the Takhatsagar Reservoir in L^3T^{-1}; Q_{rt} is the quantity of rainfall over the Takhatsagar Reservoir in L^3T^{-1}; Q_{srt} is the quantity of surface runoff from the Takhatsagar catchment in L^3T^{-1}; Q_{ot} is the quantity of outflow from the Takhatsagar Reservoir to the Chopasni Filter House through regulated pipe flow in L^3T^{-1}; Q_{evt} is the quantity of water surface evaporation from the Takhatsagar Reservoir in L^3T^{-1}; Q_{gwt} is the quantity of groundwater seeping (recharge) through the Takhatsagar Reservoir bed in L^3T^{-1}; Δt is the time step in unit of time(T); and ΔH is the change in water level in the Takhatsagar Reservoir in unit of length (L), $A(H)$ is water spread area which depends on reservoir stage.

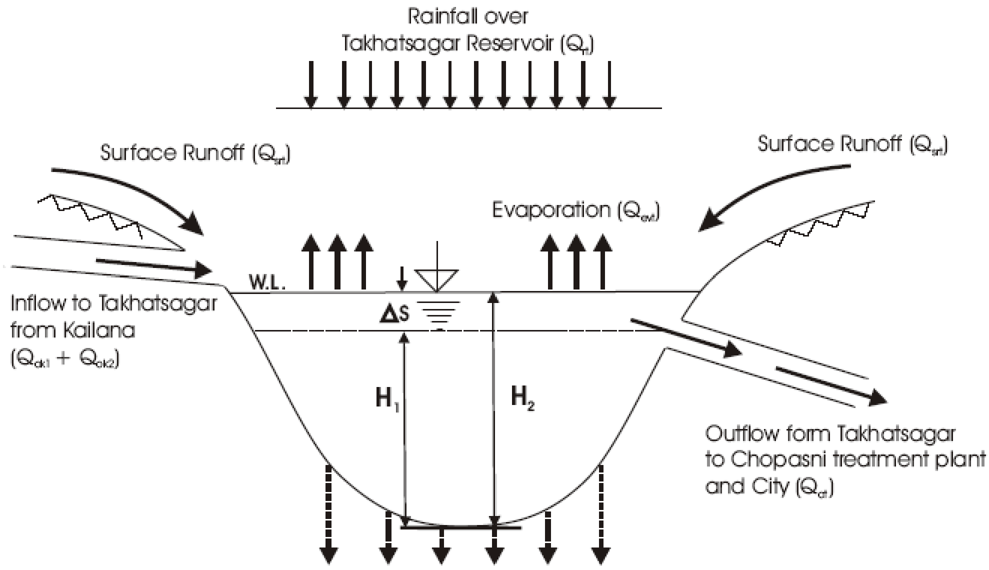

Figure 7.12 : Water balance components of the Takhatsagar Reservoir.

The components, Q_{it} is known from the daily diverted flow from the Kailana Lake; Q_{rt} is known from the daily rainfall data obtained from the IMD as shown in **Figures 4.1, 4.2 and 4.3** in **Section 4**; Q_{srt} can be estimated from the rainfall data using suitable rainfall-runoff relationship; Q_{ot} although is regulated flow, however, is not known in exact quantities as to how this is regulated and hence is to be determined; Q_{evt} can be estimated externally from the evaporation rate data given in **Figure 4.4 and Table 4.1** in Section 4.0 for the corresponding water spread area at a particular head of water above the reservoir bottom; Q_{gwt} can be estimated for a particular head of water above the reservoir bottom using seepage theory; Δt can be chosen suitably for the water balance; and ΔH is known from the measurement of heads of water in the reservoir = $H_2 - H_1$, in which H_1 is the head of water at time T_1, and H_2 is the head of water at time T_2; and $\Delta t = T_2 - T_1$, $A(H)$= water spread corresponding to height, H .

The components, Q_{evt} and Q_{gwt} have been calculated following the similar approach as explained in the case of Kailana water balance. As the daily outflows from the Takhatsagar Reservoir to the Chopasni Filter House, Q_{ct} is not exactly known though this is regulated flow; however, this quantity is computed by developing suitable rating curve adopting the following approach. A schematic of the arrangement of outflow system from the Takhatsagar Reservoir to the Chopasni Filter House is shown in **Figure 7.13.**

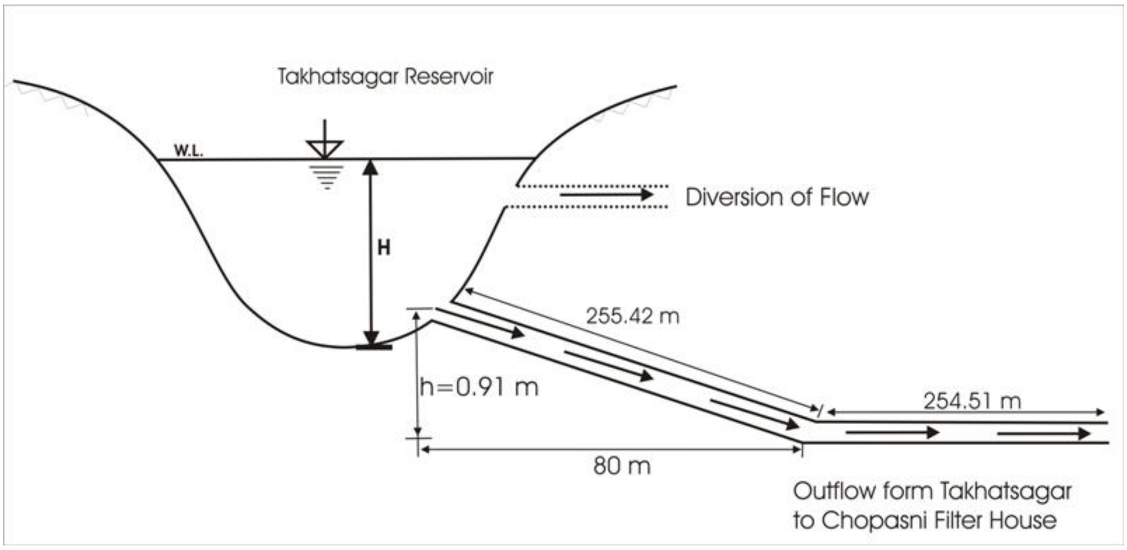

Figure 7.13: Water supply distribution arrangement of the Takhatsagar Reservoir.

The flow of water from the Takhatsagar Reservoir to the Chopasni Filter House is primarily regulated through the imbedded pipe of diameter 1m whose inlet point is placed near to the bed of the reservoir at an elevation of 255.42 m above m.s.l **(Fig.7.13).** The pipe is of about 80 m long aligned obliquely with a slope of 0.91 m vertical for a length of 80 m horizontal. After this slanting, the pipe line has moderate alignment up to the Chopasni Filter House. In addition to this gravity pipe flow, there is an additional diversion arrangement located at an elevation of 266.56 m (above msl) i.e., about 11 m above the bottom pipe, that operates when water level in the Takhatsagar Reservoir exceeds the level of 266.56 m.

Using the following formula of flow through pipe, the discharges of flow for varying heads of water in the reservoir have been calculated.

$$Q_1 = C_d \; A \; \sqrt{2 \, g \left(H_1 + h_f\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.5)$$

in which, Q_1 is the discharge of flow through the pipe (L^3T^{-1}); C_d is the coefficient of discharge that ranges 0.60 to 0.75; A is the cross-sectional area of the pipe (L^2); g is the acceleration due to gravity (LT^{-2}); H_1 is the height of water above the centre line of the pipe (L); and h_f is the head loss due to friction in the pipe. By considering the value of the frictional factor, f = 0.025; the h_f is calculated using the Darcy -Weishback formula as follows:

$$h_f = \frac{f\ L\ V_m^{\ 2}}{2\ g\ d} \qquad \text{..................................} \qquad (7.6)$$

in which, L is the length of the pipe = 80 m; V_m is the mean flow velocity in the pipe = $\sqrt{2\ g\ H_1}$; d is the diameter of the pipe = 1.0 m.

As the diversion of flow through the upper pipe takes place when the water level in the reservoir exceeds the level of 266.56 m, the combined affects of discharge of flows are calculated for varying heads of water in the reservoir by taking into account both the flows separately, and then added to have complete rating curve. The rating curve so develop is shown in **Figure 7.14.**

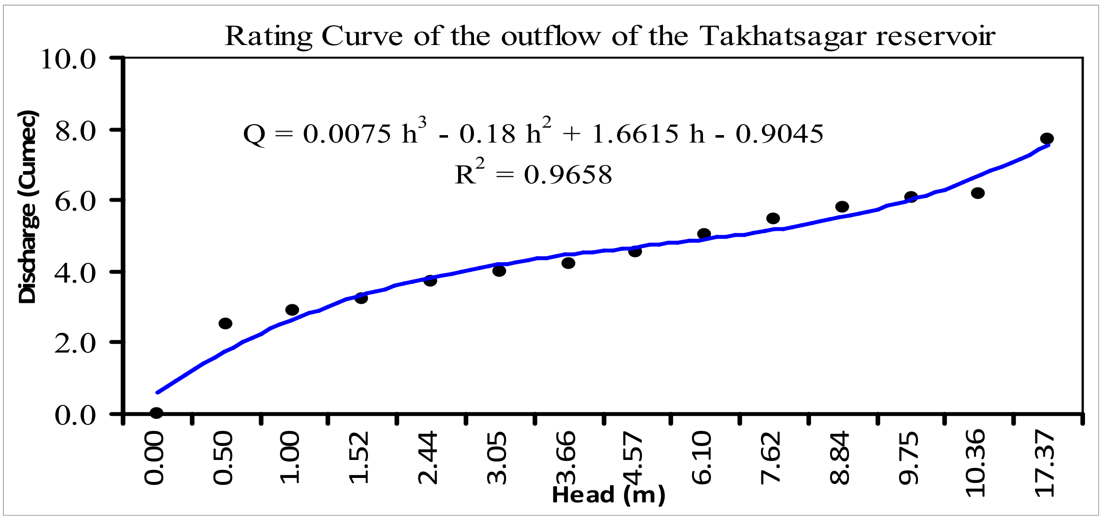

Figure 7.14 : Rating curve of the Takhatsagar Reservoir outflow.

Making use of the measured data, such as; inflows from the Kailana Lake to Takhatsagar Reservoir, rainfall, depths of water in the reservoir, and the water surface evaporations corresponding to the water spread areas, the water balance components, namely; Q_{it}, Q_{rt}, Q_{srt}, and Q_{evt} have been estimated on daily basis for different years. Using the estimated values of these components in Eq.(7.4) along with other known components, namely ΔH; and the corresponding $A(H)$, the unknown component i.e. the diverted flow from the Takhatsagar Reservoir to the Chopasni Filter House, Q_{ot} has been estimated on daily basis (i.e., $\Delta t = 1$ day) by inclusion and without inclusion of seepage component. The variations of the diverted flow from the Takhatsagar Reservoir to the Chopasni Filter House for the years 2003, 2005, 2008 and 2009 are shown in **Figures 7.15-7.18**, respectively.

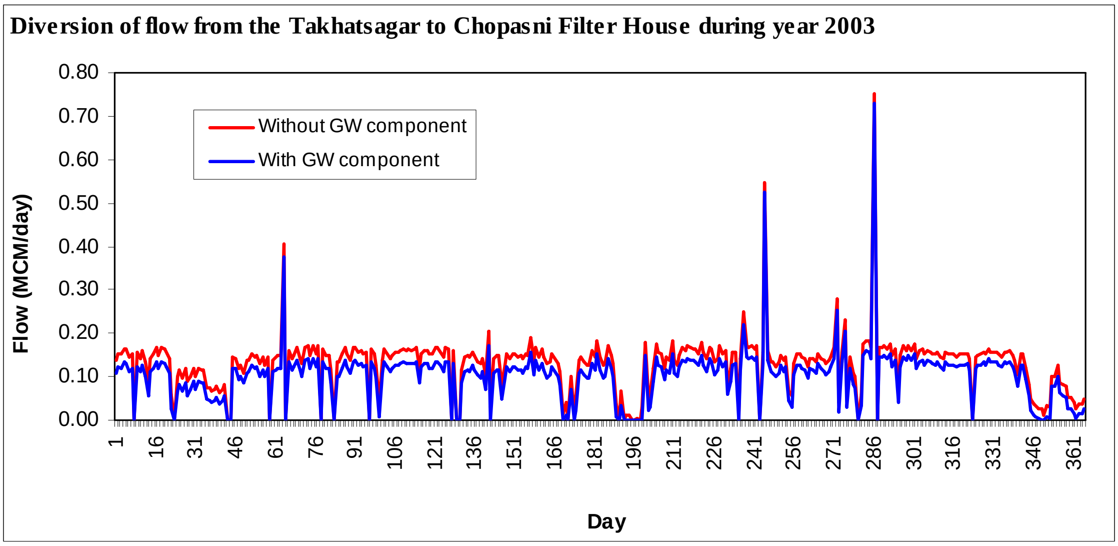

Figure 7.15 : Variation of supply of water from the Takhatsagar Reservoir to the Chopasni Filter House during the year 2003 staring from January,1 – December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

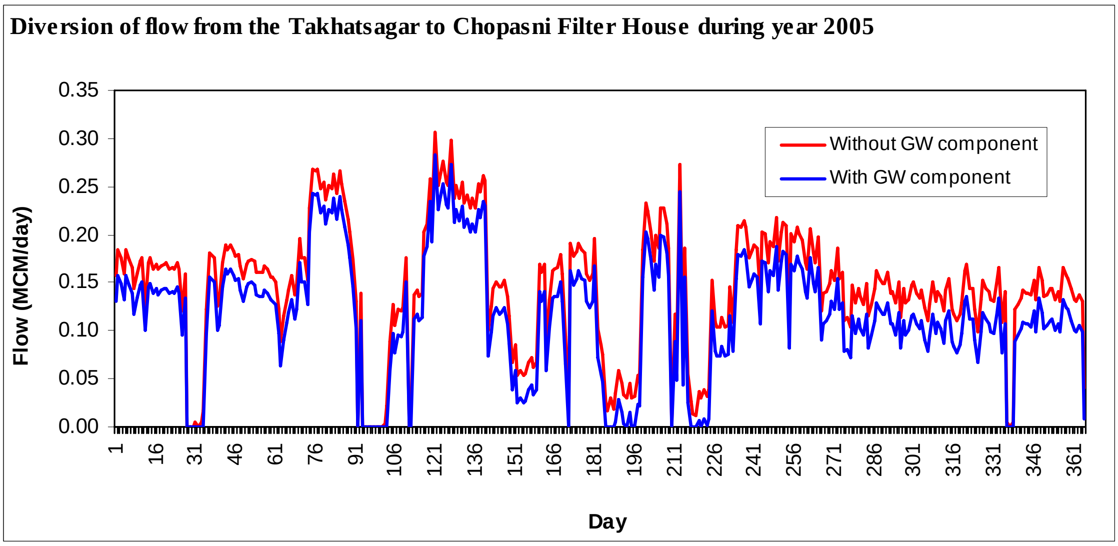

Figure 7.16 : Variation of supply of water from the Takhatsagar Reservoir to the Chopasni Filter House during the year 2005 staring from January,1 – December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

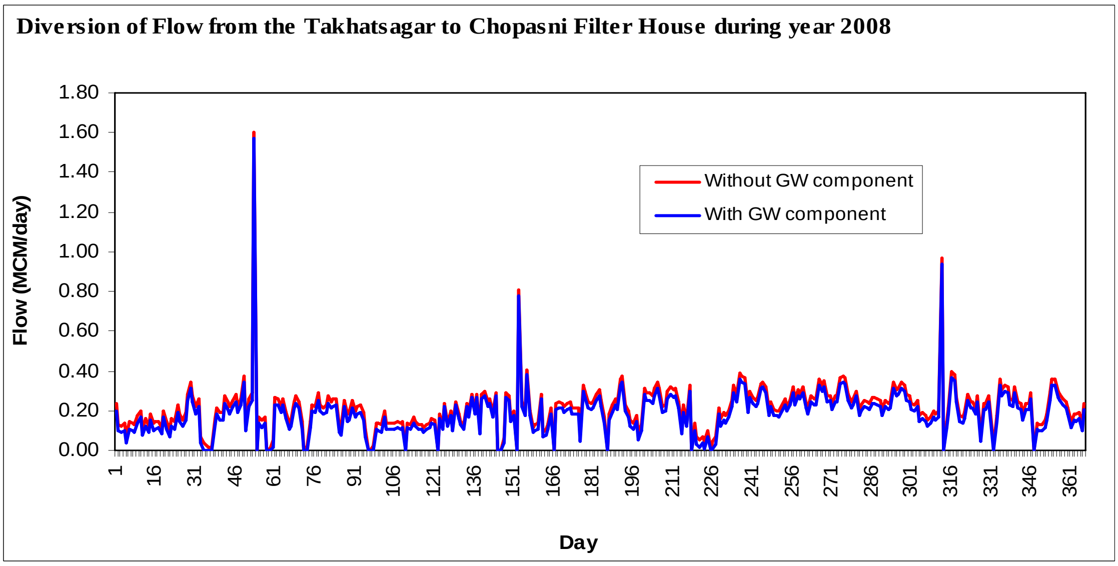

Figure 7.17: Variation of supply of water from the Takhatsagar Reservoir to the Chopasni Filter House during the year 2008 staring from January,1 –December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

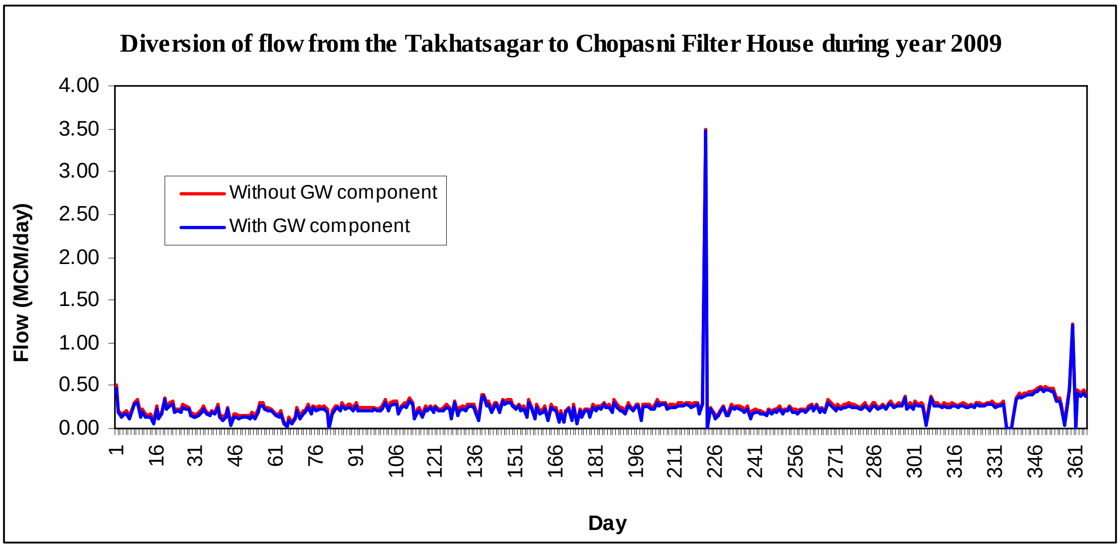

Figure 7.18: Variation of supply of water from the Takhatsagar Reservoir to the Chopasni Filter House during the year 2009 staring from January,1 –December, 31 *(red color line corresponds to without seepage component; blue color line corresponds to with seepage component).*

It can be seen from **Figs. 7.15-7.18** that, the supplies of water from the Takhatsagar to the Chopasni Filter House varied during a year, and even year to year. In some of the days in a year, virtually there was no supply of water from the Takhatsagar Reservoir, and the variation of flows followed the similar pattern as that of the supplies from the Kailana Lake to the Takhatsagar Reservoir. The variation of seepage below the reservoir bed has been estimated to be varied very marginally following the same trend as that of the outflow pattern from the Takhatsagar Reservoir, i.e., higher the rate of outflow from the Takhatsagar Reservoir to the Chopasni Filter House, larger is the rate of seepage below the reservoir bed.

The water balances of the Takhatsagar Reservoir, in terms of inflows and outflows, with and without groundwater seepage component for the year 2003, 2005, 2008, and 2009 have been shown in **Figs. 7.19-7.22**. In these figures, the differences between inflows and outflows even for the case without the groundwater seepage component are due to the losses of water by the surface water evaporation.

The year-wise sum of each water balance component which is involved in the water balance equation of the Takhatsagar Reservoir is given in Table-7.2. It can be seen from Table-7.2 that the differences between the change in storage estimated from the inflow-outflow balance and the change in storage calculated independently are very minor. These minor differences may be due to the errors in the fitting of rating curve.

Table 7.2 : Year-wise water balance components of the Takhatsagar Reservoir.

Year	Inflow (MCM)		Outflow (MCM)				Change in storage = $\sum Inflow - \sum outflow$ **(MCM)**	Change in storage calculated **(MCM)**
	Inflow to Takhatsagar	Rainfall volume	Diversion to Chopasni Filter Hose without GW component	Diversion to Chopasni Filter Hose with GW component	Ground water component	Evaporation component		
2003	45.86	0.3823	47.23	37.72	10.29	1.0767	- 2.0644 (- 2.844)*	- 1.401
2005	54.13	0.2422	52.29	42.42	10.55	1.0571	1.0251 (- 0.3451)*	1.274
2008	78.26	0.1049	78.01	67.09	11.30	1.1045	- 1.000 (- 1.1296)*	- 0.200
2009	96.02	0.000	95.87	85.43	10.58	1.0778	- 0.9278 (- 1.0678)*	- 0.110

- Indicates change in storage with groundwater component.

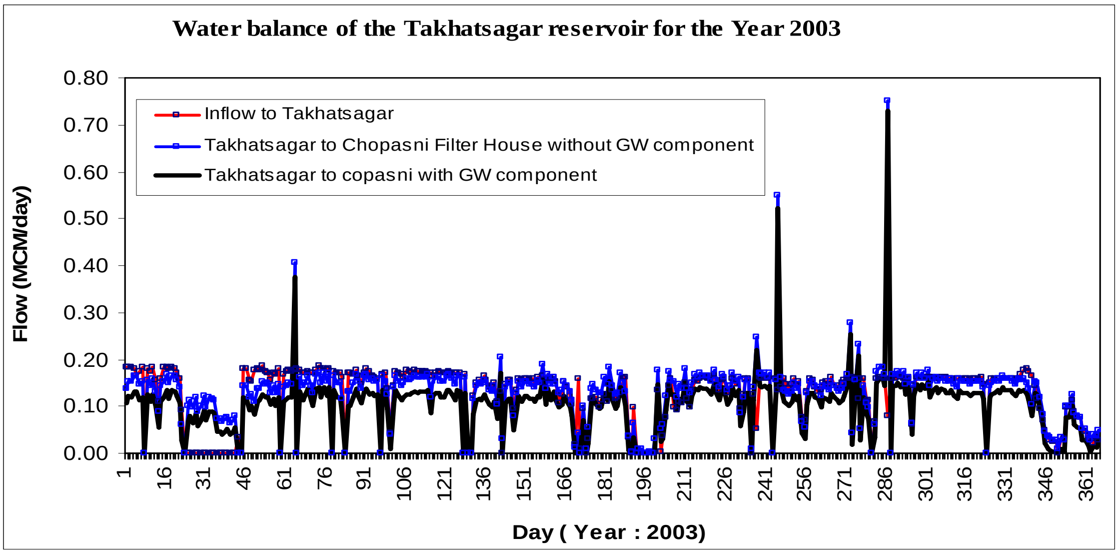

Figure 7.19 : Variation of water balance components of the Takhatsagar Reservoir during the year 2003 staring from January,1 –December, 31.

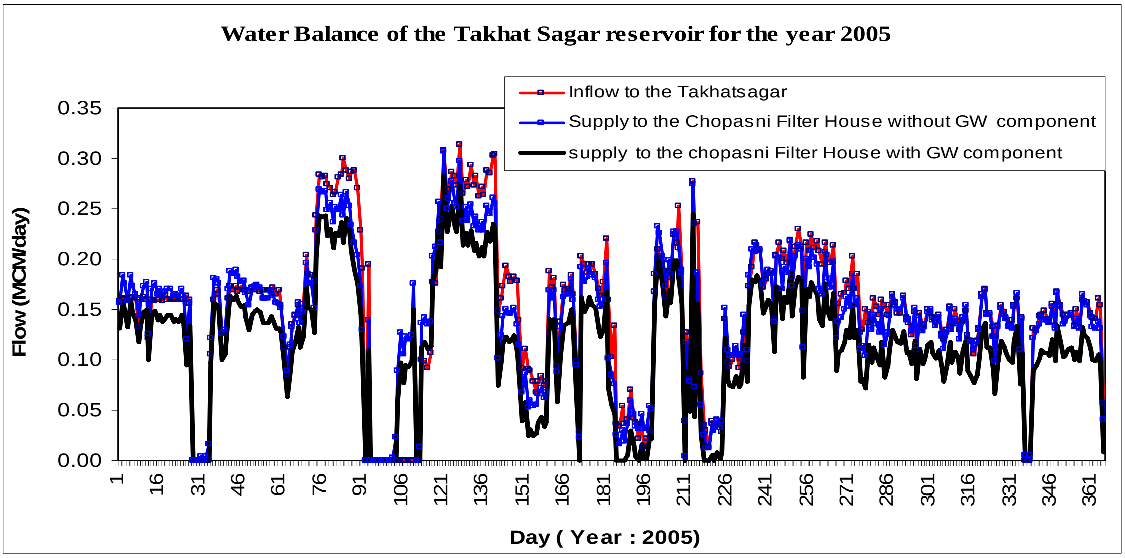

Figure 7.20 : Variation of water balance components of the Takhatsagar Reservoir during the year 2005 staring from January,1 –December, 31.

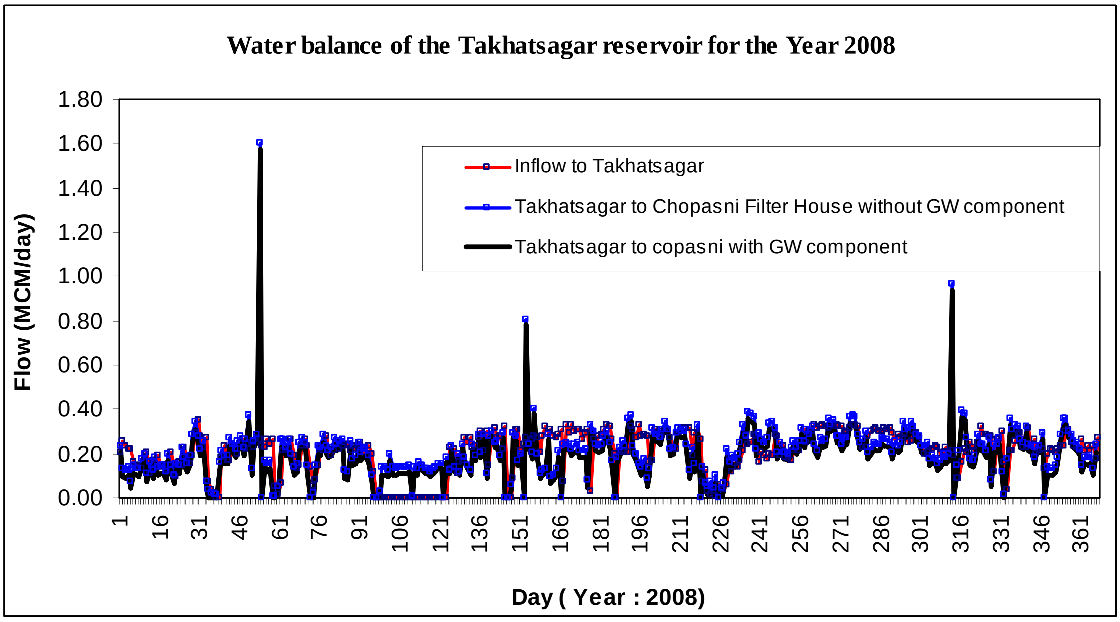

Figure 7.21 : Variation of water balance components of the Takhatsagar Reservoir during the year 2008 staring from January,1 –December, 31.

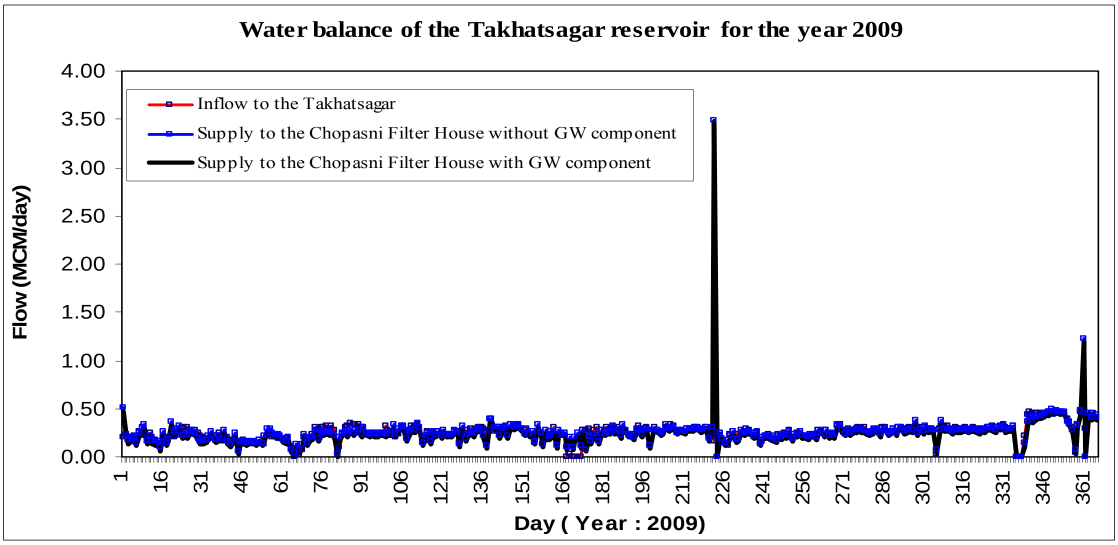

Figure 7.22 : Variation of water balance components of the Takhatsagar Reservoir during the year 2009 staring from January,1 –December, 31.

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Section – 8.0 : GROUNDWATER DATA AND ANALYSIS

Evolution of groundwater levels in an area is a combined response of the geologic formation in the area to the past and present recharge originating from transfer of water to the region and recharge to aquifer resulting from the water use, rainfall recharge, and ground water withdrawal by pumping, and change in hydrologic boundary conditions. In order to monitor the evolution of water table, the GWD, Jodhpur has set up 54 observation stations within the city area up to the year 2008, among which, there are 26 open wells, 7 tube wells , and remaining are either hand pumps or step wells. Types of wells, their locations in latitude and longitude co-ordinate system are given in **Table-A8.1** in the Annexure. From the year 1984 to 1994, the GWD used to monitor pre and post monsoon groundwater levels at 15 observation stations. Later on by the year 2000, when the groundwater level started rising in the city area, the observation points had been increased to 32 for monitoring the pre and post monsoon groundwater levels. After the year 2000, a number of new observation wells have been constructed and presently the groundwater levels are monitored at 54 observation points on monthly basis. The pre-monsoon groundwater level monitoring period is from 15th May to15th June, and the post-monsoon period is from15th October to15th November in every year. With 54 observation points in the area of about 76 sq. km., the observation network density is estimated to be 0.71 observation point per 100 hectare (10^6 sq. m), which is adequate to develop a representative water level contour map.

The groundwater levels data, supplied by the GWD, had been measured from the ground surface at the respective locations, and all those levels thus represent the depth to groundwater table. Identifying the latitude and longitude of each observation location by GPS and making use of the ground level contour map, the groundwater level at each observation point with respect to a common datum i.e., the mean sea level (MSL) is obtained. After this conversion, considering the observed data to be consistent, the pre monsoon and post monsoon water table contour maps for the years; 1996, 2000, 2004, and 2008 have been prepared.

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 $0.058 m/day$ 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 and are given in section 7.0. 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.

Presently, there are no observation wells in the close vicinity of the Kailana and Takhatsagar Reservoirs. Therefore, contours of equal water table height above MSL have been drawn for two limiting situations. In situation 1, it is envisaged that, the Kailana and Takhatsagar Reservoirs are hydraulically connected to the aquifer under the Jodhpur city. With this assumption, the reservoirs perform as a line of observation wells. Accordingly contour lines incorporating the reservoir water level have been drawn. The parallel line contours near the Kailana and the Takhatsagar Reservoir conform to this assumption. This is the most favorable condition for seepage from the Kailana-Takhatsagar to flow to the aquifer below the Jodhpur city to cause water logging.

In situation 2, it is assumed that seepage from the Kailana and Takhatsagar is insignificant. Therefore, no mound is formed under the reservoir axis. The Kailana and Takhatsagar are not hydraulically connected to the aquifer below the Jodhpur city. The contours have been drawn excluding the reservoir water level. This is the most unfavorable condition to cause water logging by seepage water from the reservoirs.

Assuming the Kailana-Takhatsagar having hydraulic connection with the aquifer below the Jodhpur city, the pre and post monsoon water table contour maps for the years 1996, 2000, 2004, and 2008 are drawn and shown in Figs. 8.1-8.4. In the year 2008, water level observations have been made at more number of observation points. Therefore, the contour maps of the year 2008 predict the cause water logging more precisely as compared to other contour maps. In these figures, the direction of groundwater flow, the water logged area in which water table lies within a depth of 3m below ground surface, and the area in which the water table lies between 3 and 5 m from ground surface are shown.

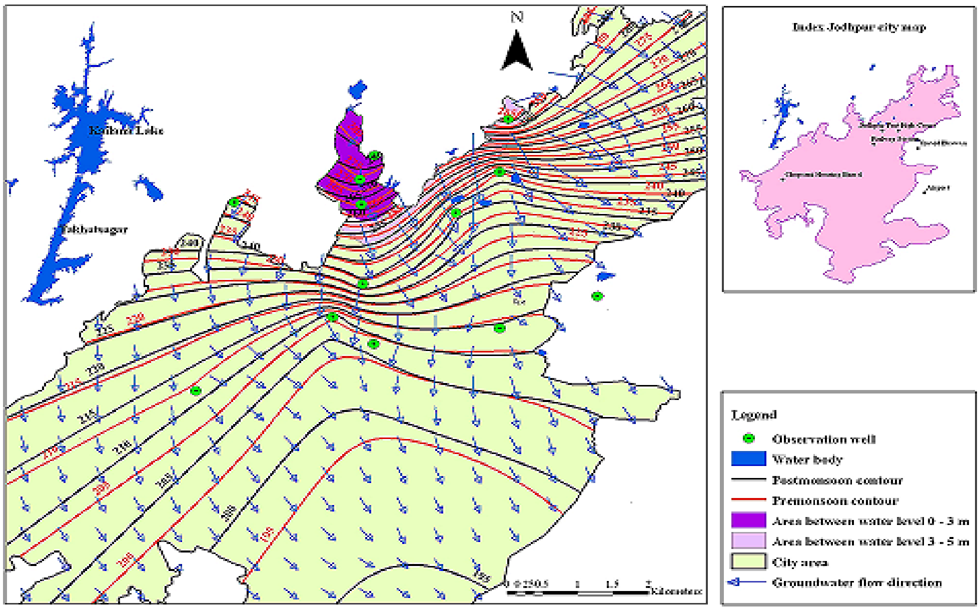

Figure 8.1: Pre (red color) and post (black color) monsoon groundwater table contour map for 1996 with the assumption that the Kailana-Takhatsagar is hydraulically connected to the aquifer below the Jodhpur city (→ Indicates groundwater flow direction).

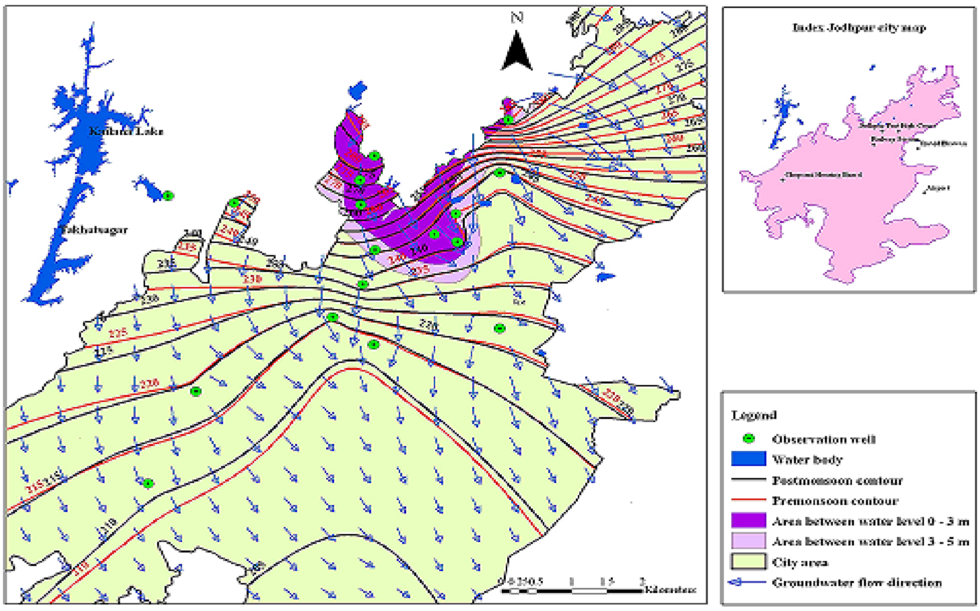

Figure 8.2: Pre (red color) and post (black color) monsoon groundwater table contour map for 2000 with the assumption that the Kailana-Takhatsagar is hydraulically connected to the aquifer below the Jodhpur city (→ Indicates groundwater flow direction).

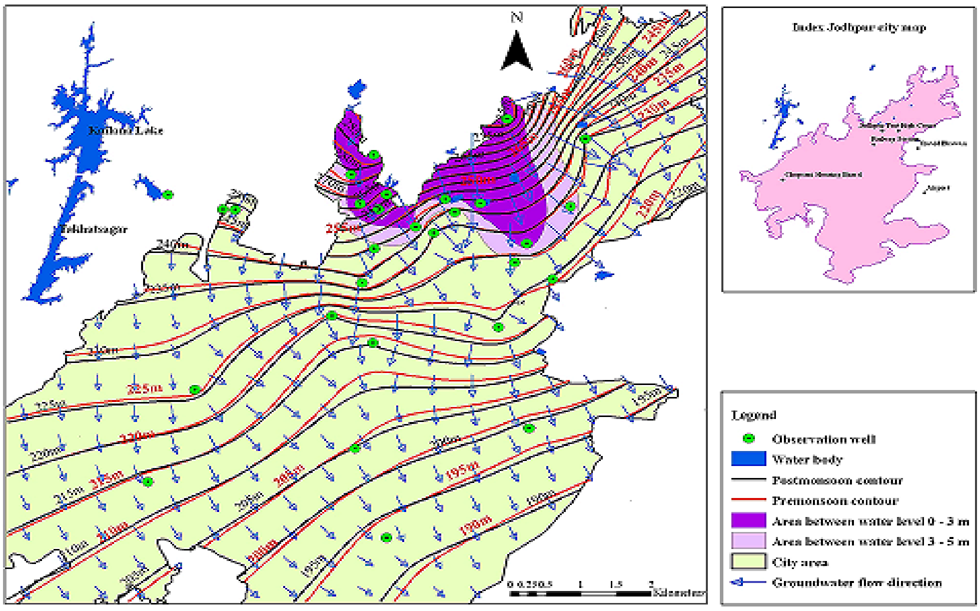

Figure 8.3: Pre (red color) and post (black color) monsoon groundwater table contour map for 2004 with the assumption that the Kailana-Takhatsagar is hydraulically connected to the aquifer below the Jodhpur city (→ Indicates groundwater flow direction).

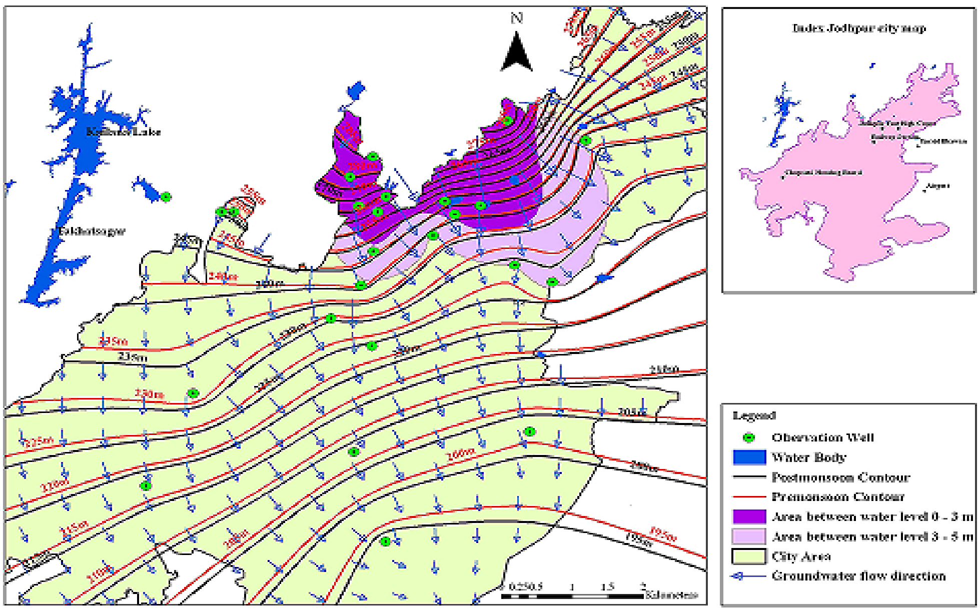

Figure 8.4: Pre (red color) and post (black color) monsoon groundwater table contour map for 2008 with the assumption that the Kailana-Takhatsagar is hydraulically connected to the aquifer below the Jodhpur city(→ Indicates groundwater flow direction).

For the second case case, in which the Kailana-Takhatsagar are assumed not to be hydraulically connected with the aquifer of Jodhpur city, the corresponding water table contour maps are shown in Figs. 8.5-8.8. In these figures, the direction of groundwater flow, the water logged area in which water table lies within a depth of 3m below ground surface, and the area in which the water table lies between 3 and 5 m from ground surface are shown.

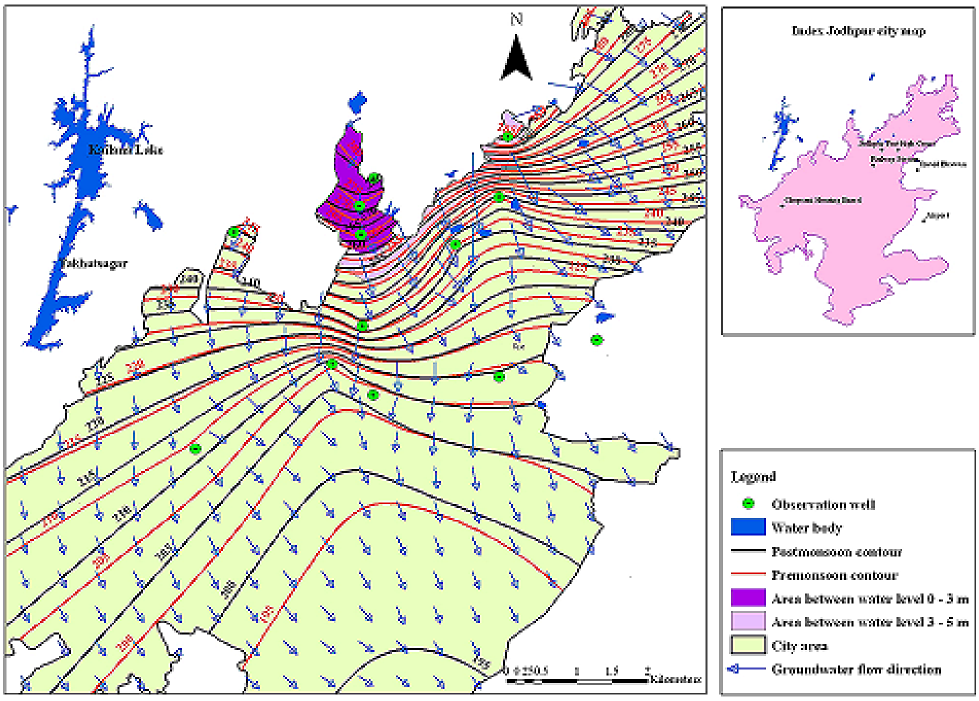

Figure 8.5 Pre (red color) and post (black color) monsoon groundwater table contour map for 1996 with the assumption that the Kailana-Takhatsagar is not hydraulically connected to the aquifer below the Jodhpur city(→ Indicates groundwater flow direction).

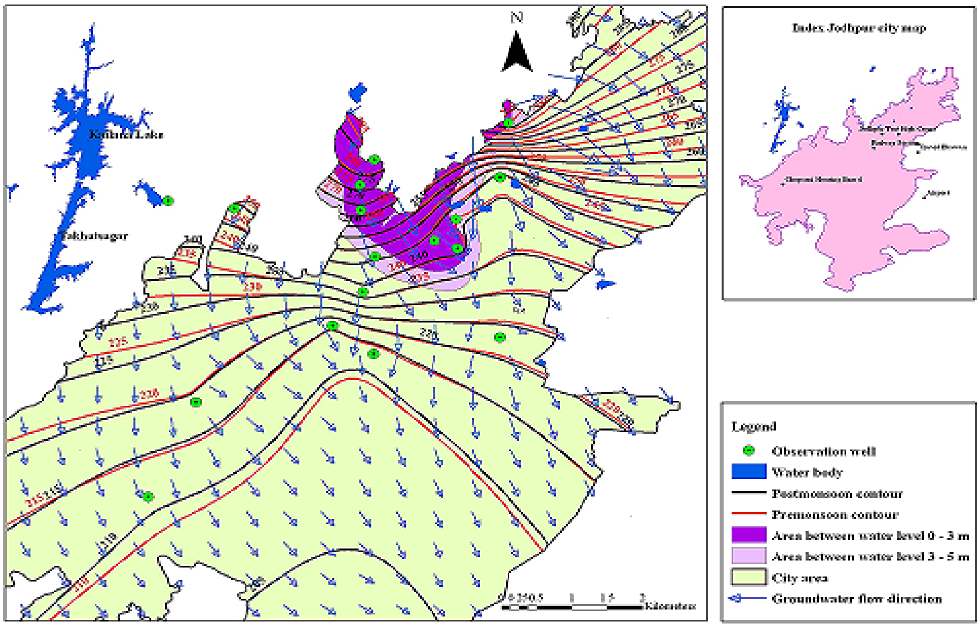

Figure 8.6 : Pre (red color) and post (black color) monsoon groundwater table contour map for 2000 with the assumption that the Kailana-Takhatsagar is not hydraulically connected to the aquifer below the Jodhpur city(→ Indicates groundwater flow direction).

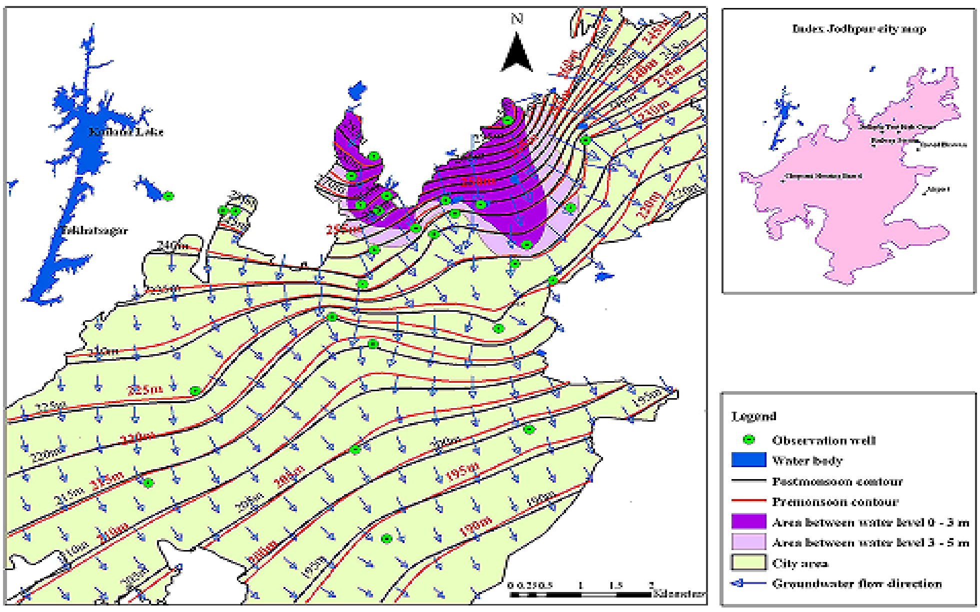

Figure 8.7 : Pre (red color) and post (black color) monsoon groundwater table contour map for 2004 with the assumption that the Kailana-Takhatsagar is not hydraulically connected to the aquifer below the Jodhpur city(→ Indicates groundwater flow direction).

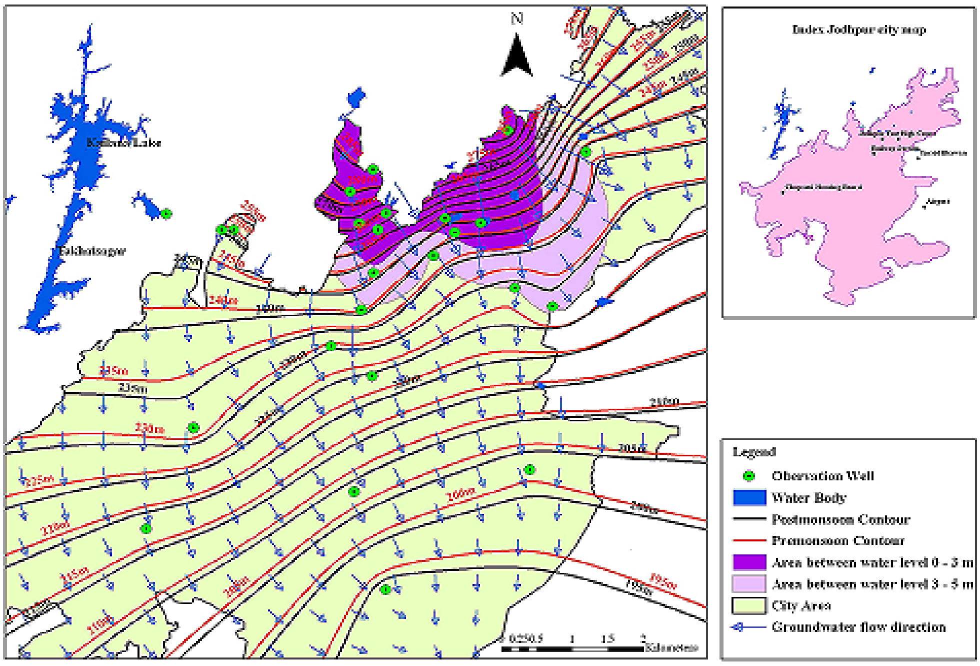

Figure 8.8: Pre (red color) and post (black color) monsoon groundwater table contour map for 2008 with the assumption that the Kailana-Takhatsagar is not hydraulically connected to the aquifer below the Jodhpur city(→ Indicates groundwater flow direction).

In the year 2008, water level observations have been made at more number of observation points. Therefore, the observed data in the year 2008 have been considered for comparison of the pre and post monsoon groundwater table contours. The comparison of the pre and post monsoon groundwater table contours maps for the cases of Kailana-Takhatsagar Reservoir hydraulically connected and hydraulically not connected with the aquifer underneath of the Jodhpur city are shown in Figs.8.9 and 8.10, respectively. It can be seen from the Figs. 8.9 and 8.10 that the groundwater table contour lines in both the cases follow the similar trend with variation in the level differences between the pre and post monsoon contours, viz., at a particular location the elevation of the post monsoon groundwater table has higher elevation than that of the pre-monsoon groundwater table. It indicates that the observed groundwater data and the generated groundwater contour maps are consistent, and the aquifer below the Jodhpur city area has a good response to the monsoon rainfall recharge.

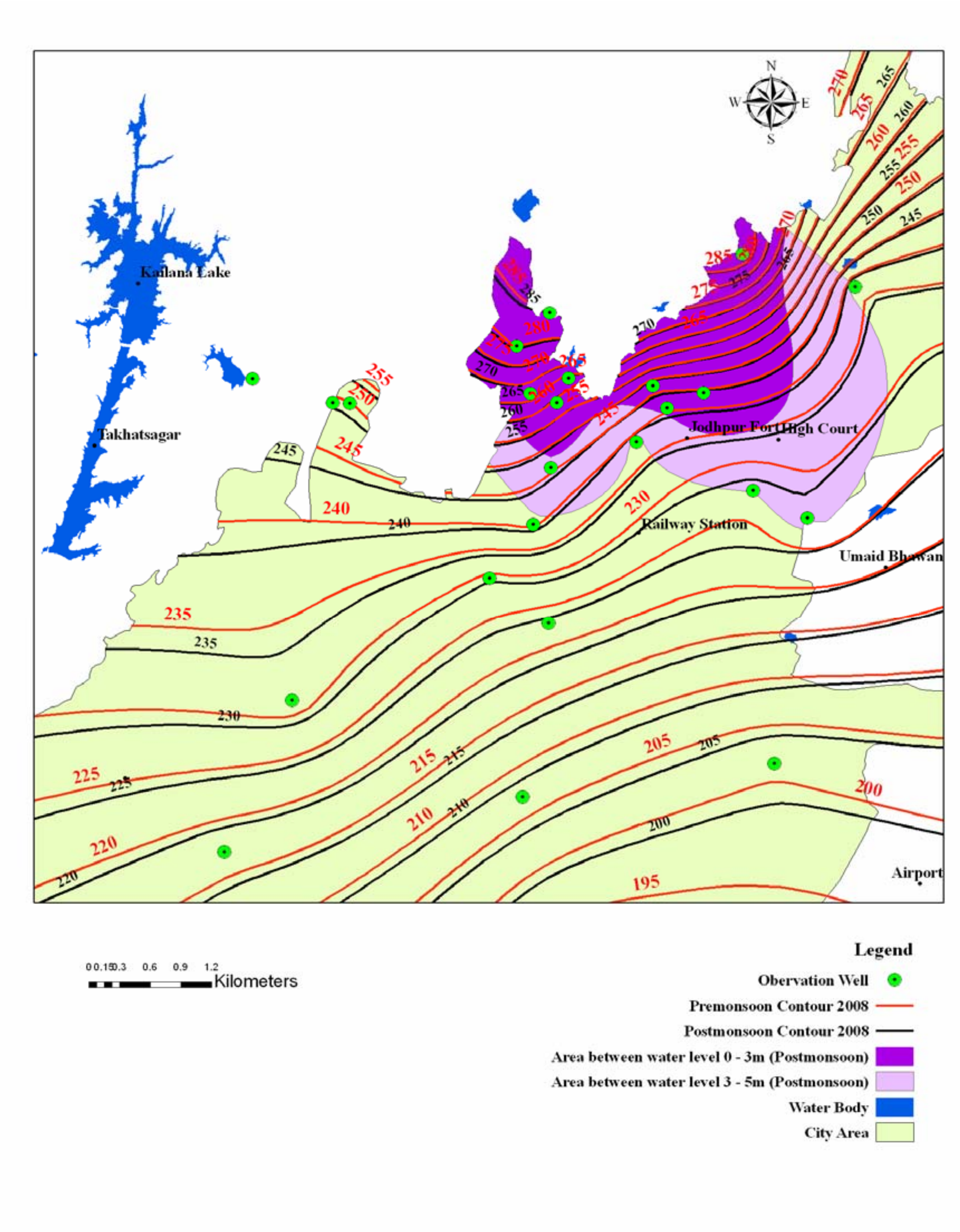

Figure 8.9 : Pre (red color) and Post (black color) monsoon groundwater table contour map for the year 2008 with assumption of the Kailana-Takhatsagar reservoir to be hydraulically connected to the aquifer below the Jodhpur city.

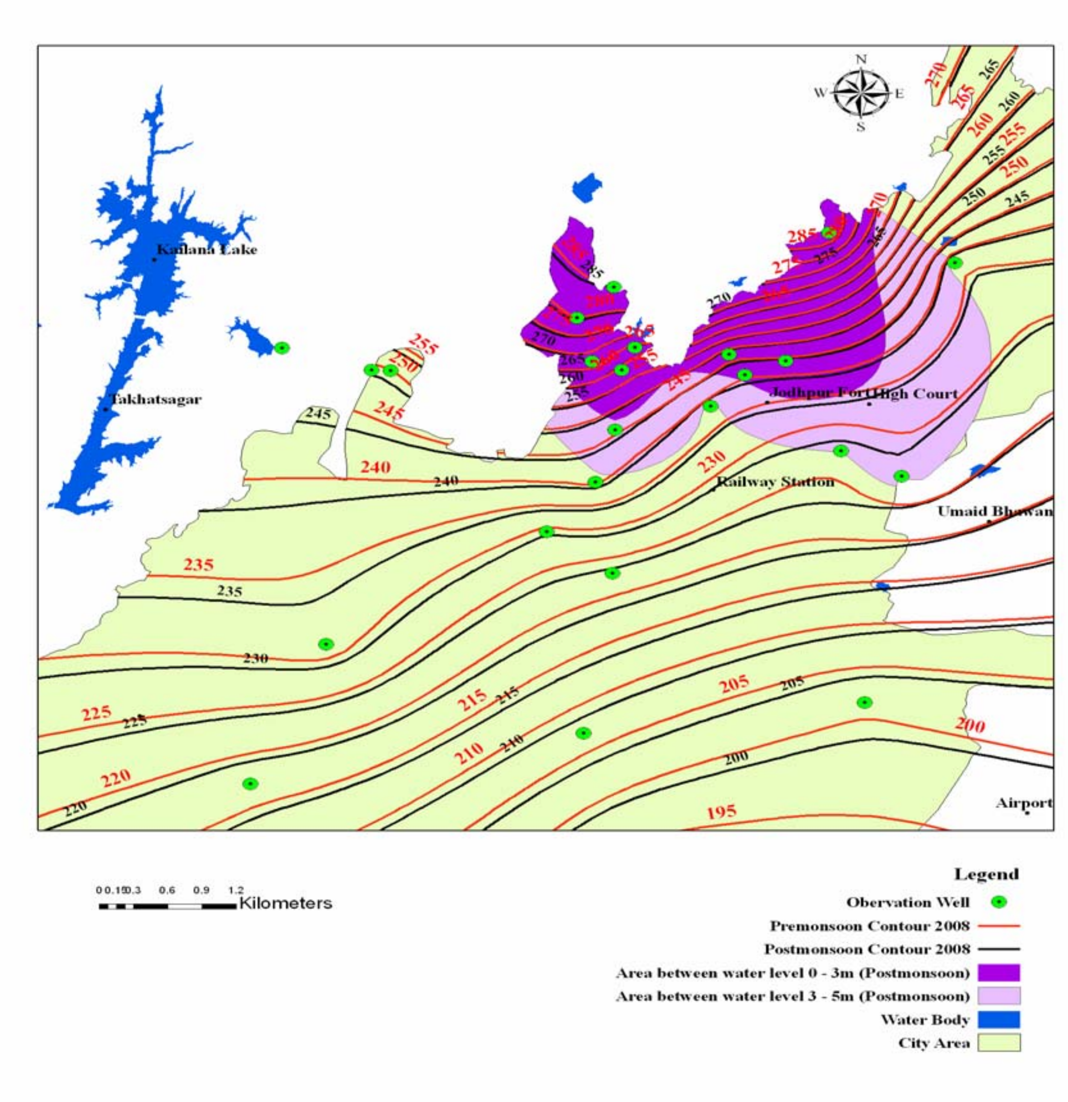

Figure 8.10: Pre (red color) and Post (black color) monsoon groundwater table contour map for the year 2008 with assumption of the Kailana-Takhatsagar Reservoir not hydraulically connected to the aquifer below the Jodhpur city.

A 3-dimensional view of the pre and post monsoon groundwater table elevation map for the year 2008 has been shown in Figs. 8.11 and 8.12, respectively. These figures clearly depict the groundwater table mounds in the uppermost region of the study area. The difference between highest (in the northern part) and the lowest (in the southernmost part) groundwater table elevetation in the study area is of the order of about 90-95 m.

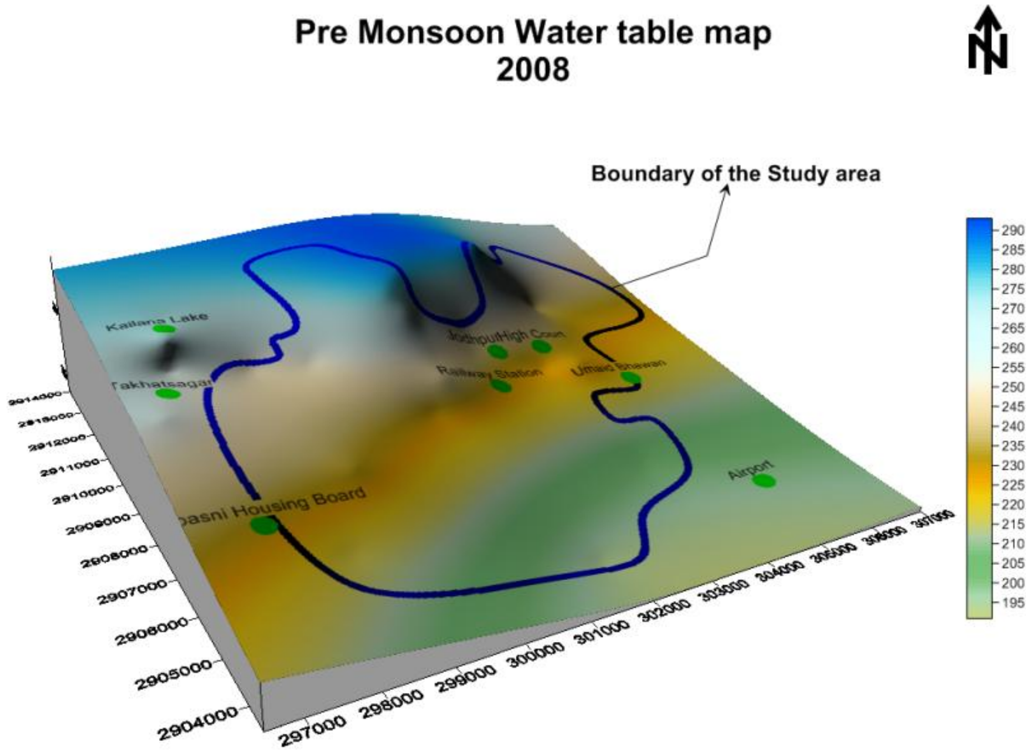

Figure 8.11 : 3-dimensional plot of the pre-monsoon groundwater table contour map for the year 2008.

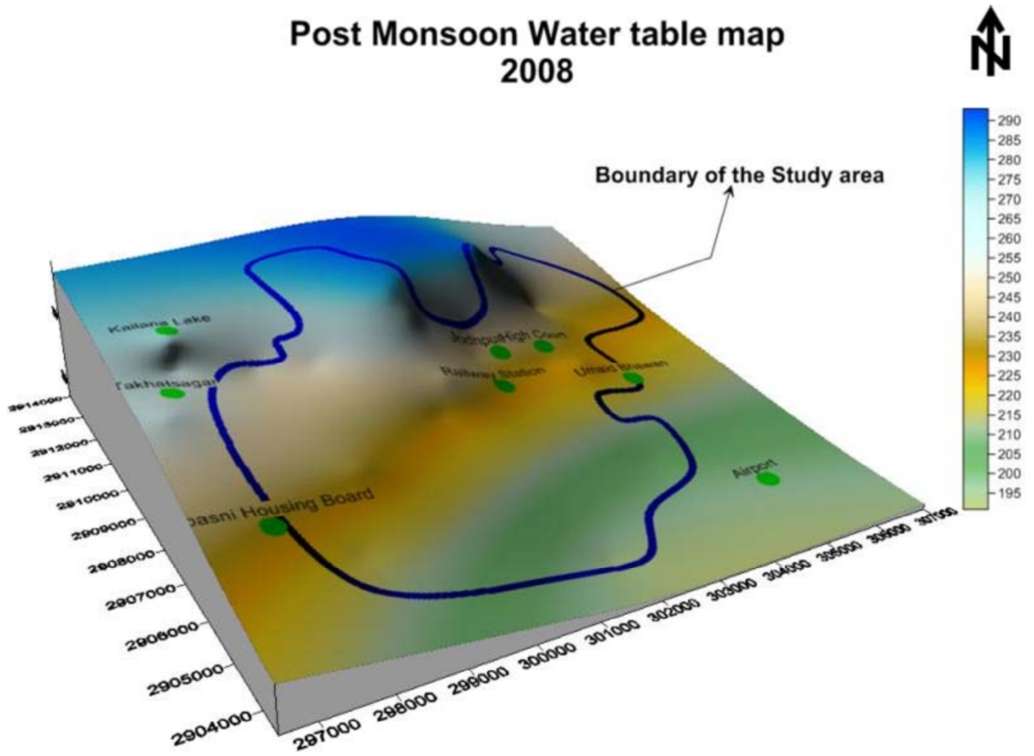

Figure 8.12 : 3-dimensional plot of the post-monsoon groundwater table contour map for the year 2008.

Since the year 1996, due to continuous rise in ground water level, the waterlogged area is spreading and has increased manifold in the Jodhpur city area particularly in the uppermost part of the study area (Figs. 8.1-8.8). Year-wise spreading of the waterlogged areas, and areas encompassed by groundwater levels at: (i) 3.0 m below the ground surface, (ii) 5.0 m below the ground surface, and area between 3.0-5.0 m below the ground surface, have been ascertained and are shown in Figure 8.13. It is found that over the period of 12 years (1996-2008), the waterlogged areas have been increased gradually to 3 times of the waterlogged area that existed in the year 1996.

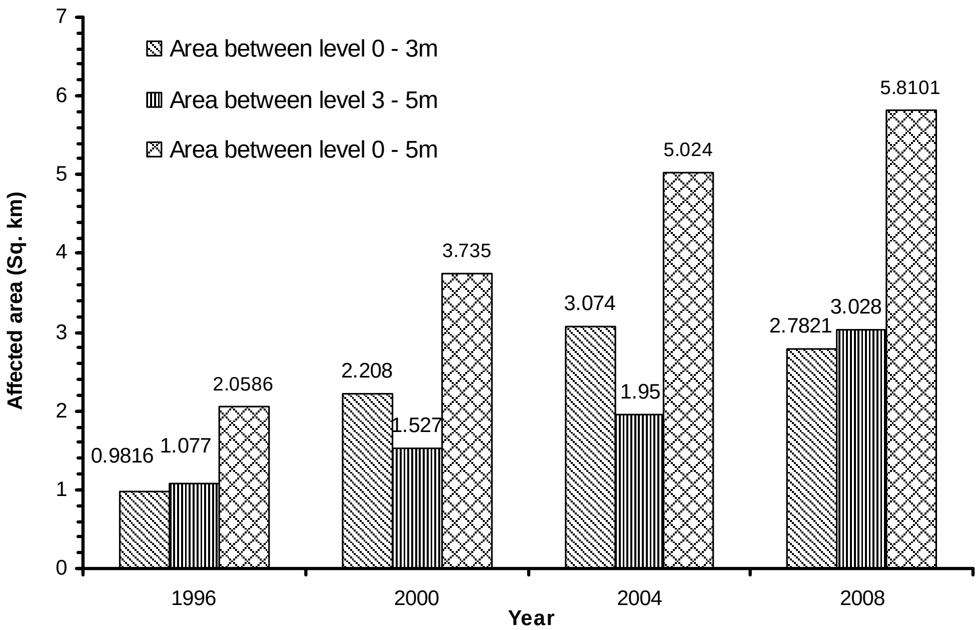

Figure 8.13: Variation of Waterlogged area in different years.

The following inference is drawn analyzing the water table contour maps:

(a) The directions of groundwater flow during all the years from 1996 to 2008 (Figs. 8.1-8.8), the pre as well as post monsoon seasons, are observed to be broadly from the north to the south and southeasterly direction with some minor deviations at local pockets,

(b) In the waterlogged region, the water table contours are closely spaced. In the southern region, the spacing between two consecutive contours is comparatively wider. The region in which the contours are closely spaced is a region of low transmissivity. This means either the hydraulic conductivity is low or the thickness of the Quaternary alluvium formation is small. The region in which the contours are widely spaced is a region of comparatively higher transmissivity indicating larger thickness of the Quaternary alluvium formation. The waterlogged area is located in the geological unit having low transmissivity where the contours are closely spaced. From hydraulics principle, water flows from a region having contours of higher water level to region with contours of lower water level. In the waterlogged area, the water table contours have higher values than those in the southern side. Since water is flowing from the waterlogged region and the North side is a hilly region and no water is coming to the waterlogged region from the north side, the source of water causing water logging is thus generated locally which is likely to be the return flow from the water supply including sewerage,

(c) The possibility of seepage from the Kailana-Takhatsagar Reservoir entering the waterlogged area is investigated making use of the contour maps. The water table contours shown in Figs 8.5-8.8 are based on the assumption that Kailana-Takhatsagar Reservoir is not hydraulically connected with the aquifer underneath the Jodhpur city. As seen from these figures, the water table contours in the waterlogged area are having higher values than those of the contours which are in the vicinity of the region where the Kailana-Takhatsagar is located. As the waterlogged area is located on a region having higher water table contours than those in the region near Kailana-Takhatsagar, from hydraulic principle, the waterlogged area will not receive any flow from the southwest side i.e., from the reservoir side, where hydraulic head is less than that in the waterlogged area. So it is inferred that groundwater flow from the Kailana-Takhatsagar side is not causing water logging in the waterlogged area,

(d) The water table contours shown in Figs 8.1-8.4 are based on the assumption that Kailana-Takhatsagar Reservoir is hydraulically connected with the aquifer underneath the Jodhpur city. The direction of flow lines, which are orthogonal to the equipotential lines, i.e., the water table contours, is not towards the waterlogged area (Figs. 8.1-8.4). The direction of flow in all the cases is broadly towards south-east direction. The seepage from the Kailana-Takhatsagar Reservoir is not entering the waterlogged area. Thus, whether the Kailana-Takhatsagar Reservoir is hydraulically connected with the aquifer underneath the Jodhpur city or not, the seepage from the lake is not flowing towards the waterlogged area in either situation,

(e) From the configurations of the flow nets (Figs.8.1-8.8), it is concluded that the Kailana-Takhatsagar Reservoir being located in the Malani group of rocks, and the Malani group of rocks have low permeability; the seepage losses from the lake will be very small, which can be quantified from a water balance study. This seepage is entering towards the south-east region in which the water table contours are having less value than those in the waterlogged area. From the consideration of hydraulic principle (flow takes place from region with higher hydraulic head to region with lower hydraulic head), and from the consideration of the direction of flow, it can be postulated that the seepage from the reservoir is not entering to the waterlogged areas.

(f) Analysis of evolution of depth to water table below ground surface in the area affected progressively due to water logging indicates that area getting waterlogged has increased every year, and dynamic equilibrium has not been reached yet.

(g) As such, there is no sign of bulk groundwater seepage from the Kailana-Takhatsagar Reservoir to the Jodhpur city area through the underneath geological formations of the respective areas. If at all seepage is taking place, it may be occurring through lineaments. The orientation of the lineaments can be seen in Fig.3.1. There is only one lineament, which is oriented towards the waterlogged area. Near to the Kailana-Takhatsagar Reservoir the connection of this lineament with the lake is not clear. The Lineament analysis survey and the geological and geophysical study conducted independently by the National Geophysical Research Institute (NGRI), Hederabad (2010) surrounding the Kailana-Takhatsagar Reservoir indicated that the lineaments are oriented in NNE-SSW to NE-SW directions with no connectivity to the city areas. A few lineaments with ESE-WNW directions are present but these are small and do not have connectivity to the city areas. The findings of the NGRI thus corroborate the present conclusion obtained flow analysis of flow direction. Therefore, the chances of seepage from the Kailana-Takhatsagar Reservoir to the waterlogged areas through lineaments are ruled out.

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Section -9.0 : SEWERAGE AND DRAINAGE DATA ANALYSIS FOR JODHPUR CITY

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 9.1. It can be seen from Figure 9.1 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.

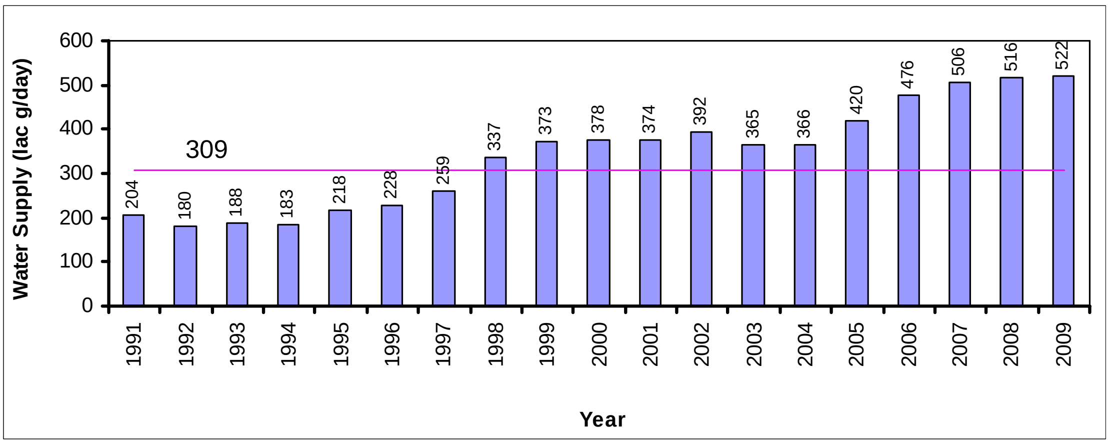

Figure 9.1: Water supplied from the Kailana-Takhatsagar Reservoir to the Jodhpur city in different years during 1991-2009.

To dispose the wastewaters generated from the use of the supplied water, the city has a network of sewerage system serving most part of the city area. The old city area, in which the waterlogged area is located, has a very older sewerage/drainage system constructed a long back than those in the areas where the city has been extended in later stages. It is necessary to ascertain whether all households located in the waterlogged area are connected to the sewerage/drainage systems. For ascertaining this aspect, a random door-to-door survey in the problematic area has been carried out making use of a simple questionnaire. A copy of the questionnaire that has been used for gathering the requisite information is given in the Annexure A9.1. The gist of the analyzed information derived from the questionnaire is given in Table 9.1. It can be seen from Table 9.1 that out of the 23 families responded, about 43% indicated disposal of domestic wastewaters through Nallahs and Soak Pits, which may join to the underneath aquifer subsequently. However, almost all the families have indicated connectivity of their toilet wastewaters to the sewerage system.

Table 9.1: Analyzed information on the random door-to-door survey carried out in the problematic area for ascertaining usages of waters and wastewaters by the householders.

Nos. of family responded to questionnaire	Source of water supply & no. of family	Method of disposal of domestic wastewater & no. of family	Method of disposal of toilet water & no. of family
23	Nagar Nigam : 21	Sewerage system : 13	Sewerage system : 22
	PHED : 2	Nallah, etc. : 5	Nallah, etc. : 1
		Soak Pit : 5	
	Total : 23	**Total : 23**	**Total : 23**

In most part of the old city area, the sewerage/drainage systems are found to be chocked by debris, and the flow velocity is sluggish. Therefore, leakage/seeping of wastewaters and return flow to the aquifer from the households, which are not connected to the sewerage system, can not be ruled out, in such cases. Currently, the city's wastewaters are drained out through three main sewerage systems, one towards the Nandri area, and the other one to the Jodhpur Airport side, and the third one is near to the Polytechnic Institute, which have the disposal outlets to the Jojri River. Of these, Nandri site has an organized sewage treatment plant having capacity of 20 MLD (Million liter per day). In the other two cases, they are directly discharged to the Jojri River without treatment. Whether or not the wastewaters generated from the water supplied to the city area, which could be of the order of 65% of the supplied water, have the clear passage to flow through the existing sewerage network, need an assessment. Some parts of the generated wastewaters in excess of the wastewaters drained out from the city area, which would remain as the accumulated storage, would join to the groundwater. In order to assess the quantity of sewages which outflows daily from the city area through the existing sewerage channels, field investigations and measurements have been carried out in the three sewerages drains; one near to the Jodhpur Airport, other one near to the Jodhpur Polytechnic Institute, and the third one at the Nandri sewage treatment site. Measurements of sewage flows from morning 6:00 A.M to evening 11:00 P.M. for a continuous 7 days at all the three locations (Figs. 9.2-9.4) have been carried out during the months of April-July, 2010 by engaging a local agency. 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, a generalized graph of time-varying discharges of flows for 24 hours for each of the three sites has been developed and given in Figs. 9.5-9.7.

Figure 9.2 : Sewage measurement location near the Jodhpur Airport site; (a) section chosen for measurement of cross-section and flow velocity, and (b) temporary structural arrangement made for measurement of cross-section and flow velocity, and measurement of depth of flow.

Figure 9.3 : Sewage measurement location near the Jodhpur Polytechnic Institute; (a) pre-calibrated V-notch installed at the site by constructing a guided channel for measurement of flow, and (b) depiction of flow over the V-notch.

Figure 9.4 : Sewage measurement location at the Nandri sewage treatment plant site; (a) calibration & fixation of the data logger connected to the current meter, and (b) measurement taken from the current meter for estimation of flow velocity.

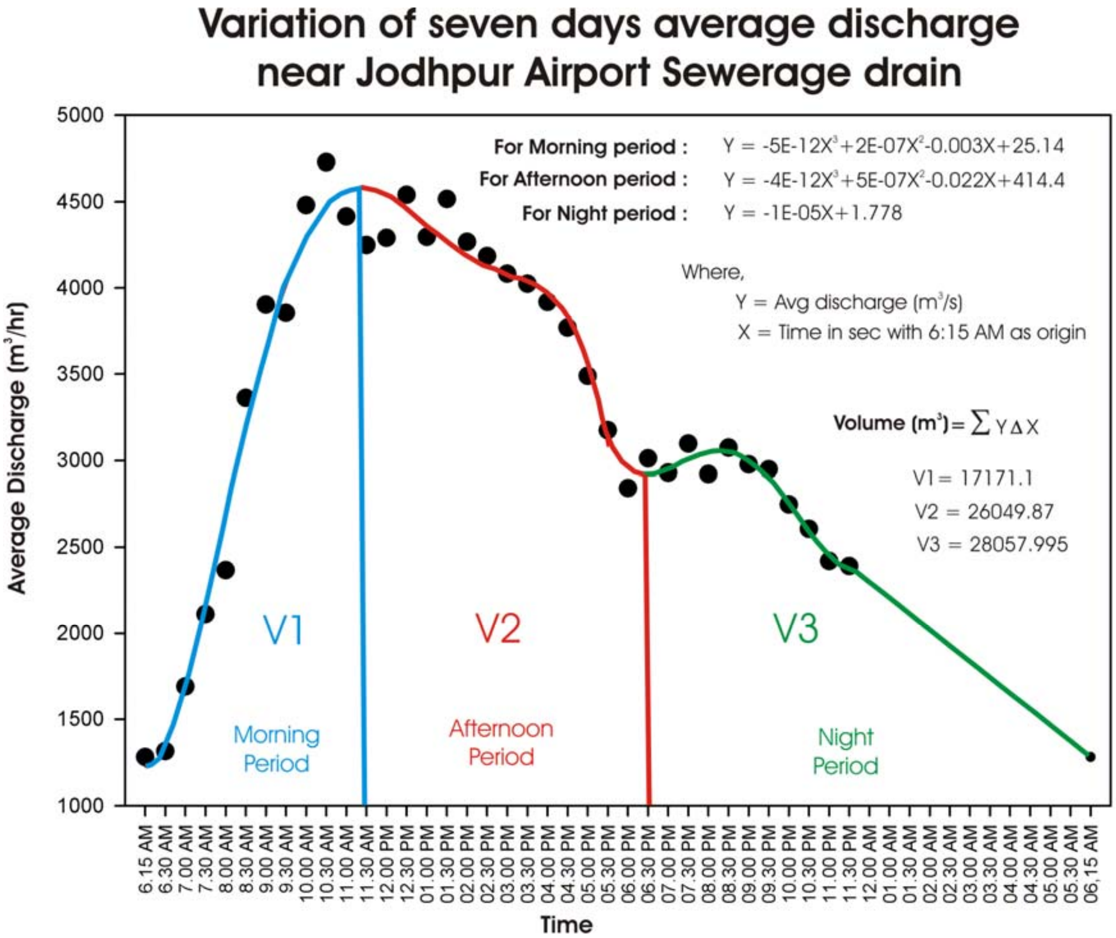

Figure 9.5 : Generalized rating curve of the sewage flows in the sewerage drain near to the Jodhpur Airport area; developed based on the continuous 7 days field measurements from 6:00 A.M to 11:00 P.M.(April, 2010).

From the rating curves (Figs. 9.5-9.7) it can be seen that sewage flows in all the three drains vary during 24 hours in a day. Largely, in a day the flows are found to be minimum in morning 6-7 A.M., thereafter, the flows gradually increase and attain to a peak value between 10:00 – 11:30 A.M; after that flows gradually reduces. A second peak is also found common in all the three cases between 9:00 P.M. to 10:30 P. M. Thereafter, the flows decrease to attain the minimum in the morning. The pattern of sewage flows depend on the uses of the supplied water by the households in the city areas. In general, the maximum uses of water are seemed to be during the morning 8:00 A.M to 12 noon, followed by evening 6:30 P.M. to 10:00 P.M.

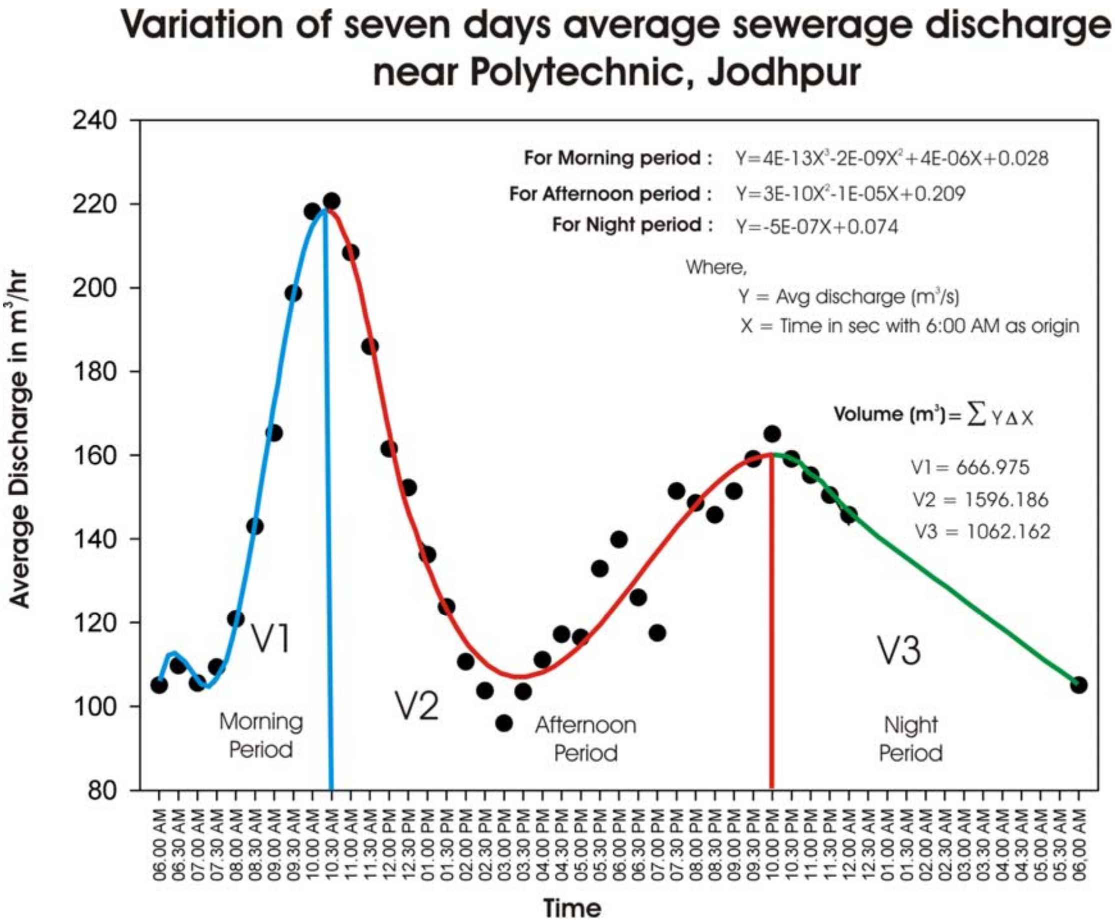

Figure 9.6 : Generalized rating curve of the sewage flows in the sewerage drain near to the Jodhpur Polytechnic Institute; developed based on the continuous 7 days field measurements from 6:00 A.M to 11:00 P.M.(June, 2010).

Out of the three sewerage drains, the Jodhpur Airport drain disposed off maximum sewages of about 71279 m^3/day (157 lacs gallon per day) followed by Nandri Treatment Plant drain of about 13235 m^3/day (29.15 lacs gallon per day); while the Polytechnic Institute drain disposed off an average of about 3325 m^5/day (7.12 lacs gallon per day). The total discharge of sewages from the city areas through these three sewerage systems in terms of the water supplied in the year 2009 is about 37%. The sewage flows may vary from season to season, even from month to month that depend on the supplies and uses of water. In addition to the three major drains, there are number of small uncounted drains, which are connected to the nearby Talabs located in the city area.

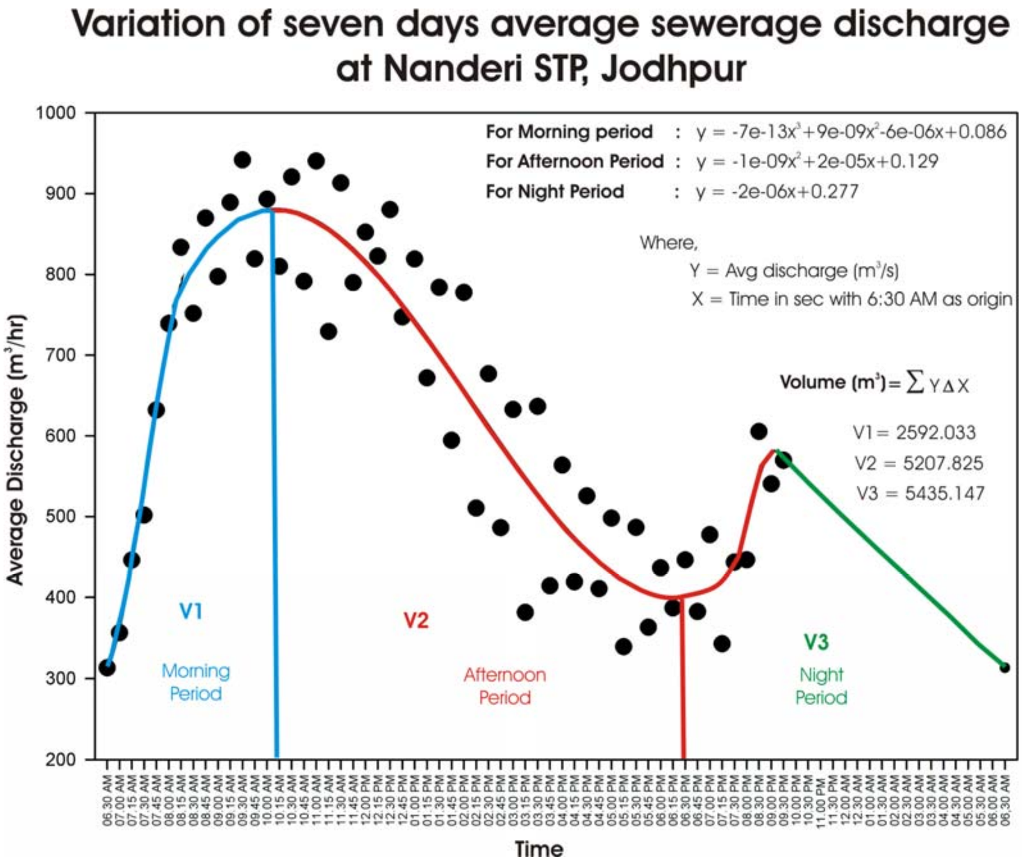

Figure 9.7 : Generalized rating curve of the sewage flows in the sewerage drain at Nandri Sewage Treatment Plant site; developed based on the continuous 7 days field measurements from 6:00 A.M to 11:00 P.M.(July, 2010).

Assuming that the wastewaters generated and their outflows from the city area are respectively, 65% and 37% of the water supplied in the respective years. The probable quantities of the wastewaters, which have been generated and disposed off from the city areas in different years, are given in Table 9.2.

Table 9.2: Probable quantities of wastewaters generated and disposed off from the city areas in different years.

Year	Water supplied (Lac gallon per day)	Probable quantity of wastewaters generated (Lac gallon per day)	Probable quantity of wastewaters disposed off (Lac gallon per day)
2000	378	245.7	139.86
2002	392	254.8	145.04
2004	366	237.9	135.42
2006	476	309.4	176.12
2008	518	335.4	190.92

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Section -10 : WATER BALANCE OF THE STUDY AREA

An assessment of the unknown fraction of surface water supply that joins the aquifer system causing water level rise in the city area has been made from surface water balance study for the city area. In water balance, one is required to confirm that the quantitative difference between sum of all inputs and outputs of the hydrological components, those are involved in the governing physical processes in a system for a specific time period, is equal to the change in water storage in the system during that time period. In the case of the present study area, the hydrological components of inputs are: (i) water supplied to the city area, and (ii) rainfalls and the corresponding runoffs; while the outputs are: (i) sewage outflows from the city area, (ii) evapotraspiration, and (iii) groundwater recharge. The surface water balance considering these components can be written as:

$$\left[\left(Q_{ws} + Q_{Ri} + Q_{Ro}\right) - \left(f\ Q_{ws} + Q_{sw} + Q_{evp} + Q_{gr}\right)\right]\Delta t = \Delta V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10.1)$$

in which Q_{ws} is the rate of water supply from the Kailana-Takhatsagar Reservoir to the city area (L^3T^{-1}); Q_{Ri} is the rainfall rate over the city area (L^3T^{-1}) = $R_i\ A_s$, R_i is the rainfall quantity (L), and A_s is the surface area on which rainfall occurs (L^2); Q_{Ro} is the runoff rate to the area corresponding to the rainfall (L^3T^{-1}); f is the fraction of the water, Q_{ws} that is lost by the consumptive use (dimensionless), Q_{sw} is the sewage & storm water outflows from the city area (L^3T^{-1}); Q_{evp} is the evapotranspiration rate of water from the study area (L^3T^{-1}); Q_{gr} is the rate of ground recharge from the study area (L^3T^{-1}); ΔV is the change in storage of water in the city area (L^3); and Δt is the time period (T).

The daily rate of water supply from the Kailana-Takhatsagar Reservoir to the city area, Q_{ws} has been given in section 7. The daily and annual variation of rainfall, R_i have been discussed in section 4. The water surface evaporation rate has also been explained in section 4. The sewage & storm water outflows rate, Q_{sw} and the fraction of consumptive use (assumed to be, f = 0.35) have been elaborated in section 9. The study area, A_s is measured to be 76 sq. km. Making use of the respective data, and assuming the time period to be annual, i.e., Δt = 1 year, the water balance of the study area is carried out. The information/data used for calculation are given in Table 10.1:

Table 10.1 : Data used for calculation of components of water balance equation of the Jodhpur study area.

Year	Study area	Rainfall & Runoff data	Wastewater components & Consumptive use factor	Groundwater recharge factor
2000, 2002, 2004, 2006 & 2008	76 sq. km.	40% of the annual rainfall is considered as immediate evaporation; Remaining 60% characterizes runoff, infiltration, interception, depression storages, etc. **Runoff** = (1- 0.4 – 0.15 - 0.15) * Rainfall Assuming 15% of the rainfall as the interception & depression storage, and 15% as the infiltration rate.	Wastewater : 65% of the supplied water; Consumptive use factor, f = 0.35 Sewage outflows from the city area: 37% of the water supplied.	15% of the rainfall.

The water balance components can vary during monsoon and non-monsoon days, even during different hours in a day, which depend on water supplied to the city area, water usages pattern, rainfall and its intensity and duration, land-uses and land cover, storage retention, temperature, etc. However, making use of the data given in Table 10.1, a lumped water balance of the study area has been made for the years 2000, 2002, 2004, 2006 and 2008 and is given in Table 10.2. The lumped storage volumes shown in Table 10.2, which are the differences of Inflow components and the outflow components, are the quantities of water those might have joined to the underneath aquifer through return flow over the respective year in addition to the normal rainfall recharge.

Table 10.2: Water balance components of the study area in different years.

Year	**Inflow components**		**Outflow components**			**Storage (ΔV) (MCM) =** $\sum Inflow - \sum Outflow$
	Water supply, V_{ws} (MCM)	Runoff volume (V_{Ri} +V_{Ro}) (MCM)	Consumptive use component; f V_{ws} (MCM)	Sewage + runoff outflow from the city area, V_{sw} (MCM)	Groundwater recharge component, Vgr (MCM)	
2000	56.62	6.087	19.82	27.036	8.492	7.356
2002	57.47	2.075	20.11	23.339	8.621	7.476
2004	56.92	6.430	19.92	27.492	8.539	7.404
2006	76.62	3.443	26.82	31.791	11.492	9.956
2008	85.57	8.618	29.95	40.281	12.836	11.124

(MCM : Million Cubic Meter)

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Section - 11.0: AQUIFER PARAMETERS ESTIMATION

In a hard rock region in Jodhpur city, aquifer tests have been conducted in small radius tube wells and in large diameter wells locally known as Bowaris. In this study, 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. Unit pulse kernel coefficients are generated and used in a Marquardt Algorithm as described in Appendices. The convolution technique used to compute drawdown is quite versatile. The parameters have also been estimated using a simpler Paul algorithm search technique.

11.1 Determination of aquifer parameters Applying Marquardt Algorithm to observed drawdown at a Piezometer during Pumping

Location: Jodhpur, Paota; Pumping Rate: Q=0.21 $m^3/\min$;
Distance of Observation Well from Pumping Well = 24.5m.

Table 11.1: Observed drawdown data at Paota

Time of observation (min)	Observed Drawdown(m)	Time of observation (min)	Observed Drawdown(m)
1	0	60	1.65
2	0.08	70	1.719
3	0.13	80	1.762
4	0.23	90	1.802
5	0.33	100	1.836
6	0.41	120	1.902
7	0.48	140	1.938
8	0.55	160	1.974
9	0.64	180	2.004
10	0.71	200	2.03
12	0.82	230	2.052
14	0.93	260	2.082
16	1.02	290	2.102
18	1.08	320	2.122
20	1.14	350	2.132
25	1.26	380	2.142

30	1.35	410	2.17
35	1.42	440	2.172
40	1.46	470	2.172
45	1.5	480	2.172
50	1.58		

Starting transmissivity value, T^* $(m^2/\min)$ = 0 .010; starting storage coefficient, ϕ^* = 0.0003.

Table 11.2 : Transmissivity and Storage coefficient as obtained through successive iteration.

Iteration no	T^*	ϕ^*	ΔT	$\Delta\phi$	Error: C(1)	Error: C(2)
1	0.017997	0.000373	8.00E-03	7.33E-05	0.00E+00	0.00E+00
2	0.028653	0.000338	1.07E-02	-3.55E-05	0.00E+00	0.00E+00
3	0.036955	0.000276	8.30E-03	-6.21E-05	0.00E+00	0.00E+00
4	0.039092	0.00027	2.14E-03	-5.46E-06	0.00E+00	0.00E+00
5	0.039129	0.000272	3.65E-05	1.32E-06	0.00E+00	0.00E+00
6	0.039133	0.000271	4.43E-06	-9.17E-08	2.78E-17	8.88E-16
7	0.039132	0.000271	-5.05E-07	1.11E-08	0.00E+00	0.00E+00
8	0.039133	0.000271	6.01E-08	-1.31E-09	-4.34E-19	0.00E+00
9	0.039133	0.000271	-7.14E-09	1.56E-10	5.42E-20	0.00E+00

Iterated Transmissivity, T= 0 .03913 $m^2/\min$ =56.35 m^2/day
Iterated Storage Coefficient, ϕ = 0.000271

Table 11.3: Comparison of observed drawdowns with simulated drawdowns

Time (min)	Observed drawdown(m)	Computed drawdown(m)	Time (min)	Observed drawdown(m)	Computed drawdown(m)
1	0	0.0875	60	1.65	1.4921
2	0.08	0.2287	70	1.719	1.5569
3	0.13	0.3417	80	1.762	1.6132
4	0.23	0.4326	90	1.802	1.6628
5	0.33	0.5081	100	1.836	1.7073
6	0.41	0.5725	120	1.902	1.7845
7	0.48	0.6285	140	1.938	1.8498
8	0.55	0.6781	160	1.974	1.9064
9	0.64	0.7226	180	2.004	1.9564
10	0.71	0.7629	200	2.03	2.0011
12	0.82	0.8337	230	2.052	2.0605
14	0.93	0.8945	260	2.082	2.1127
16	1.02	0.9477	290	2.102	2.1591
18	1.08	0.995	320	2.122	2.201
20	1.14	1.0376	350	2.132	2.2392

25	1.26	1.1285	380	2.142	2.2742
30	1.35	1.2035	410	2.17	2.3066
35	1.42	1.2672	440	2.172	2.3366
40	1.46	1.3227	470	2.172	2.3647
45	1.5	1.3717	480	2.172	2.3737
50	1.58	1.4158			

Square root of sum of square of error =0. 82m; average error = 0. 02 m.

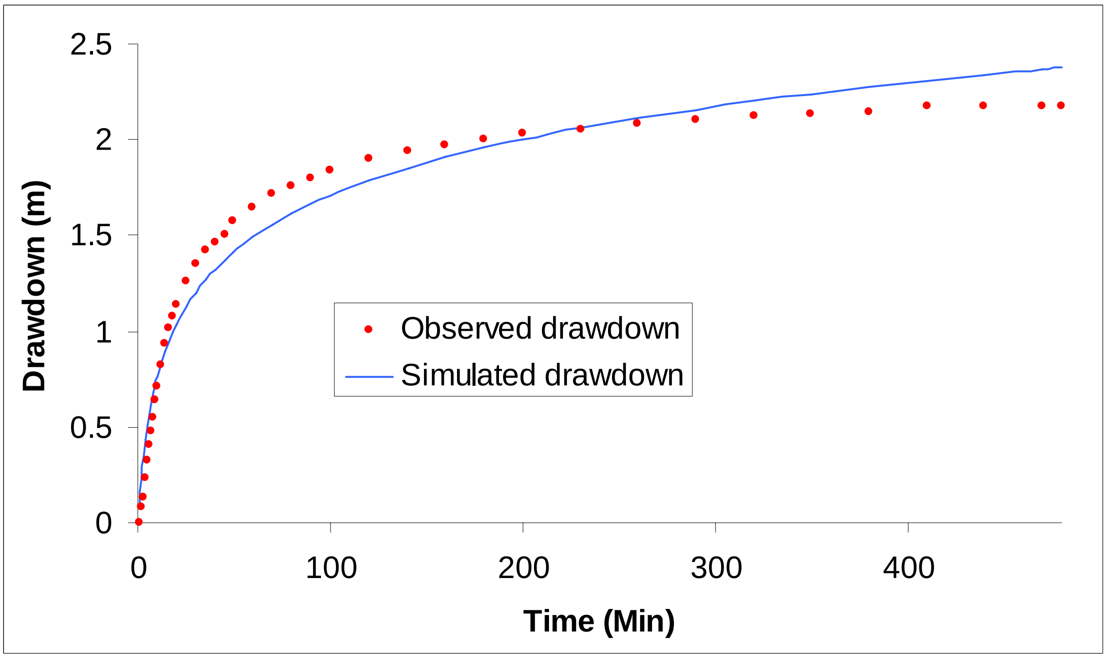

Figure 11.1: Observed and simulated drawdowns for T=0.03913 $m^2/\min$ = 56.35 m^2/day and storage coefficient, ϕ = 0.000271, Test Site at Paota.

11.2 Determination of aquifer parameters applying Marquardt Algorithm to observed drawdown in a Well during pumping; the aquifer test is conducted in a large diameter Well (Bowaris)

Location: Jodhpur, Subhash Chowk; Pumping Rate, Q=0.225 $m^3/\min$;
Radius of the Well = 1.725m

Table 11.4: Observed drawdown at Subhash Chowk

Time of observation (min)	Observed Drawdown(m)	Time of observation (min)	Observed Drawdown(m)
2	4.00E-02	30	4.45E-01
3	5.50E-02	35	5.10E-01
4	7.00E-02	40	5.70E-01

5	8.50E-02	45	6.35E-01
6	1.00E-01	50	7.00E-01
7	1.15E-01	60	8.00E-01
8	1.30E-01	70	9.80E-01
9	1.45E-01	80	1.03E+00
10	1.60E-01	90	1.13E+00
12	1.90E-01	100	1.24E+00
14	2.25E-01	120	1.43E+00
16	2.45E-01	140	1.58E+00
18	2.75E-01	160	1.71E+00
20	3.00E-01	180	1.83E+00
25	4.00E-01	200	1.97E+00

Table 11. 5: 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

Table 11.6 : Comparison of observed drawdowns with simulated drawdowns for T= 0.024 $m^2/\min$ =24.56 m^2/day and Storage coefficient, ϕ = 0.127

Time(min)	Observed drawdown(m)	Simulated drawdown(m)	Time(min)	Observed drawdown(m)	Simulated drawdown(m)
2	0.04	0.0444	30	0.445	0.5196
3	0.055	0.0656	35	0.51	0.5884
4	0.07	0.0862	40	0.57	0.6539
5	0.085	0.1063	45	0.635	0.7164
6	0.1	0.126	50	0.7	0.7763
7	0.115	0.1453	60	0.8	0.8887
8	0.13	0.1643	70	0.98	0.9926
9	0.145	0.1829	80	1.03	1.0892
10	0.16	0.2012	90	1.13	1.1793
12	0.19	0.237	100	1.235	1.2638
14	0.225	0.2717	120	1.43	1.418
16	0.245	0.3054	140	1.58	1.5557
18	0.275	0.3383	160	1.71	1.6798
20	0.3	0.3703	180	1.83	1.7924
25	0.4	0.447	200	1.97	1.8952

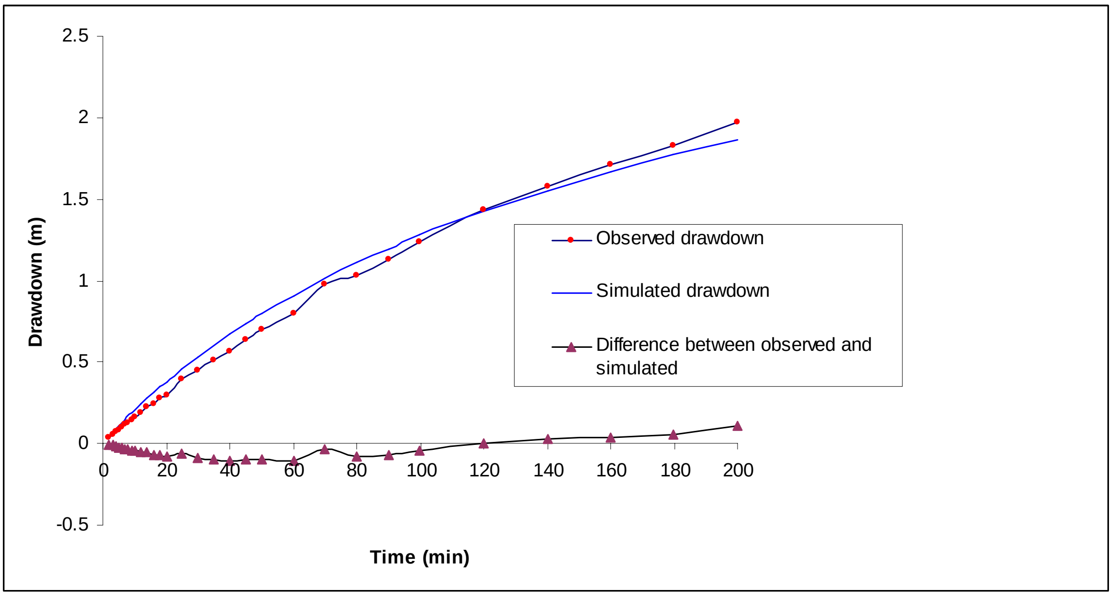

Figure 11.2: Observed and simulated drawdowns for T= $0.034\, m^2/\min$ = $49.97\, m^2/day$ and Storage coefficient, ϕ = 0.046 estimated by Marquardt Algorithm (Subhash Chowk).

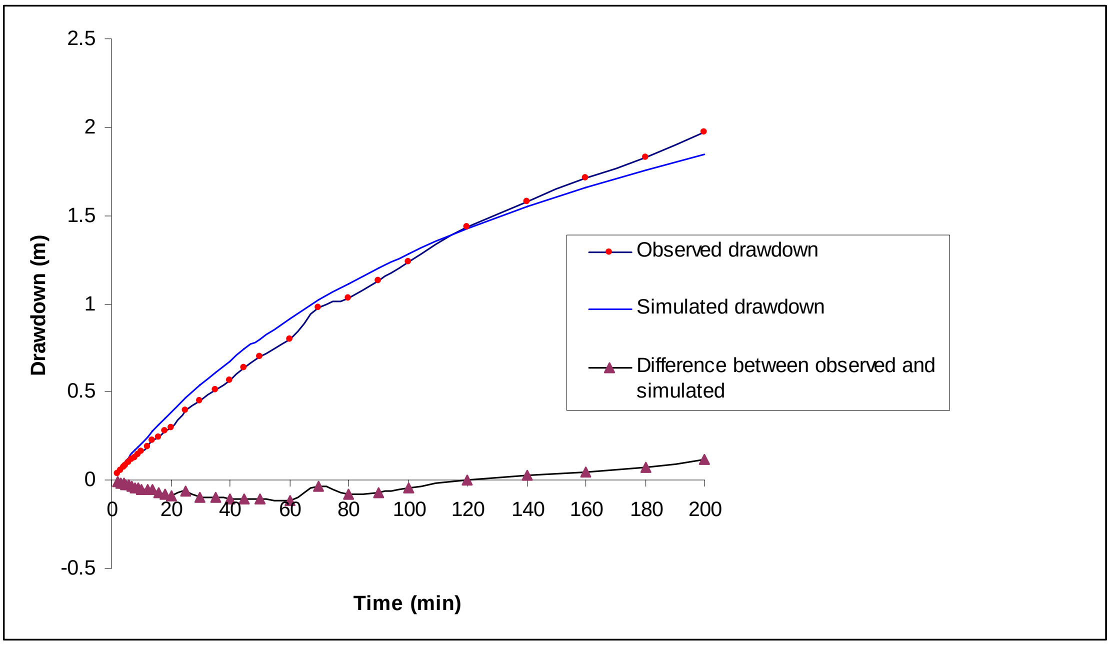

Figure 11.3: Observed and simulated drawdowns for T=$0.0396\, m^2/\min$ = $57\, m^2/day$, Storage coefficient, ϕ = 0.0298; estimated by Paul Algorithm (Subhash Chowk).

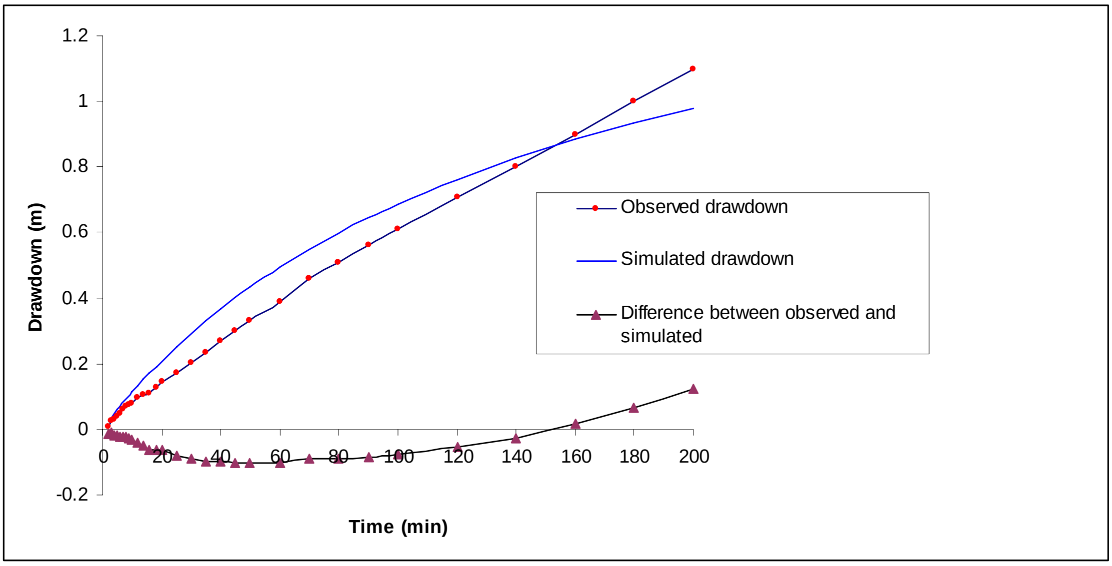

Figure 11.4: Observed and simulated drawdowns for T = 0 .1156 $m^2/\min$ =166.46 m^2/day and Storage Coefficient, ϕ = 0.2337 Estimated Using Marquardt Algorithm (Suraj kund).

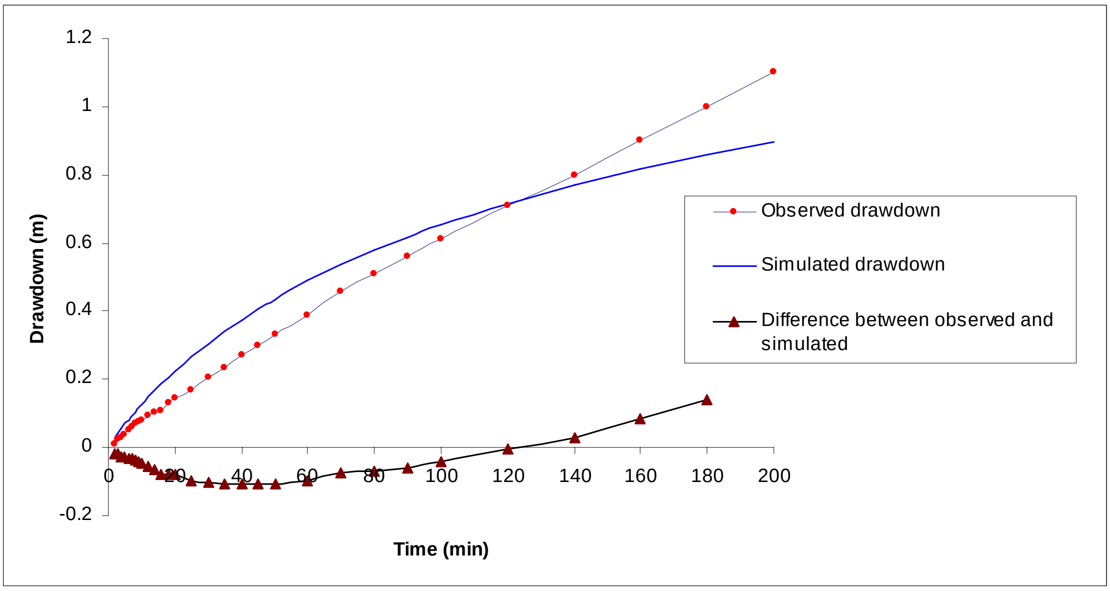

Figure 11.5: Observed and simulated drawdowns for T= 0.1 $m^2/\min$ =144.00 m^2/day and Storage coefficient, ϕ = 0.121 estimated using Paul Algorithm (Suraj kund).

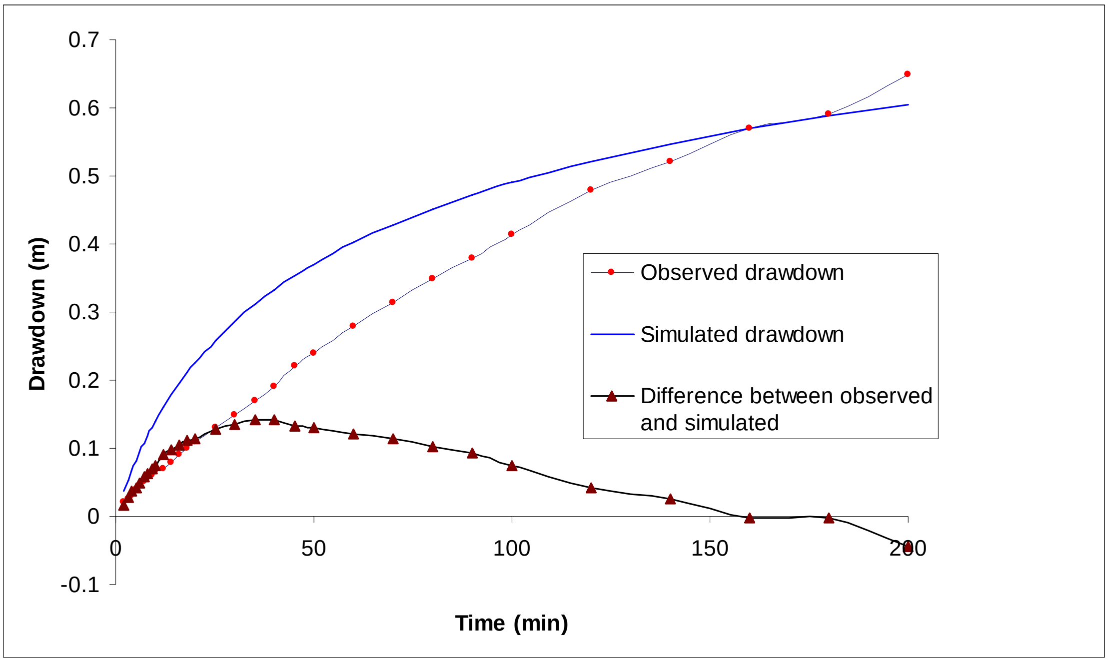

Figure 11.6: Observed and simulated drawdowns for T = 0 .17 m^2 / min =244.8 m^2 / *day*, Storage coefficient, ϕ = 0.181, estimated by Marquardt Algorithm (Sanicherji ka than).

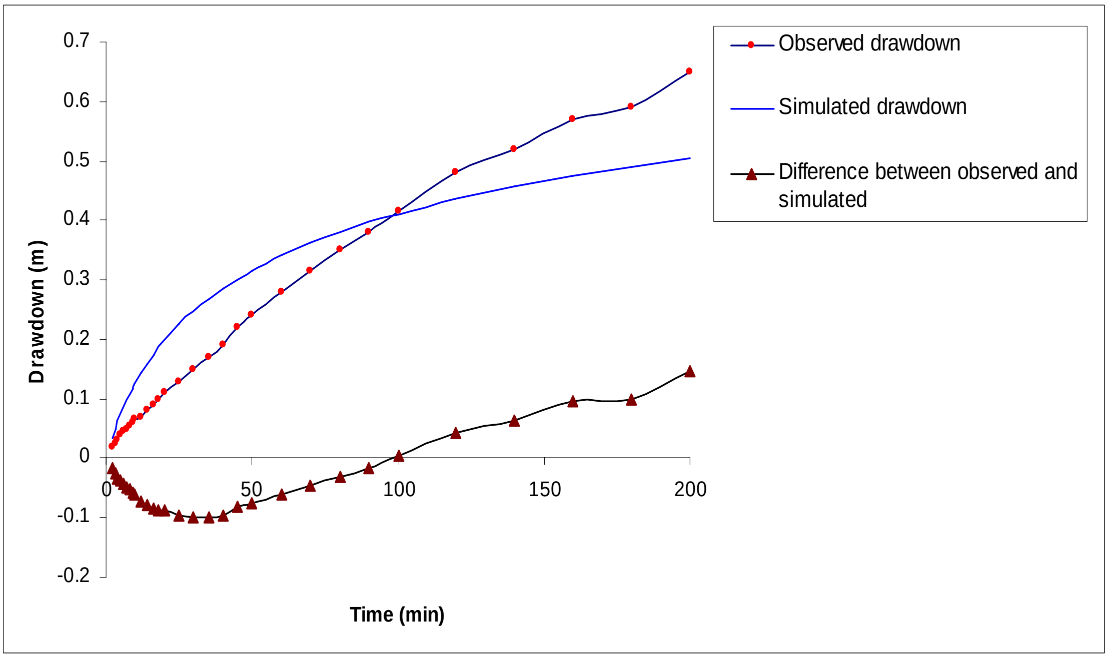

Figure 11.7 : Observed and simulated drawdowns for T= 0.2 m^2 / min = 288.00 m^2 / *day* and Storage coefficient, ϕ = 0.25; estimated using Paul Algorithm (Sanicherji ka than).

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Section -12.0: GROUNDWATER QUALITY DATA AND ANALYSIS

The significance of groundwater quality analysis is to detect the dominant water quality constituents in groundwater which exceed the permissible limit as prescribed by IS-10500, 1991 for various designated uses. The detection of water quality constituents helps not only to identify the zones of good water qualities which are within permissible limits for various uses, but also to identify their possible sources of contamination, if beyond the permissible limit. The water quality constituents are characterized by three major properties: physical properties, chemical properties and biological properties. The physical properties are: Temperature, Turbidity & Color, Salinity, Suspended Solids, and Dissolved Solids. The chemical properties are pH, BOD (Biochemical Oxygen Demand), DO (Dissolved Oxygen), COD (Chemical Oxygen Demand), Nutrients, Organic and Inorganic constituents; and the biological properties are Coliforms, Bacteria, and Algae. The indication of occurrence of some of the dominant chemical constituents in water in excess to the permissible limit can be explained as follows: presence of high concentration of TDS indicates contamination by chemical constituents, presence of high BOD concentration indicates contamination of water by organic matters, presence of high NO_3 concentration indicates contamination of water by sanitary sewages or agricultural refusal, and presence of high concentration of coliform indicates pollution of water from mixing of cattle excreta, sanitary sewages and landfills wastes to the groundwater. The standards prescribed by the BIS-10500 (Bureau of Indian Standards), 1991 for different chemical constituents are given in Tables -A12.1 and A12.2 in the Annexure.

In order to find the possible causes of waterlogging in the city area and their sources, the groundwater quality data are also considered for analysis. The PHED, Govt. of Rajasthan has monitored groundwater quality at 53 locations in the city area during the year 2009, and analyzed the monitored samples for determination of concentration of 13 chemical constituents, namely; pH, Cl_2, TDS, NO_3, EC (Electrical Conductivity), Sodium, Potassium, Calcium, Magnesium, Carbonate and Bicarbonate ions, Thorium, Fluorine. Out of these 13 chemical constituents monitored at 53 locations, data of pH, TDS, Cl_2, NO_3, Sodium, Potassium, Calcium, Magnesium, Carbonate and Bicarbonate ions for 30 locations are considered for analysis of spatial variation of concentration of different constituents in the study area. The location details of the groundwater quality monitoring sampling sites and concentration of the measured chemical constituents are given in Tables A12.3 and A12.4 in the Annexure.

The reason of selecting pH, TDS, Cl_2, NO_3, Sodium (Na^+), Potassium (K^+), Calcium (Ca^{++}), Magnesium (Mg^{++}), Carbonate (CO_3^-) and Bicarbonate (HCO_3^-) ions is; they represent dominant characteristics of water quality fate, viz., pH is one of the basic properties of water that indicates acid and alkaline characteristics of water, TDS gives concentration of total dissolved solids those include cations and anions, and is an indicator of taste of water; Cl_2 indicates salty taste, that is mostly associated with fresh/brackish water; NO_3 concentration is associated with the occurrence of sanitary/landfill/agricultural wastes; Na^+, K^+, Ca^{++}, Mg^{++}, CO_3^- and HCO_3^- ions are indicators to detect fitness of water for irrigation uses. Making use of SURFER software and employing kriging method, the thematic maps of the spatial variation of pH, Cl_2, TDS and NO_3 for pre and post monsoon within the study area have been prepared and are shown in **Figures 12.1-12.7.** The Sodium Adsorption Ratio (SAR) that gives the measure of the suitability of water for use in agricultural irrigation, has been estimated using the following formula (Richards, 1954):

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \qquad \text{...............................} \qquad (12.1)$$

in which all ionic concentrations are expressed in mill equivalent per litre.

A low SAR (2 to 10) indicates no danger from sodium; SAR between 7 and 18 indicates low to medium hazards, between 11 and 26 high hazards, and a $SAR > 26$ indicates very high hazards. The lower the Ca^{2+} and Mg^{2+} ionic strength of the solution, the greater is the sodium hazards for a given SAR (Richards, 1954). The water used for the irrigation purpose can have a SAR value maximum up to 26. The recommended classification with respect to electrical conductivity, sodium content, Sodium Absorption Ratio (SAR) and Residual Sodium Carbonate (RSC) is given in Table 12.1.

Table 12.1: Guidelines for evaluation of irrigation water quality

Water class	Na, %	EC, μS/cm	SAR	RSC, meq/l
Excellent	< 20	< 250	< 10	< 1.25
Good	20-40	250-750	10-18	1.25-2.0
Medium	40-60	750-2250	18-26	2.0-2.5
Bad	60-80	2250-4000	> 26	2.5-3.0
Very bad	> 80	> 4000	> 26	> 3.0

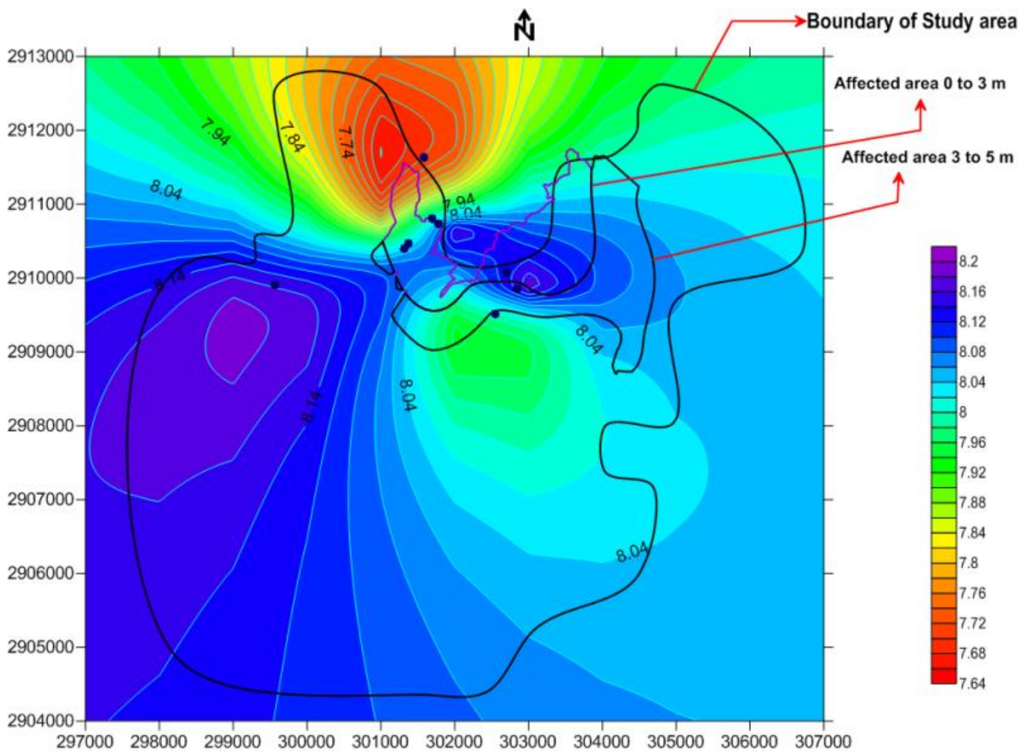

Figure 12.1: Spatial variation of pH of groundwater in the study area (• indicates location of sampling points).

It can be seen from Figure 12.1 that the pH values within the study area vary from 7.4 to 8.20, with slightly higher values in the waterlogged area. The pH values are within the permissible limit showing no sign of interference by other chemical constituents. There are three concentration peaks, two in the waterlogged area, and another in south-west. The contours around each peak show evidence of dispersion. Mechanical dispersions are caused by groundwater flow. The two peaks in water logged area indicate that the high concentration of pH is caused locally. The gradient directions of the contours and decreasing trend around the peak present in South West indicate that groundwater is not entering to the water logged area from the West or South-west.

There are two troughs one towards North and the other in South East. The contours around each trough show evidence of dispersion. From the gradient direction of the contours and decreasing trend to wards north corresponding to the trough in the North, it could be seen that no ground water flow is occurring from north to the waterlogged area.

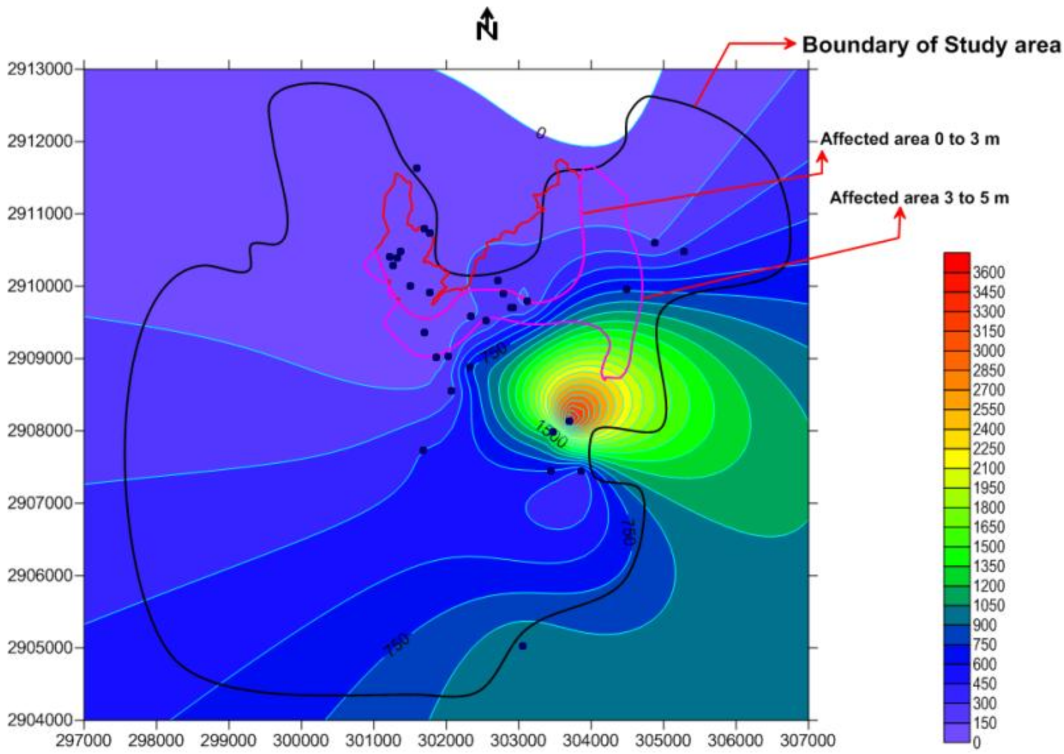

Figure 12.2: Spatial variation of Chloride (Cl_2) concentration during pre-monsoon season in the study area (• indicates location of sampling points).

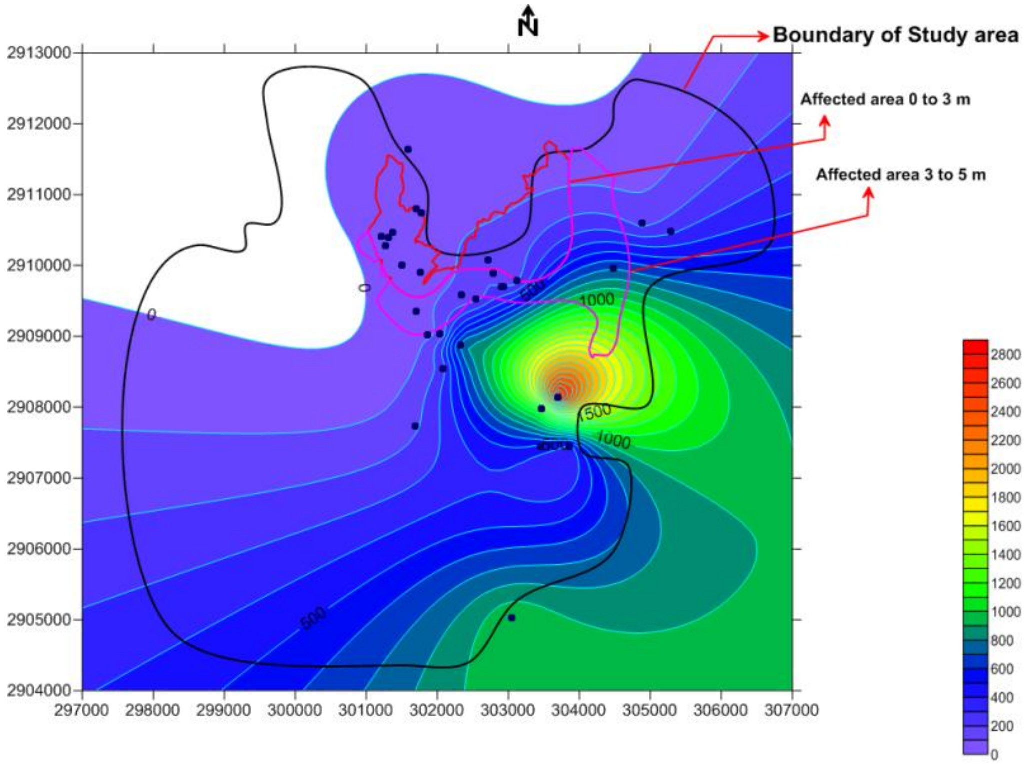

Figure 12.3: Spatial variation of Chloride (Cl_2) concentration during post-monsoon season in the study area (• indicates location of sampling points).

Figures 12.2 and 12.3, which show distribution of Cl_2 concentration in the study area during pre and post monsoon period, respectively, indicate the variation between 50 and 3550 mg/l, with higher values at a concentrated pocket down below the waterlogged area. Within the waterlogged area the concentrations of Cl_2 range between 100 mg/l and 1450 mg/l. The permissible limits range between 100 mg/l and 600 mg/l. The peak of highest chlorine concentration is out side water logged area. The reason of higher Cl_2 concentration at this particular location needs further verification. The Cl_2 concentration is low in the north-western part of the waterlogged area and increases further as one move towards the south-east direction. In general, the concentrations Cl_2 in the waterlogged area and within the study area do not indicate the source of water logging to be from the leakage of sewerage lines.

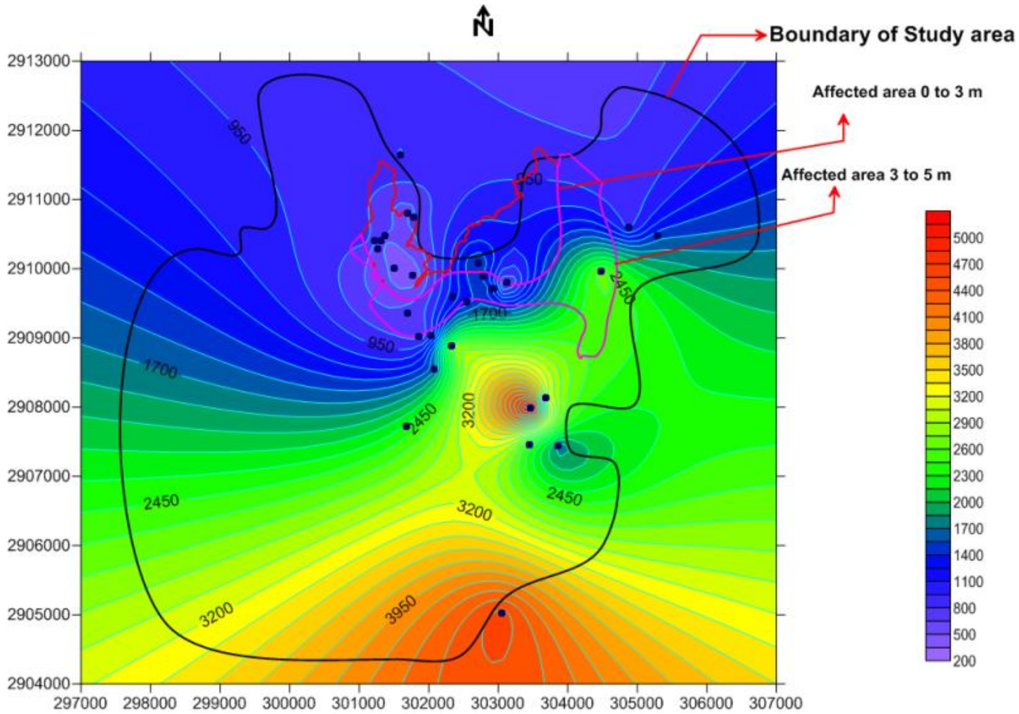

Figure 12.4: Spatial variation of TDS concentration during pre-monsoon season in the study area (• indicates location of sampling points).

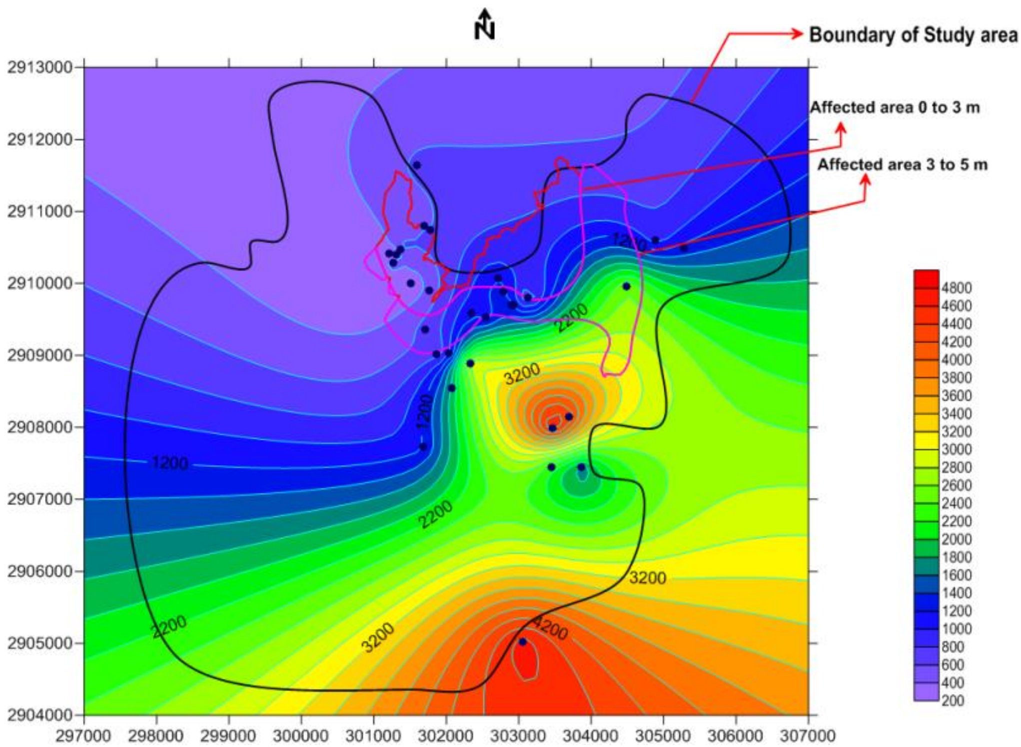

Figure 12.5: Spatial variation of TDS concentration during post-monsoon season in the study area (• indicates location of sampling points).

The spatial distribution of concentration of TDS for pre and post monsoon period has been shown in **Figures 12.4 and 12.5,** respectively. It can be seen from the figures that the TDS concentrations vary between 200 mg/l and 5000 mg/l within the study area with higher values mostly in the southern part and some concentrated zone having values range from 3000 mg/l to 5000 mg/l down below the waterlogged area. In the waterlogged area, the concentrations of TDS vary between 500 mg/l and 2300 mg/l, while the permissible limit of TDS is between 500 mg/l and 2100 mg/l. These indicate that the water being accumulated in the waterlogged areas are not influenced by leakages from the sewerage lines. The areas where the concentrations of TDS observed to be high may be due to the local intrinsic mineral composition in the aquifer.

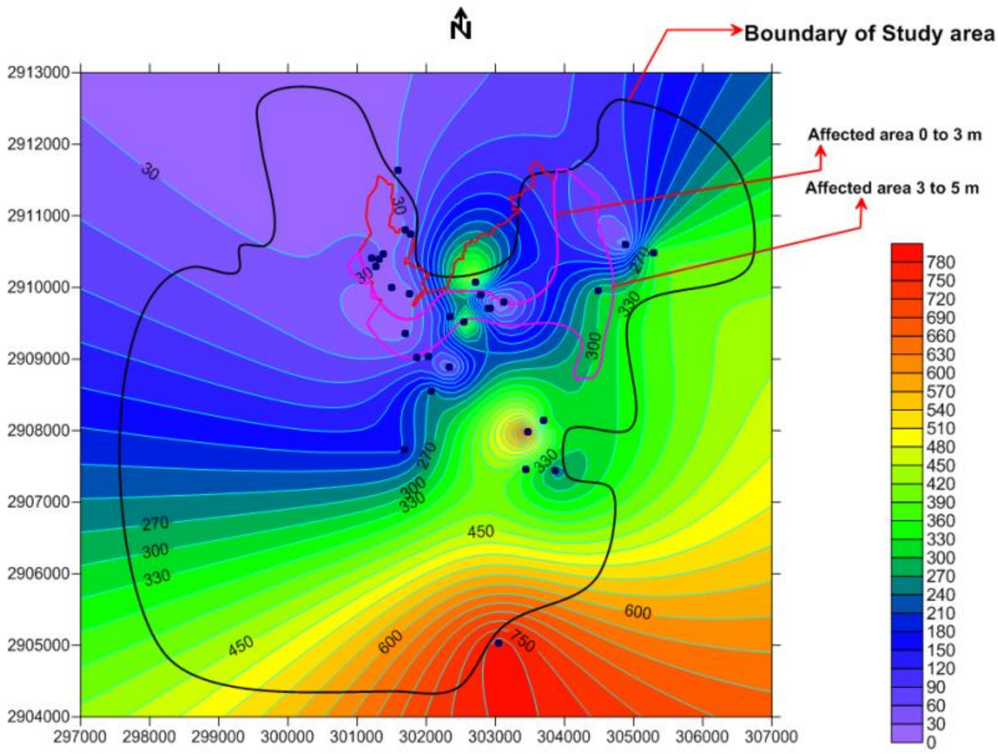

Figure 12.6: Spatial variation of NO_3 concentration during pre-monsoon season in the study area (• indicates location of sampling points).

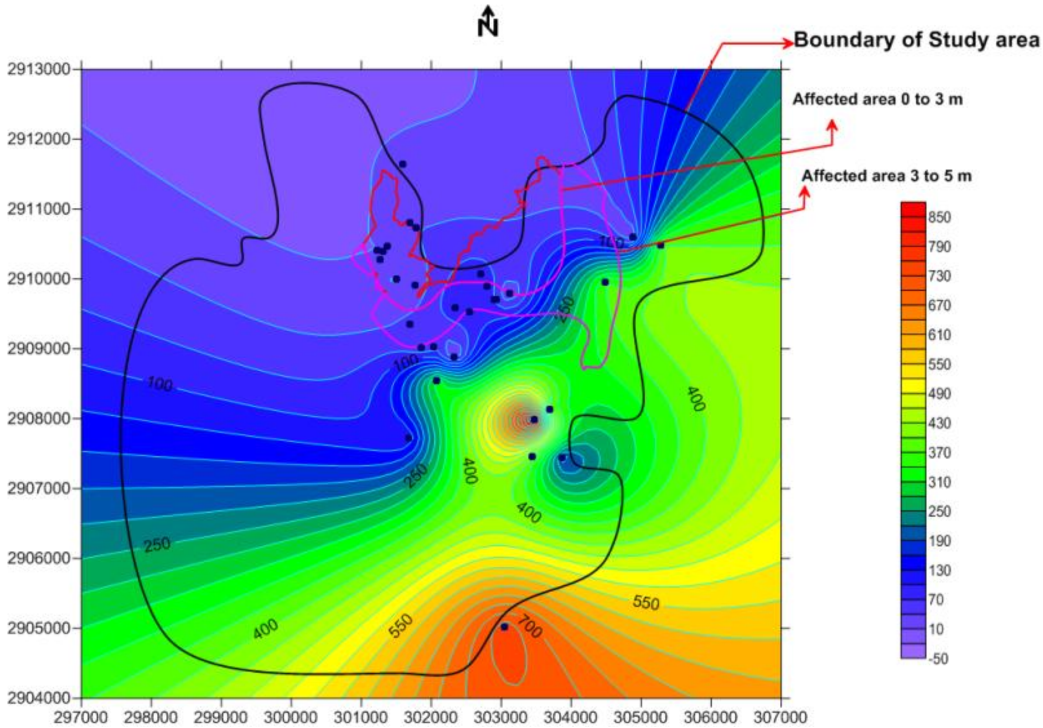

Figure 12.7: Spatial variation of NO_3 concentration during post-monsoon season in the study area (• indicates location of sampling points)

Figures 12.6 and 12.7 show the spatial variation of NO_3 concentration in the study area for the pre and post monsoon period, respectively. The variation of NO_3 concentration is observed to be between 10mg/l and 850mg/l; while the permissible limit ranges between 20 mg/l and 50 mg/l. The higher values are mainly observed in the southern part of the study area. In the waterlogged area, the values range from 50 mg/l to 350 mg/l. It indicates that the waterlogged area has some effects of NO_3 contamination. The possibilities of sewage leakage at different pockets can not be over ruled. The southernmost part of the study area has larger effect of NO_3 contamination. As stated earlier, the source of NO_3 is mainly from the septic tanks/sewage outflows or agricultural refusal. In the southern part of the study area where NO_3 concentration is more are mostly agricultural areas which are generally irrigated by city's sewage waters, mostly used for producing winter crops.

The spatial variation of SAR in groundwater of the study area is shown in **Figure 12.8.**

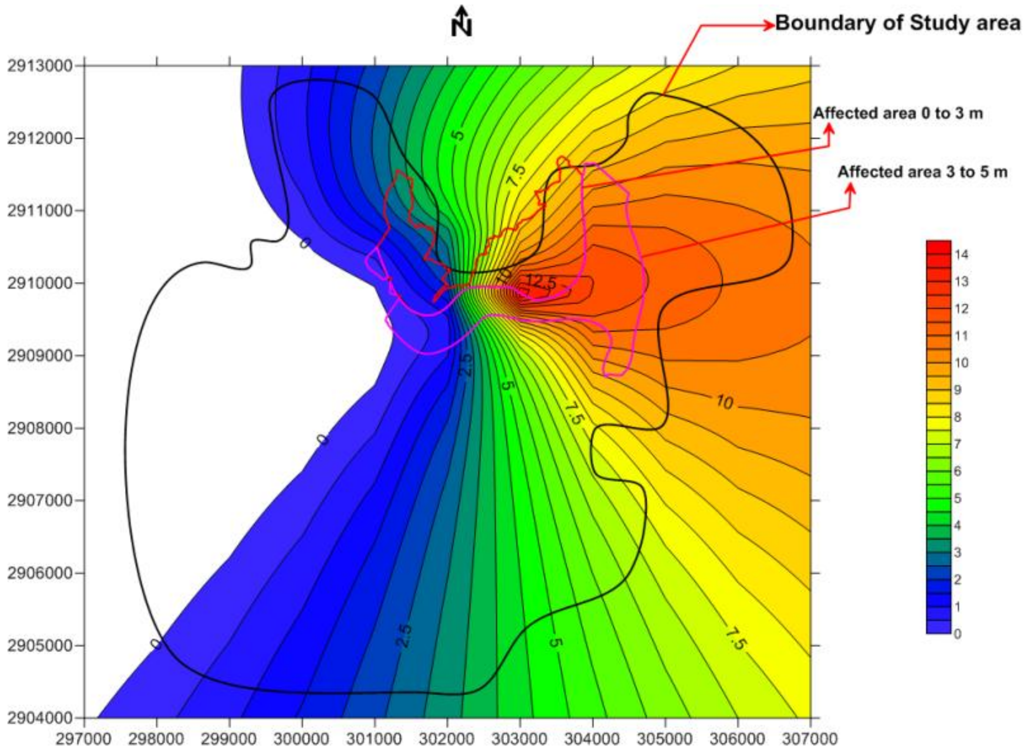

Figure 12.8: Spatial variation of SAR values in the study area.

The spatial variation of SAR in the study area calculated using eq.(12.1) based on the concentration of Na^{+}, Ca^{++}, and Mg^{++} is shown in **Figure 12.8.** It can be seen from the Fig. 12.8 that the SAR values vary between 0 and 14 within the study area. The value is higher in the eastern part of the waterlogged area and gradually decreases as one move towards the western direction. The water which can safely be used for the irrigation purpose can have the SAR value below 26. That means, the groundwater in the study area can safely be used for irrigation purposes without environmental hazards.

From the analysis following inferences are drawn:

(i) The pH values of the groundwater in the Jodhpur city area are within the prescribed permissible limit having slight leaning towards alkalinity, which may be because of excessive Chloride concentration. The Chlorine is used as a disinfectant chemical during treatment of water.

(ii) The gradient directions of the pH contours and decreasing trend around the peak present in South West indicate that groundwater is not entering to the water logged area from the West or South West.

(iii) Presence of excessive Chloride in groundwater of the Jodhpur city area indicates accumulation of relatively freshwater, which may enter into the groundwater domain through leakage from water supply lines or from the waters which are used for other than sanitary purposes.

(iv) The higher TDS values, which are mostly observed in the southern part far way from the problematic area, may be due to the local intrinsic mineral composition in the aquifer.

(v) The Nitrate concentrations in the study area have been found much higher than the permissible limit, mostly in the southern part, which are influenced by the agricultural activities using the city's sewages water. In the problematic area, in some pockets concentration of Nitrate is also observed to be beyond permissible limit. Therefore, leakage of sewerage lines or connectivity of the septic tanks outlets to the groundwater system in those pockets can not be ruled out.

(vi) The source of water logging and rise in groundwater level in some parts of the city area appears to be due to return flow of water other than the sewages.

(vii) The quality of groundwater in the city area indicates that the groundwater can safely be used for irrigation purposes.

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Section -13.0 : DISCRETIZATION OF THE STUDY AREA, AND INPUT DATA FOR GROUNDWATER MODELING

13.1 Discretization of the Study Area

The study area of about 76 sq. km. bounded between latitude of $26^0 15'$ N to 26^0 20' N and longitudes 73^0 $0'$ E to 73^0 $4'$ E 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. 13.1 and 13.2.**

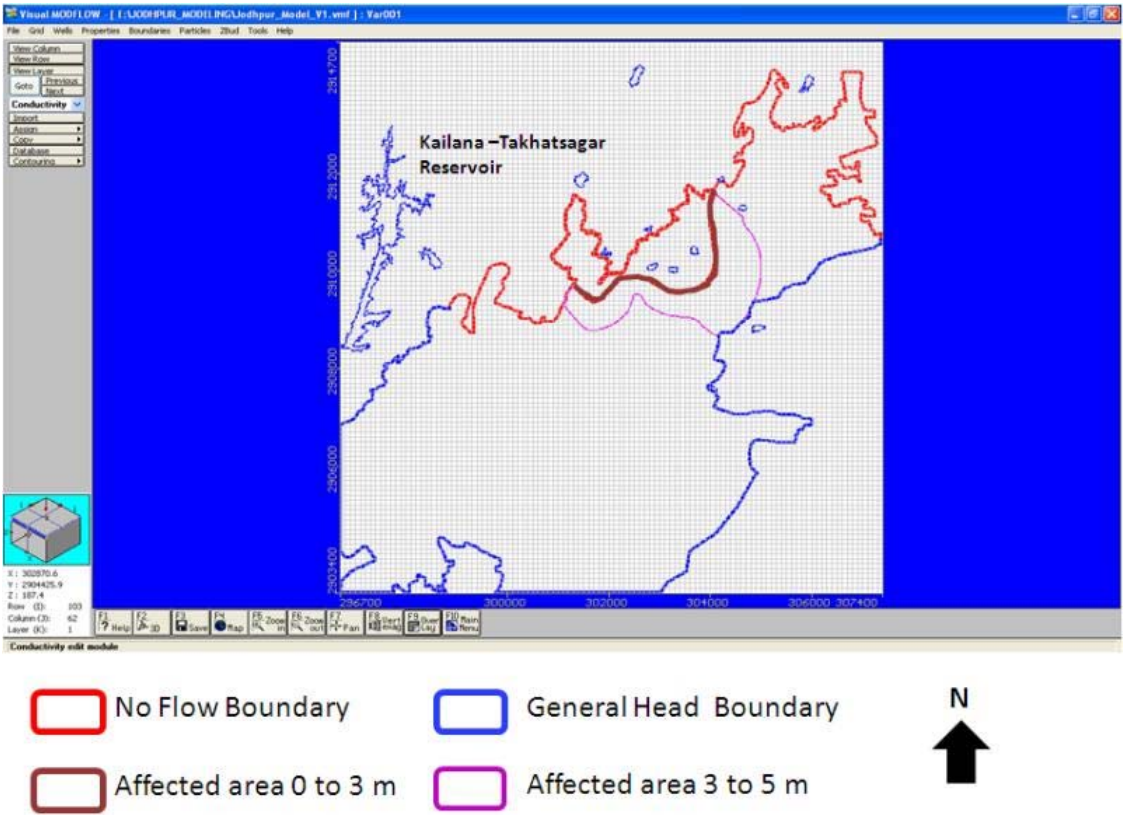

Figure 13.1: Discretized view of the study area including the water bodies and the affected area within the Jodhpur city (Number of grid along X direction = 107; Number of grid along Y direction = 113; size of each grid = 100 m x 100m).

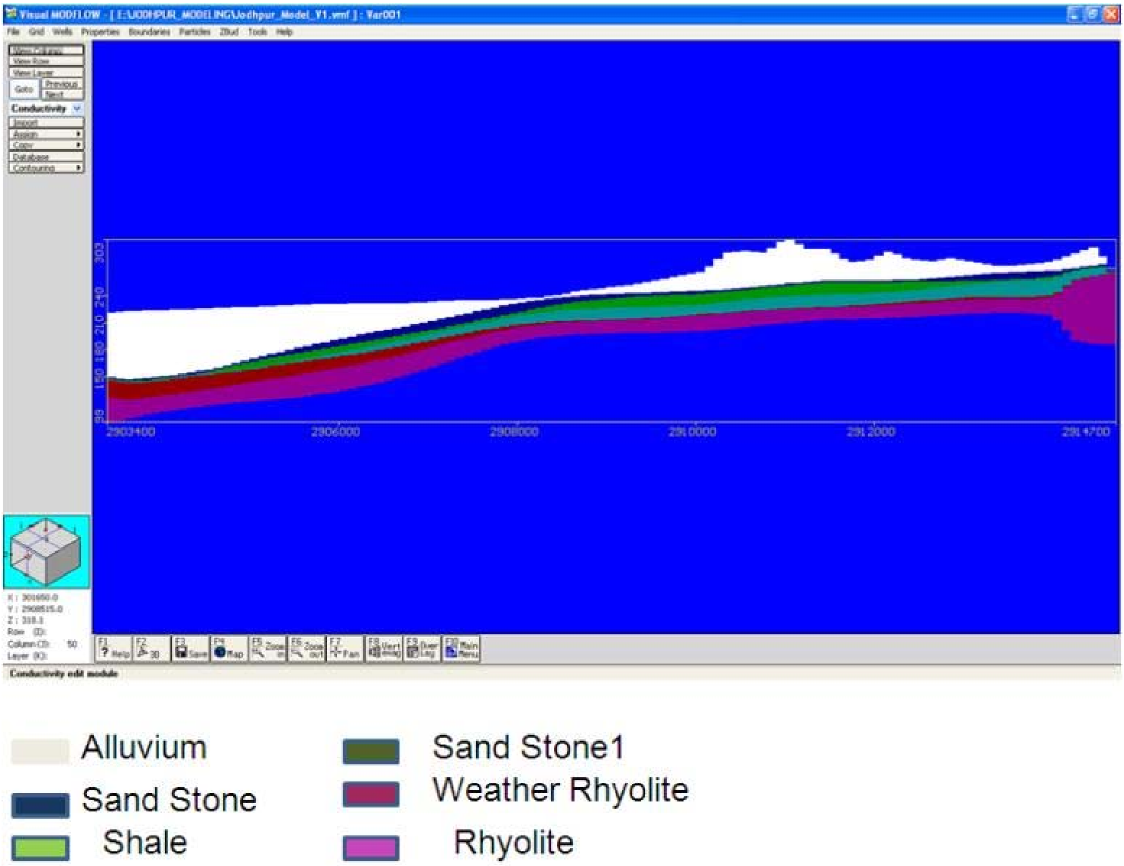

Figure 13.2: Vertical section of the study area indicating discretized view of the geological formations (Number of layers = 6 each of different thickness).

Within the discretized rectangular area (Fig. 13.1) that encompasses an area of 120.91 sq. km, the study area of 76 sq. km constitutes 7600 grids out of 12091 grids. The remaining 4491 grids constitute cells outside the ambit of the study area. For calculation purposes, the grids which fall outside the study area are considered to be inactive cells, and those come within the study area are considered to be active cells. The active cells mean they respond to perturbation, while the inactive cells do not respond to perturbation. The conceptualized domain of the study area is shown in **Fig. 13.3.**

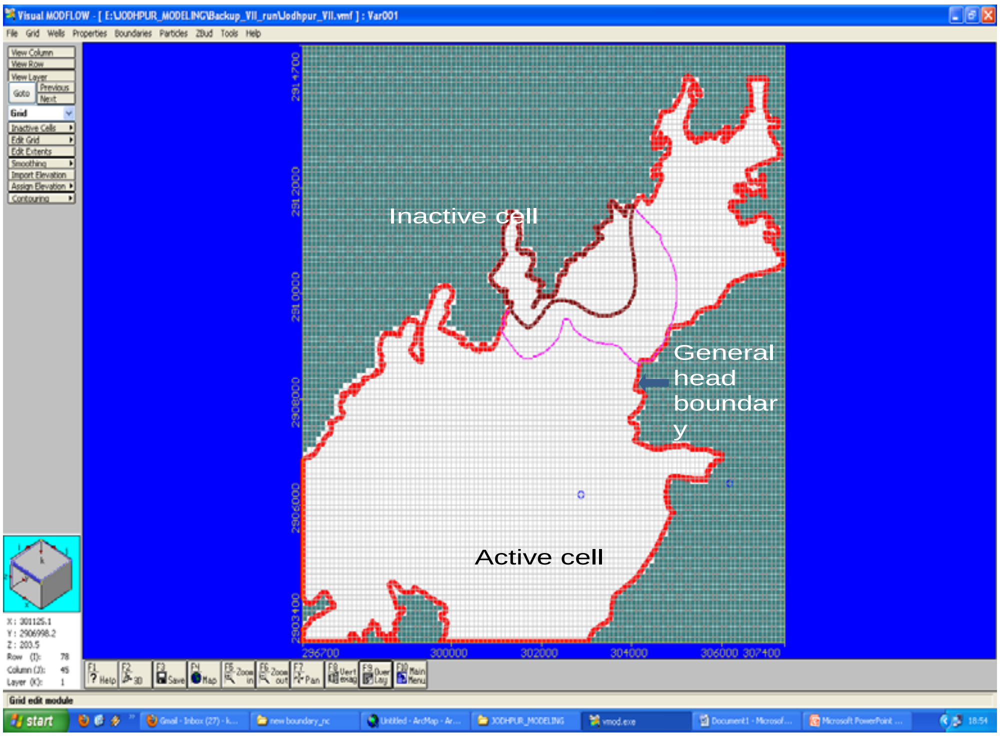

Figure 13.3 : Conceptualized setting of the modeling area showing position of the active and inactive cells.

13.2 Boundaries of the Study Area

The boundaries of the study area are shown in Fig. 13.3. Most of the northern part of the boundary constitutes hilly terrain and no flows are expected through this boundary, and hence the cells encompassing the hilly terrain are considered to be no flow boundary. The southern part of the study area has the general groundwater flow direction, and hence considered as the General Head Boundary (GHB). The western part, which is directed towards Kailala-Takhatsagar Reservoir, is partly considered as GHB and partly no flow boundary depending upon the geological formations. The eastern part of the study is considered as the GHB.

Vertically along Z-direction, the thickness of the alluvium formation varies from location to location from few centimeters to a maximum of 78.6 m below ground surface. The elevation difference of the surface topography is about 86.7 m between the maximum (269.3m) and the minimum (182.6 m) elevation in the study area. To account for the total alluvium formation in the study area, the vertical depth of 78.6 m below the ground surface has been divided into 6 layers of different thickness.

13.3 Water Bodies in the Study Area

In addition to the Kailana-Takhatsagar Reservoir from where the city's water supply is met, there are 19 small water bodies located within and in the fringe area of the city. The list of the water bodies identified with their locations and surface areas is given in **Figure 13.4** and in **Table-A13.1** in the annexure**.** These water bodies are mostly fed by monsoon runoffs. Few water bodies also receive sewerage water from the surrounding areas. The city is devoid of any natural perennial stream.

These water bodies may act repositories of groundwater recharge through seepage. The water bodies located within the study area are also considered for simulation of the groundwater levels.

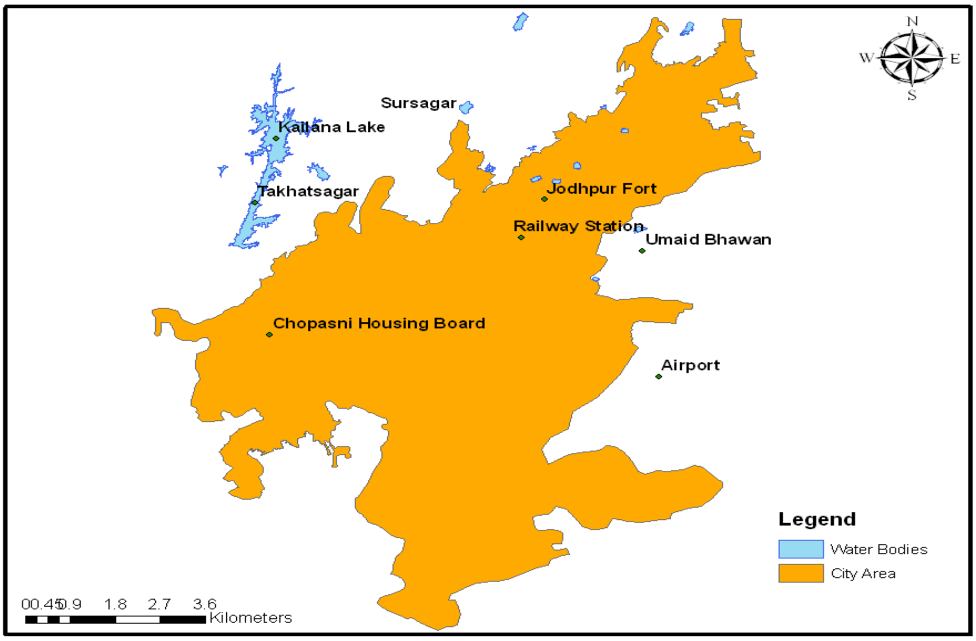

Figure 13.4 : Locations of water bodies in and around the Jodhpur city area.

13.4 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.

13.5 Aquifer Properties and Parameters

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 13.1:

Table 13.1: 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 spatial variation of the Transmissivity and Storativity values estimated for the alluvium formations from the pumping tests data (given in Section 11), which are considered as the initial guess values for each grid are shown in Figures 13.5 and 13.6, respectively.

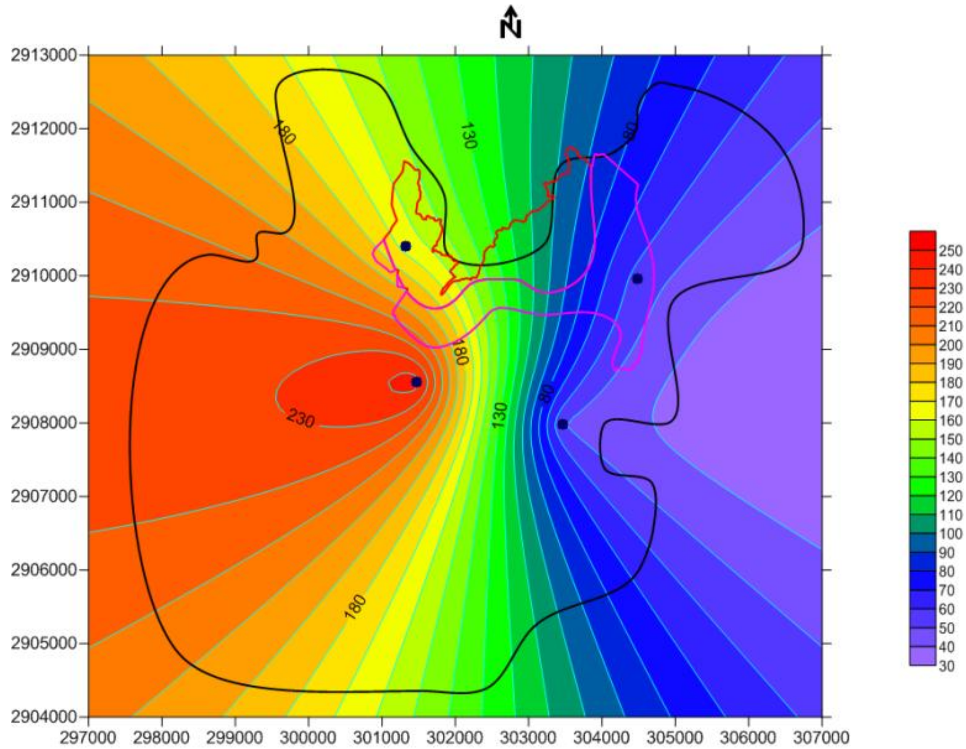

Figure 13.5: Spatial distribution of Transmissivity values (m^2/day) of the Alluvium formation in the study area; considered as the initial guess values for each grid.

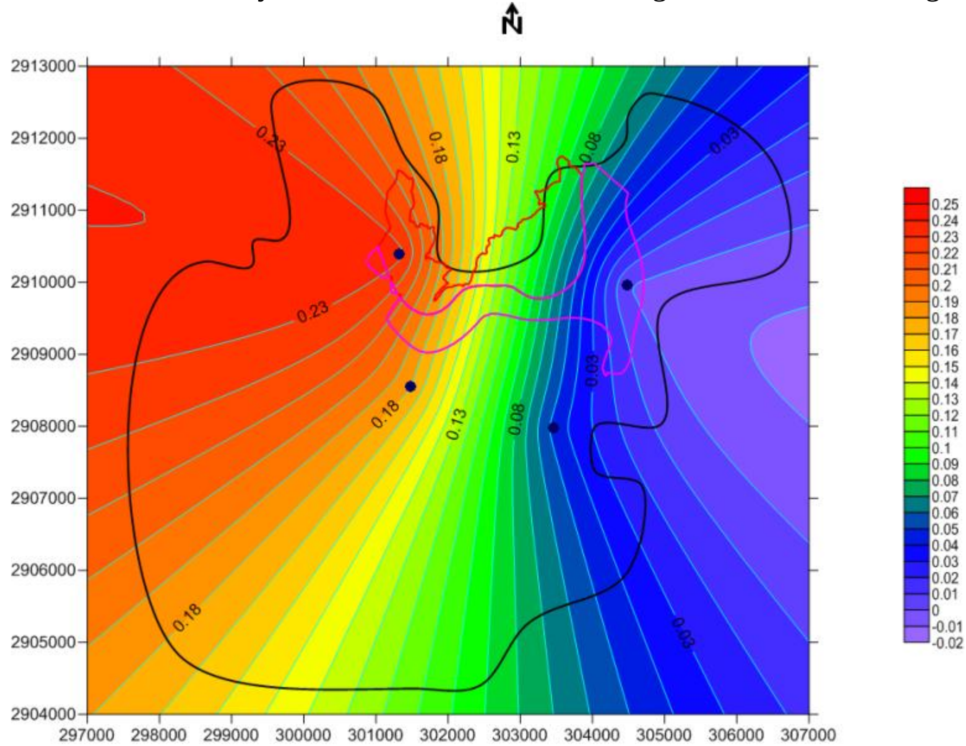

Figure 13.6: Spatial distribution of Storativity values (dimensionless) of the Alluvium formation in the study area; considered as the initial guess values for each grid.

13.6 Inflow and Outflow 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. 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 13.7.**

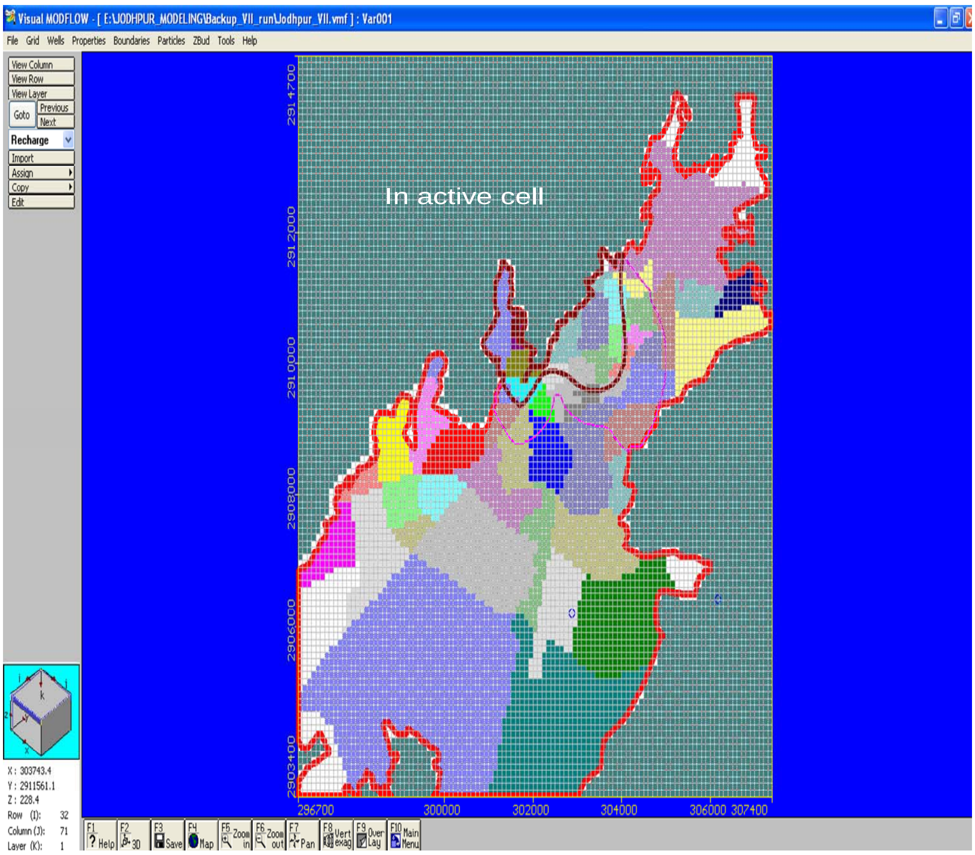

Figure 13.7: A scheme of the input stresses assigned zone wise to the modelling area.

13.7 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. That means within a period between pre to post monsoon, the stresses are considered constant.

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 .

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Section-14.0: MODELLING SCENARIOS FOR DIFFERENT REMEDIAL OPTIONS

The inputs data required for developing the simulation model have been explained in the Section 13.0. To develop the simulation model, one has to first calibrate the model parameters from the comparison of the computed and the corresponding observed groundwater table contour profiles. The calibrated parameters have thereafter to be validated with another set of computed and observed groundwater table contour profiles. If the responses of the parameters are found to be comparable with the profiles which are considered for the validation, the model parameters and the setting of the model are said to be calibrated. The calibration a model is thus a trial and error approach.

Making use of the inputs stresses and boundary conditions as explained in the Section 13.0, the model has been calibrated for steady state scenario employing the pre-monsoon groundwater profile of the year 2004. For developing the model, the software Visual Modflow 9.1 has been utilized. The model parameters were calibrated by comparing the computed and the observed water table. In absence of any physical boundary like a river or large surface water body, use has been made of the general head boundary to simulate the flux into/out of the system. Figure 14.1 shows the comparison between the pre-monsoon computed water table and the observed water table for the year 2004.

Taking the steady state scenario as the initial condition for the transient simulation, the water table elevations are computed for post-monsoon 2004. The total simulation period is taken as 180 days. During this period, the return flow from the wastewater and rainfall recharge are also taken into account. The simulated profile is shown in Fig. 14.2 along with the observed water table for the post monsoon of the year 2004.

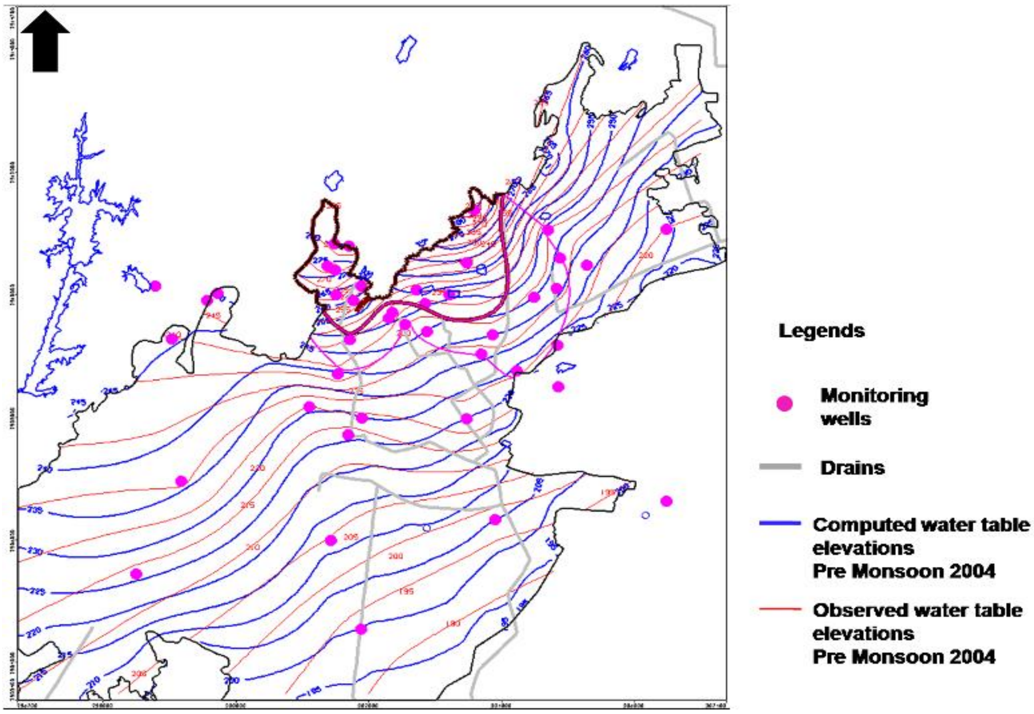

Figure 14.1 : Comparison of the steady-state simulated and observed groundwater table for the pre-monsoon period of the year 2004.

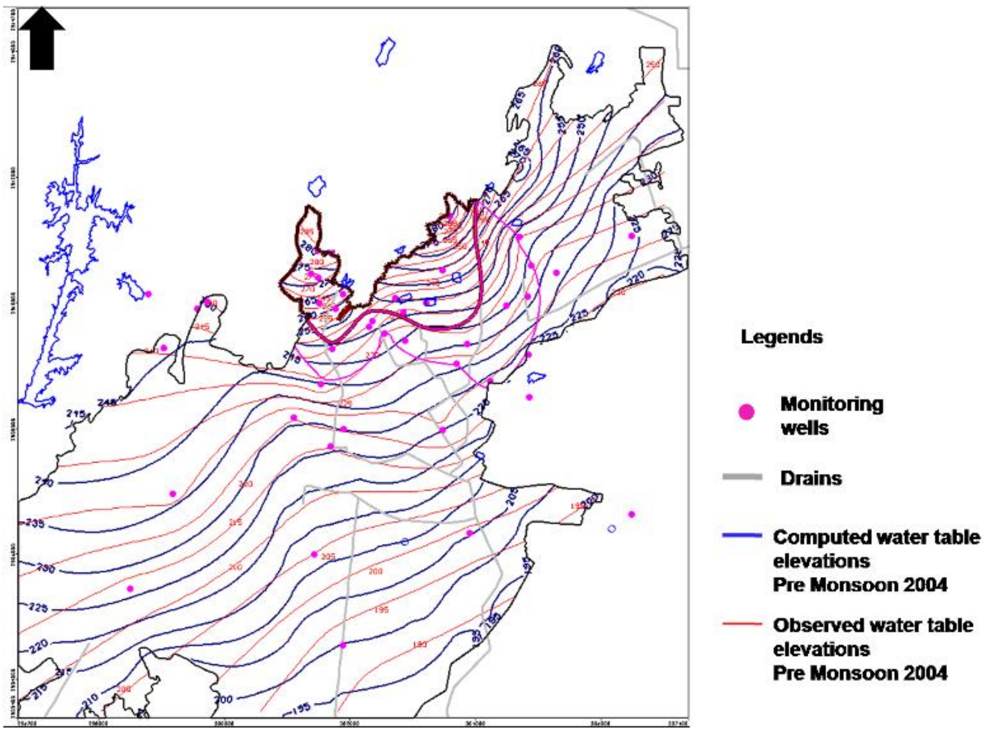

Figure 14.2 : Comparison of the steady-state simulated and observed groundwater table for the post-monsoon period of the year 2004.

From Figures 14.1 and 14.2 it can be seen that the observed and the computed groundwater table profiles match reasonably. The hydraulic properties namely: hydraulic conductivity and storativity corresponding to these scenarios are taken as the calibrated parameters of the aquifer. The calibrated parameters are shown in Figs. 14.3 and 14.4. Making use of these calibrated parameters, the responses of the aquifer for any given stresses can be calculated, and different scenarios can be obtained.

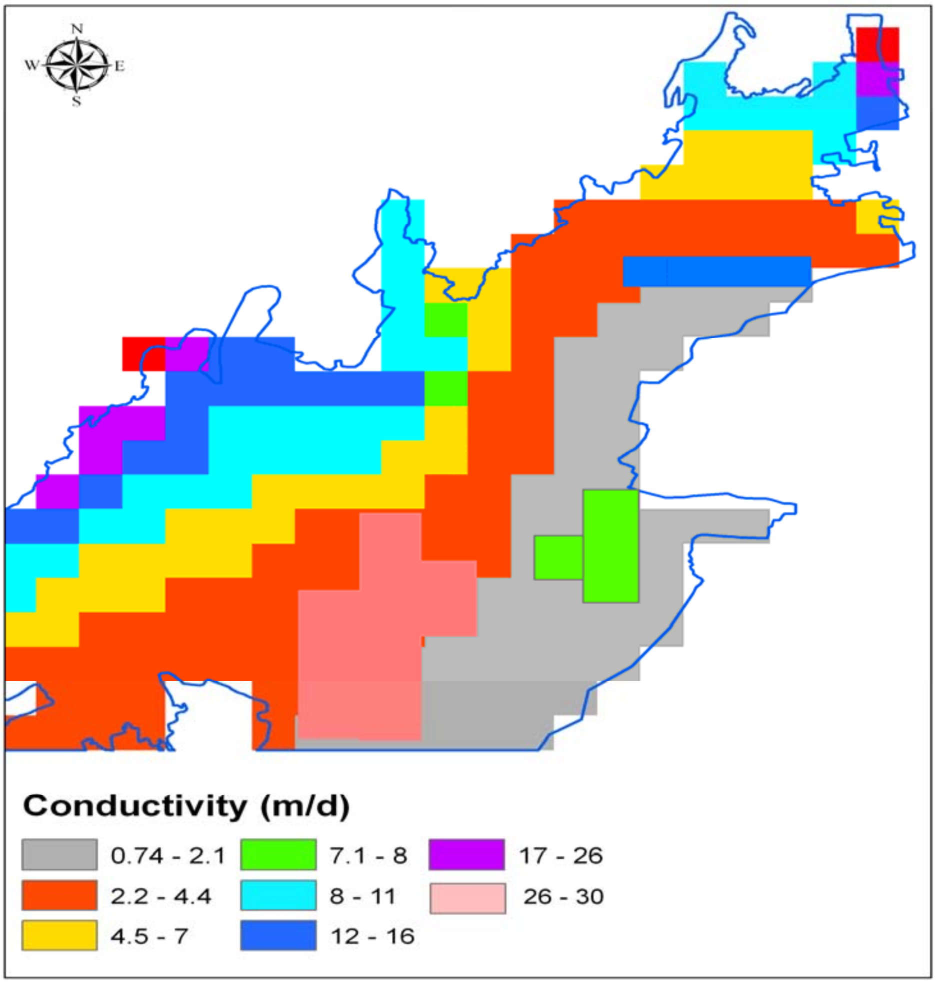

Figure 14.3 : Calibrated hydraulic conductivity (m/day) zones of the Aquifer below Jodhpur city area

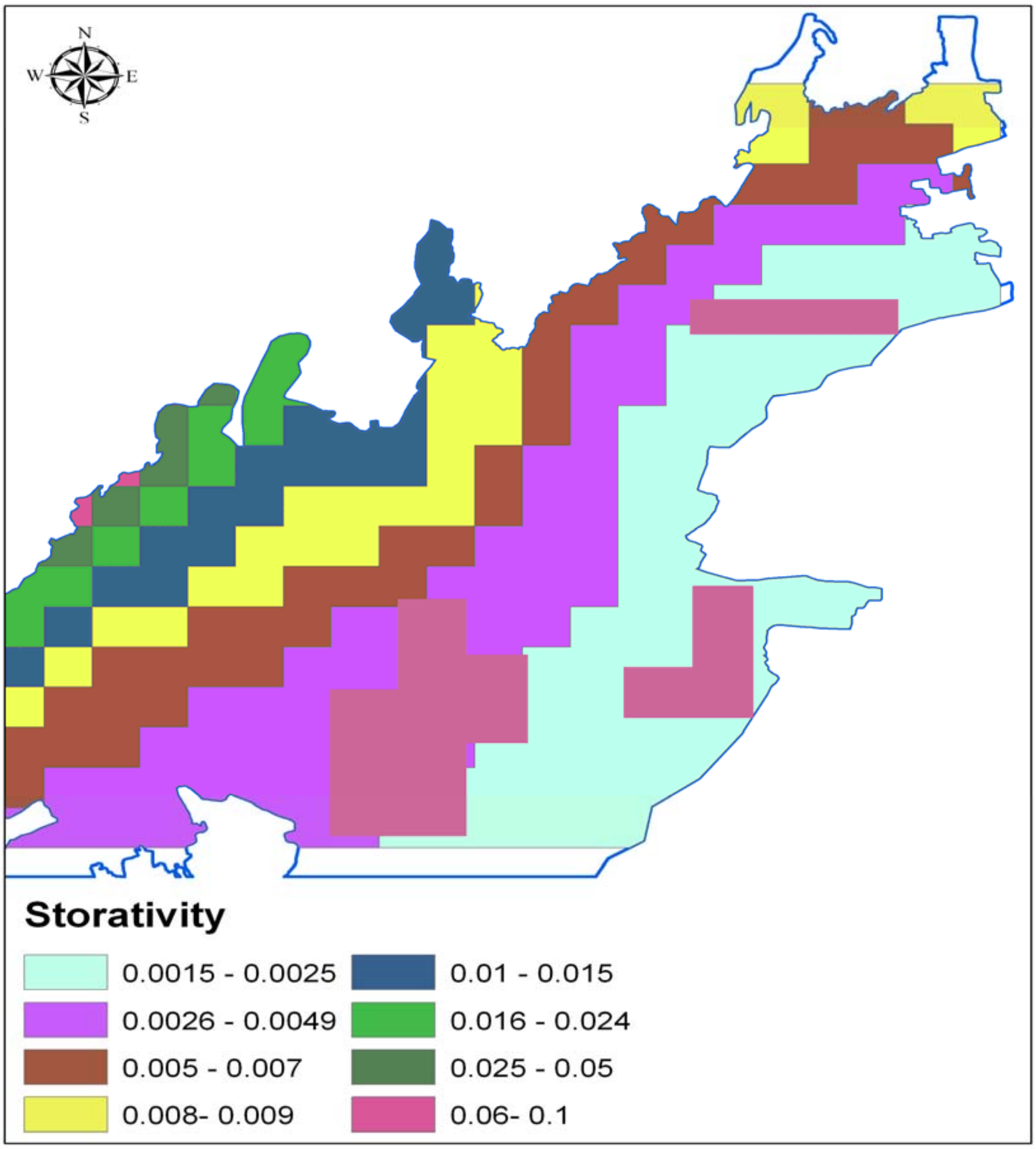

Figure 14.3 : Calibrated storativity (dimensionless) zones of the Aquifer below Jodhpur city area .

Section- 15.0: MANAGEMENT PLAN AND OPTIONS

For evolving the management plan to contain the rise in groundwater table, the following options are attempted:

(i) Envisaging the scope of putting horizontal sub-surface drainage system to drain out the water from the problematic area.

(ii) Envisaging the scope of putting network of vertical pumping wells to pump out the water from the problematic area.

(iii) Combination of horizontal sub-surface drainage system and pumping wells.

Option-1: Horizontal Sub-surface Drainage System

The topography of the city area in the problematic and adjoining part is of undulating type. The thickness of the alluvium formation varies from about 2.0 m to 13.0 m in this region. In general, considering the possibility of capillary rise in alluvium formation, groundwater table should be at least 0.5m below the foundation level. In areas where building basement floors are located, assuming that basement depth is 3.5m, and capillary rise is 0.5m, the groundwater table should be at 4.0 m below the ground surface. The groundwater level in the affected area thus has to be lowered down to a depth of 4.0 m from the ground surface elevations. Nevertheless, the problematic area is densely populated with concentrated residential and commercial buildings, and practically has very thin scope to construct horizontal sub-surface drainage system at a depth of 4.0m below the ground surface. Moreover, laying of horizontal subsurface drains will be very difficult as the required excavation will interfere with the already existing building foundation structures. All these aspects do not promote provision of a usual horizontal sub surface drainage system in the problematic area. Therefore, this option is not appeared to be a logical proposition.

Option-2: Network of Vertical Pumping Wells

Constructing vertical pumping wells is not that complicated as compared to the construction of horizontal sub-surface drainage in urban area. It requires minimum land space. Technological advancement has made construction of bore wells easier. The yields of a pumping well depend on the hydraulic properties of the aquifer and the location of the screen depth. Higher the values of hydraulic properties of the aquifer and larger the screen depth, more will be the yield of a well for a given drawdown. The disadvantages with the pumping well are: it would require continuous energy supply to run the well, and would cause noise pollution in the nearby area, and would also require provision of surface drainage system to dispose the pumped water from the problematic area.

The problematic area being located in the densely populated and congested area, provision of network of vertical pumping wells looks to be a logical proposition and can be constructed with least interference to the area. Already, a number of vertical pumping wells are in operation in the problematic area.

It is intended here to assess the number of pumping wells required to lower the water table to the required depth and to maintain its position at the desired level. It is also intended to examine how to dispose the pumped water more effectively.

The aim is to lower the groundwater table up to 4.0 m below the ground surface. The volume of water existing up to a depth of 4.0 m below ground surface in the saturated zone is assessed using the following equation:

$$V_s = A_i * H_i * S_y \qquad \text{……………………………………………..} (15.1)$$

in which, V_s is the volume of groundwater existing up to a depth of 4.0 m below ground surface in the saturated zone (m^3); A_i is the surface area of the zone for which estimation is being made (m^2); H_i is the height of saturated water column within the depth of 4.0 m from ground surface(m); S_y is the specific yield (dimensionless), and the suffix, *i* indicates zone number.

In case of an unconfined aquifer, the storage coefficient is equal to the specific yield. From pumping test, the average specific yield has been estimated to be 0.01. Using the groundwater contours map for the year 2007 and 2008, the volume of water existing up to a depth of 4.0 m below ground surface has been calculated employing equation (15.1). Within an estimated problematic area, A_i, of 2440000 sq. m, the volume of the accumulated groundwater is estimated to be 201136 m^3. The probable estimate of wastewater joining the aquifer during pre to post monsoon period is 7001 m^3. Intending to pump out these accumulated storages of 208137 m^3 within a period of six months, the number of pumping wells with a discharge of 96 m^3/day (aquifer thickness being within the range of 2 m to 13 m) for continuous 8 hours running is found to be 12. Smaller the pumping rate more is the number of wells. Already some pumping wells are present in the problematic area in which water table is within 3 m below the ground surface and within 3 and 5 m below ground surface These wells are running successfully. The required 12 numbers of wells should be constructed along two contour lines which are separated by approximately 700 m. Along one contour line six number of wells should be constructed. The wells on the two contour lines should be staggered. All the wells should be provided with screen which should be opened to the entire thickness of the aquifer at the site.

The city's surface water drainage systems are meant to dispose the sewages flow. The quality of accumulated groundwater is safe to use for irrigation purposes. If the pumped waters are discharged to the existing nearby surface water drains to avoid additional drain/conveyance system, the good quality pumped water can not be used for irrigation purpose. Since, in an arid zone, water is very precious, it is worth to construct separate drainage system to take away the pumping water to the nearby irrigation fields instead of mixing it with the sewages water. On reconnaissance survey, it is found that three large ponds, namely; Baiji Ka Talab, Fateh Sagar, and Gulab Sagar, which have considerable storage capacities, are located in the problematic area. The location details, top and bottom elevation, and the groundwater table contour elevation in the nearby area of these ponds are given in Table 15.1.

Table 15.1: Details of the ponds located within the problematic area.

Name of Talab	Longitude	Latitude	Surface Elevation (m)	Bottom Elevation (m)	Near by elevation of water table(m)	
					Max	Min
Baiji Ka Talab	73.03361	26.300136	250	242.5	256	245
Fateh Sagar	73.02949	26.296538	240	208	245	240
Gulab Sagar	73.02539	26.297016	249	219	250	240

The location of the ponds in the problematic area, groundwater table contour map, and the alignment of the major sewerage systems in the Jodhpur city area are shown in Figure 15.1.

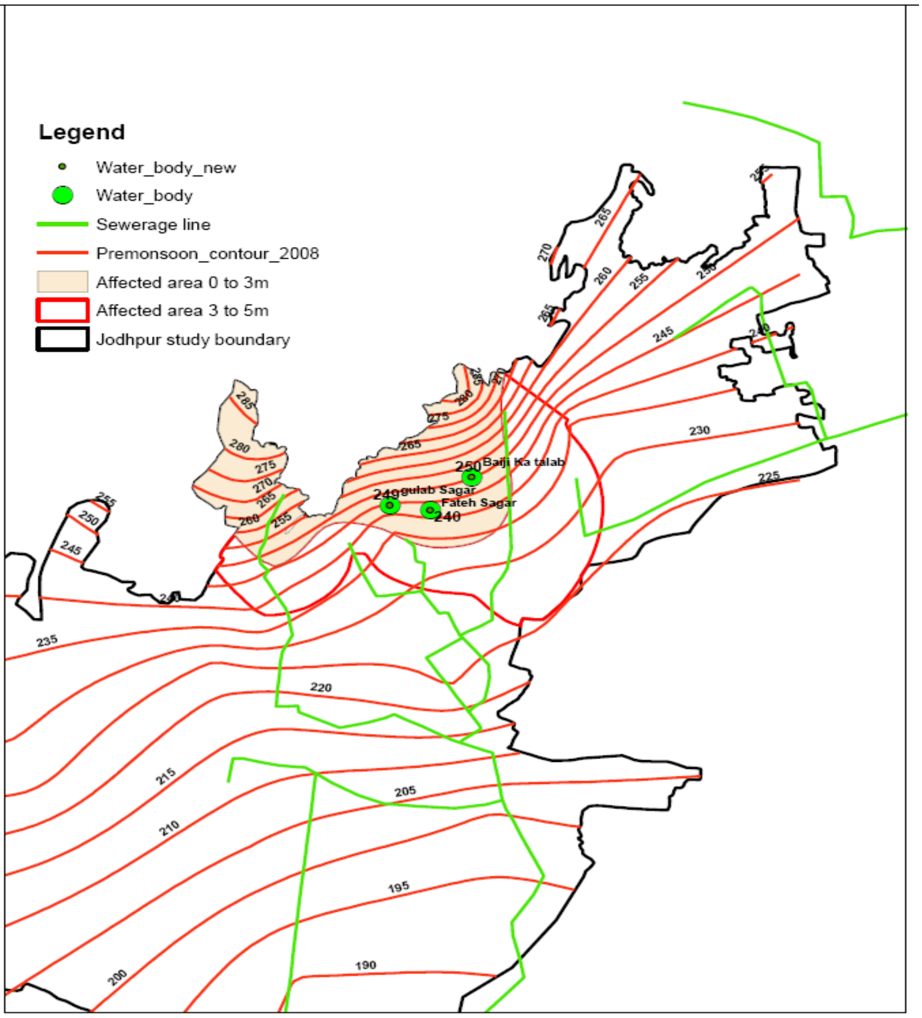

Figure 15.1 : Location of ponds in the problematic area, and the alignment of sewerage system in the Jodhpur city area.

The ponds' beds are more or less impervious, or if necessary, these can be made impervious by lining. The pumped water can be discharged to these ponds through conveyance pipe. From these ponds, surface channel can be constructed to convey the water stored in the pond to the surface drainage system through gravity.

Option-3: Combination of horizontal sub-surface drainage and pumping wells

As mentioned in the Option-1, construction of horizontal sub-surface drainage system exclusively is not a feasible solution owing to the geological formations, constructional difficulties and space problem. However, random sub surface drainage trench of 4m depth, filled with coarse sand and gravel can be constructed to control the rising water. The water coming to the trenches can be led to a collector caisson, from where water can be pumped out. Construction of such trenches to control water table rise would depend upon the local terrain and building locations. In places, where construction of subsurface drainage is not feasible, vertical pumping well(s) can suitably be adopted.

The similar approach of discharging the pumped water to the ponds located in the problematic area through conveyance pipe can suitably be implemented. From these ponds, surface channel can be constructed to convey the water stored in the pond to the surface drainage system through gravity.

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Section – 16.0: SUMMARY AND CONCLUSIONS

16.1 Summary

In order to identify the source of water, that has caused water logging, and to suggest appropriate remedial measures to control the rising trend of ground water levels in Jodhpur city, detailed analyses of the data 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 including the Kailana-Takhatsagar Reservoir have been carried out. These data have been supplied mostly by the Ground Water Department (GWD) and the Public Health Engineering Department (PHED) of Jodhpur, Government of Rajasthan; some data, which were not made available but were required for the study, have been collected from the field investigations/surveys and from other sources during course of the study.

In order 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 field ground truth.

The study area is comprised of 76 sq. km., and encompasses the old and the sprawled Jodhpur city area including the waterlogged area. The Kailana-Takhatsagar Reservoir is located outside the boundary of the study area as the study area and the reservoir are located in different geological entities. The topography of the Jodhpur city area has been analyzed making use of surveyed data supplied by the GWD, Jodhpur in conjunction with the ASTER data. The geological formations of the Jodhpur city area have been analyzed making use of the borelogs data at 93 locations supplied by the GWD, Jodhpur using ‘ROCKWORKS’ software.

The demographic data of the city area have been analyzed based on the population census of the decades from the year 1971 to 2001. The water supply requirements and the water actually supplied to the Jodhpur city area have been assessed for different years and compared with the norms prescribed by the MoWH (Ministry of Welfare and Housing, Govt. of India).

The existing arrangement of the water supply to the city area, which is based on feeding the Kailana-Takhatsagar Reservoir from the IGNP linked Rajiv Gandhi Lift canal and transferring the water from the Kailana-Takhatsagar Reservoir largely by pumping and partially by gravity flow for treatment of water and then supplying to the city, has been analyzed in details.

The Stage-Area-Capacity curves for the Kailana Lake, Takhatsagar and Umaid Sagar Reservoirs have been developed. The water balance of the Kailana Lake and Takhatsagar Reservoir involving the associated hydrological components has been carried out exclusively for two situations: (i) in the first situation, it has been assumed that the lake has a permeable bed through which water is seeping to the underneath formation in which water table lies at a large depth, (ii) in the other situation, the lake bed is impermeable, therefore, the seepage is negligible.

The groundwater levels data supplied by the GWD, Jodhpur for the years 1996-2009 have been analyzed considering two situations; (i) the Kailana-Takhatsagar Reservoir is assumed to be hydraulically connected to the aquifer below the Jodhpur city, and (ii) the Kailana-Takhatsagar is not hydraulically connected to the aquifer below the Jodhpur city. The increase in waterlogged areas in different years has been ascertained.

The sewages generated from the refusal of water usages, and the drainage data of the city area have been analyzed in details. In order to assess the quantity of sewages flown out daily from the city area through the existing sewerage channels, field investigations and measurements have been carried out in the three major sewerages drains. Measurements of sewages' flows from morning 6:00 A.M to evening 11:00 P.M. for a continuous 7 days in all the three drains have been made during the months of April-July, 2010.

A lumped water balance of the study area has been carried out for different years making use of the associated hydrological components in order to asses the probable fraction of the surface water supplied to the city getting recharged to the aquifer below the Jodhpur city.

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 advanced algorithms.

The groundwater quality scenarios in the study area for the year 2009 have been analyzed based on the data supplied by the PHED, Jodhpur. The spatial variations of the parameters pH, Cl_2, TDS, NO_3 and SAR have been analyzed and their possible reasons of occurrence and fate in the study area have been analyzed in details.

Making use of the estimated hydrological and hydro-geological components and their variability in the Visual MODFLOW software, a groundwater flow model for the study area after proper calibration and validation has been developed. The developed model has been extended to evolve management plan and to suggest remedial measures to the water logging problem of the Jodhpur city.

16.2 Conclusions

Based on the analyses of data and detailed results reported in different chapters, the following conclusions are drawn:

(i) The waterlogged area and it's extent are mainly located in the Quaternary alluvium formation below the Jodhpur city area.

(ii) The Kailana-Takhatsagar Reservoir forms one continuous depression storage reservoir. The reservoir is located in a single geological unit, which is separated by a divider of two distinct watersheds at a distance of about 5 km from the city area.

(iii) Largely, the topographic slope of the Jodhpur city area is towards south-west, south, and south-east directions, except in the hilly terrain in the North-Western side. The southern terrain has flatter slope than the South-West and South-East terrains. The topographic level within the city area varies between 202 m and 360 m above msl with a small stretch near to the fort area, which has higher elevation. Much of the city area has mostly a flat terrain having elevation below 250 m, above msl.

(iv) The Kailana-Takhatsagar and the Jodhpur city areas are located on two distinct geological units. The Kailana-Takhatsagar area is located on Rhyolite formation, whereas, Jodhpur city area is mainly located on the Quaternary alluvium, Sandstone and Shale formation. These formations have different hydro-geological properties and hence, cannot be considered as a single system.

(v) The geological formations of the Jodhpur city area indicated presence of an unconfined aquifer comprised of Quaternary alluvium formation having thickness varying from few centimeters around NW and NE direction, to a large depth ranging from 6 to 75 m in the SW to SE direction. The unconfined aquifer is underlain by Shale, Sandstone and Rhyolite formation of different thickness varying from location to location. As such, there is no existence of any deeper aquifer below the Jodhpur city area up to a depth of 75 m, below the ground surface.

(vi) Thirty six years (1971-2006) daily rainfall data of the Jodhpur city showed the average annual rainfall of 378 mm.

(vii) The Jodhpur city that had a population of about 3,65,000 in the year 1971, was expected to have a population of the order of 11,00,000 by the year 2010. The population censuses of previous four decades (1971-2001) indicated a growth rate of 3.21% per year.

(viii) The water supply requirements to the population in the city area are primarily met by the Jodhpur Municipality through water supply & distribution systems managed by the Public Health Engineering Department (PHED), Jodhpur. As such, no prescribed guidelines towards quantity of water per capita per day to be supplied are followed; it is based on thumb rule in accordance to the supply-demand norm.

(ix) 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% on higher side than the quantity of 140 lcpd prescribed by the MoWH .

(x) For both pre and post monsoon seasons, the directions of groundwater flow are broadly observed from the north to the south and southeasterly direction with some deviations at local pockets.

(xi) In the waterlogged area, the water table contours are closely spaced. In the southern region, the spacing between two consecutive contours is comparatively wider. The region in which the contours are closely spaced is a region of low transmissivity. The region in which the contours are widely spaced is a region of comparatively higher transmissivity indicating larger thickness of the Quaternary alluvium formation. The waterlogged area is located in the geological unit having low transmissivity where the contours are closely spaced. In the waterlogged area, the water table contours have higher values than those in the southern side. Since water has flown from the waterlogged region and the North side is a hilly region and no water has come to the waterlogged region from the north side, the source of water causing water logging is thus appeared to be generated locally which is likely to be the return flow from the water supply including sewages.

(xii) The possibility of seepage from the Kailana-Takhatsagar Reservoir entering the waterlogged area investigated making use of the contour maps assuming that the Kailana-Takhatsagar Reservoir is not hydraulically connected with the aquifer underneath the Jodhpur city, and the Kailana-Takhatsagar Reservoir is hydraulically connected with the aquifer underneath the Jodhpur city. For the former case, it is noted that the waterlogged area does not receive any flow from the southwest side i.e., from the reservoir side. So it is inferred that groundwater flow from the Kailana-Takhatsagar side is not causing water logging in the waterlogged area. For the later case, it is noted that the direction of flow lines is not towards the waterlogged area. The direction of flow in all the cases is broadly towards south-east direction. The seepage from the Kailana-Takhatsagar Reservoir is not entering the waterlogged area. Thus, whether the Kailana-Takhatsagar Reservoir is hydraulically connected with the aquifer underneath the Jodhpur city or not, the seepage from the lake is not flowing towards the waterlogged area in either situation.

(xiii) The Kailana-Takhatsagar Reservoir being located in the Malani group of rocks and the Malani group of rocks has low permeability; the seepage losses from the lake, if at all, will be very small. This seepage is entering towards the south-east region in which the water table contours are having less value than those in the waterlogged area. From the consideration of hydraulic principle, and from the consideration of the direction of flow, it is postulated that the seepage from the reservoirs is not entering to the waterlogged areas.

(xiv) Evolution of the water table has caused water logging progressively. Area getting waterlogged has increased every year, and a dynamic equilibrium has not been reached.

(xv) As such, there is no sign of bulk groundwater seepage from the Kailana-Takhatsagar Reservoir to the Jodhpur city area through the underneath geological formations of the respective areas. If at all seepage had taken place, it might have occurred through lineaments. There is only one lineament, which is oriented towards the waterlogged area. The Lineament analysis survey and the geological and geophysical study conducted independently by the National Geophysical Research Institute (NGRI), Hederabad (2010) surrounding the Kailana-Takhatsagar Reservoir indicated that the lineaments are oriented in NNE-SSW to NE-SW directions with no connectivity to the city areas. A few lineaments with ESE-WNW directions are present but these are small and do not have connectivity to the city areas. The findings of the NGRI thus corroborate the present finding based on hydraulic principle. The chances of seepage from the Kailana-Takhatsagar Reservoir to the waterlogged areas through lineaments are, therefore, ruled out.

(xvi) The measurements and analyses of the sewages data of the year 2009 indicated sewages disposal of about 37% of the supplied water through three major sewerage systems, i.e., Airport drain, Polytechnic Institute drain and Nandri sewage treatment plant drain.

(xvii) The pH values of the groundwater in the Jodhpur city area are within the prescribed permissible limit having slight leaning towards alkalinity, which may be because of excessive Chloride concentration. The Chlorine is used as a disinfectant chemical during treatment of water. The contours of pH concentration indicate that the ground water flow direction is not towards the water logged area.

(xviii) Presence of excessive Chloride in groundwater of the Jodhpur city area indicates accumulation of relatively freshwater, which may enter into the groundwater domain through leakage from water supply lines or from the waters which are not used for sanitary purposes.

(xix) The higher TDS values, which are mostly observed in the southern part far way from the problematic area, may be due to the local intrinsic mineral composition in the aquifer.

(xx) The nitrate concentrations in the study area have been found much higher than the permissible limit, mostly in the southern part, which are influenced by the agricultural activities using the city's sewages water. In the problematic area, in some pockets concentration of nitrate is also observed to be beyond permissible limit. Therefore, leakage from sewerage lines or connectivity of the septic tanks' outlets to the groundwater system in those pockets can not be ruled out.

(xxi) The source of water logging and rise in groundwater level in some parts of the city area appears to be due to return flow of water from water supply system and from the source other than the sewage waters. In some pockets, the seepage from sewage system cannot be ruled out.

(xxii) The quality of groundwater in the city area indicates that the groundwater can safely be used for irrigation purposes.

(xxiii) Vertical drainage system is feasible and easy to construct in the urbanized area. Constructing subsurface horizontal drain is not feasible because of the existing basements.

(xxiv) Pumped water can also be used for irrigating gardens and parks. Therefore, the pumped water should not be discharged into the existing surface drains which are meant for disposal of sewages.

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Section -17: RECOMMENDATIONS

Towards remedial measures, the following recommendations are made:

1. As the first and foremost remedial measure, it is suggested to regulate the quantity of water being supplied to the city area at the source itself, i.e., regulation of water from the Kailana-Takhatsagar Reservoir. The regulation needs to be based on per capita per day water requirement basis. The Jodhpur city being located in the arid and water scarce region, about 110 liters per capita per day could be taken as the guideline. The break up of 110 liters is as follows: 70 liter (drinking, bathing & toilet flushing) + 20 liter (commercial uses) + 20% conveyance losses. Industrial water requirements are to be included separately. For 110 lpcd supply, the quantity of water requirement for the estimated population of 11,08,950 in the Jodhpur city for the year 2010 is worked out to be 268.69 lac gallon per day. To meet water requirement for domestic animals, and kitchen gardens and public parks 1/3 of the requirement for the population i.e., about 73 lac gallon per day extra water be supplied, which will reduce the quantity by about 35% over the quantity supplied (521.7 lac gpd) in the year 2009. The per capita per day water supply requirement is estimated to be 140 litre.

2. In the affected area, the water supply lines need to be thoroughly checked to find the locations of leakages, and suitable remedial measures to stop the leakages need to be taken up. The sewages/drainage lines in the affected area need to be properly sealed to stop seepage, if any.

3. The topography of the city area in the northern and middle part is of undulating type. The thickness of the alluvium formation varies from about 2.0 m to 13.0 m in that part. Therefore, a single generalized safe ground water level is incorrect to suggest. In general, considering the possibility of capillary rise in alluvium formation, groundwater table should be at least 0.5m below the foundation level. In areas where building basement floors are located, assuming that basement height is 3.5m, and capillary rise is 0.5m, the groundwater table should be at 4.0 m below the ground surface. The groundwater level in the affected area thus has to be lowered down below 4.0 m from the respective ground surface elevation. The highest groundwater table elevation in the affected area is about 285 m.

4. The terrain being undulating, the area being an urban area, the requirement of lowering the water table by 4m, minimum depth of alluvium being 2m, all these aspects do not promote provision of a usual horizontal sub surface drainage system. However random sub surface drainage trench of 4m depth, filled with coarse sand and gravel can be constructed to control the rising water which can be led to a collector caisson, from where water can be pumped out. Construction of such trenches to control water table rise would depend upon the local terrain and building locations.

5. Provision of vertical drainage system i.e., by pumping the water from the aquifer in the problematic area looks feasible; as drainage wells can be constructed with least interference in the urbanized area. The pumping rate and schedule can be controlled, the number drainage wells can be increased in a locality as required, and already such practice has been initiated in the area, all these factors favor provision of vertical drainage. In region of low transmissivity area i.e., transmissivity $< 30 m^2/day$, large diameter wells of 0.5m can be constructed. However, vertical drainage system would require electrical energy, and would cause noise pollution.

6. There are three large ponds, namely, Baiji Ka Talab, Fateh Sagar, and Gulab Sagar (details given in table below), located near to the problematic area. The pond beds are more or less impervious, or if necessary, these can be made impervious by lining. The pumped water can be discharged to these ponds through conveyance pipe. From these ponds surface channel can be constructed to convey the water stored in the pond to the existing surface drainage system through gravity. These waters can be used for agricultural irrigation purposes. It should not be mixed with sewage waters.

Name of Talab	Longitude	Latitude	Surface Elevation (m)	Bottom Elevation (m)	Near by elevation of water table(m)	
					Max	Min
Baiji Ka talab	73.03361	26.300136	250	242.5	256	245
Fateh Sagar	73.02949	26.296538	240	208	245	240
gulab Sagar	73.02539	26.297016	249	219	250	240

7. A Bentonite clay grout curtain across the lineament which is terminating before but directing towards the water logged area can be constructed proximity to the reservoir site to check the groundwater flow, if any, from the reservoirs to the water logged area.

REFERENCES

1) Abramowitz, M. and Stegun, I. A. (1970). Handbook of Mathematical Functions. Dover Publications, INC., New York, 231.

2) Carslaw, H. S., and Jaeger, J. C. (1959). Conduction of Heat in Solids. Oxford Univ. Press, London and New York. 261

3) Harr, M. E., (1962). Groundwater and Seepage. McGraw-Hill Book Company, New York, 315p.

4) Morel-Seytoux, H. J. (1975). Optimal legal conjunctive operation of surface and ground water. Proc. Second World Congress. Intl. Water Resour. Assoc., New Delhi, Vol. IV, 119-129.

5) Model-Seytoux, H. J. and C. J. Daly (1975). A discrete kernel generator for stream-aquifer studies. Water Resour. Res., 11(2): 253-260.

6) Mahdi S. Hantush (1961). Drawdown around a partially penetrating well. J. Hydr. Div., ASCE, 87(HY4),83-98.

7) Sandford, H.J. (1938).”Diffusing pits for recharging water into underground formation: chemical well cleaning methods”. American Water Works Association Journal, 30(11):1755-1766.

8) Todd, D.K. (1985) Groundwater Hydrology. New York.

ANNEXURES

Table A3.1 : Locations of 93 borelogs of the Jodhpur Area (Reference : Section-3.0)

Bore	Township	Latitude	Longitude	Elevation	Total Depth
Bh-01	12th Road, Sardarpura	26^{0}16'33"	73^{0}00'07"	243	45
Bh-02	Ajeet colony park	26^{0}17'00"	73^{0}02'10"	230.8	56
Bh-03	Ajit colony	26^{0}17'01.0"	73^{0}02'9.5"	231	37.5
Bh-04	Bacha Ki Gali	26^{0}17'44"	73^{0}01'26"	246.6	55.5
Bh-05	Badlon ka chowk	26^{0}17'56"	73^{0}01'31"	253	43.5
Bh-06	Bagar chowk	26^{0}18'01"	73^{0}01'38"	253.47	92
Bh-07	Bager, Rawat Building	26^{0}17'58"	73^{0}01'38"	254	52.52
Bh-08	Bagri Basti	26^{0}16'24"	72^{0}59'55"	243.5	70
Bh-09	Baiji Talab, Jalori Gate	26^{0}17'10"	73^{0}01'13"	242	39
Bh-10	Bhadwasiyal near school	26^{0}18'54"	73^{0}03'15"	239.69	64
Bh-11	Bambs	26^{0}17'33"	73^{0}01'47.2"	239	49
Bh-12	Bank colony	26^{0}17'24.2"	73^{0}02'37.8"	233.8	44
Bh-13	Beldar Basti	26^{0}20'18"	72^{0}59'16"	280	61
Bh-14	Beldaron Ka Mohalla	26^{0}17'21"	73^{0}01'20"	242	54
Bh-15	Bhakri Bas soorsagar	26^{0}17'18"	73^{0}00'55"	248	61
Bh-16	Bhatiya Choraya Harijan Basti	26^{0}16'35"	73^{0}02'13.4"	236	67
Bh-17	Bhil Basti	26^{0}17'38.9"	73^{0}03'58"	221	61
Bh-18	Bhil Basti, Soorsagar, W.W. Tank	26^{0}18'19.1"	73^{0}00'35"	282	46
Bh-19	Bhiyali Bera Mandore	26^{0}21'03"	73^{0}02'37"	241	59
Bh-20	Bhuta Basti	26^{0}18'04"	73^{0}01'53"	247.79	51
Bh-21	Chandana Bhaker II	26^{0}16'15.9"	72^{0}59'07.7"	247	54
Bh-22	Chopasmi Village	26^{0}15'36.3"	72^{0}56'37.9"	237.5	60
Bh-23	Digadi village chowk	26^{0}17'40.5"	73^{0}05'5.2"	216.8	38
Bh-24	Digadi, Brahmanon Ka mohalla	26^{0}17'30.5"	73^{0}05'11.3"	216.59	46
Bh-25	Gandhi Hospital	26^{0}18'01"	73^{0}01'09"	306	55
Bh-26	Ghasmandi	26^{0}17'28"	73^{0}01'26"	242	49
Bh-27	Ghoron Ka Chowk II Harijan Basti	26^{0}17'18"	73^{0}01'19"	292.7	61
Bh-28	Gorind Baori	26^{0}17'30.9"	73^{0}01'20.4"	243.5	37
Bh-29	Gulab sagar, near choki	26^{0}17'45"	73^{0}01'25"	247.5	48.15
Bh-30	Gulzarpura Behind kesi House	26^{0}17'26"	73^{0}01'45"	238	64
Bh-31	Hanwant School	26^{0}18'18"	73^{0}03'37"	230.17	49
Bh-32	Hathi chowk	26^{0}16'18.9"	73^{0}01'37.6"	227.29	50
Bh-33	High court Colony	26^{0}16'18.9"	73^{0}01'39.6"	226.8	39
Bh-34	Jakir Hussin Col. I	26^{0}17'03.6"	73^{0}00'19.6"	255.7	55
Bh-35	Jalori gate, Norsingh house	26^{0}17'16"	73^{0}01'04"	246	45
Bh-36	Jalori Gate, Roshnidan	26^{0}17'00"	73^{0}01'01"	243.5	40.52

Bore	Township	Latitude	Longitude	Elevation	Total Depth
Bh-37	Jatio ki Dahni. Bilada	$26^0$19'26.1"	$73^0$01'2.4"	276	47
Bh-38	Jawahar Khana	$26^0$17'31"	$73^0$00'27"	284.15	49
Bh-39	Jogiyon Ka bas, Siw. Gate	$26^0$17'20"	$73^0$00'43.6"	252.5	43
Bh-40	Kabutaro Ka Chowk in jal	$26^0$17'19"	$73^0$01'05"	247	43.5
Bh-41	Kabutaron Ka Chowk	$26^0$17'18"	$73^0$01'0.6"	246.6	57
Bh-42	Kaga	$26^0$18'32"	$73^0$01'57"	294.5	58
Bh-43	Kagdi Bhil Basti	$26^0$18'19"	$73^0$01'57"	247.7	50
Bh-44	Kamla Nehru Nag. Rly Gate	$26^0$16'38.2"	$72^0$59'15.6"	250.7	66
Bh-45	Karni bagh locality , High Court Col.	$26^0$16'17"	$73^0$01'32"	228	92
Bh-46	Khetandi I	$26^0$19'22"	$73^0$02'33.6"	271	52.5
Bh-47	Khetandi II	$26^0$19'23"	$73^0$02'30.3"	267.7	53
Bh-48	Kuldeep Type writer, Naya Talab	$26^0$17'47"	$73^0$01'59"	239.39	55.5
Bh-49	Kumaron Ki Dhani Digari	$26^0$17'44.6"	$73^0$05'56.2"	211.87	38.4
Bh-50	M.G. Hospital road	$26^0$17'01"	$73^0$01'07"	242	45.1
Bh-51	Mahavir chowk , Fateh sagar	$26^0$17'45"	$73^0$01'47"	243	52.52
Bh-52	Maliyon Ka Bas sursagar	$26^0$19'00"	$73^0$00'13"	270	52
Bh-53	Masliyia Meghwal Basti	$26^0$16'30.5"	$72^0$59'55.6"	246	55
Bh-54	Masurie Bhil Basti	$26^0$16'22.5"	$72^0$59'46.0"	245.15	55
Bh-55	Merti gate, guide ki gali	$26^0$17'38"	$73^0$01'49"	240.34	45
Bh-56	Merti silavion Ka bas inside Sojati Gate	$26^0$17'22"	$73^0$01'21"	242	58
Bh-57	Middle Raj Mahal School	$26^0$17'58"	$73^0$01'39"	253.7	55.5
Bh-58	Mochi Basti, Siw. Gate	$26^0$17'09.9"	$73^0$00'42.7"	249	55
Bh-59	Mooliyaon Ki chowk Siw. gate	$26^0$17'18.2"	$73^0$00'44.9"	251.4	45.72
Bh-60	Moti chowk Kbapta	$26^0$17'33.9"	$73^0$01'11.2"	247	46
Bh-61	Nagori gate of nansida patehsagar	$26^0$17'45"	$73^0$01'43"	243.5	49
Bh-62	Nanak Chowk	$26^0$17'43"	$73^0$01'21"	257.42	43.5
Bh-63	Nandore Near Bank	$26^0$20'58"	$73^0$02'16"	246	92
Bh-64	Navdiyon Ki Ghati	$26^0$18'12.9"	$73^0$05'41"	216.56	58
Bh-65	Near Chorbhuija	$26^0$17'18"	$73^0$01'29"	242.18	68
Bh-66	Udai Mandir, Harijan Basti	$26^0$17'37"	$73^0$01'12"	247.8	54
Bh-67	Patehsagar near obs	$26^0$17'40"	$73^0$01'41"	241.33	61
Bh-68	PHED campus Riktitya	$26^0$16'07"	$73^0$01'10.9"	229.5	100
Bh-69	Puajla, Mandore	$26^0$20'12"	$73^0$03'33"	240	53
Bh-70	Raj mahal girls school	$26^0$17'50"	$73^0$01'37"	248	52.52
Bh-71	Ram Bovra Road Hasurian	$26^0$16'19.1"	$72^0$59'45.4"	244.5	53
Bh-72	Ram Dev Petrol pump sursagar	$26^0$18'06"	$72^0$59'46"	263	59
Bh-73	Ramola	$26^0$18'20"	$73^0$02'08"	247.3	52
Bh-74	Ratanada, Ganesh mandir	$26^0$16'33.2"	$73^0$02'19.8"	246	49
Bh-75	Ratnada Kesar Bag, Harijan, Basti	$26^0$16'35.8"	$73^0$02'11.2"	229	36
Bh-76	Rupawaton Ka Bear	$26^0$20'52"	$72^0$59'13"	272	50
Bh-77	Sakina colony	$26^0$17'03.1"	$73^0$00'29.1"	248.7	52
Bh-78	Satya narain Mandir, hathi ram ka oda	$26^0$17'41"	$73^0$01'34"	243.25	60

Bore	Township	Latitude	Longitude	Elevation	Total Depth
Bh-79	Shiv Mandir	26^{0}17'47.4"	73^{0}01'48.1"	244.15	58.5
Bh-80	Sindhi Ka Nayati Siw. gate inside	26^{0}17'17.2"	73^{0}00'42.6"	251	52
Bh-81	Sindhi Mohalla(Katiyaron Ka chowk	26^{0}17'12"	73^{0}00'44"	249.29	43.5
Bh-82	Sindhiyon Ka Mohalla, Siw. gate	26^{0}17'13"	73^{0}00'49"	248.65	56
Bh-83	Siw. Gate Goshala	26^{0}17'15.2"	73^{0}00'35.6"	252.5	52
Bh-84	Siw. Gate Middle school infront	26^{0}17'15.2"	73^{0}00'27.9"	264.7	45.71
Bh-85	Siw. Gate, Bus stand	26^{0}17'11.5"	73^{0}00'36.9"	251	54
Bh-86	Siw. Gate, Nagriyon Ka bas	26^{0}17'14"	73^{0}00'33"	253.29	52.5
Bh-87	Turje Ka Jhalra	26^{0}17'49"	73^{0}01'26"	248	61
Bh-88	Udai Mandir	26^{0}17'39"	73^{0}02'10"	235.18	37
Bh-89	Umed chowk	26^{0}17'54"	73^{0}01'28"	252	45.1
Bh-90	Umed hospital	6^{0}17'07.5"	73^{0}00'41.5"	248.5	58
Bh-91	Vedik Kanyapath Sala,Bagar	26^{0}18'06"	73^{0}01'45"	251.7	60
Bh-92	Vijay chowk	26^{0}18'01"	73^{0}01'47"	250	48
Bh-93	Zakir Hussain Colony (III) Kabutaraon Ka chowk	26^{0}17'19"	73^{0}01'05"	247	50

Table A 6.1 : Area and Capacity data of the Kailana for different stages of water level in the Lake (Reference : Section 6.0).

Stage (meter)	Area (sq. km)	Capacity (MCM)
0.000	0.013	0.000
0.305	0.014	0.000
0.610	0.016	0.006
0.914	0.019	0.011
1.219	0.022	0.017
1.524	0.025	0.023
1.829	0.028	0.031
2.134	0.032	0.037
2.438	0.034	0.047
2.743	0.039	0.057
3.048	0.042	0.069
3.353	0.046	0.095
3.658	0.051	0.106
3.962	0.059	0.126
4.267	0.067	0.147

4.572	0.074	0.162
4.877	0.080	0.190
5.182	0.087	0.215
5.486	0.093	0.244
5.791	0.098	0.275
6.096	0.104	0.302
6.401	0.111	0.365
6.706	0.118	0.377
7.010	0.126	0.414
7.315	0.137	0.456
7.620	0.149	0.487
7.925	0.163	0.549
8.230	0.177	0.597
8.534	0.190	0.657
8.839	0.204	0.714
9.144	0.219	0.783
9.449	0.232	0.850
9.754	0.246	0.920
10.058	0.258	0.994
10.363	0.274	1.079
10.668	0.289	1.184
10.973	0.302	1.252
11.278	0.317	1.354
11.582	0.330	1.450
11.887	0.344	1.557
12.192	0.359	1.664
12.497	0.379	1.767
12.802	0.399	1.892
13.106	0.422	2.010
13.411	0.441	2.141
13.716	0.467	2.294
14.021	0.491	2.415
14.326	0.515	2.577
14.630	0.539	2.704
14.935	0.567	2.911
15.240	0.597	3.105
15.545	0.622	3.276
15.850	0.650	3.446
16.154	0.683	3.639

16.459	0.713	3.865
16.764	0.749	4.131
17.069	0.787	4.361
17.374	0.837	4.616
17.678	0.880	4.814

Table A6.2: Area and Capacity data of the Takhatsagar Reservoir for different stages of water level in the reservoir (Reference: Section -6.0).

Stage (meter)	Area (sq. km)	Capacity (MCM)
0	0.002	0.000
3.048	0.074	0.120
6.096	0.186	0.535
9.144	0.278	1.260
12.192	0.342	2.195
15.24	0.431	3.373
18.288	0.517	4.817
21.336	0.601	6.523

Table A6.3 : Stage - Capacity data of the Umaidsagar Reservoir (Reference : Section-6.0).

Stage (meter)	Capacity (MCM)
0.610	0.003
0.762	0.007
0.914	0.014
1.067	0.021
1.219	0.028
1.372	0.042
1.524	0.050
1.676	0.057
1.829	0.071
1.981	0.099
2.134	0.113
2.286	0.142
2.438	0.156
2.591	0.184
2.743	0.204
2.896	0.241
3.048	0.283
3.200	0.326
3.353	0.368
3.505	0.413
3.658	0.462

3.810	0.510
3.962	0.566
4.115	0.629
4.267	0.691
4.420	0.765
4.572	0.838
4.724	0.920
4.877	0.991
5.029	1.090
5.182	1.161
5.334	1.274
5.486	1.359
5.639	1.444
5.791	1.557
5.944	1.648
6.096	1.784
6.248	1.903
6.401	2.010
6.553	2.129
6.706	2.265
6.858	2.413
7.010	2.520
7.163	2.662
7.315	2.775
7.468	2.959
7.620	3.115
7.772	3.285
7.925	3.426
Stage (meter)	**Capacity (MCM)**
8.077	3.568
8.230	3.738
8.382	3.964
8.534	4.163
8.687	4.361
8.839	4.587
8.992	4.814
9.144	5.040
9.296	5.267
9.449	5.522
9.601	5.748
9.754	6.003
9.906	6.230
10.058	6.485
10.211	6.754
10.363	7.079
10.516	7.306
10.668	7.646
10.820	7.929
10.973	8.269
11.125	8.608
11.278	9.005
11.430	9.401
11.582	9.854

Table A 8.1: Location of the groundwater level observation points (Reference : Section -8.0).

S.no	Well Location	Type of Well	Latitude	Longitude	R.L.of ground surface
1	Raj Basera	Open Well	26° 15' 59.04"	73° 3' 43.80"	206.875
2	Polo ground	Tube Well	26° 15' 47.99"	73° 2' 10.98"	219.8
3	New Campus Univ.	Piezometer	26° 14' 49"	73° 00' 59"	224.6
4	Thorion Ki Dhani		26° 14' 18"	72° 58' 16"	228.375
5	Subhash Chowk	Open Well	26° 16' 41.36"	73° 1' 54.42"	229.375
6	R. T. O. Office	Hand Pump	26° 18' 23.18"	73° 3' 41.52"	230.58
7	Jetta Bera,Opp Chand Baori	Open Well	26° 17' 50.99"	73° 0' 56.0"	265.5
8	Ground Water Dept.	Piezometer	26° 15' 36"	73° 0' 42.0	231.8
9	Gauesala/Umed Club	Open Well	26° 17' 15.79"	73° 2' 2.04"	233.8
10	Ajeet Bhawan	Open Well	26° 17' 7.19"	73° 2' 21.40"	233.9
11	Laxmi Nagar	Open Well	26° 18' 3.32"	73° 2' 58.56"	234.21
12	Nehru Park	Open Well	26° 16' 32.1456"	73° 0' 50.31"	234.5
13	Rai Ka Bag(Near RAE)		26° 17' 21.06"	73° 2' 43.02"	234.65
14	High Court	Hand Pump	26° 17' 25.90"	73° 2' 8.09"	235.28
15	Tar Ghar Mahavir Complex Sardar pura		26° 16' 40.80"	73° 0' 57.70"	235.28
16	Jalam Singh ka Hatta	Hand Pump	26° 17' 51"	73° 2' 42"	236.53
17	Paota"B"Road(Near Ghanshyam Singh)	Open Well	26° 17' 46"	73° 2' 30"	236.8
18	Amritiya Bera(Mahamandir)	Open Well	26° 18' 7"	73° 2' 44"	237
19	Khema Ka Kua	Open Well	26° 15' 16.82"	72° 58' 56.69"	237.45
20	CAZRI	Piezometer	26° 15' 17"	72° 59' 42"	239.52
21	Sardarpura 3 road	Open Well	26° 16' 46.28"	73° 0' 29.12"	241.37
22	Mahamandir Ka Jhalra	Step Well	26° 18' 22"	73° 2' 37"	241.85
23	Nai Sarak(mehro Ka Chowk)		26° 17' 27"	73° 1' 32"	243.15
24	Gorinda Baori	Step Well	26° 17' 31"	73° 1' 20.39"	243.38
25	Gantaghar/Do Kotho Ke Beech	Open Well	26° 17' 42"	73° 1' 31"	244.39
26	Ramanuj Kot	Open Well	26° 17' 47"	73° 1' 44"	244.85
27	Deo Nagar	Open Well	26° 16' 6"	72° 59' 20"	245.38
28	Siwanchi Gate	Open Well	26° 17' 4"	73° 0' 44.3"	246.85
29	Moti Chowk		26° 17' 33.9"	73° 1' 11.20"	247.35
30	Katla Bazar	Hand Pump	26° 17' 37"	73° 1' 13"	247.38
31	Sindhi Bhtoo Ki Maszid		26° 18' 4"	73° 1' 53"	248.39
32	Tunwar Ji Ka Jhalra	Step Well	26° 17' 49"	73° 1' 26"	248.68
33	Bhram Bag(Galori Gate)	Open Wel	26° 16' 59"	73° 2' 44"	248.85
34	Khanda Falsa	Open Wel	26° 17' 22.24"	73° 0' 50.2194"	249.78
35	Dau Ki Dhani	Open Well	26° 17' 22"	72° 59' 14"	252.41
36	Akhe Raj ji ka Talab	Open Well	26° 17' 49.30"	72° 59'5"	254.63
37	Kaylana I	Piezometer	26° 17' 41.89"	72° 59' 32.60"	258.85
38	Nav Chokiya		26° 17' 43"	73° 0' 52"	259.68
39	Ganwa(Pratap Nagar)	Open Well	26° 17' 46"	72° 59' 38"	260.12
40	Kailana II	Piezometer	26° 17' 41.87"	72° 59' 38.80"	262.85

S.no	Well_Location	Type_of Well	Latitude	Longitude	R.L.of ground surface
41	Chand Baori	Step Well	26° 17' 51"	73° 0' 56"	268.29
42	J.N Vyas Park	Open Well	26° 17' 46"	73° 0' 42.64"	269.38
43	Hathi nahar Jhalra	Step Well	26° 19' 30"	72° 58' 7.20"	277.125
44	Chandpole	Open Well	26° 17' 59"	73° 0' 41.79"	279.85
45	Opposite Diet (Vidya Shala School)	Hand Pump	26° 18' 12.89"	73° 0' 41"	280.75
46	Raghunath baori	Step Well	26° 18' 12.89"	73° 0' 37.50"	281.84
47	Kriya Ka Jhalra	Step Wel	26° 18' 12.01"	73° 0' 49.12"	285.5
48	Kaga ji	Open Well	26° 18' 32"	73° 1' 56"	291.85
49	Chaukha	Open Well	26° 16' 58"	72° 55' 23"	no contour
50	Golasni		26° 18' 27"	72° 56' 54"	no contour
51	Kali Beri	Open Well	26° 20' 30.72"	72° 59' 17.29"	no contour
52	Roopawaton Ka Bera	Open Well	26° 21' 21.23"	72° 59' 3"	no contour
53	Chopasani	Step Well	26° 15' 39.75"	72° 56' 44.87"	no contour
54	Mandore police Thana	Piezometer	26° 22' 2"	73° 3' 47"	no contour

Table A 9.1 : Questionnaire used for door-to-door survey to assess the **connectivity of** the households to the sewerage/drainage systems in the problematic area (Reference : Section 9.0).

प्रश्नोत्तरी

1.- नाम :--

2.:-पिता का नाम:--

3.-मकान न0 एवं मौहल्ला: --

4.-परिवार के सदस्यो का संख्या :--

5.-परिवार में इस्तेमाल होने वाले पानी की संख्या प्रतिदिन (बालटियों में):--------------------------------

6.-घर मे पानी सप्लाई कहाँ से आती है :-

(क) नगर निगम (ख) खुद के बोर बेल से (ग) कुएँ से (घ) बाबडी से (ङ) अन्य

7.- घर मे पानी सप्लाई :-

(क) कितने घंटे

(ख) कब -कब

8.- घर का बेकार पानी (Waste Water) कहाँ जाता है :-

(क) नाले मे (ख) पास के प्लाट मे

(ग) सोक पीट मे (घ) अन्य

9.- घर के शौचालय का बेकार पानी (Waste Water) कहाँ जाता है :-

(क) सीवर लाईन में (नगर निगम की) (ख) नाले में

(ग) सोक पीट में (घ) पास के प्लाट में

(ङ) अन्य

10. - घर मे आने वाला पानी:-

(क) पर्याप्त है (ख) अत्यधिक है

(ग) कम है (घ) अन्य कोई समस्या

11.-घर मे जाने वाले बेकार पानी से संम्बधित कोई समस्या :--

12.-भूजल से संम्बधित कोई समस्या :-

(क) आपके मौहल्ले में

(ख) शहर के अन्य क्षेत्रो में ।

* यह सूचना देने वाले का नाम किसी भी रिपोर्ट मे नही आयेगा ।
* यह जानकारी केवल वैज्ञानिक शोध कार्य के लिए है इसका अन्य प्रयोग नही होगा ।

Annexure A11.1 (Reference : Section 11.0)

(A) The Marquardt Algorithm

Introduction

Predicting response of an aquifer to a pumping pattern, whose transmissivity and storage coefficient are known a priori, is classified as a direct problem. Estimating the aquifer parameters from a set of observed response of the aquifer to a known pumping pattern is an inverse problem. An inverse problem could be solved provided the corresponding direct problem has been solved a priori.

Using Theis' basic solution i.e. by matching the time drawdown curve with Theis' type curves, we can determine the parameters of an aquifer which is confined, homogeneous, isotropic, and is of infinite area and the pumping well has small radius. The aquifer is to be initially at rest condition, and the aquifer test is conducted under constant pumping rate. These are the assumptions on which Theis' solution is based.

Mishra Chachadi's type curves (Mishra, Chachadi, 1986) could be used for determining parameters of a confined aquifer if the test is conducted in a large diameter well. These type curves include both the pumping phase and recovery the recovery phase

To avoid human error while curve matching, the inverse problem could be solved conveniently using Marquardt Algorithm (Marquardt, 1963). Berg (1971), and Chander et.al.(1981) have used the algorithm to predict parameters of aquifers in different hydro geological settings.

The Theis' solution, which provides evolution of drawdown in a confined aquifer in response to constant continuous pumping from a fully penetrating well with small radius having negligible well storage, is

$$s(Q,T,\phi,r,t)=\left\{\frac{Q}{4\pi T}\right\}\left[\int_{r^2\phi/(4Tt)}^{\infty}\frac{e^{-u}}{u}du\right]=F_1\left(Q,r,t,T,\phi\right) \quad \ldots\ldots\ldots \quad \text{(A11.1)}$$

where $s(Q,T,\phi,r,t)=$ is the draw down in piezometric surface at distance r and time t after the onset of pumping ; $Q=$ constant pumping rate; $T=$ transmissivity of the confined aquifer, and $\phi=$ storage coefficient.

Partial derivative of $s(Q,T,\phi,r,t)$ with respect to T is

$$\frac{\partial s(Q,T,\phi,r,t)}{\partial T}=\left\{\frac{-Q}{4\pi T^2}\right\}\left[\int_{r^2\phi/(4Tt)}^{\infty}\frac{e^{-u}}{u}du\right]+\left\{\frac{Q}{4\pi T}\right\}\left[-\left(\frac{e^{-r^2\phi/(4Tt)}}{r^2\phi/(4Tt)}\right)\left(-\frac{r^2\phi}{4T^2t}\right)\right]$$

$$=\left\{\frac{Q}{4\pi T^2}\right\}\left[e^{-r^2\phi/(4Tt)}-\int_{r^2\phi/(4Tt)}^{\infty}\frac{e^{-u}}{u}du\right]=F_2(Q,r,t,T,\phi)\ \ldots\text{(A11.2)}$$

Partial derivative of $s(Q,T,\phi,r,t)$ with respect to ϕ is

$$\frac{\partial s(Q,T,\phi,r,t)}{\partial \phi}=\left\{\frac{Q}{4\pi T}\right\}\left[-\left(\frac{e^{-r^2\phi/(4Tt)}}{r^2\phi/(4Tt)}\right)\left(\frac{r^2}{4Tt}\right)\right]=-\frac{Q}{4\pi T\phi}e^{-r^2\phi/(4Tt)}=F_3(Q,r,t,T,\phi)\ldots\quad\text{(A11.3)}$$

$F_1(Q,r,t,T,\phi), F_2(Q,r,t,T,\phi), F_3(Q,r,t,T,\phi)$ are functions of T ϕ Q, r, and t.

Let T^* and ϕ^* be the approximate values of transmissivity and storage coefficient near to the true values of transmissivity and storage coefficient. Initially, T^* and ϕ^* are to be guessed. Let ΔT and $\Delta\phi$ be incremental values in transmissivity and storage coefficient so that $T^*+\Delta T$ and $\phi^*+\Delta\phi$ are nearer to the true values. ΔT and $\Delta\phi$ are unknown and are to be predicted by Marquardt algorithm. Performing Taylor series expansion of drawdown $s(Q,T,\phi,r,t)$ about T^* and ϕ^*, and neglecting the higher order terms, the following equation is obtained:

$$s(Q,T,\phi,r,t)\Big|_{T^*+\Delta T,\phi^*+\Delta\phi}=s(Q,T,\phi,r,t)\Big|_{T^*,\phi^*}+\frac{\partial s(Q,T,\phi,r,t)}{\partial T}\Big|_{T^*,\phi^*}\Delta T+\frac{\partial s(Q,T,\phi,r,t)}{\partial \phi}\Big|_{T^*\phi^*}\Delta\phi$$

$$=F_1(Q,r,t,T^*,\phi^*)+F_2(Q,r,t,T^*,\phi^*)\Delta T+F_3(Q,r,t,T^*,\phi^*)\Delta\phi\ \ldots\ldots\text{(A11.4)}$$

The pumping rate Q and the distance r of the piezometer from the pumping well being constants, we abbreviate $s(Q,T,\phi,r,t)$ by $s(t,T,\phi)$, $F_1\left(Q,r,t,T^*,\phi^*\right)$ by $F_1\left(t,T^*,\phi^*\right)$, $F_2\left(Q,r,t,T^*,\phi^*\right)$ by $F_2\left(t,T^*,\phi^*\right)$ and $F_3\left(Q,r,t,T^*,\phi^*\right)$ by $F_3\left(t,T^*,\phi^*\right)$.

Let $s_o\left(i\right)$ be the i^{th} observed drawdown in piezometric surface in the piezometer at time t_i. The predicted drawdown , $s_c\left(t_i,T^*+\Delta T,\phi^*+\Delta\phi\right)$, at observation time t_i from equation (A11.4) is

$$s_c\left(t_i,T^*+\Delta T,\phi^*+\Delta\phi\right)=F_1\left(t_i,T^*,\phi^*\right)+F_2\left(t_i,T^*,\phi^*\right)\Delta T+F_3\left(t_i,T^*,\phi^*\right)\Delta\phi \quad \text{.......(A11.5)}$$

The error in the i^{th} prediction, $E\left(i\right)$, is,

$$E\left(i\right)=s_o\left(i\right)-s_c\left(t_i,T^*+\Delta T,\phi^*+\Delta\phi\right)$$

$$=s_o\left(i\right)-\left\{F_1\left(t_i,T^*,\phi^*\right)+F_2\left(t_i,T^*,\phi^*\right)\Delta T+F_3\left(t_i,T^*,\phi^*\right)\Delta\phi\right\} \quad \text{........ (A11.6)}$$

The Marquardt algorithm minimizes sum of the squares of error for a set of N observations and the minimization problem is,

$$\underset{\Delta T,\,\Delta\phi}{Min}\left\{\sum_{i=1}^{N}\left[s_0\left(i\right)-\left\{F_1\left(t_i,T^*,\phi^*\right)+F_2\left(t_i,T^*,\phi^*\right)\Delta T+F_3\left(t_i,T^*,\phi^*\right)\Delta\phi\right\}\right]^2\right\} \quad \text{........ (A11.7)}$$

Differentiating sum of the squares of the error with respect to ΔT and equating it to zero

$$\sum_{i=1}^{N}\left\{-2\left[s_0\left(i\right)-\left\{F_1\left(t_i,T^*,\phi^*\right)+F_2\left(t_i,T^*,\phi^*\right)\Delta T+F_3\left(t_i,T^*,\phi^*\right)\Delta\phi\right\}\right]F_2\left(t_i,T^*,\phi^*\right)\right\}=0 \quad \text{.. (A11.8)}$$

Simplifying, equation (A11.8) reduces to

$$\left\{\sum_{i=1}^{N}\left[F_2\left(t_i,T^*,\phi^*\right)F_2\left(t_i,T^*,\phi^*\right)\right]\right\}\Delta T+\left\{\sum_{i=1}^{N}\left[F_3\left(t_i,T^*,\phi^*\right)F_2\left(t_i,T^*,\phi^*\right)\right]\right\}\Delta\phi$$

$$=\sum_{i=1}^{N}\left[s_0\left(i\right)F_2\left(t_i,T^*,\phi^*\right)\right]-\sum_{i=1}^{N}\left[F_1\left(t_i,T^*,\phi^*\right)F_2\left(t_i,T^*,\phi^*\right)\right] \quad \text{....... ... (A11.9)}$$

Differentiating sum of the squares of the error with respect to $\Delta\phi$ and equating it to zero

$$\sum_{i=1}^{N}\left\{-2\left[s_0\left(i\right)-\left\{F_1\left(t_i,T^*,\phi^*\right)+F_2\left(t_i,T^*,\phi^*\right)\Delta T+F_3\left(t_i,T^*,\phi^*\right)\Delta\phi\right\}\right]F_3\left(t_i,T^*,\phi^*\right)\right\}=0 \quad \ldots \text{(A11.10)}$$

Simplifying, equation (A11.10) reduces to

$$\left\{\sum_{i=1}^{N}\left[F_2\left(t_i,T^*,\phi^*\right)F_3\left(t_i,T^*,\phi^*\right)\right]\right\}\Delta T+\left\{\sum_{i=1}^{N}\left[F_3\left(t_i,T^*,\phi^*\right)F_3\left(t_i,T^*,\phi^*\right)\right]\right\}\Delta\phi$$

$$=\sum_{i=1}^{N}\left[s_0\left(i\right)F_3\left(t_i,T^*,\phi^*\right)\right]-\sum_{i=1}^{N}\left[F_1\left(t_i,T^*,\phi^*\right)F_3\left(t_i,T^*,\phi^*\right)\right] \quad \ldots\ldots\ldots \quad \text{(A11.11)}$$

Equations (A11.9) and (A11.11) are written as

$$a(1,1)\Delta T+a(1,2)\Delta\phi=c\left(1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.12)}$$

$$a(2,1)\Delta T+a(2,2)\Delta\phi=c\left(2\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad \text{(A11.13)}$$

Solving for $\Delta\phi$ and ΔT, we get

$$\Delta\phi=\frac{\dfrac{c(1)}{a(1,1)}-\dfrac{c(2)}{a(2,1)}}{\dfrac{a(1,2)}{a(1,1)}-\dfrac{a(2,2)}{a(2,1)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(A11.14)}$$

and

$$\Delta T=\frac{c(1)}{a(1,1)}-\frac{a(1,2)}{a(1,1)}\Delta\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.15)}$$

where

$$a(1,1)=\sum_{i=1}^{N}\left[F_2\left(t_i,T^*,\phi^*\right)F_2\left(t_i,T^*,\phi^*\right)\right]; \quad a(1,2)=\sum_{i=1}^{N}\left[F_3\left(t_i,T^*,\phi^*\right)F_2\left(t_i,T^*,\phi^*\right)\right]$$

$$c(1)=\sum_{i=1}^{N}\left[s_0\left(i\right)F_2\left(t_i,T^*,\phi^*\right)\right]-\sum_{i=1}^{N}\left[F_1\left(t_i,T^*,\phi^*\right)F_2\left(t_i,T^*,\phi^*\right)\right]$$

and

$$a(2,1)=\sum_{i=1}^{N}\left[F_2\left(t_i,T^*,\phi^*\right)F_3\left(t_i,T^*,\phi^*\right)\right]; \quad a(2,2)=\sum_{i=1}^{N}\left[F_3\left(t_i,T^*,\phi^*\right)F_3\left(t_i,T^*,\phi^*\right)\right]$$

$$c(2)=\sum_{i=1}^{N}\left[s_0\left(i\right)F_3\left(t_i,T^*,\phi^*\right)\right]-\sum_{i=1}^{N}\left[F_1\left(t_i,T^*,\phi^*\right)F_3\left(t_i,T^*,\phi^*\right)\right]$$

The improved transmissivity and storage coefficient are given by

$$T^*\Big|_{new}=T^*\Big|_{old}+\Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad \text{(A11.16)}$$

$$\phi^*\big|_{new} = \phi^*\big|_{old} + \Delta\phi \qquad \text{..........................} \qquad \text{(A11.17)}$$

This iteration procedure is to be repeated till ΔT and $\Delta\phi$ tend to very small values.

Evaluation of the Functions $F_1\left(t_i, T^*, \phi^*\right)$ and $F_2\left(t_i, T^*, \phi^*\right)$

The functions $F_1\left(Q, r, t_i, T^*, \phi^*\right)$ and $F_2\left(Q, r, t_i, T^*, \phi^*\right)$ are evaluated for different observation time t_i using a convolution technique. Let the observation time span be discretized by uniform time steps. In case of aquifer test, a convenient time step size is one minute as observations are generally made at different intervals of minutes. Accordingly, in the functions $F_1\left(Q, r, t_i, T^*, \phi^*\right), F_2\left(Q, r, t_i, T^*, \phi^*\right)$ and $F_3\left(Q, r, t_i, T^*, \phi^*\right)$, the unit of pumping rate is 1 m^3 per minute, and unit of transmissivity is m^2 per minute. Let $Q(i)$ be pumping rate during i^{th} time period. During recovery period, the pumping rate is zero. Under variable pumping rate, $Q(t)$, the drawdown $s(Q(i), T^*, \phi^*, r, n)$ at the end of n minutes is derived as follows (Morel- Seytoux, 1975)

$$\begin{aligned} s(Q(t), T^*, \phi^*, r, n) &= \int_0^n \frac{Q(\tau)}{4\pi T^*(n-\tau)} e^{-\frac{r^2\phi^*}{4T^*(n-\tau)}} d\tau \\ &= \int_0^1 \frac{Q(1)}{4\pi T^*(n-\tau)} e^{-\frac{r^2\phi^*}{4T^*(n-\tau)}} d\tau + \int_1^2 \frac{Q(2)}{4\pi T^*(n-\tau)} e^{-\frac{r^2\phi^*}{4T^*(n-\tau)}} d\tau + \ldots \\ &+ \int_{\gamma-1}^{\gamma} \frac{Q(\gamma)}{4\pi T^*(n-\tau)} e^{-\frac{r^2\phi^*}{4T^*(n-\tau)}} d\tau .., + \int_{n-1}^{n} \frac{Q(n)}{4\pi T^*(n-\tau)} e^{-\frac{r^2\phi^*}{4T^*(n-\tau)}} d\tau \\ &= \sum_{\gamma=1}^{n} Q(\gamma)\delta(n-\gamma+1) \qquad \text{....................} \qquad \text{(A11.18)} \end{aligned}$$

The unit response function coefficient $\delta(m)$ is given by:

$$\delta(m) = \int_0^m \frac{1}{4\pi T^*(m-\tau)} e^{-\frac{r^2\phi^*}{4T^*(m-\tau)}} d\tau - \int_0^{m-1} \frac{1}{4\pi T^*(m-1-\tau)} e^{-\frac{r^2\phi^*}{4T^*(m-1-\tau)}} d\tau$$

$$= \frac{1}{4\pi T^*} \int_{\frac{r^2\phi^*}{4T^*m}}^{\infty} \frac{e^{-u}}{u} du - \frac{1}{4\pi T^*} \int_{\frac{r^2\phi^*}{4T^*(m-1)}}^{\infty} \frac{e^{-u}}{u} du$$

$$= \frac{1}{4\pi T^*} W\left(\frac{r^2\phi^*}{4T^*m}\right) - \frac{1}{4\pi T^*} W\left(\frac{r^2\phi^*}{4T^*(m-1)}\right) \quad \text{……………………..} \quad \text{(A11.19)}$$

$W\left(\frac{r^2\phi^*}{4T^*m}\right)$ is Theis' Well function with argument $\frac{r^2\phi^*}{4T^*m}$. $W\left(\frac{r^2\phi^*}{4T^*m}\right)$ is an exponential integral. For argument *X*, the exponential integral, $W(X)$, is computed using the following polynomial approximation.

For $X \le 1$

$$W(X) = -\ln(\mathrm{X}) - 0.57721566 + 0.99999193\mathrm{X} - 0.24991055\mathrm{X}^2$$

$$+0.05519968 * \mathrm{X}^3 - 0.00976004\mathrm{X}^4 + 0.00107857\mathrm{X}^5 \quad \text{…….A11.20)}$$

For $X > 1$

$$Xe^X W(X) = \frac{\mathrm{X}^4 + 8.5733287\mathrm{X}^3 + 18.059017\mathrm{X}^2 + 8.6347608\mathrm{X} + 0.26777373}{\mathrm{X}^4 + 9.5733223\mathrm{X}^3 + 25.632956\mathrm{X}^2 + 21.099653\mathrm{X} + 3.9584969} \quad \text{….(A11.21)}$$

An Example

A set of synthetic observation data generated using $T = 0.1m^2/\min$ and storage coefficient $\phi = 0.001$ are as given in Table 1. Predict the T, ϕ making an initial guess $T^* = 0.01m^2/\min$ and $\phi^* = 0.003$. The piezometer is located at a distance of $20m$ from the pumping well. The pumping rate is $Q = 0.2m^3/\min$.

Table A11.1: Synthetic drawdown data generated using equation (A11.18)

Time of observation (min)	Observed Drawdown(m)	Time of observation (min)	Observed Drawdown(m)
1	0.035	60	0.562
2	0.089	70	0.587
3	0.132	80	0.608
4	0.166	90	0.626
5	0.195	100	0.643

6	0.219	120	0.671
7	0.24	140	0.696
8	0.258	160	0.717
9	0.275	180	0.736
10	0.29	200	0.752
12	0.317	230	0.774
14	0.339	260	0.794
16	0.359	290	0.811
18	0.377	320	0.827
20	0.393	350	0.841
25	0.427	380	0.854
30	0.455	410	0.866
35	0.478	440	0.877
40	0.499	470	0.888
50	0.534	480	0.891

Table A11.2: Convergence of T^* and ϕ^* with Successive Iteration

Iteration no	T^*	ϕ^*	ΔT	$\Delta\phi$	C(1)	C(2)
1	0.020507	0.004138666	1.05E-02	1.14E-03	0.00E+00	3.64E-12
2	0.040832	0.003697811	2.03E-02	-4.41E-04	-1.14E-13	0.00E+00
3	0.07088	0.001491592	3.00E-02	-2.21E-03	1.42E-14	0.00E+00
4	0.092492	0.001075698	2.16E-02	-4.16E-04	0.00E+00	-1.14E-13
5	0.099488	0.001004064	7.00E-03	-7.16E-05	0.00E+00	1.42E-14
6	0.099998	0.001000018	5.10E-04	-4.05E-06	0.00E+00	0.00E+00
7	0.1	0.001	2.42E-06	-1.81E-08	0.00E+00	0.00E+00
8	0.1	0.001	5.43E-11	-4.07E-13	0.00E+00	2.12E-22
9	0.1	0.001	2.98E-16	-9.44E-18	0.00E+00	-8.08E-28

Thus using synthetic drawdown data, we have checked that Marquardt Algorithm successfully predicts the true transmissivity and storage coefficient when the initial guess was different from the true value.

B. Determination of Transmissivity and Storage coefficient using data of an aquifer test conducted in a large diameter Well

In hard rock region, the shallow aquifers have low transmissivity ranging from 25 to 100 m^2/day Therefore, in hard rock region, wells with diameter ranging from 1 to 2 m are constructed to have reasonable yield. An aquifer test can be conducted in a large diameter well and the recovery data can be used for a reasonable estimate of storage coefficient and transmissivity.

Solution to unsteady flow to a dug-cum-bore well, that takes well storage into account, has been derived by Papadopulos and Cooper (1967). According to them, the well storage dominates the time-drawdown curve up to a time, *t*, given by $t = \left(25r_c^2\right)/T$ where r_c is radius of the well casing, and *T* is transmissivity of the aquifer. If a short duration aquifer test is conducted in a large diameter well, the transmissivity can be estimated reasonably well, but the storage coefficient may differ by an order of magnitude. This is because, the type curves presented by Papadopulos and Cooper contain straight line portions, which are parallel, and a short duration time-drawdown curve if matched with one of the straight lines, it could be matched as well with either of the adjacent straight lines. Discretising the time domain by uniform time steps, and generating unit response function coefficients from Thies' basic solution for unsteady flow to a well with small radius, Patel and Mishra (1983), Mishra and Chachadi (1985) have derived simple analytical solutions to unsteady flow during pumping, and during recovery respectively. These solutions, as well as that by Papadopulos and Cooper are applicable for a bore well with small radius having large casing.

Hantush has derived an analytical solution to unsteady flow to a well with finite radius assuming that all the water pumped is from aquifer storage. The effect of well storage on time drawdown curve has not been taken into account in the solution. Discretising the time domain by uniform time steps, and generating unit response function coefficients from Hantush's basic solution, we derive a simple analytical solutions to unsteady flow to a large diameter well during pumping and recovery. The well storage contribution during pumping, and well storage effect on drawdown have been accounted. After solving the direct problem, the inverse problem has been solved using the Marquardt Algorithm as described below. Pumping as well as recovery data could be used for estimating the aquifer parameters.

Let the total time of observation including pumping and recovery periods be discretised to N units of equal time steps of size Δt. Let the pumping continued until the end of m^{th} time step. During any time step n, the quantity of water pumped is sum of the quantity drawn from aquifer storage and the quantity drawn from well storage. Therefore,

$$\frac{Q_a\left\{(n-1)\Delta t\right\}+Q_a\left(n\Delta t\right)}{2}\Delta t+\frac{Q_w\left\{(n-1)\Delta t\right\}+Q_w\left(n\Delta t\right)}{2}\Delta t=\frac{Q_p\left\{(n-1)\Delta t\right\}+Q_p\left(n\Delta t\right)}{2}\Delta t \quad (1)$$

in which, $Q_a\left(n\Delta t\right)$, $Q_w\left(n\Delta t\right)$ and $Q_p\left(n\Delta t\right)$ are withdrawal rates from aquifer storage and well storage, and pumping rate respectively at time $t=n\Delta t$. The time step size Δt can be chosen conveniently. Incorporating $\frac{Q_a\left\{(n-1)\Delta t\right\}+Q_a\left(n\Delta t\right)}{2}=\bar{Q}_a\left(n\right)$ $\frac{Q_w\left\{(n-1)\Delta t\right\}+Q_w\left(n\Delta t\right)}{2}=\bar{Q}_w\left(n\right)$ and $\frac{Q_p\left\{(n-1)\Delta t\right\}+Q_p\left(n\Delta t\right)}{2}=\bar{Q}_p\left(n\right)$ in equation(1),

$$\bar{Q}_a\left(n\right)+\bar{Q}_w\left(n\right)=\bar{Q}_p\left(n\right) \quad \text{.......................... (A11.23)}$$

Let the well discharge be constant equal to Q_p. For $n\le m, \bar{Q}_p\left(n\right)=Q_p$; and for $n>m,\quad \bar{Q}_p\left(n\right)=0$.

Drawdown, $s_w\left(n\right)$, at the well face at the end of time step n is given by (Patel and Mishra, 1983)

$$s_w\left(n\Delta t\right)=\frac{1}{\pi r_c^2}\sum_{\gamma=1}^{n}\bar{Q}_w\left(\gamma\right)\Delta t \quad \text{............................... (A11.24)}$$

in which, $\bar{Q}_w\left(\gamma\right)$ is average withdrawal rate from well storage during time step γ. $\bar{Q}_w\left(\gamma\right)$ values are unknown a priori. A negative value of $\bar{Q}_w\left(\gamma\right)$ means replenishment of well storage from aquifer storage during time of recovery. r_c is radius of well casing. For some well r_c is equal to well bore radius r_w.

Following Duhamels' principle and method of convolution, drawdown at the well face at the end of time step $n\left(t=n\Delta t\right)$ due to abstraction from aquifer storage is given by (Morel-Seytoux, 1975)

$$s_a\left(r_w, n\Delta t\right) = \sum_{\gamma=1}^{n} \bar{Q}_a\left(\gamma\right)\delta\left(r_w, \Delta t, n-\gamma+1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.25)}$$

where $\delta\left(r_w, \Delta t, N\right)$ is a unit pulse response function coefficient derived from unit step response function using a time step size Δt (Morel-Seytoux, 1975) , and N is an integer. The kernel coefficient $\delta\left(r_w, \Delta t, N\right)$ is given by

$$\delta\left(r_w, \Delta t, N\right) = \frac{1}{\Delta t}\left\{U\left(r_w, N\Delta t\right) - U\left(r_w, \left(N-1\right)\Delta t\right)\right\}; N > 1 \quad \ldots\ldots\ldots\ldots \quad \text{(A11.26)}$$

For $N = 1,\ \delta\left(r_w, \Delta t, 1\right) = \frac{1}{\Delta t}U\left(r_w, \Delta t\right)$.

For well with small radius $U\left(r, I\Delta t\right)$ is the drawdown corresponding to unit pumping rate which could be computed using Theis' solution. The time step size Δt can be chosen conveniently. In an aquifer test, draw down observations are made at different intervals of minutes. Therefore, for solving an inverse problem, it is convenient to choose $\Delta t = 1$ minute. Accordingly, pumping rate is to be chosen in m^3 per minute and transmissivity in m^2 per minute. For a well with finite radius, the unit step response function has been derived by Hantush as given in **Annexure A11.1**

Assuming that there is no surface of seepage at the well face, the drawdown in the well is equated to the drawdown in the aquifer at the well face i.e. $s_w\left(n\right) = S_a\left(r_w, n\right)$. Equating equations (A11.24) and (A11.25)

$$\frac{\Delta t}{\pi r_c^2}\sum_{\gamma=1}^{n} \bar{Q}_w\left(\gamma\right) = \sum_{\gamma=1}^{n} \bar{Q}_a\left(\gamma\right)\delta\left(r_w, \Delta t, n-\gamma+1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad \text{(A11.27)}$$

From equation (A11.23)

$$\bar{Q}_w\left(n\right) = \bar{Q}_p\left(n\right) - \bar{Q}_a\left(n\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.28)}$$

Incorporating (A11.28) in (A11.27)

$$\frac{\Delta t}{\pi r_c^2}\sum_{\gamma=1}^{n}\left\{\bar{Q}_p\left(\gamma\right) - \bar{Q}_a\left(\gamma\right)\right\} = \sum_{\gamma=1}^{n} \bar{Q}_a\left(\gamma\right)\delta\left(r_w, \Delta t, n-\gamma+1\right) \quad \ldots\ldots\ldots\ldots\ldots \quad \text{(A11.29)}$$

Splitting each temporal summation into two parts, the first part up to $(n-1)^{th}$ step, and the second part the n^{th} step, incorporating $\Delta t = 1$ minute and solving for $\bar{Q}_a(n)$

$$\bar{Q}_a(n) = \frac{\sum_{\gamma=1}^{n} \bar{Q}_p(\gamma) - \sum_{\gamma=1}^{n-1} \bar{Q}_a(\gamma) - \pi r_c^2 \sum_{\gamma=1}^{n-1} \bar{Q}_a(\gamma)\,\delta(r_w, \Delta t, n-\gamma+1)}{1+\pi r_c^2 \delta(r_w, \Delta t, 1)} \quad \ldots\ldots\ldots \text{(A11.30)}$$

In particular for time step $n = 1$

$$\bar{Q}_a(1) = \frac{Q_p(1)}{1+\pi r_c^2 \delta(r_w, \Delta t, 1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.31)}$$

Assuming $Q_a(0)$ to be very near to zero,

$$Q_a(1) = \frac{2Q_p(1)}{1+\pi r_c^2 \delta(r_w, \Delta t, 1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.32)}$$

$\bar{Q}_a(n), n = 1, ..., N$ are solved in succession. After solving $\bar{Q}_a(n)$, for n=1, 2,…,N, the drawdown in the aquifer at any distance r is found generating the corresponding kernel coefficients $\delta(r, \Delta t, N)\left[= \frac{1}{\Delta t}\left\{U(r, N\Delta t) - U(r, (N-1)\Delta t)\right\}\right]$ and applying the convolution technique.

Having solved the direct problem, the inverse problem is solved next.

Solution to the Inverse Problem

Let T^* and ϕ^* be approximate values differing by ΔT and $\Delta\phi$ from the true transmissivity and storage coefficient of the confined homogeneous and isotropic aquifer which was at rest prior to the aquifer test. For solving the inverse problem, the objective function to be minimized is sum of the squares of the error, i.e., squares of the differences in observed drawdowns and predicted drawdowns corresponding to T^* and ϕ^*.

$$\underset{\Delta T,\, \Delta\phi}{Min}\left\{ \sum_{i=1}^{N} \left\{ s_0(i) - s_c\left(t_i, T^* + \Delta t, \phi^* + \Delta\phi\right)\right\}^2 \right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(A11.33)}$$

An initial guess is made for T^*, ϕ^* and ΔT and $\Delta\phi$ are solved through minimizing the error. The Taylor series expansion of $s_c(t_i, T, \phi)$ at $T = T^*$ and $\phi = \phi^*$, and neglecting higher order terms,

$$s_c\left(t_i, T^* + \Delta T, \phi^* + \Delta\phi\right) = s_c(t_i, T, \phi)\Big|_{T^*,\phi^*} + \left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*} \Delta T + \left.\frac{\partial s_c(t_i, T, \phi)}{\partial \phi}\right|_{T^*,\phi^*} \Delta\phi \quad \text{.....(A11.34a)}$$

The partial derivatives are to be determined numerically as follows:

$$\left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*} = \frac{s_c\left(t_i, T^* + \varepsilon_1, \phi^*\right) - s_c\left(t_i, T^*, \phi^*\right)}{\varepsilon_1} \quad \text{............ (A11.34b)}$$

$$\left.\frac{\partial s_c(t_i, T, \phi)}{\partial \phi}\right|_{T^*,\phi^*} = \frac{s_c\left(t_i, T^*, \phi^* + \varepsilon_2\right) - s_c\left(t_i, T^*, \phi^*\right)}{\varepsilon_2} \quad \text{.............. (A11.34c)}$$

where $\varepsilon_1, \varepsilon_2$ are small increments in transmissivity and storage coefficient.

Incorporating $s_c\left(t_i, T^* + \Delta T, \phi^* + \Delta\phi\right)$ i.e. equation (A11.34a), in equation (A11.33), the minimization problem reduces to

$$\underset{\Delta T,\,\Delta\phi}{Min}\left[\sum_{i=1}^{N}\left\{s_0(i) - \left(s_c(t_i, T, \phi)\Big|_{T^*,\phi^*} + \left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*} \Delta T + \left.\frac{\partial s_c(t_i, T, \phi)}{\partial \phi}\right|_{T^*,\phi^*} \Delta\phi\right)\right\}^2\right] \quad \text{..... (A11.35)}$$

Equating the partial derivative of the above objective function with respect to ΔT with zero

$$\left[\sum_{i=1}^{N} -2\left\{s_0(i) - \left(s_c(t_i, T, \phi)\Big|_{T^*,\phi^*} + \left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*} \Delta T + \left.\frac{\partial s_c(t_i, T, \phi)}{\partial \phi}\right|_{T^*,\phi^*} \Delta\phi\right)\right\} \left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*}\right] = 0 \quad (15)$$

Simplifying

$$\left[\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*}\right)^2\right\}\right]\Delta T + \left[\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c(t_i, T, \phi)}{\partial \phi}\right|_{T^*,\phi^*} \left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*}\right)\right\}\right]\Delta\phi$$
$$= \sum_{i=1}^{N}\left\{s_0(i)\left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*}\right\} - \sum_{i=1}^{N}\left\{s_c(t_i, T, \phi)\Big|_{T^*,\phi^*} \left.\frac{\partial s_c(t_i, T, \phi)}{\partial T}\right|_{T^*,\phi^*}\right\} \quad \text{........ (A11.37a)}$$

or

$$a(1,1)\Delta T + a(1,2)\Delta\phi = c(1) \quad \text{...................... (A11.37b)}$$

where

$$a(1,1)=\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\right)^2\right\};\ \mathrm{a}\left(1,2\right)=\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\right)\right\}\text{ and}$$

$$c(1)=\sum_{i=1}^{N}\left\{s_0\left(i\right)\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\right\}-\sum_{i=1}^{N}\left\{\left.s_c\left(t_i,T,\phi\right)\right|_{T^*,\phi^*}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\right\}$$

Similarly, equating the partial derivative of the objective function with respect to $\Delta\phi$ with zero

$$\left[\sum_{i=1}^{N}-2\left\{s_0\left(i\right)-\left(\left.s_c\left(t_i,T,\phi\right)\right|_{T^*,\phi^*}+\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\Delta T+\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\Delta\phi\right)\right\}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right]=0 \quad (17)$$

Simplifying

$$\left[\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\right)\right\}\right]\Delta T+\left[\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right)^2\right\}\right]\Delta\phi$$

$$=\sum_{i=1}^{N}\left\{s_0\left(i\right)\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right\}-\sum_{i=1}^{N}\left\{\left.s_c\left(t_i,T,\phi\right)\right|_{T^*,\phi^*}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right\} \quad \text{.... (A11.39a)}$$

or

$$a(2,1)\Delta T+a(2,2)\Delta\phi=c\left(2\right) \quad \text{.................... (A11.39b)}$$

where

$$a(2,1)=\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial T}\right|_{T^*,\phi^*}\right)\right\};\ a(2,2)=\sum_{i=1}^{N}\left\{\left(\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right)^2\right\}\text{ and}$$

$$c(2)=\sum_{i=1}^{N}\left\{s_0\left(i\right)\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right\}-\sum_{i=1}^{N}\left\{\left.s_c\left(t_i,T,\phi\right)\right|_{T^*,\phi^*}\left.\frac{\partial s_c\left(t_i,T,\phi\right)}{\partial \phi}\right|_{T^*,\phi^*}\right\}$$

The unknown ΔT and $\Delta\phi$ are solved from the algebraic equations (A11.37b) and (A11.39b)

Solving for $\Delta\phi$ and ΔT we get

$$\Delta\phi=\frac{\dfrac{c(1)}{a(1,1)}-\dfrac{c(2)}{a(2,1)}}{\dfrac{a(1,2)}{a(1,1)}-\dfrac{a(2,2)}{a(2,1)}} \quad \text{......................... (A11.40)}$$

and

$$\Delta T=\frac{c(1)}{a(1,1)}-\frac{a(1,2)}{a(1,1)}\Delta\phi \quad \text{......................... (A11.41)}$$

An Example

A set of synthetic observation data generated using $T = 0.015m^2/\min$ and storage coefficient $\phi = 0.3$ are as given in Table 1. Predict the T, ϕ making an initial guess $T^* = 0.01m^2/\min$ and $\phi^* = 0.2$. The drawdown is measured in the large diameter well of radius 1.725m. The pumping rate is $Q = 0.225m^3/\min$.

Table 11.3: Synthetic drawdown data

Time of observation (min)	Observed Drawdown(m)	Time of observation (min)	Observed Drawdown(m)
2	4.39E-02	30	5.12E-01
3	6.47E-02	35	5.81E-01
4	8.50E-02	40	6.47E-01
5	1.05E-01	45	7.10E-01
6	1.24E-01	50	7.70E-01
7	1.43E-01	60	8.85E-01
8	1.62E-01	70	9.92E-01
9	1.80E-01	80	1.09E+00
10	1.98E-01	90	1.19E+00
12	2.33E-01	100	1.28E+00
14	2.67E-01	120	1.44E+00
16	3.00E-01	140	1.59E+00
18	3.33E-01	160	1.73E+00
20	3.64E-01	180	1.86E+00
25	4.40E-01	200	1.98E+00

Table 11.4: Convergence of T^* and ϕ^* with Successive Iteration

Iteration no	T^*	ϕ^*	ΔT	$\Delta\phi$	C(1)	C(2)
1	0.01	0.2	0.002018	0.160276	0.00E+00	2.32E-09
2	0.012018	0.360276	0.002534	-0.05646	0.00E+00	-6.99E-09
3	0.014552	0.303812	0.000435	-0.00361	8.88E-16	3.81E-10
4	0.014987	0.300203	0.000012	-0.00018	0.00E+00	-2.10E-11
5	0.014999	0.300024	0.000001	-2.2E-05	1.73E-18	-2.50E-12
6	0.015	0.300002	0	-2E-06	0.00E+00	5.66E-13

Thus using synthetic drawdown data in a large-diameter well, we have checked that Marquardt Algorithm successfully predicts the true transmissivity and storage coefficient starting with an initial guess different from the true value.

C. Discrete Kernel, $\delta\left(r_w, \Delta t, N\right)$

Hantush(1964) has derived the well function for computation of drawdown in an artesian aquifer due to pumping from a fully penetrating well of finite radius starting from the basic solution given by Carslaw and Jaeger (1959) for an analogous heat conduction problem. Let the unit step response function for piezometric rise at the well face of a fully penetrating recharge well and a confined aquifer system be designated as $U\left(r_w, I\Delta t\right)$. According to Hantush (1964) it is given by :

$$U\left(r_w, N\Delta t\right) = \frac{1}{4\pi T}\left[\frac{4}{\pi}\int_0^{\infty}\{1-\exp(-\tau x^2)\}\ f_1(x)dx\right] \quad \text{.....................} \quad \text{(A11.41)}$$

in which,

$\tau = \frac{T\,t}{\varphi r_w{}^2}; t = N\Delta t;$ $f_1(x) = \frac{J_1(x)Y_0(\rho x) - J_0(\rho x)Y_1(x)}{x^2\left[J_1{}^2(x) + Y_1{}^2(x)\right]}$; $\rho = \frac{r}{r_w} = 1;$ $J_0(x)$, $J_1(x)$ = Bessel functions of first kind of zero and first order respectively; $Y_0(x)$ $Y_1(x)$= Bessel functions of second kind of zero and first order respectively; T= transmissivity (m^2/day), and ϕ=storativity of the aquifer; r_w = radius of the well or shaft(m).

The integral in (A11.41) is an improper integral as the upper limit of integration is infinite. The improper integral is reduced to a proper integral as described below.

$$I = \int_0^{\infty}\left[1-exp(-\tau x^2)\right] f_1(x)dx$$

$$= \int_0^{1}\left[1-exp(-\tau x^2)\right] f_1(x)dx + \int_1^{\infty}\left[1-exp(-\tau x^2)\right] f_1(x)dx$$

$$= I_1 + I_2$$

$$I_1 = \int_0^{1}\left[1-exp(-\tau x^2)\right] f_1(x)dx = 0.5\int_{-1}^{1}\left[1-exp\{\frac{-\tau(1+v)^2}{4}\}\right] f_1(\frac{1+v}{2})dv$$

Expanding the exponential term, and applying L' Hospital's rule, it can be shown that as v tends to -1, the integrand tends to 0. The integral I_1 is a proper integral and can be evaluated numerically using Gauss qudrature.

$$I_2=\int_1^{\infty}\left[1-exp(-\tau x^2)\right] f_1(x)dx=\int_0^1\left[1-exp(-\tau/v^2)\right] f_1(1/v)\frac{dv}{v^2}$$

$$=0.5\int_{-1}^{1}\left[1-\exp\left\{\frac{-4\tau}{(1+y)^2}\right\}\right] f_1(\frac{2}{1+y})\frac{4dy}{(1+y)^2}$$

Limit of the integrand at the lower is found as described below.

As $y\rightarrow -1$, $\left[1-exp\left\{\frac{-4\tau}{(1+y)^2}\right\}\right]\rightarrow 1$

$$[\frac{4}{(1+y)^2}]\ f_1(\frac{2}{1+y})=\left[\frac{4}{(1+y)^2}\right]\frac{J_1(\frac{2}{1+y})Y_0(\rho\frac{2}{1+y})-J_0(\rho\frac{2}{1+y})Y_1(\frac{2}{1+y})}{(\frac{2}{1+y})^2\left[J_1^2(\frac{2}{1+y})+Y_1^2(\frac{2}{1+y})\right]}$$

$$=\frac{J_1(\frac{2}{1+y})Y_0(\rho\frac{2}{1+y})-J_0(\rho\frac{2}{1+y})Y_1(\frac{2}{1+y})}{\left[J_1^2(\frac{2}{1+y})+Y_1^2(\frac{2}{1+y})\right]}$$

$$=\frac{J_1(\frac{2}{1+y})Y_0(\rho\frac{2}{1+y})}{\left[J_1^2(\frac{2}{1+y})+Y_1^2(\frac{2}{1+y})\right]}-\frac{J_0(\rho\frac{2}{1+y})Y_1(\frac{2}{1+y})}{\left[J_1^2(\frac{2}{1+y})+Y_1^2(\frac{2}{1+y})\right]}$$

As $y\rightarrow -1$, $Y_1(\frac{2}{1+y})\rightarrow 0$; hence,

$$\frac{J_1(\frac{2}{1+y})Y_0(\rho\frac{2}{1+y})}{\left[J_1^2(\frac{2}{1+y})+Y_1^2(\frac{2}{1+y})\right]}$$

$$\cong \frac{J_1(\frac{2}{1+y})Y_0(\rho\frac{2}{1+y})}{J_1^2(\frac{2}{1+y})} = \frac{Y_0(\rho\frac{2}{1+y})}{J_1(\frac{2}{1+y})} \frac{\sqrt{\frac{(1+y)}{\rho\pi}}\; sin\left(\frac{2\rho}{1+y}-\frac{\pi}{4}\right)}{\sqrt{\frac{(1+y)}{\pi}}\; cos\left(\frac{2}{1+y}-\frac{3\pi}{4}\right)}$$

=1 (since ρ =1)

Similarly,

$$\frac{J_0(\rho\frac{2}{1+y})Y_1(\frac{2}{1+y})}{\left[J_1^2(\frac{2}{1+y})+Y_1^2(\frac{2}{1+y})\right]} \rightarrow 1$$

Thus I_2 can be evaluated using Gauss qudrature.

Table A12.1 : Designated best uses of water

Designated Best Use	Class	Criteria
Drinking Water Source without conventional treatment but after disinfection	A	1.Total Coliforms Organism MPN/100ml should be less than 50 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 6mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 2mg/l or less
Outdoor bathing (Organised)	B	1.Total Coliforms Organism MPN/100ml should be less than 500. 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 5mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 3mg/l or less
Drinking water source which will be subjected to conventional treatment and disinfection	C	1. Total Coliforms Organism MPN/100ml may be 5000 or less 2. pH between 6 and 9 3. Dissolved Oxygen 4mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 3mg/l or less
Propagation of Wild life and Fisheries	D	1. pH between 6.5 and 8.5 2. Dissolved Oxygen 4mg/l or more 3. Free Ammonia (as N) 4. Biochemical Oxygen Demand 5 days 20 °C, 2mg/l or less
Irrigation, Industrial Cooling, Controlled Waste disposal	E	1. pH between 6.0 and 8.5 2. Electrical Conductivity at 25 °C micro mhos/cm, maximum 2250 3. Sodium absorption Ratio Max. 26 4. Boron Max. 2mg/l
	Below-E	Not meeting any of the A, B, C, D & E criteria

Table A12.2: Water Quality Standards in India (Source: IS 10500:1991)

Characteristics	Designated best use				
	A	B	C	D	E
Dissolved Oxygen (DO)mg/l, min	6	5	4	4	-
Biochemical Oxygen demand (BOD)mg/l, max	2	3	3	-	-
Total coliform organisms MPN/100ml, max	50	500	5,000	-	-
pH value	6.5-8.5	6.5-8.5	6.0-9.0	6.5-8.5	6.0-8.5
Colour, Hazen units, max.	10	300	300	-	-
Odour	Un-objectionable			-	-
Taste	Tasteless	-	-	-	-
Total dissolved solids, mg/l, max.	500	-	1,500	-	2,100
Total hardness (as $CaCO_3$), mg/l, max.	200	-	-	-	-
Calcium hardness (as $CaCO_3$), mg/l, max.	200	-	-	-	-
Magnesium hardness (as $CaCO_3$), mg/l, max.	200	-	-	-	-
Copper (as Cu), mg/l, max.	1.5	-	1.5	-	-
Iron (as Fe), mg/l, max.	0.3	-	0.5	-	-
Manganese (as Mn), mg/l, max.	0.5	-	-	-	-
Cholorides (as Cu), mg/l, max.	250	-	600	-	600
Sulphates (as SO_4), mg/l, max.	400	-	400	-	1,000
Nitrates (as NO_3), mg/l, max.	20	-	50	-	-
Fluorides (as F), mg/l, max.	1.5	1.5	1.5	-	-
Phenolic compounds (as C_2H_5OH), mg/l, max.	0.002	0.005	0.005	-	-
Mercury (as Hg), mg/l, max.	0.001	-	-	-	-
Cadmium (as Cd), mg/l, max.	0.01	-	0.01	-	-
Salenium (as Se), mg/l, max.	0.01	-	0.05	-	-
Arsenic (as As), mg/l, max.	0.05	0.2	0.2	-	-
Cyanide (as Pb), mg/l, max.	0.05	0.05	0.05	-	-
Lead (as Pb), mg/l, max.	0.1	-	0.1	-	-
Zinc (as Zn), mg/l, max.	15	-	15	-	-
Chromium (as Cr^{6+}), mg/l, max.	0.05	-	0.05	-	-
Anionic detergents (as MBAS), mg/l, max.	0.2	1	1	-	-
Barium (as Ba), mg/l, max.	1	-	-	-	-
Free Ammonia (as N), mg/l, max	-	-	-	1.2	-
Electrical conductivity, micromhos/cm, max	-	-	-	-	2,250
Sodium absorption ratio, max	-	-	-	-	26
Boron, mg/l, max	-	-	-	-	2

Table A12.3 : Locations, date of sampling and concentration of chemical constituents measured in the Jodhpur city area (Reference : Section 12.0)

S.NO.	PLACES	DATE	CHEMICAL PARAMETERS (mg/L)			
			TDS	Cl_2	NO_3	F
1		24-2-09	877	150	5	0.50
		13-8-09	897	140	5	1.10
		19-9-09	903	160	5	0.60
2	Toorji Ka Jhalra	24-2-09	1625	290	500	1.20
		18-9-09	1176	160	90	0.90
3	Gorinda Bawdi	24-2-09	1300	190	450	0.30
		25-3-09	1200	170	150	0.50
		17-9-09	1111	160	90	0.40
4	Golnadi	24-2-09	305	44	300	0.20
		18-9-09	682	100	5	0.60
5	Satya Narayan Bawdi	24-2-09	903	140	15	0.20
		13-8-09	1014	170	70	2.60
		19-9-09	1157	180	60	0.40
6	Mirchi Bazar Ghantaghar	24-2-09	1430	240	50	0.30
		19-9-09	1332	210	100	0.50
7	Loharo Ki Gali, Panna Niwas	24-2-09	1560	300	80	0.10
		19-9-09	1261	220	75	0.20
8	Bamba Masjid	24-2-09	871	150	10	0.40
9	Police line Bawdi	24-3-09	3220	740	350	3.50
		17-8-09	1430	220	175	3.40
		19-9-09	4420	1350	1870	3.00
		21-9-09	4420	1350	1875	3.20
		21-10-09	4322	1040	400	6.20
		24-12-09	4550	1120	900	7.17
10	Police line Kuyan	24-3-09	11560	3700	1500	3.60
		19-9-09	9100	2800	1250	5.00
		21-9-09	9100	2800	1200	4.60
		21-10-09	9295	3650	1125	4.50
		24-12-09	9035	2840	2500	4.00
11	Fateh nagar Talab	24-3-09	540	100	5	0.40
12	Old campus Kuyan	24-3-09	4630	1040	800	1.60
13	Gayu shala maidan kuya	24-3-09	5630	1680	800	1.00
		24-12-09	6012	2060	1250	0.64
14	Kharbooja bawdi	24-3-09	960	180	30	0.40
		19-8-09	702	100	40	0.50
		19-9-09	643	80	20	0.50
15	Tapi bawdi	25-3-09	732	80	20	0.30
		17-9-09	695	80	50	0.10
16	Ladji Ka Kuya	25-3-09	925	110	60	0.40
		17-9-09	780	90	60	0.30
17	Braham Bagh	25-3-09	1620	240	250	0.70

		17-9-09	1820	250	330	0.30
18	Harnathji Kuya	25-3-09	2000	330	215	1.70
		17-9-09	1950	340	250	0.60
19	Baiji ka talab	25-3-09	2900	770	5	0.40
20	Jalap bawdi	25-3-09	770	100	80	0.30
		17-9-09	754	100	40	0.20
21	Bodo ka kuya	25-3-09	950	120	125	0.30
		17-9-09	955	130	80	0.20
22	Narsingh Thada	25-3-09	780	100	100	0.30
		17-9-09	832	80	70	0.50
23	Dabgaro ka Kuyan	25-3-09	1360	180	250	0.50
		17-9-09	1495	200	200	0.70
24	Najraji ki bawdi	25-3-09	1000	120	15	0.30
		13-8-09	838	100	70	0.50
		17-9-09	845	100	60	0.20
25	Vimalraj ji ka Kuyan	25-3-09	1200	140	150	0.80
		17-9-09	1189	140	100	0.70
26	Achalnath bawdi	25-3-09	1590	220	300	0.60
		17-9-09	1189	140	100	0.70
27	Nehru park	25-3-09	2330	460	175	1.00
		17-9-09	1170	180	100	0.60
28	Bheru Bagh	26-3-09	1050	120	100	3.70
29	Krishan Mandir Ratanada	17-8-09	2470	600	350	1.30
		24-3-09	2080	430	350	0.80
		18-9-09	6045	1950	500	0.80
		21-9-09	2275	480	400	0.80
		21-10-09	2210	470	400	1.10
30	Kiya Ka Jhalra	19-8-09	533	80	20	0.80
		19-9-09	525	80	20	1.00
31	Jalechi Jhalra	19-8-09	708	100	60	0.60
		19-9-09	663	100	40	0.40
32	Vidhyashala	19-8-09	975	160	90	0.80
		19-9-09	650	80	35	0.30
33	Ram bawdi	19-8-09	682	100	30	0.40
		19-9-09	650	100	35	0.40
34	Raghunath bawdi	19-8-09	663	90	20	0.60
		19-9-09	650	90	30	0.30
35	Vishnoi dharamshala	24-3-09	1760	340	250	1.00
		19-9-09	1690	310	100	0.80
		21-9-09	1690	310	100	0.90
		21-10-09	1657	320	175	1.40
		24-12-09	1625	340	300	1.20
36	Subhash chowk	24-3-09	5320	1380	700	1.50
		18-9-09	4875	1950	625	0.60
		21-9-09	4875	1950	625	0.80
		21-10-09	4582	1280	900	1.10
		24-12-09	3770	1080	900	1.45
37	Jnana park bawdi	24-3-09	7360	2080	1500	0.70

		19-9-09	5981	2200	800	0.80
		21-10-09	3445	830	450	1.40
		24-12-09	4550	1320	1500	1.23
38	Chand bawdi	25-3-09	640	120	25	0.30
39	Kotwali bera, Navchowkiya	25-3-09	350	62	12	0.20
		17-9-09	468	60	20	0.20
40	Vyas park	25-3-09	480	70	16	0.40
		17-9-09	240	30	5	0.30
41	Naleshwar Kuya	25-3-09	430	68	5	0.40
		17-9-09	240	30	5	0.20
42	Tapadiya bera	25-3-09	540	80	30	0.60
43	Mata ka kund	25-3-09	820	150	60	0.50
		19-9-09	201	28	6	0.20
44	Navlakha bawdi	19-9-09	7280	3600	800	0.90
		21-9-09	7280	3600	750	0.60
		21-10-09	5980	1900	800	0.70
		24-12-09	4485	1400	1500	1.12
45	Shanicharji ka than	17-9-09	2080	360	175	0.60
46	West Patel nagar	19-9-09	2080	500	160	2.20
		21-9-09	2080	500	150	2.40
		21-10-09	1430	280	80	1.60
		24-12-09	1775	390	225	1.60
47	Maheshwario Ka Bagicha	19-9-09	6045	1900	875	0.60
		21-9-09	6045	1800	800	0.60
		21-10-09	6045	1520	900	1.00
		24-12-09	5915	1560	1500	1.25
48	Suraj kund	19-9-09	377	60	20	0.50
49	Aasan Kuya	18-9-09	1495	280	150	0.50
50	Pawta B. Road	24-8-09	2730	730	300	4.00
51	Lakshmi nagar II	24-8-09	1495	290	375	3.40
52	Shakti nagar II	7/9/2009	1625	350	300	3.00
53	Lakshmi nagar park	7/9/2009	1495	230	125	1.80

Table A12.4 : Concentration of groundwater quality constituents of different locations in the Jodhpur City area (2009).

S.NO.	Location	$EC*10^6$ micro-siemens/cm at 25^0c	TDS	pH	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	SO_4^{2-}	$Co3^{2-}$	$HCo3^{2-}$	No^{3-}
1	Chand Baori	440	240	7.9	14	5	62	12	28	0	0	207	14
2	Raghu nath Baori	1220	645	7.7	62	16	108	44	85	34	0	500	46
3	Suraj kund	680	454	8.1	30	11	104	19	50	53	0	342	16
4	Ram Baori	450	252	8.1	17	30	46	12	28	0	0	220	8

5	Jalechi baori	1300	834	8.2	100	27	144	23	142	72	0	403	124
6	Kriya Jhalra	2300	1215	7.7	150	176	92	36	177	120	0	513	207
7	Kharbooja Baori	1730	1077	7.6	175	44	114	56	241	163	0	537	15
8	Umaid	10200	7372	8.2	1327	70	371	328	2057	985	0	488	1990
9	Umaid Udhyan	6400	3895	7.8	649	141	289	173	1007	432	0	488	961
10	Toorji ka Jhalra	2300	1489	8.1	251	285	20	66	305	255	0	574	21
11	Gorunda Baori	1120	684	7.8	78	34	92	44	142	10	0	452	59
12	Shardul Bhawan Baori	3700	2242	7.8	338	188	186	64	440	298	0	513	471
13	Kailana, Filter House		180	8.2			56	50	30		106		2
			180	7.4			56	54	30		110		2

Table A13.1 : Details of the small water bodies in and around the Jodhpur city (Reference : Section 13.0).

S.No	Waterbody Name	Longitude	Latitude	Perimeter (km)	Area (Sq. km)
1	Baiji ka talab	73.0336	26.3001	0.5676	0.017702
2	Bal samand Lake	73.0217	26.3324	1.3688	0.058785
3	Fateh sagar	73.0295	26.2965	0.5291	0.015306
4	Gulab Sagar	73.0254	26.2970	0.6139	0.017686
5	Guru ka talab	72.9820	26.2979	2.1151	0.061934
6	Jaswant thada	73.0246	26.3040	0.5394	0.007698
8	Kaylana Lake	72.9732	26.3079	23.6186	0.824213
9	Manasagar	73.0431	26.3082	0.4653	0.012666
10	Padamsar talab	73.0157	26.2994	0.6296	0.008227
11	Ranisar talab	73.0166	26.2990	0.5490	0.006955
12	Sursagar	73.0110	26.3129	1.0337	0.048338
13	Takht sagar	72.9692	26.2889	12.0486	0.486942
14	Tal sagar	73.0554	26.3314	1.6055	0.038024
15		72.9621	26.2973	0.3079	0.001735
16		72.9624	26.2986	0.6593	0.010696
17		73.0464	26.2860	0.8684	0.023305
18		73.0378	26.2746	0.4230	0.009298
19		73.0388	26.3134	0.4116	0.006187
			Total	**48.3543**	**1.66**