Groundwater modelling using FDM in Chaksu region, Jaipur (India)

Ph.D. THESIS

by

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MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY, JAIPUR

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Groundwater Modelling using FDM in Chaksu region, Jaipur (India)

This thesis is submitted

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by

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DECLARATION CERTIFICATE (Candidate)

I, NIDHI POONIA, declare that this thesis titled Groundwater Modelling using FDM in Chaksu Region, Jaipur (India) is my own bonafide work. The work has been carried out under the supervision of Dr. Mahender Choudhary, Associate Professor, Civil Engineering, Malviya National Institute of Technology Jaipur. I confirm that:

i. This work has been done wholly or mainly while in candidature for a PhD degree at MNIT Jaipur.
ii. Where any part of this thesis has previously been submitted for a degree or any other qualification at MNIT Jaipur or any other institution, this has been clearly stated.
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v. I have acknowledged all main sources of help.
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SUPERVISOR’S CERTIFICATE

This is to certify that the thesis report entitled “**Groundwater Modelling using FDM in Chaksu Region, Jaipur (India)**” being submitted by **Ms. Nidhi Poonia** to the Malviya National Institute of Technology, Jaipur for the award of the degree of Doctor of Philosophy, is a bonafide record of research work carried out by her under my supervision and guidance. The thesis work, in my opinion has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy.

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ABSTRACT

Groundwater being the major source of fresh water is being utilized by domestic, industrial and agriculture sectors worldwide. The present developmental activities have put pressure on the groundwater and the results are in the form of depleting groundwater level. Quantitative assessments of groundwater resources require conceptualization, quantification and modelling of often vast, complex and heterogeneous groundwater systems. Chaksu being in close proximity to Jaipur and historically rich in groundwater resources is selected for present study. Chaksu Tehsil of Jaipur district in Rajasthan covers the southern part of the Jaipur district. Pace of decline in water level has caused drying up of dug wells and compelled farmers to get these deepen by boring or replacing by tube wells and thereby incurring additional expenditure for well deepening and pumpage. A regional groundwater flow model was developed for the Chaksu region. The finite difference code, MODFLOW was chosen to solve the equation for hydraulic heads in the study area. MODFLOW has a modular structure that allows it to be modified to adapt the code for special applications. The groundwater flow modelling results reveals that the general groundwater flow is from north-west to south-eastern direction. In calibration, the RMS error has been found to be 5.154 % whereas the NRMS error came out to be 6.693 %. Simulations indicate the mean recharge rates are 130 mm/yr in Chaksu watersheds, which represent 16% of mean annual precipitation.

Key words: Groundwater, Groundwater Modelling, MODFLOW, Simulation, Calibration, RMS

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LIST OF ABBREVIATIONS USED

USGS: United States Geological Survey
BCM: Billion Cubic Meters
GEC: Groundwater Estimation Committee
CGWB: Central Groundwater Board
NCIWRD: National Commission for Integrated Water Resources
GIS: Geographical Information System
MCM: Million Cubic Meters
PPM: Parts Per Million
RMS: Root Mean Square Error
NRMS: Root Mean Square Error

LIST OF SYMBOLS USED

Symbols	**Explanation**
h	Hydraulic Head
x,y,z,t	Spatial Dimensions and Time
$K_{xx,}$ $K_{yy,}$ K_{zz}	Hydraulic Conductivities in X, Y And Z Direction
S_s	Aquifer's Specific Storage
W	Volumetric Flux Per Unit Volume Representing Sources and/or Sinks of Water
e	Unknown Function Derived By The Use Of Taylor Series Expansion
K_f	Hydraulic Conductivity
S_o	Storage
W	Well Function
S	Drawdown;
T	Transmissivity
e_i	Average Of The Absolute Errors
h_s	Simulated Head
h_m	Measured Head

CHAPTER-1

INTRODUCTION

1.1 GENERAL

Water being the prime requirement for all the living beings, is becoming a rare resource in the world (Gupta 2015). The International Water Management Institute predicts that, in India alone by 2025, one person in three will live in conditions of absolute water scarcity (IWMI 2003). Groundwater is the major source of freshwater being utilized by domestic, industrial and agriculture sectors worldwide. Since our dependency on groundwater as source of freshwater has increased, large extent of groundwater contamination has become issue of public concern worldwide (Pye and Kelle 1984). The consequences of groundwater contamination are that it makes the resource unusable due to the fact that groundwater has high residence time. And making resource unusable put pressure on the already limited groundwater resource. The present developmental activities again put pressure on the already depleting groundwater thereby deteriorating water quality.

Due to its nature, direct observation and quantification of groundwater is not possible. Quantitative assessments of groundwater resources require conceptualizing, quantifying and modelling of vast, complex and heterogeneous groundwater systems. Therefore, the need arises for practical and cost-effective methods for characterization of groundwater that could be applied in the real-world groundwater management. Thus, keeping into mind all the above conditions, mathematical modelling provides a good synthetic insight into functioning of groundwater systems.

An essential characteristic of groundwater systems are time scales of the inherently coupled processes of water flow and solute transport. Knowledge of travel time between recharge and discharge sites of groundwater is important for consideration of how disturbances like contamination and effects of land-use and climate changes propagate through the groundwater system. Through mathematical modelling and application of tracers, we can obtain the travel time distributions of water and solutes. This information is then used to quantify time lags associated with responses of the system for both commencement and cessation of these disturbances, as well as to quantify mixing properties of the geological medium that influence dispersion and removal of contaminants. The essential components related to groundwater flow for understanding and quantitative characterization are:

1. Three-dimensional structure of groundwater flow paths;
2. Timescales of water flow and solute transport;
3. Water fluxes across interfaces between system components.

To locate and link recharge and discharge areas, it is important to have the knowledge of groundwater flow paths. Therefore in this regard, specific attention is given to groundwater and surface water interactions, examples of which are indirect recharge from rivers and lakes and discharge of groundwater to them. Groundwater also plays an important role as an essential supporting element for various types of groundwater dependent ecosystems. For reliable monitoring and predictions of contaminant movement, comprehensive three-dimensional structure of water flow paths even in unconfined, relatively homogeneous aquifers is required.

For sustaining the good water quality, wise use of this natural resource is necessary. There is need to understand and maintain every water cycle component as shown in Fig1.1 for sustainability of water resources (USGS 2016). Groundwater constitutes one of the major components of the hydrological cycle.

The modern techniques like remote sensing satellite data, geographical information system, (GIS), geophysical investigation and mathematical modelling help in searching potential groundwater sites and in planning, developing and managing of water resources.

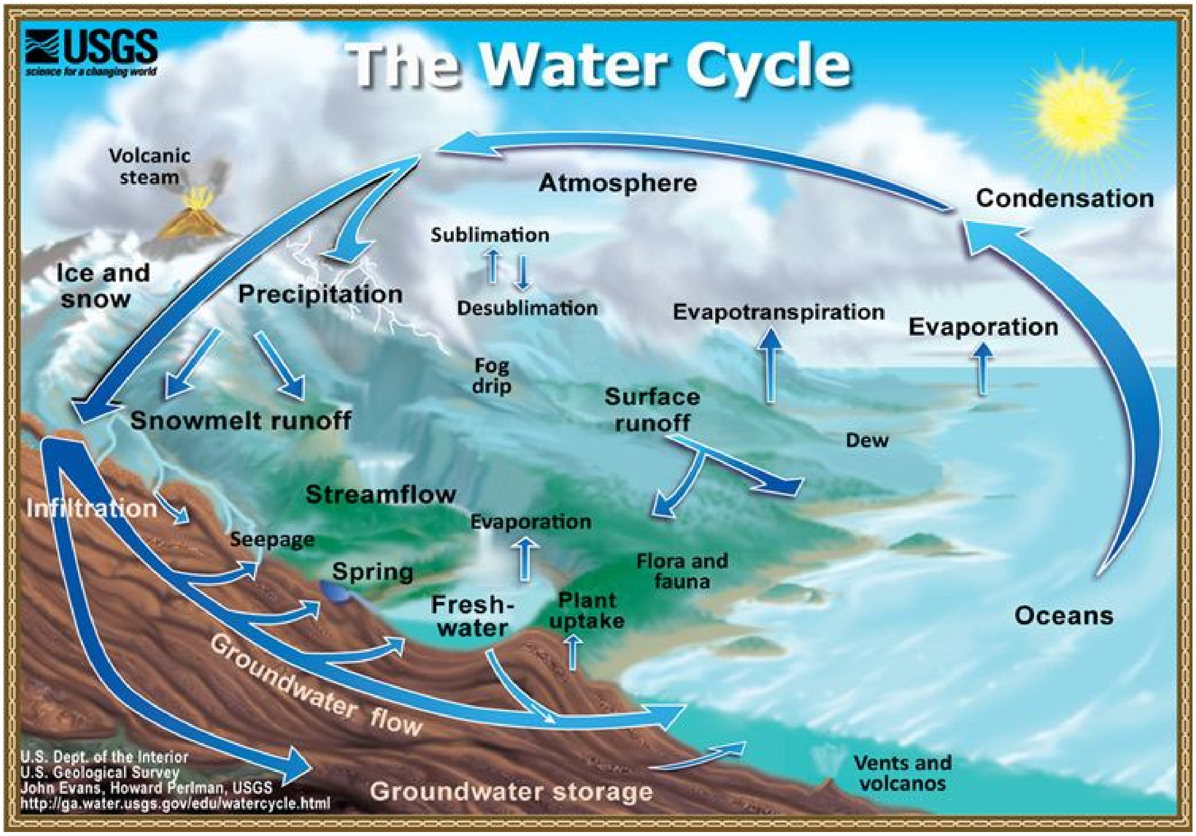


Fig.1.1: Hydrological Cycle (USGS 2016)

Chaksu region of the Jaipur district in Rajasthan, India falls in a semiarid region. Jaipur is witnessing fast economic growth along with the Indian economy. Lot of new projects like SEZ, Metrorail, New universities and Institutions are coming up in and around Jaipur. Chaksu being 40km away from Jaipur has location advantage of fast economic growth but it is not able to keep pace mainly owing to reducing water availability and deteriorating water quality. The groundwater is the main resource being used by the competing user sectors such as agriculture, domestic and industrial sectors. It is therefore important to understand the behavior of groundwater flow. However prior to this it would be highly desirable to know about the global and national status and challenges being faced by global water resource in general and that of groundwater in particular.

1.2 GLOBAL WATER SCENARIO

About 97% of the water available on Earth is found in oceans which due to its high salt contents, cannot be used by living beings. The remaining 3% water is fresh water that can be of use by living beings. Out of this 3% fresh water, 68.7% is covered as icecaps and glaciers, 30.1% as groundwater and 0.9% as surface water. The 0.9% surface water covers 2% in rivers, 11% in swamps and 87% in lakes (Fig 1.2) (USGS, earth water).

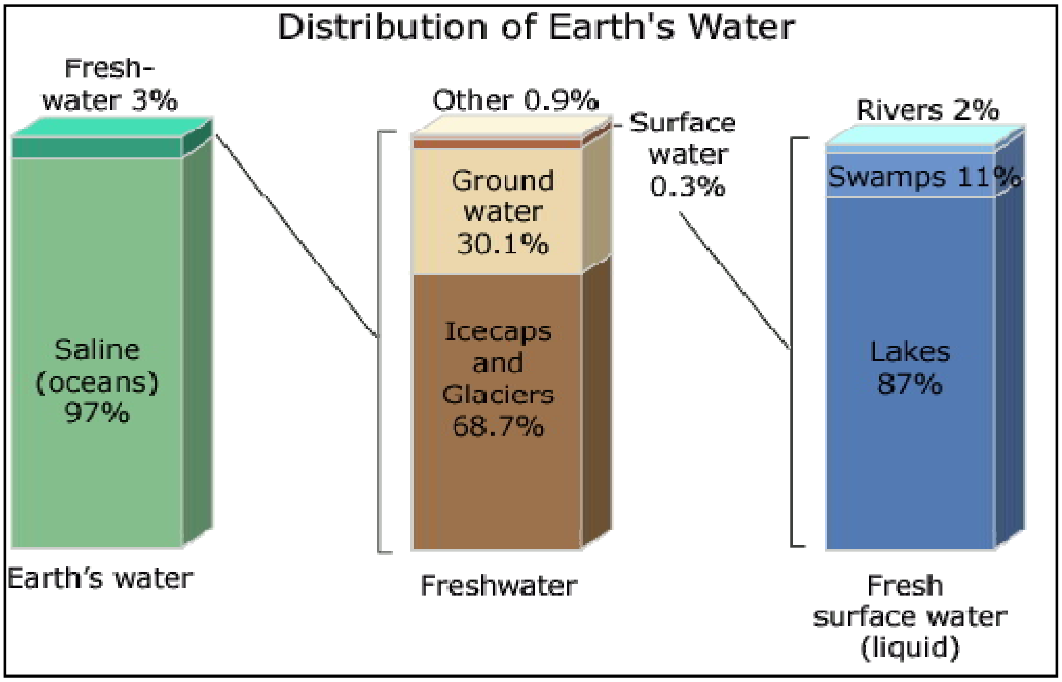


Fig.1.2: Earth's Distribution of Water (USGS, earth water)

In the world, 67% water is consumed in agricultural sector followed by households 9%; water supply 8%; electricity and gas 7%; manufacturing 4%; mining 25 % and other uses 3% (Fig 1.3) (www.climate.org/topics/water.html).

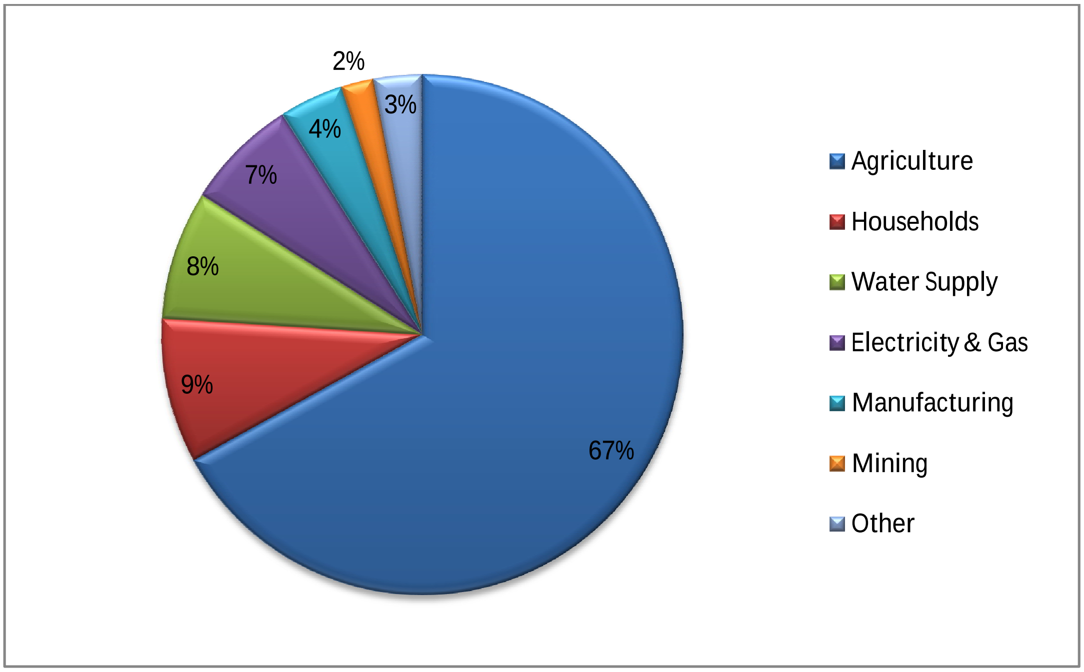


Fig.1.3: Fresh Water Use (www.climate.org/topics/water.html)

Although the water availability exceeds its use on the global scale, the main problem is that water resources are not evenly distributed in space or time thus, affecting the per capita water availability. Most of the regions of the world are experiencing the water stress situation particularly dry regions. The major factors affecting the global water resources future are:

1. Population growth;
2. Economic growth;
3. Changes in production and trade patterns;
4. Increasing competition over water because of increase in demands for domestic, industrial and agricultural purposes; and
5. The way in which different sectors of society will respond to increasing water scarcity and pollution.

The above factors have been quoted in Global Water Future 2050. This is a study on how to prepare the upcoming generation for coming water scenarios by UNESCO and the United Nations World Water Assessment Program (Cosgrove and Cosgrove 2012; Gallopin 2012). In this study, ten different drivers of change are identified as an important tool to assess water resources in future: technology, water stocks, demography, economy, water infrastructure, climate, policy, environment, social behaviour, and governance. Table 1.1 illustrates the global water distribution on the earth. The water resource distribution in terms of cubic miles as well as cubic kilometres have been enumerated (Shilomanov 1993).

Table 1.1: Estimate of Global Water Distribution (Percents are rounded, so will not add to 100)

Water Source	**Water Volume, (Miles 3)**	**Percent of Fresh water**	**% of Total Volume**
Oceans, Seas, & Bays	321,000,000	--	96.5
Ice caps, Glaciers, & Permanent Snow	5,773,000	68.7	1.74
Ground water	5,614,000	--	1.69
Fresh	2,526,000	30.1	0.76
Saline	3,088,000	--	0.93
Soil Moisture	3,959	0.05	0.001
Ground Ice & Permafrost	71,970	0.86	0.022
Lakes	42,320	--	0.013
Fresh	21,830	0.26	0.007
Saline	20,490	--	0.006
Atmosphere	3,095	0.04	0.001
Swamp Water	2,752	0.03	0.0008
Rivers	509	0.006	0.0002
Biological Water	269	0.003	0.0001

1.3 GLOBAL GROUNDWATER CHALLENGES

Groundwater plays a major role in both hydrologic and human systems. The majority of the world's drinking water is provided from groundwater (Vrba and Vandergun 2004). In the last half century, there has been a tremendous boom in agricultural groundwater use which in turn has provided improved livelihoods and food security to billions of farmers and consumers. However, this boom may soon turn into bust as increased groundwater use has also created problems, since groundwater being the critical dissolving, mobilizing and transport medium for the contaminants. The major global challenges associated with groundwater use are-

1. The groundwater consumption is increasing in every sector resulting in the overexploitation of groundwater and thus, creating the problem of water scarcity even for drinking purposes.
2. The urban areas are the hot spot for over-exploitation of groundwater because of high density population, industrial and commercial needs.
3. The ecological imbalance has been created due to overexploitation of groundwater.
4. The scarcity of groundwater triggers the recurring droughts and less crop production which in turn create food scarcity.
5. Consequences of climate change increase groundwater exploitation and may alter and reduce the groundwater recharge.

To address such challenges significant international meetings have been held globally (First World Water Forum 1997; the Second World Water Forum 2000; and the World Summit on Sustainable Development 2002). More events held globally have shown that the global water resources issue has achieved a central place in discussions about international economic development and environmental policy. Such discussions require an overview and assessment of the current and future world water scenarios.

Despite the above challenges, one most important challenge is the uneven distribution of the rainfall on the earth as depicted in Fig 1.4(CPC unified precipitation). Precipitation being the major source of groundwater recharge, its unequal distribution affects the groundwater occurrence.

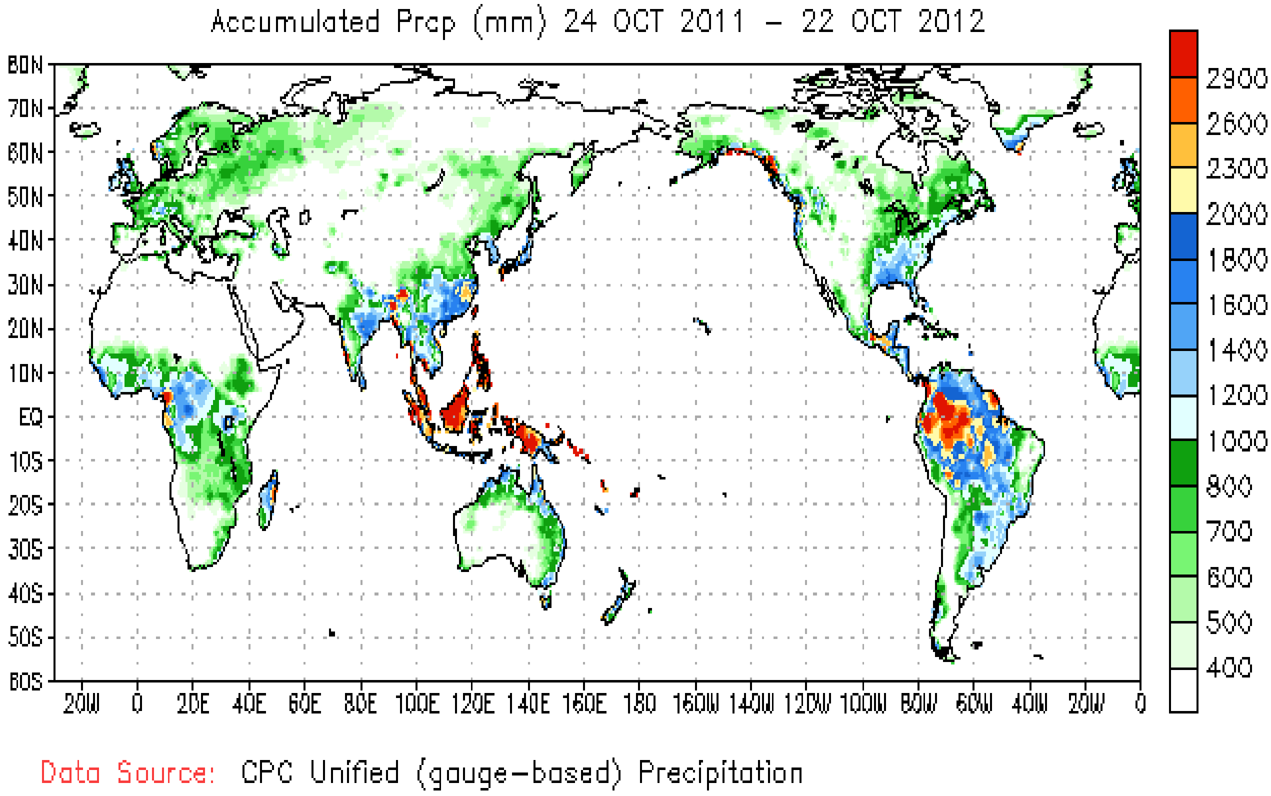


Fig. 1.4: Uneven Global Precipitation (CPC unified precipitation)

1.4 GROUNDWATER RESOURCES SCENARIO IN INDIA

Groundwater is the most preferred source of water in India’s various user sectors due to its near universal availability, dependability and low capital cost. In the growth of India’s economy and socio economic development, groundwater plays an important catalyst and has its own significant contributions. More than 85 percent of India’s rural domestic water requirements, 50 percent of its urban water requirements and more than 50 percent of its irrigation requirements are being met from ground water resources (Jha 2007). The increasing dependency on ground water has resulted in its large-scale and indiscriminate development in various parts of the country, without due regard to the recharging capacities of aquifers. India being a vast country has highly diversified hydrogeologic set-up. The complex ground water behavior is mainly due to the occurrence of diversified geological formations with considerable lithological and chronological variations, complex tectonic framework, climatological dissimilarities and various hydro chemical conditions. The rock formations in India range in age from Archaean to Quaternary-Recent period. The Archaean rocks cover the southern states where as the recent sediments are confined to Indo-Gangetic alluvial plains. There are three major geological formations in India:

1. Consolidated formations: This formation is represented by igneous and metamorphic rocks. The rock type included in this consists of granites, charnockites, quartzites and phyllite, slate etc;

2. The semi consolidated rock formations: This type of formations is represented by rocks of mesozoic and tertiary period with rock types represented by limestone, sandstone, pebbles and boulder conglomerates.

3. The unconsolidated formations: This formation belongs to pleistocene to recent period and is represented by rocks such as boulders, pebbles, different grade of sands, silt-clay.

These rocks form the major potential aquifer zones in India as shown in Fig 1.5 (Jha and Sinha 2008).

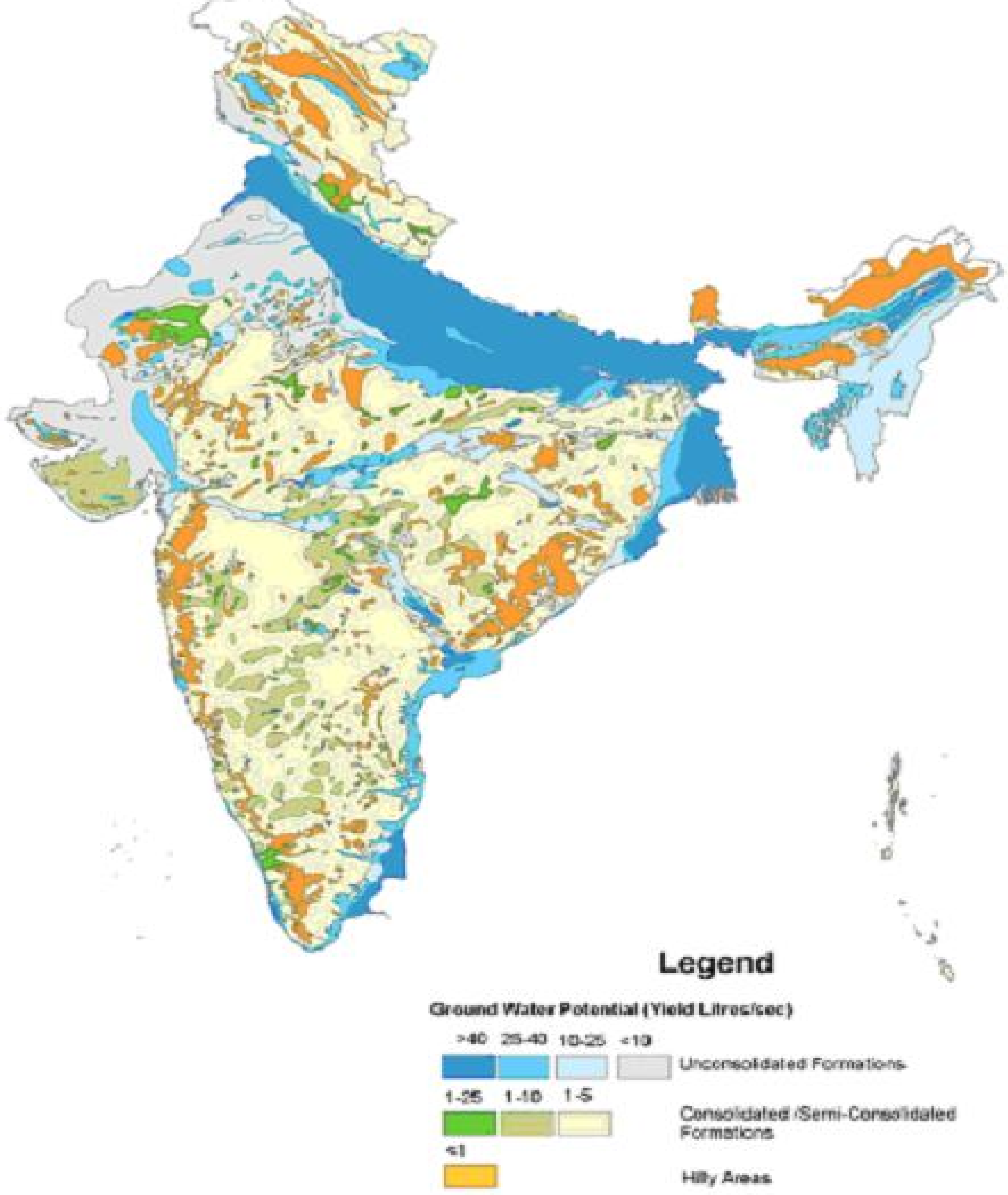


Fig.1.5: Hydrogeological Map of India (Jha and Sinha 2008)

The whole coverage and groundwater potential for different aquifer system in India has been shown in Table 1.2 (CGWB 2006).

Table 1.2: Ground Water System in the Country (CGWB 2006)

System	Coverage	Ground Water Potential
Unconsolidated Formations - Alluvial	Indo - Gangetic, Brahmaputra Plains	Enormous reserves down to 600 m depth. High rainfall and hence recharge is ensured. Can support large-scale development through deep tube wells.
	Coastal Areas	Reasonably extensive aquifers but risks of saline water intrusion.
	Part of Desert area - Rajasthan and Gujarat	Scanty rainfall, Negligible recharge. Salinity hazards, Availability at great depths.
Consolidated / Semi-Consolidated formations-sedimentary, Basalts and Crystalline rocks	Peninsular Areas	Availability depends on secondary porosity developed due to weathering, fracturing etc. Scope for groundwater availability at shallow depths (20-40 m) in some areas and deeper depths (100 -200 m) in other areas. Varying yields.
Hilly	Hilly States	Low storage capacity due to quick runoff.

Based on reports of all the states and union territories, the groundwater resource of the country has been estimated. These estimations are as per the technical guidance of Research and Development Advisory Committee on groundwater estimation. Groundwater resources have been estimated as per GEC’97 methodology and are depicted in Appendix I (Groundwater Scenario of India 2009).

The annual replenishable groundwater resource for the entire country is 433 billion cubic meter (bcm). The assessed ground water is the dynamic resource that is replenished each year. This replenishable groundwater resource is contributed by two sources i.e. rainfall and sources that include canal seepage, irrigation return flow, seepage from water bodies and artificial recharge due to water conservation structures. The overall contribution of rainfall to groundwater resource is 67% and the share of other sources taken together is 33%. State-wise groundwater resources of India as on March, 2004 is given in appendix I. In India, the most prevalent contributor of rainfall is south-west monsoon. Thus, about 73% of country’s annual groundwater recharge takes place during the kharif period of cultivation. The net groundwater available for utilization for the entire country is 399 bcm. The annual groundwater draft is 231 bcm, out of which 213 bcm is for irrigation use and 18 bcm for domestic and industrial use. In general, the irrigation sector remains the main consumer of ground water with about 92% of total annual ground water draft for all uses.

India’s dependency on precipitation for surface water and subsurface water flow is high on account of the fact that India is a monsoon country. Average rainfall in India is about 1170 mm. The total precipitation comes out to be about 4000 bcm. There is wide variation in the spatial distribution of rainfall in the country. The average annual rainfall varies from about 1000 cm in north-eastern part of the country to less than 10 cm in the western part of the country as shown in Fig 1.6(Ministry of water resources 2011). In India, the rainfall mostly occurs during the monsoon and that too through a few spells of intense rainfall. It has been estimated that 33% of net sown area falls in lower rainfall zone (less than 750 mm annual rainfall). The medium rainfall zone (750-1125 mm) accounts for 35% of net sown area, the high rainfall zone (1125 to 2000 mm) covers 24% of net sown area where as very high rainfall zone (more than 2000 mm) covers remaining 8% of net sown area.

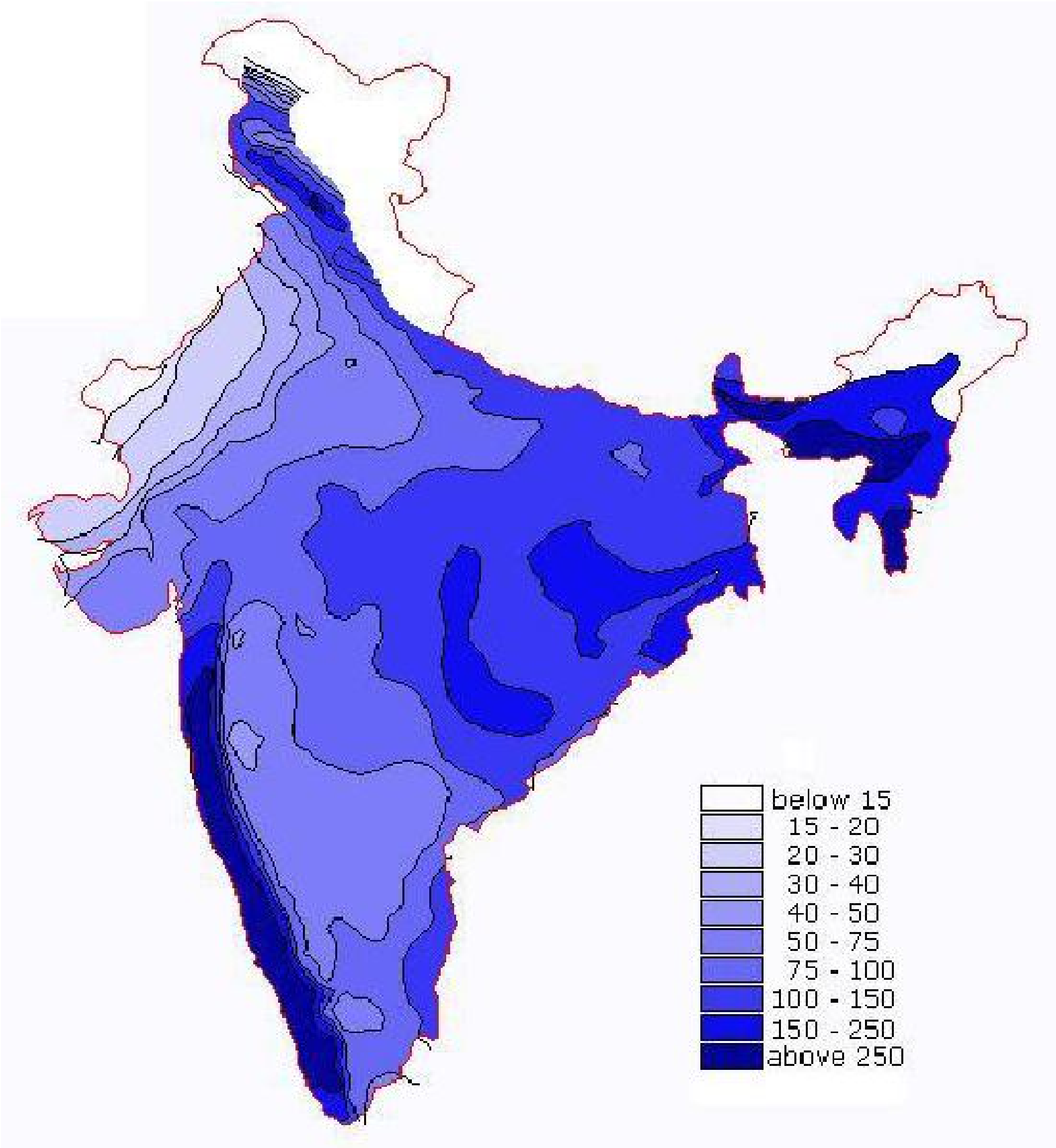


Fig.1.6: Spatial Variation in Rainfall (cm) (Ministry of water resources 2011)

The GEC’97 recommends that for assessing the alluvium, the assessment unit could be block, but for hard rock, it should be watershed. Out of 5723 assessed administrative units 4078 units were found to be ‘Safe’, 550 units were ‘Semi-critical’, 226 units were ‘Critical’, 839 units were ‘Over-exploited’ and 30 units were ‘Saline’. Number of over-exploited and critical administrative units was found to be significantly higher in Andhra Pradesh, Delhi, Gujarat, Haryana, Karnataka, Punjab, Rajasthan and Tamil Nadu and also the union territories of Daman & Diu and Pondicherry. Fig 1.7 (GEC’97) shows the categorization of units on the basis of their exploitation status.

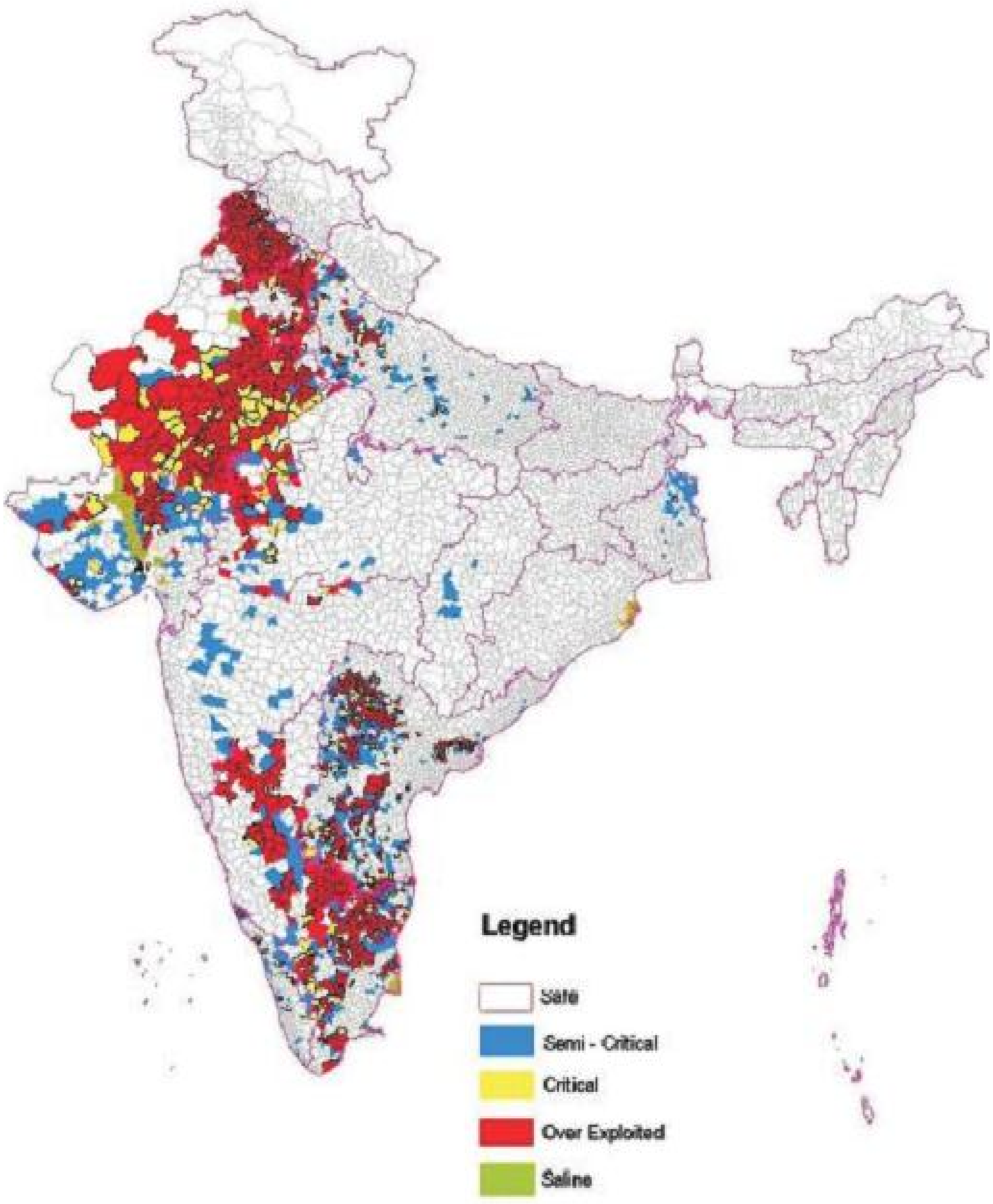


Fig. 1.7: Categorization of Units on the Basis of Exploitation Status (GEC'97)

The total annual water available in India has been estimated to be 1869 bcm. But, owing to hydrological characteristics and topographical constraints, the water that can be utilized works out to be only 1123 bcm, out of which about 690 bcm is from surface water and about 433 bcm is through replenishable ground water. In India there are considerable variations in availability of water as in the case of rainfall. About 60% of the total annual water available in country is contributed by the Ganga-Brahmaputra river basin. The basin-wise average annual water availability is given in Table 1.3(Ministry of water resources 2011).

Table 1.3: Basin-wise Average Annual Water Availability

S. No.	River Basin	Average Annual Water Availability (in BCM)
1	Indus	73.31
2	Ganga sub-basin	525.02
	Brahmaputra & Barak sub-basin	585.6
3	Godavari	110.54
4	Krishna	78.12
5	Cauvery	21.36
6	Pennar	6.32
7	East Flowing Rivers between Mahanadi and Pennar	22.52
8	East Flowing Rivers between Pennar and Kanyakumari	16.46
9	Mahanadi	66.88
10	Brahmani and Baitarni	28.48
11	Subarnrekha	12.37
12	Sabarmati	3.81
13	Mahi	11.02
14	West Flowing Rivers of Kutchh, Saurashtra including Luni	15.1
15	Narmada	45.64
16	Tapi	14.88
17	West Flowing Rivers from Tapi to Tadri	87.41
18	West Flowing Rivers from Tadri to Kanyakumari	113.53
19	Area of Inland Drainage in Rajasthan Desert	Negligible
20	Minor River Basins Draining into Bangladesh and Myanmar	31
	Total	1869.37

The largest uncommitted surface water volume is available in the Ganga-Brahmaputra and Meghna Basin, but as the water table is within 3m in most parts of the basin, the sink is limited. The largest sink is available in the Indus Basin since the water table depth here is more than 15m in most of the area, but the uncommitted surface water volume is restricted. The uncommitted surface water for recharge is also limited in the Krishna, Cauvery, Pennar, Sabarmati, Mahi and Tapi Basins although aquifer space is available in these hard rock areas (Ministry of Water Resources 2011).

1.5 GROUNDWATER CHALLENGES IN INDIA

1. Decrease in per capita water availability

In India, per capita water availability is decreasing. For the year 1951, the per capita water availability was 5177 cubic meter for 361 million populations which have become 1027 cubic meter for 1820 million populations in year 2010 (Table 1.4) (Ministry of Water Resources 2011).

Table 1.4: Per Capita Water Availability in the Country

Year	Population (In Millions)	Per Capita Water Availability (Cubic Meter)
1951	361	5177
2010	1027	1820
2025 (Projected)	1394	1341
2050 (Projected)	1640	1140

2. Irrigation development in agriculture sector

The gross ultimate irrigation potential has been estimated to be about 139.9 million hectare (Mha). In the year 1951, the total irrigation potential created was about 22.6 Mha. About 108 Mha i.e. about 77% of the ultimate irrigation potential has since been created. The ultimate irrigation potential and the irrigation potential created through various projects are given in Table 1.5.

Table 1.5: Ultimate Irrigation Potential and Irrigation Potential Created (in Mha)

Description	Major & Medium	Minor		Total
		Surface Water	Ground Water	
Ultimate Irrigation Potential	58.47	17.38	64.05	139.9
Potential Created	45.26	15.84	47.11	108.21
Balance Potential	13.21	1.54	16.94	31.69

3. Increase in demand of water

Water demand in every sector is increasing day by day, which ultimately will lead to shortage of water in future. As the population increases, the water demand also increases since water requirements increases. National Commission for Integrated Water Resources Development (NCIWRD) assessed the water demand for the years 2010, 2025 and 2050. NCIWRD has made assessment both for low and high demand scenario in the year 2050 (Table 1.6).

Table 1.6: Projected Demand for Water for Various Uses (in BCM)

Uses	Year 2010		Year 2025		Year 2050	
	Present Demand	% of Total Demand	Projected Demand	% of Total Demand	Projected Demand	% of Total Demand
Irrigation	557	78%	611	72%	807	68%
Domestic	43	6%	62	7%	111	9%
Industries	37	5%	67	8%	81	7%
Environment	5	1%	10	1%	20	2%
Others	68	10%	93	12%	161	14%
Total	710	100%	843	100%	1180	100%

4. Deteriorating Groundwater Quality

As a result of chemical and biochemical interactions between water and geological materials through which it flows and contributions from atmosphere and surface water bodies, groundwater contains wide varieties of dissolved inorganic chemical constituents. Groundwater in shallow aquifers is mainly of calcium bicarbonate and mixed type and is suitable for use for different purposes. Only in some cases, ground water has been found unsuitable for specific use due to various contaminations mainly because of geogenic reasons.The quality of groundwater is declining day by day. Some common geogenic groundwater problems in various parts of the country are high fluoride, iron, nitrate, arsenic and salinity.

5. Reducing water table depth

Depth of water table is declining in north-western, western and southern parts of the country. The groundwater level scenario (premonsoon 2013) of over-exploited blocks in the country is shown in Fig 1.8 (CGWB 2013).

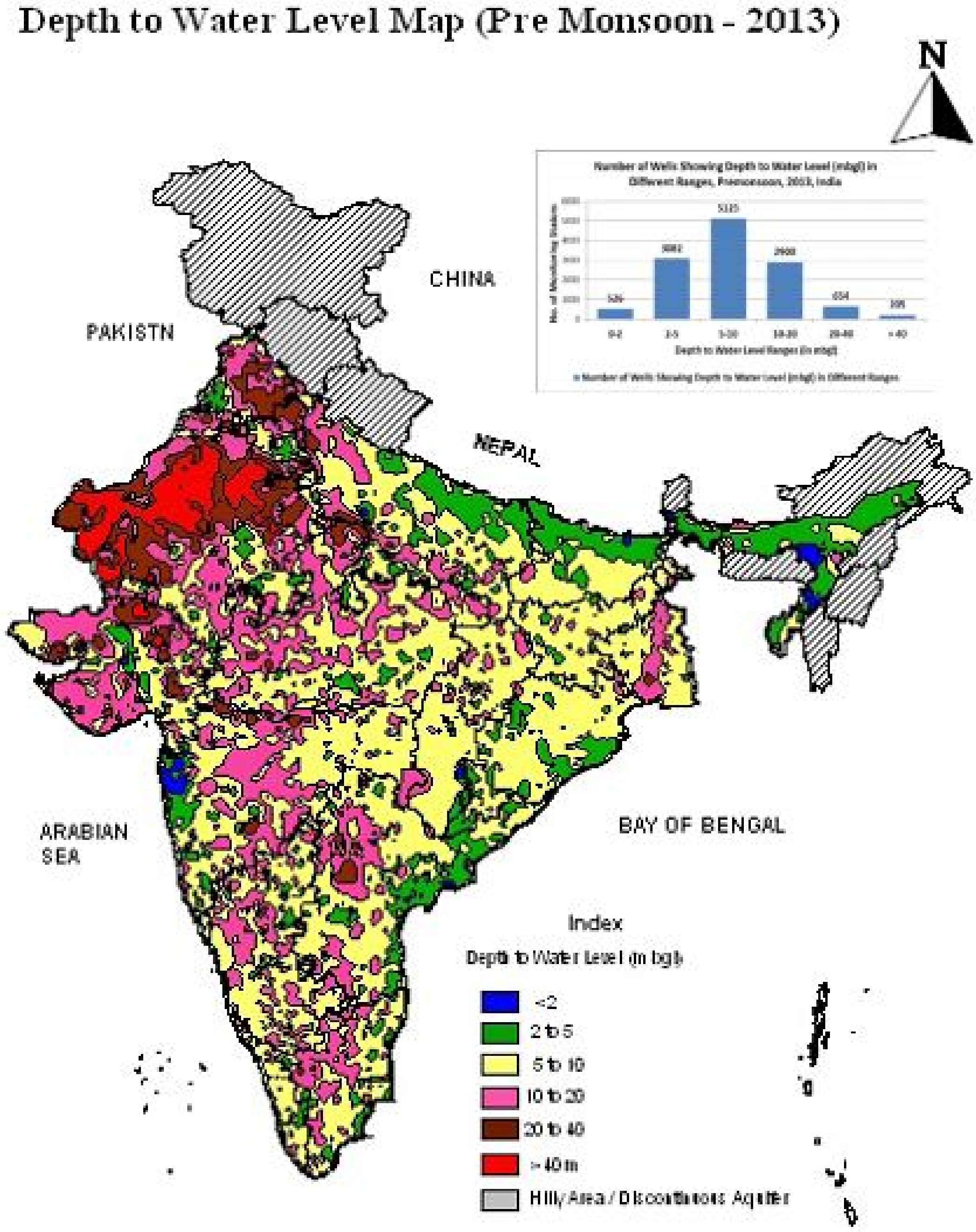


Fig.1.8: Depth of Water level –Premonsoon 2013 (CGWB 2013)

1.6 Study Area

Chaksu Tehsil of Jaipur district in Rajasthan is the study area mainly covering the southern part of the Jaipur district, falling under the Survey of India Toposheet nos 45N/13; 45N/14 and 54-B/2. The geo-coordinates of Chaksu are 26°36′N latitude to 75°57′E longitude (Fig.1.9) covering more than 200.sq. km**.** area. Geomorphologically, the region have alluvial plain area while geologically, the area has rocks of Archaean age and blown sand. The main river in the block is Dhund River. It has an average elevation of 297 m (974 ft).

The important aspect of the study area is that it falls in sub catchment Zone of Morel Rivers which is ephemeral in character. The region is in close proximity of Jaipur city and is suffering from depleting groundwater level and deteriorating groundwater quality. High fluoride groundwater and salinity has adversely affected the health of the community of this region. Groundwater is the main source of drinking water as well as agriculture use. In view of the alarming water situation it has become essential to understand the behavior of groundwater flow and its interaction with the other component of the environment prevalent in this region.

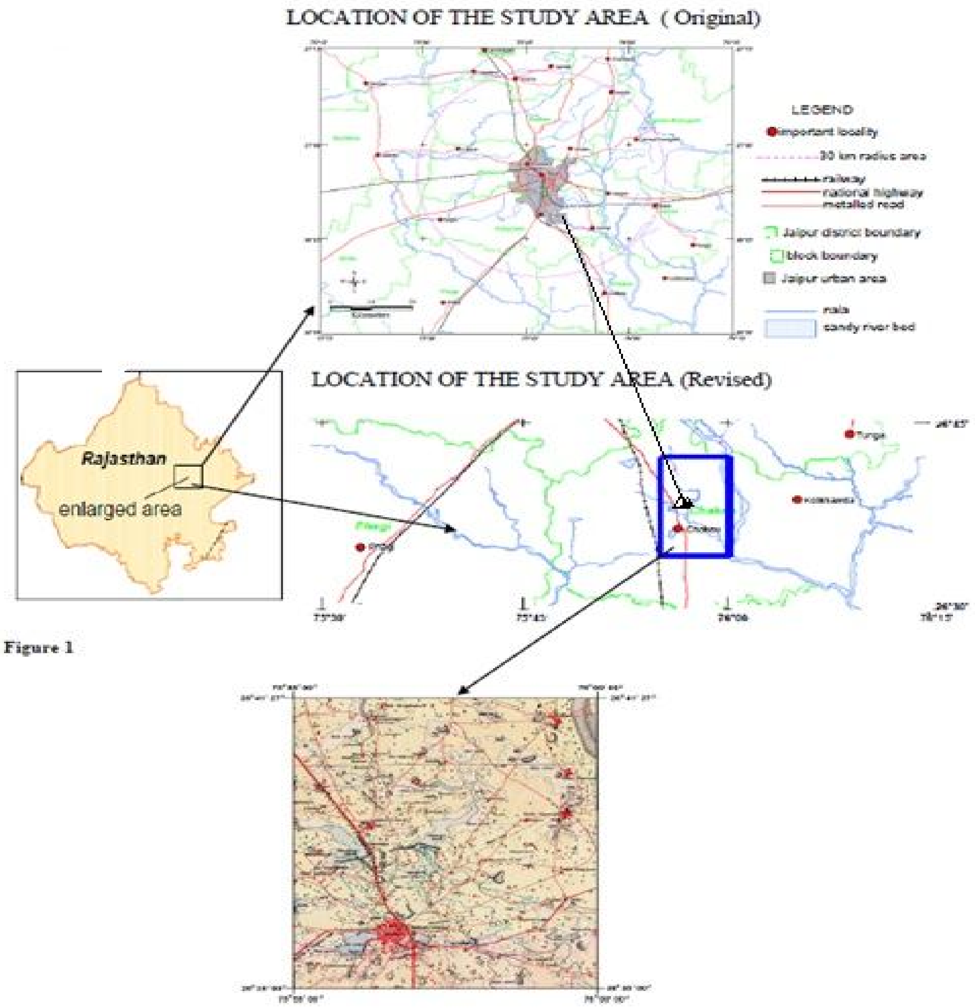


Fig.1.9: Location Map of Chaksu Block

Chaksu is well connected to other parts of the state. In Chaksu block, the main type of soils are loamy sand to sandy loam; sandy clay loam; sandy clay; wind-blown and river sand (District Groundwater Brochure, 2007, CGWB, Jaipur). The major land use/land cover categories in the block are given in Table 1.7 (CGWB 2007).

Table 1.7: **Land use/Land cover in Chaksu Block**

Land Use/Land Cover	Area (Sq. Km.)	Percentage of Total Area
Area not suitable for cultivation (Forest, Hills, Pasture land, Barren land, Ponds)	265.92	25.33
Area suitable for cultivation but not under cultivation	66.99	6.38
Area under cultivation	479.01	45.62
Area under irrigation	238.06	22.67
Total	1049.98	100.00

1.7 AIMS AND OBJECTIVES

The main aim of this study is to present conceptual framework and operational tools for groundwater system characterization as related to surface waters and dependent ecosystems. It also includes assessment and prevention of threats to groundwater quantity and quality.

Elaboration of adequate groundwater characterization tools are required to protect groundwater resources from deterioration. Both directives explicitly recognize that knowledge of flow patterns in groundwater bodies is an inherent element of risk assessment and management schemes.

The investigation being presented here is carried out with following objectives:

1. To study the movement of groundwater and long term behavior of groundwater in space and time.
2. To evaluate the groundwater balance of the study area.
3. To develop and execute a numerical groundwater flow model for the semi-arid and environmentally stressed Chaksu region.
4. To infer future predictions of groundwater regime.

1.8 SCOPE OF PRESENT STUDY

The groundwater is the main freshwater source being used by all sectors in the Chaksu block. The groundwater model generated gives spatial and temporal pattern view of the groundwater flow and its behavior in the block under different scenario which helps in planning, development and management of groundwater in the study area.

A regional groundwater flow model was developed for the Chaksu region. The study consisted of two main parts:

1. Data collection: The first part was to collect necessary data, from existing databases and previous studies. To determine possible locations for groundwater monitoring and measure groundwater levels, field trips of the study area were planned.
2. Model development: The second part was the development of conceptual and numerical groundwater flow model. After the numerical groundwater flow model development, the model was calibrated and verified using two different observation sets of groundwater level data. Hydraulic head contour maps and maps showing groundwater flow directions were generated and interpreted with respect to local hydrogeology and groundwater withdrawals. Finally, the distribution of seasonal groundwater decline with respect to future scenarios was determined using the developed model.

1.9 BRIEF DESCRIPTIONS OF THE CHAPTERS

The Thesis is divided into five chapters. The brief description of the chapters is given below:

Chapter-1 which is introductory one contains the general aspects of water resources at global and groundwater scenario at national level. Brief description of study area, aims and objectives and scope of the study are also discussed.

Chapter-2 describes the detailed literature review of work already done by various authors.

Chapter-3 describes the hydrogeological status of the Chaksu area. The chapter contains the geological setup, aquifer systems, water table depth and groundwater flow, water table fluctuation and groundwater quality of the study area.

Chapter-4 carries the theoretical consideration important for groundwater modeling technique

Chapter- 5 describes the development of groundwater flow modelling and the model output predictions under varying scenarios.

Chapter- 6 sums up the entire research which has been carried out stating its importance and significance for better understanding the groundwater regime of the area. It also puts forward certain recommendations which may be used for long term water management and planning.

CHAPTER 2

LITERATURE REVIEW

2.1 LITERATURE SURVEY

The groundwater hydraulics and dynamics has been a major area of research for decades. Henry Darcy (1856) was the one who initiated the study on groundwater hydraulics (Brown and Glenn 2002). Later similar work was done by Slitcher (1899) and King (1899). Study of geohydrology and change in groundwater storage over time (Meinzer 1928; Meinzer 1923) were carried out in detail. Contribution to groundwater movement and flow were put forward by Hubbert (1940) and Jacob (1940). By advent of computers using numerical modelling and integrated approaches, further advancements in groundwater studies were done. Water resources managers aiming to streamline supply and demand often rely on numerical models as useful water management tools (Johnston and Smakhtin 2014).The part of groundwater research that is presently receiving great importance in India is numerical modelling of aquifer system. Aquifer parameters affect the quantity of water flowing through them. To model complex aquifer, numerical flow and transport models have been used for mapping wellhead protected areas. Most of the widely used groundwater flow models assume the media flow to be porous, which is the flow, associated with granular aquifer and fractured rock aquifer. Toth (1962, 1963) developed a theoretical understanding and analytical formulation of groundwater systems and distribution of recharge– discharge areas in small drainage basins. A transient groundwater flow model for the confined aquifer under the Afyon Plain in Turkey was developed by Atilla (2002). As per the decline in piezometric level and water quality deteriorating conditions, the prediction of the overexploitation effects requires that the current head distribution be identified. Winter (1978) simulated three-dimensional groundwater flow near lakes and investigated the conditions of seepage.

Flow modelling of groundwater aquifer system was done by several people like Bear (1988), Mc Donald and Harbaugh (1988), Franz and Guigerm (1990), Khublarian et al (1990), Wilson Guiger and Thomas Franz (1996). Bronders and De Smedt (1985) developed and applied regional groundwater models specifically aimed at predicting groundwater discharge and the location of the saturated source areas. Stoertz and Bradbury (1989) used the budget calculation of MODFLOW with a specified, measured water table configuration, to calculate flows to (discharge) and away from (recharge) the water table. . Hunt et al. (1996) followed this approach for simulation of groundwater inflow to a wetland system. Using recharge distribution coefficients, finite element simulation of phreatic flow domain was done by Sulekha and Rastogi (1997). They have carried studies consisting of recharge from rainfall, seepage from canal and irrigation return flow over normal input to lager aquifer system. Determination of the quantity of net recharge into aquifer is very difficult. Pumping and others sources that contributes to aquifer are generally difficult to estimate exactly. Reeve et al. (2001) used MODFLOW in modelling the regional groundwater flow to peatlands, and the DRAIN package to remove surface runoff and to constrain the simulated phreatic water level to the land surface.

Unsteady flow in subsurface, surface and their hydrology has been investigated for seepage loses and groundwater flow (Neuman and Witherspoon 1971; Pinder and Gray 1977; Yeh 1981 and Rastogi and Prasad 1992). In a coastal plain of the Seto Inland Sea, Japan, Wang et al. (2007) developed three-dimensional finite element model for groundwater flow characterization. Groundwater flow realization (GFR) models based on finite element method were used by Rai (2002) for understanding the dynamic groundwater flow behaviour in the region of schoneiche, a German municipality, disposal site.

Water balance modelling with emphasis on basin wise spatial distribution of groundwater recharge was done by Sophocleous and McAllister (1998). They formulated budget, by using minimal daily weather as input data and soil plant-water system. They characterised spatial distribution of hydrologic components of water balance within the basin. Study on numerical stimulation of groundwater flow to understand the hydrodynamics in Bukeleru river basin in Nalgonda district, a granitic terrain was done by Thangarajan (1999). This study indicates that the phreatic aquifer can sustain the present reduced cost of adhoc experimentation. Two dimensional steady state sea water intrusion problems were solved by non-linear solute transport model by Rastogi and Ukaranda (2002). They determined the field parameters like discharge, hydraulic conductivity influence on sea water intrusion and found productive results. Aquifer modelling of Ganga-Mahawa sub basisn has been attempted by Ala-Eldin et al. (2000) to integrate all available information and provided a tool that could be used for predictive simulation. For the preliminary assessment of the impact of red mud packing on the aquifer system, solute modelling studies was done in Orissa by Dhar et al. (1994). More pollutant migration researches were carried on by Subba Rao et al. (1997) and Sheng (1997). They formulated underground stimulation model for groundwater pollution. They coupled unsaturated and saturated models successfully and provided new technique for solute transport modelling. Similar study was carried on by Bear (1988).

A numerical modeling study for the groundwater system in the Akaki catchment of central Ethiopia was conducted by Ayenew, Demlie and Wohnlich (2007). For quantification of the groundwater fluxes and for analyzing the subsurface hydrodynamics in the catchment, a three dimensional steady state finite-difference groundwater flow model was developed.

Afshari, Mandle, and Li (2008) applied an integrated hierarchical patch dynamics paradigm (HPDP) to model detailed well dynamics and interactions. It helped in converting a large complex problem into a network of hierarchically nested and dynamically coupled patch models and thus solve the model easily. Andras and Thorne (2001) developed a model for groundwater and surface water interactions. They proved that a groundwater model coupled with surface water model can be a key water resource management tool for supporting feasibility studies and designing drainage network capable for controlling flood waters. Chahar and Dhaka (2013) formulated a groundwater model for Banas river basin, Rajasthan. The model outputs presented an insight to groundwater scenarios of research area and evaluated that there is a need for judicious and planned management of resources. Russo et al. (2015) analyzed coastal groundwater basin for assessing of the suitability for managed aquifer recharge and impact of managed aquifer recharge activities on groundwater levels. And found out that managed aquifer recharge increases the groundwater levels.

Groundwater flow model for catchments – Osmansagar and Himayathsagar- was developed using MODFLOW for year 2005 to 2009 by Varalakshmi et al. (2014). Model outputs indicated that the average input to the aquifer system is 321.96 mcm whereas the output is 322.14 mcm. If the same conditions prevailed, the water level will decline to more than 45m in the study area. Thus to avoid such critical stage, the present draft must be decreased by about 40%. A transient numerical model for evaluating the relation of accelerated pumping during draught period was developed by Moustadraf, Razack and Sinan (2008). This accelerated pumping lead to well desertion due to intrusion of sea water in the Chaouia coat aquifer, Morocco.

Neupauer (2015) used the MODFLOW software as groundwater flow simulator, to simulate the stream depletion by using the standard and adjoint approaches. The outputs from the model helped in eliminating the candidate well location, leading to stream depletion. The reduction in the stream flow rate by pumping from groundwater wells, connected hydraulically to stream, causes stream depletion. Rejani et al. (2007) developed a two dimensional groundwater flow and transport model of Balasore coastal groundwater basin in Orissa using visual MODFLOW package. The model was developed to analyze the aquifer response to five different pumping scenarios under existing cropping conditions. Sensitivity analysis of the model indicated that the aquifer system in question is more sensitive to rainfall recharge, river seepage and interflow than the hydraulic conductivities and specific storage. The results also suggested that for proper management of the basin, pumpage from the second aquifer must be reduced to 50% in downstream region whereas pumpage from the first and second aquifer at potential locations must be increased by 150%.

Ahmed and Umar (2009) presented a groundwater flow modelling study of Yamuna-Krishini inter stream, Uttar Pradesh. River boundary package was used for simulation of river aquifer interaction. Water balance deficit period for June 2006 to June 2007 was shown in zone budget results. The deficit balance was 73.35 mcm. The model was more sensitive to recharge parameters and hydraulic conductivities. Assessment of potential for irrigation water as a base study was conducted by Palma and Bentley (2007) in Leon Chinandega basin. They formulated a regional flow model for simulation of transient conditions using MODFLOW. Study on sustainable aquifer development and management was carried on by Sakiyan and Yazicigil (2004) for Kucuk Menderes basin.

Kumar (2005) developed a finite difference steady state model using MODFLOW for Nalgonda, Andhra Pradesh. Conceptual model was prepared for two layered fractured aquifer system. Results computed that the groundwater levels are in good agreement with observed levels. A field scale ground water model was prepared by Robinson and Gallagher (1999) for simulation of near shore hydrological processes linked with groundwater discharge from unconfined coastal aquifer.

2.2 HYDROGEOLOGY

To have a better management of groundwater, a proper understanding of aquifer system characterization, groundwater level fluctuation, and recharge and groundwater flow mechanisms is required. Importance of hydrogeology is well explained by Chow (1964). Later detailed study on groundwater assessment, evaluation and management in relation to water resources and hydrological engineering were initiated by several authors (Walton 1970; Todd 1980; Price 1985; Karanth 1987; Ramesham 1987; Ward and Robinson 1989 and Ragunath 1990). Heath (1984) have carried out notable studies in the field of urban and basic groundwater hydrology. Hydrogeological studies mainly targeting on groundwater gained importance (Altovsky 1959; Brown et al. 1972; Lawrence and Balasubramanian 1994; Howard et al. 1996; Nour 1996; and Pulido et al. 1997).Singh and Gupta (1999) did a detailed study on infiltration and artificial recharge. Similar type of study was also done by Abu - Taleb (1999). Study on aquitard distribution in valley aquifer was done by Dominico et al. (1996).In later years aerial photos were used for groundwater potential zones delineation(Bhattacharya 1972). Similar subject was used for study by Rao et al. (1997). Das (1990) used satellite remote sensing in subsurface water targeting. El. Kadiai et al. (1994) discussed the use of GIS (Geographical information system) in area specific groundwater modelling. They argued that GIS is genetic in nature since no modification is necessary in numerical modelling. Similar types of work were done by EI Shazl et al. (1980), Baburao and Babu (1997); Mukherjee (1997) and Ramadoss et al. (1997). Use of GIS in water quality mapping is made clear by Nas and Berktay(2010).

In determination of infiltration capacities, permeability and other aquifer parameters, different isotopic studies on aquifer recharge is helpful. The isotopic study also helps in delineation of different aquifer interconnection and is studied by several authors (Yakutseni 1968; Dincer et al. 1974; Ferronsky 1978; Downing et al. 1979; Gaye and Edmunds 1996;

Allison 1987; Kovalevsky and Zlobina 1987; Sukhija et al. 1996 and Abu - Taleb 1999; Sinha, Srivastava, and Sexena 2000). Studies on hydrogeological charecterization for aquifer recharge have also been illustrated by Sinha (2007) ; Scanlon et al. (2010) and Vadodaria and Chahar (2006). Urbanization has its direct impact on groundwater quantity as well as quality (Jat, Khare and Garg, 2009).

CHAPTER-3

HYDROGEOLOGICAL STATUS OF STUDY AREA

3.1 INTRODUCTION: ASPECT OF HYDROGEOLOGY

Nation's most important natural resource is groundwater. Owing to the number of benefits of groundwater, its large scale development has resulted in undesirable consequences. These consequences threaten the sustainability of the resource in some areas. These consequences can be reductions in stream flow, storage depletion, land subsidence, saltwater intrusion, and loss of wetland and riparian habitats. The management decisions regarding the locations, rates, and timing of stresses imposed on a ground-water system, such as ground-water withdrawals and artificial recharge are affected by demand of groundwater system. These stresses lead to modification in ground-water levels, discharge rates, and water quality, which in turn affects environmental conditions of groundwater dependent habitats. Changes to the groundwater system and associated ecosystem bring about changes in the management of the system.

For an effective management of groundwater system and its sustainable use, better understanding of occurrence, movement and distribution of groundwater is required. These topics are being covered under hydrogeology. The science dealing with occurrence, movement, distribution and chemical composition of groundwater is termed as hydrogeology. The geologic environment which controls the properties of the groundwater is made up of various types of rocks, its composition and the structures and its interaction with various components of atmosphere, biosphere and hydrosphere. Hydrogeology, being both qualitative and quantitative science has many applications to the modern environment. Most important ones are:

1. Identification of the geologic characteristics of groundwater resources beneath any landscape, and quantitatively determining how much groundwater is available for use without compromising the resource;

2. Assigning the role of groundwater discharge in maintaining the base flows of surface-water bodies, and the hydrology of natural areas, such as natural lakes and wetlands; and
3. Assessing the relative sensitivity of groundwater to contamination across the landscape, this is based on a combination of the geologic framework and empirical case studies of groundwater quality. Even small differences in the geologic framework can cause groundwater characteristics to vary enormously from place to place.

3.2 HYDROGEOLOGICAL SET UP

3.2.1 Brief Indian Hydrogeological Scenario

India has been divided into different hydrogeologic provinces depending on different geological framework as well as physiographic and geomorphic set up. These provinces are Northern Mountainous Terrain and Hilly areas; Indo-Gangetic-Brahmaputra Alluvial Plains; Peninsular Shield Area; Coastal areas and Cenozoic Fault Basin and Low Rainfall Areas.

3.2.2 Rajasthan Hydrogeological Sceanrio

The Chaksu sub watershed area which constitutes the study area for the present work comes under the state of Rajasthan. Rajasthan state is part of the peninsular shield hydrogeological province and has arid to semiarid climate. The arid region is characterized by low mean annual rainfall coupled with high coefficient of variability, large amplitude of diurnal and annual temperature, strong wind regimes, and high potential evaporation. The substantial portion of such arid lands i.e. about 60 % lies in Rajasthan state which also includes Thar Desert.

Rajasthan is one of the naturally water scarce regions in India. The water availability in the state is controlled by the rainfall, topography, climate, soils and aquifer characteristics. All these factors have high degree of uneven distribution. The mean annual rainfall, in the state varies significantly from 100 mm in Jaisalmer to around 1100 mm in Jhalawa (Fig 3.1). The Thar Desert in Rajasthan receives the lowest annual rainfall of the entire country. Along with variations in rainfall, the number of rainy days also varies with lowest figures for the areas having lowest rainfall in western parts to relatively larger number of rainy days for areas receiving higher rainfall in southern parts. This is one of the most important characteristics of Indian rainfall. Number of rainy days decreases gradually from 31-40 days in the south-east to less than 20 days in the north-west (Pisharoty 1990).

The Aravalli ranges lying in the north east-south west direction make a considerable influence on the rainfall in Rajasthan. There is a sharp reduction in the amount of rainfall on the western side of Aravalli ranges, making western Rajasthan the most arid part of India.

High evaporation is one of the climatic variables that present the greatest challenge to groundwater management in Rajasthan. The annual reference evapotranspiration values range from 1500 mm in the southern part of the state to 2000mm in western part in Jaisalmer (GOI 1990). In addition to rainfall and lithological characteristics, the evolution of groundwater aquifers and recharge to such aquifers is largely determined by the geomorphic properties of the land, especially slope, drainage patterns and the nature and thickness of the unconsolidated/semi consolidated layers over the bedrock formations.

A good connection exists between the hydrogeological properties of non-hard rock areas and the geomorphic properties of the land. Fig 3.2 shows the physiographic and drainage view of Rajasthan.

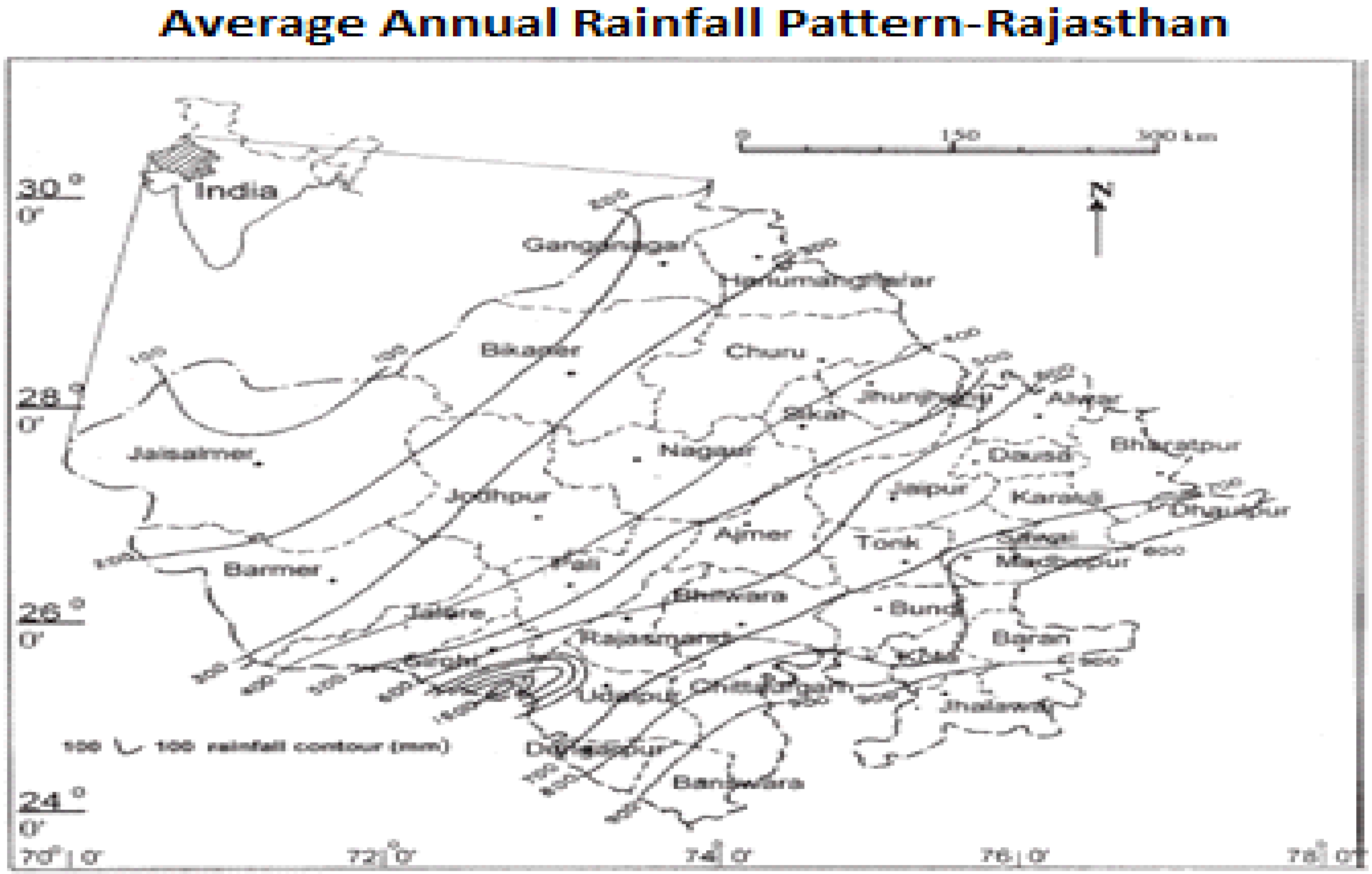


Fig.3.1: Average Annual Rainfall Pattern of Rajasthan

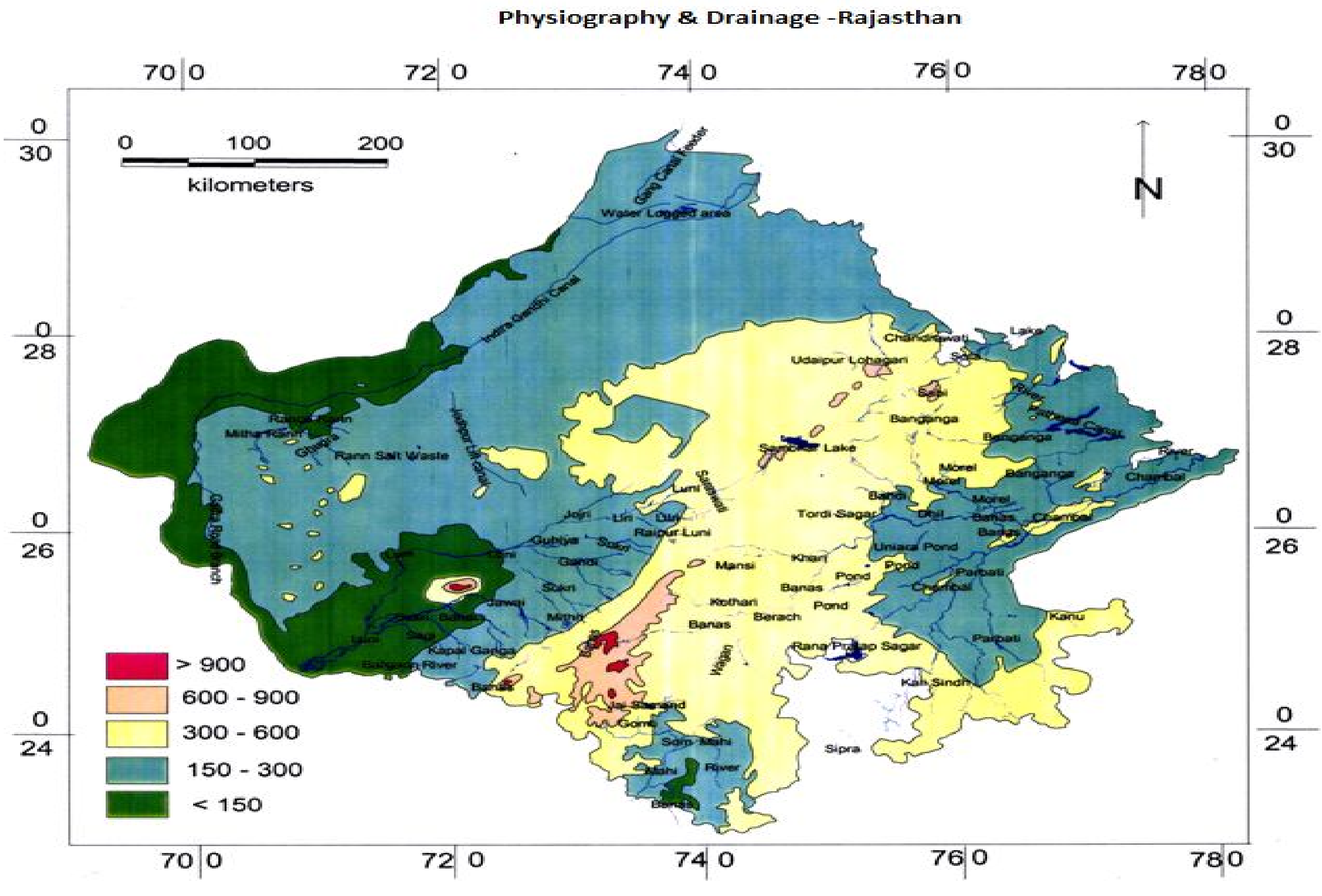


Fig.3.2: Physiography and Drainage of Rajasthan (CGWB 2013)

The geo-hydrological map of Rajasthan (Fig 3.3) shows that the state is characterized by diversity in groundwater conditions. The state has formations, viz., unconsolidated, semi consolidated fully consolidated, with varying groundwater potential.

The State has a diverse assembly of geological formations ranging from the Archean to recent alluvium and blown sand (Heron 1936, 1953; Sharma 1992). The water potential of different lithological units depends on their hydrogeological characteristics and structural control. In Rajasthan, groundwater potential areas are not widespread and homogenous, but found as isolated basins with unique hydrological parameters. The groundwater quality depends entirely on the site specific physical properties of the formation, the extent and nature of weathering, and other specifics.

The unconsolidated formations include: recent alluvium, brown sand, clay, silt and gravel, pebble, calcareous concretion, which are fairly thick and regionally extensive, confined to semi-confined aquifers; and older alluvium, laterite, silt, sand, ferruginous concretion and cobbles, confined to semi confined aquifers to a depth of 39-300 metre below the ground. They are porous formations. The aquifer potential varies widely between (40-100 litres per second) for the very good ones, to 10-40 litres per second for moderately good ones to less than 10 lps for low potential ones.

The semi-consolidated formations include: clay-stone, sandstone, grit, silt stone, conglomerate, and limestone. They also form porous aquifers, and have groundwater potential varying from less than 10 lps to 100 lps.

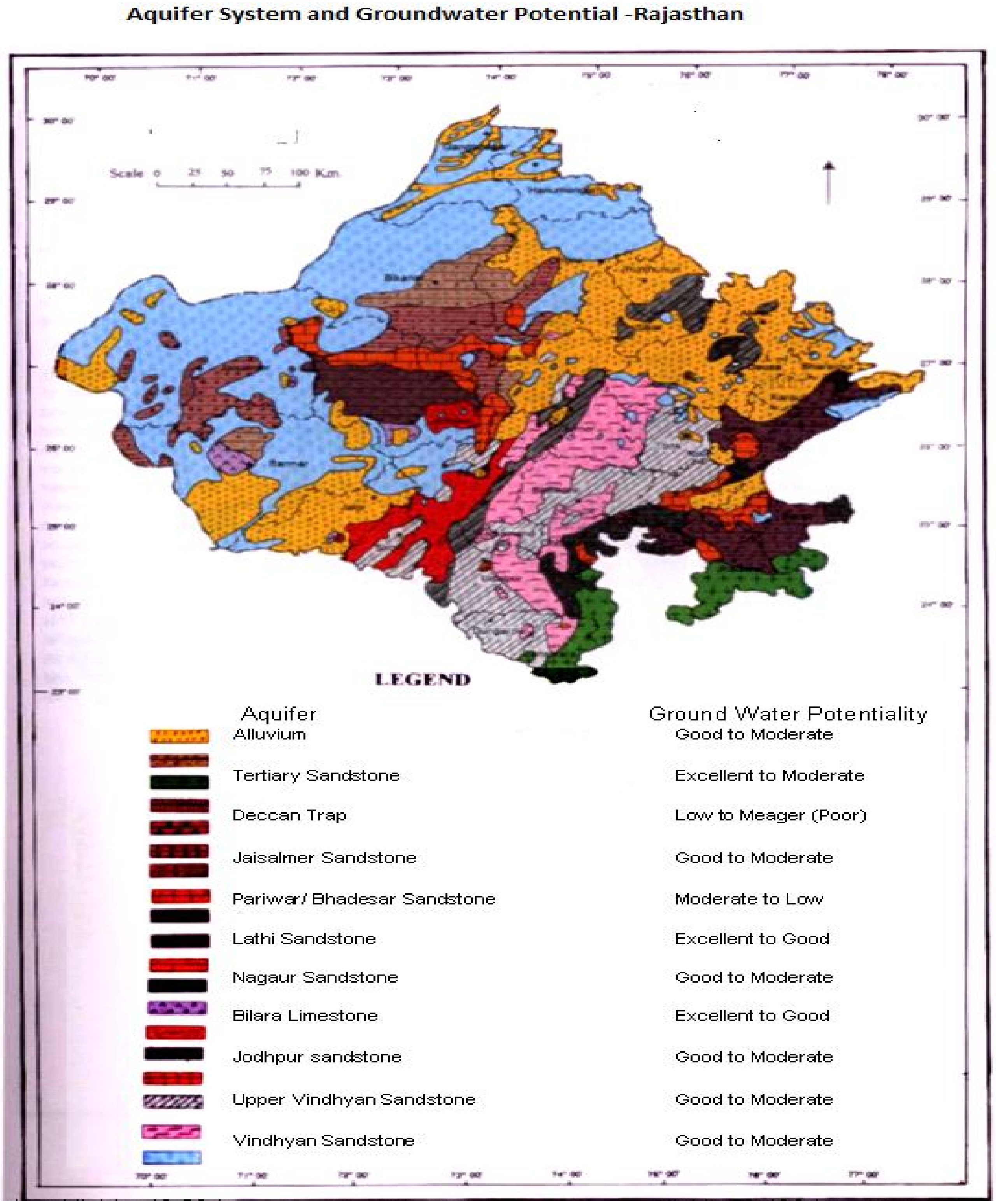


Fig.3.3: Aquifer System and Groundwater Potential of Rajasthan (CGWB 2013)

The consolidated formations can be classified into four categories:

1. Effusive: comprising of basalt with inter-trappean clay;
2. Sedimentary: comprising of sandstone, limestone, dolomite and shale;
3. Meta-sedimentary and meta volcanic: comprising of slate, quartzite, schist, gneiss and marble; and
4. Basal crystalline: comprising of phyllite and granite.

All these are fissured rocks. The yield of the aquifers varies widely between 5-10 litres per second to below one litre per second. In south Rajasthan, the hilly aquifers are found in very small pockets. For greater clarity of classification, groundwater potential zones have been divided into 5 groups, 15 zones, 13 sub-zones and 94 sub-sub zones (Table 3.1).

Table 3.1: Groundwater Potential Zone

Formations	**Number of**				**Notation**
	Zone	**Sub-Zones**	**Sub-Sub-Zones**	**Total**	
GROUP I- UNCONSOLIDATED					
Younger Alluvium	32	16	2	50	A
Older Alluvium	71	48	20	139	A_0
GROUP II- TERTIARY FORMATIONS					
Tertiary Sandstone and Gravel					T
Tertiary formations (Mixed Aquifer)	3	13	-	16	T
GROUP-III CONSOLIDATED SEDIMENTARY FORMATIONS					
Parewar Formations	-	2	-	2	P
Bhadesar Formation	-	3	-	3	Bh
Lathi Formation	1	8	-	9	L
Sandstone (M.SG/Vindhyan's)	35	8	27	70	SS
Shale(M.SG/Vindhyan's)	9	8	-	17	Sh
Limestone (M.SG / Vindhyans / Aravallis / Delhi etc)	17	8	16	41	LS
Slate(M.SG /Vindhyan's / Aravallis etc)	2	-	-	2	SL
GROUP IV – CRYSTALLINE –IGNEOUS FROMATIONS					
Basalt	14			14	B
Rhyolite (Malani)	5			5	R
Granite (Malani/post-Delhi/Aravallis	14	20		34	Gr
Ultrabasic (Ultrabasic(Dolerite/Diorite)	1			1	Ub
GROUP V –METAMORPHIC S					
Quartzite (Delhi/Arawallis)	24	2	-	26	Q
Schist/Phyllites(Calc/Mica/Biotite)	72	16	-	88	Sc/Ph
Gniesses /BGC	46	20	-	66	Gn

3.2.3 Rainfall and Groundwater

Groundwater availability is determined by the rainfall distribution and quality. Rajasthan is divided into three rainfall zones: arid zone- with rainfall 500 mm or less, semi-arid zone- with rainfall 500 to 650 mm, sub-humid- with rainfall 650 to 750 mm and humid zone- with rainfall more than 750 mm. The total area classified as arid is 196,150 km ,covering about 61% of total area; as semi-arid is 121,020 km, about 13% of total area and as sub-humid is 21,248 km. Rainfall distribution is highly variable, both in time and space. Annual rainfall across the state varies from more than 900 mm in the southeastern part to less than 100 mm in the west (Sharma 1992).

3.2.4 Hydrogeology of Chaksu Block

Chaksu block is one of thirteen blocks of Jaipur district belonging to the state of Rajasthan, India. The overall geology and hydrogeological setup of Chaksu region is compatible with that of Jaipur region with a little physiographic variability**.**

The oldest rock in the Jaipur district are the gneisses and schist of Bhilwara Super Group overlain by quartzite, schist, conglomerates, dolomite limestone etc. belonging to Alwar and Ajabgarh Groups of Delhi Super Group along with granite, pegmatite and amphibolites intrusive of Post Delhi age. Hard rocks are covered by Quaternary fluvial and Aeolian deposits mainly composed of sand, silt, clay, gravel and kankar (CGWB 2007). The altitude at Kotkaoda is 273.47 m in Chaksu block. Alluvial thickness is less in Chaksu area. Alluvial thickness is between 90 m and 100 m at Chomu, Jairampura, Nangal Bharra, Dhaunauta area whereas its thickness is over 100 m at Risani village.

Groundwater in the chaksu block occurs in unconsolidated Quaternary formations and consolidated formations of Bhilwara and Delhi Super Groups comprising of granulitic gneisses, quartz mica schist, phyllite along with granite and pegmatite intrusive. In major part of the block, alluvial deposits consists mainly of fine sand and silt and serve as potential aquifers. Table 3.2 illustrates the hydrogeology of Jaipur District (CGWB 2007).

Table 3.2: Hydrogeology of Jaipur District

S. No.	Hydrogeological Unit	Description Of The Units	Occurrence
1	Younger Alluvium (Quaternary)	It mainly includes windblown sand, talus and scree deposits with some fluvial deposits along drainage channels. Alluvium is composed of fine medium grained sand, silt, clay and kanker in varying proportions. The deposits on the flank of hills are consisted of fine to coarse-grained sand and angular fragment of rocks. Thickness of alluvium varies considerably. It generally increases northward and in major part of the area noticed less than 100m.	The lithological units, leaving aside some southern peripheral blocks like Chaksu. Phagi, Dudu and part of Sambhar block, occupies major part of area.
2	Older Alluvium (Quaternary)	It includes fine to medium grained sand, silt, clay and kanker in varying proportion. Thickness of alluvium generally encountered less than 50m.	The litho unit covers entire Sanganer blocks and spreads in major part of Smbhar, Phagi, Dudu, Chaksu and Bassi blocks.
3	Quartzite	The litho unit is generally of Grey colour but fawn, buff and white colours have also been found in the area. Quartzite is medium to coarse grained and varies from feldspathic grit of sericitic quartzite.	The litho unit occurs as small-localised pocked in Amber, Bairath, Bassi,Jamwa-Ramgargh and Kotputli blocks.
4	Phyllite and schist, Granite Gneiss	Phyllite and schist included argillaceous meta in sediments. Granite and gneiss characteristically have gneissic structure comprising light coloured feldspathic and dark ferro-magnessian minerals.	Phyllites and schist occupy small area in southern peripheral part in Dudu, Jamwa- Ramgargh and Phagi blocks. Granite gneiss cover extensive area in Dudu blocks and extends in western peripheral part of Phagi blocks.

3.3 GROUNDWATER POTENTIAL ZONES

In the Chaksu block, two types of groundwater potential zones exist. These are given below:

1. Older alluvium

The average yield of dug well or dug-cum-bore wells with pumps was 70 m^3/day in older alluvium potential zone. There were 6163 dug well or dug-cum-bore well with pumps for irrigation use and 80 dug well or dug-cum-bore well with pumps for domestic use in the block in this potential zone. There were 185 dug well or dug-cum-bore well without pumps having yield 2.1 m^3/day and 18 tube wells having yield 90 m^3/day in this potential zone. The total groundwater draft in this potential zone was 54.5463 mcm.

2. Schist

In the schist rock potential zone, the average yield of dug well or dug-cum-bore wells with pumps was 52m^3/day. There were 1534 dug well or dug-cum-bore well with pumps for irrigation use and 53 dug well or dug-cum-bore well with pumps for domestic use in the block in this potential zone. There were 69 dug well or dug-cum-bore well without pumps having yield 2.1 m^3/day and 19 tube wells having yield 75 m^3/day in this potential zone. The total groundwater draft in this potential zone was 11.1511 mcm. Table 3.3 illustrates the hydrogeology of Chaksu Tehsil.

Table 3.3: Hydrogeology of Chaksu Tehsil

S. No.	Zone	Hydrological Formation	Zone Area	Main Village Zone	Stage Of Development
1	A	Younger Alluvium	104.2200sq.Km	Titria	52.23%
2	B	Older Alluvium	447.8361sq.Km	Chandlai	70.29%
				Chaksu	
				Dholera	
				Gurwasa	
				Kadera	
				Kohlya	
				Sheodaspura	
3	C	Mica Schist Gneisses	177.2965sq.Km	Aalooia	160.11%
				Kothoon	
				Sanwas	

3.3.1 Water Level in Chaksu Block

The water level in Chaksu block has been quite variable. During 98 (premonsoon) the depth to water level was less than 10 mbgl in the northern part while southern part showed the depth to water level from 10 to 20 mbgl.

Again as per the water table monitoring carried during 2006 by CGWB, the western, central, southern and north-central-western parts was having water level 10-20 m and eastern, north-eastern, north-western parts had 20-40 m water table depth during pre-monsoon 2006. During post-monsoon 2006, the water table depth was 10-20 m in central, southern, south-western and north-eastern parts and 20-40 m in eastern and south-western and north-western parts of the block (CGWB, 2007).

The present study show the depth to water level for year 2007 for 222 pumping wells as shown in Appendix II. Fig 3.4 shows the water level fluctuation of Chaksu Tehsil.

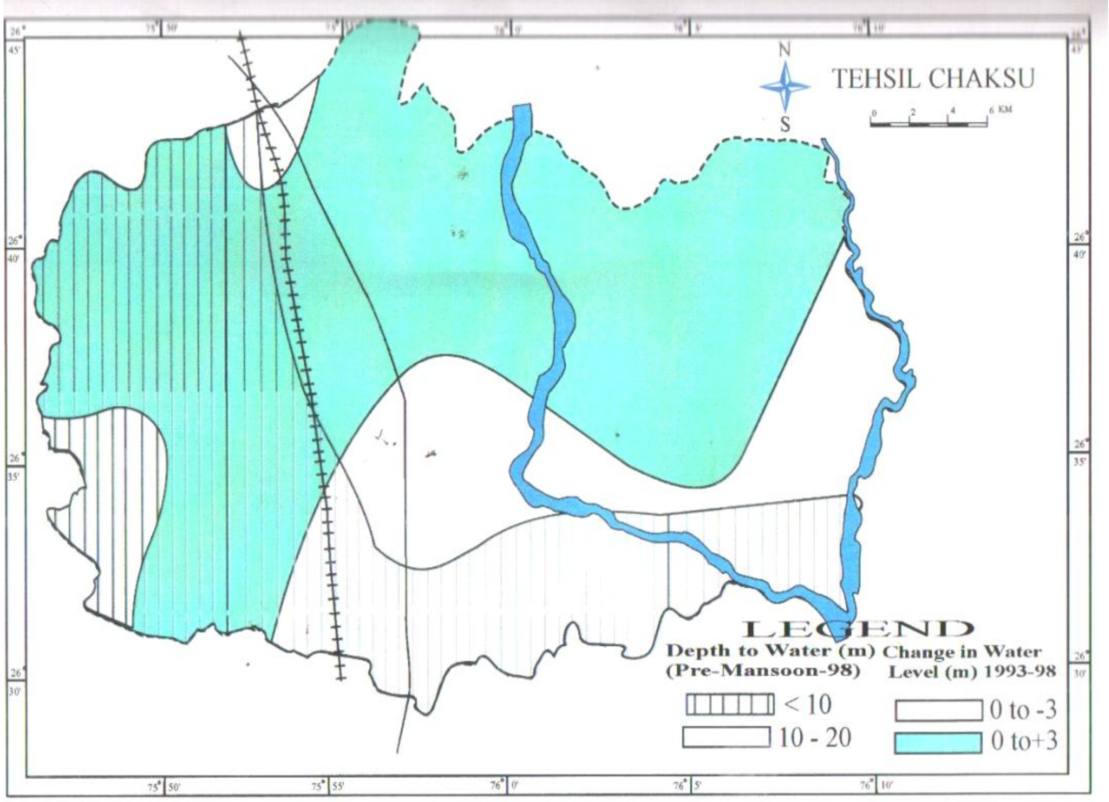


Fig.3.4: Water level Fluctuation (CGWB 2007)

3.4 WATER LEVEL FLUCTUATION

As per information available water level fluctuation observed during 1993-1998 has been to the extent of 3 m depletion in southern part of Chaksu region while 3m rise was observed in the northern part.

During the year 2006, there was minimum 14.5 m and maximum 33.3m below groundwater level during pre-monsoon season while there was minimum 14.7 m and maximum 31.25 m below groundwater level during post-monsoon season in the Chaksu block. The rise in water level during pre-monsoon and post-monsoon was 0.40 in minimum and 4.40m in maximum. The fall in water level during pre-monsoon and post-monsoon was 0.2m in minimum and 5.2m in maximum (Table 3.4)(CGWB 2007).

Table 3.4: Seasonal Water Level Fluctuation

Block	Water Level Pre-Monsoon, 2006 (m)		Water Level Post-Monsoon, 2006 (m)		Water Level Fluctuation Pre-Post, 2006 (m)			
					Rise (m) Wells Measured		Fall (m) Wells Measured	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Chaksu	14.5	33.3	14.7	31.25	0.4	4.4	0.2	5.2

3.4.1 Temporal Change in Water Level

In the year 1984, the average water level was 9.62 m which declined to 11.85 m in the year 1996. In the year 2001, the water level was 13.58 m which declined to 22.58 m in the year 2006. The average rate of water level declined from 1984 to 2006 was 0.60 m per year in the block (Table 3.5) (CGWB 2007).

Table 3.5: Temporal Change in Water Level

Block	Average Water Level 1984 (m)	Average Water Level 1996 (m)	Average Water Level 2001 (m)	Average Water Level 2006 (m)	Average Water Level Fluctuation Pre-Post 2006	Average Rate of Water Level Decline 1984-2006 (m/yr)	Average Rate of Water Level Decline 1996-2006 (m/yr)	Average Rate of Water Level Decline 2001-2006 (m/yr)
Chaksu	9.62	11.85	13.58	22.73	1.6	0.6	1.09	1.83

3.5 GROUNDWATER RESOURCES IN THE CHAKSU BLOCK

In the Chaksu block, 729.36 sq. km. area is groundwater potential zones. In this potential zone, net groundwater availability was 41.1316 mcm as on March 2004. The gross groundwater draft for irrigation was 64.0379 mcm; gross groundwater draft for domestic and industrial uses was 4.3561 mcm. Thus, the total draft was 68.3939 mcm and the groundwater development was 166.28% i.e. the block was over-exploited (Table 3.6).

Table 3.6: Ground Water Resources in Chaksu Block as on 31.03.2004 (CGWB, 2007)

Block	Area of Block (Sq. Km.)	Potential Zone Area (Sq. Km.)	Net Annual Ground Water Availability (mcm)	Existing Gross Ground Water Draft for Irrig. (mcm)	Existing Gross Ground Water Draft for Dom. & Indus. Use (mcm)	Existing Ground Water Draft for All Uses (mcm)	Allocation for Dom.& Industrial Requirement As Projected for the Year 2025 (mcm)	Stage of Ground Water Development (%)	Category
Chaksu	811.92	729.36	41.1316	64.0379	4.3561	68.3939	10.421	166.28	Over-Exploited

CHAPTER 4
GROUNDWATER FLOW MODELLING

4.1 INTRODUCTION

Water being the most important source of life on earth, its distribution varies from place to place on earth. The main source of all surface and subsurface water is precipitation. Some percentage of this precipitation that flows over land is known as surface runoff whereas percentage that penetrates into the ground and flows under the surface is known as subsurface flow. All subsurface water cannot be categorized as groundwater. The water found between the two soil layers is termed as groundwater. Vadose zone is the layer next to surface where air and water both are present in voids of soil granules. Just underneath this layer is the saturated zone, where the voids are filled with water. Between these two layers water table acts as a boundary. The rise and fall of water table varies according to the amount of groundwater present. When the entire area underneath the ground surface gets saturated, flooding is caused, since all the upcoming precipitation remains on the surface. Groundwater is the essential source of fresh water for communities, irrigation and industries. It also recharges wells, rivers, lakes and springs. When comparing with surface water, groundwater has its own pros and cons. The advantages of using groundwater are:

1. No water treatment is required as water quality is on the safe side as compared to surface water.
2. Natural filtering of microorganisms and minute particles through soil passage takes place as the organic and inorganic compounds gets removed through attaching to clay minerals.
3. Relatively constant temperature and quality over time.
4. Slower dispersion of pollution.
5. Negligible sediment content.

Table 4.1 illustrated the comparison of groundwater and surface water qualities:-

Table 4.1: Comparison of Groundwater and Surface Water

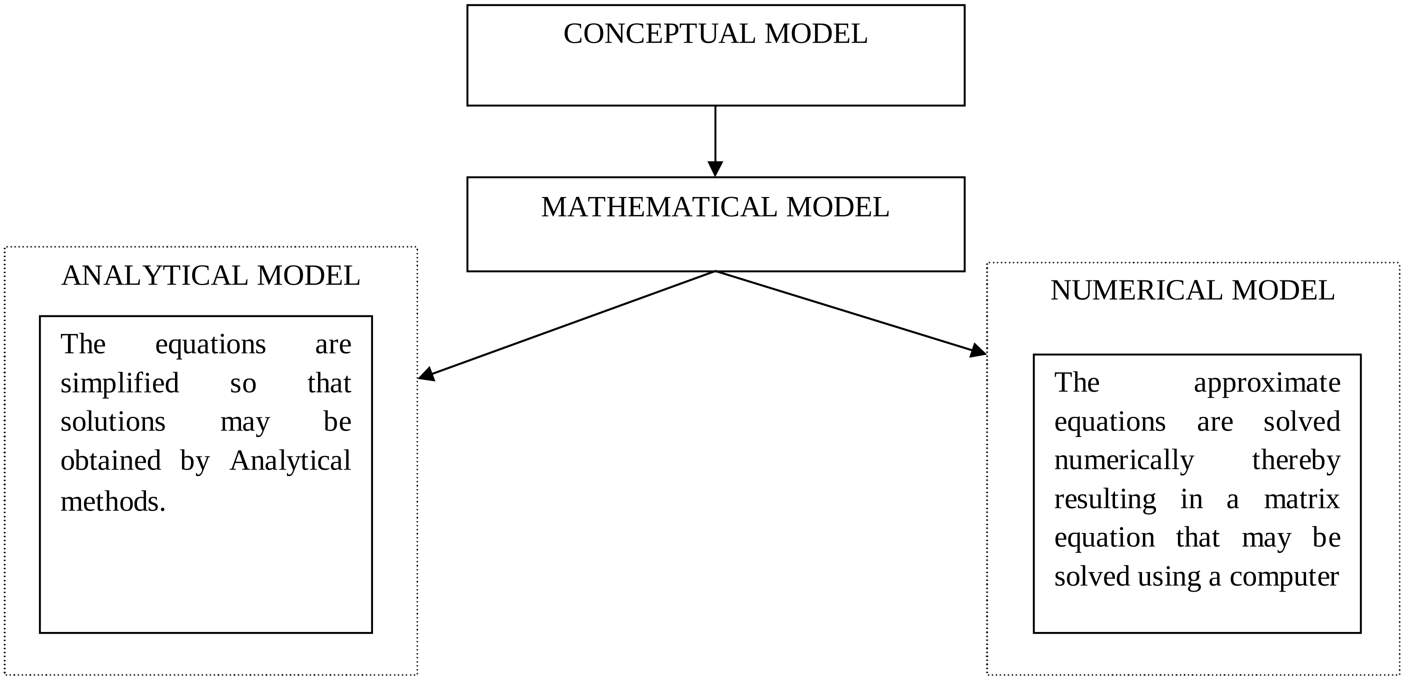
Feature	**Groundwater Resources & Aquifers**	**Surface water resources & Reservoirs**
Hydrological Characteristics		
Reserve	Enormous Reserves	Limited
Areas under cover	Unrestricted	Restricted
Flow	Slow	Range from moderate to high
Residence Time	Generally decades / Centuries	Mainly Weeks / Months
Drought Vulnerability	Generally Low	Generally High
Evaporation Losses	Low and Localized	High for Reservoirs
Resources Evaluation	High Cost and Significant Uncertainty	Lower Cost and Often Less Uncertainty
Abstraction Impacts	Delayed and Dispersed	Immediate
Natural Quality	Generally (But not Always) High	Variable
Pollution Vulnerability	Variable Natural Protection	Largely Unprotected
Pollution Persistent	Often Extreme	Mainly Transitory
Socio - Economic Factors		
Public Perception	Mythical, Unpredictable	Aesthetic, Predictable
Development Cost	Generally Modest	Often High
Development Risk	Less than often Perceived	More than often assumed
Style of Development	Mixed Public and Private	Largely Public

The disadvantages of groundwater are:

1. Large quantity of dissolved minerals and hardness.
2. Difficulty in management.
3. Groundwater resources require advanced skills and methods for exploration and characterization.
4. Treatment of groundwater if required is costly.

4.2 GROUNDWATER FLOW MODELLING

Models describe the physical systems using mathematical equations in the form of conceptual descriptions or approximations. Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Groundwater models are the replicas of groundwater flow process at the study area. Models when complemented with monitoring studies can be used in evaluating and forecasting groundwater flow and transport. For a model to be reliable, it should be based on accurate field data and prior knowledge of the area. The model can be physical, analogue or mathematical (James and Charles, 1980). To simplify the complex real-world systems, there is a need for planning and management decisions. The simplification in the form of set of assumptions is introduced which expresses the system’s nature and its behaviour features relevant to the problem (Bear et al. 1992). According to James and Charles (1980), the conceptual model is basis for mathematical modelling as shown in Fig 4.1. The mathematical model can then be solved in two ways: either analytically (Choudhary and Chahar 2007) or numerically.



The equations are simplified so that solutions may be obtained by Analytical methods.

The approximate equations are solved numerically thereby resulting in a matrix equation that may be solved using a computer

Fig.4.1: Logic Diagram for Developing a Mathematical Model (James and Charles 1980)

According to Bear et al. (1992), appropriate conceptual model selection and the degree of simplification in any particular case depends on:

1. Management problem objectives;
2. Resources available;
3. Field data;
4. Legal and regulatory framework applying to the situation.

Developing conceptual model for a given problem is not a conclusive activity but a continuous process. In this process the initial assumptions are re-examined, added, deleted and modified as the investigations continue. Field data, that is required for model calibration and parameter estimation, plays an important role in deciding the type of conceptual model selected and the degree of approximation involved. Expressing the conceptual model in the form of mathematical model is the next step in modelling process. The solution of the mathematical model is in the form of predictions required for the real-world system's behaviour in response to various sources and/or sinks. A mathematical model can be fully expressed by the following items:

1. Considered domain's geometry and boundaries.
2. The balance of the considered extensive quantity expressed in the form of equations.
3. The relation between the flux of the considered extensive quantity and the relevant state variables of the problem expressed as flux equations.
4. The behaviour of the fluids and solids involved defined in the form of constitutive equations.
5. The initial conditions that describe the known state of the considered system at some initial time expressed in equations.
6. Equations that define boundary conditions describing the interaction between considered domain and its environment.

The conceptual model is then translated into mathematical model and is expressed in equations that are solved analytically and numerically. The solution to mathematical model is obtained by transforming it into numerical model and then writing a computer program known as code. This code is solved using a digital computer. There are different methods for solving the governing equations of the numerical models:

1. Finite-difference method;
2. Finite-element method;
3. Boundary-element method;
4. Particle tracking method;
5. Method of characteristics method;

6. Random walk method;
7. Integrated finite-difference method.

Various applications of different types of flow models are depicted in Fig 4.2 (James and Charles 1980).

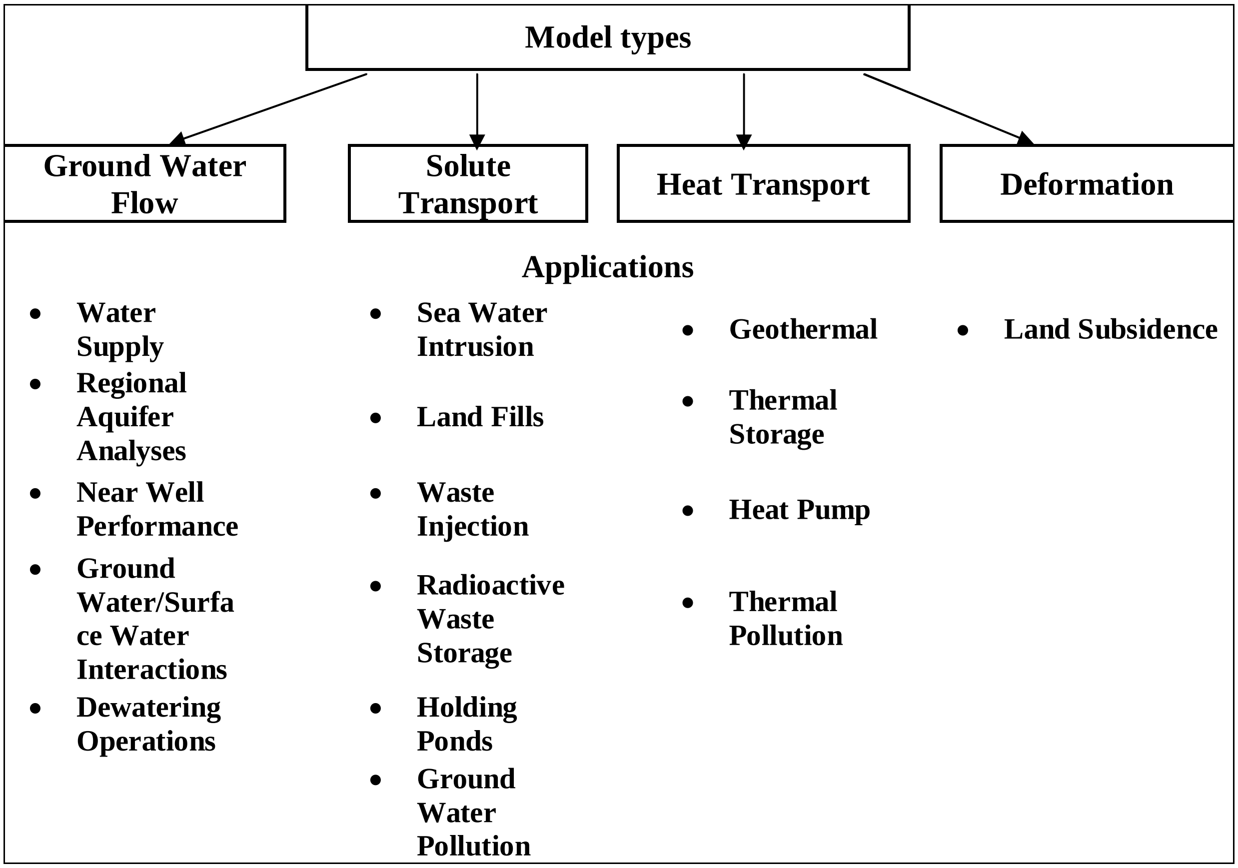


Fig.4.2: Applications of Various Flow Models (James and Charles 1980)

The groundwater flow models can be applied to different water related problems like: water supply; for analysis of regional aquifer system; for well performance; for interactions between groundwater and surface water etc. The solute transport models are used for analysis of contamination flow like sea water intrusions; landfills; waste injections etc. Heat transport models are used in analysis of geothermal related problems like heat pump; thermal pollution; thermal storage. For land subsidence problems, deformation models are used.The groundwater modeling process is summarized in Fig 4.3.

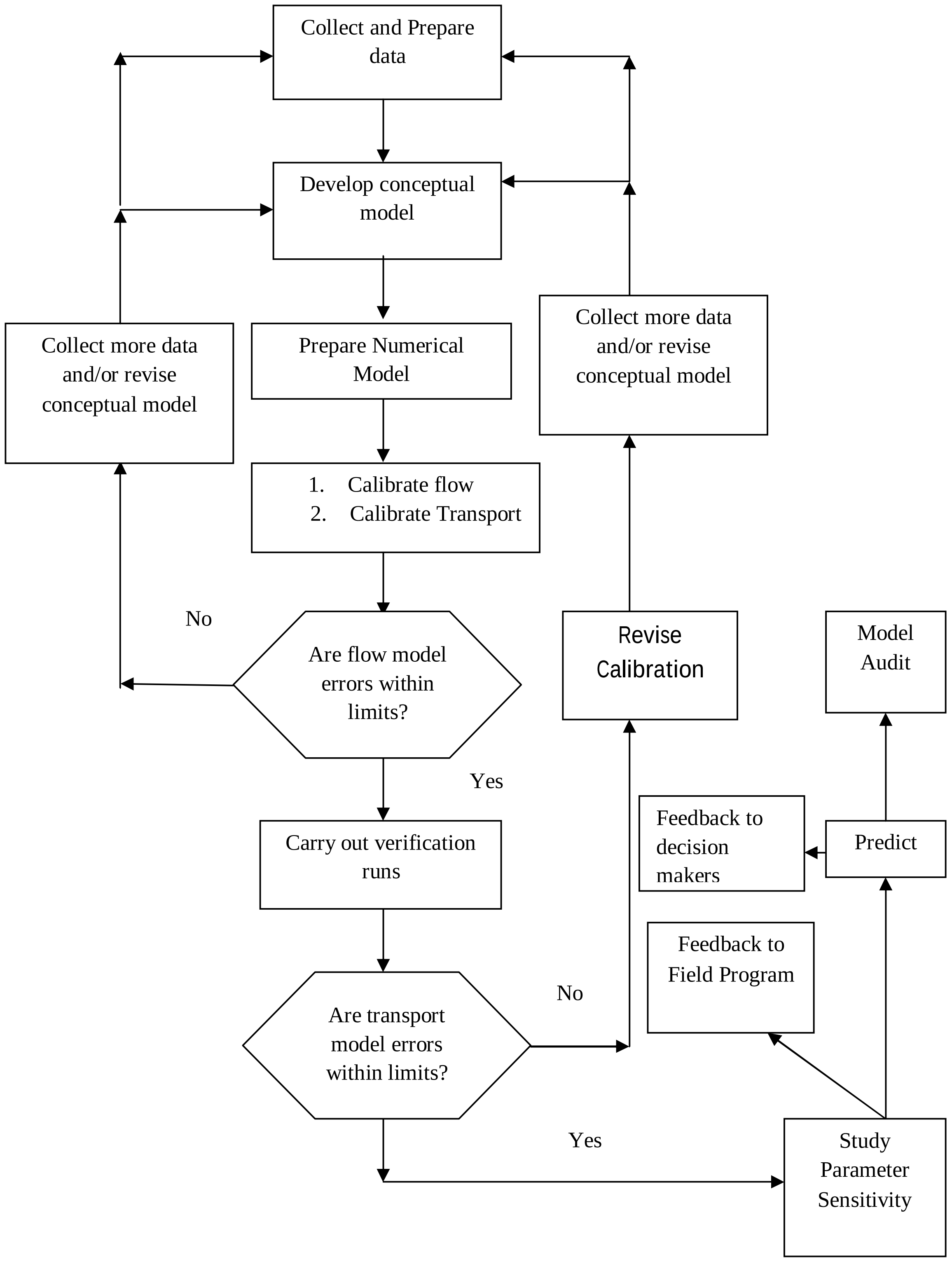


Fig. 4.3: Groundwater Modeling Process

4.3 TYPES OF GROUNDWATER MODELS

Groundwater flow models can be classified in several ways but there are three main classes in which models can be distinguished (Essink 2000):

1. A physical model or Scale model
2. An analogue model
3. A mathematical model

In the present investigation a mathematical model was being used. A mathematical model simulates the groundwater flow indirectly with the help of governing equations. These equations represent the physical processes of the system. These equations also represent the heads or flows along the boundaries of the model. Mathematical models of groundwater flow, known as white box model and have been in use since the late 1800s. For derivation of equations different fundamental theories, principles and assumptions are used. Since the field situations are too complicated to be simulated exactly, simplifying assumptions are made to construct a model. Assumptions generally incorporated in groundwater flow models are:

1. One aquifer system is modeled with only one storage coefficient in vertical direction.
2. Ratio of horizontal to vertical conductivity is 10.
3. The aquifer is bounded at the bottom by an impermeable layer.
4. The upper boundary of the aquifer is either an impermeable as in confined aquifer, or a slightly permeable layer as semi-confined aquifer or a free water table i.e. in unconfined aquifer.
5. Darcy's law (head loss varying linearly with apparent velocity of flow) and Dupuit's assumptions (negligible vertical flow) are applicable.
6. The aquifer has head-controlled, flow controlled, and/or zero-flow boundaries: the first two of these boundaries may vary with time.
7. The process of infiltration and percolation of rain and surface water and of capillary rise and evaporation, taking place in the unsaturated zone of aquifer (above water

table), can't be simulated. This means that net recharge to the aquifer must be calculated separately and prescribed in the model.

Mathematical models are required to be solved approximately by using numerical techniques, to provide a real world scenario. The equation that governs the flow of groundwater for three-dimensional, transient conditions and in a heterogeneous and anisotropic aquifer is given as Eq. 4.1:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_S\frac{\partial h}{\partial t}$$

(Eq. 4.1)

Here, h = Hydraulic Head;

x, y, z, t = Spatial Dimensions and Time;

K_{xx}, K_{yy}, K_{zz} = Hydraulic Conductivities in x, y and z direction;

S_s = Aquifer's Specific Storage

W = Volumetric flux per unit volume representing sources and/or sinks of water

The equation is derived by applying the mass balance principle on finite element method. The system represents the saturated porous medium and the groundwater flux terms are substituted by Darcy's law.

Mathematical groundwater models can be classified into two different groundwater models:

4.3.1 NUMERICAL MODELS

Numerical models are being used in problems where complex mathematical models are needed to be solved. Groundwater flow and transport are analyzed by using different sets of equations. The two numerical techniques used for solving numerical models are called finite differences method and finite elements methods (Kumar 2005). These methods provide a logical base for solving the differential equations that are used for model formulation and then transform them into algebraic equations.

A discrete solution is obtained by numerical modelling by using algebraic equations. Solution is attained by using iterative methods or direct methods. In many cases numerical solution provides more practical outputs then the analytical solution. Grid pattern are used for solving the differential equations numerically. Depending upon the problem to be solved, selection is to be made between a finite difference and finite element model. The two numerical solution methods are:

1. Finite Difference Method

The Finite Difference method is one of the oldest methods for solving partial differential equations (Smith 1985). The domain to be computed is discretized by rectangular or quadrilateral cells. The cell dimensions Δx and Δz are constant or even Δx=Δz. The unknown are defined in nodes, and are placed at cell centers or at the cell boundaries intersection points (Hinkelmann 2008). Depending on the finite difference model, the groundwater heads and concentrations are calculated as separate values at the nodes of the grid, or at the cells center points (Spitz and Moreno 1996). The complex boundaries and inner structures can be presented in a more simplified way by using the step functions.

The unknown function 'e' is derived by the use of Taylor series expansion, expressed in Eq.4.2 for the *x* direction. For simplification, constant Δx=Δz are assumed:

$$e_{i+1j} = e_{ij} + \Delta x \frac{\partial e_{ij}}{\partial x} + \frac{(\Delta x)^2}{2} * \frac{\partial^2 e_{ij}}{\partial x^2} + \frac{(\Delta x)^3}{6} * \frac{\partial^3 e_{ij}}{\partial x^3} + \frac{(\Delta x)^4}{24} * \frac{\partial^4 e_{ij}}{\partial x^4} + 0(\Delta x^5)$$

(Eq. 4.2)

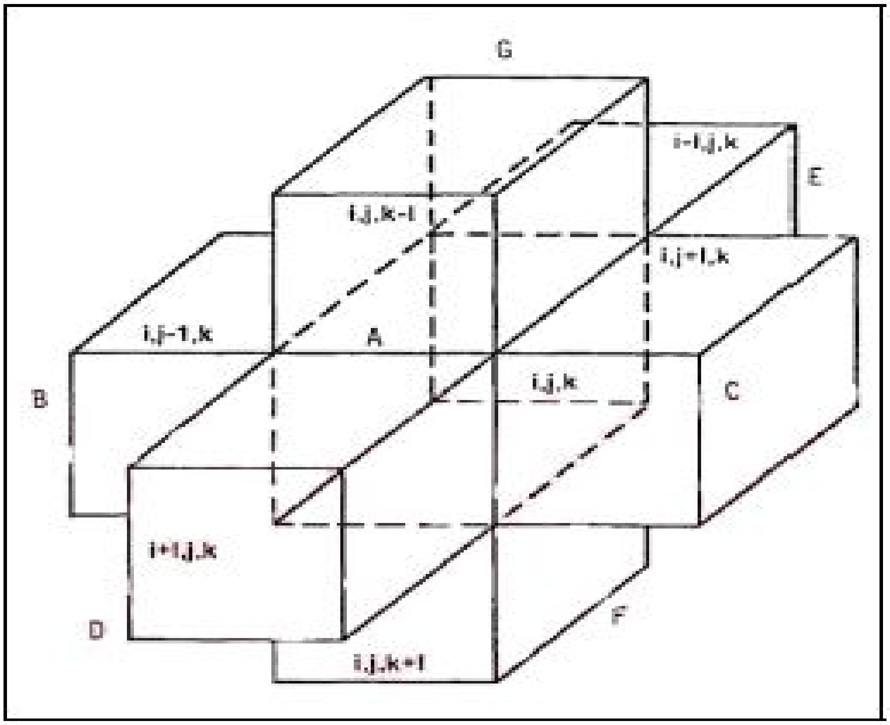


Fig. 4.4: Illustration of a Finite-Difference Computational Molecule (Spitz and Moreno 1996)

Eq.4.3 explains the finite difference method use in groundwater flow process. Here, the hydraulic conductivity K_f and storage S_o are considered constant along with one dimension consideration:

$$S_0 \frac{\partial h}{\partial t} - div - \left(K_f gradh\right) = 0 \Leftrightarrow \frac{\partial h}{\partial t} - \frac{K_f}{S_0} \frac{\partial^2 h}{\partial^2 x^2} = 0 \qquad \text{(Eq. 4.3)}$$

By taking into account the initial boundary conditions, cells continuity equations were established. Each cell’s inflow and outflow were determined using the controlling equation. The solution for each cell was derived by the controlling equations after designating the continuity equation for unknown heads. Number of codes for solving the groundwater flow equations by finite difference methods exists. MODFLOW-2000 is among them. (Harbaugh 2000).

MODFLOW-2000 is a computer code that is used to solve the groundwater flow equations with the help of finite difference method. It was developed by United States Geological Survey (USGS) in 1984 and was coded entirely in FORTRAN-77 language. For better simulation of hydrological studies, new enhancements have been added to the code since its release. During simulations these enhancements are used separately and are divided into different modules. For complete achievement of simulation including all parts like model defining, memory allocation, equation formulation etc, each module performs different process (Wang et.al. 2007).

MODFLOW can be adapted to any modification in the code for different scenarios due its modular structure. It is used for flow simulation of irregularly shaped aquifer system. The flow can be either transient or steady whereas the aquifer system can be confined, unconfined, or both. Flow from external stresses can also be simulated such as flow to wells, aerial recharge, evapotranspiration, flow to drains, and flow through river beds. Specified head and specified flux boundaries can be simulated as a head dependent flux across the model's outer boundary. It allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a source of water outside the modeled area and the boundary block. The groundwater flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform (USGS 2008). Solute transport and parameter estimation are also incorporated.

2. Finite Element Method

The solution of groundwater flow model using finite element method is a contemporary development as compared to finite difference method. The approximation of groundwater flow equations are done by integration whereas in finite difference method it is done by differentiation. Same as in the finite difference method, the whole model area is divided into sub-areas known as elements. It can be implemented with variety of element types but triangular element is the best starting point for complete description of the method. (Anderson and Wang 1990). But since there are no restrictions on the shapes of elements, the user can use any shape. This makes finite element method more flexible (Spitz and Moreno 1996).

4.3.2 ANALYTICAL MODELS

For the exact solution of controlling differential equations, analytical models are chosen. For one-dimensional, transient groundwater flow, the controlling equation can be expressed as Eq.4.4. The aquifer is considered to be homogenous and confined:

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 \mathrm{h}}{\partial x^2} \qquad \text{(Eq. 4.4)}$$

The initial boundary conditions are needed to be defined, and a function of hydraulic head, depending on space and time, is retrieved. The best and most used example of analytical model is the Theis solution and is formulated as Eq.4.5:

$$s = \frac{Q}{4\pi T} W(u) \qquad \text{(Eq. 4.5)}$$

Here,

W (u) = well function;

u = Dimensionless Time Parameter;

s = Drawdown;

T = Transmissivity

The continuous solution over the model domain is provided by analytical models. Analytical models are computationally more efficient than numerical models and provide more realistic solutions. They are applicable even for finite data and useful for initial estimation of systems behavior. Analytical models are difficult to apply to complex model geometry. The analytical solution for the controlling equation requires practical mathematical techniques. Due to many limitations in using analytical models they are confined to one dimensional or two dimensional problems.

4.4 DATA REQUIREMENTS FOR GROUNDWATER MODELLING

The compilation of relevant secondary data for the flow model is an important step in modelling. The type of data required for groundwater modeling can be distinguished in two frameworks: the hydrologic and physical framework. The foremost step of model study consists of collecting and evaluating input data of system under research. Input data by the model are required for (Spitz and Moreno 1996):

1. Defining Problem: Data in the form of geometry of hydraulic units and properties of materials.

2. Requirements for numerical solutions like boundary conditions, initial conditions, and steady or transient state conditions.

3. Modelling i.e. for calibrating, validating, and defining different scenarios.

Data on pumping, fluxes, recharge, precipitation, hydraulic heads and evapotranspiration are included in the hydrological framework. Hydrological data can be represented in the form of potentiometric maps and water table for the aquifers in question, surface water levels and discharge rates, groundwater head hydrographs, hydraulic conductivity and transmissivity distribution maps, distribution of groundwater recharge, pumping of groundwater, natural groundwater discharge and evapotranspiration.

The geometry of the system including thickness and properties, geological information of the system like cross section maps, topographic maps, and maps showing thickness of streams and lake sediments are the type of data included in physical framework. Information on heads and fluxes are included within the hydrologic framework. This information is then used for formulation of model and for calibrating model. Aquifer properties and hydrologic stresses are defined in hydro geologic. Information on evapotranspiration, pumping, and recharge are also included. Most challenging parameter to estimate is recharging (Anderson 2008).

4.5 MODEL CALIBRATION AND VALIDATION

4.5.1 MODEL CALIBRATION

In the Model calibration the input aquifer parameters are altered consistently until the approximate condition that matches the field conditions arises. The approximate conditions can be within the acceptable criteria, also known as calibration errors. The calibration is said to be complete when we obtain such set of parameters that result in simulated fluxes and heads. These simulated results should match the observed values and should be within an already established error range. Calibration process is an inverse modelling problem as in this the aquifer parameters are estimated through matching of simulated and observed hydraulic heads data. In an inverse problem, the aquifer parameters are obtained from data about water level heads, whereas in direct problem parameters like recharge rate is stated and the head values are calculated. The basic need of the calibration is to minimize the calibration criterion error. Statistics arising from calibration can be defined in any form listed below:

1. **Mean absolute error**:

Mean absolute error (MAE) is the arithmetic mean of the absolute value of the differences between the simulated and measured heads as expressed in Eq. 4.6.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|h_{s-}h_m| = \frac{1}{n}\sum_{i=1}^{n}|ei| \text{ (Eq. 4.6)}$$

Average of the absolute errors $e_i = h_s - h_m$ gives the mean absolute error.

Here, h_s = calculated value;

h_m = measured value.

2. **Mean error**:

Mean error (ME) is the arithmetic mean of variations between simulated and measured heads as shown in Eq. 4.7. Precaution must be taken while interpreting the mean error as in this the negative and positive residuals cancel out and thus results in a low error.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s) \qquad \text{(Eq. 4.7)}$$

Here, h_m = measured heads; and

h_s = simulated heads.

Calculation of mean error is easy but is not advisable to use this as both negative and positive variations are counted in the mean and thus, cancel out the error.

3. **Root mean square error (RMS)**:

Root mean square error is the standard deviation of the variations in simulated and measured heads as shown in Eq. 4.8. If the errors are normally distributed, then root mean square error is the best measure of error. Depending upon the significance of head change in the model domain, the adequate value for calibration criteria is decided. The errors represents the small part of overall model response if the ratio between the root mean square error and system's head range is small.

$$x_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x^2\, i} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots\ldots\ldots + x_n^2}{n}} \qquad \text{(Eq. 4.8)}$$

These three errors only quantify the average calibration error but do not define anything about distribution of error. By comparing the contour maps of head, we only get qualitative and subjective idea about the error distribution. Thus, error distribution's quantitative analysis should be the essential part of calibration. The residual error should be evenly distributed over the contours or grid (Anderson and Woessner 1992). There are two methods for estimation of model parameters and solving inverse problem:

1. Parameters trial and error adjustment: In trial and error calibration, aquifer parameters that were originally assigned to grid element or node are adjusted manually in

consecutive model runs and the simulated heads and flows are compared to calibrated values.

2. Automated parameter estimation: In automated parameter estimation method the codes, that are specifically designed, use either a direct or indirect technique for solution of inverse problem.

The unknown parameters are categorized as dependent variables in a direct solution. The input values for nodes must be heads. At the points where the observation wells are, the head values are known. Thus, for estimation of heads elsewhere in the grid, interpolation is used. The model parameter values and the nodal mass balance error are minimized in the solution. The indirect approach is identical to trial-error calibrations. PEST is the best calibration tool for performing automated parameter estimation. This tool was developed by John Doherty of Watermark Computing. It works with all types of models (Doherty 2004). PEST performs by using a template file that is a copy of the MODFLOW file and contains parameters to be estimated. The parameters are substituted by a code that advices PEST from where to obtain the parameters. Thus, the parameters that are to estimated must be written to the MODFLOW file. This file is generally the boundary condition files or .bcf package file.

4.5.2 MODEL VALIDATION

Model validation is the testing of model as whether it can be used as prediction tool or not. This is done by establishing that the calibrated model is a competent representation of the study area. Due to the unpredictability in the input data, the set of parameter input values attained by calibration process do not exactly represent the observed values. To establish a greater confidence in calibrated model, model validation is required. During validation process, aquifer parameters values and hydrologic stresses determined during calibration are used for simulation of transient model. For simulation, an independent and different set of field data exists. If there was significant change in calibrated parameters during validation, it is not possible to match the calibration targets using the new parameter values. In this case it is necessary to repeat the process until a set of parameter values is identified that produces a good match to both the calibration and verification targets. If parameter adjustment is required during validation, then the validation process becomes a second calibration and different independent data set is required to perform the validation. Validation is achieved when the validation targets match without any change in calibrated parameter values (Anderson and Woessner 1992).

4.6 LIMITATIONS OF GROUNDWATER MODELLING

There are different ways in which models can be misused such as overkill, inappropriate prediction and misinterpretation (Prickett 1979). To avoid these misuses, it is important to know and understand the limitations and possible sources of error in numerical models. As all numerical models are based on a set of assumptions, this limits their use for certain problems. To avoid applying a valid model to an inappropriate field situation, it is important to understand the field behaviour and assumptions that form the base of the model. For example, a two-dimensional model should be applied with care to a three-dimensional problem involving aquifer series. The other potential sources of error in the numerical model are replacement of the model differential equations by a set of algebraic equations. It is not possible to get the exact solution of the algebraic equations due to round-off error as a result of the finite accuracy of computer calculations. The assessment of the error caused by erroneous aquifer description data is difficult to since the true aquifer description is never known (James and Charles 1980). Therefore, precaution should be taken in formulating mathematical model for getting a real-world scenario which gives realistic future predictions of the aquifers.

CHAPTER 5

MODEL DEVELOPMENT

5.1 GROUNDWATER FLOW MODELLING

Groundwater flow can be described in the form of groundwater models using mathematical equations based on simplifying assumptions. These assumptions involve direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of bedrock within the aquifer. Groundwater models are used to calculate the rate and groundwater flow direction through aquifers and confining units in the sub-surface. Mathematical modelling basically involves four steps:

1. Formulation: It is the process of selecting the basic equations that governs the flow with domain specification and initial boundary conditions.

2. Approximation: This process refers to selection of numerical method used to solve the algebraic equations. The most commonly used solution strategies are: Finite Difference; Finite Element and Integrated Finite Difference.

3. Computation: This is the process of obtaining solution to differential equations used. This is done by coding the steps and using computer programme to solve the governing equations.

4. Application: This includes calibration and validation of the model, sensitivity analysis and prediction of the model for different scenarios.

5.2 FINITE DIFFERENCE MODELLING

The equation that describes the three dimensional movement of groundwater of constant density through a porous earth material under anisotropic steady state conditions is the partial differential equation given in Eq. 5.1(Don et al 2006).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_S\frac{\partial h}{\partial t} \qquad \text{(Eq.5.1)}$$

Here, h = Hydraulic Head;

x, y, z, t = Spatial Dimensions and Time;

K_{xx}, K_{yy}, K_{zz} = Hydraulic Conductivities in x, y and z direction;

S_s = Aquifer's Specific Storage

W = Volumetric flux per unit volume representing sources and/or sinks of water

The finite difference code, MODFLOW (McDonald and Harbaugh 1988) was chosen to solve the equation for hydraulic heads in the area. The MODFLOW model, which has been improved and verified by academia and engineers in many countries, has been used for more than 30 years. The model is extremely accurate and its suitability has been verified (Weiss and Gvirtzman 2007). In MODFLOW model, layers can be simulated as confined or unconfined. Flow associated with external stresses, such as wells, areal recharge, evapotranspiration, drains, and rivers, can also be simulated (Harbaugh 2000). A two-dimensional (2D) steady state groundwater flow model was constructed using Modflow (Harbough 2000), under the graphical user interface of Visual Modflow software. The model accounts for infiltration into and processes in the saturated zone, but does not simulate surface runoff and percolation through the unsaturated zone. The model was calibrated for steady state by trial-and error methods.

5.3 PROBLEM STATEMENT

Chaksu Watershed in Jaipur district is undergoing rapid development. It is estimated that the population in Chaksu Watershed will become more than double between the years 2000 and 2030. The sole source of drinking water for residents in this area is groundwater, and groundwater is also a major source of water for agricultural and commercial concerns. Recent and projected increases in water demand have raised concerns about potential impacts on water availability and water quality in the aquifers of Chaksu Watershed. A better understanding of the hydrogeologic system is essential in making proper and informed management decisions concerning groundwater use in this area. Given the complexity of aquifer characteristics and development patterns, a numerical groundwater flow model not only helps in understanding and conceptualizing the current groundwater flow system, but also provides a quantitative evaluation of changes in groundwater levels under current and projected water use conditions. For the present study area a regional groundwater flow was developed. Calibration and validation was done for model verification and finally the distribution of seasonal groundwater decline with respect to future scenarios was determined using the developed model. From the calibrated model, optimum groundwater utilization scenarios under different stress conditions can be framed. Fig 5.1 shows the model domain area.

Fig. 5.1: Model Area (model boundary shown by red colour)

5.4 CONCEPTUALIZATION OF GROUNDWATER FLOW MODEL

In developing the groundwater flow model, the first step is to define the area of interest and define boundary conditions for flow. Based on this information the flow system of the study area is then conceptualized. The conceptual hydrogeological model is a synthesis of all relevant data and describes the groundwater flow within the area of interest. The following information has been used for developing the conceptual model for the study area:

1. Hydrogeologic framework i.e. subsurface extent and aquifer thickness;
2. Aquifer's hydraulic properties;
3. Boundary conditions that control rate and direction of groundwater movement;
4. Magnitude and distribution of groundwater recharge.

The available data have been then analyzed and used for model formulation.

5.5 HYDROGEOLOGIC FRAMEWORK

In developing groundwater flow model, the initial stage is to define the region of interest and number of lithological units and their thickness. Study area extent has been defined using the watershed approach (GEC 1997). Watershed, enclosing the Chaksu region has been adopted as the horizontal extent of the aquifer. This block covers an area of 811.92 sq km. The hydro geological formations are Mica Schist and Older Alluvium. Two potential zones have been delineated in the block viz. "Ao" & "Sc" and are depicted in Fig 5.2:

ZONE 'Ao':

This zone covers an area of 552.06 sq km. The main water bearing formation is semi consolidated Older Alluvium. The depth to water varies from 14.00 meters (Chaksu) to 27.20 meters (Dehlala) below ground level as observed during pre-monsoon, 2008. The average yield of the wells with pump is 70,000 liters per day. The average discharge of the tube wells is 9.00 m^3/hr. The chemical quality of ground water is generally suitable for agriculture and domestic purposes. The present stage of ground water development is 168.82%. The long-term trends of water levels have shown the significant decline in pre and post monsoon periods, therefore, this zone has not been recommended for further ground water exploitation.

ZONE ‘Sc’:

This zone occupies an area of 177.30 Sq.km. The main water bearing formation is Schist and groundwater generally occurs in weathered and permeable zone and along schist, joints and fractured planes. The depth to water varies from 15.75 meters (Sanwasa) to 23.40 meters (Akoriya) below ground level as observed during pre monsoon, 2008. The average yield of the wells with pump is 52,000 liters per day whereas the average discharge of the tube wells is 7.50 m^3/hr. The chemical quality of ground water is generally suitable for agriculture and domestic purposes. The present stage of ground water development is 198.44%. The long-term trends of water levels have shown significant decline in pre and post monsoon periods, therefore, this zone has not been recommended for further ground water exploitation.

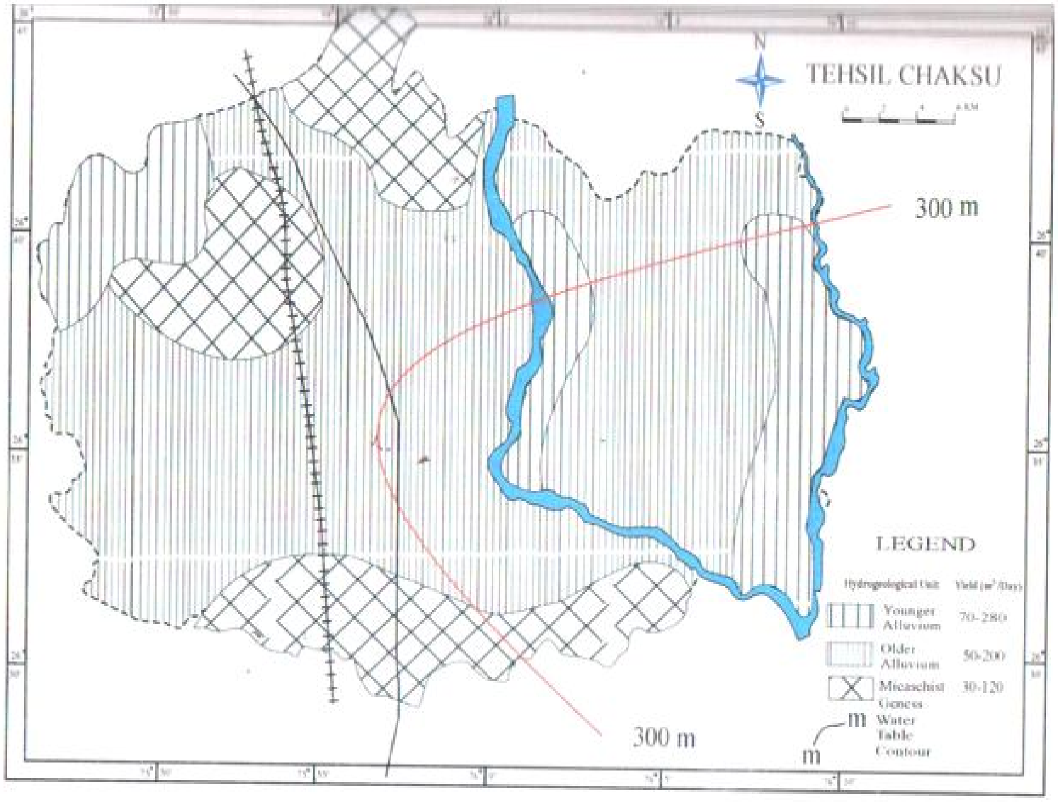


Fig.5.2: Groundwater Potential Zone and Aquifer (Chaksu region) (CGWB)

The block Chaksu as a whole has been categorized as **“**Over-Exploited**”** with stage of ground water development 173.36% and, thus, not recommended for further ground water exploitation. Lithological section of the aquifer is presented in Fig 5.3.

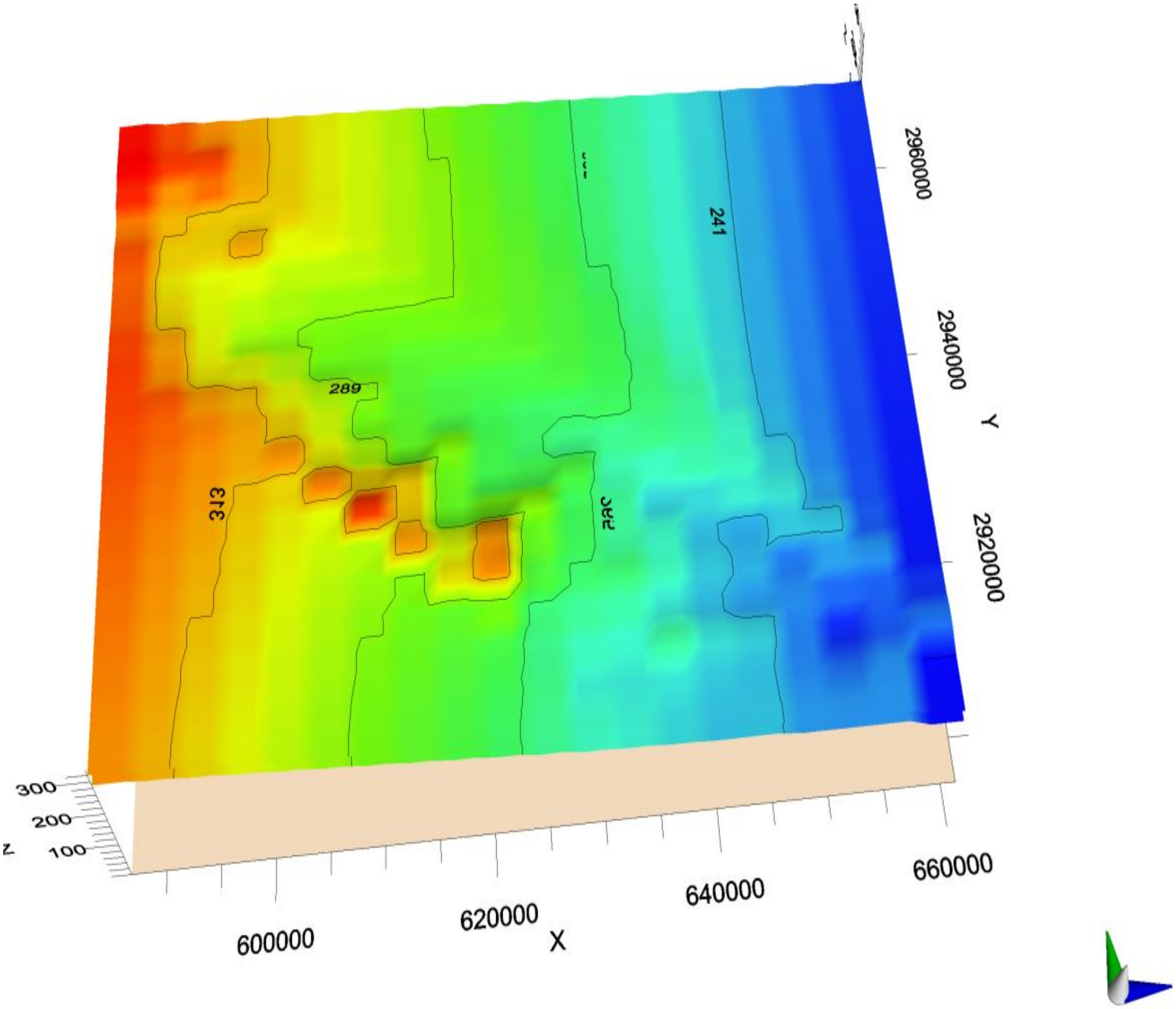


Fig.5.3: Lithological Section of the Aquifer

The top and bottom ground elevation of the aquifer is shown in Fig 5.4 and Fig 5.5.

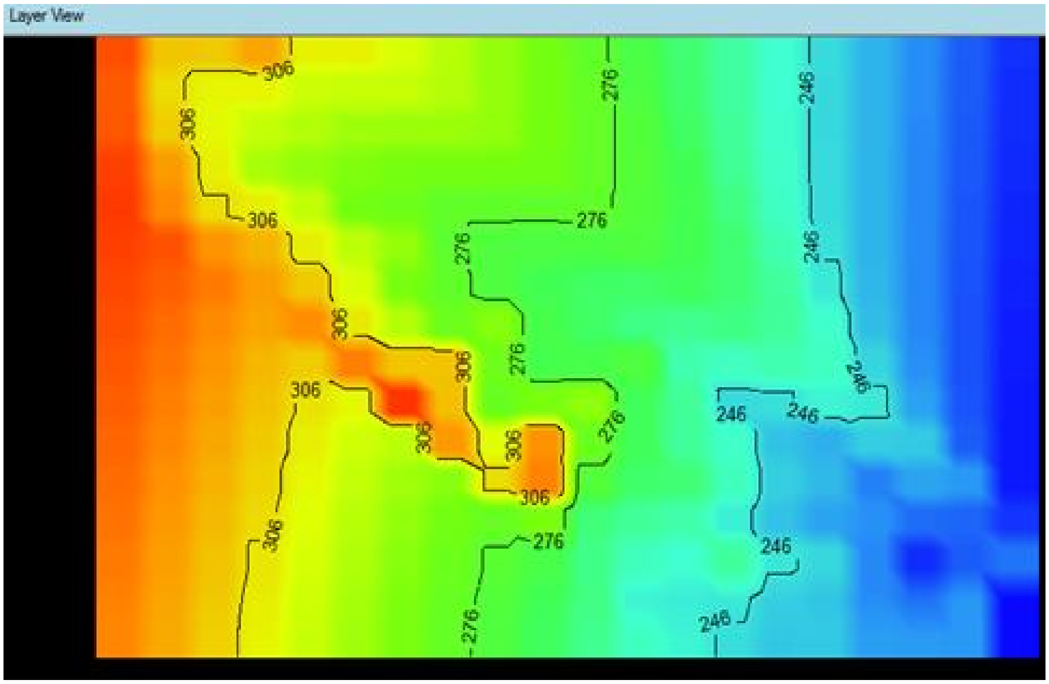


Fig. 5.4 (a): Ground Surface Elevation at top of Aquifer

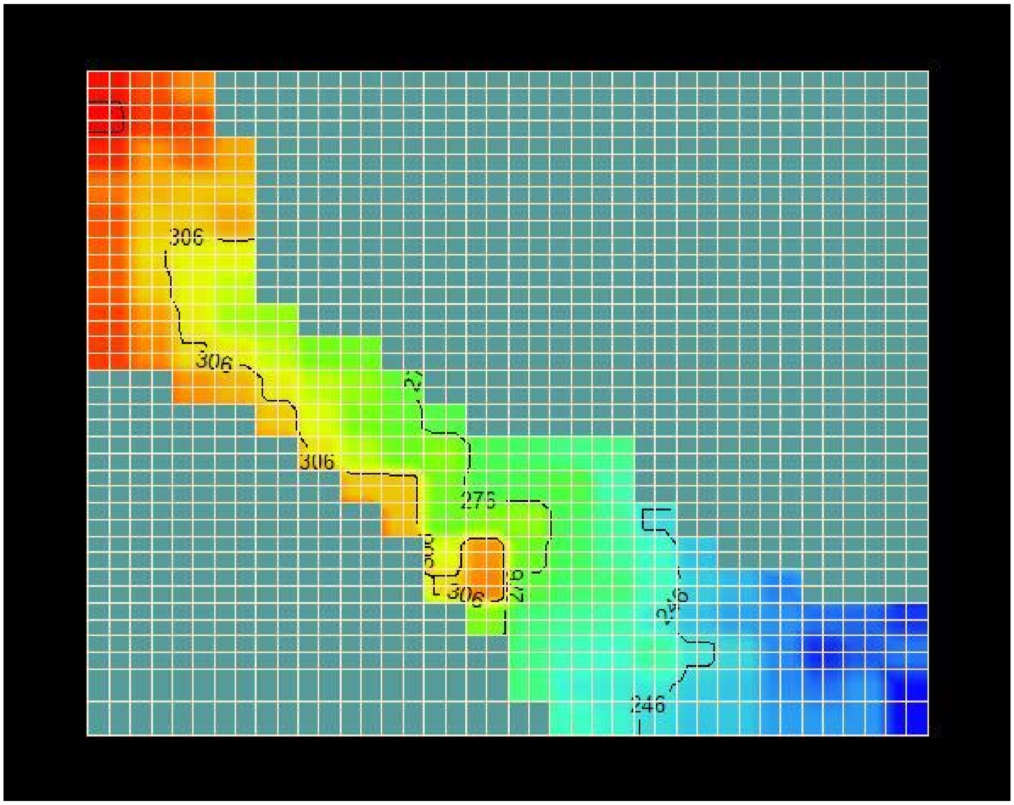


Fig. 5.4 (b): Ground Surface Elevation at top of Aquifer

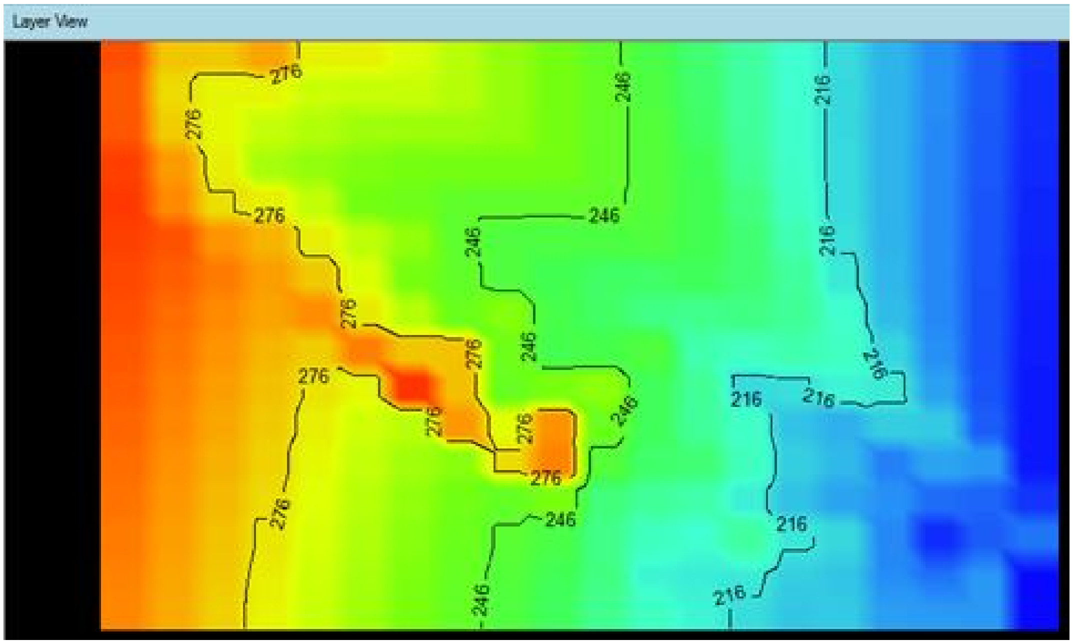


Fig. 5.5 (a): Ground Surface Elevation at bottom of Aquifer

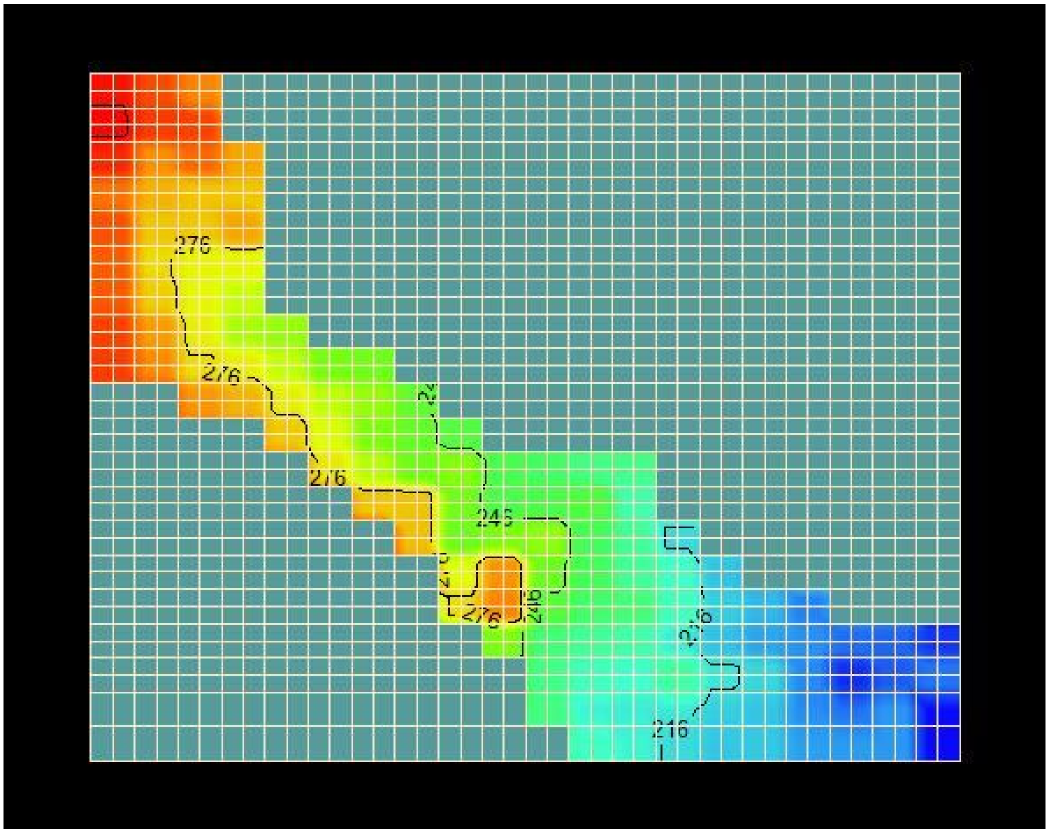


Fig. 5.5 (b): Ground Surface Elevation at bottom of Aquifer

5.6 MODEL FORMULATION

The three dimensional groundwater flow model of the study area, expressed as flow equations were solved using the model code MODFLOW-2000. This code is based on finite difference method. Same extents as that of study area boundaries were used as extent of the modelling domain as shown in Fig 5.6.

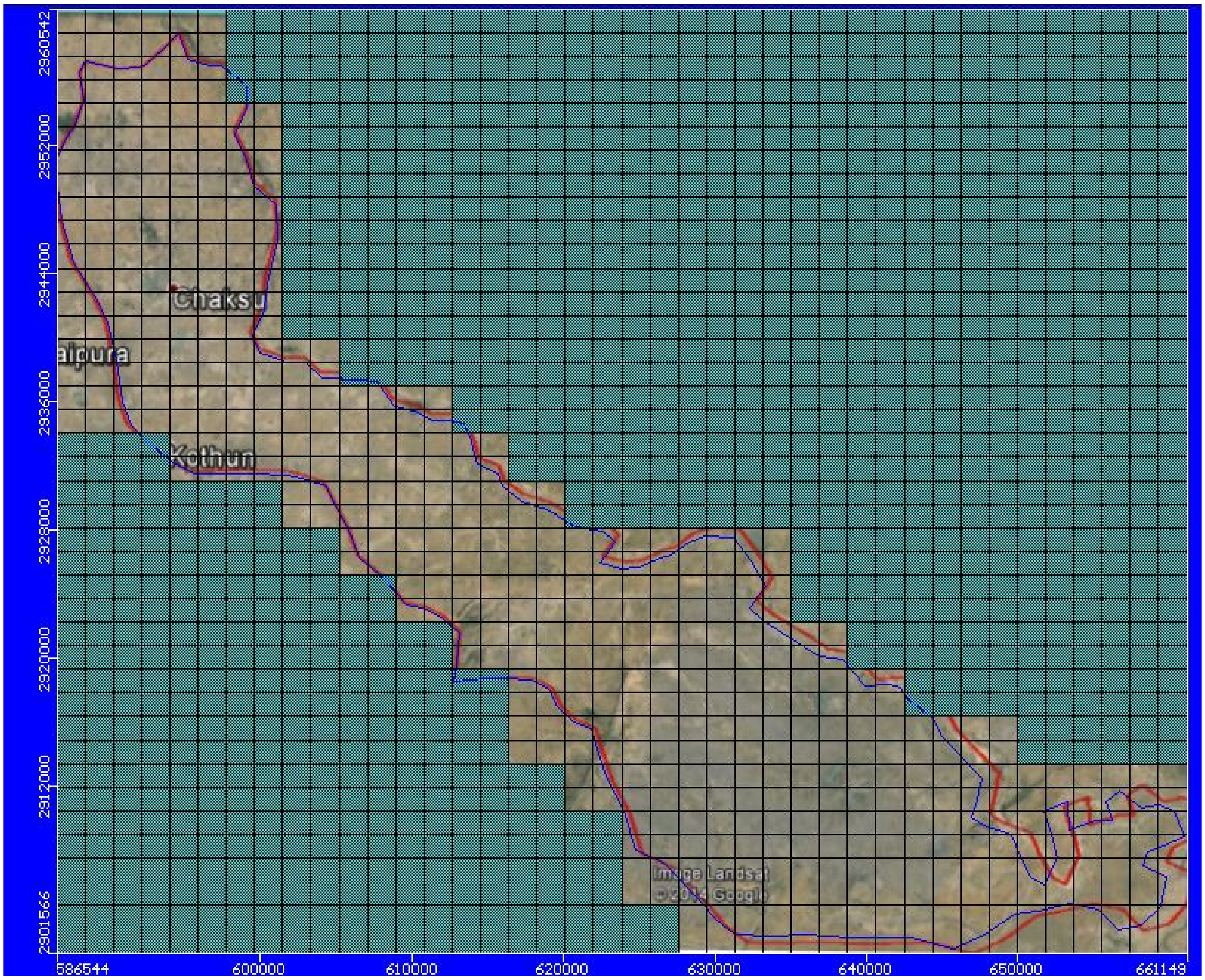


Fig. 5.6: Active Model Domain Area

Geologically, the area is occupied with Alwar quartzites in the east and fluvio-aeolian deposits in the rest of the district. The borehole data of Central ground Water Board (CGWB) shows alternation of fluvial bands with Aeolian bands in sporadic manner. The sediments are mostly silt with medium to fine sand, clay and kankar. The most significant hydrostratigraphic unit in terms of water supply considerations is the alluvium unit since it represents the water source for the vast majority of the domestic wells constructed through this unit. Information pertaining to the hydrogeological characteristics of this unit was available from the geological studies carried out by Geological Survey of India (GSI). Therefore, the model consisted of a single layer representing the alluvium unit. The layer type was specified as unconfined. As such, the hydraulic conductivity of the layer was held constant throughout the simulations. The boundaries of the model were determined in such a way that it encompasses entire study area. Numerical model require approximations to solve differential equations that describe groundwater flow. These approximations require that the model domain and time be discretized. In this process, model domain is represented by network of grid cells and time of simulation is represented by time steps. The regional hydro geologic framework of Chaksu watershed has been defined by a model grid consisting of 40 columns, 38 rows and 1 vertical layer. Each cell has dimension of 1871m by 1476m resulting in total of 1520 cells. Fig 5.7 depicts the active model design and discretization. The formulated model was then calibrated and verified and sensitivity analysis was carried out for aquifer parameters- hydraulic conductivity and recharge. The simulated model results were then used for model predictions. These have been discussed in further paragraphs.

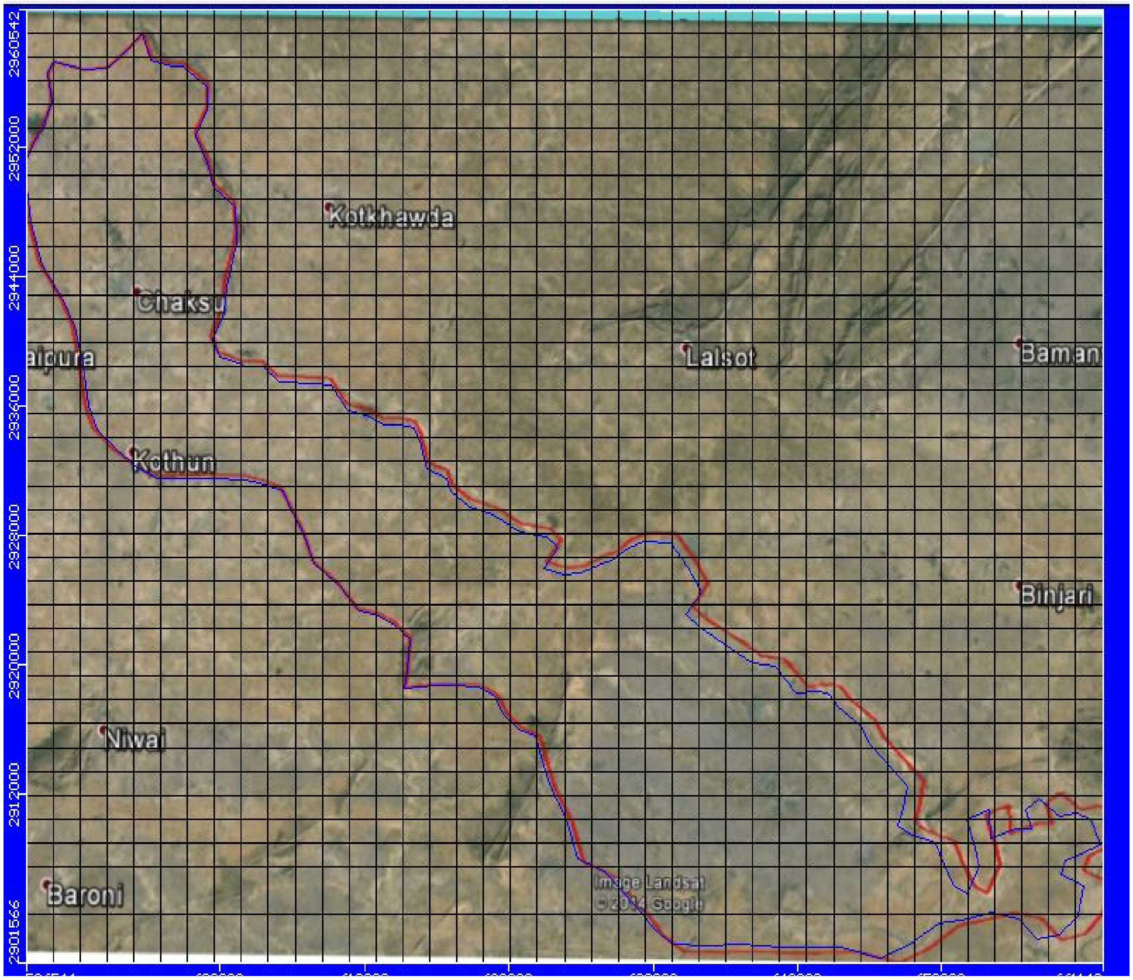


Fig. 5.7: Model Design and Discretization

5.7 GROUNDWATER LEVELS

The aquifer disposition was established on the basis of lithology of exploratory well drilled by CGWB and State GW department. The ground water level data was collected during field visit and historical data of groundwater monitoring station were collected from CGWB and State GW department. Seasonal (pre and post monsoon) water levels have been obtained for all the wells for a period of 12 years (2001 to 2012). Pre monsoon water levels have been measured at the end of May. Post monsoon water levels have been measured at the end of

November. Water level variations in pre and post monsoon for older alluvium zone and schist zone of Chaksu block have been shown in Fig 5.8 and Fig 5.9.

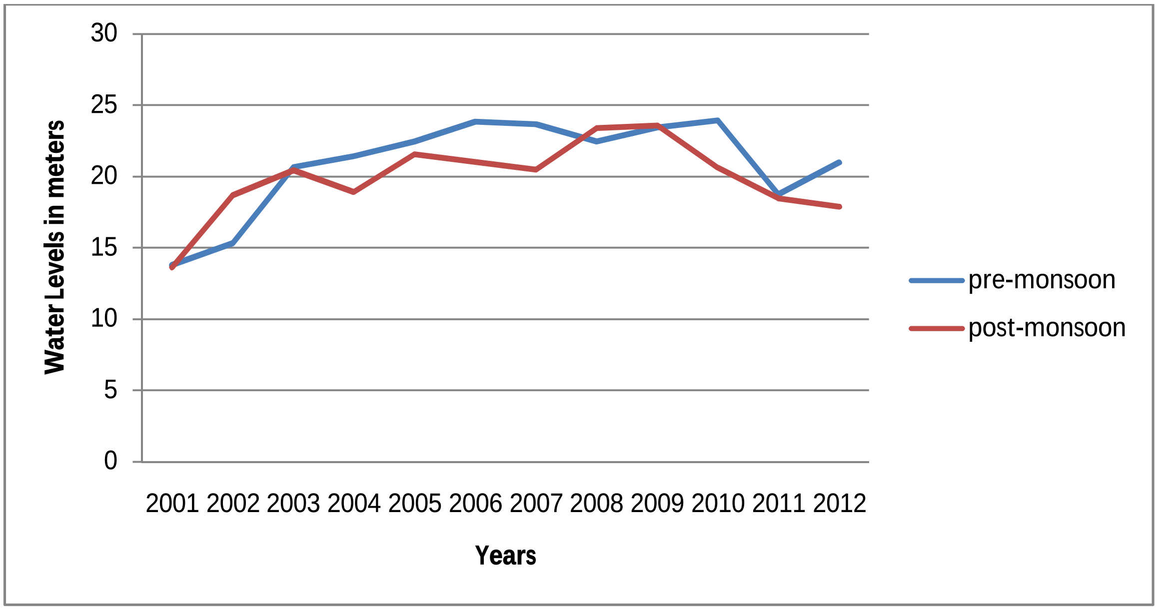


Fig. 5.8: Pre and Post monsoon Water Level Trend for Older Alluvium Zone of Chaksu Block

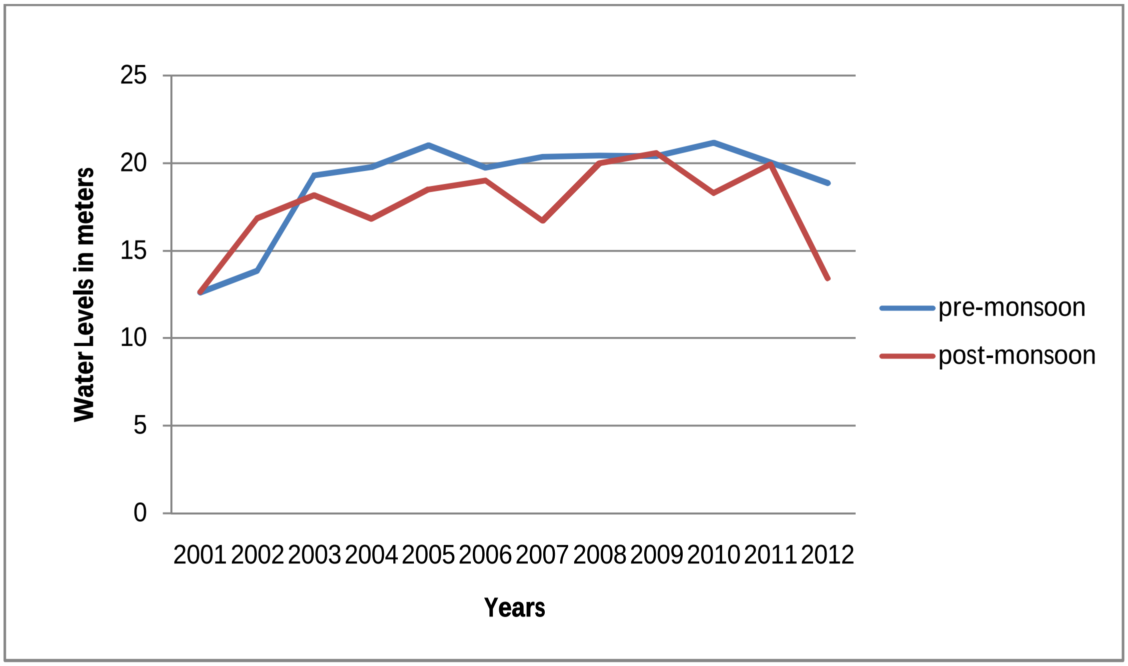


Fig. 5.9: Pre and Post Monsoon Water Level Trend for Schist Zone of Chaksu Block

Location of different water table observation and pumping wells is shown in Fig 5.10 and Fig 5.11.

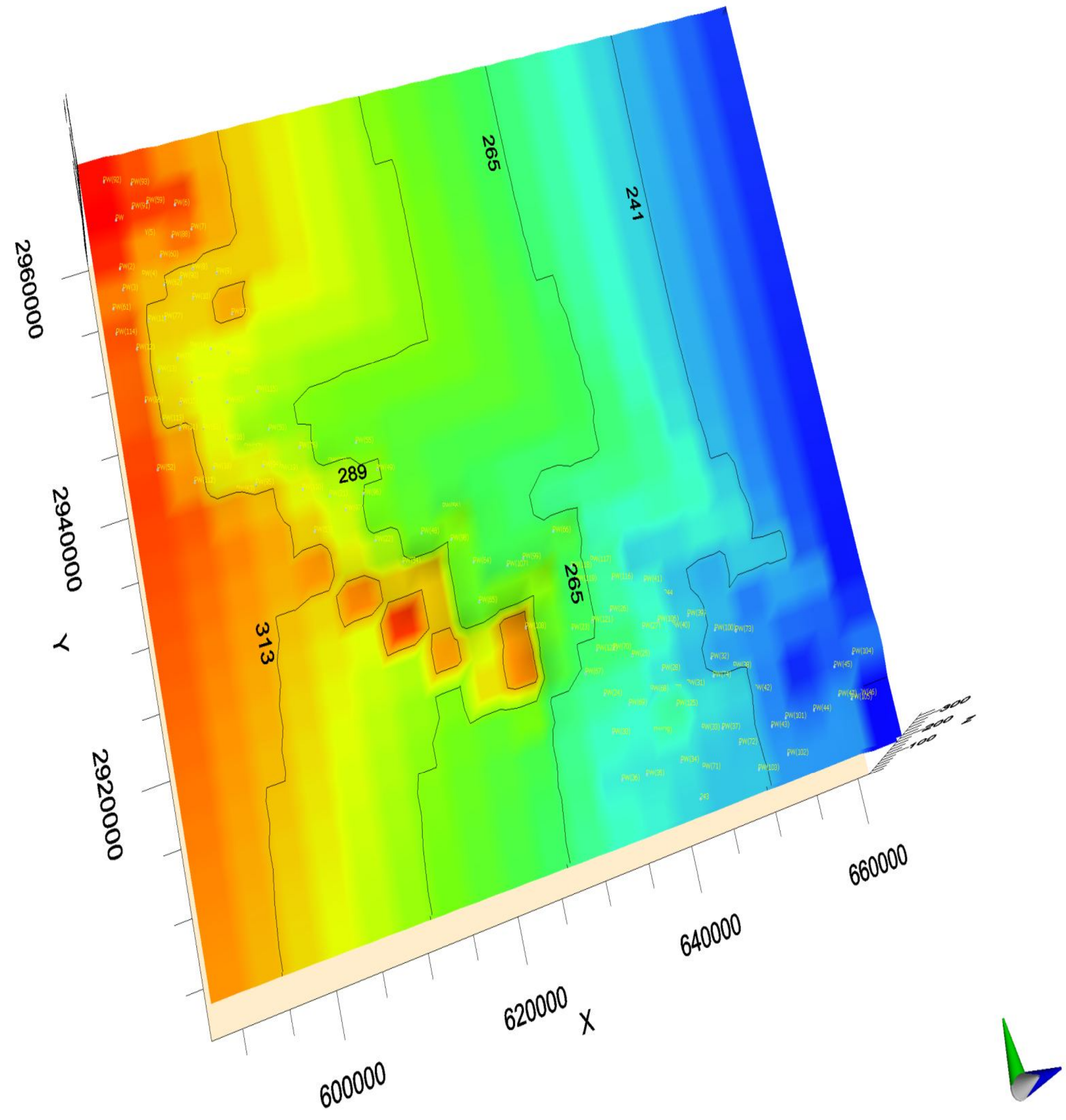


Fig. 5.10: Location of Water Table Observation and Pumping Wells

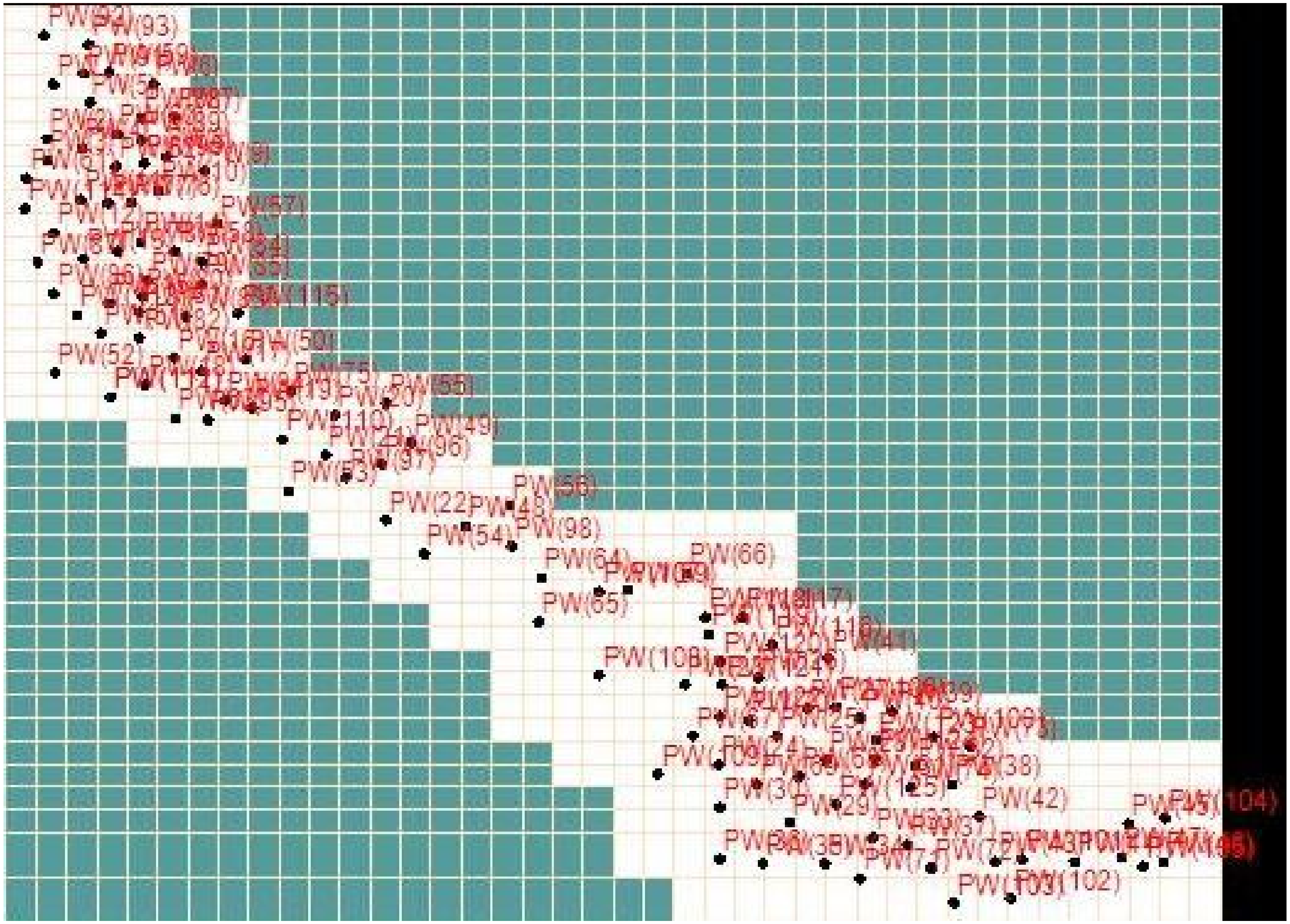


Fig 5.11: Pumping Wells Location

5.8 BOUNDARY CONDITIONS

For development of accurate model,it is important to conceptualize the groundwater flow system as how and where water originates and how and where it leaves the system (Reilly 2001). The flow domain expended vertically and horizontally to meet the physical features of Groundwater sysem, can be represented as boundaries. Boundary conditions are to be specified along the entire boundary of 3D flow domain, to obtain a solution for groundwater flow equation. In the present study, depending upon the topographical information, Groundwtaer flow direction and geological features of the area, boundary conditions have been decided. Fig 5.12 shows the different types of boundaries considered in the present investigation. The area is underlain by hydro-stratigraphic units, namely an upper unconsolidated zone and a lower fractured rock zone. The groundwater is recharged from rainfall. The ground water flow follows topography and flows from north-western boundary of the model area towards south- easterly direction. Accordingly, these have been simulated as constant head boundaries in the model. There are 5 constant head boundaries with heads as 320m, 233m, 275m, 233m, and 305m. Groundwater outflow from study area takes place from south-eastern boundary. Groundwater contours are widely spaced and indicates presence of porous aquifer. Rest of the boundary is designated as no flow boundary as it is a watershed boundary or water divide. It is represented by ridge. That’s why it was considered that flow will not take place through ridge hence no flow boundary was considered.

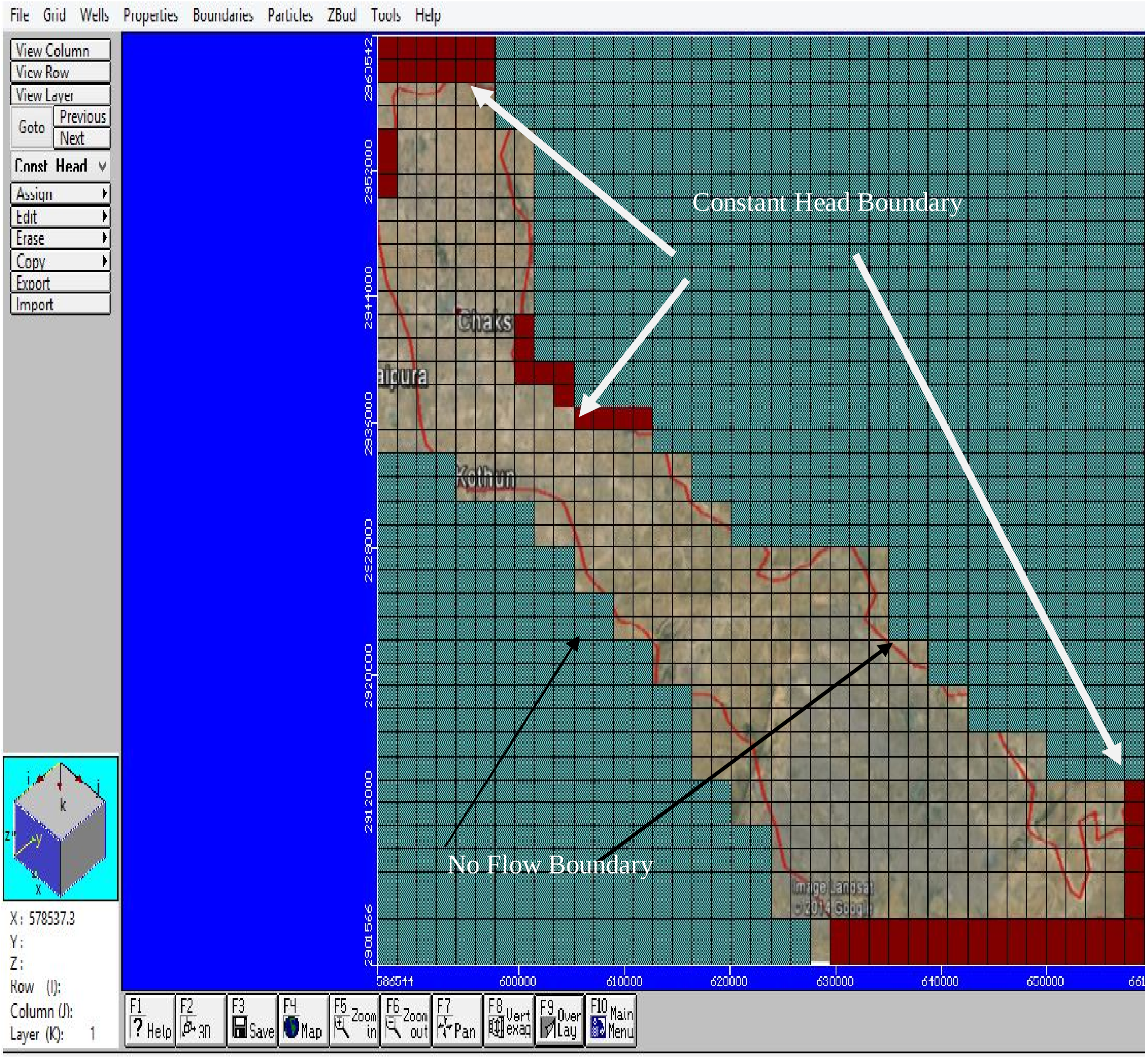


Fig. 5.12: Map Showing Boundary Conditions

5.9 MODEL CALIBRATION AND VALIDATION

Model calibration is the process of varying model input parameters within a reasonable range until the model output matches observed conditions within some acceptable error criteria (Anderson 1992). The RMS should be less than 10% of the head difference across the domain in a well-calibrated model. The calibration can be either to steady-state or transient state conditions. Steady-state model simulations eliminate the time terms in the governing equations and provide a picture of the hydraulic conditions in a stable aquifer system. An inherent assumption with this type of simulation is that the system has achieved an equilibrium condition. Steady state results are also commonly used as initial conditions for subsequent transient simulations. For models that are affected by a variety of constantly changing stresses, transient calibration is necessary to ensure that the model is providing a reliable representation of the system. Once a model is considered calibrated, it is then validated against at least one different set of observed conditions using the hydraulic parameters established during calibration. A model is considered validated when the set of model parameters from the calibration process yields a similar satisfactory degree of agreement between field observations and computed model results for the independent validation period(s). If the validation results are not satisfactory, then the model calibration process resumes, continuing until a satisfactory agreement is obtained for the calibration and validation datasets. The quality of the steady state calibration was evaluated in several different ways, including error statistics and calibration target figures. A model's calibration is measured mathematically by the use of error statistics. The three criteria generally used are the mean error (ME), mean absolute error (MAE), and the root mean square (RMS) error.

A steady-state calibration is accomplished for the year 2001. The general groundwater flow direction is from north- west to south east. The calibrated steady-state model conditions have been used as initial conditions for the transient model. Validation of the model results has been carried out by comparing simulated water levels and observed water levels in selected observation wells. Fig 5.13 shows the validation of model where simulation results are in close agreement with observed results.

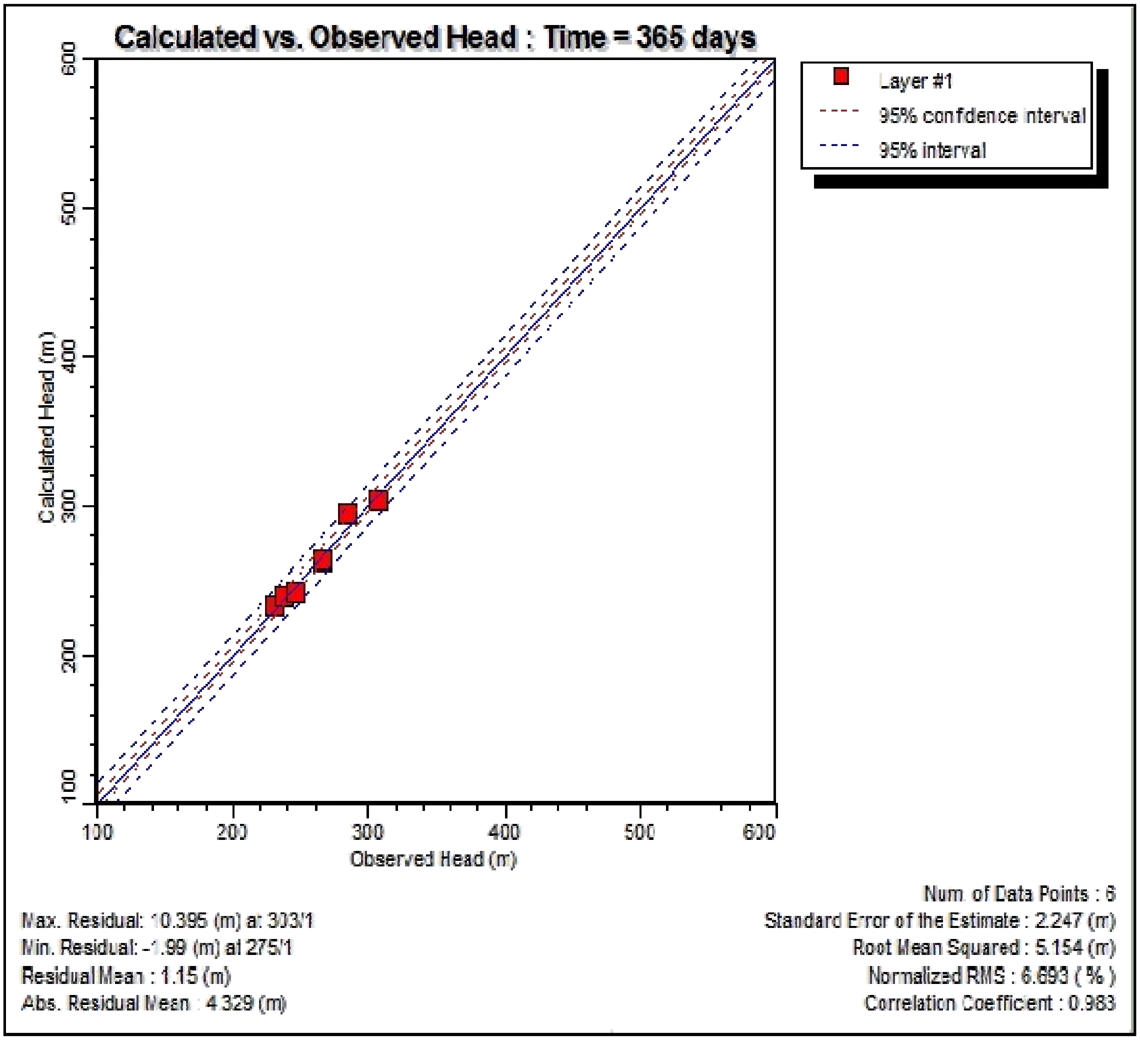
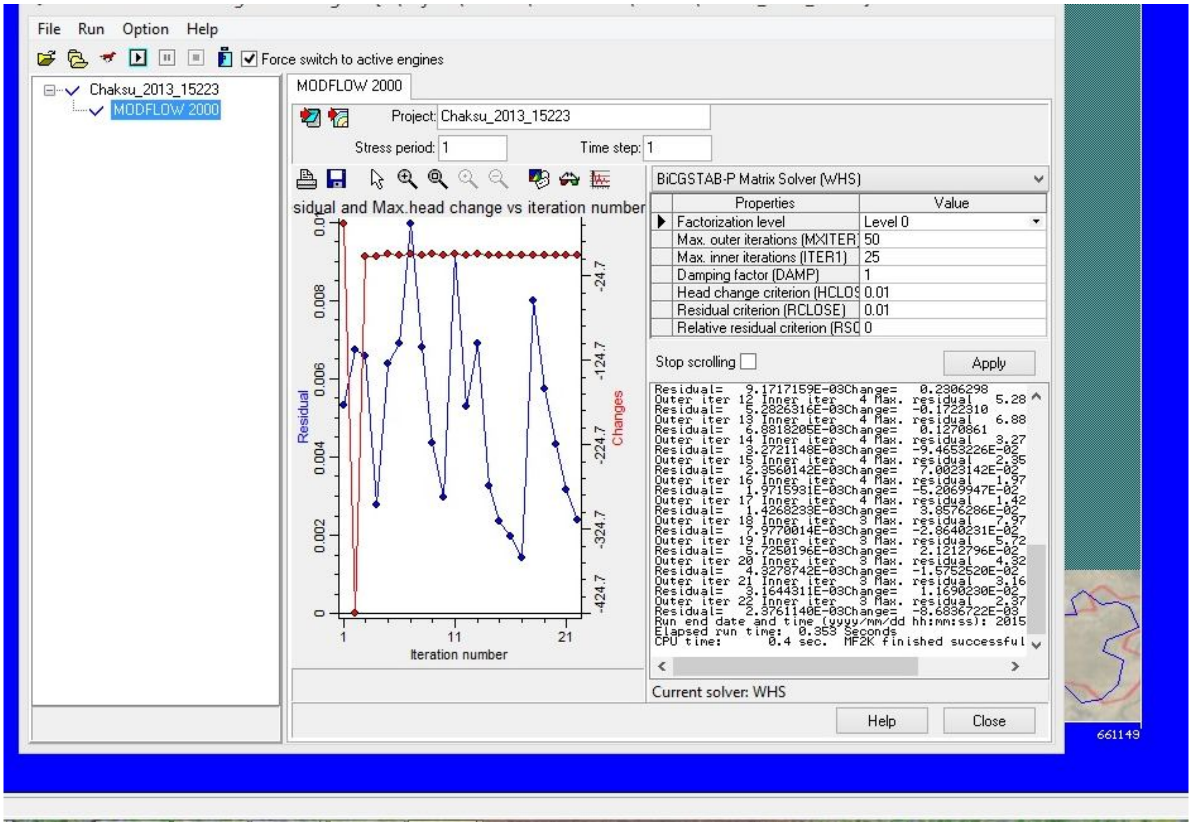


Fig. 5.13: Simulated and Measured Water Levels

Initially hydraulic conductivity in X and Y directions has been assumed same, while in Z direction, it has been assumed as one tenth of the horizontal conductivity in X direction. During the calibration process, it was observed that the hydraulic conductivity in Y and Z directions is relatively insensitive. Accuracy of the model has been judged by comparing RMS, NRMS and standard error of the differences between the calculated head and observed heads. The RMS error has been found to be 5.154 m whereas the NRMS error came out to be 6.693 % which are within satisfactory range. Validation results reveal that there is a good agreement between simulated and observed groundwater levels and there is no further need for calibration refinement. Fig 5.14 depicts the model run.



MODFLOW 2000

Project: Chaksu_2013_15223

Stress period: 1

Time step: 1

BiCGSTAB-P Matrix Solver (WHS)

Properties	Value
Factorization level	Level 0
Max. outer iterations (MXITER	50
Max. inner iterations (ITER1)	25
Damping factor (DAMP)	1
Head change criterion (HCLOS	0.01
Residual criterion (RCLOSE)	0.01
Relative residual criterion (RSC	0

Stop scrolling ☐

```
Residual=   9.1717159E-03Change=   0.2306298
Outer iter 12 Inner iter   4 Max. residual   5.28
Residual=   5.2826316E-03Change=  -0.1722310
Outer iter 13 Inner iter   4 Max. residual   6.88
Residual=   6.8818205E-03Change=   0.1270861
Outer iter 14 Inner iter   4 Max. residual   3.27
Residual=   3.2721148E-03Change=  -9.4653226E-02
Outer iter 15 Inner iter   4 Max. residual   2.35
Residual=   2.3560142E-03Change=   7.0023142E-02
Outer iter 16 Inner iter   4 Max. residual   1.97
Residual=   1.9715931E-03Change=  -5.2069947E-02
Outer iter 17 Inner iter   4 Max. residual   1.42
Residual=   1.4268233E-03Change=   3.8576286E-02
Outer iter 18 Inner iter   3 Max. residual   7.97
Residual=   7.9770014E-03Change=  -2.8640231E-02
Outer iter 19 Inner iter   3 Max. residual   5.72
Residual=   5.7250196E-03Change=   2.1212796E-02
Outer iter 20 Inner iter   3 Max. residual   4.32
Residual=   4.3278742E-03Change=  -1.5752520E-02
Outer iter 21 Inner iter   3 Max. residual   3.16
Residual=   3.1644311E-03Change=   1.1690230E-02
Outer iter 22 Inner iter   3 Max. residual   2.37
Residual=   2.3761140E-03Change=  -8.6836722E-03
Run end date and time (yyyy/mm/dd hh:mm:ss): 2015
Elapsed run time:  0.353 Seconds
CPU time:      0.4 sec.  MF2K finished successful
```

Current solver: WHS

Fig. 5.14: Model Run

5.10 MODEL SIMULATION RESULTS

Groundwater flow path revealed by mathematical modelling shows that groundwater enters in to the study area from Shivdaspura and Padampura situated in north-western boundary and outflows from the two locations viz. Nandgaon Basri and Sankra, located south east. The spatial distributions of horizontal hydraulic conductivity within model layers was determined by gridding observations and estimates of K, spatial averaging of results into zones of similar K values. Sedimentary deposits typically exhibit anisotropic hydraulic properties - specifically, they are more permeable in the horizontal direction than they are in the vertical direction (Anderson and Woessner, 1992). An initial value of 10:1 was selected for the starting vertical anisotropy ratio of K (horizontal K: vertical K). This initial anisotropy value was adjusted during the calibration process. Simulations indicate the mean recharge rates are 130 mm/yr in Chaksu watersheds, which represent 16% of mean annual precipitation

(=560mm/yr.). The recharge and discharge areas in the model domain are shown in Fig 5.15(a) and Fig 5.15(b).

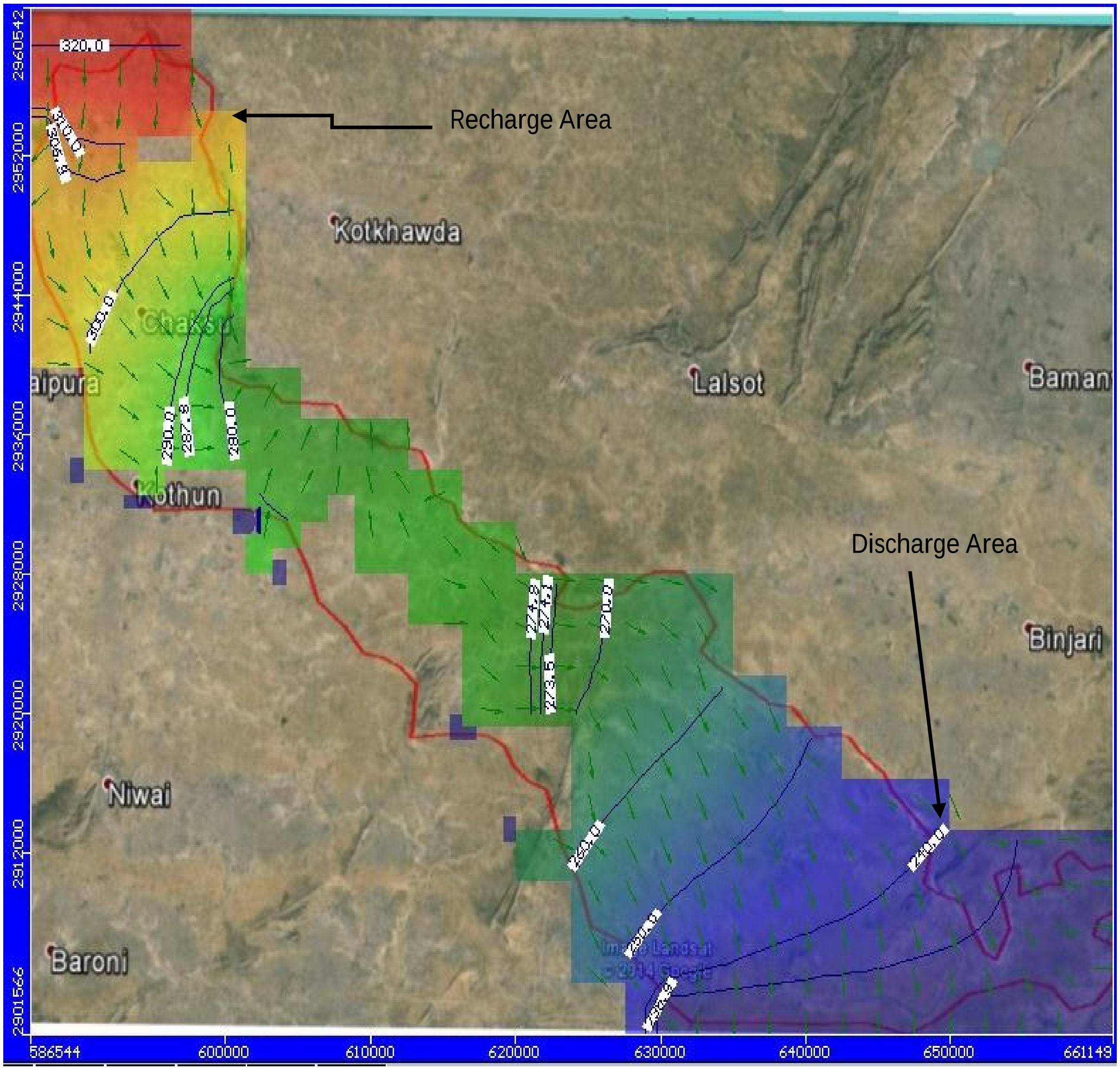


Fig. 5.15 (a): Recharge and Discharge Areas in the Model Domain

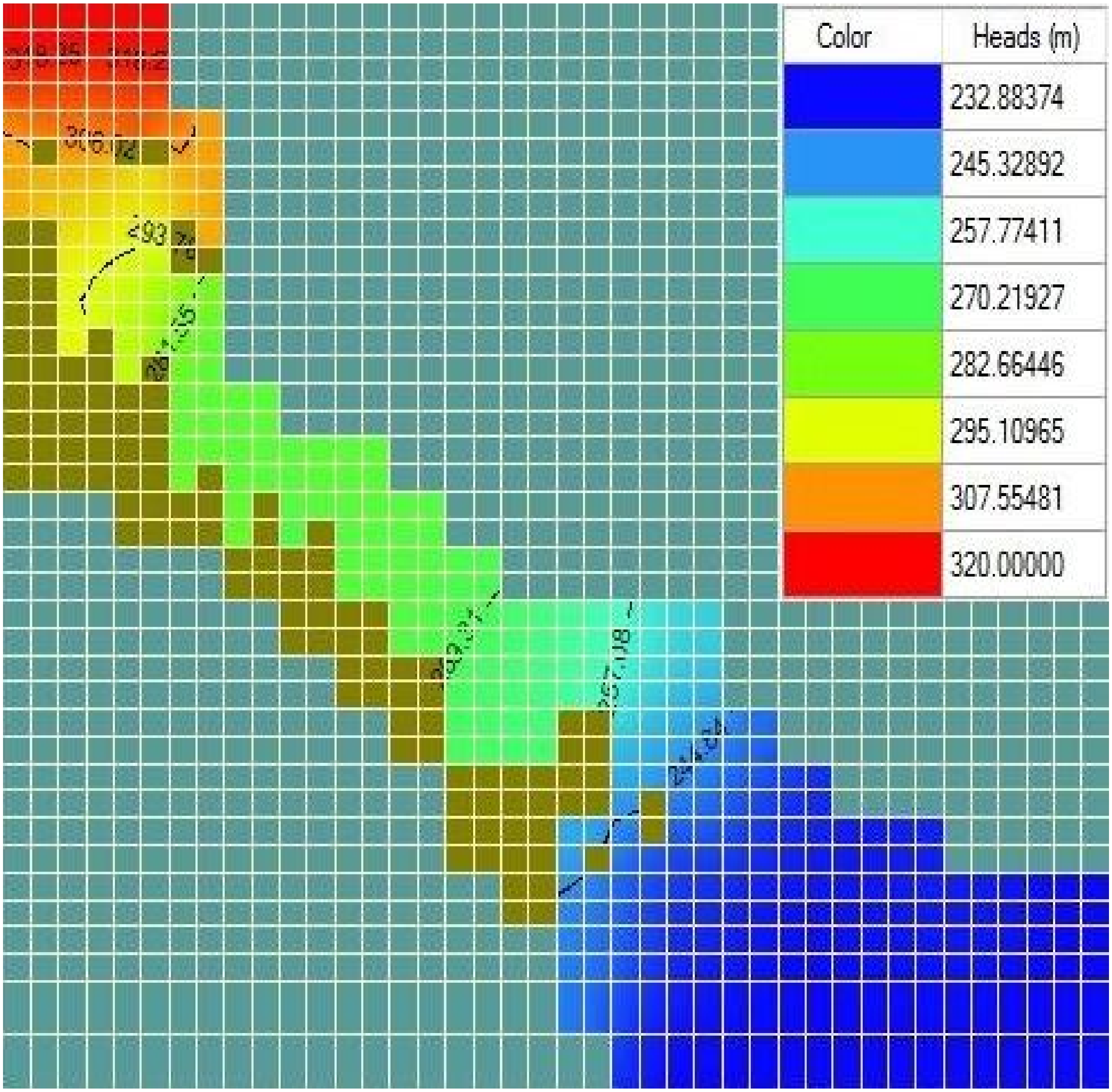
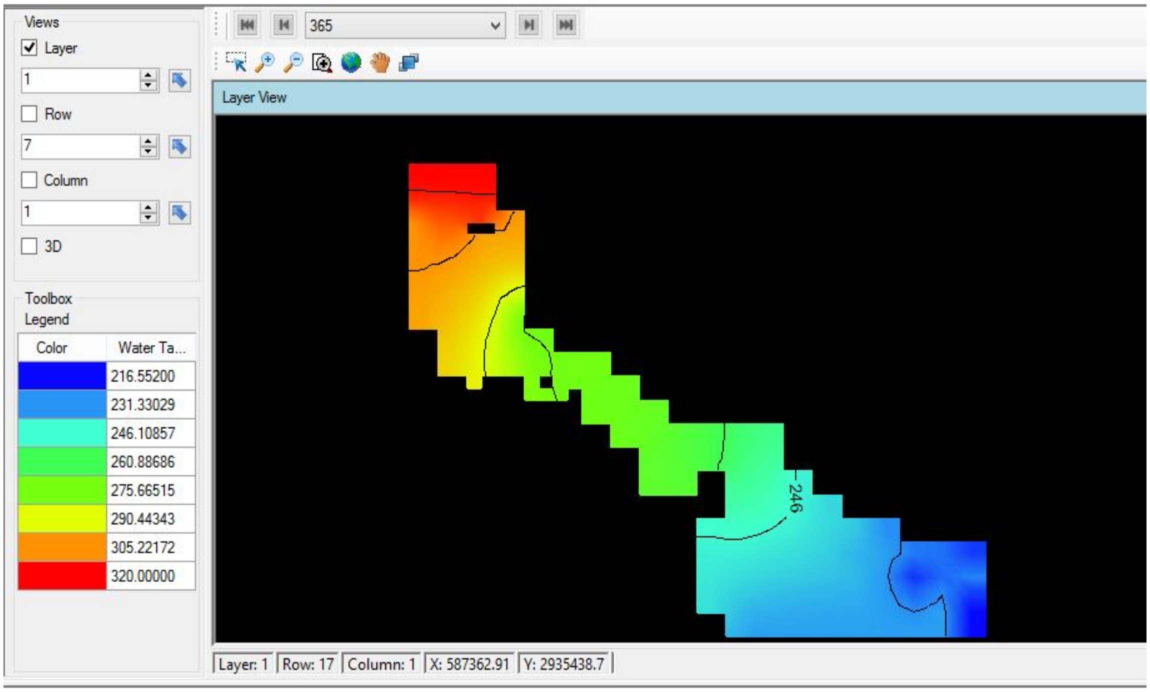


Fig. 5.15 (b): Recharge and Discharge Areas in the Model Domain

Simulated results have been carried out for different set of time periods. Sample results for groundwater table, heads, and drawdown is shown in Fig 5.16, Fig 5.17 and Fig 5.18 respectively. The head values ranged from 233m to 320m. The groundwater table level ranged from 216.55 to 320m.


Views

☑ Layer

1

☐ Row

7

☐ Column

1

☐ 3D

Toolbox

Legend

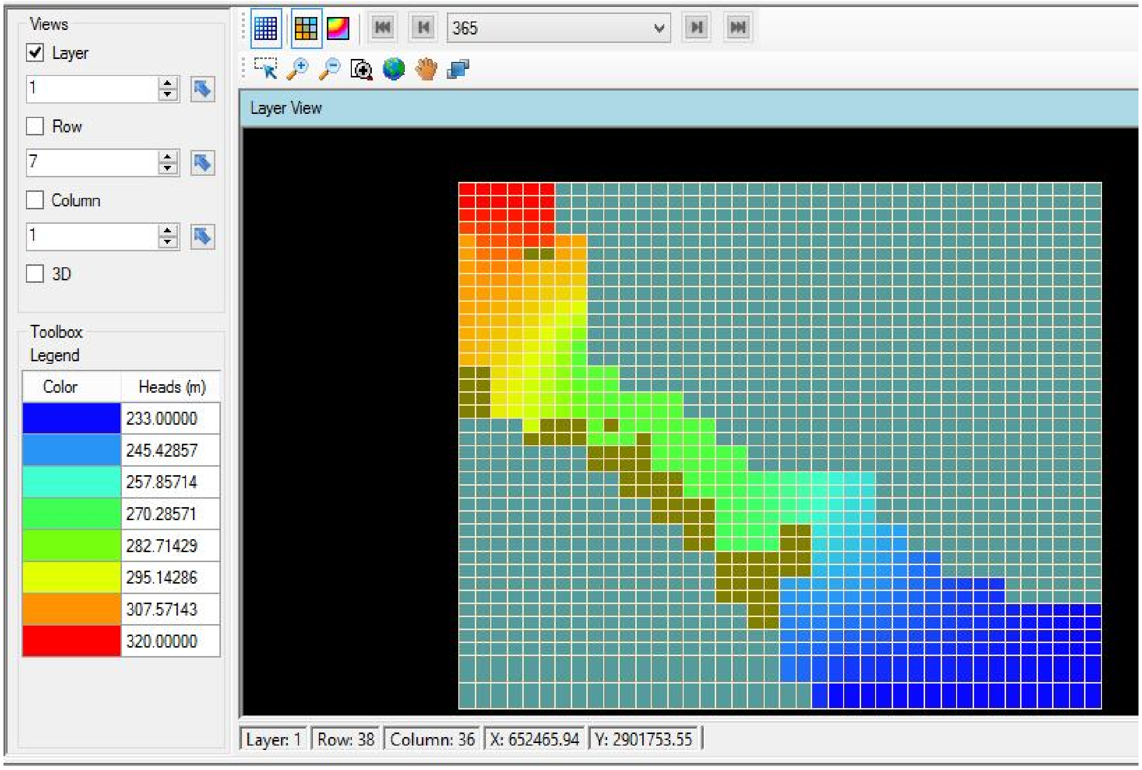
Color	Water Ta...
🟦	216.55200
🟦	231.33029
🟦	246.10857
🟩	260.88686
🟩	275.66515
🟨	290.44343
🟧	305.22172
🟥	320.00000

365

Layer View

Layer: 1 | Row: 17 | Column: 1 | X: 587362.91 | Y: 2935438.7

Fig. 5.16: Simulated Groundwater Table


Views

☑ Layer

1

☐ Row

7

☐ Column

1

☐ 3D

Toolbox

Legend

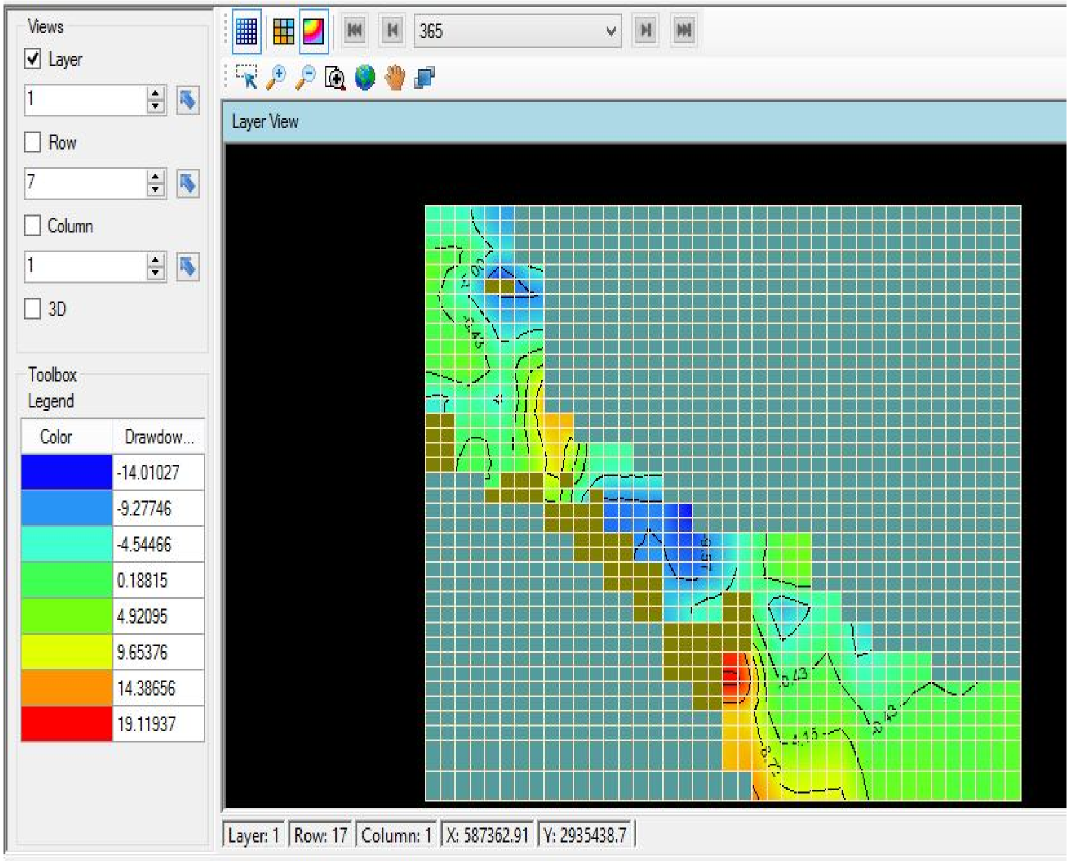
Color	Heads (m)
🟦	233.00000
🟦	245.42857
🟦	257.85714
🟩	270.28571
🟩	282.71429
🟨	295.14286
🟧	307.57143
🟥	320.00000

365

Layer View

Layer: 1 | Row: 38 | Column: 36 | X: 652465.94 | Y: 2901753.55

Fig. 5.17: Simulated Heads



☑ Layer: 1

☐ Row: 7

☐ Column: 1

☐ 3D

Time step: 365

Legend

Color	Drawdow...
🟦	-14.01027
🟦	-9.27746
🟩	-4.54466
🟩	0.18815
🟩	4.92095
🟨	9.65376
🟧	14.38656
🟥	19.11937

Layer: 1 | Row: 17 | Column: 1 | X: 587362.91 | Y: 2935438.7

Fig. 5.18: Predicted Drawdown

5.11 WATER BUDGET CALCULATION

Water budget for the year 2013, 2025 and 2050 were calculated. Water budget results of the model revealed that for the 2013, 87% of the total inflow is from rainfall recharge whereas only 12% from surrounding areas. There is 66% increase in pumping outflow in year 2050 as compared to year 2013. Thus, indicating more stress on already over exploited groundwater resource. Results of water-budget calculations (Table 5.1) indicate that there is significant inflow to the alluvium aquifer from the constant-head boundary. Water-budget calculations also show that a majority of this flow exits the model through constant-head nodes, which is consistent with the conceptual model for the area. Water-budget results indicate that the rainfall recharge is the primary source of water for the alluvium aquifer rather than inflow from surrounding areas. From the Fig 5.19, representing the water balance it is clear that the total outflow will increase in year 2050 thus, putting more stress on the groundwater resource.

Table 5.1: Water Balance of the Model Area

Flow Component	**2013** (m^3/Year)	**2025** (m^3/Year)	**2050** (m^3/Year)
Net Inflow from surrounding area	127,46,909	118,85,680	134,22,992
Recharge Inflow	931,12,512	931,67,504	925,07,520
Total Inflow	1058,59,421	1050,53,184	1059,30,512
Pumping Outflow	36865000	438,00,000	558,01,200
Net Outflow to surrounding area	68994424	612,53,132	501,29,304
Total Outflow	1058,59,424	1050,53,132	1059,30,504

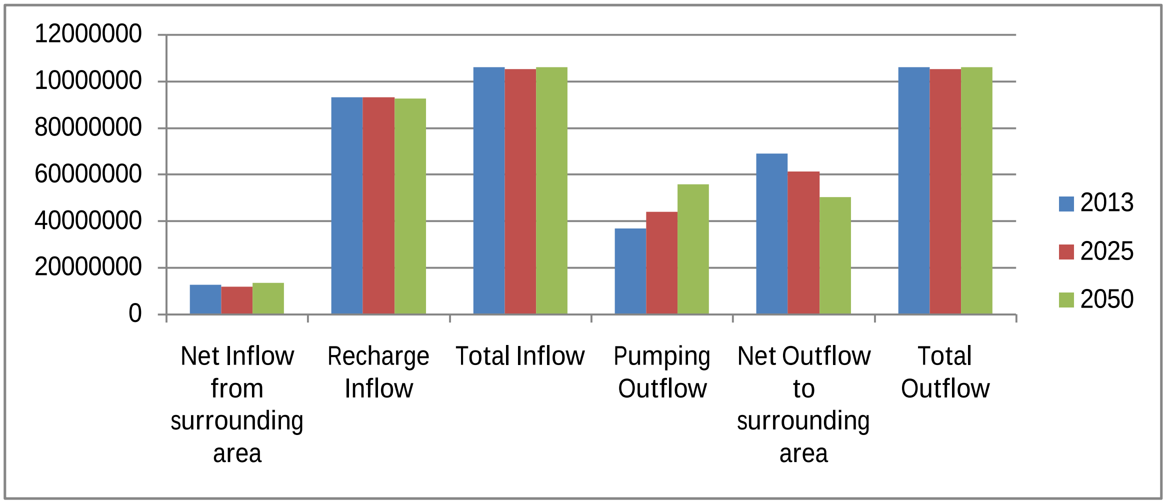


Fig. 5.19: Graph Representing the Water Balance

5.12 FUTURE SCENARIOS

It is projected that the demand for public water supply and irrigation demand in the Chaksu study area will increase by approximately 30 percent between 2013 and 2050. To understand how this increased pumping may affect groundwater flow and water budgets, we assumed that this increased demand will be supplied by existing wells and simulated the increased water demand by increasing concurrently the pumping rate for all current irrigation wells by 30 percent. Comparison of predicted water levels during increased pumping to previous model-simulated results indicates that the maximum head decline in the Alluvium aquifer will be approximately 2.5meters by 2050 (Fig 5.20, Fig 5.21 and Fig 5.22). The maximum head decline (about 4 meters) is in northern part of model area.

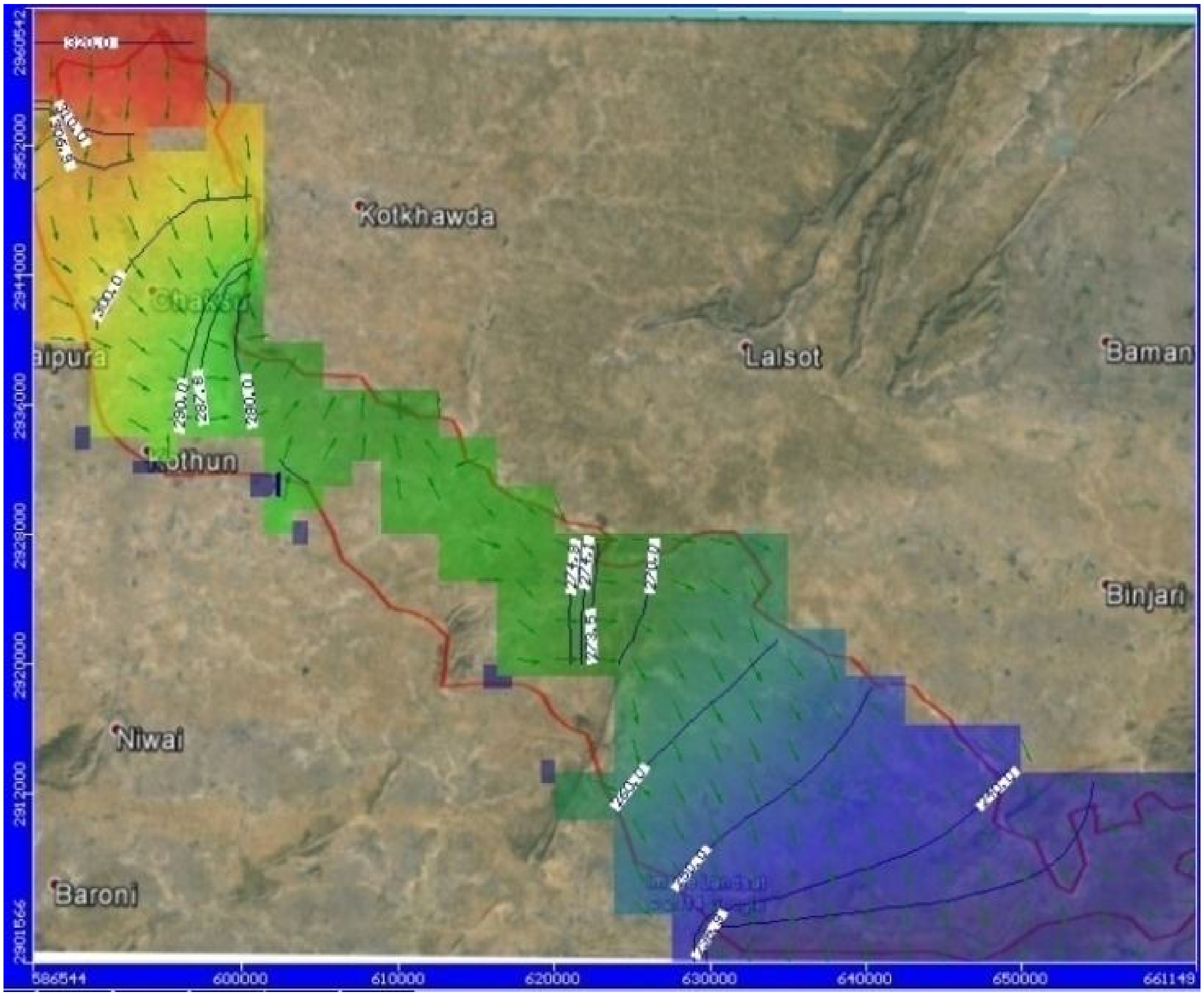


Fig. 5.20 (a): Observed Head in 2013

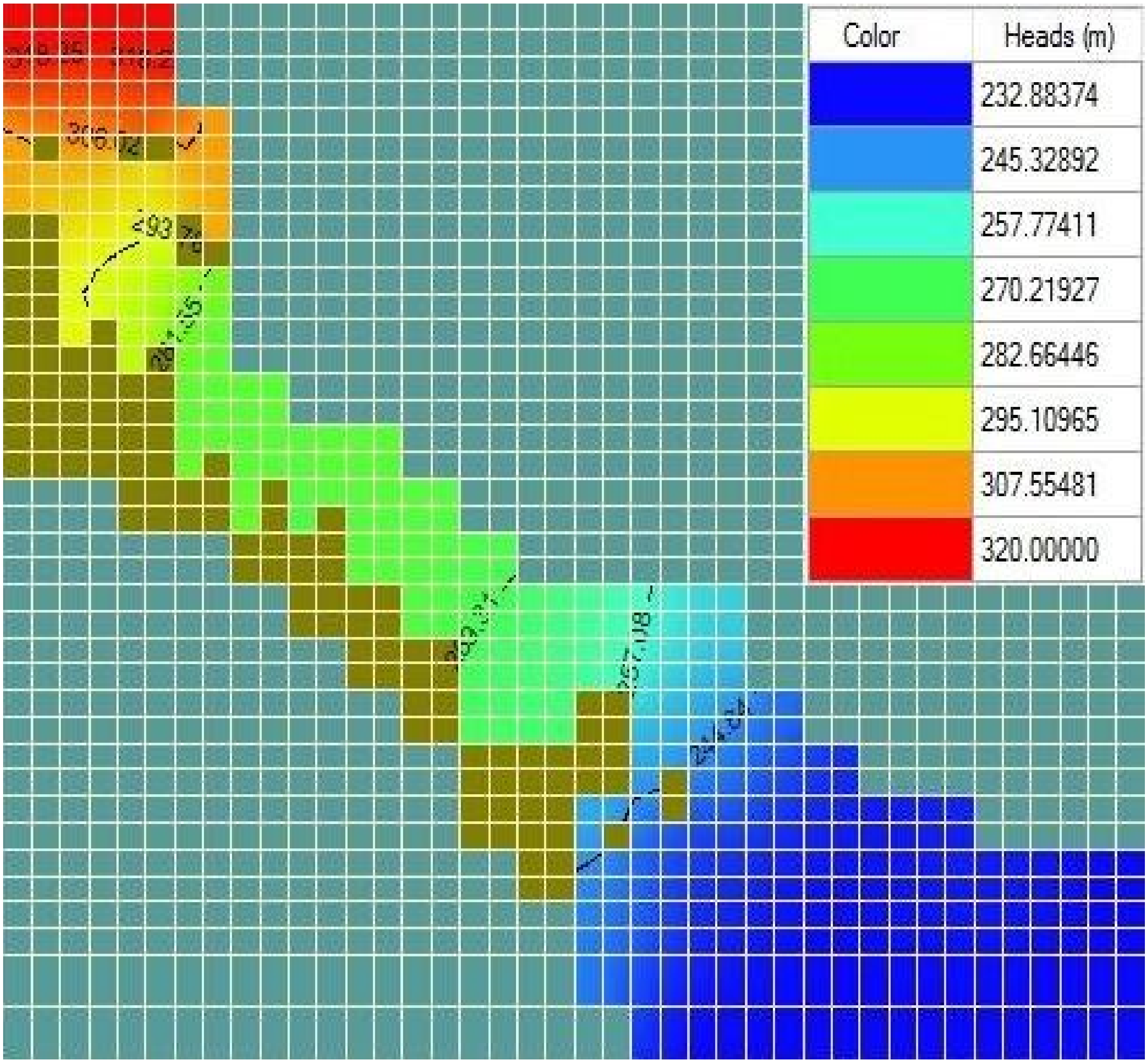


Fig. 5.20 (b): Observed Head in 2013

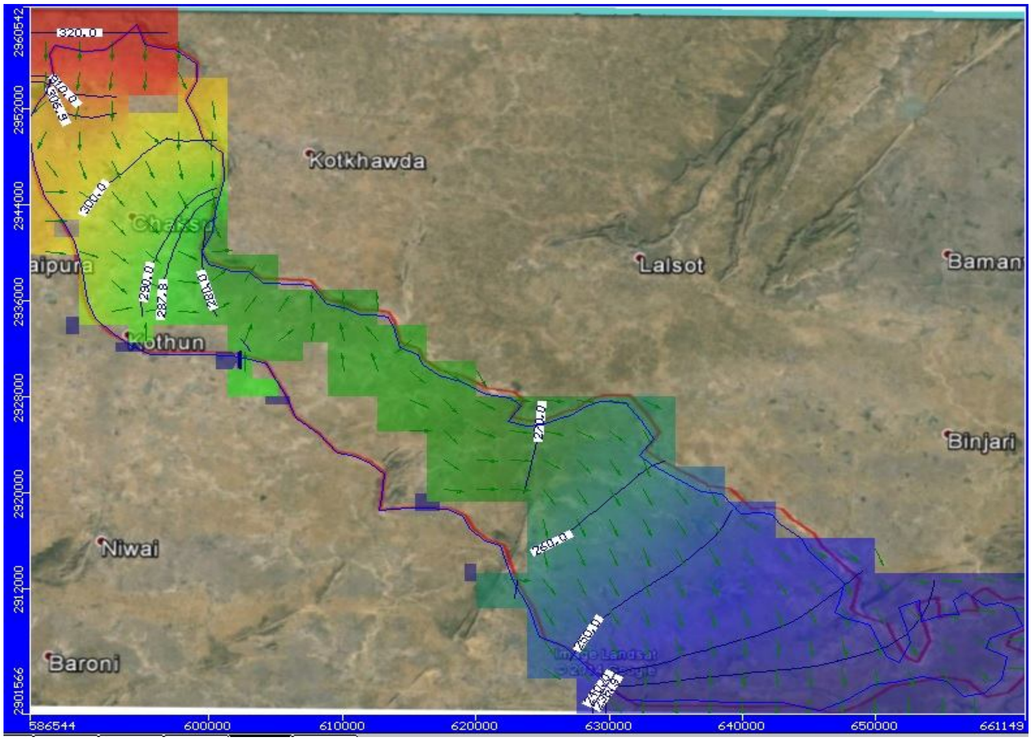


Fig. 5.21 (a): Model Computed Head in 2025

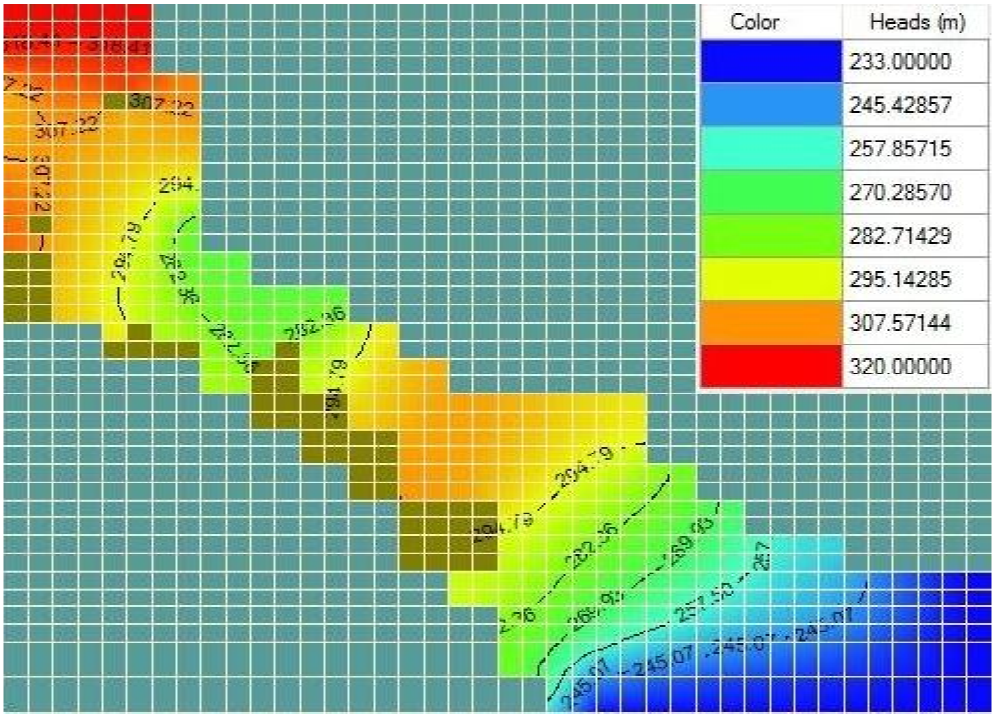


Fig. 5.21 (b): Model Computed Head in 2025

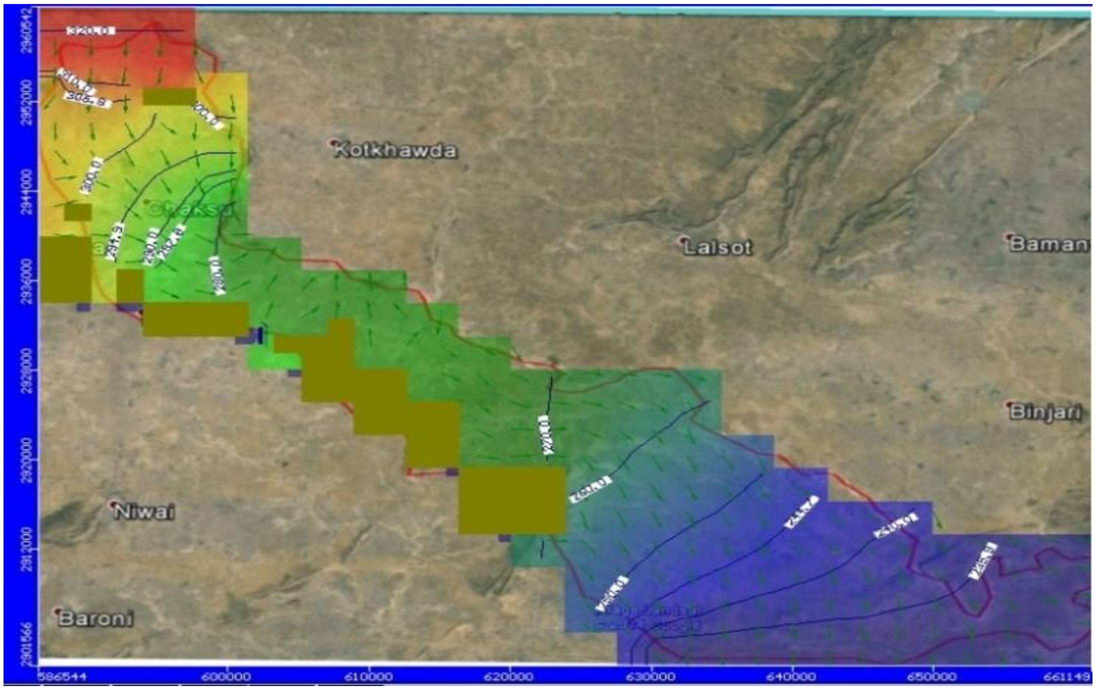


Fig. 5.22 (a): Model Computed Head in 2050

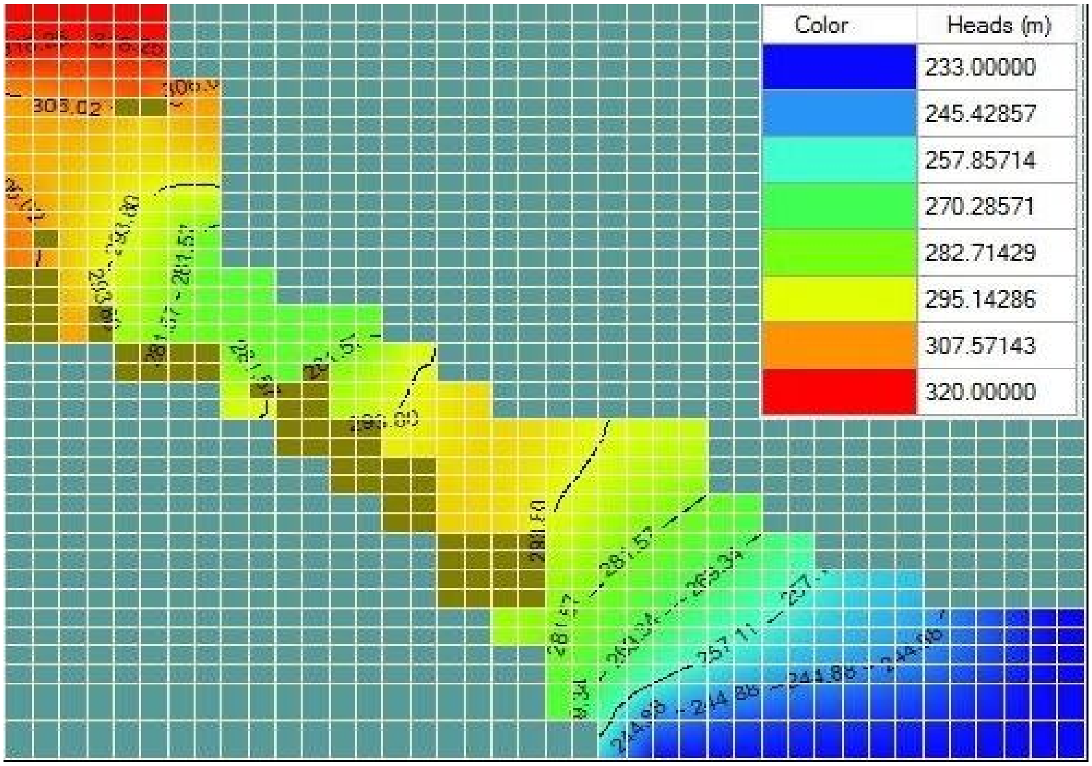


Fig. 5.22 (b): Model Computed Head in 2050

5.13 SENSITIVITY ANALYSIS

Sensitivity analysis brings out and helps to understand significant role played by individual parameters in computation of model simulation output. The purpose is to demonstrate the sensitivity of model simulations to uncertainty in model input data values. In the present study, the sensitivity analysis has been performed for aquifer parameters- hydraulic conductivity and for recharge values. Model has been run for different values of parameters considered for sensitivity analysis and change in RMS and NRMS error have been recorded. The model has been found to be more sensitive to recharge values as compared to hydraulic conductivity as indicated by the relative mobility in the value of mean errors between the mean errors corresponding to calibrated values and errors as tabulated in Table 5.2 and Table 5.3. Changes in error (%) with respect to change in parameters have been shown in Fig 5.23 and Fig 5.24.

The input hydraulic conductivity values were changed 10 to 30. NRMS error increases by 9.63 % with increase in hydraulic conductivity by 30%. Similarly, RMS error increase by 7.57% with increase in hydraulic conductivity by 30%. It is observed from the analysis that the NRMS does not vary above 3% for increase or decrease of K value from 10 -30. Hence, the model is not sensitive to aquifer parameter - hydraulic conductivity.

Table 5.2: Sensitivity Analysis for Hydraulic Conductivity

% Change in K value	RMS error	Normalized RMS error
20	5.154	6.693
15	7.21	8.82
10	8.91	8.07
25	6.22	8.9
30	7.57	9.63

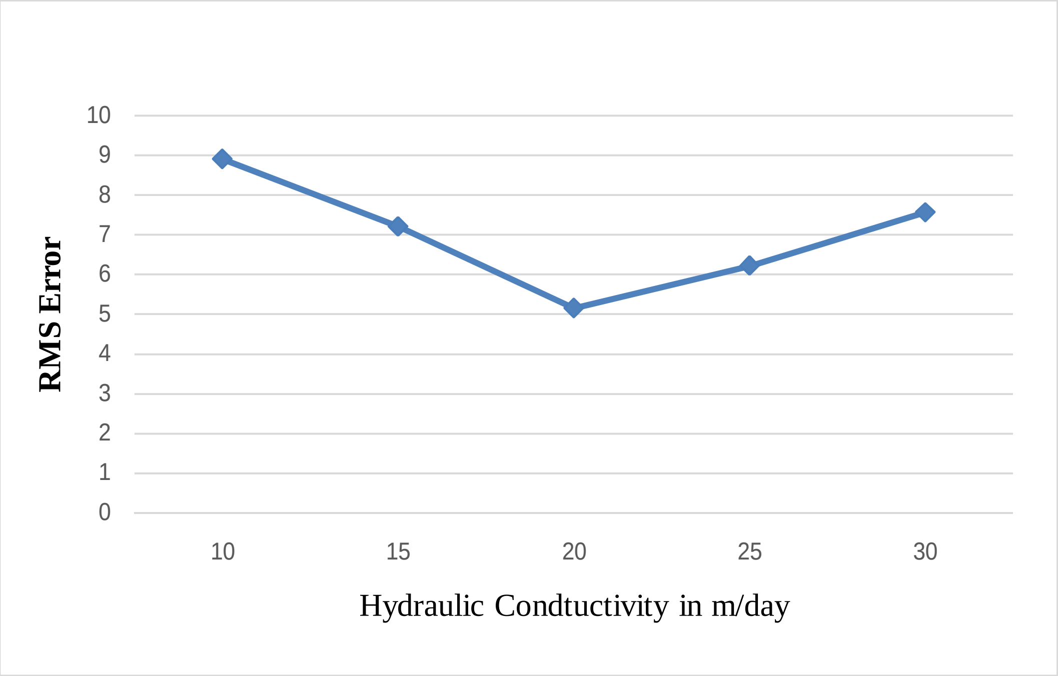


Fig. 5.23: Sensitivity Analysis of Hydraulic Conductivity Parameter

The input recharge values were changed from 27 to 36 mm. With the increase of 36% in recharge value, the NRMS error increases by 13.24%. Similarly, the RMS error increases by 6.84% with the increase in recharge value by 36%. It is observed from the analysis that the NRMS varies from 6.69 to 13.24 for increase in recharge value. Hence, the model is sensitive to recharge.

Table 5.3: Sensitivity Analysis for Recharge

%Change in Recharge Value	RMS error	Normalized RMS error
30	5.154	6.693
33	6.73	8.75
27	6.44	8.37
36	6.84	13.24

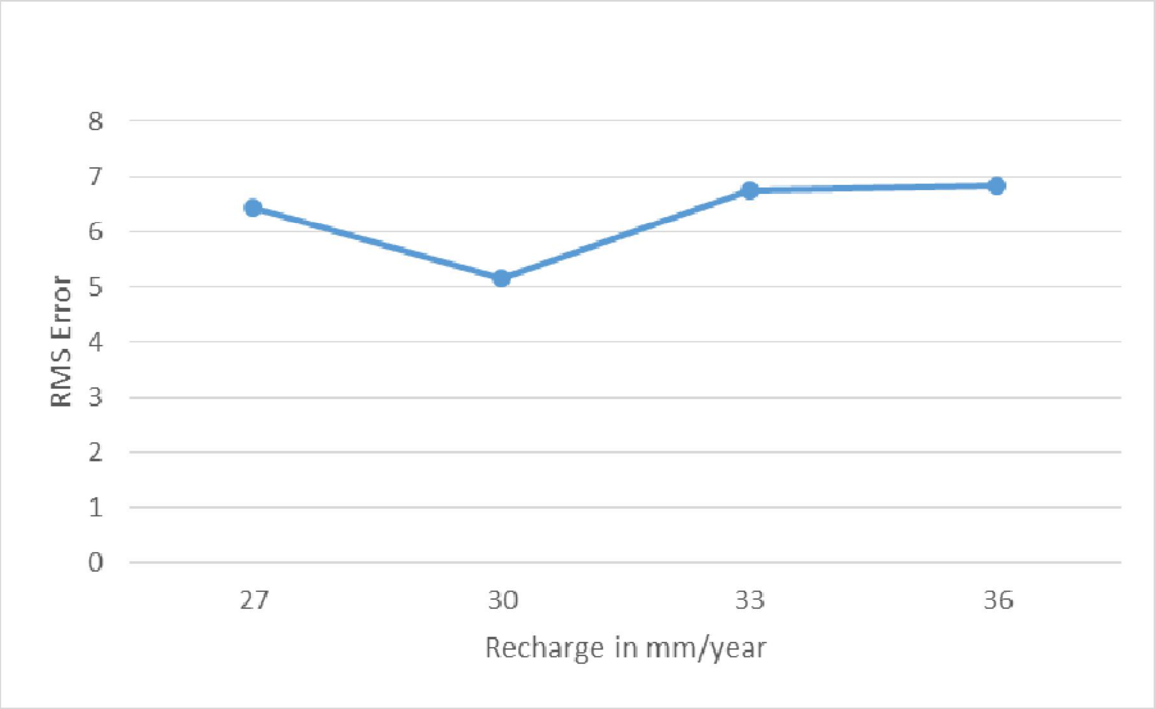


Fig. 5.24: Sensitivity Analysis of Recharge Parameter

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS

The Chaksu sub-watershed area which constitutes the study area for the present work comes under the state of Rajasthan. The arid region is characterised by low mean annual rainfall coupled with high coefficient of variability, large amplitude of diurnal and annual temperature, strong wind regimes, and high potential evaporation. Pace of decline in water level has caused drying up of dug wells and compelled farmers to get these deepen by boring or replacing by tube wells and thereby incurring additional expenditure for construction and pumpage. Average rate of water level decline has enhanced over period of time.

1. The purpose of this work was to understand groundwater flow and groundwater levels due to pumping, predict changes in flow and groundwater levels due to changes in pumping, and evaluate the completeness and suitability of existing hydro geological data.

2. The flow system of the study area was conceptualized using the different information about the hydrogeologic framework, aquifer properties and boundary conditions of the study area. Boundary conditions were specified along the entire boundary of flow domain.

3. The groundwater flow modelling results reveals that the general groundwater flow is from north-west to south-eastern direction. The groundwater recharge area has been identified in north – western boundary. The interactions between aquifer, topography, surface water bodies, and pumping wells also create complex spatial variability in horizontal flow directions. Flow directions within the alluvium aquifers are directed from cells underlying topographically high areas toward streams.

4. Simulations indicate the mean recharge rates are 130 mm/yr in Chaksu watersheds, which represent 16% of mean annual precipitation (= 560mm /yr.).

5. A steady-state calibration was accomplished for the year 2001. The general groundwater flow direction is from north- west to south east. The calibrated steady-state model conditions were used as initial conditions for the transient model. Validation of the model results was carried out by comparing simulated water levels and observed water levels in selected observation wells. In calibration the RMS error has been found to be 5.154 % whereas the NRMS error came out to be 6.693 % which are within satisfactory range for difference between the calculated and observed head.

6. Water budget for the year 2013, 2025 and 2050 were calculated. Water budget results of the model revealed that for the 2013, 87% of the total inflow is from rainfall recharge whereas only 12% from surrounding areas. There is 66% increase in pumping outflow in year 2050 as compared to year 2013. Thus, indicating more stress on already over exploited groundwater resource. Water-budget results indicate that the rainfall is the primary source of recharge to groundwater for the alluvium aquifer rather than inflow from surrounding areas.

7. Contour maps of head indicate that the majority of water is leaving the model domain along the southern boundary of the model area.

8. Comparison of predicted water levels during increased pumping to previous model-simulated results indicates that the maximum head decline in the Alluvium aquifer will be approximately 2.5 meters by 2050.

9. The Sensitivity of the model to input parameters was tested by varying the aquifer parameters over a range of values, and monitoring the response of the model by determining the RMS and NRMS error of the simulated heads compared to the measured heads.

10. The input hydraulic conductivity values were changed 10 to 30. NRMS error increases by 9.63 % with increase in hydraulic conductivity by 30%. Similarly, RMS error increase by 7.57% with increase in hydraulic conductivity by 30%. It was

observed from the analysis that the NRMS does not vary above 3% for increase or decrease of K value from 10 to 30.

11. The input recharge values were changed from 27 to 36. With the increase of 36% in recharge value, the NRMS error increases by 13.24%. Similarly, the RMS error increases by 6.84% with the increase in recharge value by 36%. It is observed from the analysis that the NRMS varies from 6.69 to 13.24 for increase in recharge value.

12. The model was found to be more sensitive to recharge values as compared to hydraulic conductivity as indicated by the relative mobility in the value of mean errors between the mean errors corresponding to calibrated values and errors.

13. Since there was lack of input data available so with the availability of more refined data, the results can be improved. However the study is successful in simulating the groundwater behaviour of study area corresponding to recharge and withdrawal stresses and application of model in demonstrated in determining operational scenarios of groundwater resource.

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APPENDIX-I

State-Wise Groundwater Resources Availability, Utilization and Stage of Development, India

Sr. No.	States/Union Territories	Annual Replenishable Ground Water Resources					Natural Discharge During Non-Monsoon Season	Net Annual Ground Water Availability	Annual Ground Water Draft			Projected Demand For Domestic & Industrial Uses Upto	Ground Water Availability For Future Irrigation	Stage of Ground Water Development (%)
		Monsoon Season		Non-Monsoon Season		Total			Irrigation	Domestic & Industrial Uses	Total			
		Recharge from Rainfall	Recharge from other Sources	Recharge from Rainfall	Recharge from other Sources									
	States													
1	Andhra Pradesh	16.04	8.93	4.2	7.33	36.50	3.55	32.95	13.88	1.02	14.9	2.67	17.65	45
2	Arunachal Pradesh	1.57	0.00009	0.98	0.0002	2.55	0.26	2.3	0.0008	0	0.0008	0.009	2.29	0.04
3	Assam	23.65	1.99	1.05	0.54	27.23	2.34	24.89	4.85	0.59	5.44	0.98	19.06	22
4	Bihar	19.45	3.96	3.42	2.36	29.19	1.77	27.42	9.39	1.37	10.76	2.14	16.01	39
5	Chhattisgarh	12.07	0.43	1.3	1.13	14.93	1.25	13.68	2.31	0.48	2.79	0.7	10.67	20
6	Delhi	0.13	0.06	0.02	0.09	0.30	0.02	0.28	0.2	0.28	0.48	0.57	0	170
7	Goa	0.22	0.01	0.01	0.04	0.28	0.02	0.27	0.04	0.03	0.07	0.04	0.19	27
8	Gujarat	10.59	2.08	0	3.15	15.82	0.79	15.02	10.49	0.99	11.48	1.48	3.05	76
9	Haryana	3.52	2.15	0.92	2.72	9.31	0.68	8.63	9.1	0.35	9.45	0.6	-1.07	109
10	Himachal Pradesh	0.33	0.01	0.08	0.02	0.44	0.4	0.39	0.09	0.03	0.12	0.04	0.25	30
11	Jammu & Kashmir	0.61	0.77	1	0.32	2.70	0.27	2.43	0.1	0.24	0.34	0.42	1.92	14
12	Jharkhand	4.26	0.14	1	0.18	5.58	0.33	5.25	0.7	0.38	1.08	0.56	3.99	20
13	Karnataka	8.17	4.01	1.5	2.25	15.93	0.63	15.3	9.75	0.97	10.72	1.41	6.48	70

Sr. No.	States/Union Territories	Annual Replenishable Ground Water Resources					Natural Discharge During Non-Monsoon Season	Net Annual Ground Water Availability	Annual Ground Water Draft			Projected Demand For Domestic & Industrial Uses Upto	Ground Water Availability For Future Irrigation	Stage of Ground Water Development (%)
		Monsoon Season		Non-Monsoon Season		Total								
		Recharge from Rainfall	Recharge from other Sources	Recharge from Rainfall	Recharge from other Sources				Irrigation	Domestic & Industrial Uses	Total			
14	Kerala	3.79	0.01	1.93	1.11	6.84	0.61	6.23	1.82	1.1	2.92	1.4	3.04	47
15	Madhya Pradesh	30.59	0.96	0.05	5.59	37.19	1.86	35.33	16.08	1.04	17.12	1.74	17.51	48
16	Maharashtra	20.15	2.51	1.94	8.36	32.96	1.75	31.21	14.24	0.85	15.09	1.51	15.1	48
17	Manipur	0.2	0.005	0.16	0.01	0.38	0.04	0.34	0.002	0.0005	0.0025	0.02	0.31	0.65
18	Meghalaya	0.79	0.03	0.33	0.005	1.16	0.12	1.04	0	0.002	0.002	0.1	0.94	0.18
19	Mizoram	0.03	0	0.02	0	0.05	0.04	0.04	0	0.0004	0.0004	0.008	0.04	0.9
20	Nagaland	0.28	0	0.08	0	0.36	0.04	0.32	0	0.009	0.009	0.03	0.3	3
21	Orissa	12.81	3.56	3.58	3.14	23.09	2.08	21.01	3.01	0.84	3.85	1.22	16.78	18
22	Punjab	5.98	10.91	1.36	5.54	23.79	2.33	21.44	30.34	0.83	31.17	1	-9.89	145
23	Rajasthan	8.76	0.62	0.26	1.92	11.56	1.18	10.38	11.6	1.39	12.99	2.72	-3.94	125
24	Sikkim	-	-	-	-	0.00	0	0.08	0	0.01	0.01	0.02	0.05	16
25	Tamil Nadu	4.91	11.96	4.53	1.67	23.07	2.31	20.76	16.77	0.88	17.65	0.91	3.08	85
26	Tripura	1.1	0	0.92	0.17	2.19	0.22	1.97	0.08	0.09	0.17	0.2	1.69	9
27	Uttar Pradesh	38.63	11.95	5.64	20.14	76.36	6.17	70.18	45.36	3.42	48.78	5.3	19.52	70
28	Uttaranchal	1.37	0.27	0.12	0.51	2.27	0.17	2.1	1.34	0.05	1.39	0.06	0.68	66
29	West Bengal	17.87	2.19	5.44	4.86	30.36	2.9	27.46	10.83	0.81	11.64	1.24	15.33	42
	Total of States	247.8	69.52	41.84	73.16	432.38	34.9	398.0	212.37	18.05	230.42	29.09	161.3	58.0
	Union Territories													
1	Andaman & Nicobar	-	-	-	-	0.33	0.005	0.32	0	0.01	0.01	0.008	0.303	4
2	Chandigarh	0.016	0.001	0.005	0.001	0.023	0.002	0.02	0	0	0	0	0.02	0
3	Dadara & Nagar	0.059	0.005			0.064	0.003	0.06	0.001	0.008	0.009	0.008	0.051	14

	Haveli													
4	Daman & Diu	0.006	0.002	0	0.001	0.009	0.004	0.008	0.007	0.002	0.009	0.003	-0.002	107
5	Lakshadweep	-	-	-	-	0	0.009	0.004	0	0.002	0.002			63
6	Pondicherry	0.057	0.067	0.007	0.029	0.16	0.016	0.144	0.121	0.03	0.151	0.031	-0.008	105
	Total of UTS	0.138	0.138	0.012	0.031	0.59	0.597	0.556	0.129	0.052	0.181	0.05	0.365	33
	Grand Total	248.0	69.59	41.85	73.18	433.0	33.77	399.2	212.5	18.10	230.59	29.14	161.3	58.0

APPENDIX-II

Water Level Data of Chaksu District

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
1	MANPURDUNGRI	263732.7	755540.4	296	8.21	11.34
2	MANPURDUNGRI	263749.3	755515	323	14.71	11.1
3	MANPURDUNGRI	263800.7	755536.4	330	10.01	4.86
4	MANPURDUNGRI	263804.3	755516	317	16.81	13.22
5	MANPURDUNGRI	263802.7	755522.7	314	14.34	11.55
6	BARKHERA	264120	755456.8	322	13.13	4.08
7	BARKHERA	264136	755457.8	321	20.85	3.05
8	BARKHERA	264141	755525.6	327	14.21	9.2
9	NANGALPOORAN	264157.1	755624	325	17.51	11.85
10	NANGALPOORAN	264152.6	755636.5	325	Nil	Nil
11	DAHAR	264112.3	755622.8	325	17.76	17.1
12	DAHAR	264113.1	755630.8	326	Nil	Nil
13	SALAGRAMPURA	264048.1	755619.8	333	12.15	9.85
14	SALAGRAMPURA	264100.4	755612.2	329	15.52	7.5
15	KHAJALPURA	264143.9	755718.7	347	26.57	24.2
16	KHAJALPURA	264133.9	755747.6	318	33.36	28.53
17	KHAJALPURA	264124.8	755757.5	320	25.55	25
18	BHAWANIPURA	264155.9	755657.2	324	22.56	15.65
19	RAIPURIYA KHURD	264223.2	755617.2	324	19.44	15.03
20	RAIPURIYA KHURD	264233.2	755550.9	318	12.34	4.2
21	THOONI-JAILALPURA	264242.2	755518.7	323	Nil	Nil
22	THOONI-JAILALPURA	264252.9	755458.4	325	17.18	12.05
23	KALKIPURA	264259.9	755301.8	339	Nil	Nil
24	KALKIPURA	264306.7	755316.8	344	Nil	Nil

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
25	PRAHLADPURA	264411.3	755253.1	350	19.27	15.04
26	PACHOORA	264328.6	755435.2	340	Nil	Nil
27	PACHOORA	264328.9	755459.2	340	Nil	Nil
28	BADA PADAMPURA	264323.5	755559.1	339	20.29	15.9
29	BADA PADAMPURA	265628.3	755628.3	338	21.62	17.8
30	DHARMPURA	264332.4	755646.2	340	Nil	Nil
31	DHARMPURA	264318.9	755658.2	336	Nil	Nil
32	DEOKINANDANPURA	264407.9	755544.3	331	15.06	9.7
33	SWAIMADHOSINGHPURA	264414.5	755607.6	331	14.97	9.4
34	DHROLA	264457.7	755631.2	325	5.82	1.05
35	BALLOOPURA	264252.5	755802.7	328	21.5	18.1
36	BALLOOPURA	264254.6	755749.7	328	Nil	Nil
37	BALLOOPURA	264254.3	755744.4	332	Nil	Nil
38	BALLOOPURA	264315	755756.2	334	15.48	11.5
39	BARALA	264354.1	755842.6	318	7.1	5.75
40	BARALA	264412.6	755847.7	317	Nil	Nil
41	BARALA	264414.4	755848.5	315	Nil	Nil
42	SAMBHARIYA	264422	755944	325	Nil	Nil
43	SAMBHARIYA	264356.9	755936.9	322	Nil	Nil
44	DADANPURA	263959.3	755541.6	318	12.28	8.9
45	DADANPURA	263951.2	755529.4	323	Nil	Nil
46	THOONI-RUPNIWAS	264015.3	755700.8	317	15.37	11
47	THOONI-RUPNIWAS	264017.7	755708.8	312	Nil	Nil
48	LAKHAWAS	263923.2	755704.7	316	16.3	14
49	LAKHAWAS	263939.4	755658	316	17.61	9.15
50	LAKHAWAS	263934.2	755645.2	310	Nil	2
51	BHADADWAS	264219.3	755841.7	321	17.34	13.17

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
52	BHADADWAS	264155.7	755849.4	320	Nil	Nil
53	BHADADWAS	264156.9	755814.2	321	23.68	23.98
54	BAGARIYA	264147.5	760026	321	28.15	23.75
55	BAGARIYA	264140.2	760041.6	325	23.28	22.5
56	AKODIYA	264101.7	755926.9	315	15.72	8.45
57	AKODIYA	264111.8	755902.6	321	17.84	17.5
58	AKODIYA	264058.2	755906.7	317	Nil	Nil
59	AKODIYA	264041.5	755908.4	314	16.12	12.8
60	NIMORIYA	263943.1	755920.6	316	16.2	14.25
61	NIMORIYA	263918	755915.7	317	Nil	Nil
62	NIMORIYA	263907.6	755936.7	315	22.6	13
63	NIMORIYA	263902	755924.6	321	23.85	26.48
64	NIMORIYA	263819.2	755844	318	Nil	Nil
65	BARH MAHAWATAN	263703.8	755808	309	10.2	6.87
66	BARH MAHAWATAN	263707	755758.2	310	Nil	Nil
67	BARH MAHAWATAN	263702.4	755750.4	308	10.28	10.7
68	BARH MAHAWATAN	263710.3	755731.4	306	12.04	8.73
69	LAXMIPURA	263905.1	755818.1	313	18.98	15
70	LAXMIPURA	263854.9	755809	307	24.36	15.75
71	SARONJYA	263919.6	755816	308	Nil	Nil
72	SARONJYA	263916.9	755821.2	307	Nil	Nil
73	SARONJYA	263912	755801.4	312	17.03	0.5
74	HUKKAN	264006.8	755724.7	314	Nil	Nil
75	HUKKAN	263957.8	755730.6	314	19.42	18
76	HUKKAN	263959.4	755721.5	314	Nil	Nil
77	DAYAPURA	263838.2	755830.4	313	15.42	10.25

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
78	DAYAPURA	263844.6	755842.4	313	Nil	Nil
79	DAYAPURA	263848.6	755845.5	314	Nil	Nil
80	TIGARIYA	265808.6	755808.6	297	16.78	15.03
81	NANDGAON BASRI	263419.9	755933.5	288	Nil	Nil
82	RAGHOPURA	263441.7	755934.5	295	7.49	3.25
83	RAGHOPURA	263451.6	755929.7	293	7	3.7
84	RAGHOPURA	263450.6	755921	296	Nil	Nil
85	RAMNIWAS	263611.8	760002.5	298	14.64	13.3
86	RAMNIWAS	263619	755953.4	298	Nil	Nil
87	RAMNIWAS	263627.6	760008.5	297	18.14	19.81
88	RAMNIWAS	263623.7	755941.8	294	Nil	Nil
89	BHAGWANPURA	263734.9	755841.6	313	17.78	15.04
90	BHAGWANPURA	263746.7	755850.6	311	Nil	Nil
91	BHAGWANPURA	263752.9	755904.7	307	20.3	17.34
92	BEER-PANARPURA	263735	755909.1	307	17.2	15.39
93	BEER-PANARPURA	263735.8	755932.2	309	14.86	13.24
94	BEER-PANARPURA	263742.4	755923	309	Nil	Nil
95	BEER-PANARPURA	263732.3	755920.8	305	15.51	13.54
96	RAMLAXMANPURA	263656.1	755913.3	304	16.36	14.3
97	RAMLAXMANPURA	263648.1	755906.8	299	Nil	Nil
98	RAMLAXMANPURA	263638.4	755918.1	300	13.96	16.3
99	RAMLAXMANPURA	263648.2	755911.8	302	18.75	18.12
100	GANESHPURA	263851.5	760033.1	304	Nil	Nil
101	GANESHPURA	263857.7	760026.3	306	14.88	15.08
102	GANESHPURA	263841.7	760027.4	308	Nil	22.3
103	CHHADEL KHURD	263750.7	760058.4	308	Nil	Nil
104	CHHADEL KHURD	263755.5	760055.5	308	11.12	11.41

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
105	CHHADEL KHURD	263752.1	760041	305	Nil	Nil
106	CHHADEL KALAN	263730.4	760030.4	305	12.98	12
107	CHHADEL KALAN	263726.9	760021.1	309	Nil	Nil
108	CHHADEL KALAN	263731.9	760048.8	301	13.25	12.3
109	CHHADEL KALAN	263720.4	760013.9	303	Nil	Nil
110	CHHADEL KALAN	263715.1	755954.5	305	Nil	Nil
111	RAMPURA BAS GONER	264432.5	755459.6	337	17.31	14.97
112	CHAKSHIVDASPURA NO.1	264315.6	755505.8	329	18.11	13.3
113	SHIVDASPURA	264237.2	755358.4	333	Nil	Nil
114	SHIVDASPURA	264226.3	755346.4	329	Nil	Nil
115	SHIVDASPURA	264245.7	755342.7	340	Nil	Nil
116	SHIVDASPURA	264238.4	755336.4	343	Nil	Nil
117	SHIVDASPURA	264240.9	755327.6	343	Nil	Nil
118	SHIVDASPURA	264248.1	755313.7	345	22.07	15.55
119	SHIVDASPURA	264232.9	755311.6	347	19.01	Nil
120	SHIVDASPURA	264221.6	755317.2	344	18.42	15.65
121	SHIVDASPURA	264203.1	755353.2	339	Nil	Nil
122	GOPIRAMPURA	264104.6	755521.5	326	14.91	10.3
123	GOPIRAMPURA	264101.4	755529	322	16.47	14.85
124	GOPIRAMPURA	264112.9	755511	325	Nil	Nil
125	BAPUGAON	263900.1	760206.3	314	18.65	20.1
126	YARLIPURA	264030.6	755428.7	323	12.51	4.3
127	YARLIPURA	264040	755430.4	325	Nil	Nil
128	YARLIPURA	264052.6	755440.9	326	Nil	13.65
129	YARLIPURA	264057.3	755457.7	322	17.48	12.05
130	YARLIPURA	264106.7	755454.4	324	Nil	Nil
131	CHANDLAI	264144	755310.5	336	5.13	2.08

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
132	CHANDLAI	264124.4	755257.2	336	Nil	Nil
133	CHANDLAI	264112.1	755250.5	333	Nil	Nil
134	CHANDLAI	264113.1	755247	338	9.66	0.57
135	CHANDLAI	264119.8	755238	339	14.31	6.27
136	CHANDLAI	264131.2	755215.9	341	5.21	1.26
137	CHANDLAI	264115.3	755224.1	341	9.01	2.02
138	CHANDLAI	264101.7	755234.3	340	Nil	Nil
139	CHANDLAI	264058.1	755220.1	337	6.48	2.64
140	CHANDLAI	264033.5	755235.9	334	Nil	Nil
141	PUROSHOTTAMPURA	264003.3	755228.7	334	12.45	5.6
142	PUROSHOTTAMPURA	263943.5	755235.4	336	Nil	Nil
143	UDAIPURA	263935.1	755242.9	333	14.31	11.11
144	UDAIPURA	263918	755239.1	330	18.01	12.23
145	UDAIPURA	263927.5	755251.1	330	Nil	Nil
146	UDAIPURA	263926.1	755256.2	325	Nil	Nil
147	DRAGPALPURA	263819.1	755254.8	331	24.13	23.83
148	DRAGPALPURA	263807.3	755253.8	332	20.41	21.94
149	BHOJYA NAND	264045.2	755158.4	333	10.26	11.44
150	BEER-SURATRAMPURA	263812.9	755501.7	318	17.65	13.97
151	BEER-SURATRAMPURA	263802.6	755455.2	321	Nil	Nil
152	AZAMNAGAR	263827.7	755414.2	322	21.39	15.86
153	AZAMNAGAR	263825.4	755415.1	311	Nil	Nil
154	AZAMNAGAR	263819.3	755410.3	320	14.88	11.43
155	AZAMNAGAR	263836.6	755426.1	320	18.41	18.03
156	NARHARPURA	263904.3	755315.3	323	15.45	14.11
157	NARHARPURA	263855	755312.7	327	Nil	Nil

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
158	NARHARPURA	263849.3	755325.7	323	Nil	9.95
159	KAREDA KHURD	263728	755246.6	326	29.68	18.37
160	KAREDA KHURD	263719.3	755241	339	34.54	24.61
161	KALYANPURA	263712.8	755332	333	16.61	22.46
162	KALYANPURA	263731.1	755337.5	333	15.71	11.49
163	KALYANPURA	263731.9	755314	327	Nil	Nil
164	KALYANPURA	263719.3	755333.4	327	19.01	10.19
165	KALYANPURA	263708	755335.5	329	Nil	Nil
166	MEERAPURA	263624.7	755347.7	327	15.65	12.83
167	MEERAPURA	263622	755357.5	327	14.11	8.14
168	MEERAPURA	263617.7	755406.7	324	Nil	Nil
169	RASOOLPURA	263605.4	755351.9	326	9.71	11.46
170	JANKI BHALLABHPURA	263923.5	755444	315	Nil	17.18
171	JANKI BHALLABHPURA	263905.7	755452.2	318	Nil	16.8
172	BIHARIPURA	263856.5	755512.2	318	17.61	17.8
173	BIHARIPURA	263901.9	755527.3	318	15.41	11.55
174	BIHARIPURA	263906.9	755519.3	322	17.21	14.1
175	CHOSLA	263928.5	755409	333	21.37	14.9
176	CHOSLA	263928.2	755416.6	321	17.76	15
177	CHOSLA	263936.8	755419.3	321	16.81	13.2
178	CHOSLA	263947.8	755346.7	323	11.16	8.5
179	KATHAWALA	263943.6	755434.2	323	18.05	12.5
180	KATHAWALA	263938.2	755444.1	319	Nil	Nil
181	KATHAWALA	263923.3	755455.8	325	21.65	15.35
182	JHUJHARPURA	263941.4	755527.3	320	5.65	2.75
183	JHUJHARPURA	263939.8	755520.8	319	Nil	Nil
184	CHAKSU	263522.5	755444.8	339	5.36	2.74

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
185	CHAKSU	263540.4	755447.4	317	Nil	Nil
186	CHAKSU	263545.2	755453.6	315	6.01	4.05
187	CHAKSU	263601.9	755507.2	317	Nil	Nil
188	CHAKSU	263623.7	755518.1	315	Nil	Nil
189	CHAKSU	263622.6	755553.8	309	3.71	1.93
190	CHAKSU	263622	755607.6	313	7.51	3.92
191	CHAKSU	263633.8	755614.7	306	12.71	7.25
192	CHAKSU	263701.9	755722.8	302	14.96	6.75
193	CHAKSU	263653.8	755711.1	299	10.31	1.85
194	CHAKSU	263641.3	755707.6	303	7.35	7.47
195	CHAKSU	263650.3	755653.1	296	8.51	8.43
196	CHAKSU	263636.9	755649.1	301	3.31	1.07
197	CHAKSU	263710.9	755618.8	301	15.12	7.85
198	CHAKSU	263650	755628.2	300	10.71	3.2
199	CHAKSU	263643.1	755636.7	300	7.71	3.21
200	CHAKSU	263634.4	755631	303	Nil	Nil
201	CHAKSU	263551.7	755754.2	296	Nil	Nil
202	CHAKSU	263558	755744.2	297	7.91	5.25
203	CHAKSU	263550.4	755740.2	302	Nil	Nil
204	CHAKSU	263558.1	755736.1	304	Nil	Nil
205	CHAKSU	263557.1	755726.9	307	11.12	8.8
206	CHAKSU	263602.6	755716.4	308	6.97	4.9
207	CHAKSU	263559.2	755637.3	306	3.15	2.15
208	CHAKSU	263543.6	755632.8	314	13.41	9.78
209	CHAKSU	263536.9	755639	313	Nil	Nil
210	CHAKSU	263551.1	755645.7	311	Nil	Nil
211	CHAKSU	263531.8	755711.7	311	13.45	10.69

S.NO.	VILLAGE	LATITUDE	LONGITUDE	ELEVATION	PRE-MONS00N	POST-MONSOON
					W.L. (M)	W.L. (M)
212	CHAKSU	263525.6	755652.8	312	13.15	12.1
213	CHAKSU	263547.8	755652.7	315	Nil	Nil
214	CHAKSU	263604.7	755659.6	311	Nil	3.2
215	CHAKSU	263621.7	755711.3	305	6.45	3.15
216	CHAKSU	263618.8	755701.3	303	3.91	2.6
217	CHAKSU	263617.7	755656.7	309	6.01	3.75
218	CHAKSU	263620.3	755633.2	311	10.61	9.31
219	RAMPURA BAJORI	263803.1	755434.9	319	21.15	19.55
220	RAMPURA BAJORI	263752.7	755431.9	316	Nil	Nil
221	RAMPURA BAJORI	263749.2	755447.7	315	Nil	Nil
222	BAJROLI	263942.2	754752.3	332	18.85	Nil

Groundwater level data of Chaksu Block (2001 to 2012) APPENDIX III

S. No.	Well No.	Name of Village	Co-ordinates		Reduced Level	Total Depth	2001		2002		2003	
			Longitude	Latitude			PRE	POST	PRE	POST	PRE	POST
1	2	3	5	6	7	8	9	10	12	13	15	16
BLOCK: CHAKSU												
ZONE: O-ALLUVIUM												
1	45 N14 Dd1	CHANDLAI	75°51'10"	26°40'15"	330.00	18.00	7.63	7.60	8.40	13.60	14.35	13.90
2	54 B2 Ccl	CHAKSU	75° 57'30''	26°36'30''	301.50	16.00	6.10	5.80	7.30	9.70	11.17	11.00
3.	54 B1 Gd	DEHLALA	76°06'45"	26°36'45"	293.00	34.00	21.88	21.80	23.70	29.80	31.85	31.55
4.	54 B2 Ca	GURWASA	76°03'00"	26°36'20"	311.00	33.60	18.21	18.13	20.05	27.30	28.53	28.40
5.	45 N14 Fb	HINGONIA	75°56'30"	26°30'45"	320.00	18.00	15.65	15.51	15.90	14.50	16.10	15.98
6.	45 N14 Bd2	KADERA	75°51'00"	26°30'45"	315.00	36.00	14.17	14.11	17.10	22.10	23.06*	22.78
7.	45 N14 Bd4	KOHLYA*	76°02'10"	26°39'00"	304.00	27.00	17.11	17.00	18.70	22.00	Dry	Dry
8.	54b2 eA	kotkhawda*	76°05'10"	26°40'05"	302.00	22.50	15.90	15.75	17.40	20.25	Dry	Dry
9.	54 B2 Db	RUPAHERI	75°55'10"	26°32'15"	300.00	25.00	13.61	13.53	14.25	17.25	18.40	18.03
10.	45 n14 dC2	SHEODASPURA	75°54'20"	26°43'10"	331.00	24.00	13.71	13.65	15.42	20.30	22.17	22.17
11.	45 N14 Bc	TITRIYA	75°50'00"	26°40'10"	324.60	25.00	15.83	15.64	17.65	21.40	23.13	22.90
12.	45 N14 Bc1	TUNTOLI	75°49'05"	26°38'05"	320.50	23.00	12.30	12.17	12.97	16.85	18.04	17.75
13.		SHEODASPURA Pz										
14.	54 B2 CA2	GARUDWASI T/W	76°03'02"	26°36'22"	306.00	50.00	7.31	6.40	10.40	8.20	NA	NA
		Avg, of Zone					**13.80**	**13.62**	**15.33**	**18.71**	**20.68**	**20.45**
ZONE: QUARTZITE												
1	45 N14 GD	AKORIYA	75°59'15"	26°42'00"	318.00	24.00	13.93	13.87	16.05	19.15	21.86	20.18
2	45 N14 Id	KOTHUN	75°58'20"	26°31'00"	320.00	25.00	14.87	14.80	15.75	19.40	21.08	21.12
3	54 B2 Cb1	SANWASA (SANWALL)	76°01'00"	26°32'15"	305.00	20.65	9.05	9.30	9.85	12.00	14.08	13.20
		Avg. of Zone					**12.62**	**12.66**	**13.88**	**16.85**	**19.31**	**18.17**
		Avg. of Block					**13.58**	**13.44**	**15.06**	**18.36**	**20.36**	**19.92**

S. No.	**Well No.**	**Name of Village**	**2004**		**2005**		**2006**		**2007**		**2008**		**2009**	
			PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
1	2	3	18	19	21	22	24	25	27	28	30	31	33	34
BLOCK: CHAKSU														
ZONE: O-ALLUVIUM														
1	45 N14 Dd1	CHANDLAI	15.20	14.10	16.60	15.70	15.90	15.50	16.50	17.20	16.70	16.10	16.95	17.15
2	54 B2 Ccl	CHAKSU	10.60	10.50	12.70	12.60	Dry	14.70	Dry	Dry	Dry	Dry	Dry	Dry
3.	54 B1 Gd	DEHLALA	32.20	23.60	33.10	30.00	33.30	31.25	33.65	29.50	27.20	33.20	29.90	30.15
4.	54 B2 Ca	GURWASA	29.30	20.10	30.80	27.10	31.40	28.05	32.60	28.90	26.10	32.10	32.50	32.69
5.	45 N14 Fb	HINGONIA	16.70	15.80	17.10	16.30	17.40	16.90	17.65	15.40	17.70	17.60	17.75	17.90
6.	45 N14 Bd2	KADERA	23.50	23.10	24.80	29.45	25.10	25.30	25.15	23.10	25.30	25.80	25.20	25.35
7.	45 N14 Bd4	KOHLYA*		22.45	Dry	Dry	Dry	Dry	21.00	18.70	21.15	20.80	21.15	21.25
8.	54b2 eA	KOTKHAWDA*		Dry	Dry	Dry	Dry	20.10	21.50	18.60	21.60	21.10	21.60	21.65
9.	54 B2 Db	RUPAHERI	19.10	17.80	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
10.	45 n14 dC2	SHEODASPURA	22.60	19.60	23.20	20.30	23.30	20.40	23.55	19.10	23.65	23.20	23.65	23.80
11.	45 N14 Bc	TITRIYA	23.70	23.20	24.10	23.65	24.40	20.30	24.75	18.10	24.60	24.30	24.70	24.90
12.	45 N14 Bc1	TUNTOLI	18.50	17.90	19.80	19.15	19.95	17.75	20.25	16.20	20.35	19.80	21.00	20.95
13.		SHEODASPURA Pz												
14.	54 B2 CA2	GARUDWASI T/W		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Avg, of Zone	**21.44**	**18.92**	**22.47**	**21.58**	**23.84**	**21.03**	**23.66**	**20.48**	**22.44**	**23.40**	**23.44**	**23.58**
ZONE: QUARTZITE														
1	45 N14 GD	AKORIYA	22.40	22.10	23.10	22.75	23.20	18.80	23.35	16.70	23.40	23.10	23.35	23.65
2	45 N14 Id	KOTHUN	22.50	14.30	23.80	17.10	21.60	18.55	22.10	16.20	22.22	21.80	22.17	22.35
3	54 B2 Cb1	SANWASA (SANWALL)	14.50	14.05	16.20	15.70	14.50	19.70	15.70	17.30	15.75	15.20	15.78	15.80
		Avg. of Zone	**19.80**	**16.82**	**21.03**	**18.52**	**19.77**	**19.02**	**20.38**	**16.73**	**20.46**	**20.03**	**20.43**	**20.60**
		Avg. of Block	**20.83**	**18.47**	**22.11**	**20.82**	**22.73**	**20.56**	**22.90**	**19.62**	**21.98**	**22.62**	**22.75**	**22.89**

S. No.	Well No.	Name of Village	2010		2011		2012	
			PRE	POST	PRE	POST	PRE	POST
1	2	3	36	37	39	40	42	43
BLOCK: CHAKSU								
ZONE: O-ALLUVIUM								
1	45 N14 Dd1	CHANDLAI	17.30	16.70	17.10	16.95	17.40	5.80
2	54 B2 Ccl	CHAKSU	Dry	8.60	11.80	12.10	12.05	3.90
3.	54 B1 Gd	DEHLALA	30.05	29.65	25.65	24.95	25.05	24.05
4.	54 B2 Ca	GURWASA	26.75	25.60	21.80	22.10	22.70	20.10
5.	45 N14 Fb	HINGONIA	18.30	17.65	16.80	16.70	25.40	24.30
6.	45 N14 Bd2	KADERA	26.50	26.05	10.45	10.69	18.00	16.20
7.	45 N14 Bd4	KOHLYA*	25.20	23.60	25.70	24.40	27.70	26.70
8.	54b2 eA	KOTKHAWDA*	23.25	13.80	19.50	19.05	23.00	18.30
9.	54 B2 Db	RUPAHERI	Dry	Dry	23.80	23.41	23.00	21.10
10.	45 n14 dC2	SHEODASPURA	Dry	Dry	10.80	10.15	19.20	17.35
11.	45 N14 Bc	TITRIYA	Dry	Dry	18.40	19.00	18.50	18.90
12.	45 N14 Bc1	TUNTOLI	24.10	23.75	21.90	22.08	21.70	18.60
13.		SHEODASPURA Pz			19.60	18.30	19.20	17.35
14.	54 B2 CA2	GARUDWASI T/W	NA	NA	NA	NA	Damaged	Damaged
		Avg, of Zone	**23.93**	**20.60**	**18.72**	**18.45**	**20.99**	**17.90**
ZONE: QUARTZITE								
1	45 N14 GD	AKORIYA	23.80	18.60	22.45	19.55	17.00	15.80
2	45 N14 Id	KOTHUN	23.10	21.95	20.00	22.15	20.00	8.10
3	54 B2 Cb1	SANWASA (SANWALL)	16.65	14.30	17.65	18.10	19.60	16.40
		Avg. of Zone	**21.18**	**18.28**	**20.03**	**19.93**	**18.87**	**13.43**
		Avg. of Block	**23.18**	**20.02**	**18.96**	**18.73**	**20.59**	**17.06**

BIO DATA

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Senior Secondary	2003	CBSE	Maths, Science	78.8	
B.E	2007	University of Rajasthan	Civil Engineering	68.81	
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6. Publications:

I. Nidhi Poonia, Dr. Mahender Choudhary, “ Groundwater Modelling Using FDM in Chaksu region, Jaipur, India” International Journal of Civil Engineering, 4(4), 1-10.

II. Dr.Mahender Choudhary, Nidhi Poonia “Climate Change and Water Resources Management”, Conference Proceedings on Climatic Changes and Sustainable Development, RIET Jaipur, CCSD-2011.

III. Nidhi Poonia, Dr. M.K Jat “Characterization and Treatment of Grey water for Recycling”, Nature Environment and Pollution Technology, Technoscience Publications, vol. no. 10, pp.435-438,2011