

Study of fluvial geomorphology and tectonics of the Khari-Mashi drainage basin, Rajasthan, for data-base preparation and groundwater recharge capability assessment

(Final Report)

By

S. Sinha-Roy
Principal Investigator

Birla Institute of Scientific Research
Statue Circle, Jaipur 302001

CONTENTS

	Page
1. SUMMARY	7
2. INTRODUCTION	9
3. PROJECT DETAILS	10
4. OBJECTIVES	11
5. LOCATION OF THE STUDY AREA	12
6. WORK COMPONENTS AND RESULTS	12
6.1. Geomorphology	13
6.1.1. Drainage Basin Morphology	
6.1.2. Stream Network	
6.1.3. Longitudinal River Profiles	
6.1.4. Altitude Range Distribution	
6.1.5. Hypsometry	
6.1.6. Ground Slope	
6.1.6.1. Ground Slope and Groundwater Recharge	

6.2. Geology	19
6.2.1. Recharge Capability of Bed-rocks	
6.3. Tectonics	21
6.3.1. Fault and Fracture Zone Intersections	
6.3.2. Drainage Density & Gully in Relation to Fracture Zones	
6.4. Soils and Sub-soil sediments	25
6.4.1. Soil-rock Interaction & Recharge of Fractured Bed-rocks	
6.4.2. Recharge Capability of Soils and Sub-soil Sediments	
6.4.3. Texture of Soils and Sub-soil sediments	
6.4.3.1. Textural Variations	
6.4.4. Hydraulic Conductivity	
6.4.4.1. Methodology	
6.4.4.2. Hydraulic Conductivity of Soils & Sub-soil Sediments	
6.4.4.3. Relation of Hydraulic Conductivity and Texture of Soils & Sub-soil sediments	
6.4.4.4. Regional Variation of Hydraulic Conductivity	
6.5. Groundwater Table	34
6.5.1. Groundwater Table Geometry	
6.5.2. Groundwater Table Fluctuation in Pre-and Post-Monsoon Periods	
6.5.3. Groundwater Table, Topography and Geomorphology	
6.5.4. Groundwater Table and Neotectonics	
6.6. Groundwater Flow Regime	40
6.6.1. Relation of Groundwater Flow and Neotectonic Blocks	
6.6.2. Relation of Groundwater Temperature and Fault Systems	
6.7. Analysis for Delineation of Groundwater Recharge Domains	44
6.7.1. Thematic Data Overlay Analysis	
6.7.1.1. Methodology	
6.7.1.2. Potential Recharge Domain	
6.7.2. Quantitative Matrix Analysis	
6.7.2.1. Methodology	
6.7.2.2. Potential Recharge Blocks	
6.7.3. Groundwater Recharge Zones	
7. CONCLUSIONS	49
Acknowledgements	53
Papers published	54
8. REFERENCES	54

LIST OF TABLES

- Table 1. Extent of different geomorphic units and their recharge potentials.
- Table 2. Stream network of the Khari-Mashi drainage basin.
- Table 3. Stream bifurcation ratio of Khari-Mashi drainage basin.
- Table 4. Stream channel gradients upstream and downstream of knickpoints on longitudinal profiles.
- Table 5. Valley-and along-stream gradients of major rivers of the Khari-Mashi basin.
- Table 6. Altitude range frequency distribution in the study area..
- Table 7. Altitude range frequency distribution of Khari, Dai and Mashi sub-basins.
- Table 8. Groundwater recharge capability of areas belonging to different ground slope categories, based on assigned weights.
- Table 9. Rock groups showing the extent and groundwater prospects of bed-rock aquifers and the relative recharge capability of the rock types.
- Table10. Groundwater recharge capability of fault and fracture zone intersections based on assigned weights.
- Table11. Location and extent of gullied areas.
- Table12. Groundwater recharge capability weights assigned to different attributes and characters of the soils and the sub-soil sediments
- Table13. Groundwater recharge capability scores estimated from cumulative weights of different characters of the soil and the sub-soil sediments developed in different geomorphic units.
- Table14. Texture of soils of different geomorphic units.
- Table15. Texture of sub-soil sediments of different geomorphic units.
- Table16. Hydraulic conductivity of soils of different geomorphic units.
- Table17 : Hydraulic conductivity of sub-soil sediments of different geomorphic units.
- Table18. Rank and Parameter Importance Value (PIV) of 11 parameters used to compute Cumulative Recharge Capability Score (CRCS) in Matrix Analysis.
- Table19. Recharge Capability Weights (RCW) of different attributes of 11 parameters, used in Matrix Analysis.
- Table20. Cumulative Recharge Capability Scores (CRCS) of 394 matrix cells.

LIST OF FIGURES

- Figure 1. Location of the Khari-Mashi drainage basin (the study area) within the Banas basin. Also shown are the major fault zones and dissected pediment.
- Figure 2. Geomorphologic map of the study area showing the geomorphic units and their relative recharge capabilities.
- Figure 3. Disposition of the different drainage sub-basins of the study area.
- Figure 4. Stream network of the Khari-Mashi drainage basin.
- Figure 5. Longitudinal profile of the Khari river showing the position of the knickpoints and the stretches used for stream gradient estimation.
- Figure 6. Longitudinal profile of the Dai river showing the position of the knickpoints and the stretches used for stream gradient estimation.
- Figure 7. Longitudinal profile of the Mashi river showing the position of the knickpoints and the stretches used for stream gradient estimation.
- Figure 8. Altitude range distribution map of the study area.
- Figure 9. Hypsometric curve for the Khari-Mashi basin.
- Figure 10. Hypsometric curve for the Khari sub-basin.
- Figure 11. Hypsometric curve for the Dai sub-basin.
- Figure 12. Hypsometric curve for the Mashi sub-basin.
- Figure 13. Map showing the regional ground slope of the study area.
- Figure 14. Regional ground slope directions of the study area.
- Figure 15. Map showing the spatial distribution of different ground slope categories and the areas of variable recharge potentials.
- Figure 16. Geological map of the study area.
- Figure 17. Map showing the distribution of neotectonic structures and tectonic landforms.
- Figure 18. Frequency distribution of intersections of faults and fracture zones computed on 50 km² cell grid.
- Figure 19. Contour diagram showing the percent frequency of intersections of faults and fracture zones.

- Figure 20. Map showing areas of moderate to high drainage density and their qualitative artificial recharge potentials.
- Figure 21. Map showing the gully areas of the study area.
- Figure 22. Map showing the distribution of the soils and the sub-soil sediments developed in different geomorphic units.
- Figure 23. Map showing the distribution of relative recharge capability scores of the soils and the sub-soil sediments.
- Figure 24. Location of the soil samples showing their hydraulic conductivity.
- Figure 25. Location of the sub-soil sediment samples showing their hydraulic conductivity.
- Figure 26. Grain-size distribution of the soils of different geomorphic units.
- Figure 27. Grain-size distribution of the sub-soil sediments of different geomorphic units.
- Figure 28. Contour diagram showing the spatial variation of contents of grit and coarse grained sands (> 2 mm to 0.5 mm) in the soils.
- Figure 29. Contour diagram showing the spatial variation of contents of grit and coarse sands (> 2 mm to 0.5 mm) in the sub-soil sediments.
- Figure 30. Relation between hydraulic conductivity and grain-size of the soils and the sub-soil sediments of different geomorphic units.
- Figure 31. Contoured diagram showing the distribution pattern of hydraulic conductivity of the soils.
- Figure 32. Contour diagram showing the distribution pattern of hydraulic conductivity of the sub-soil sediments.
- Figure 33. Hydraulic conductivity ranges of the soils, their impact rank and recharge capability.
- Figure 34. Hydraulic conductivity ranges of the sub-soil sediments, their impact rank and recharge capability.
- Figure 35. Contour diagram showing depth-to-water table (January-February, 2005).
- Figure 36. Contour diagram showing depth-to-water table (September-October, 2005).
- Figure 37. Water table configuration map (January-February, 2005).
- Figure 38. Water table configuration map (September-October, 2005).
- Figure 39. Water table configuration map (after Irrigation Department, Govt. of Rajasthan, 1998).
- Figure 40. Location of the wells showing depth-to-water table (January-February, 2005).
- Figure 41. Location of the wells showing depth-to-water table (September-October, 2005).
- Figure 42. Areas of the post-monsoon rise of the water table and its relation with major fault zones.

Figure 43. Topographic profiles showing relations between the water table, major tectonic features and geomorphic units.

Figure 44. Relation between major faults and the water table configuration.

Figure 45. Groundwater flow pattern in relation to faults and bed-rock ridges.

Figure 46. Generalised groundwater flow pattern in fault-bound groundwater blocks.

Figure 47. Groundwater temperature in the vicinity of major faults.

Figure 48. Favourable groundwater recharge domains delineated by Thematic Data Overlay Analysis.

Figure 49. Location of matrix cells used for Quantitative Matrix Analysis for estimation of Cumulative Recharge Capability Score (CRCS).

Figure 50. Cell-wise distribution of CRCS value-ranges, determined by Quantitative Matrix Analysis.

Figure 51. Location of the most favourable recharge cell-clusters having CRCS values >1400 numbered 1 to 10.

Figure 52. Detailed maps (nos. 10) of the most favourable recharge cell-clusters showing the location of suitable recharge zones.

Study of fluvial geomorphology and tectonics of the Khari-Mashi drainage basin, Rajasthan, for data-base preparation and groundwater recharge capability assessment

(Final Report)

By

S. Sinha-Roy
Principal Investigator

Birla Institute of Scientific Research
Statue Circle, Jaipur 302001.

1. SUMMARY

The project deals with the study and analysis of a number relevant geologic, geomorphologic and hydrologic parameters to assess the groundwater recharge potentials, and to delineate the suitable recharge zones in the Khari-Mashi drainage basin (18, 814 km²), Rajasthan.

The morphometric analysis indicates that the study area is a 5th order Hortonian sub-basin of the Banas drainage basin. The variable development of streams of different orders and the non-uniformity in the drainage density and frequency of the stream network are due to inhomogeneity in the type of the bed-rocks and their tectonic grains. The longitudinal river profiles and the hypsometry indicate the presence of active faults that modified the drainage network, caused block movements and drove differential mass-wasting.

The study area comprises the crystalline and metasedimentary rocks of Precambrian age. These rocks have variable secondary porosity and permeability due to the presence of deformation structures such as faults, fracture and damage zones. A number of faults, both extensional and strike-slip types, and fracture zones, mapped from space imageries and field observations, are related to the major older dislocation zones that have been reactivated in the Quaternary and recent times to produce various tectonic geomorphologic features. The density of intersection of these planar structural elements shows variable spatial distribution.

The study area is geomorphologically complex where 13 geomorphic units have been identified and mapped. The complexity is due to the combined effect of neotectonics

and polycyclic landform evolution. These units have variable groundwater potentials as well as recharge capabilities for which a scale of impact weights has been assigned to them. The regional ground slope of the area that has been dissected into three physiographic terrains, namely, the highland of the Aravalli hill-range, the midland of the pediments, and the lowland of the alluvial tracts, ranges between $<0.1\%$ to $>1.8\%$, and the slope is generally from the northwest to the southeast.

The land-cover material comprises the soils of various taxonomic types and the sub-soil sediments of either Quaternary fluvial deposits or aeolian sand bodies of different generations. The soil types vary with the geomorphic units. The study of the texture of the soils and the sub-soil sediments (219 samples) of these units indicates that the grain-sizes and the contents of the different size-fractions in them are variable. This factor has an influence on the recharge capability of the land-cover materials. The distribution frequency of the coarse fraction ($> 2 \text{ mm} - 0.5 \text{ mm}$) of the soils, and the sub-soil sediments indicates that the coarse grained material has a restricted occurrence in the area, and that the texture of the soil profile does not mimic that of the sub-soil sediments. This feature would need the soils and the sub-soil sediments to be examined separately for their texture to ensure the maximum recharge efficacy and sustainability.

The analysis of the soils and the sub-soil sediments for their hydraulic conductivity brought out the variable nature of the conductivity, ranging from 1 cm/hr to as high as 66 cm/hr, in different geomorphic units. In general, the percentage of coarse-grained gritty and sandy fractions ($>2 \text{ mm}-0.5 \text{ mm}$) of the soils and the sub-soil sediments shows a positive correlation, and the percentage of the finer grained fractions ($0.10 \text{ mm}-< 0.06 \text{ mm}$) shows a negative correlation with hydraulic conductivity.

The water table geometry has been deduced from the depth-to-water table measurements in 249 dug wells, spread over the study area, for pre-monsoon (January-February, 2005) and post-monsoon (September-October, 2005) periods. The water table configurations for these two periods indicate that the water table in specific areas has gone up by 0.5 m to 13 m during the post-monsoon period. This suggests that in these areas the unsaturated shallow aquifer has been recharged to variable degrees by the run-off water. Neotectonic faults and fracture zones of various dimensions played a significant role in post-monsoon recharge.

Three groundwater blocks defined by major fault zones have been identified. These blocks show different groundwater flow regimes. Multi-directional groundwater flow is the result of aquifer tilting in fault-bound blocks, and of variable transmissibility across and along faults that act either as conduits or barriers. Analysis of fault and fractures patterns and their intersection densities in relation to the water table configuration and flow pattern indicate that tectonic features play an important role in the recharge of shallow unconfined aquifer.

The groundwater temperature data across and along the major fault zones indicate that the water in uplifted hanging-wall blocks of some of the barrier faults is colder by about $2^{\circ}-3^{\circ} \text{ C}$ than the water in the downthrown footwall block. This suggests that the

shallow aquifer is recharged by colder surface water in the uplifted block and that water flow and mixing across the barrier faults is minimal. However, some extensional fault zones show good lateral transmissibility such that groundwater flow is parallel to and along the fault conduit, and that the recharged water mass gets mixed with hotter water down the flow gradient in which direction the water temperature increases.

Multi-parametric data-sets and multi-component thematic maps are used to identify potential recharge domains by following two methodologies, namely, Thematic Data Overlay Analysis (TDOA), and Quantitative Matrix Analysis (QMA). Several domains suitable for recharge have been identified by TDOA using 8 important parameters while Cumulative Recharge Capability Scores (CRCS) of 394 matrix-cells (unit cell = 50 km²) have been computed using 11 such parameters by QMA. The two approaches produced nearly similar results for identifying favourable recharge domains, indicating that the delineation of the recharge domains is not methodology-specific, and that the impact factors of the parameters are more relevant than the number of parameters chosen. A number of specific recharge zones have been located in the favourable recharge domains, identified on the basis of CRCS scores (> 1400) from consideration of several domain-scale features, including faults and fractures, hydraulic conductivity, groundwater flow-paths and landform characteristics.

The data-sets generated and the multi-parametric thematic maps prepared in the project have potential for use in and hold prospect to serve as the data-base for further study on GIS platform to generate stochastic groundwater models.

2. INTRODUCTION

In spite of the fact that India is a tropical country receiving a good amount of annual rainfall a large part of the run-off water is lost to the sea. The varied hydrogeologic conditions prevent rapid infiltration of the surface waters to recharge the unsaturated aquifer systems, and replenish the dynamic, or replenishable groundwater resources. There is thus an imbalance between recharge and groundwater development in many parts of the country (Raju, 1998). It is, therefore, imperative that unutilized run-off water should be harvested and utilized for recharging the depleted aquifers.

The recharging programmes should necessarily take into consideration various factors including hydrology, geology, and geomorphology etc. Many workers have studied different aspects of these factors to select or suggest sites for groundwater recharge (Bourgeois, 1972; Woods, 1978; Ramasamy and Anbazhagan, 1997; Beckman et al., 1996)

The groundwater table in most parts of Rajasthan is steadily going down due to over-exploitation and inadequate natural recharge, resulting from frequent drought conditions in a region where the erratic annual rainfall is below 50-60 cm in most parts. In order to address the problem of the imbalance between abstraction and resources, it is necessary to augment the groundwater potential by artificial recharge of the depleted aquifers in a scientific and well-studied manner. Clearly, for efficient recharge, the sites

favorable for the purpose will have to be identified, apart from hydrology, on the basis of primarily geologic, geomorphologic and land-cover attributes. The present project aims to address some of these aspects with reference to a hydrogeomorphologic unit, i.e., a drainage basin.

Generally, groundwater recharge requires applying water in surface and near-surface spreading basins, pits and trenches, using the unsaturated porous and permeable zones and the fracture planes to transport and store water. The hydrogeology of the unsaturated zones, particularly the vertical hydraulic conductivity of the land-cover materials, including the soils and the sub-soil sediments, frequency of fractures and fault zones, lineaments etc., play a critical role in transporting and storing the recharged water (Flint, 2002). Therefore, the study and evaluation of this zone and its geologic, tectonic, geomorphologic and land-cover attributes is important and necessary for selecting areas or sites for groundwater recharge.

3. PROJECT DETAILS

The project was approved by the Ministry of Water Resources, Govt. of India, New Delhi in September 2003 (vide letter no. 23/27/2003 – R&D/830/842, dated September 11, 2003). A grant of Rs. 3.73 lakhs for the first year was received on December 12, 2003. The work on the project was started subsequently with the procurement of space imagery data products and recruitment of two Junior Research Fellows.

A grant of Rs. 5,06,034 for the work during the second year was received on December 18, 2004. The last installment of the grant of Rs. 2.40 lakhs was received on January 19, 2007. An extension of the project for six months after December, 2006 was requested in order to identify specific recharge sites in favourable recharge blocks, using multivariate data sets.

The Annual Progress Report for the period December 12, 2003 to March 31, 2004 was submitted to the Ministry of Water Resources, Govt. of India, New Delhi and to INCOH, Roorkee, in May 2004. The results of the work carried out during this period were presented at the R&D Session Meeting of INCOH in Chandigarh during September 30 – October 1, 2004.

The Annual Progress Report for the period April 1, 2004 to March 31, 2005 was submitted in June 2005. The progress of the second year's work was presented at the R&D Session Meeting of INCOH at Hyderabad during September 26-27, 2005. The Annual Progress Report for the work during April 1, 2005-March 31, 2006 was submitted in May, 2006. The results of the work carried out during 2005-06 were presented at the R & D Session Meeting of INCOH at the Banaras Hindu University, Varanasi, during August 24-25, 2006. The Annual Progress report for the work during April 1, 2006 – March 31, 2007, has been submitted in May, 2007.

4. OBJECTIVES

The study area is one of the drought prone areas of the semi-arid terrains of Rajasthan. During the last decade the groundwater table is steadily falling due to an imbalance in groundwater abstraction and recharge. The objective of the project, as set out in the proposal, is to study the response of fluvial processes depicted in various geomorphic units and stream network characteristics in order to understand their role in and possible contribution they can make to groundwater recharge. The other objective was to study the geologic, tectonic and land-cover characteristics of the study area to assess their importance and role in groundwater recharge. The final objective was to analyse and integrate the multi-parametric data-sets, and by assigning weights and impact values to each parameter, to derive the recharge capability scores, using matrix analysis and to identify the possible recharge zone.

The above broad objectives of the project have been divided into the following components which were addressed in the study, using various methodologies. These methodologies are outlined and the results discussed in the relevant sections of the report.

(i) Demarcation of the Khari-Mashi drainage basin and work out the drainage network characteristics by morphometric analysis, including longitudinal stream profiles.

(ii) Preparation of altitude range maps and carry out hypsometric analysis in order to understand the erosion and the accretionary landform processes.

(iii) Preparation of geological map, and delineation of the distribution of different lithologic units with assigned groundwater recharge impact weights.

(iv) Preparation of tectonic map showing the distribution of major fracture zones and faults, and other tectonic geomorphic features from the study of space imageries (IRS 1D LISS II on scales 1: 250,000 and 1: 50,000), and by field studies. Study of the distribution of density per unit area of the intersections of faults, lineaments and fracture zones.

(v) Preparation of geomorphologic map differentiating the different landform units from study of space imageries and field observations, and also to assess the groundwater recharge prospect of the individual geomorphic units.

(vi) Preparation of regional ground slope map showing the regional gradient and the general directions of the ground slope, and assessment of the control of ground slope on groundwater recharge.

(vii) Preparation of map of soils and sub-soil sediments, and study of the hydraulic conductivity and textural characteristics of soils and subsoil sediments of different geomorphic units in order to assess their recharge capabilities.

(viii) Preparation of groundwater table maps from water level measurements in dug wells during pre-monsoon and post-monsoon periods.

(ix) Study of the relation of the depth-to-water table and tectonic and geomorphic features.

(x) Analysis of texture, grain-size frequency and hydraulic conductivity of the soils and sub-soil sediments..

(xi) Determination of the water table geometry of the shallow aquifer by repeat measurements of the water depths of selected dug wells, and monitoring of these dug wells for pre-monsoon and post-monsoon periods for ascertaining the water table fluctuations.

(xii) Investigation of the interrelations between the water table geometry, topography and geomorphology.

(xiii) Determination of the groundwater flow pattern and investigation of the relations of faults and fracture zones and the groundwater flow regime.

(ix) Delineation of favourable recharge zones by integrating the multi-parametric data-sets and carrying out matrix analysis.

5. LOCATION OF THE STUDY AREA

The Khari-Mashi drainage basin, Rajasthan, the study area, measures 18,814 km², and forms a part of the major Banas drainage basin in south-central Rajasthan (Figure 1). The study area is bounded by Latitude 27°15' – 25°30' and Longitude 73°50' – 74°50' in parts of the Survey of India topographic sheets 45 G,J,K,M,N,O in segments of Udaipur, Jaipur, Ajmer, Bhilwara and Tonk districts.

The area receives an erratic annual rainfall of 50-70 cm, and constitutes the southeast margin of the Thar desert. It lies in an important geological and geomorphic region between the Aravalli hill range in the north-east and the Vindhyan plateau in the south-east. It comprises various rock types of different ages, and contains contrasting geomorphic, land-cover and tectonic attributes.

6. WORK COMPONENTS AND RESULTS

In order to meet the broad objectives of the project and its various components, outlined above, the study has been carried out on various themes that have been divided into a number of parameters, relevant to the objectives. Since the matrix analysis for delineating favourable recharge zones would require both thematic and quantified data-sets, the thematic multi-component parameters have been studied both for their spatial distribution and for numeric attributes.

6.1. Geomorphology

The landform characteristics play an important role in both surface water and groundwater potentials of drainage basins. Moreover, the different geomorphic units that characterize the landform of the drainage basin contribute significantly to the recharge capability and groundwater prospect of specific areas of drainage basins.

Many authors (Bhattacharyya et al., 1979; Steven, 1991; Millington and Townshed, 1986; Toleti et al., 2000; Srivastava et al., 1996) have used remote sensing data and GIS methodologies to demarcate prospective zones of groundwater by identifying hydrogeomorphologic features. A few studies have been made taking geomorphology as one of the parameters for delineating groundwater recharge zones, using remote sensing techniques (Chandrashekhar et al., 2001; Ramasamy and Anbazhagan, 1997; Singh et al., 2000; Saraf and Chaudhary, 1998). In order to assess the groundwater recharge capability of the geomorphic units, the Khari-Mashi drainage basin has been studied, and various landform units have been identified and mapped by remote sensing analysis, topographical map studies and field observations.

Figure 2 shows the distribution of the geomorphologic units with their assigned qualitative groundwater recharge capability in the study area. Ten such units have been identified which have got variable groundwater prospects as well as recharge potentials, varying from poor to excellent. The geomorphic units having poor groundwater recharge prospect include residual hills, inselbergs and salt lake fills whereas the units having moderate recharge capability include pediments and gully areas. The dissected alluvial fans, intermontane valley fills, palaeochannel fills and alluvial plains have good to very good recharge capability. The flood plains of the major river valleys have excellent recharge capability.

Table 1 shows the details of the areas covered by the different geomorphic units with their assigned recharge prospects in the Khari-Mashi drainage basin. The maximum area (15,042 km², 79.5% of the total basin area) is covered by the alluvial plains that have very good recharge prospect, followed by the flood plain and the channel fill areas having excellent recharge prospect cover 986 km² (5.24% of the total basin area). Therefore, the area having good to excellent recharge potential for groundwater is quite large. Depending on the availability of other favorable recharge factors these two geomorphic units may provide suitable sites for artificial groundwater recharge. This aspect will be explored further in the matrix analysis for delineation of the recharge zones.

6.1.1. Drainage Basin Morphometry

The Khari-Mashi basin has been demarcated on the basis of its drainage divides within the Banas drainage basin in southeastern Rajasthan (Figure 1). The Khari-Mashi basin, the study area, lies on the left bank of the Banas river, and it covers about 35% of the Banas basin. The Luni basin lies in the northwest across the Aravalli hill range and the Chambal basin occurs in the southeast at the fringe of the Vindhyan plateau.

The Khari-Mashi basin occupies a large part of the dissected Bhilwara pediment, and it incorporates the wind-gap in the Aravalli hill range marked by the topographic depression of the Sambhar saline lake in the northern extremity of the basin.

Figure 3 shows the spatial disposition of the details of the sub-basins of the study area. The interfluvium of the Khari and the Mashhi rivers is represented by the Dai sub-basin. The areas covered by these sub-basins are as follows : Khari – 6615 km², Mashhi – 8500 km², and Dai – 3160 km².

6.1.2. Stream Network

Figure 4 shows the drainage network of the study area, and Table 2 gives the quantified drainage network data. The stream ordering of the sub-basins indicates the following features.

Both the Khari and the Mashhi rivers are 5th order Hortonian streams while the Dai river is a 4th order stream. The Mashhi river contains the maximum number of 1st order streams (248), followed by the Khari river (185), and the Dai river (124). The number of 2nd and 3rd order streams show decreasing trends similar to that of the 1st order streams.

The ratio of 1st, 2nd and 3rd order streams varies from 9.8 : 3.6 : 1.0 for the Mashhi sub-basin, 23.1 : 5.5 : 1.0 for the Khari sub-basin and 31 : 7.5 : 1.0 for the Dai basin. Clearly, there is a variation in the relative development of streams of different orders in the study area. The Dai basin shows the maximum development of low order streams in contrast to higher order ones, followed by the Khari sub-basin. This variation is probably due to lithologic controls in terms of differential rock erodibility, and structural controls in respect of spatial distribution of faults and fracture zones on stream network development. The geologic and tectonic analysis of the study area (see later) substantiates this conclusion.

The relative lengths of the different orders of streams are also variable. The ratios of 1st, 2nd and 3rd order stream lengths vary from 2.74 : 1.12 : 1.0 for the Mashhi sub-basin, 2.3 : 0.98 : 1.0 for the Khari sub-basin, and 1.6 : 1.05 : 1.0 for the Dai basin. These data indicate that for the Dai basin the proliferation of the 1st and 2nd order streams has been uniform in contrast to the Khari and the Mashhi sub-basins which although show similar stream networking for the 2nd and 3rd order streams, the 1st order streams have developed strongly in them. This would indicate that the Dai basin is more homogeneous than the Khari and the Mashhi sub-basins with respect to geology and structure that control the drainage network development.

The above stream network characteristics are reflected in the drainage frequency and drainage density of the different sub-basins. The highest drainage frequency (0.39) is shown by the 1st order streams of the Dai basin. Similar drainage frequencies in decreasing order are shown by the network of the Mashhi sub-basin (0.29) and the Khari sub-basin (0.27). The drainage frequency diminishes drastically from the 1st order to the 2nd and the 3rd order streams. For example, for the Dai basin the frequency drops from 0.39 for the 1st order streams to 0.009 and 0.0013 for the 2nd and the 3rd order streams, respectively. A similar trend is shown by the stream networks of the Khari and the Mashhi sub-basins.

The drainage density for the 1st order streams is the maximum in the Dai basin (0.127) while it is 0.097 and 0.108 for the 1st order streams of the Mashhi and the Khari sub-basins, respectively. The drainage frequency diminishes as the stream order increases for all the studied stream networks. Since the variation in stream frequency and stream density

is a function of rock types and the frequency of faults and fracture zones, the heterogeneity of these stream network parameters would suggest the spatial variability in the geologic and structural attributes. This variability is further indicated by the stream bifurcation ratios of the studied basins (Table 3). The average bifurcation ratio varies from 2.6 (1st / 2nd orders) in the Khari sub-basin to 7.5 (2nd / 3rd orders) in the Dai sub-basin. The bifurcation ratios of the streams within a particular basin are also variable. For example, the Khari sub-basin shows a variation of the ratios from 2.6 (3rd / 4th orders) to 5.5 (2nd / 3rd orders). Notably, for all the sub-basins the highest bifurcation ratios are in respect of 2nd / 3rd order streams.

6.1.3. Longitudinal River Profiles

Longitudinal river profiles are strong tools to decipher the state of denudation, mass transport and accretion, and to understand the controls of tectonic features in drainage development. All these attributes have important bearing on surface run-off pattern, and eventual groundwater recharge.

The longitudinal profiles of the Kahri, Dai and Mashi rivers are shown in Figures 5, 6, and 7, respectively. The profiles indicate the following features.

The Dai river shows more mature and equilibrated profile than the Khari and the Mashi rivers, suggesting a more mature topography of the former basin than the latter. The Mashi sub-basin is, however, more mature than the Khari sub-basin. The longitudinal profiles show prominent gradient breaks and knickpoints, signifying the presence of active tectonic zones across the river valleys. The locations of these knickpoints are shown in Figure 5, 6, and 7. The gradients of the rivers upstream and downstream of each knickpoints are given in Table 4.

The Khari and the Mashi rivers show the maximum number of knickpoints (nos. 4) while the Dai river shows only two knickpoints. In the Mashi river, knickpoints - A, B, and C are located near the source region at Didwara (45 J/14), Bhagadit (45 N/2) and 1.75 km NE of Jugalpara (45 N/3), respectively. The mid-stream knickpoint is located at 1.2 km NE of Mandap (45 N/11), nearly 33 km upstream of the confluence with the Banas river. The gradients across the highest knickpoint - A, situated at an elevation of 393 m varies, vary from 0.92% in the upstream to 0.11% downstream, thus making this knickpoint a prominent tectonic feature crossing the Mashi river. Another important knickpoint - B, having a similar tectonic significance, is located at 377 m elevation where the upstream gradient is 0.11%, changing to steeper gradient of 0.45% downstream.

The knickpoint - A on the Dai river is situated at an elevation of 410 m, nearly 20 km downstream of the source region at Jaswantpura (45 J/16). This knickpoint locates a prominent fault zone across the Dai river valley because the gradient in the upstream of the knickpoint changes from 0.91% to 2.1% downstream. The gradient upstream of this knickpoint changes sharply to 0.13%.

In the Khari river two knickpoints (A and B) are located in the higher elevations at the source region at 593 m (Losani, 45 K/2) and at 577 m (3 km north of Kartha, 45 K/2), respectively. The gradient upstream of knickpoint - A is 0.46% that changes to 0.15% downstream while the gradient (0.15%) upstream of knickpoint - B changes to 0.23%

downstream. In the middle stretch of the river, knickpoints-C and D at an elevation of 437 m and 381 m, respectively, are located at 3.75 km east of Bhimlat (45 K/9) and at Dhanop (45 K/13), respectively. The change of gradient across these knickpoints is not as prominent as in the higher elevation knickpoints in the source regions of the rivers because the difference in the gradients across the knickpoints in the midstream region varies from 0.10% to 0.03%.

Table 5 gives the values of the valley and along-river gradients in different stretches with respect to the knickpoints identified on the longitudinal profiles of the Khari, Dai and Mashri rivers. Clearly, the along-river gradients of all the stretches are lower than the valley gradients, although the difference between them is not significantly high. For example, the average along-river gradient of the Khari river is 0.21% while the valley gradient is 0.25%. Similarly, for the Dai and the Mashri rivers, the along-river gradients are 0.52% and 0.33%, respectively, while the valley gradients are 0.55% and 0.35%, respectively. Such a small difference between the along-river and valley gradients for the major rivers of the study area would indicate that the rivers maintain almost straight courses, and that they do not show any significant meandering, suggesting that these rivers are generally controlled by the tectonic features such as fault traces and fracture zones in the bed-rocks.

6.1.4. Altitude Range Distribution

The altitude range distribution of the study area is shown in Figure 8. The altitude frequency indicates the flowing features.

The elevation ranges from 200 m to > 800 m. The highest elevation of 853 m is located on the Aravalli hill range in the southwestern part of the study area, to the west of Bhim. The Aravalli hills in the area ranges in elevation from 500 m to 800 m, and it constitutes the highlands and the prominent water divide for the basin. The midland segment at the southeastern slopes of the Aravalli hills, represents a pediment dominated by the presence of thick colluvium and alluvial fan deposits that are good host of shallow aquifer systems, and are also good infiltration zones for groundwater recharge. This zone, well-developed in Kishangarh, Nasirabad and southwest of Gulabpura areas, ranges in elevation from 400 m to 500 m. A similar range of elevation is also present in the northern part of the area in the north of Jaipur and Samod regions where the dissected midland domain is present. The dissected nature of the midland pediment indicates the tectonics-controlled geomorphic modification of the basin. The lowland area is the most extensive, and it covers the southeastern part of the study area in the Banas river valley. Its elevation ranges from 200 m to 400 m, and it contains a thick alluvium and pedogenised older sand dunes.

The areal extents of the different altitude ranges of the drainage sub-basins are given in Table 6. Nearly 55% of the study area falls in the altitude range of 300-400 m, followed by 31% in the range of 400-500 m. The highland with the altitude range of 500->800 m covers nearly 6% of the total area. Such asymmetric spatial coverage of the altitude ranges would signify neotectonic controls on catchment uplift and subsidence, and an unequal response of the catchment segments to denudation processes.

The areas covered by the different altitude ranges within the individual sub-basins of the study area are given in Table 7. In conformity with the character of the total basin the individual sub-basins also show the maximum area coverage by the altitude range of 300-400 m in the Mashi and the Dai sub-basins (Mashi – 71%, Dai – 63%), while the Khari sub-basin shows 55.1% of the area in the altitude range of 400-500 m. The Khari sub-basin has the maximum (nearly 16%) in the highland region and the Dai sub-basin contains the maximum area in the midland terrain.

6.1.5. Hypsometry

The altitude frequency data for the study area have been used to analyse the hypsometric characteristics of the drainage basin. Hypsometry deals with the relationship between the elevation and the area, and is a powerful tool for recognizing the landform characters in terms of their denudation state and the controls of tectonic features in landform evolution.

The hypsometric curve for the entire Khari-Mashi drainage basin is shown in Figure 9, and the individual hypsometric curves for the Khari, the Dai and the Mashi sub-basins are shown in Figures 10, 11, and 12, respectively. The hypsometry of the total basin shows a concave upward curve indicating the predominance of fluvial erosion over diffusive mass-flow in the basin. However, the individual sub-basins show a difference in the location of the inflection points on the respective hypsometric curves. For example, the inflection point for the Khari sub-basin has a higher a/A value which is the ratio of the sub-basin area (a) and the total basin area (A), than that for the Mashi and the Dai sub-basins. This implies that the slope recession due to mass-wasting has advanced to a greater extent in the Dai and the Mashi sub-basins than in the Khari sub-basin.

The hypsometric integral (Ea), giving the extent of terrain denudation, is also variable. The Ea value for the Khari basin is 0.27 while it is 0.15 for the Mashi and 0.21 for the Dai sub-basins. The Ea value for the total Khari-Mashi basin is 0.24. These data indicate that the hypsometry of the study area is generally controlled by the area-elevation characteristics of the Khari and Dai sub-basins. This would also indicate that the Mashi sub-basin has reached a more advanced stage of denudation than the other sub-basins of the study area. The shape of the hypsometric curves also suggests the existence of a well-defined pediment in the Khari-Mashi basin. This pediment at the eastern fringe of the Aravalli hill range, identified from the altitude frequency, and discussed above, is well-developed in the Khari sub-basin, as shown by the convex-up bulge of its hypsometric curve.

6.1.6. Ground Slope

Apart from the various geomorphic features and the morphologic attributes of the drainage basins the ground slope is also an important factor controlling the availability of adequate run-off water for groundwater recharge. Moreover, topographic features including the ground slope play an important role in the selection of the recharge sites. In view of this, a regional ground slope map of the study area has been prepared (Figure 13). The

ground slope values range from $<0.1\%$ to $>1.8\%$. The following features are brought out by the regional ground slope.

The areas showing high ground slope ($>1.8\%$) occur in the highland terrain and the midland pediment zone of the Aravalli hill range on the northern and northwestern water divide of the Khari-Mashi basin. Isolated areas of high slope also occur at the water divide on the northern margin of the drainage basin in Jaipur-Samod region. The central part of the basin, particularly the lowland region, has a low slope ($<0.1\%$) with isolated regions where the slopes show the following ranges : $0.1 - 0.3\%$, $0.3 - 0.5\%$ and $0.5 - 0.7\%$. However, within this low ground slope region there are a few isolated high slope areas in the range of $>1.8\%$ (Asalpur, 45 N/5), $1.5 - 1.8\%$ (Gulabpura, 45 K/9, and Jobner, 45 N/5)), $1.3 - 1.5\%$ (Jamola, 45 J/12), and $1.1 - 1.3$ (Naraina, 45 N/1). The southern and southwestern margin of the Khari sub-basin generally has similar to higher slope ($0.9 - 1.5\%$) than that of its southeastern, northeastern and northwestern boundaries.

The ground slope characteristics, described above, pertain to regional slope pattern, implying that on smaller and local scale the slope may be variable even within a particular slope category, shown on the map (Figure 13). Therefore, in order to estimate the run-off rate at any chosen recharge site a detailed slope analysis will have to be made although the slope pattern, detailed above, would provide weighted data input in the ranking of areas in terms of recharge potentials, attempted in the study.

Ground Slope Direction: The direction of regional ground slope, computed from topographic map analysis, is shown in Figure 14. The ground slope directional characteristics are as follows.

The down-slope direction in the northwestern water divide of the basin, located along the Aravalli hill range and its pediment from Devgarh to Kishangarh, is towards the interior parts of the basin, generally from the northwest to the southeast, in the direction of the master river, the Banas. A complex ground slope direction pattern is shown by the Khari sub-basin where in the middle part of the sub-basin, the directions vary from westerly to easterly and southerly to northerly. Similar variation and reversal of ground slope is also present in the northern segment of the Mashi sub-basin (45 N/5,10). These variable slope directions are considered to have been caused by neotectonic block faulting and tilting, described later.

The data on regional ground slope are useful in planning and execution of groundwater recharge programs, and locating recharge areas. However, as already mentioned, for locating recharge structures a detailed slope analysis will be necessary.

6.1.6.1. Ground Slope and Groundwater Recharge

Since the ground slope magnitude and direction controls the surface water run-off pattern it has an important bearing on both natural and artificial recharge of groundwater. In order to determine the spatial variation of control of ground slope on the groundwater recharge, the slope parameter has been classified into 5 categories and assigned weights from 0 to 20 (Table 8). Slope category of 0.1 – 0.3% has been assigned the highest weight (20) having excellent recharge impact while 1.5 – >1.8% slope category has been given the lowest weight (0), having poor recharge impact. Other ground slope categories are 0.3 – 0.7% (weight: 15, recharge impact: very good), category 0.7 – 1.1% (weight: 10, recharge impact: good) and category 1.1 – 1.5% (weight: 5, recharge impact: moderate).

The spatial distribution of the above ground slope categories, showing areas of variable groundwater recharge prospects, based on impacts of ground slope, is shown in Figure 15. The following are the major features.

The areas of excellent recharge prospect are present in the major part of the Khari-Mashi basin, covered by the alluvial plains of the lowlands. The highland terrain and the midland pediment region at the northern and northeastern water divides of the basin show poor recharge prospect because of moderate to high slope with variable slope directions. The ground slope characters show a very good recharge prospect for the isolated parts of the alluvial plain in the southwestern, central, and northern part of the basin where the ground slope is low to moderate. The important parameter of ground slope has been used in conjunction with other parameters for the delineation of groundwater recharge zone, using matrix analysis, discussed later.

6.2. Geology

The geologic attributes of an area play an important role in determining the possibility and efficacy of groundwater recharge, particularly where significant lateral and/or vertical groundwater flow is required between recharge and discharge locations (Phillips, 2002). Geological features are also important in areas where hard rock aquifer systems are of prime concern, and also where the shallow alluvial aquifers are interconnected with the deeper bed-rock aquifers. The key features such as faults and fractures, spatially extensive porous and permeable lithologies, such as loose to fine-grained sedimentary rocks, and deep regolith zones, can exert dominant controls on a flow system and on the fate of water in and from artificial recharge sites. The controls of geological factors, especially of hydraulic properties of rock types, have been given due importance in recharge evaluations in many studies (Wodeyar et al., 2001; Vaya, 2001; Saraf and Chaudhary, 1998).

The study area contains various rock groups belonging to the Archaean and the Proterozoic stratigraphies (Figure 16). The major part of the area on the southeast is covered by the Mangalwar Complex rocks comprising calc-silicate gneisses, mica-schist, cherty quartzite and migmatites; the latter occurring in a vast tract from Shahpura (45 K/14) in the southwest to Samod (45 M/16) in the northeast. Another tract of quartzofelspathic gneisses and mica schists occurs to the northwest of the study area that belongs to the Sandmata Complex of Late Archaean to Palaeoproterozoic age. The gneissic

terrain contains enclaves of mafic intrusives, amphibolite and high-grade (granulite-facies) pelitic gneisses. This ensemble has been intruded by granite, granodiorite, charnockite and enderbite. The high-grade gneisses occur as thrust-bound slivers within the migmatites and quartzofelspathic gneisses. Because of this tectonic setting, the region covered by the Sandmata Complex rocks in the northwestern part of the study area contains a number of faults, structural lineaments and fracture zones in the basement rocks. The different shear zones and thrusts, identified within the Sandmata Complex, are interpreted to be linked with the major dislocation zone, the Kaliguman Lineament (Gupta et al. 1997) or the Delwara Dislocation Zone (DDZ) (Sinha-Roy et al., 1998) that acted as a sole thrust.

A major dislocation zone, the South Delhi Fault (SDF), separates the Sandmata Complex rocks from the Proterozoic Delhi Supergroup rocks that constitute the Aravalli hill range. There are evidences to suggest that the SDF is a dextral transpression fault that dislocated and emplaced exotic (suspect terrain) of the Aravalli rocks within the Delhi fold belt (Sinha-Roy, 2004). A dextral strike-slip fault, the Sambhar-Jaipur-Dausa Fault (SJDF), occurring in the northern and northeastern part of the study area, transects the DDZ and the NE-SW trending structural grains of the Sandmata and Mangalwar Complex rocks. In the southeastern part of the Khari-Mashi drainage basin, at its water divide, occurs a prominent crustal-scale dislocation zone, the Banas Dislocation Zone (BDZ) that has thrust the Mangalwar Complex rocks onto the younger Proterozoic sequences (Jahazpur Group) (Sinha-Roy, 2000). All these major and older dislocation zones show evidence of reactivation in the Quaternary and recent times. The terrains, including the study area, traversed by these structural zones record tectonics-driven mult-stage geomorphic evolution and formation of various neotectonic landform features to which the drainage system and the hypsometry responded (Sinha-Roy, 2001a, b; 2002). These features, discussed later in the text, are relevant for groundwater recharge of depleted aquifers of the study area.

The metasedimentary cover sequences of the Mangalwar Complex rocks and the Sandmata Complex rocks are represented by the Aravalli Supergroup (Palaeo- to Mesoproterzoic) and the Delhi Supergroup (Meso-to Neoproterzoic). The Aravalli Supergroup, represented by calc-gneisses, marble, quartzite, mica schist and carbon phyllite, occur in a restricted area near Kadera (45 O/1) and Ghordan (45 O/2). There is a patch of the Aravalli Supergroup rocks occurring to the southwest of Shahpura (45 K/10), which is an extension of the main Aravalli fold belt, lying to the south.

The Delhi Supergroup rocks, represented by calc-gneisses, marble, mica schist, quartzite and conglomerate, occur in the northwest fringe of the study area, and these extend from north of Kishangarh (45 J/14) to northwest of Devgarh (45 G/14) through Nasirabad (45 J/11). These lithologies occur in isolated exposures and as highly tectonized bodies, and are separated from the Sandmata Complex rocks by a prominent dislocation zone, known as South Delhi Fault (SDF) (Figure 1). Isolated patches of the Delhi Supergroup rocks, dominated by quartzites, occur as outliers in the northern part of the study area to the northwest and west of Jaipur, especially in Samod (45 M/16), Jaitpura (45 M/12) and north of Jaipur (45 M/16) areas.

6.2.1. Recharge Capability of Bed-rocks

Since the bed-rock aquifer characteristics for groundwater storage and transmission depend to a large extent on the rock types and their hydrological properties, the rocks of the different supergroups, described above, have been grouped into four categories on the basis of their groundwater storage and recharge prospects (Table 9). The grouping is based on qualitative and relative secondary porosity (fracture porosity) and transmissibility characters, and therefore, they also represent a measure of their groundwater recharge capability. The four groups are as follows.

Group 1: conglomerate and quartzite with excellent groundwater prospect and recharge capability; Group 2: mica schist and gneisses with very good recharge capability and groundwater prospect; Group 3: fractured marble and calc-gneisses with good groundwater prospect and recharge capability, and Group 4: fractured and weathered granites and migmatites with moderate groundwater prospect and recharge capability.

The extent of these lithologic groups and their main locations in the study area are shown in Table 9. Clearly, Group 4 rocks with moderate groundwater recharge prospect cover the largest area (11,288 km², 59.99% of the study area). Group 2 lithologies (mica schists and gneisses), having very good groundwater recharge prospect, cover 7,075 km² area (37.60% of the study area). Group 1 (conglomerate and quartzite), having excellent groundwater recharge prospect, covers 170 km² area (0.92% of the study area). Group 3 (fractured marble and calc-gneisses) with good groundwater recharge prospect covers 281 km² area (1.49% of the study area).

Since the rock types of recharge-related groups, described above, are deformed and metamorphosed to variable degrees, showing recrystallization features, their primary porosity, particularly of the arenite units, is generally poor. However, because of deformation that produced the shear and fracture zones and the close-spaced joint sets in most parts of the bed-rocks, a secondary porosity has developed in many rock types. This feature controls the specific yield of the individual lithologic units, and has been taken as an index of the recharge capability of the rocks for groundwater flux of the bed-rock aquifers, and also as one of the indicators of possible sites for groundwater recharge. In many cases, the joint sets and wide fracture zones in the bed-rocks extend up to the surface, and cause local topographic depressions and water channels. These provide good sites for bed-rock aquifer recharge.

6.3. Tectonics

Tectonic features play an important role in the infiltration and transmission of the surface water underground through accessible zones of weakness and fractures of the bed-rocks as well as of the weathered zones and soil profiles for aquifer recharge. Many studies have emphasized the importance of such structural features, particularly faults, lineaments and fracture zones in groundwater recharge through hydrological tests (Lattman and Parizek, 1964; Garza, 1986), and through remote sensing studies (Das and Khan, 2001; Kulkarni et. al., 2001; Travaglia, 1998). The control of permeability of faults in recharge and aquifer transmissibility has been demonstrated by Flint (2002), Phillips (2002), and Woolfenden and Koczet (2001).

In order to delineate the tectonic zones that aid surface water infiltration underground, the study area has been mapped, using space imageries, identifying and depicting such tectonic features as extensional gravity faults and strike-slip faults that form major structural elements, and also the major fracture zones, highly jointed areas and tectonic depressions (Figure 17).

The above neotectonic features have been identified and delineated on the basis of tectonic geomorphologic attributes that in the study area are controlled by the reactivation of the older dislocation zones such as BDZ, DDZ, SJDF, SDF etc. (Sinha-Roy, 1986; 2002). A study on neotectonics of the central Aravalli terrain, Rajasthan (Sinha-Roy, 2001a, 2002, 2005) indicated that active tectonics in these dislocation zones has modified the fluvial geomorphology, and produced a number of fault-bound tilted tectonic blocks and pull-apart tectonic basins. These blocks control the magnitude and the directions of regional and local ground slope, while the tectonic basins are sites of thick Quaternary and recent sediments, having good potentials for groundwater storage and recharge.

The extensional faults generally trend north-south in the northern and eastern part in the Mashī sub-basin while they trend almost east-west in the southwestern part in the Khari sub-basin. In the Mashī sub-basin, the length of these fault traces varies from 10 km to about 40 km while in the Khari sub-basin their length varies from 25 km to as high as 60 km. In most cases, the fault traces are rectilinear, but some faults (e.g., the fault located between Moyana (45 J/8) in the north and Rajiyas (45 K/13) in the southeast, and a fault between Kemri (45 K/6) in the south and Dantra (45 K/5) in the north are curvilinear. This feature suggests that most of the extensional faults are vertical or have very steep dips. In contrast, the strike-slip faults are generally rectilinear, and have longer traces and higher frequency than those of the extensional faults. In the Mashī sub-basin, the strike-slip faults trend east-west, and show dextral offsets of streams and hill range ridge-lines, suggesting neotectonic movement along these faults. In the area near the southern water divide of the Mashī sub-basin in Tonk and to its southwest, the strike-slip faults associated with the BDZ show stream offsets ranging between 250 m and 5 km (Sinha-Roy, 2005), indicating a strong neotectonic activity in the region. The length of the strike-slip fault traces in the Mashī sub-basin varies from 35 km to as long as 110 km. Notably, the strike-slip and the extensional faults cross-cut one another at very high angles in the Mashī sub-basin. In the Khari sub-basin, the strike-slip faults trend ENE-WSW, and their trace-lengths vary from 20 km to 60 km.

There are numerous fracture zones of variable widths and lengths in the area whose traces have been marked on the tectonic map (Figure 17). The distribution frequency of these fracture zones is variable. For example, there is a high density of fracture system in the northwestern and southeastern parts of the Khari sub-basin. The former high density region is related to the neotectonic activities along the South Delhi Fault and the Kaliguman Lineament, while the latter appears to be related to the parallel fault system of the Banas Dislocation Zone.

The fracture systems have variable orientation, and are both linear and curvilinear. Generally, the fracture zones that vary in length from nearly 5 km to as long as 60 km are almost parallel to the strike-slip faults in the Mashī sub-basin while they are oblique to the strike-slip faults in the Khari sub-basin. Since in many cases the fracture system controls the location of the tributary streams of all orders and their channel orientation it is inferred

that most of the fracture systems of the area are of neotectonic origin. These have affected in some cases the sediments of the alluvial plains and stabilized sand dunes, and also the older soil profiles, and therefore, these would play a significant role in groundwater recharge under favorable hydrogeological conditions. Similar argument applies to the highly jointed areas identified on the basis of landform characteristics, such as reticulate drainage pattern and gullies. Such areas occur in the eastern part of the Mashhi sub-basin in parts of toposheet numbers 45 N/11, 45 N/14 and 45 N/15, and also in isolated patches in areas to the southeast of the Mashhi sub-basin in toposheet numbers 45 O/2 and 45 O/5.

Two types of tectonic depressions filled with Quaternary and recent sediments have been identified. These are : (i) Pull-apart basins associated with strike-slip faults. These are recognized in Bhojpura (45 N/10), Jobner (45 N/5), south of Naiwala (45 N/9) and Naraina (45 N/1), in Ramsar and 20 km east of Nasirabad, located at the intersection of two strike-slip faults in the northeastern part of the Mashhi basin, and in Phuliya (45 K/13) in the central part of the Khari basin. (ii) Graben structures associated with extensional faults. These are recognized in Rupaheli (45 K/9), Raila (45 K/10) and Ramgarh (45 K/5) areas in the Kharibasin. Type (i) tectonic depressions are more common in the Mashhi sub-basin than in the Khari sub-basin.

6.3.1. Fault and Fracture Zone Intersections

As mentioned above, the tectonic features such as strike-slip faults, extensional gravity faults and fracture zones have variable orientations, and therefore, they cross-cut one another. The frequency distribution of the intersections of these tectonic features depends on the spacing and the spatial variations in the frequency of the individual tectonic feature. Figure 18 shows the frequency distribution of intersections of faults and fracture zones, measured on 50 km² grids. Figure 19 shows the contoured frequency distribution. The following conclusions have been made from this study.

The intersection frequency can be divided into 7 groups with values ranging from 0 to 16 intersections per 50 km². The highest frequency of 16 per 50 km² occurs in a restricted area about 10 km west of Nagar (45 N/13). The intersection frequency range of 13-15 per 50 km² occurs in two areas, namely, Dantra (45 N/1) in the Mashhi sub-basin and in Hirapura (45 J/16) in the Khari sub-basin. These two high frequency areas constitute about 0.7% of the total data points, and represent approximately the same proportion of the study area. These areas of high fault-fracture intersection frequency occur roughly on the Kaliguman Lineament as well as in zones where the strike-slip and extensional faults cross one another.

The major part of the study area belongs to the frequency group of 1-3 intersections per 50 km². Other frequency groups (4-6, 7-9, 10-12 per 50 km²) occur in isolated areas where mostly the intersections are between fracture zones of different orientations. The intersection frequency distribution does not seem to have any relationship with the lithologic variation in the area, rather they are related to the spacing and the location of the fault systems and fracture zones, both being controlled by the major dislocations.

The categories of fault and fracture intersection frequency groups, mentioned above, have been given weights from 0 to 20 for groundwater recharge capability (Table 10). Intersection frequency of more than 16 per 50 km² has been given the highest weight (20), and is considered an excellent factor for recharge while the frequency of 1-2 per 50 km² has been assigned weight of 5, and considered a moderate to poor recharge factor. These weights and impact factors of fault-fracture intersection frequency are used for an integrated approach to delineate the potential recharge zones, described later.

6.3.2. Drainage Density and Gullies in Relation to Fracture Zones

The degree of jointing of the bed-rock, and the pervasiveness and frequency of fault and fracture systems in an area, control the drainage morphometry, including frequency, density and orientation pattern of the drainage network. The drainage density is particularly sensitive to the rock erodibility and to the frequency of fault and fractures of the bed-rock. Higher the fault and fracture frequency per unit area, greater is the drainage density, and consequently, higher and faster is the run-off of the area.. The less permeable rocks that have a low infiltration capacity and less resistant lithology will develop a drainage system with high drainage density (Macka, 2001; Carston, 1963). Based on these arguments it has been suggested that areas having high to moderate drainage density do not generally encourage ‘natural’ recharge of groundwater (Das and Khan, 2001). However, since the high drainage density areas are sites of high concentration of fracture, fault and joint systems, and their intersections, these areas would provide suitable sites for ‘artificial’ groundwater recharge.

The drainage density (*Dd*) of the stream network of the study area shows a wide variation due to the variable extent of rock fracturing and variations in the lithology. A major part of the area has *Dd* values < 0.35 km/km² while the maximum *Dd* is > 0.60 km/km² (Figure 20). Within this range of *Dd* values 5 categories have been made, and their impact on artificial groundwater recharge capability of the zones has been categorised as poor (*Dd*: 0.35 – 0.40 km/km²), excellent (*Dd*: 0.56 – >0.60 km/km²), moderate (*Dd*: 0.41 – 0.45 km/km²), good (*Dd*: 0.46 – 0.50 km/km²) and very good (*Dd*: 0.51 – 0.55 km/km²). Areas having high *Dd* values are located in Dantra (45 N/1) – Dudu (45 N/2) region in the Mashī sub-basin, and in Bagsuri (45 J/12) – Bhinai (45 J/16) region in the Khari sub-basin.

The *Dd* values match well with the intersection frequency of faults and fractures (Figure 18), such that the Dantra – Dudu region has the intersection values between 7-13 intersections per 50 km² and the Bagsuri – Bhinai region shows an intersection frequency in the range of 3-15. The highest intersection frequency of 16, located at 10 km west of Nagar (45 N/13) and 10 km northeast of Tihari (45 J/15), shows *Dd* values < 0.35 km/km². This feature suggests that high density of intersection of faults and fracture zones does not always produce high drainage density because of lithological variations, particularly of the resistant rock types which in the present case are the granitoids of the Sandmata Complex.

Drainage density range of 0.46 – 0.50 km/km² offering a good impact factor for recharge is the most frequent category in the area located in Salariya (45 K/15), Raila (45 K/10) and Gulabpura – Agucha (45 K/9) areas in the Khari sub-basin. In the Mashī sub-basin this range of *Dd* values occurs in areas around Kishangarh (45 J/14) – Nagar (45

N/13), Manoharpura (45 N/4) – Morla (45 N/3) and Bansthali (45 N/15) – Bhankrota (45 N/10) regions.

Geomorphologic studies have shown that in some parts of the study area extensive gullies have developed (Figure 2). These areas are located in the eastern part of the Khari sub-basin near the Banas river, and in the eastern and northeastern parts of the Mashī sub-basin (Figure 21). The total gullied area in the Khari-Mashī drainage basin is estimated at 203.65 km² (Table 11).

Although the exact mechanism of gully formation is controversial, many studies have shown that density, orientation and geometry of gullies are controlled by the joint and fracture systems of the bed-rock. This means that higher the joints and fractures in the bed-rock, greater is the gully frequency in the overburden. Based on this assumption, highly jointed areas have been demarcated on the drainage density map (Figure 20). Except for a small part in the Mashī sub-basin where joint-controlled gully system overlaps the moderate drainage density areas, all other highly jointed areas, deciphered from gully frequency, do not coincide with areas showing drainage density > 0.35 km/km². This would mean that the soil profile and the sub-soil sediments that have been gullied do not control the development of the stream network of the area, and hence, they have little or no relationship with the drainage density of the drainage system.

6.4. Soils and Sub-soil Sediments

It has been emphasized by many workers that apart from factors such as climate and hydrology, land-cover and land-use are also critical factors to consider when assessing the availability of groundwater in any area of interest because groundwater recharge is directly influenced by these factors. The availability of groundwater or sustainable yield of an aquifer can be evaluated through estimating recharge (Ash and Malmquist, 2004). One of the principal components of land-cover is the soils whose extent, types, drainage and hydraulic characters control, to a large degree the recharge potential of a site.

The map showing the distribution of the soil types has been prepared for the study area (Figure 22) on the basis of data extracted and modified from the Soil Resource Map of Rajasthan (Shyampura and Sehgal, 1995) and the Resource Atlas of Rajasthan (1994). 219 soil and sub-soil sediment samples have been collected from different geomorphic units. These have been analysed for hydraulic conductivity and textures that are two important characteristics of the soils and the sub-soil sediments for assessment of recharge potentials.

As already discussed and shown in Figure 2, a number of geomorphic units (nos. 13) has been recognized and mapped in the study area. These units have been grouped into 7 geomorphic terrains, and the contents of their soil types are shown in Figure 22. These terrains are hilly terrain, intermontane valley, gently sloping land with monadnocks, pediment, river valley, dune field and saline lake margin. The soil types have been classified mainly on the basis of the thickness (shallow to very deep), the texture (sandy, loamy, clayey), the calcareousness, and the salinity and sodicity (Table 12). The distribution of the soil types in relation to geomorphology indicates the following features.

The hilly terrain, located mostly along the southeastern fringe of the Aravalli hill range of the highland in the northwestern part of the area in Bhim – Nasirabad –

Kishangarh tract, and also the isolated hill ranges of the Mashī sub-basin, contain shallow loamy and sandy skeletal soils with rock outcrops. The intermontane valleys, especially in the Aravalli hill range, contain deep to moderately shallow calcareous coarse loamy soil, and sub-soil sediments, at places saline.

A large segment of the study area in the central part contains moderate to deep, fine to coarse loamy soil, at places clayey, sodic and saline in the gently sloping midland region, comprising the alluvial plain with monadnocks. At many places, the soil horizon has developed on sub-soil sediments composed of partially oxidized coarse to medium grained alluvial sands or stabilized dune sands.

The foothills of the Aravalli hill range, extending from Devgarh (45G/14) in the southwest through Nasirabad (45J/11) to Chausla (45J/14), contains a well-developed pediment, at places dissected by the 1st and 2nd order stream network. Dissected pediment also occurs in the northeastern corner of the Mashī sub-basin to the east of Samod (45 M/16) and north of Jaipur (45 N/13). The pediment contains shallow to moderately deep calcareous fine to coarse loamy and sandy soil. The soil profiles often show pebble layers and nodular to massive groundwater calcretes beneath loamy soil, especially in the pediment regions. The river valleys contain deep calcareous sandy soil on top of the sub-soil fluvial sediments that are particularly well-developed in the Banas river valley in the southeast.

The northeastern part of the Mashī sub-basin is characterized by both stabilized old dunes and recent dune fields. The western limit of this dune field extends from Naraina (45 N/1) in the northwest through Mozamabad (45 N/6) to Bansthali (45 N/15) in the southeast. The soil types developed in this terrain are deep calcareous sandy soil, moderately saline at places and very deep coarse loamy soil. In the southern part of the Sambhar Lake (45 N/1), located in the northwestern part of the Mashī sub-basin, deep sandy strongly saline soil has developed.

6.4.1. Soil-rock Interaction and Recharge in Fractured Bed-rocks

Groundwater recharge is an important but often a highly uncertain boundary condition when modeling groundwater flow in bed-rock aquifer systems that underlie soils and sub-soil sediments. The so-called inter-aquifer recharge, such as that from soil/sediment aquifer into the underlying bed-rock, is much more difficult to quantify (Bockgard and Niemi, 2003). A large proportion of water infiltrating at the soil or sediment surfaces may not become recharge at the water table. Furthermore, often only a small part of water that reaches the water table will eventually enter the underlying bed-rock aquifer where the interconnectivity is poor. Studies on soil-rock and sub-soil-sediment-rock interactions by Bockgard and Niemi (2003) have shown that the recharge flux into the rock domain below the soil and sub-soil sediments is concentrated into some distinct high conductivity flow paths. In cases with large drainage rates unsaturated zones can develop even below the water table. This happens in areas of high conductivity contrasts.

The above features would suggest that the recharge capability of the soils and the sub-soil sediments, discussed below, may not always aid recharge of the deeper bed-rock

aquifers. However, the following areas contain soil types and sub-soil sediments having good to excellent recharge capability (capability score 50-80, for details see below), and also highly jointed bed-rocks (Figure 17) and high intersection frequencies of faults and fractures (Figure 18), implying high hydraulic conductivity of the bed-rocks.

(i) The area 10 km to the northeast and east of Tihari (45 N/13) where the frequency of fault and fracture intersections in the bed-rock ranges from 4 to >16 per 50 km², (ii) west of Naraina (45 N/1) in the Mashī sub-basin where the frequency of fault and fracture intersections ranges from 4 to 15 per 50 km² and soil recharge capability score is 55, (iii) Banasthali (45 N/15) – Bhojpura (45 N/10) region in the Mashī sub-basin where the bed-rock is highly jointed and fractured, and the soil recharge capability score is 55, (iv) Rajawas area (45 M/16), 10 km north of Jaipur which contains highly fractured bed-rock zone having soil recharge capability score of 60.

6.4.2. Recharge Capability of Soils and Sub-soil Sediments

In order to determine the relative recharge capabilities of the different land-cover materials of the 7 categories of landform terrains, on the basis of parameters such as thickness, texture, calcareousness, salinity and sodicity of the soils and the sub-soil sediments, weights from 0 to 20 have been assigned to the specific characters of these parameters (Table 12). For example, for thickness parameter, 0 weight has been given to very deep soil horizon and 20 weight to shallow horizon. Deep to moderately shallow horizons have been given 5 to 15 weights. Similarly, for texture, clayey soil has been given 0 weight while 20 weight has been assigned to sandy soil, and for fine loamy, loamy and coarse loamy soils weights of 5, 10 and 15, respectively, have been given. Calcareous soil has been given 0 weight and non-calcareous soil, 20, because carbonate cement in soil and sediment matrix would reduce the porosity and the hydraulic conductivity. Since the water quality for recharge will be affected by soil salinity and sodicity, highly saline and sodic soils have been given 0 weight while moderately saline and sodic, and non-saline and non-sodic soils have been assigned weights of 10 and 20, respectively.

Based on the impact weights assigned to different characters of the identified soil parameters (Table 12), groundwater recharge capability score for the soil types of the individual geomorphic terrain has been estimated (Table 13). The scores have been deduced by adding the weights of the individual soil character of a particular soil type. For example, in the hilly terrain shallow (weight: 20), loamy (weight: 10), non-calcareous (weight: 20) and non-saline (weight: 20) soil will have a score of 70. This method of assigning impact scores to different soils and sub-soil sediments has been followed for all the soils and sub-soil sediments, and their scores are given in Table 13. The following inferences are drawn from the data on recharge impact scores of the soils and the sub-soil sediments.

The highest scores (80 – 70) are shown by shallow, sandy, non-calcareous, non-saline soils developed in the hilly terrain, particularly in the Aravalli hill range and its pediment. The score for the soils and sub-soil sediments of the gently sloping land of the alluvial plains with monadnocks, a terrain that covers the maximum area of the Khari-

Mashi drainage basin, ranges from 20 to 60. The land-cover material of the midland pediment generally has a high impact score, ranging from 60 to 75 with a few soil types having score between 30 and 50. Other terrains such as the intermontane valleys, dune fields and river valleys have scores ranging from 35 to 60.

The impact score values suggest that for groundwater recharge, the hilly terrain covered by shallow sandy to loamy, non-calcareous, non-saline soil, and the pediments covered by very shallow, coarse loamy, non-calcareous, non-saline soil and sub-soil sediments would provide favourable sites for recharge. In the gently sloping landforms covered by moderately shallow, fine loamy, non-calcareous, non-saline land-cover materials would also be suitable for this purpose.

In order to find out the spatial distribution pattern of groundwater recharge impact scores of land-cover materials, the scores, estimated as per the method described above, has been superimposed on the soil map (Figure 23). The following are the relevant inferences.

In the northwestern segment of the Khari sub-basin, in areas west of Bhim (45 K/2) and 10 km east of Devgarh (45 G/14), the pediment and the hilly terrain show high impact scores of 75 – 80. Good to very good recharge capability with impact scores between 55 and 70 obtains principally in three areas, namely, Babana (45 K/2), Asind (45 K/6) and Ramgarh (45 K/5) in the Khari sub-basin. In the Mashi sub-basin similar good to very good recharge prospects occur in Botunda (45 O/5) and Golhar (45 O/9) areas, and also in the dune fields. The major part of the study area, dominated by the alluvial plain, has poor to moderate recharge prospect in terms of impact scores (20 – 45) of land-cover materials.

6.4.3. Texture of Soils and Sub-soil Sediments

It has been already mentioned that the various geomorphic units, developed in the study area, contain different types of soils and sub-soil sediments. The physical properties, especially the texture of the land-cover materials of these units, are important for assessing their capability for groundwater recharge. In order to analyze the textures of soils and sub-soil sediments of different geomorphic units, the area has been systematically sampled (nos. 219) for the land-cover materials. The locations of the sites of soil and sub-soil sediment samples are shown in Figures 24 and 25, respectively.

Methodology of Texture Analysis : The samples collected from the field were well-dried in the laboratory, and roots and other organic matter removed. After cone and quartering, 250 to 300 grams of material was taken for sieve analysis (BSS Standard) by which percentage of fractions in the range of >2 mm (grit), 2 to 1 mm (very coarse sand), 1 to 0.5 mm (coarse sand), 0.5 to 0.25 mm (medium sand), 0.25 to 0.10 mm (fine sand), 0.10 to 0.06 mm (very fine sand), <0.06 mm (silt + clay) was determined for each sample.

Texture of Land-cover Material of Geomorphic Units : The results of the grain size analyses of the soil and the sub-soil sediments of the different geomorphic units, such as pediment, dissected alluvial fan, intermontane valley-fill, flood plain, palaeochannel-fill, alluvial plain, alluvial plain with sand cover, gully area, and exhumed calcrete are given in

Tables 14 and 15, respectively. The textural characteristics of the land-cover materials of the above geomorphic units are as follows.

The frequency distribution of each grain-size fraction for the soils and sub-soil sediment of the different geomorphic units is shown in Figures 26 and 27, respectively. All the size fractions from grit to clay are represented in the soil and the sub-soil sediment of the pediment. The size distribution is skewed towards the middle fraction e.g. 1 – 0.5 mm (coarse sand) to 0.25 – 0.10 mm (fine sand). In different alluvial fan deposits, the grain size of the soils has almost equal distribution of all the size grades, while in the sub-soil sediment, the size range of 1 – 0.5 mm (coarse sand) to 0.25 – 0.1 mm (fine sand) is the most dominant. In the alluvial plain, the most extensive geomorphic unit, the grain size of the soil and the sub soil sediment has almost similar distribution pattern with almost equal percentage of all the size grades except for 0.25 – 0.10 mm (fine sand) which has the highest percentage. In the alluvial plain with dune sand cover, where the soil is poorly developed; similar size distribution pattern is recognized. Within the gullied areas, developed in some parts of the alluvial plain, 0.50 – 0.25 mm (medium sand) is the dominant fraction together with a significant concentration of 0.25 – 0.10 mm (fine sand) fraction. On the other hand, in the sub-soil sediment of the gullied area, the medium grained sand fraction (0.50 – 0.25 mm) is less dominant than the coarse sand (1 – 0.5 mm) and very fine (0.10 to 0.06 mm) sand. In the intermontane valley-fill sediments 1 – 0.5 mm (coarse sand) and 0.25 – 0.10 mm (fine sand) sizes are the two dominant fractions, a situation similar to the sediments of the flood plain.

6.4.3.1. Textural Variations

From granulometric analysis of 219 samples the grain size frequency distribution of the soil and the sub-soil sediment has been determined for the different geomorphic units. As the above discussion indicates, the soils and the sub-soil sediments, overlying the shallow aquifers, contain variable proportions of grit and coarse sand (>2 mm to 0.5 mm) and silt and clay (0.1 mm to 0.06 mm).

Generally, the soils of the pediment and the alluvial plains contain higher percentage of coarse fractions than those of the dissected alluvial fans. Similarly, the sub-soil sediments of the pediment and the alluvial plain contain higher percentage of coarse fraction than those of the intermontane valley-fill, palaeochannel, flood plain and dissected alluvial fan. Flood plain, alluvial plain and intermontane valley-fill deposits contain appreciable quantities of fine fractions.

Since the content of the coarse fraction (>2 mm – 0.5 mm) is an important parameter for transmission of recharge water in the shallow aquifer the spatial distribution of the percentage of this fraction in the land-cover materials has been studied. The contour diagrams of the frequency of this size fraction for the soils and the sub-soil sediments are given in Figures 28 and 29, respectively. The following features are noted.

Generally, the percentage of grit and coarse to medium grained sands in the soil varies between 20% and 80%. Soils containing a high content (> 60%) of the coarse

fraction occur in tracts between Bhinai and Tihari, west of Shahpura, east of Malpura, and southeast of Devgarh. In the case of sub-soil sediments, the content of the coarse fraction also shows a spatial variation. High content (> 60%) is shown by the sediments occurring to the west of Shahpura, southwest and northwest of Kekri, north of Malpura and north of Devgarh.

There is a difference in the textural characteristics of the soils and the subjacent sediments in that generally the coarse texture of the sediments is not reflected in the overlying soil. This feature is indicated by the variable distribution pattern of the size fraction frequency for the soils and the sub-soil sediments (Figs. 28, 29). This would suggest that the soil profile which is generally poorly developed is modified, dissected and stripped to variable degrees, due probably to extensive aeolian activity and denudation processes.

6.4.4. Hydraulic Conductivity

Hydraulic conductivity is an important for determining the internal drainage of the land-cover materials for recharge of the subjacent aquifer systems. For the study of groundwater recharge, hydraulic conductivity of these materials is, therefore, an important control parameter. 219 samples of the soil and the sub-soil sediments of the different geomorphic units have been studied for their hydraulic conductivity. The location and the hydraulic conductivity values of the studied soil samples and that of the sub-soil sediment samples are shown in Figures 24 and 55, respectively.

6.4.4.1. Methodology

The hydraulic conductivity of the soil and subsoil sediment samples has been determined by Constant Head method as outlined in Baruah and Barthakur (1997). In this method, well-dried sample cleaned of roots and other organic matter was taken in a cylindrical steel container having a perforated bottom and open top, fabricated for these measurements. A filter paper disc was put at the bottom of the cylinder, and the sample in the cylinder was saturated with water. A constant head of water was then maintained over the sample in the container. At equilibrium, the quantity of water 'Q' that flowed out of the sample of length 'L' and cross-sectional area 'A' for a given hydraulic head drop of 'Δh' is measured for a given time 't'.

The hydraulic conductivity 'K' was then calculated using the Darcy's equation as follows:

$$\frac{Q}{(A.t)} = -K \left[\frac{\Delta h}{L} \right]$$

$$\text{Or} \quad K = \frac{Q.L}{t. \Delta h.A}$$

The fabricated cylindrical steel container measured 11.2 cm in length (L) and 11.56 cm in diameter, which gives the cross-sectional area (A) of the cylinder at 36.29 cm². The air-dried sample was uniformly packed by tapping the cylinder for at least 20 times on a wooden block to a height of 2.5 to 3 cm. The cylinder was filled with water and a constant head was maintained while the discharge water was collected in a measuring cylinder for a given amount of time (30 seconds to 1 minute). Two to three replicate measurements have been made for each sample and the average discharge water volume recorded.

6.4.4.2. Hydraulic Conductivity of Soils and Sub-soil Sediments of Geomorphic Units

The results of the hydraulic conductivity (K) measurement of the soils and the sub-soil sediments of the different geomorphic units are given in Tables 16 and 17, respectively. The values of K for the different geomorphic units are variable. Moreover, K values for the soils and the sub-soil sediments are also different for each geomorphic unit. The important aspects of hydraulic conductivity variations are as follows.

The K values of the soils of the pediment are generally higher than those of the sub-soil sediments, reaching up to 35.42 cm/hr in an area 25 km southwest of Chandsen. The minimum K value in the pediment unit for the soils (8.63 cm/hr), near Ajmer, is, however, lower than that (12.13 cm/hr), 1 km east of Ambapura, of the sub-soil sediment. The situation for the dissected alluvial fan is opposite to that for the pediment in that the sub-soil sediments of the alluvial fan areas show the highest conductivity of 73.18 cm/hr in Ruppura area while the soils show the highest K value of 24.26 cm/hr in Kanakheri area.

The K values for both the soils and the sub-soil sediments of the intermontane valleys are generally lower than those for the pediment and dissected alluvial fans. This is because of the finer grain size and the higher clay contents of the intermontane valley-fill sediments. The K values for the flood plain soils and sub-soil sediments show a wide range of variation reaching up to 50 to 60 cm/hr, particularly for the sub-soil sediments. Similarly, the soils and sub-soil sediments of the alluvial plain, the extensive geomorphic unit of the study area, show a large variation in K values, reaching up to 25 to 30 cm/hr. Generally, the higher K values are shown by the sub-soil sediments.

6.4.4.3. Relation of Hydraulic Conductivity and Texture of Soil and Sub-soil Sediment

It is known that vertical hydraulic conductivity (K) of the transmitting medium is controlled among other factors, by the grain-size of the medium. Finer the grain-size, particularly in the clay and silt sizes, lesser the hydraulic conductivity and vice-versa. In order to investigate the relationship between hydraulic conductivity and the grain-size, the respective data are analyzed for their interrelations. The relations are shown in Figures 30 a, b, c, d, and e. These figures show the relation of K and the percentage of two grain-size fractions, namely, 0.1 – <0.06 mm that represents clay + silt + very fine sand (finer

fraction) and 0.50 to >2 mm that represents grit + very coarse to coarse sand (coarser fraction) for the geomorphic units such as the pediment (Figure 30 a), the dissected alluvial fan (Figure 30 b), the intermontane valley-fill (Figure 30 c), the flood plain (Figure 30 d) and the alluvial plain (Figure 30 e).

Pediment : The combined data of the soils and the sub-soil sediments of the pediment indicate that, as expected, K is negatively correlated with the finer grain-size fractions (0.1 to <0.06 mm) while a general positive correlation between them can be recognized for the coarser grain-size fraction (0.50 to >2 mm). Notably, the finer fraction for the soil and the sub-soil sediment is less than 30%, while the majority of samples analyzed contain more than 50% of the coarser grain material. Therefore, the pediment region is likely to form a moderate to good recharge zone.

Dissected Alluvial Fan : The alluvial fans, developed at the foothill part of the Aravalli hill range in the pediment region, generally spread over the pediment surface, and are dissected by the present-day drainage system, being overlapped by the alluvial plain. In the finer grain-size fraction which is less than 20%, two clusters can be recognized with respect to K values. In one, the K values range from 8 to 20 cm/hr and in the other, from 15 to 30 cm/hr. Independently, these two clusters show a negative correlation between K and the percentage of the finer size fraction. Similar two-fold data cluster is also recognizable for the coarser size fraction which shows a positive correlation between K and the percentage of the size fraction. The content of coarser material of the soils and the sub-soil sediments of this geomorphic unit generally varies between 40% and 80 % which means that this geomorphic unit can also serve as a good recharge zone.

Intermontane Valley-Fill : In the K and the grain-size relationship diagram, two clusters in both finer and coarser size fractions can be recognized. The finer fraction comprises less than 25% of the intermontane valley-fill material while the coarser fraction makes about 30% to 75%. The percentage of the finer fraction is poorly negatively correlated with K, while the coarser fraction shows a weak positive correlation with K. The variation of K values in samples having similar contents of coarse and finer size fractions within this geomorphic unit as well as in others is likely to be due to variable porosity.

Flood Plain : The flood plain deposits contain less than 30% finer size material and a high content of coarser size material, between 30% and 75%. This fact would make this geomorphic unit a very good recharge zone. The percentage of the finer fraction shows a very strong negative correlation with the K values while three clusters of the coarser material show a weak positive correlation with K.

Alluvial Plain : The extensive alluvial plain contains a wide range of size fractionated soils and sub-soil sediments. The content of the finer size material is generally below 40% with the maximum number of samples having 8% to 20% finer size fraction, while the content of the coarser size material ranges between 3% and 88% with a maximum number of samples having 50% to 75% coarser size fraction.. These size fractions also show a wide range of K values from 0 to 30 cm/hr. These features suggest that the recharge capability of the soils and the sub-soil sediments of the alluvial plain is area-specific. The

favorable recharge zones need to be located on this geomorphic unit at sites where the soils and the sub-soil sediments contain between 50% and 80% coarser material and the K values for the material is appreciably high. Figure 30e shows that K is negatively correlated with the percentage of the finer size fraction while the positive correlation between K and the percentage of the coarser size fraction is not straightforward.

6.4.4.4. Regional Variation of Hydraulic Conductivity

In order to understand the nature of variation of the vertical hydraulic conductivity of the soils and the sub-soil sediments on a regional scale, the hydraulic conductivity data for the samples collected from the different geomorphic units, described above, have been contoured. Figures 31 and 32 show the contoured K values of the soils and the sub-soil sediments, respectively. The regional distribution pattern of the K values for these two types of land-cover materials is almost similar except for some variations in the location of the higher K values. The latter feature is evident from the hachured diagram (Figures 33 and 34), prepared from the contoured K values. Figures 33 and 34 also show K-based recharge capability of the soils and the sub-soil sediments, respectively. From the study of the regional distribution pattern of the K values, the following conclusions are made.

The highest K values between 30 and 40 cm/hr for the soils are located to the east and northeast of Malpura, and the values between 20 and 25 cm/hr are located to the east of Devgarh and southeast of Asind. The lowest K values in the soils are represented in areas northwest of Shahpura, north of Phalamoda and northeast of Masuda.

The highest K values between 30 and 40 cm/hr for the sub-soil sediments are located to the southeast of Fatehgarh, west of Phuliya, west of Asind, south of Ramsar, southeast of Patan, east of Bisundhi and at Pachewar. Other areas with high values of K between 20 and 25 cm/hr are located at a number of places to the south of Mundota, south of Jobner, southeast of Kishangarh, south of Bandanwara, and east of Malpura. The sub-soil sediments near Devgarh, south of Patan, Shahpura, south of Bhinai, Jhirana, and south of Dudu show the lowest K values less than 5 cm/hr.

In general, the sub-soil sediments of most of the areas show higher hydraulic conductivity than that of the overlying soils. For example, the large stretch of the area covered with soils having low conductivity (0.5 to 10 cm/hr) in Bhinai, Dudu, Masuda and Malpura areas contain sub-soil sediments that have conductivity values in isolated areas ranging between >30 to 10-20 cm/hr. Moreover, the conductivity maxima (>30 cm/hr) for the sub-soil sediments also occur in the east of Devgarh, west of Asind, and southwest of Masuda areas where the conductivity of the overlying soils varies between 0.5 to 10 cm/hr. The regional variation of the K values and K-based recharge capability of the soils and the sub-soil sediments are used, along with other parameters, for recharge capability assessment of the study area.

6.5. Groundwater Table

In order to assess the scope and the importance of different geologic, geomorphologic, tectonic and soil/sub-soil sediment characteristics for groundwater recharge, it is necessary to understand the groundwater table geometry in terms of the spatial variation of the depth-to-water table and the water table configuration. For this purpose, water table depth measurements were made in 249 dug wells distributed over the entire area, and located in different geologic, geomorphologic and land-cover units. The measurement of the water table was carried out in two phases, namely, during January-February, 2005, representing the pre-monsoon period, and during September-October, 2005, representing the post-monsoon period.

6.5.1. Groundwater Table Geometry

Depth-to-Water Table : Based on the water level measurements in the dug wells for the pre-monsoon and the post-monsoon periods, contour maps showing the depth-to-water table for these periods have been prepared (Figures 35 and 36). During the pre-monsoon period, the depth-to-water table of the shallow aquifer varies from 3 m to as deep as 70 m whereas during the post-monsoon period the depth varies from 1 m to 65 m. The deepest water levels (65 to 70 m) during both these periods were recorded in areas to the north of Jaipur in the vicinity of Samod and Mundota, and also in Malpura area where the depth varies from 25 to 35 m. The geometry of the water table for both pre-and post-monsoon periods is almost similar except for some minor differences in the northwestern boundary of the drainage basin. The latter feature is due to high degree of recharge in the pediment zone at the water divide of the Aravalli hill range.

In general, the depth-to-water table decreases systematically from the northern and western boundaries of the drainage basin toward the central and southeastern parts of the basin. In the north, the depth decreases from 65 to 70 m in Samod area to about 10 m in Phagi area in a southerly direction. Similarly, the depth decreases from nearly 15 to 25 m in Devgarh-Asind area in the northwest to nearly 5 m near Shahpura in an easterly direction. Clearly, the direction of decrease of water table depth is toward the Banas river which forms a part of the eastern margin of the drainage basin. Moreover, the topographic elevation also decreases towards the Banas river. The greater depth in Malpura region is due to the hilly tract in Malpura-Toda Raisingh area.

Water Table Form : Based on the water level measurement data, water table contour maps, showing the water table form surface geometry, have been prepared for the pre-and post-monsoon periods (Figures 37 and 38). These maps have been used to decipher the groundwater flow directions, discussed later. The following features are noted from the water table form surface maps.

The water table shows depressions (troughs) and elevations (ridges) because of differential aquifer permeability and conductivity characteristics, and due to the presence of both conductive (conduit) and non-conductive (barrier) faults and fracture zones. Several ridges on the water table occur, for example, in stretches between Bhinai and Kekri and

between Tihari and Dhasuk areas. These ridges persist in the water table configurations of both pre-and post-monsoon periods.. Linear depressions in the water table both in pre- and post-monsoon periods occur in stretches between west of Masuda – Phuliya and between north of Dudu and Khera areas. These ridges and linear depressions are related to major faults. For example, Bhinai – Kekri ridge is caused by a cluster of strike-slip faults whereas Tihari – Dhasuk ridge is caused by a prominent strike-slip fault. The water table depressions are linked with major extensional faults.

Although most of the ridges and linear depressions in the water table form-surface persist both in pre-and post-monsoon periods, the water table form exhibits a few domes and basins exclusively for these periods. For example, the pre-monsoon trough with a drop of 20 m in depth-to-water table occurs about 25 km east of Kekri, a feature that does not persist in the post-monsoon period. The post-monsoon water table form contains a few domes, for example, in areas 15 km north of Masuda, the depth-to-water table decreases by 20 m, and 10 km southwest of Masuda, the decrease is 40 m.

The regional pattern of the water table contour on the basis of 1996-98 data have been reported by the Irrigation Department, Govt. of Rajasthan (1998) (Figure 39). Although this map is generalized, the broad features of linear depressions and ridges in water table, described above, are recognizable in 10-year old water table configuration. This feature would suggest a near stable and persistent control of geologic, geomorphic and tectonic features on the water table geometry of the study area.

6.5.2. Water Table Fluctuation in Pre-and Post-monsoon Periods

The depth-to-water table measured at different locations during the pre-monsoon period (January-February, 2005) and the post-monsoon period (September-October, 2005) are shown in Figures 40 and 41, respectively.

A comparison of the pre-and post-monsoon water table data indicates that, in general, the water table has gone up in specific areas to a maximum of 13 m in the post-monsoon period. Figure 42 shows the areas of rise of the water table, grouped into two categories, namely, areas showing a rise between 0.5 m to 5 m, and areas showing a rise between 5 m to 13 m. Areas showing a rise between 5 m and 3 m occur in large tracts in Devgarh region, Patan-Gulabpura area and north of Masuda area. Apart from these major areas, sporadic rise in the water table between 5 m and 13 m is recorded in Asind, southeast of Bhinai, Ramsar-south Arain, southeast of Dudu and south-southwest of Samod. Areas showing moderate rise of the water table, between 0.5 m to 5 m, are located in Thana-Amdala tract, Patan-Asind and Nimbahera regions, Bhinai-Nandsi stretch, a large tract in Nasirabad, Kishangarh, Tihari and Ramsar areas, Naraina-Duau tract, Jobner-Bagru tract, Phagi-Kadera tract, and Kekri-Malpura-Toda Raisingh areas.

The post-monsoon rise of the water table seems to be related to the following features. The maximum rise in the water table is noticed at the northwestern margin of the study area. This margin represents the water divide constituted by the Aravalli hill range

and its pediment. This signifies that the pediment region of the Aravalli hill range forms a good recharge zone for the shallow aquifer.

In contrast, the eastern and southwestern water divides of the drainage basin that do not have appreciable relief, are poorly dissected, and do not contribute to any significant post-monsoon rise of the water table, because this region is composed of thick alluvium and consolidated old dune material with frequent impermeable calcrete and clay horizons at shallow levels.

A part of the eastern margin of the basin is drained by the Banas river. A comparison of the water table depth data for the pre-and post-monsoon periods indicates that there has been a marginal rise (1 m to 2 m) in the water table in post-monsoon period in the vicinity of the Banas river, particularly in its old flood plain areas. This suggests that the Banas river is an effluent river in this region, and that appropriate water management of the river can contribute to the recharge of the shallow aquifers of the eastern part of the Khari-Mashi drainage basin.

The water table fluctuations appear to have a relation with the tectonic features, described earlier in the report. Detailed analysis of the neotectonic attributes, including the fault and fracture systems and their intersections, indicates the presence of a number of extensional and strike-slip faults in the study area. Insofar as the contribution of the faults to groundwater recharge is concerned, the data indicate that several faults and some segments of one large fault may form conduits for the surface water contributing to groundwater recharge. For example, the extensional fault (50 km long), extending from Habaspura to Phagi through Dudu, is located in the region that shows a significant rise in the water table in the post-monsoon period, whereas except for the northern segment of a large extensional fault (65 km long), running from Masuda-Kotari to Phuliya, is not associated with any significant rise in the water table for the same period.. Another significant extensional fault (55 km long), running from north-northwest of Toda Raisingh through east of Malpura to Phagi, occurs at the eastern fringe of a large area where the water table has risen by 0.5 m to 5 m in the post-monsoon period. If this fault acted as a conduit for groundwater recharge and caused the water table to rise only on one side (west) of the fault trace the reason for the asymmetry in recharge and water table rise is not known. It is likely to be related to the complex aquifer geometry in relation to the fault system.

The northeastern part of the drainage basin contains a number of strike-slip faults (Figure 42) which in part are located in areas showing a general rise in the post-monsoon water table, such as in Bagru, Jobner, Mozamabad, north of Dudu, north of Dhasuk, etc. Similar relationship also exists in the case of the strike-slip faults, located in Patan-Gulabpura, Asind-Phalamoda, and Bhinai-Nandsi areas. It seems that the strike-slip faults have played a more important role as conduits for surface water infiltration for groundwater recharge than the extensional faults. One of the reasons for this feature is the occurrence of pull-apart extension zones, graben structures and tectonic depressions in strike-slip fault zones.

The intersections of the major faults have played an important role in the post-monsoon rise of the water table. For example, the intersection zone of the fault running from Masuda to Phuliya and the fault running from north of Phalamoda to the northeast of Agucha and beyond shows post-monsoon rise of the water table by 1.5 m. Intersection zone of an extensional fault (65 km long), running from north of Masuda to Fatehgarh, with a set of strike-slip faults, running from north of Bhinai to Bisundhi and west of Ramsar to south of Kekri, shows the water table rise of 7 m and 2.5 m, respectively.

The study of the intersections of faults and fractures in the area indicated that the frequency of such intersections per 50 km² varies from 0 to 16. The highest frequency of 16 per 50 km² occurs in a restricted area about 10 km east of Nagar (45 N/13). This area records the post-monsoon rise of the water table of 3 m. The intersection frequency range of 13-15 per 50 km² occurs in two areas, namely, Dantra (45 N/1) and Hirapura (45 J/16) areas that show the post-monsoon rise of the water table of 0.5 m and 7 m, respectively. In Devgarh area, the rise of the water table by 7 to 9 m is located in an area showing 10-12 intersections per 50 km². In many cases, however, the areas recording significant post-monsoon rise of the water table do not correspond to the areas of high density of fault and fracture intersections. This feature would suggest that although intersection zones of faults and fractures are important conduits for groundwater recharge in some areas, other geologic and geomorphologic features contribute to the water table rise in post-monsoon period in other areas.

There is a good correspondence between the areas recording the rise in the water table during post-monsoon period and the areas of highly jointed rocks and tectonic depressions. For example, the rise of the order of 5 m to 13 m of the water table in Patan-Gulabpura area has occurred in a tectonic depression between a strike-slip fault in the southwest and an extensional fault in the northeast. Similarly, the rise of 5 m to 13 m in Phalamoda-Nimbahera-Asind areas has taken place in an isolated tectonic depressions associated with both extensional and strike-slip faults. In Jobner-Bagru stretch the area of water table rise (0.5-5 m) in the post-monsoon period corresponds to isolated zones of tectonic depressions in an area associated with intersecting strike-slip and extensional faults. The highly jointed area in Phagi-Kadera area corresponds with the zone of rise of the water table in the post- monsoon period.

6.5.3. Relations of Water Table, Topography and Geomorphology

The configuration of the water table is dependent on and controlled by many factors of which topography, geomorphology and tectonic features are important. In order to investigate these relationships, five profiles across the Khari-Mashi drainage basin have been chosen (Figure 42, inset). Figure 42 shows the relations of topography, water table, geomorphologic units, and major faults and fracture zones on each of these profiles. The following conclusions are made from these relations.

Although the water table configuration, in general, mimics the topography profile, there is a variation in the depth-to-water table among the profiles and also within the single profile. For example, in Profile-1 in the Mashi sub-basin in the northeast, the topography

slopes gently from northwest to southeast with the water table occurring at an appreciably lower depth (45 m) at the higher topographic level, but it is relatively shallow (5 to 20 m) at the lower topographic level. No such notable variation in the depth-to-water table in relation to topography is encountered in other profiles.

Figure 43 shows the location and the extent of the different geomorphic units along the profiles. Eleven geomorphic units are encountered along the studied profiles. The groundwater levels measured in the wells along the profile lines indicate variations in the depth-to-water table within different geomorphic units as well as within a single geomorphic unit in one particular profile. Based on the depth-to-water table along these profiles, five depth classes are recognized. These are: Class-I = 0-10 m (very shallow), Class-II = 10-20 m (shallow), Class-III = 20-30 m (moderately shallow), Class-IV = 30-40 m (moderately deep), and Class-V = 40-50 m (deep).

The northeastern profiles (Profiles- 1 and 3) fall in the Mashhi sub-basin while Profiles- 4 and 5 fall in the Khari sub-basin. The principal geomorphic unit in the profile line across the Mashhi sub-basin is the alluvial plain, some parts of which in Profile-1 are gullied. The pediment also forms a significant geomorphic unit in Profile-2 in the central part of the Mashhi sub-basin. In the Khari sub-basin, covered by Profiles- 4 and 5, apart from the alluvial plains, there are flood plain deposits and minor segment of the pediment. There is a marked variation in the depth-to-water table between profiles in the Mashhi sub-basin in that within the alluvial plains, the water table depth is generally between 30 m and 40 m (Class-IV) with a few locations where the depth is between 40 m and 50 m (Class-V), but in Profile-2 and in an area about 60 km to the southwest, the dominant water table depth is between 5 m and 10 m (Class-I) with a few localities where the depth is between 10 m and 20 m (Class-II). The water table depth within the alluvial plains in the southwestern-most profile (Profile-3) of the Mashhi sub-basin varies between 5 m and 10 m (Class-I) and 10 m and 20 m (Class-II). In the Khari sub-basin, the water table depth in the alluvial plain is almost similar to that of the southwestern segment of the Mashhi sub-basin where the dominant depth is between 5 m and 10 m (Class-I). The water table depth in the flood plains of the major rivers varies between 5 m and 10 m (Class-I) in all the profiles except for deeper level at 15-20 m (Class-II) in Profile-5 of the Khari sub-basin. The water level within the pediment intersected in Profiles-2, 3 and 4 varies between 5 m and 7 m (Class-I) and 25 m and 30 m (Class-III) with the deepest level (35 m) encountered in Profile-2 in the central part of the Mashhi sub-basin. The depth-to-water table in the palaeochannels recorded in Profile-1 in the Mashhi sub-basin and in Profile-4 in the Khari sub-basin varies between 15 m and 20 m (Class-II).

The above-mentioned fluctuations in the depth-to-water table of unconfined shallow aquifer within the different geomorphic units are due to the difference in the hydraulic conductivity of the land-cover materials composing the geomorphic units, and the tectonic features controlling the tectonic geomorphology of the basin. This is evident from the hydraulic conductivity study, discussed earlier, and the relations of water table and neotectonics, discussed below.

6.5.4. Relation of Water Table and Neotectonics

The variation in the depth-to-water table within a particular geomorphic unit in a profile and in different profiles, described above, is due to neotectonic activity and differential transmissibility of fault and fracture zones. These fault and fracture zones are shown in the profiles across the study area (Figure 43). Since the variation in the depth-to-water table can also be caused by highly undulating and dissected topography, the study on the control of fault and fracture zones on depth-to-water table variations studied in the profiles across the study area is attempted in sections of the profile where the topography is without any significant undulations. Figure 44 shows the relation between the water table configuration and major fault. The location of the major faults, numbered 1 to 12, and the profile lines are shown in Figure 45. The profile lines cross-cut neotectonic zones that contain both extensional faults and strike-slip faults. From field studies it became evident that the strike-slip faults generally have appreciable dip-slip components, and therefore, these might have controls on groundwater depths in faulted aquifers. From the groundwater flow regime, discussed later, three groundwater blocks (Blocks -1,2,3), having different flow patterns, have been identified (Figure 46). Profile-wise description of the relation between the faults and the water table are as follows.

Profile-1 : This profile lies in groundwater Block-3 in the northeastern segment of the Mashi sub-basin. This profile intersects three major strike-slip faults (numbered 1, 2, 3) that have variable dip-slip components, and are likely to affect the aquifer. As a result, the water table shows a level differences and displacement at these faults. Fault-1, the trace of which is located on the Bandi river channel, has vertically dislocated the water table by ca. 12 m while Fault-2 near Ramachandrapura has displaced the water table by ca. 7 m. Another fault (Fault-3), located ca. 5 km southeast of Fault-2, has dislocated the water table by similar amount. It appears that the block between Faults-2 and 3 has been tilted anticlockwise. These features suggest that the strike-slip Faults-1, 2, and 3 have displaced the shallow aquifer to variable degrees, and these faults act as barriers to groundwater movement. This conclusion is corroborated by the relation of these faults with the groundwater flow direction, discussed earlier.

Profile-2 : This profile, located in groundwater Blocks-2 and 3, intersects three major faults (Faults-4, 5, and 6) of which Faults-4 and 6 are extensional faults and Fault-5 is a strike-slip fault that marks the boundary between groundwater Blocks-1 and 2. Faults-4 and 5 show a vertical dislocation of about 6 m while Fault -6 (a 5 km wide extensional fault zone) bounds a graben structure where the water table has been vertically downthrown between 15 m on the northwest fault zone boundary and about 5 m on the southeast fault boundary. A horst structure can be recognized in this profile between Faults-4 and 5 in the stretch between Sirohi and Dudu where the water table has gone up relative to the areas away from the faults. Clearly, the tectonic features including block movements and tilting have caused appreciable change in the depth-to-water table in the study area.

Profile-3 : This profile is located exclusively in the groundwater Block-2, and it intersects two strike-slip fault zones (Faults-5 and 7). Notably, the strike-slip fault (Fault-5) which has caused the water table dislocation in Profile-2, located in the northeast, and

intersected Fault-5 in its eastern segment, has not caused any such dislocation in this profile. This would suggest that the groundwater transmissibility across the faults is variable along a particular fault zone. Strike-slip Fault-7 in this profile, located near Bhartolav, has caused displacement of the water table by ca. 8 m.

Profile-4 : It is located in the groundwater Blocks-1 and 2, and it cross-cuts two extensional fault zones (Faults-8 and 9), out of which Fault -9 is a groundwater block-bounding fault (Blocks-1 and 2). Fault-8 has dislocated the water table by ca. 5 m. The block between these two faults is a graben structure where the depth-to-water table is deeper than the surrounding areas by ca. 5 m to 10 m.

Profile-5 : It is located exclusively in the groundwater Block-1, and it crosses two strike-slip faults (Faults-10 and 11) in the northwest and an extensional fault (Fault-12) in the southwest. These faults have dislocated the water table by ca. 5 m to 8 m. Faults-11 and 12 bound a graben block where the depth-to-water table is greater by ca. 5 m to 10 m than that in the surrounding areas.

Although the profile lines cut across a number of other faults (Figure 45), these are not shown in section (Figure 44) because these faults do not have any control on the water table configuration. Clearly, this study indicates that the faults demarcated in the study area belong to two types insofar as their controls on the water table configuration and groundwater movement are concerned. One type (Faults-1 to 12) traversed by the profiles are non-conductive faults that acts as barriers to groundwater movement, and the other type, acts as conduits to groundwater flow. This aspect is explored further in the study on groundwater flow regime, discussed below.

6.6. Groundwater Flow Regime

The groundwater flow regime (Figure 45) has been deduced from the groundwater table geometry. Figure 45 also shows the major faults and fracture zones, and bed-rock quartzite ridges for deciphering the controls, if any, of these features on the groundwater flow-paths. Some of the principal faults have been numbered (Faults-1 to 12) for reference to their locations on profile studies involving topography, groundwater table disposition, geomorphology and tectonics.

Although the generalized water table contour map (Figure 39) (Irrigation Department, Govt. of Rajasthan, 1998) shows the general flow direction toward east, the flow pattern map (Figure 45), prepared from close-spaced data collected in the present study, indicates that in detail the flow-paths are quite variable and multi-directional. The groundwater flow direction and the water table geometry are controlled significantly by the impervious to semi-pervious barrier zones, such as, massive quartzite ridges, sealed faults and fracture zones, and effluent or influent drainage systems.

The main river systems of the study area are the Khari in the south, Dai in the middle, Mashi in the north and the Banas in the east. The groundwater flow, in general, is orthogonal or at a high angle to Khari, Dai and Mashi river channels, irrespective of the depth of the water table. In some areas, the water table is slightly elevated near the river channels. In case of the Banas river, however, the groundwater flow in the vicinity of the river channel is either away or nearly parallel to the river course. These features would suggest that the main drainage system of the Khari-Mashi drainage basin does not significantly control the groundwater regime or in part, it is an effluent system. This is one of the reasons why most of these rivers are ephemeral. The Banas, the main 6th order river of the area, has a reasonably high discharge, particularly during monsoon period, and it appears to locally influence the groundwater regime by way of its general effluent nature.

Figure 45 shows the groundwater flow directions and their relation with the major fault systems. It has been mentioned earlier that these extensional and strike-slip faults are either reactivated older faults or are of neotectonic origin, and that these are likely to have affected the aquifer systems. Based on the fault pattern, three neotectonic blocks are identified (Figure 46). These blocks are : Devgarh – Asind – Shahpura block (Block-1) in the west, Masuda – Bhinai – Kekri block (Block-2) in the centre and Dudu – Mundota – Banasthali block (Block-3) in the northeast. Block-1 and Block-2 are separated by a prominent extensional fault (Masuda – Phuliya Fault) while Block-2 and Block-3 are separated by a strike-slip fault (Tihari – Banasthali Fault).

Notably, Block-1 represents exactly the Khari sub-basin, while Block-3 represents the major part of the Mashi sub-basin, and Block-2 contains the Dai and a small part of Mashi sub-basins. Figure 46 shows the generalized groundwater flow directions in each of these neotectonic blocks. The general flow direction in Block-1 is toward east, while that in Block-3 is toward southwest and south. In Block-2, the flow direction swerves from southerly to almost westerly near the alluvial plain of the Banas river. Such a notable variation in the groundwater flow directions within the neotectonic blocks is probably due to tilting of the aquifer in response to active faulting. These features signify the presence of three discrete groundwater blocks in the study area that are controlled by the configuration of the drainage sub-basins and the disposition of the major faults.

Apart from the above mentioned variations in the groundwater flow directions within the neotectonic blocks, each of these groundwater blocks also shows local variations in flow directions that are either caused by subsidiary fault systems or by impermeable bed-rock barrier ridges (Figure 45).

6.6.1. Relation of Groundwater Flow and Neotectonic Blocks

The groundwater flow pattern and the path-ways in relation to geological features such as faults, fracture zones and bed-rock ridges in the neotectonic blocks that define the groundwater blocks, described above, are as follows.

Groundwater Block-1 : This block contains a number of almost east-west trending strike-slip faults and a conjugate set of north-south and northeast-southwest trending

extensional faults. Moreover, there are northeast-southwest trending quartzite ridges of variable extents from 5 km to 60 km which are prominent in the northwestern margin of the drainage basin. The groundwater flow is generally parallel to the traces of the strike-slip faults, a feature that signifies that the fracture system associated with these faults would behave as a good conduits for groundwater lateral transmission. Some of the extensional faults are athwart the groundwater flow-paths, and these are likely to act as local barriers to groundwater movement. Notably, the Masuda -Phuliya extensional fault occurs along the axis of a trough on groundwater form surface, and the flow of groundwater on both sides of the fault is toward the fault. This feature would signify that the eastern fault zone, bounding Block-1, is a significant groundwater transmission zone toward southeast.

Groundwater Block-2 : This block contains a strike-slip fault zone trending NNW-SSE in a stretch between Bhinai and Kekri, and also an extensional fault zone, trending almost east-west at the northern boundary of the strike-slip fault zone. Groundwater flow-path diverges from the strike-slip fault zone, signifying that in contrast to the situation in Block-1, the strike-slip fault zone in Block-2 is a zone of poor groundwater transmission. On the other hand, the extensional fault in the north acts as a good transmission zone along which the groundwater movement takes place from east of Masuda to Malpura. An extensional fault associated with about 10 km long quartzite ridge to the east of Malpura appears to act as a barrier to groundwater flow from east toward west.

Groundwater Block-3 : The groundwater flow pattern indicates that the strike-slip fault zone (Tihari-Banasthli Fault), bounding this block in the southwest, is a good conduit of groundwater movement. This is in contrast to a set of east-west trending strike-slip faults between Dudu and Mundota where the groundwater movement is essentially athwart the trend of the strike-slip fault zones. This feature would suggest that these strike-slip fault zones do not act as barriers nor do they facilitate fault parallel groundwater movement because of low to poor lateral transmissibility. There is a conjugate extensional fault system trending NNW- SSE and north-south. Relation between groundwater flow-paths and these conjugate fault systems suggests that these extensional fault zones are good conduits for lateral groundwater movement.

6.6.2. Relation of Groundwater Temperature and Fault System

Many studies have shown that in cases where faults act as barriers to groundwater movement and cause displacement of the water table also show a difference in water temperatures and dissimilar thermal profiles across the fault zone (Flint, 2002). This is caused by recharge of groundwater at the higher level by colder surface water and restricted or no flow of groundwater at lower levels across the fault where the temperature is higher. Such studies are useful in elucidating the recharge behaviour of the aquifer in relation to faults and fracture zones.

In order to investigate the variation of water temperatures across faults, nine faults that act as barriers to groundwater flow, have been chosen on the basis of the water table configuration, discussed above. The groundwater temperature was measured in selected dug wells during post-monsoon period in the months of September – October, 2005. The

location of the fault and the groundwater temperatures in the vicinity of these faults are shown in Figure 47. This figure also shows the generalized groundwater flow directions in relation to these faults. The characteristics of groundwater temperature across these faults, and their significance are as follows.

Fault- 4 : As mentioned earlier, this fault acts as a barrier to the groundwater flow across it, but the flow pattern around the fault indicates that the fault zone represents a channel-way for groundwater movement down the water table gradient toward southeast and south. The water table RL data indicate that in the northeastern part of the fault, the water table has been displaced downward relative to that in the southwestern part of the fault by ca. 6 m to 10 m. The temperature distribution data indicate that in the southern part of the fault, the groundwater occurring at a higher level has a temperature range of 26° to 27.5°C while the groundwater temperature across the fault in the eastern part has a range of 27.5° to 29° C. This indicates that the groundwater occurring at a higher level has a lower temperature by about 2° to 3°C. This would mean that the groundwater at the higher level is recharged by colder surface waters from the run-off. This is corroborated by the fact that the upper reaches of the Mashī river run almost parallel to the fault in the southwestern part where the water table is at higher elevation than in the southwestern part.

Fault-6 : This is an extensional fault zone with a graben structure in the east where the water table is lower by ca. 10 m than that in the western part of the fault. The groundwater temperature in the eastern part within the graben zone, drained by the Sohadra river, southwest of Jhirana, ranges from 24.7° to 25° C while that in the western part it is 24.7° to 29°C. Clearly, the groundwater temperature in the fault-bound graben structure is lower than that in the hanging-wall part of the fault. This is probably because of the high recharge of the groundwater by the Sohadra river and a part of the tributary system of the Mashī river, northwest of Jhirana. The generalized groundwater flow in the hanging-wall of Fault-4 as well as in the footwall graben zone is towards east across the trace of the fault. Unlike in Fault-4, there is no lateral groundwater movement parallel to the fault zone. The temperature and the elevation difference of the water table would suggest that Fault-6 acts as a partial barrier to the groundwater movement.

Fault-7 : The footwall part of this fault contains groundwater temperature between 25° and 26.2° C while the hanging-wall part has the groundwater temperature in the range of 25° to 27.5° C. This means that the footwall groundwater is slightly colder than that of the hanging-wall. This feature is probably related to the recharge of groundwater in the footwall by the upstream tributaries of the Dai river, and to the restricted flow of groundwater across the fault.

Fault-8 : The groundwater flow pattern suggests that this fault acts in part as a barrier to the groundwater flow and in part as conduit to lateral movement along the fault zone. As a consequence, the hanging-wall block where the water table is at a higher elevation than the footwall block has a temperature of 24° C whereas in the footwall block the temperature is between 25° and 26.7° C.

Fault- 9 : Like Fault-8, this extensional fault also acts as both passive zone for groundwater transmission across the fault as well as a conduit for fault-parallel lateral groundwater flow. As a result of the former feature, particularly in the northern part of the fault, the groundwater temperature on the footwall block where the water table elevation is lower than that in the hanging-wall block is 29° C whereas on the hanging-wall block the temperature is 26.2° C. This indicates that the hanging-wall block is recharged by the tributary system of the Khari river, and that there are restricted movements of recharge water towards the footwall block across the fault zone. Moreover, the groundwater temperature shows an increase from 26.5° to about 29° C down the flow-path parallel to the fault trace in the fault zone. This indicates the passage of colder recharge water along the fault acting as a lateral conduit and mixing of younger and colder recharge water with older and hotter water in the the fault zone.

Fault-10 : No significant variation of groundwater temperature across this fault is noticed. This is probably because the groundwater flow is parallel to the fault trace, indicating water movement essentially along the fault zone. This is corroborated by the lower water temperature (26.5° C) in the recharge zone on the western segment of the fault than that (28.5° C) in the eastern segment of the fault zone, down the groundwater flow-path.

For other faults, no systematic or appreciable variation of groundwater temperature can be recognized. This would suggest that in these fault zones variable degrees of mixing of recharged water with the existing groundwater, and temperature homogenisation have taken place. From the available data, it is difficult to evaluate the relative contribution of the recharged colder water and of the fault characteristics for water transmission across and along these faults from the variations of groundwater temperature in these fault zones.

6.7. Analysis for Delineation of Groundwater Recharge Domains

A multi-parametric approach was adopted to delineate potential domains and blocks of groundwater recharge in the study area. Two methodologies, namely, Thematic Data Overlay Analysis and Quantitative Matrix Analysis, were followed to integrate the spatial and quantitative data of recharge-controlling multi-component parameters to identify potential groundwater recharge domains. The procedure and the results are discussed below.

6.7.1. Thematic Data Overlay Analysis

The spatial distribution of the multi-component attributes of the different parameters such as geology, tectonics geomorphology, land-cover and hydrologic characteristics that control aquifer recharge, discussed above, are variable. This puts a constraint in defining the potential recharge zones using multiple parameters. Moreover, the presence of more than one favourable parameter in a specific zone of interest enhances its recharge potential by several orders of magnitude. This aspect has been considered in

defining the potential recharge domains by overlaying the thematic spatial data of selected parameters.

6.7.1.1. Methodology

The methodology followed in this procedure was first to select the most favourable parameters for groundwater recharge. The following parameters selected for this exercise are considered the most effective for recharge domain identification.

- (i) Fault and fracture intersections,
- (ii) Flood plains,
- (iii) Palaeochannels,
- (iv) Tectonic depressions and graben structures,
- (v) Hydraulic conductivity of soil (>20 cm/hr),
- (vi) Hydraulic conductivity of sub-soil sediments (>20 cm/hr),
- (vii) Post-monsoon rise of groundwater table (8 - >12 m),
- (viii) Influent stream segments.

All the above parameters, considered equally important for recharge, are assigned a uniform impact weight 10 each. The domains covered by each parameter of weight 10 were extracted from the individual thematic maps of the parameter concerned. A superposed composite map was prepared from the overlays of the spatial data of 8 parameters so extracted. From the composite map the areas of overlap enclosing more than one parameter fields were demarcated, and assigned a Cumulative Recharge Capability Score (CRCS) by adding the weights contributed by each parameter in the composite domains. Higher the CRCS value, greater is the recharge potential of the domain.

This procedure can be effectively executed on GIS platform, not included and attempted in the present project.

6.7.1.2. Potential Recharge Domains

The potential recharge domains identified on the basis of CRCS values derived from the weights of the highest ranked component of the selected parameters, described above, are shown in Figure 48. The following inferences are drawn from this analysis,

A major part of the area, particularly the Dai and the Mashī sub-basins in the central and eastern parts of the study area, contains low CRCS values (<10 – 20). There are a few isolated domains having moderate CRCS value (30) in these drainage basins (e.g., northeast of Tordi, east of Phuliya). The most promising recharge domains are located in the Khari sub-basin in the southwest. In a stretch of ca. 30 km of the Khari river valley from ca. 15 km east of Ojiyana to ca. 10 km west of Phuliya, the domain contains the CRCS values ranging from 30 to 60. There is a stretch of high recharge capability domain (CRCS = 40-60), having an area of ca. 150 km² in the above mentioned Khari valley which also contains a small zone (ca. 10 km²) of very high recharge capability area (CRCS = 60) near

Shikhrani. There is a domain of moderate to high CRCS value (30-50), spread over an area of ca. 60 km² to the east of Devgarh.

6.7.2. Quantitative Matrix Analysis

Quantitative matrix analysis is a powerful tool to treat multivariate data-sets for working out the spatial distribution pattern of the interactive parameters, weighed according to their impact factor and their rank in parameter hierarchy that control the importance in groundwater recharge. The procedure is useful to delineate the matrix cells or the blocks where either a process is likely to operate efficiently or an attribute to be identified for such a process. In the present case, both these aspects are important because the process involves transmission of surface water in the underground, and the attribute concerns recharge capability of the terrain.

6.7.2.1. Methodology

The following steps are followed in the analysis.

- (a) The study area has been divided into 394 matrix cells on a grid (Fig. 49) with each complete cell having an area of 50 km². At the margin of the study area the cell dimensions are less than this unit cell area, and are variable because of the irregular nature of the drainage basin outline.
- (b) The following parameters having high impact factors have been chosen for the analysis.
 - (i) Geology represented by 5 bed-rock types,
 - (ii) Geomorphology represented by 5 units,
 - (iii) Ground slope characters,
 - (iv) Fault and fracture zone intersection density,
 - (v) Drainage density and bed-rock jointing,
 - (vi) Soil profile represented by 5 morphologic types,
 - (vii) Hydraulic conductivity of soil,
 - (viii) Hydraulic conductivity of sub-soil sediments,
 - (ix) Grain size of soil,
 - (x) Grain size of sub-soil sediments,
 - (xi) Post-monsoon rise of groundwater table.
- (c) Quantitative thematic maps prepared for each of the above parameters, and the data-sets extracted from them have been used for the analysis.
- (d) Each parameter has been ranked (1 to 5) on the basis of their importance factor and positive impact value on groundwater recharge potential (Table 18). The ranks indicate the impact value scale from slight (Rank 1) through appreciable (Rank 2), significant (Rank 3), major (Rank 4) to strong (Rank 5). The highest rank (5) has been assigned to the hydraulic conductivity of the soil and the sub-

soil sediment, and the post-monsoon rise of the water table while Rank-4 has been given to the drainage density and the bed-rock jointing, the density of intersection of fault and fracture zones, the taxonomic types of soil, the texture of the soil and the sub-soil sediment. Rank-3 has been assigned to the geomorphic attributes including ground slope while the lowest rank (2) is given to the lithologic parameter because the purpose of this exercise is to determine the recharge potentials of the terrain for shallow Quaternary alluvial aquifer system.

- (e) The importance and impact factor of each of the above parameters has been expressed as Parameter Importance Value (PIV) which is obtained by dividing the parameter rank value by the sum total of all the rank values assigned to all the parameters (Table 18). In the present case, the total rank value is 43. In order to make the PIV values whole numbers, the values are multiplied by 100. The PIV values thus obtained vary between 4.65 and 11.62
- (f) The attributes of each of the 11 parameters are assigned Recharge Capability Weights (RCW) between 5 (poor), and 25 (excellent) through 10 (moderate), 15 (good) and 20 (very good) (Table 19).
- (g) Each cell contains more than one attributes of a single parameter, and therefore, for each cell the sub-areas in km^2 covered by the individual attributes of each parameter is calculated. Each sub-area value is multiplied by the respective RCW value of the individual attributes concerned to obtain the Weighted Recharge Capability (WRC) value of the attribute of the cell. Since the area of the cells at the margin of the study area is variable, and is less than the unit cell area (50 km^2), the WRC values are normalised against the unit cell area to obtain the Normalised Weighted Recharge Capability (NWRC) value for each attribute of the cell.
- (h) For each cell the NWRC values of all the attributes of a single parameter is added and the total NRWC value is multiplied by the PIV value of the parameter concerned to obtain the Recharge Capability Score (RCS) of the cell with respect to that particular parameter.
- (i) Following the above procedure the RCS values of 11 parameters present in each cell are computed. All these RCS values are added to obtain the Cumulative Recharge Capability Score (CRCS) for each cell.

6.7.2.2. Potential Recharge Blocks

Table 20 lists the CRCS values of 394 matrix cells of the study area. Figure 50 shows the cell-wise distribution of the CRCS values, grouped in 5 range-classes, namely, 800-1000, 1001-1200, 1201-1400, 1401-1600, and 1601-1800. Out of these, the CRCS values > 1400 are considered the most significant, and the blocks having the CRCS values

in the range of 1400-1800 might have very good to excellent groundwater recharge potential. The most potential recharge blocks are shown in Figure 51.

The following inferences are made from the quantitative matrix analysis, and the CRCS distribution pattern.

The major part of the study area has CRCS values in the range of 1200-1400, representing moderate recharge potentials. Cells having CRCS values in the range of 1000-1200, representing poor recharge potential, occur as isolated blocks within regions covered by CRCS values in the range of 1200-1400, particularly in the Mashi and the Dai sub-basins in the central and northeastern parts of the area.

The Khari sub-basin in the southwest is the most promising region for recharge because it contains a number of blocks having CRCS values in the range of 1400-1600, representing very good recharge potential, and 1600-1800, representing excellent recharge potential. The highest CRCS values in the range of 1600-1800 are present in the southwestern corner of the area in Devgarh region. This region represents the constricted part of the Khari sub-basin at the water-divide of the Aravalli hill range. Another block, having moderately high CRCS value range (1400-1600), occurs to the east of Asind in this sub-basin. These two regions are the most favourable recharge domains of the study area, and are considered suitable for launching recharge programme.

Generally, the rest of the Aravalli water-divide at the northwestern margin of the study area do not show appreciably high CRCS values, except for several isolated blocks to the east and north of Nasirabad (CRCS = 1400-1600). This feature would suggest that unlike in many catchments the hilly water-divide tract may not offer favourable zones of recharge although the run-off there may be high.

A comparison of the results of recharge zone delineation, using two methodologies, discussed above (Figs. 48, 50), indicates that the distribution pattern of the favourable recharge domains, identified by the two methods, is almost similar, although in Thematic Data Overlay Method a limited number of parameters (nos. 8) has been used in contrast to greater number of parameters (nos. 11) used in Matrix Analysis Method. This feature would further suggest that the identification of recharge zones may not be methodology-specific, and that parameter characteristics and their impact values are more important than the number of parameters.

6.7.3. Groundwater Recharge Zones

As mentioned in the above discussion, a number of cell-clusters, having CRCS values > 1400 that are considered the most favourable for recharge, have been identified. The location of these cell-clusters, numbered 1 to 10, is shown in Figure 51. In order to further reduce the recharge area from unit cell size (50 km²) and to locate specific recharge zones for implementation of possible recharge programmes within each of these cell-clusters detailed maps on scales varying from 1 : 250,000 to 1 : 50,000 have been prepared

for all the 10 cell-clusters. These maps contain the details of topography, stream network, fault and fracture zones, areas of high bed-rock jointing, tectonic depressions and graben structures, hydraulic conductivity of the soil and the sub-soil sediment and groundwater flow-paths. These maps are shown in Figures 52 a,b,c,d,e,f,g,h,i,j. The most potential recharge zones of 1-2 km² dimensions in each cell-clusters have been identified taking the following factors into consideration.

- (i) Intersection zones of the maximum number of faults and fractures zones, and highly jointed bed-rock substrate,
- (ii) Zones of the highest hydraulic conductivity of soil and sub-soil sediment.
- (iii) Up-flow segments of groundwater flow-paths,
- (iv) Low ground slope at topographic lower elevations,
- (v) Tectonic depressions where the thickness of the Quaternary sediments, hosting the shallow aquifers is likely to be high.

In individual blocks a combination of more than one of the above factors has been used, and the favourable recharge zones have been identified where more than two or three of the above features converged and occur together.

Based on these criteria a number of possible recharge zones have been identified in each of 10 cell-clusters having high CRCS values. These recharge zones are shown in separate diagrams under Figure 52. It may be noted that the location of these zones are indicative of their general geographic and geologic setting, and may serve as a guide for selection of the most favourable and specific recharge sites within them. The actual site location for recharge structures would depend on other site-specific factors such as local landform, including ground slope, degree of landform dissection and erosion, nature of soil and sub-soil sediment profiles, especially the presence of impervious calcrete and hard pan zones, and surface hydrology. A study of these site-specific factors, and also of the efficacy of vertical and horizontal water transmission for recharge of shallow aquifer by geochemical tracer investigations would help locate the most effective and sustainable recharge sites in each cell-cluster, identified from the matrix analysis.

7. CONCLUSIONS

The results of the study contained in this report pertains to the analysis and synthesis of multiple parameters and their various components for an assessment of groundwater recharge capability of, and identification of suitable recharge zone in the Khari-Mashi drainage basin (18,814 km²) in Rajasthan. The principal conclusions are as follows.

- (i) The study area is a 5th order Hortonian drainage basin that represents a tributary sub-basin of the 6th order Banas drainage basin. There is a spatial difference in the relative development of streams of different orders, and also in the drainage density and frequency of the stream network which is due to lithologic and structural inhomogeneities of the area. The longitudinal profiles and the along-river gradients of the 5th order streams indicate the presence of

several knickpoints. The knickpoints suggest the presence of active and neotectonic fault zones that caused relative block uplift, graben formation and block tilting.

- (ii) The altitude range frequency indicates three topographic terrains, namely, the highland (500->800 m), corresponding to the Aravalli hill range, the midland (400-500 m), corresponding to the Aravalli foothills and the pediment, and the lowland (200-400 m), corresponding to the extensive peneplain (Bhilwara peneplain) and the Banas alluvial plain. The hypsometry of the drainage basin indicates concave-up curves, suggesting that fluvial erosion has dominated over regional diffusive mass-wasting.
- (iii) The principal lithologies of the geologic formations are gneisses, schists, quartzites and granitoids that have low to medium primary porosity and permeability. However, structural features such as faults, fractures and joints have produced secondary porosity and transmissibility.
- (iv) A number of major older dislocation zones have been reactivated in the Quaternary and recent times to produce neotectonic features such as faults (extensional and strike-slip faults), fracture zones, lineaments, and tectonic landforms. The fault and fractures systems are potential zones of recharge, particularly at locations of high-density of their intersections. The intersection density varies from 0 to 16 per 50 km². A number of categories of intersection frequencies, based on relative recharge capabilities, have been made, and their spatial distribution delineated.
- (v) Several hydrogeomorphologic units (nos. 13) have been identified and mapped, using space imageries and field checks. The most extensive geomorphic unit is the peneplain, comprising the alluvial-fill and the flood plains. The different geomorphic units have variable groundwater prospects as well as recharge capabilities.
- (vi) The regional ground slope, an important recharge factor controlling the run-off and the water availability for recharge, varies from <0.1% to >1.8% while the slope direction is generally from NW to SE, toward the master river, the Banas. There are local variations and slope reversals caused by vertical movement and tilting of fault-bound blocks.
- (vii) The soil and sub-soil sediments developed in different geomorphic terrains vary in their basic attributes such as thickness, texture, carbonate content and salinity/sodicity. Based on these, 28 soil/sediment types have been differentiated in different geomorphic terrains. The recharge capability score of each type of land-cover material has been derived from the cumulative weights of their multiple attributes, and the spatial distribution pattern of the scores determined. The highest score pertains to soils/sediments of the highland and parts of the adjoining pediment while parts of the alluvial plain with gently sloping topography and residual hills give low to moderate recharge scores for the soils and the sub-soil sediments.
- (viii) The water table geometry shows troughs and ridges. Many of these features persist in the pre-to post-monsoon periods, indicating stable controls of geologic, geomorphologic and tectonic features on the water table

configuration. The general water table form has persisted at least for the last 10 years.

- (ix) The strike-slip faults with dip-slip components played a more important role in groundwater recharge from run-off waters than the extensional normal faults because of the association of the former with the pull-apart extensional fracture zones in graben basins and tectonic depressions.
- (x) In general, the fault and fracture intersections caused a rise in the water table in post-monsoon period, although the rise is not exclusive to high-density structural intersection zones. Other factors such as geomorphology, strike-slip faults, tectonic depressions disposed along the strike-slip faults and the tectonic zones occurring between normal faults and strike-slip faults played a major role in controlling the recharge and rise of the water table in the post-monsoon period.
- (xi) Three groundwater blocks, bounded by major fault zones, and corresponding roughly to the configuration of the Khari, Dai and Mashi su-basins, have been identified. These blocks have different groundwater regimes in terms of the depth-to-water table and the groundwater flow pattern.
- (xii) The extensional faults bounding the groundwater blocks are generally good zones of groundwater transmission. On the contrary, lateral transmissibility of groundwater along strike-slip fault zones is generally poor in some and moderate in others. This would mean that the tectonic dilation related to transverse extension in the strike-slip fault zones is variable, a feature that has imparted variable transmissibility to the strike-slip fault zones.
- (xiii) The three groundwater blocks, defined by major faults, show variable and multi-directional groundwater flow-paths. In the southwest of the study area (Block-1), the flow is generally toward the east. In the middle (Block-2), the flow swerves from southerly to westerly from the higher elevation in the pediment toward the Banas flood plain. In the northeast (Block-3) the flow is toward the southwest and the south. Apart from this regional variation, smaller fault-blocks also show variable flow-paths. This feature is likely to have been caused by variable degrees of both clockwise and anticlockwise block and aquifer tilting in response to active faulting.
- (xiv) At places, the water table is higher near, and the average flow direction is athwart or at low angles to the channels of the major rivers such as Khari, Dai, Mashi, and Banas, suggesting the general effluent nature of the drainage system.
- (xv) The relation of the topography and the water table configuration indicates that although the unconfined water table follows the topography at lower elevations, at higher elevations, however, the water table shows appreciable departure from the near parallelism with the topography. This feature is the result of both fault-tectonics that deformed the aquifer and geomorphology that controlled the degree of aquifer recharge and saturation.
- (xvi) The relation of the extensional and strike-slip faults with the water table indicates that the water table is displaced by 5-15 m at some faults. This suggests that these active faults have affected the shallow aquifers, and that they have also acted as barriers to the groundwater movement across them.

The fault geometry also suggests that the fault-bound blocks have been tilted, causing changes in the groundwater flow regime, both within one neotectonic block as well as between the adjacent neotectonic blocks.

- (xvii) The groundwater temperature data across the barrier faults indicate that the water temperature at higher elevations of the water table in the uplifted hanging-wall block is lower by 2°-3° C than that at the lower elevations in the down-faulted footwall block. This feature is interpreted by preferential recharge of unsaturated aquifer at a higher elevation by colder surface water, particularly from the effluent streams and fault-fracture-controlled infiltration, and by restricted or no flow and limited or no mixing of waters across the barrier faults. Contrarily, lower elevation water table within the graben and tectonic depressions often shows temperatures lower than those of the higher elevation in the hanging-wall block due to aquifer recharge by colder water in topographic and tectonic depressions. The water temperature variations also suggest that in case of faults that act as conduits for lateral movement of groundwater along the fault zone, younger and colder recharged water mixes with older and hotter water down the groundwater flow direction where the water temperature increases. In many cases, no systematic variation of water temperatures with fault zone and groundwater flow pattern is discernable. These situations are the result of a complex pattern of recharge, water table configuration and groundwater flow regime, which would need further study.
- (xviii) The textural analysis of the soils and the sub-soil sediments (219 samples), composing the different geomorphic units, indicates that they contain varying proportions of grit and coarse sands (>2 mm to 0.5 mm), and silt and clay (0.1 mm to <0.06 mm). Generally, the soils of the pediment and the alluvial plains contain higher percentage of coarse fractions than the dissected alluvial fans. Similarly, the sub-soil sediments of the pediment and the alluvial plain contain higher percentage of coarse fraction than those of the intermontane valley-fill, the palaeochannel, the flood plain and the dissected alluvial fan. The flood plain, the alluvial plain and the intermontane valley-fill deposits contain appreciable quantities of the fine fractions. The textural variations of the land-cover materials have important bearing on the recharge capability of the area.
- (xix) The vertical hydraulic conductivity of the soils and the sub-soil sediments of the different geomorphic units is variable. In general, high hydraulic conductivity is shown by the soils of the flood plain (66-32 cm/hr) and by the pediment (30-25 cm/hr) while the soils of the alluvial plain show a large variation, ranging from 1.5 cm/hr to 29 cm/hr. The sub-soil sediments of the intermontane valley-fill show a wide range (1.9-71 cm/hr) while the pediment consistently shows high to moderate values (13-25 cm/hr). The sub-soil sediments of the alluvial plain show low to moderate conductivity (1-27 cm/hr) although in some isolated areas highly conductive (59-36 cm/hr) sub-soil sediments are present.
- (xx) One of the important factors of groundwater recharge is the transmissibility and hydraulic conductivity of the land-cover materials, including soils and sub-soil sediments. This factor is dependent on two important features, namely, the presence of coarse grained materials (grit and coarse sands) that

aid water transmission, and of silt and clay that impede transmission. The spatial distribution of the contents of the coarse materials (> 2 mm to 0.5 mm) in the soils and the sub-soil sediments indicates that the coarse fraction maxima (> 60%) occur in isolated zones, and that the textural characters of the soils do not generally mimic those of the substrate sediments. Therefore, in order to study the groundwater recharge capability of the land-cover materials, and to locate sites for recharge structures, apart from other relevant factors, the texture of the soils and the sub-soil sediments needs to be examined separately.

- (xxi) Based on the data-sets prepared on various components of parameters such as geology, geomorphology, land-cover materials, and groundwater hydrology two approaches, one using Thematic Data Overlay Analysis (TDOA), and the other, Quantitative Matrix Analysis (QMA), have been adopted to identify the most favourable and potential groundwater recharge domains and zones. TDOA demarcated a few favourable recharge domains, and QMA model delineated recharge blocks of various categories from the Cumulative Recharge Capability Scores (CRCS). A number of recharge zones have been identified within 10 recharge blocks having CRCS values >1400. The study reveals that the delineation of recharge domains is not methodology-specific, and that the importance and impact values of multivariate parameters are more important than the number of parameters.
- (xxii) The recharge zones, thus identified, hold promise for selection of viable and sustainable recharge sites within them for implementing groundwater recharge programmes for augmenting the groundwater resources of depleted and unsaturated shallow aquifers of the study area. However, a number of site-specific factors, discussed in this report, need to be examined in selecting the specific sites for construction of recharge structures for efficient and sustainable groundwater recharge.
- (xxiii) The multi-parametric data-sets collected and the multi-component thematic maps prepared in the project have potentials for use in, and may form the basis for groundwater modeling studies on a GIS platform.

Acknowledgements

This work was carried out with the financial assistance from the Ministry of Water Resources, Govt. of India, New Delhi. The cooperation received from Dr. S. M. Husain, Director, R & D, Ministry of Water Resources, New Delhi, and Dr. Ramakar Jha, Member Secretary, INCOH, Roorkee, is thankfully acknowledged. Dr. P. Ghosh, Executive Director, Birla Institute of Scientific Research, Jaipur, is thanked for providing the facilities for the work. Shri Jitendra Kumar, JRF, Shri Manish Dogra, JRF and Shri. Navneet Surana, JRF assisted in data collection and processing at various stages of the project.

Papers Published

1. Sinha-Roy, S. 2004. Geological and hydrogeochemical controls of fluoride distribution in the groundwaters of a part of Rajasthan. Proceedings of Workshop on Medical Geology (IGCP-454), Special Publication, Geol. Surv. India, 83, 79-95.
2. Sinha-Roy, S. 2007. Control of neotectonic structures on recharge , flow and mixing of groundwater in semi-arid drainage basin in Rajasthan. International Conference on Geo-environment : Challenges Ahead, Jammu University, Jammu, (Abstract), 12-14.
3. S. Sinha-Roy, S. 2007. Wetland-groundwater interaction, water transfer mechanism and aquifer recharge protocol : example from semi-arid drainage basins, Central Rajasthan. National seminar on Wetland and Their Conservation Strategies and Policy options, Social Policy Research Institute, Jaipur, (Extended Abstract), 58-61.
4. Sinha-Roy, S. 2007. Fault-controlled groundwater flow regime and its significance in depleted aquifer recharge in a semi-arid drainage basin, Rajasthan. National Seminar on Hydrocare-2007, Annamalai University, Annamalainagar, (Abstract), 26-28.
5. Sinha-Roy, S. 2009. Polyparametric approach to groundwater recharge capability assessment : an example from Rajasthan. Workshop on Water Scenario, Efficient Use and Management in Rajasthan, Central Groundwater Board, Western Region, Jaipur, 34-43.
6. Sinha-Roy, S. 2009. Climate change-forcing of groundwater recharge in arid-semi-arid regions : an insight from Rajasthan. National Symposium on Climate Change and Water Resources in India. National Institute of Hydrology, Roorkee, (Extended Abstract), 37-40.
7. Sinha-Roy, S. 2009. A protocol for groundwater recharge capability assessment using multi-thematic parameters : an example from semi-arid region of Rajasthan, India, International Conference on Water, Environment, Energy and Society (WEES-2009), Allied Publishers Pvt. Ltd., New Delhi, Vol. I. 417-424.
8. Sinha-Roy, S. 2010. Focussed groundwater recharge in arid and semi-arid regions in a climate-change scenario : an insight from Rajasthan. National Conference on Groundwater Resource Development and Management in Hard Rocks, Dept. of Geology, Pune, (Extended Abstract), 100-101.
9. Sinha-Roy, S. 2011. Surface water-groundwater interactions in wetlands of semi-arid drainage basin at Thar desert fringe, Rajasthan, India, HydroEco-2011, Vienna, (Abstract), A-45.
10. Sinha-Roy, S. (in press). Controls of geomorphology, landuse-landcover and neotectonics on groundwater recharge in a semi-arid drainage basin, Rajasthan, Geol. Soc. India.

8. REFERENCES

- Ash, J.M. and Malmquist, P. 2004. Recharge potential quantification using soil discharge factors and drainage basin data. National Groundwater Association Conference, Las Vegas, Nevada, USA. (Abstract).
- Baruah, T.C. and Barthakur, H.P. 1997. A Textbook of Soil Analysis, Vikash Publishing House Pvt. Ltd., pp. 334
- Beekman, H.E., Gieske, A., and Selaolo, E.T. 1996. GRES : Groundwater recharge studies Botswana 1987-1996, Botswana Jour. Earth Sci., 3, 1-17.
- Bhattacharyya, A.K., Kurien, T.K., Krishnanunni, K. and Seth, D.N. 1979. Geomorphic mapping in parts of Kerala State, Jour. Indian Soc. Remote Sensing, 7(1), 1-9.
- Bockgard, N. and Niemi, A. 2003. Role of soil-rock interaction on recharge into fractured rock. Proc. TOUGH Symposium. Lawrence Berkeley National Laboratory, Berkeley, California, 1-4.
- Bourgeois, P.O. 1972. Notes on developing groundwaters. Water and Pollution Control, 110(10), 24-28.
- Carlston, C.W. 1963. Drainage density and stream flow. US Geol. Surv. Prof. Paper, Denver, 422C.
- Chandrashekhar, H., Venugopal, T.N., Reddy, G.S. and Sridhara, V. 2001. Application of remote sensing technique and GIS for the groundwater resources management in Chitradurga district, Karnataka. In : Groundwater Resources : Evaluation and Management, (Eds. : H. Bhu and V. Agrawal), Dept. of Geology, MLS University, Udaipur, 87-96.
- Das, D. and Khan, F. 2001. Application of remote sensing and GIS techniques for selecting artificial recharge sites of groundwater – a case study. In : Groundwater Resources : Evaluation and Management, (Eds. : H. Bhu and V. Agrawal), Dept. of Geology, MLS University, Udaipur, 97-105.
- Flint, A.L. 2002. The role of unsaturated flow in artificial recharge projects. In : Artificial Recharge Workshop Proceedings, Sacramento, California, (Eds. : G.R. Aiken and E.L. Kuniatsky), USGS Open File Report, 02-89.
- Garza, L.D.L. 1986. Relation between areas of high transmissibility and lineaments – the Edwards aquifer, Barton Springs segment, Travis and Hays counties. In : The Balcones Escarpment, Central Texas, (Eds. : P.L. Abbott and C.M., Jr. Woodruff), Geol. Soc. Amer., 131-135.
- Gupta, S.N., Arora, Y.K., Iqbaluddin, Prasad, B., Sahai, T.N., and Sharma, S.B. 1997. The Precambrian geology of the Aravalli region, Southern Rajasthan and NE Gujarat, Mem. Geol. Surv. India, 123, pp. 262 .
- Heron, A.M. 1953. The geology of central Rajputana, Mem. Geol. Surv. India, 78, pp.389.

- Irrigation Department, Govt. of Rajasthan, 1998. Water Resources Planning For Banas River Basin, pp. 125 .
- Kulkarni, M.D., Puranik, S.C., and Wodeyar, J.K. 2001. Characters of bore wells in relation to geomorphic units and lineaments, Hosur Halla basin, Belgaum district, Karnataka. In : Groundwater Resources : Evaluation and Management, (Eds. : H. Bhu and V. Agrawal), Dept. of Geology, MLS University, Udaipur, 119-124.
- Lattman, L.H. and Parizek, R.R. 1964. Relationship between fracture traces and the occurrence of groundwater in carbonate rocks. *Jour. of Hydrology*, 2, 73-91.
- Macka, Z, 2001. Determination of texture of topography from large-scale contour maps, *Geografski Vestnik*, 73(2), 53-62.
- Millington, A.C. and Townshed, JH.R.G. 1986. The potential of satellite remote sensing for geomorphological investigation – an overview. In : *International Geomorphology Pt.-II*, (Ed. : V. Gardinaer), John Wiley & Sons, pp. 715 .
- Phillips, S.P. 2002. The role of saturated flow in artificial recharge projects. In : *Artificial Recharge Workshop Proc.*, Sacramento, California, (Eds. : G.R. Aiken and E.L. Kuniansky), USGS Open File Report, 02-89.
- Raju, K.C.B. 1989. Importance of recharging depleted aquifers : state of art of artificial recharge in India, *Jour. Geol. Soc. India*, 51, 429-454.
- Ramasamy, SM. and Anbazhagan, S. 1997. Criteria and techniques of detecting site specific mechanisms for artificial recharge – a case study from Ayyar basin, India. *Jour. Geol. Soc. India*, 50, 449-456.
- Resource Atlas of Rajasthan. 1994. Department of Science and Technology, Govt. of Rajasthan, Jaipur, pp. 231 .
- Saraf, A.K. and Chaudhary, P.R. 1998. Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. *Int. Jour. Remote Sensing*, 19(10), 1825-1841.
- Singh, A.K., Kundu, P. and Sarma, B. 2000. Delineation of groundwater potential zones in Bakhar sub-watershed, Mirzapur and Sonbhadra districts, U.P., using integrated remote sensing, geoelectrical and GIS techniques. *Proc. ISRS National Symposium*, Kanpur, 320-329.
- Sinha-Roy, S. 1986. Himalayan collision and indentation of the Aravalli orogen by the Bundelkhand wedge : implications for neotectonics in Rajasthan. *Proceedings International Symposium on Neotectonics in South Asia*, Wadia Institute of Himalayan Geology, Dehra Dun, 13-24.
- Sinha-Roy, S. 2000. Plate tectonic evolution of crustal structures in Rajasthan. In : *Research Highlighs in Earth System Science*, (Eds. : O.P. Verma and T.M. Mahadevan), Dept. of Science and Technology, Govt. of India, New Delhi, 17-25.
- Sinha-Roy, S. 2001a. Neotectonic significance of longitudinal river profiles : an example from the Banas drainage basin, Rajasthan. *Jour. Geol. Soc. India*, 58, 143-156.

- Sinha-Roy, S. 2001b. A new approach to the analysis of transverse river profiles and implications for morphotectonics : a case study in Rajasthan. *Curr. Sci.*, 81(1), 106-112.
- Sinha-Roy, S. 2002. Hypsometry and landform evolution : a case study in the Banas drainage basin, Rajasthan with implications for Aravalli uplift. *Jour. Geol. Soc. India*, 60, 7-26.
- Sinha-Roy, S. 2004. Intersecting Proterozoic transpressional orogens, major crustal and suspect terranes in Rajasthan craton : a plate tectonics perspective. *Special Publ. Geol. Surv. India*, 84, 207-226.
- Sinha-Roy, S. 2005. Intracratonic neotectonic deformation, active fault systems and tectonic landforms in central Aravalli terrane, Rajasthan using space imagery. Annual Progress Report, ISRO (RESPOND) Research Project, pp. 27. (unpublished).
- Sinha-Roy, S., Malhotra, G., and Mohanty, M. 1998. *Geology of Rajasthan*. Geol. Soc. India, Bangalore, 278 pp.
- Shyampura, P.L. and Sehgal, J. 1995. *Soils of Rajasthan for optimizing land use*. NBSS Publ. (Soils of India Series), National Bureau of Soil Survey and Landuse Planning, Nagpur, 76+6 Sheet Soil Map (1:500,000 scale).
- Srivastava, A., Tripathi, N.K., and Gokhale, K.V.G.K. 1996. Hydrological investigation in Gangetic Basin using remote sensing and basement DEM – a case study, *GIS Development (Geoscience)*, ACRS-1996, 1-4.
- Steven, E. 1991. Satellite remote sensing of mountain geomorphic surfaces. *Canad. Jour. Remote Sensing*, 17(3), 65-67.
- Toleti, B.V.M.R., Chaudhary, B.S., Kumar, K.E., Saroha, G.P, Yadav, M., Singh, A., Sharma, M.P., Pandey, A.C., and Singh, P.K. 2000. *GIS Development (Water Resources)*, ACRS-2000, 1-6.
- Travaglia, C. 1998. Groundwater exploration by satellite remote sensing in the Syrian Arab republic, *FAO, UN, RSC Series*, 76.
- Vaya, P.L. 2001. Integrated management of surface and groundwater : a case of Chambal command area. Kota. In : *Groundwater Resources : Evaluation and Management*, (Eds. : H. Bhu and V. Agrawal), Dept. of Geology, MLS University, Udaipur, 132-138.
- Wodeyar, J.K., Patil, R. and Puranik, S.C. 2001. Geological, geomorphological and hydrogeological studies of Kandra basin, Panhala taluk, Kolhapur district, Maharashtra, In : *Groundwater Resources : Evaluation and Management*, (Eds. : H. Bhu and V. Agrawal), Dept. of Geology, MLS University, Udaipur, 139-142.
- Woods, W.W. 1978. Use of laboratory data to predict sulfate sorption during artificial water recharge. *Ground Water*, 16(1), 22-31.

Woolfenden, L.R. and Koczot, K.M. 2001. Numerical simulation of groundwater flow and assessment of the effects of artificial recharge in the Riolto-Colton basin, San Bernardino County, California, USA., Geol. Survey, Water Resource Investigation Report, 4243, pp. 147.