International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

A Protocol for Groundwater Recharge Capability Assessment Using Multi-Thematic Parameters: An Example from a Semi-Arid Region of Rajasthan, India

S. Sinha-Roy
Birla Institute of Scientific Research
Statue Circle, Jaipur - 302 001, INDIA
E-mail: ssinharoy@yahoo.com

ABSTRACT: The shallow to middle level aquifer systems in semi-arid regions of central Rajasthan, India, are depleted of groundwater resources, showing a steady fall in the water table, due to an imbalance in recharge and abstraction. The Khari-Mashi semi-arid drainage basin (18,800 km^2) in central Rajasthan has been studied for assessing artificial recharge capability by extracting thematic data-sets on different attributes of such parameters as geology, tectonics, geomorphology, hydraulic conductivity and texture of land-cover materials, and pre-and post-monsoon water table fluctuations. The data-base has been used to develop a protocol to identify favourable recharge blocks by quantitative matrix analysis, using multiple parameters, and estimating the Cumulative Recharge Capability Score (CRCS) of 394 cells (50 km^2 unit cell). Several specific sites (1–2 km^2) for artificial recharge have been identified, using the combination of high impact components of selected parameters in blocks having CRCS values between 1400 and 1800.

INTRODUCTION

In spite of the fact that India is a tropical country receiving a good amount of rainfall over large regions a significant part of the runoff water is lost to the sea. The varied hydrogeologic and geomorphologic conditions of many terranes prevent rapid and sustained infiltration of surface waters to replenish the dynamic groundwater system. There is thus an imbalance between abstraction and recharge of groundwater resources. It is therefore imperative to harvest and use unutilized runoff waters to recharge depleted and depleting aquifers (Raju, 1998). Recharge programmes should necessarily take into account many factors including geology, geomorphology and hydrology. Many workers have studied various aspects of these factors using different methodologies to identify favourable sites of groundwater recharge in many countries (Bourgeosis, 1972; Woods, 1978; Ramasamy and Anbazhagan, 1999; Beckman *et al.*, 1996).

In most parts of Rajasthan, India, particularly in arid and semi-arid regions, the aquifers, especially the shallow and middle level ones, are getting depleted at a fast rate, resulting in a rapid drop in water table levels. Because of erratic rainfall and frequent drought conditions together with overexploitation, the groundwater resource is under an acute stress. In order to replenish the depleted aquifers and maintain a sustainable balance between demand and resources artificial recharge is necessary in a scientific manner. For this purpose, the favourable recharge sites need to be identified using various controlling parameters. The purpose of the paper is to present a protocol for recharge zone delineation by quantitative matrix analysis using different attributes of multiple parameters. The case study for the protocol development was carried out in the Khari-Mashi composite drainage basin (18,800 km^2) in central Rajasthan (Figure 1).

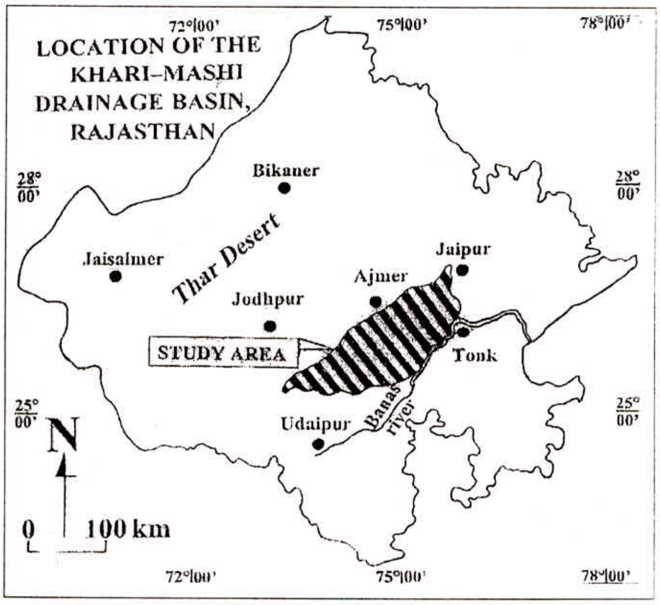

Fig. 1: Location of the study area

GEOLOGIC AND TECTONIC SETTING

The geologic attributes play an important role in determining the potential and efficacy of groundwater recharge, particularly where significant lateral and/or vertical groundwater flow is required between recharge and discharge locations (Phillips, 2002). The key features such as faults and fractures, and spatially extensive porous and permeable lithologies, and suitable land-cover materials 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 drainage basin is a part of the Precambrian terrane of the Rajasthan craton, and it contains basement rock sequences of the Mangalwar Complex and the Sandmata Complex, and the cover rocks of the Proterozoic foldbelts, represented by the Aravalli and the South Delhi foldbelts (Sinha-Roy, *et al.*, 1998). The major part of the area in the southeast is covered by the Mangalwar Complex rocks comprising calc-silicate gneisses, mica-schist, cherty quartzite and migmatites. Another tract of quartzofelspathic gneisses, mica schist and pelitic granulites occurs in the north-west of the study area that belongs to the Sandmata Complex of Late Archaean to Palaeoproterozoic age. The high-grade gneisses occur as thrust-bound slivers within the migmatites and quartzofeldspathic gneisses. Because of this tectonic setting, the region covered by the Sandmata Complex rocks in the northwestern part of the area contains a number of structural lineaments and fracture zones in the basement rocks.

A major dislocation zone, the South Delhi Fault (SDF), separates the Sandmata Complex rocks from the Proterozoic Delhi Group rocks that constitutes the Aravalli hill range. There is evidence to suggest that the SDF is a dextral transpressional fault. At the south-eastern part of the 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 (Sinha-Roy, 2000). Tectonic geomorphologic attributes of all these major dislocation zones indicate their reactivation in Quaternary and Recent times. These features are relevant for groundwater recharge of depleted aquifers of the study area.

The metasedimentary cover sequences are represented by the Aravalli Group (Palaeo- Mesoproterzoic) and the Delhi Group (Meso- Neoproterzoic). The Aravalli Group contains calc-gneisses, marble, quartzite, mica schist and carbonaceous phyllite. The Delhi Group, represented by calc-gneisses, marble, mica schist, quartzite and conglomerate, occurs in the northwest fringe of the area.

Tectonics

Tectonic features play an important role in the infiltration of surface waters underground through accessible zones of weakness and fractures of the bedrocks 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 controls of permeability of faults in recharge and aquifer transmissibility have been demonstrated by Flint (2002), Phillips (2002) and Woolfenden and Koczet (2001).

In order to delineate the tectonic zones that would aid surface water infiltration underground, different types of tectonic features such as extensional faults, strike-slip faults, major fracture zones, highly jointed zones and tectonic basins have been mapped. Study on neotectonics of central Aravalli terrane, Rajasthan (Sinha-Roy, 1986, 2001) indicated that active tectonics in these dislocation zones has produced a number of fault-bound tilted tectonic blocks and pull-apart basins. These blocks control the magnitude and direction of regional and local ground slope, while the tectonic basins are sites of 30–75 m thick Quaternary and Recent sediments that host shallow aquifer systems.

The extensional faults generally trend north-south in the northern and eastern parts of the Mashi sub-basin while they trend almost east-west in the southwestern part of the Khari sub-basin. In the Mashi 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. The length of strike-slip fault traces varies from 20 km to as long as 110 km, and they off-set the stream courses at many places. The strike-slip and extensional faults cross-cut one another at high angles in the Mashi sub-basin.

There are many fracture zones of variable widths and lengths. The frequency of these fracture zones is variable. For example, there is a high density of fracture zones in the northwestern and southeastern parts of the Khari sub-basin. The fracture zones have variable orientation, and are both linear and curvilinear. Generally, these zones vary in length from nearly 5 km to as high as 60 km, and are almost parallel to the strike-slip faults in the Mashi sub-basin while they are oblique to the strike-slip faults in the Khari sub-basin. Since in many cases the fault and fracture system controls the location and channel orientation of the tributary streams of all orders, it is inferred that most of these structural zones are neotectonic in origin or are products of Quatrenary reactivation of older structures. These have affected in some cases the sediments of alluvial plain 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.

Fault and Fracture Zone Intersections

The frequency of intersection of the tectonic features depends on their individual spacing and on the spatial frequency variations of the individual tectonic zone. The following are the principal features.

The intersection density is divided into 7 groups with values ranging from 0 to 16 intersections per 50 km^2. The high density (14–16 per 50 km^2) is restricted in the northern part of the area. The major part belongs to the density group of 1–3 per 50 km^2. Other frequency groups (4–6, 7–9, 10–12 per 50 km^2) occur in isolated areas where the intersections are mostly between fracture zones of different orientations. The intersection frequency does not seem to have any relationship with the lithological variation, rather it is related to the spacing and location of the fault systems and fracture zones.

GEOMORPHOLOGIC SETTING

Landform characteristics play an important role in replenishment of both surface water and groundwater resources of drainage basins. Moreover, the different geomorphologic units, characterizing the landform, contribute significantly to the recharge capability 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).

The study area is a 5th order drainage sub-basin of the major Banas basin. There is a spatial variation in the development of streams of various orders within the sub-basin. This feature together with the variation in drainage density and drainage frequency indicate inhomogeneous bedrock lithology and non-uniform tectonic grains of the terrane. The streams traversing major fault zones show prominent knickpoints in their longitudinal profiles that provide clue to the location of buried faults. Tilting of tectonic blocks is indicated by the reversal of the ground slopes, and by variations in along-river and valley gradients. The altitude frequency indicates three altitudinal domains, namely, the highland (500–800 m), represented by the Aravalli hill range, the midland (400–500 m), comprising the Aravalli foothills and the pediment, and the lowland (200–400 m), representing the expansive peneplain filled with alluvium and dune materials. Hypsometry of the area indicates extensive advective mass-wasting, and area-specific erosion in the highland, and colluvium generation and mass accretion in the midland due to spatially variable neotectonic activity (Sinha-Roy, 2002).

The altitudinal domains contain 9 important geomorphic units. These are: inselberg, pediment, alluvial fan, intermontane valley, flood plain, palaeochannel, alluvial plain, gully with exhumed calcrete, saline lake. These units have different groundwater recharge capabilities because of their variable transmissibility caused by variable hydraulic conductivity of the land-cover materials comprising soils and sub-soil sediments.

GROUNDWATER TABLE GEOMETRY

The depth to groundwater table in the area in the pre-monsoon period varies from 3 m to 70 m, and in the post-monsoon period, from 1 m to 65 m. The range of variation of water table depth between these two periods is not large, but in specific areas the differential may be high. The general geometry of water table of shallow aquifers during pre-and post-monsoon periods is almost similar except for rise in the water table in the pediment zone of the highland due to natural recharge at the water divide. The depth decreases from the highland catchment boundary toward the central part of the drainage basin in the midland and lowland regions (Figure 2).

The groundwater table geometry (Figure 3) shows several troughs and ridges because of variations in aquifer transmissibility and hydraulic conductivity of land-cover materials in 3-D, and also due to intervention of faults that act either as conduit of or barrier to groundwater flow. Water table troughs are associated with major strike-slip fault zones while the extensional faults have given rise to water table ridges. The geometry is almost stable through the year 2005 between pre- and-post-monsoon periods, and also during the last 10 years, suggesting a strong impact of faults, geomorphic features and land-cover materials on groundwater recharge and flow regimes.

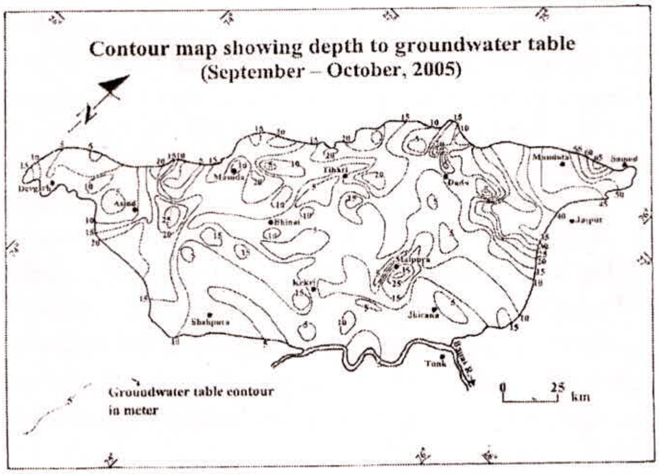

Fig. 2: Depth to water table configuration

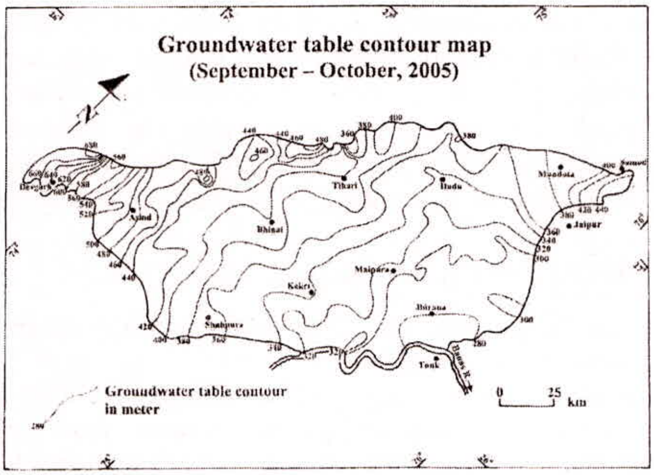

Fig. 3: Water table geometry

GROUNDWATER FLOW PATTERN

The groundwater flow pattern (Figure 4) has been deduced from the water table configuration. The diagram also shows the locations of the major faults, numbered 1–12. The flow pattern is multi-directional, considered to have been caused by the influence of faults and fractures zones, and the quartzite ridges that dissect the aquifer system, all of which acting either as barrier to or conduits of groundwater flow, and by the influent or effluent streams.

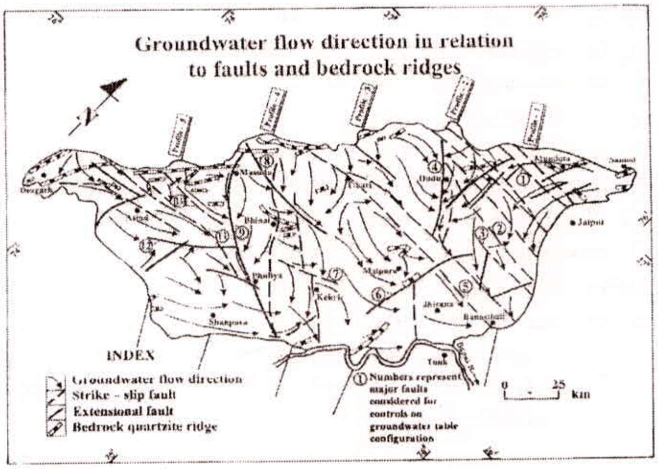

Fig. 4: Groundwater flow pattern in relation to faults

Neotectonic study (Sinha-Roy, 1986, 2001) reveals the presence of prominent faults that divide the area into three neotectonic blocks showing variable groundwater flow patterns (Figure 5). The general flow directions in Block 1 is toward east while that in Block 3 it is toward southwest and south. In Block 2 the flow swerves from southerly to almost westerly near the alluvial plains of the Banas river. Clearly, neotectonics have influenced the flow regime, dividing the aquifer system into groundwater domains.

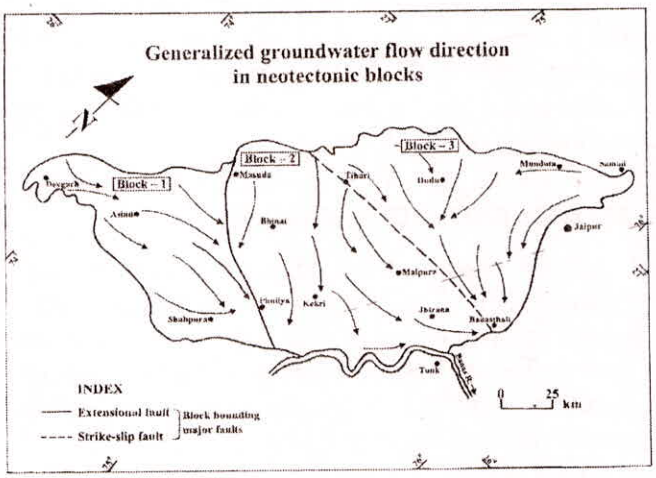

Fig. 5: Flow pattern in fault-bound groundwater domains

RECHARGE CAPABILITY ASSESSMENT PROTOCOL

The record shows that the groundwater table of the study area is steadily falling in recent years (Resource Atlas of Rajasthan, 1994). This would mean that the shallow aquifers are heavily depleted, and contains unsaturated zones that would offer targets for artificial recharge. For effective and sustainable recharge schemes the assessment of the recharge capability of the study area and identification of specific recharge sites are important. Since many factors, some of which have been mentioned above, either control or contribute to recharge process and its efficacy multi-parametric approach for generating a protocol for recharge capability assessment is useful. Moreover, the approach will be strengthened if multiple attributes of each parameter are considered for recharge assessment analysis.

The protocol is based on quantitative matrix analysis using a data-base involving multiple parameters and more than one attribute of each parameter of the recharge controlling factors.

Recharge Controlling Parameters

The data-base used for matrix analysis included the following parameters and their multiple attributes.

1. Geology represented by 5 recharge-controlling rock types, namely conglomerate, quartzite, mica schist, migmatites and fractured marble.
2. Geomorphology represented by 5 recharge-controlling geomorphic units, namely, flood plain, palaeochannel, alluvial fan, intermontane valley, gullied area.
3. Ground slope of 5 categories with slope range varying between 0.3% and > 1.8%.
4. Fault and fracture zone intersection density of 5 categories with density range varying between 1 and 16 per 50 km^2.
5. Drainage density of 5 categories with density range varying between 0.40 and > 0.60 km/km^2.
6. Soil profile represented by 5 morphologic types, namely, sandy, loamy, calcareous, calcareous loamy and saline/acidic.
7. Hydraulic conductivity of soil divided into 5 categories with values ranging between < 0.5 and > 30 cm/hr.
8. Hydraulic conductivity of sub-soil sediments divided into 5 categories with values ranging between < 0.5 and > 30 cm/hr.
9. Grain size of soil represented by recharge-controlling size-range (0.5 mm > 2 mm) whose frequency has been divided into 5 categories between < 20% and > 80%.
10. Grain size of sub-soil sediments represented by recharge-controlling size-range (0.5 mm > 2 mm) whose frequency has been divided into 5 categories between < 20% and > 80%.
11. Post-monsoon rise of groundwater table represented by 5 categories within the range of 0 (no change) to > 12 m.

Matrix Analysis

Quantitative matrix analysis is a powerful method to treat multivariate thematic and spatial data-sets of parameters extracted from various components of a terrane in order to identify the matrix cells that would have concentration of high-ranked parameter attributes having high impact values. The analysis is thus capable of locating blocks where the desired process is likely to operate effectively or a favourable domain characters are likely to be present. In the present protocol, both these aspects are important because the desired process involves infiltration of surface waters underground, and the domain character concerns recharge capability.

The protocol involves the following steps.

1. The study area is divided into 394 cells on a grid with each unit cell having an area of 50 km^2. At the margin of the study area the cell dimensions are less than the unit cell area, and are variable because of irregular nature of the drainage basin water divide.
2. Quantified thematic maps are prepared for each of the 11 recharge-controlling parameters.
3. Each parameter has been ranked (1 to 5) on the basis of their importance factor and positive impact value on groundwater recharge potential. The rank values indicate an impact scale from slight (rank 1) through appreciable, significant, major to strong (rank 5). The highest rank (5) has been assigned to hydraulic conductivity of soil and sub-soil sediments and post-monsoon rise of groundwater table while rank-4 has been given to drainage density and bed-rock jointing, fault and fracture zone intersection density, soil types, grain-size of soil and sub-soil sediments. Rank-3 has been assigned to geomorphologic attributes including ground slope while the lowest rank (2) is given to lithologic attributes because the purpose of this exercise is to determine the recharge potentials of the terrane for shallow to middle level Quaternary alluvial aquifer system.
4. 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. In the present case, the total rank value is 43. In order to make PIV values whole numbers, the values are multiplied by 100. The PIV values thus obtained vary between 4.65 and 11.62.
5. 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).
6. 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), WRC values are normalised against the unit cell area to obtain the Normalised Weighted Recharge Capability (NWRC) value for each attribute of the cell.

7. 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.
8. 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.

Potential Recharge Blocks and Sites

Figure 6 shows the cell-wise distribution of the CRCS values grouped into 5 range-classes, namely, 800–1000, 1001–1200, 1201–1400, 1401–1600, and 1601–1800. Out of these, CRCS values > 1400 are considered significant, and the blocks, numbered 1–10 (Figure 7), having the CRCS values in the range of 1400-1800 might have very good to excellent groundwater recharge potential.

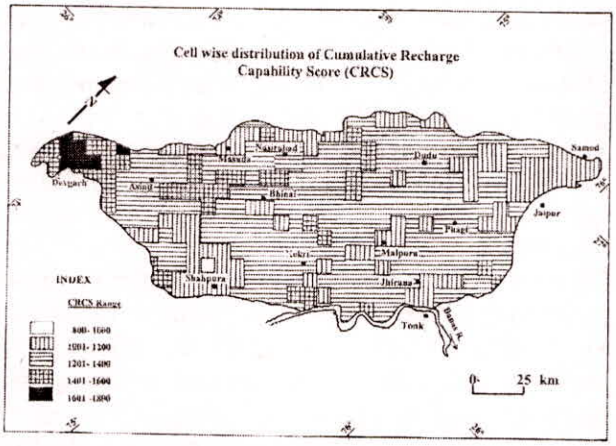

Fig. 6: Cell-wise spatial distribution of CRCS values

In order to further reduce the area of potential recharge from unit cell size (50 km^2) to smaller area locating specific recharge sites for execution of recharge programmes within each of these cell-clusters detailed maps have been prepared for all the 10 cells showing the details of topography, stream network, fault and fracture zones, areas of high bed-rock jointing, tectonic basins and graben structures, hydraulic conductivity of soil and sub-soil sediments and groundwater flow directions. A combination of the following factors is taken in into account to locate the specific recharge sites of 1–2 km^2 dimension in each cell: (i) intersection zones of the maximum number of faults and fractures zones, and highly jointed bed-rock substrate, (ii) highest soil and sub-soil sediment hydraulic conductivity zones, (iii) up-flow segments of groundwater flow paths, (iv) low ground slope at topographic lower elevations, (v) tectonic basins where the thickness of the Quaternary sediments, hosting the shallow aquifers, is high. An example of one such cell-cluster, showing the recharge sites, is given in Figure 8.

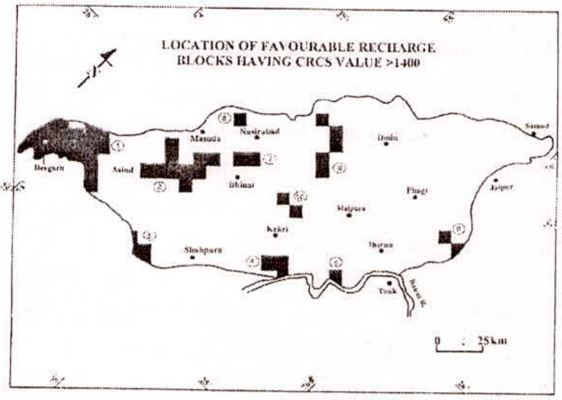

Fig. 7: Cell-wise distribution of recharge favourable CRCS values > 1400

SUMMARY

The groundwater table in arid and semi-arid regions of Rajasthan, is steadily falling in recent years because of an imbalance in groundwater recharge and abstraction. The shallow to middle level aquifer systems are heavily depleted, and form potential targets for artificial recharge. In view of this, the Khari-Mashi drainage basin (18,800 km^2) in semi-arid central Rajasthan has been studied to develop a protocol for recharge capability assessment and recharge site identification, using multiple parameters.

A number of attributes of each of 11 parameters, comprising geology, tectonics, geomorphology including ground slope and hypsometry, hydraulic conductivity of land-cover materials, and pre-and post-monsoon water table fluctuations, have been used in quantitative matrix analysis to estimate Cumulative Recharge Capability Score (CRCS), ranging from 800 to 1800, of 394 cells (unit cell = 50 km^2). 10 cell-clusters having CRCS values between 1400 and 1800, considered significant and most favourable for recharge, have been identified. On the basis of spatial distribution of high impact components of studied parameters several specific recharge sites (1–2 km^2) have been located in each high CRCS cell clusters.

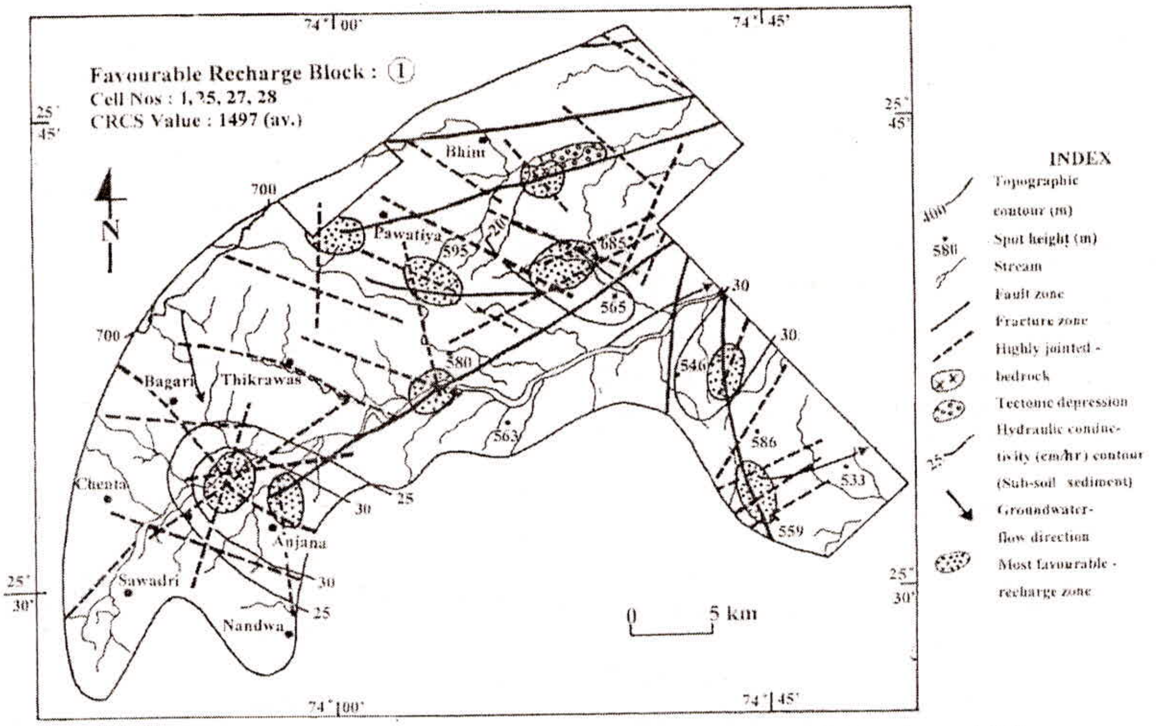

Fig. 8: Location of potential recharge sites in cell-cluster of CRCS value > 1400

ACKNOWLEDGEMENTS

The study forms a part of the project sponsored by the Ministry of Water Resources, Govt. of India, New Delhi. The support of the INCOH Secretariat, Roorkee, is thankfully acknowledged.

REFERENCES

Beckman, H.E., Gieske, A. and Selaolo, E.T. (1996). "GRES: Groundwater rechrage studies in Botswna 1987–1996." *Botswana J. 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." *J. Indian Soc. Remote Sensing*, 7(1), 1-9.

Bourgeosis, P.O. (1972). "Notes on developing groundwaters." *Water and Pollution Control.* 110(10), 24–28.

Das, D. and Khan, F. (2001). "Application of remote sensing and GIS techniques for selecting artificial rescharge 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.

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.

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. Kuniansky), *USGS Open File Report*, 02–89.

Garza, L.D.L. (1886). "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. Abbot and C.M. Jr. Woodruff), *Bull. Geol. Soc. Amer.* 131-135.

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." *J.. of Hydrology*, 2, 73–91.

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*, London, 715 pp.

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, *J. Geol. Soc. India*, 51, 429–454.

Ramasamy, S.M. and Anbazhagan, S. (1997). "Criteria and techniques of detecting site specific mechanisms for artificial recharge—a case study from Ayyar basin, India." *J. Geol. Soc. India*, 50, 449–456.

Resource Atlas of Rajasthan. (1994). *Department of Science and Technology, Govt. of Rajasthan,* Jaipur, 231 pp.

Saraf, A.K. and Chaudhary, P.R. (1998). "Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites." *Internat. J. 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 Sonebhadra 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." *Proc. Internat. Symp. 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 Highlights 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. (2001). "Neotectonic significance of longitudinal river profiles—an example from the Banas drainage basin, Rajasthan." *J. Geol. Soc. India*, 58, 143–156.

Sinha-Roy, S. (2002). "Hypsometry and landform evolution—a case study in the Banas drainage basin, Rajasthan with implications for Aravalli uplift." *J. Geol. Soc. India*, 60, 7–26.

Sinha-Roy, S., Malhotra, G. and Mohanty M. (1998). Geology of Rajasthan, *Geol. Soc. India,* Bangalore, 278 pp.

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. J. 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: Eavaluation and Management, (Eds.: H. Bhu and V. Agrawal), *Dept. of Geology, MLS University,* Udaipur, 132–138.

Wodenyar, J.K., Patil, R. and Puranik, S.C. (2001). "Geological, geomorphological and hydrogepological 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. Surv. Water Resource Investigation Report,* 4243, 147 pp.