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New Indicator Based Method SALDIT for Delineation of Natural Groundwater Recharge Areas

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Abstract

A structured approach based on indicators evaluation technique has been developed as a technical tool to help demarcating the potential groundwater recharge areas. The tool is a generic and can be applied universally. Based on a combination of field experience and expert opinion six measurable indicator parameters viz**.,S**lope of the ground, **A**quifer specific yield, **L**and and soil cover, **D**epth to groundwater table, **I**nfluence of surface geology and **T**opographic features of the location have been identified for assessing the groundwater recharge potential. The acronym **SALDIT** is formed from the highlighted and underlined letters of the indicator parameters for ease of reference. Each of these indicators was assigned **a relative weight** and **importance ratings** for the indicator variables based on the Delphi technique. The total indicator score derived by summing the individual indicator scores obtained by multiplication of importance ratings with the corresponding indicator weight can be used for delineating the potential groundwater recharge areas. In the paper the methodology is explained and the application of the method is given.

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1. Introduction

An important aspect of managing groundwater involves understanding how, where and how much groundwater resource is being replenished or recharged. As water moves from the surface through the unsaturated zone a proportion will be lost to evaporation, some will be taken up by plants (evapotranspiration) and some will remain within the unsaturated zone. These processes determine a rainfall threshold above which groundwater recharge can effectively occur. Rainfall amounts below the recharge threshold make little or no contribution to groundwater recharge.

The significance of each of the factors controlling recharge will vary from place to place and may vary over time as land-use and vegetation cover changes. The removal of deep rooted plants in favour of crops, or plantation establishment in former pasture country can have an impact on the volume of water entering groundwater systems. It can be important to manage land use to protect both the quality and volume of water entering aquifer systems.

Groundwater recharge is defined as water which infiltrates into the ground to a depth below the root zone. This definition does not differentiate between recharge to aquifers and recharge to non-aquifers. The sources of recharge to a groundwater system include both natural and human-induced phenomena. Natural sources include recharge from precipitation, lakes, ponds, and rivers (including perennial, seasonal, and ephemeral flows), and from other aquifers. Human-induced sources of recharge include irrigation losses from canals and fields, leaking water mains, sewers, septic tanks, and over-irrigation of parks, gardens, and other public amenities. Recharge from these sources has been classified as *direct or diffuse recharge* from percolation of precipitation and *indirect recharge* from runoff ponding.

The geographical location and aerial extent from where the recharge takes place are crucial factors as these influence the water quality and quantity of recharge. For sustainable groundwater quality and quantity the groundwater recharge areas therefore need to be protected from adverse effects arising from human activities at all times.There are various well-established methods for the quantitative estimation of recharge to the groundwater regime (Alivia et al. 2009, Cook et al. 1989, Kennet et al. 1994, Mandal and Singh, 2004, Sukumar and Sankar 2010, Thomas Harter 2002, TimothejVerbosek 2006 etc). However, methodology for identification and delineation of potential groundwater recharge areas are inadequate.

2. Problem definition

The literature reviews indicate that there is need to develop aversatile scientific method to identify and delineate the areas of natural groundwater recharge in a watershed taking into account important intrinsic parameters of the area and the aquifer. Therefore, in the present study it is aimed to develop an indicator based mapping system that is simple enough to apply using the available data, and yet capable of making best use of available data in a technically valid and useful way. The Paper discusses developing predictive relationships for natural groundwater recharge based on the major recharge-influencing factors, and regionalizing point recharge data.

3. Methodology

One of the systems for evaluation of natural groundwater recharge sites include an indicator based system which is computed from hydrogeological, morphological, and other aquifer characteristics in a well-defined way. The adoption of an index has the advantage of, in principle, eliminating or minimizing subjectivity in the ranking process.

3.1 Suggested system of evaluation and ranking

Inherent in each of the watersheds are the physical characteristics of the system that affect the natural groundwater recharge potential at a point. The most important measurable parameters (indicators) that influence the natural groundwater recharge are found to be;

1. **S**lope of the Ground.
2. **A**quifer Specific Yield.
3. **L**and and Soil Cover.
4. **D**epth to Groundwater Table.
5. **I**nfluence of Surface Geology.
6. **T**opographic Features of the Location.

The acronym **SALDIT** is formed from the highlighted first letter of each of the parameters for ease of reference. These parameters, in combination, are determined to include the basic requirements needed to assess the potential of natural groundwater recharge at a location. **SALDIT** parameters represent measurable parameters for which data are generally available from a variety of sources.

A numerical ranking system to assess recharge potential in hydrogeologic settings has been devised using **SALDIT** parameters. The system contains three significant parts: weights, ranges and ranking. Each **SALDIT** parameter has been evaluated with respect to the other to determine the relative importance of each parameter. The basic assumption made in the development of the technique include: spatially unlimited water table aquifer without vertical flow retarding layers in the vadose zone. The rainfall will occur uniformly over the area.

The various parameters adopted in the evolution of the present indicator tool include:

(i) Identification of all the ***parameters*** influencing the natural recharge to groundwater.
(ii) Assigning ***weights:*** parameter weights depict the relative importance of the given parameter to recharge process. The most significant parameters have highest weight of 6 andthe least a lowest weight of2 indicating parameter of less significance in the process of groundwater recharge. Parameter weights may be considered as constants and may not be changed under normal circumstances.
(iii) Assigning of ***rankings***to parameter variables. Each of the parameter is subdivided into variables according to the specified attributes to determine the relative significance of the variable in question on the process of groundwater recharge. The ranking range between 1 and 14. Higher ranking indicates high recharge potential in the location.
(iv) ***Decision criterion*****:** Is the total sum of the individual parameter scores obtained by multiplication of values of rankings with the corresponding parameter weights and dividing it by total of the weights. Higher the value of the score at a location; more is the potential for groundwater recharge.

4. An open ended model

The system presented here allows the user to determine a numeric value for any watershed setting by using an additive model. This model is an open-ended model allowing for addition and deletion of one or more parameters. However, under normal circumstance, present set of parameters should not be deleted and any addition and deletion of the parameters(s) would require re-deriving of the weights and the classification table. Following are the weights assigned to each of the parameters identified for the purpose:

Parameters influencing recharge	Relative weights
1. **S**lope of the Ground.	3
2. **A**quifer Specific Yield.	2

3.	**L**and and Soil Cover.	4
4.	**D**epth to Groundwater Table.	5
5.	**I**nfluence of Surface Geology.	6
6.	**T**opographic Features of the Location.	6

In the above list of parameters the last two have equal weights indicating these two parameters are equally important in affecting the recharge potential at a location. The sum of the total weights is therefore 26.

4.1 Indicator description

Slope of Ground (S): ground slopes can be expressed in percentage slope indicating steepness of the ground. Slopes which provide greater opportunity for rainwater to infiltrate will be associated with high recharge areas. **Table 1** contains the slope ranges which are identified as significant relative to recharge to groundwater. These slope ranges are adopted from DRASTIC (1987) model. The slope ranges are assigned ranks assuming that 0 to 2 percent slope provides greatest opportunity for the rainwater to infiltrate. Conversely 18+ percent slope affords a high runoff capacity and therefore a lesser probability of infiltration. Slope map can be generated from Survey of India or other Topographical map.

Table 1. Ranks assigned to different ground slopes

Parameter	Weight	Ground slope ranges in %	Assigned ranks
Slope of Ground	3	0 - 2	10
		>2 – 6	9
		>6 – 12	5
		>12 – 18	3
		>18	1

***Aquifer specific yield (A)**:* If at a given location on the ground one requires to find the recharge potential then it is necessary to have an adequate storage space below that site to accommodate the recharged water in other words the aquifer underneath should have reasonably adequate specific yield value. The aquifer storage capacity can be expressed in terms of its storativity/specific yield.**Table 2** provides various ranges of aquifer specific yield and the corresponding ranks for computing the score of this indicator. Thus the aquifer having higher specific yield should be able to absorb and retain more water and hence higher rank. The information required for the above variable can be gathered from analysis of aquifer test data and reference tables based on the geological information in the location.

Table 2. Ranks assigned to different ranges of aquifer specific yields

Parameter	Weight	Range of the Parameter (fraction)	Assigned ranks
Aquifer Specific Yield	2	<0.01	1
		>0.01 to 0.04	2
		>0.04 to 0.08	3
		>0.08 to 0.10	4
		>0.10 to 0.15	5
		>0.15 to 0.20	6
		>0.20	7

Land and Soil Cover (L):The US SCS Curve Number method was developed by Ogrosky and Mockus (1957) for determining peak rate of runoff from small watersheds. A runoff curve number (CN) was developed through field studies by measuring runoff from different soils at various locations. The antecedent moisture condition and the physical characteristics of the watershed are correlated to give hydrologic soil groups. The four soil types as defined by the Soil Conservation Services are as under:

- **Soil Group A:** Soils with low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand, gravel, loess and aggregated silts (high rate of water transmission of 8 - 12 mm/hr).
- **Soil Group B:** Soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep and well drained soils with moderately fine to coarse textures. These soils have a moderate rate of water transmission (4 - 8 mm/hr). Shallow loess and sandy loam are main constituents.
- **Soil Group C:** Soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine textures such as clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay. These soils have a low rate of water transmission of 1 – 4 mm/hr).
- **Soil Group D:** These soils have high runoff potential and have very low infiltration rates when wetted thoroughly and consist chiefly of clay soils with a high swelling potential, soils with permanent high water table, soils with clay pan at or near surface, shallow soils over nearly impervious material, heavy plastic clays and saline soils. These soils have a very low rate of water transmission of 0 - 1 mm/hr.

Generally the US SCS curve numbers range from less than 30 to 100, the highest curve number representing more runoff or less groundwater recharge. In the present model the US SCS curve numbers from 30 onwards have been grouped into ranges with an increment of 5 and sequential rank numbers have been assigned to each range (**Table 3**). The curve number less than 30 will have the highest rank of 15. Higher the rank number more the recharge to groundwater.

Table 3. Rank assigned for ranges of US SCS Curve numbers

Parameter	Weight	CN Range	Assigned ranks
Land and Soil Cover	4	<30	15
		>30-35	14
		>35-40	13
		>40-45	12
		>45-50	11
		>50-55	10
		>55-60	9
		>60-65	8
		>65-70	7
		>70-75	6
		>75-80	5
		>80-85	4
		>85-90	3
		>90-95	2
		>95	1

The curve numbers are derived for conditions of normal antecedent moisture condition (AMC) II and I_a=0.2S, where I_a is initial abstraction consisting of interception, depression storage and infiltration and S is potential maximum retention in the US SCS method of runoff estimation. The information on the soil types can be gathered from the existing soil maps of the watershed or field surveys and land use maps and satellite images can provide land cover data to find the CN values.

Depth to groundwater table (D): Pre monsoon depths to groundwater table are important primarily because it determines the extent of storage space available for recharged water. Very shallow water table conditions (< 2m) may not be suitable as little space is available for recharged water to get stored. The following **Table 4** shows the relative importance of the water table depths with ranking values.As the depth to water table increases the thickness of the vadose zone increases and this zone shall retain most of the recharged water in the form of soil moisture and hence may not add significantly to the groundwater table therefore the low value of ranking are given. In humid areas 5 to 10m water table depth is observed to receive maximum recharge to aquifer. The situation of "absence of water table and vadose zone" can be witnessed in steep slopes, escarpments, compact rocks etc., and "no water table but presence of permeable vadose zone" situation may be seen on plateaus, hill tops, elevated areas, mountains and hill slopes where the groundwater recharge takes place due to presence of permeable vadose zone which later slowly percolates downhill to recharge the lower areas. This situation is given high ranking because the recharged water moves out steadily from the vadose zone and is available for recharging the lower reaches of the area even after cessation of precipitation.

Table 4. Ranks assigned to different ranges of depth to water levels

Parameter	Weight	Depth to water level below ground (m)	Assigned Ranks
Depth to Water Table below Ground	5	<2	1
		>2 - 5	5
		>5 – 10	6
		>10 – 15	4
		>15 – 25	3
		>25	2
		Water Table and Vadose Zone absent	1
		No Water Table but Permeable Vadose Zone exist	**5**

WT depth ranges are adopted from DRASTIC (1987) model with modifications. The data is generally obtained from the field by measurements of water levels in open wells.

Influence of Surface Geology (I): The nature of geological surface exposed as outcrop plays an important role in influencing the infiltration rate at a site. The rainwater first comes in contact with the exposed rocks on the surface and therefore the characteristics of these outcrops should be considered while assessing the recharge potential of a site. The following **Table 5** gives the rank values for different outcrop surfaces. The data related to the parameter variable can be obtained from topographic/geological/soil maps and other sources.

Table 5. Ranks assigned to different surface geological outcrops

Parameter	Weight	Parameter Variables	Assigned ranks
Influence of Surface Geology	6	Soft and Permeable surface materials, ex: , unconsolidated sediments, glacial sediments, valley fill sediments, alluvial deposits, sand dunes etc.	4
		Hard but Weathered and Fractured rocks, ex: Precambrian rocks, laterites etc	3
		Soft but impermeable rock/soil matrix, ex: compact sand stone, lime stone, clay, silt etc	2
		Hard and Compact rocks, ex: granite, basalt, laterites etc	1

Topographic features (T): The topography of an area is represented by surface expressions of the land mass. Topography is significant because gradient and direction of flow often can be inferred for water table conditions. The nature of topographic features help in identifying the areas suitable for groundwater recharge. The concave shaped plateaus with inward slopes can retain rainwater for longer periods and help recharge the groundwater compared convex plateaus from where the rainwater rapidly drains as surface runoff (**Fig. 1**). The following **Table 6** shows the broad topographic features that are generally found. The data related to the parameter variable can be obtained from topographic maps and other sources.

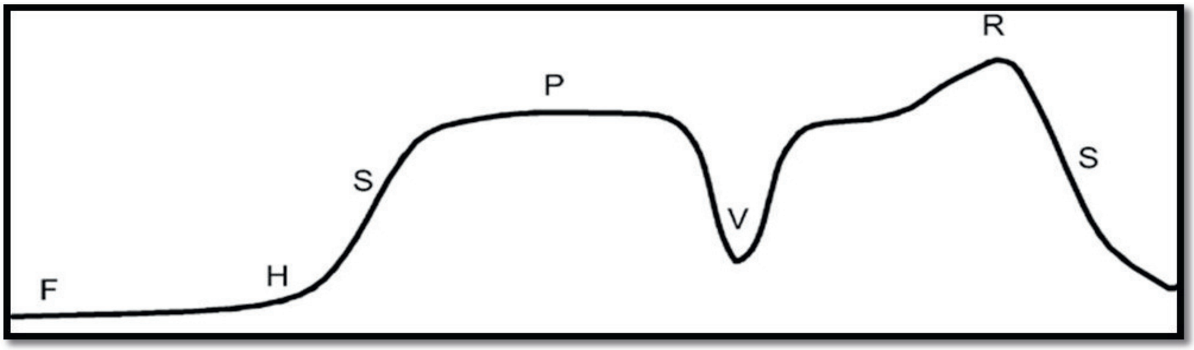

Fig. 1.Topography classes. V: valley bottoms, R: ridges, P: plateaus, S: slopes, F: flatlands in topographic lows and H: foothills

Table 6. Ranks assigned to different topographic features

Parameter	Weight	Parameter Variables	Assigned ranks
Topographic Features	6	Flat/Plain Areas; flood plains, coastal plains, intermountain valley	6
		Plateaus with Concave surface	5
		Plateaus with Convex surface	3
		Valley Floors	4
		Foot Hills of Mountains	3
		Mountain/Hill Slopes	2
		Mountain/Hill Ridges	1
		Permeable Karst topography	7

It is evident that all the parameters are interacting and dependent variables. Their selection is based on a subjective understanding of "real world" conditions at a given location. The values of the parameters can be obtained and meaningfully mapped in a minimum time at a minimum cost. The scheme can be applied for comparative evaluation.

5. Computing the SALDIT index

Each of the six parameters has a pre-determined fixed weight that reflects its relative influence on groundwater recharge potential. The SALDIT **I**ndex score is then obtained by computing the individual parameter scores and summing them as per the following expression:

$$\textbf{SALDIT-Index score} = \sum_{i=1}^{6} \{(W_i)R_i\} / \sum_{i=1}^{6} W_i \qquad (1)$$

Where W_i is the weight of the i^{th} parameter and R_i is the rank value of the i^{th}parameter variable.

Thus, the user can use hydrogeological, soil, vegetation, geological, landuseand topographic information of the area of interest and choose variables to reflect specific conditions within that area and select corresponding rank values and compute the SALDIT parameter score. This system allows the user to determine a numerical value for any hydro-geographical setting by using this additive model. The **maximum SALDIT-Index score** is obtained by substituting the maximum ranking values of the parameter variables as shown below:

$$Max = \{(W_1)*R_1 + (W_2)*R_2 + (W_3)*R_3 + (W_4)*R_4 + (W_5)*R_5 + (W_6)*R_6\} / \sum_{i=1}^{6} W_i \quad (2)$$

where, $W_1, W_2, \ldots\ldots\ldots W_6$ are the weights of the parameters 1 to 6 respectively and $R_1, R_2, \ldots\ldots\ldots\ldots\ldots, R_6$ are the corresponding maximum rank values of each parameter variables. By substituting the parameter weights and the maximum rank values of the variables of each parameter we get the maximum SALDIT-Index score as;

$$Maximumscore= \{(3)*10 + (2)*7 + (4)*15 + (5)*6 + (6)*4 + (6)*7\} / 26= 7.69 \quad (3)$$

Similarly, the **minimum SALDIT-Index score** is obtained by substituting the minimum rank values of each parameter variable as shown below:

$$Minimumscore= \{(3)*1 + (2)*1 + (4)*1 + (5)*1 + (6)*1 + (6)*1\} / 26 = 1 \quad (4)$$

Therefore, the minimum and maximum SALDIT index score values are**1** and **7.69** respectively. The potential of the area to natural recharge is assessed based on the magnitude of the SALDIT Index score. In a general way, lower the index score lesser recharge to groundwater.

6. Decision criteria

Once the SALDIT-Index has been computed, it is therefore possible to classify the location in question into various categories of recharge potential. The range of SALDIT-Index scores (1 to 7.69) is divided into 4 categories as shown in **Table 7** below**.**

Table 7.Categorization of groundwater recharge potential using SALDIT index

Sr. no.	SALDIT-Index Range	Recharge Potential Category
1	1 to <3	Least
2	3 to <5	Moderate
3	5 to 7	High
4	>7	Very High

7. Application of the SALDIT-case study in Goa, India

The above methodology has been applied to a case study area. The study area falls in South Goa District located along the Arabian Sea coast. The area is covered in toposheet no 48E15-SE of 1:25000 scale, and cover an area of 41 km^2 (**Fig.2(a)**). The villages that fall in the area include Consu, Velsao, Cansaulim, Arrosim, Majorda, Utorda, Betalbatim, Colva, and Benaulim from north to south. The area is generally plain except in the northern part where a lateritic plateau exists at about 60 to 80m above mean sea level (msl) and rest of the area has 5m to 20m above msl which includes the stretches of sandy beach, mudflats, fields and settlement areas**Fig. 2(b)**. The major part of the study area is covered by settlements and in the low lying valley plains paddy cultivation is extensively practiced. The beach is seen to extend along the western margins from north to south. The area is covered mainly by loose

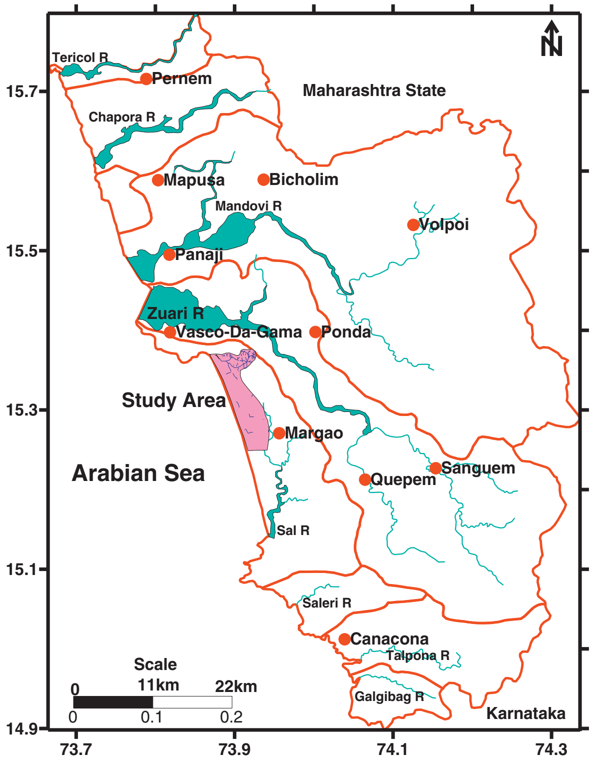

Fig. 2(a): Location of the study area in Goa India

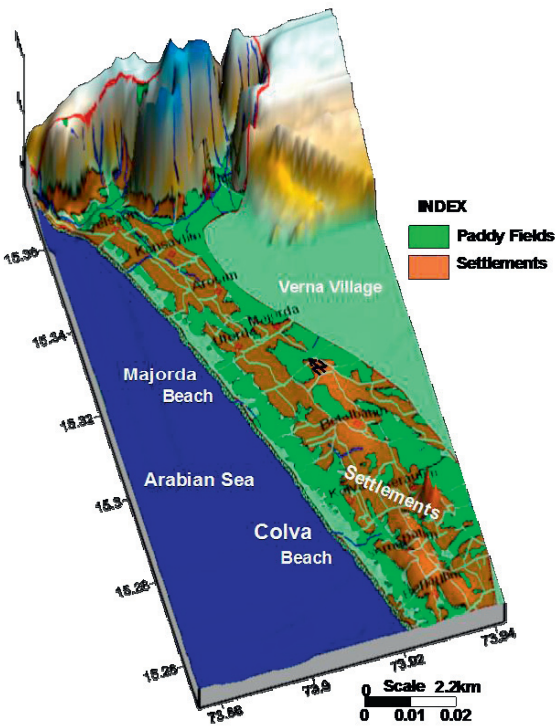

Fig. 2(b): 3D topography of the study area

sandy loam and at places lateritic rocks, majority of the sand dunes are stabilized and have plantations and settlements on them. The underlying parent rocks include weathered metabasalts and meta-gabbros in the north eastern and central region and granitic gneiss in the southern region.

The SALDIT index scores at each of the 100 groundwater level observation well locations were computed. These SALDIT values were used in the SURFER package to draw the contour map depicting potential groundwater recharge areas as shown in **Fig. 3(a)**. The groundwater level fluctuation map for the area is shown in **Fig. 3(b)** which does not exactly corroborate the SALDIT score map. Higher water table fluctuations are not necessarily the areas of potential groundwater recharges. Major portion of the study area shows moderate to high recharge potential.

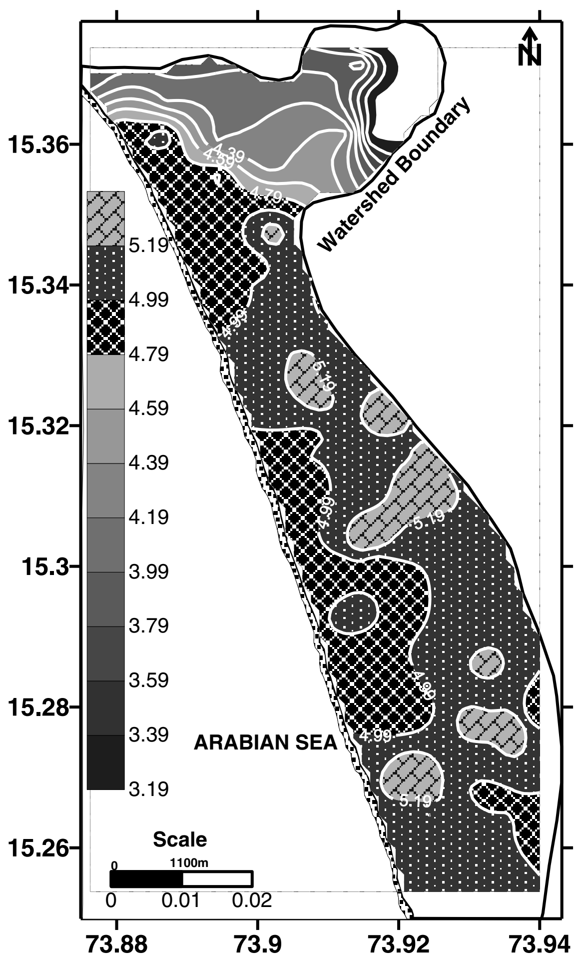

Fig. 3(b) Water table fluctuation map for the study area

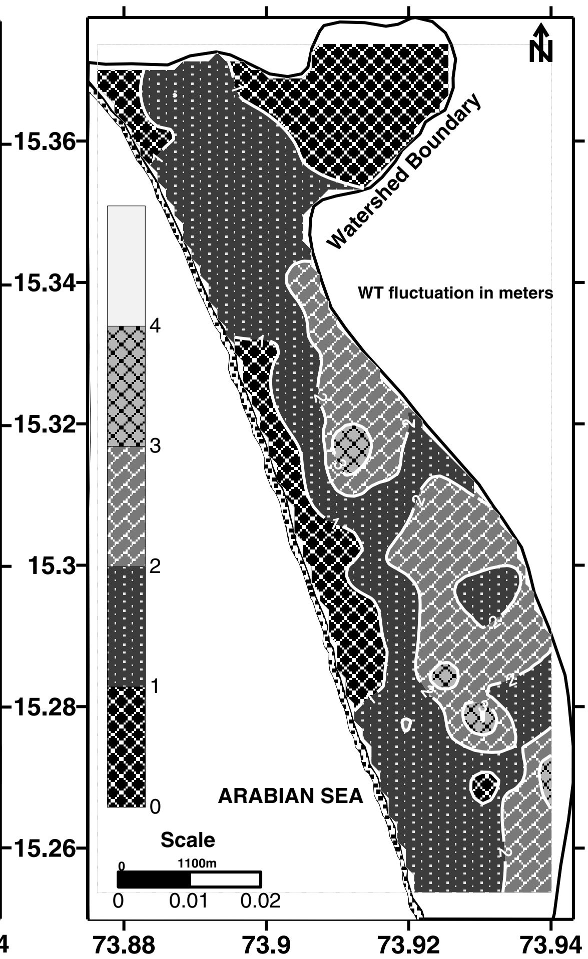

Fig. 3(a) SALDIT final score map for the study area

8. Conclusions

New technique has been developed for assessing and mapping of the potential groundwater recharge areas in a given watershed. The method is based on the data which can be easily retrievable from the records and measured in field with minimum costs. The maps derived can be used as a tool for management of the potential groundwater recharge areas like protection zoning to safeguard the areas of groundwater recharges.The maps can also be prepared using GIS or if the area is small, point values of the recharge indices can be obtained from equation (1) and then contoured using SURFER.

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