CHAPTER 6 HYDRO GEOLOGICAL MODELLING

6.1 INTRODUCTION:

Groundwater is one of the most important sources of the needed fresh water for human beings that form the largest supply of the Earth's fresh water after the glaciers and ice caps. Unfortunately, the groundwater resources have not been managed scientifically. As a result, decrease of groundwater level throughout Iran due to much extraction of water and digging wells without license is an obstacle.

The distress for water resources is growing as a result of population growth, climate change, and alarming signs that in many parts of the world, especially in the developing countries, groundwater resources are being depleted at an unsustainable rate. Hence, for sustainability, much greater emphasis should be on groundwater management rather than on searching for new groundwater resources.

This has provoked a check on the water resources. In many countries, to meet the increased demand for water, groundwater resources must be tapped. The excessive use and continued mismanagement of water resources to supply ever increasing water demands to reckless users have led to water shortages, increasing pollution of fresh water resources and degraded ecosystems worldwide (Clarke, 1991; Falkenmark and Lundqvist, 1997; de Villiers 2000; Tsakiris, 2004). On the other hand, uninterrupted augmented withdrawals from a groundwater reservoir in excess of replenishable recharge may result in regular decrease of water table. In such condition, crisis is drying of shallow wells and increase in pumping head for deeper wells and tube wells. This requires planned and optimal development of water resources. A suitable approach would be planning that is based on conjunctive use of surface water and groundwater. For a sustainable development of water resources, it is essential to make a quantitative assessment of the existing water resources. For this it is necessary to make a rational evaluation of the surface water and groundwater resources and then plan their use in so that it meets crop water requirements and there is no water-logging or undue lowering of groundwater table. It is necessary to maintain the groundwater reservoir in a state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the monsoon and non-monsoon seasons. Groundwater is a dynamic system.

The fact that water is finite and vulnerable resource and it must be used wisely for present and future generations

As of the past three to four decades it is observed that the widespread use of groundwater resources for irrigation and other public water supplies due to the scarce availability of the surface water. This is due to either over exploitation of groundwater resources or monsoon failure results the reduction in recharge rate. However, the aquifer depletion due to over-exploitation and the growing pollution of groundwater are threatening our eco-systems water availability (Bouwer, 1999; Sophocleous, 2005, Sophocleous 2010). Thus, most of the weathered zones in hard rock regions become an unsaturated zone. Excessive pumping has led to alarming decrease in groundwater levels in several parts of the country like Gujarat, Haryana, Orissa, Punjab, Rajasthan, Tamil Nadu and West Bengal (CGWB, 2006). Hence, the key concern is how to maintain a long-term sustainable yield from aquifers (Hiscock et al., 2002; Alley et al., 2004) desires that the essential of the study and evaluation of the groundwater potential in micro watershed or sub basin scale. Groundwater is particularly important in arid and semi-arid regions that lack perennial sources of surface water due to low rainfall and high evapo-transpiration. (S.Ahmed et.al, 2008).

On the other hand, continuous increased withdrawals from a groundwater reservoir in excess of replenishable recharge may result in regular lowering of water table. In such a situation, a serious problem is created resulting in drying of shallow wells and increase in pumping head for deeper wells and tubewells. This has led to emphasis on planned and optimal development of water resources. An appropriate strategy will be to develop water resources with planning based on conjunctive use of surface water and groundwater. For a sustainable development of water resources, it is imperative to make a quantitative estimation of the available water resources. For this, the first task would be to make a realistic assessment of the surface water and groundwater resources and then plan their use in such a way that full crop water requirements are met and there is neither water-logging nor excessive lowering of groundwater table. It is necessary to maintain the groundwater reservoir in a state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the monsoon and non-monsoon seasons.

The development and over-exploitation of groundwater resources in certain parts of the country have raised the concern and need for judicious and scientific resource management and conservation. The „National Water Policy" adopted by the Government of India in 1987 and revised in 2002 and 2012, regards water as one of the most crucial elements in developmental planning.

"Draft National Water Policy (2012)", Ministry of Water Resources, Government of India, As recommended by National Water Board in its 14th meeting held on 7th June, 2012.

The sustainable use and management of groundwater resources is now a great challenge for many countries of the world. Recently groundwater modelling has been an effective way to address this challenge. There are a number of modelling software exist to simulate groundwater flow. Groundwater management involves both quantity and quality-related issues (Das and Datta, 2001)

6.2 HYDRO GEOLOGICAL MODELLING

Groundwater modeling is an important tool to provide guidance for management of groundwater particularly in the areas where the hydrological cycles are predicted to be accelerated due to climate change (Mall et al., 2006). To add to the problem, increasing threat to groundwater quality due to human activities has become a matter of great concern. A vast majority of groundwater quality problems present today are caused by contamination and by over-exploitation, or by combination of both (CPCB, 2007).

Groundwater models play an important role in the development and management of groundwater resources, and in predicting effects of management measures. With rapid increases in computation power and the wide availability of computers and model software, groundwater modelling has become a standard means and regarded as the best tool to conceptualize the hydro geological situation in the groundwater basin and to predict the potential environment and socioeconomic impacts of the groundwater abstractions.

Groundwater models are used to predict the effects of hydrological changes on the behavior of the aquifer and are often named groundwater simulation models and are used in various water management plans. Groundwater modelling has produced answers to many difficult questions that arise in the course of hydrogeological investigations . It is, thus, imperative to manage the groundwater resources in an optimal manner. Management schemes can be evolved, only if the groundwater potential is assessed in more realistic manner

The success of any groundwater study, to a large measure, depends upon the availability and accuracy of measured/recorded data required for that study. Therefore, identifying the data needs and collection/monitoring of required data form an integral part of any groundwater exercise. The first phase of any groundwater study consists of collecting all existing geological and hydrological data on the groundwater basin in question. Any groundwater balance or numerical model requires a set of quantitative hydrogeological data that fall into two categories:

1. Data that define the physical framework of the groundwater basin and
2. Data that describe its hydrological framework

Mathematical groundwater models are used to simulate aquifer conditions, to estimate aquifer parameters, and to predict groundwater condition. In addition, as groundwater is essentially a hidden resource, studies on groundwater under both natural and artificial boundary conditions require modeling techniques. As groundwater is fundamentally a concealed resource and there are many breaks in the accessible data; consequently studies of groundwater under both natural and artificial conditions have used modeling techniques. Groundwater models express groundwater flow using mathematical equations that are based on definite simplifying assumptions. As a result, groundwater modeling has become a very important process in managing groundwater resources [Hashemi 2013]

6.3 MODFLOW

MODFLOW (Modular Three Dimensional Finite-Difference Ground water Flow Model) is the name that has been given to the United State Geological Survey (USGS) Modular Three-Dimensional ground water flow model which assumes that aquifers consist of porous media only [McDonald and Harbaugh, 1988]. Because of its ability to simulate a wide variety of systems, its extensive publicity, available documentation, and its rigorous USGS peer review, MODFLOW has became the worldwide standard ground water flow model. MODFLOW is used to simulate systems for water supply,containment remediation and mine dewatering. When properly applied, MODFLOW is the recognized standard ground water model (Kumar, 1992; Pollock, 1994; Anderman and Hill, 1997; Hill et al., 2000; Konikow, 2001; Merritt and Konikow, 2000; Kumar, 2001 and Jyrkama et al., 2002). Visual MODFLOW software in groundwater modeling has been universally accepted and well documented in many research journals from Authors such as Henk, V Haitjema et al. (2001), T A Fouepe et al. (2009), Thomas Reimann (2009), R. Rajamanickam et al. (2010), C P Kumar (2013), Singh (2013), S Needhidasan (2013), K V Pradeep et al. (2014), A.Anjali etal (2015) have used MODFLOW .

Ground-water models are conceived, constructed, and calibrated with the objective of understanding a physical system, testing hypotheses, and making predictions to support environmental management decisions. In this respect, the predictions made with ground-water models may be of paramount importance. (Tonkin, 2000)

This chapter deals with a modflow model that was created through conceptual modeling approach in GMS. GMS is a premier modeling software for groundwater modeling. It uses GIS style feature objects like point, line and polygon.

The modeling package MODFLOW employed in the Groundwater Modeling System (GMS), was applied for this purpose.

Groundwater modeling begins with a conceptual understanding of the physical problem. The next step in modeling is translating the physical system into mathematical terms.

In general, the results are the familiar groundwater flow equation and transport equations. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]-W=S_s\frac{\partial h}{\partial t}$$

Kxx, Kyy & Kzz are values of hydraulic conductivity along the x, y & z co-ordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity

h is piezometric head.

W is a volumetric flux per unit volume and represents sources and/or sinks of water.

Ss is the specific storage of the porous material.

t is time.

The conceptual model of the hydro-geologic system was developed through a detailed study of the geology, bore hole lithology, hydrological parameters like pumping test, draw down, specific heads, water level fluctuations and other related details in wells. From the Geology and Lithology of the bore hole it can be said that groundwater in the study area is found to occur in alluvial formations as well as underlying rocks formations. In order to consider the variations in lithologic and hydraulic characteristic with depth, all these layers were considered. The first layer of 1 to 5 m constitutes the soil cover or Top Soil. The other layers are of varying thickness and vary from clay to sand of different sizes based on the location and Geology.

6.3.1 Methodolgy:

6.3.1.1 Importing base map (Steps 1 to 3)

The base map or toposheet collected from Survey of India was updated with satellite images for a real time boundary conditions of the major rivers i.e Sakar and Sang. This was digitized in four themes viz., boundary, river, lake and well locations using Arc GIS and imported to the Modflow conceptual model in GMS.

The cells located at the border of the model and out of the model were designated as inactive cells. The size of each grid cell is 100m x 100m. Step 1 to 3 shows the model with active and inactive cells area.

6.3.1.2 Assigning boundary conditions (Steps 4 to 7)

Based on the interpretation of borehole lithology and physiography, four boundary conditions were assigned to the study area. The southern eastern side of the study area near Gandhidham was considered as specific head. The second boundary condition was for lake area which was considered as General Head. The third was considered as a river and the remaining area was considered as land area were the wells were located.

6.3.1.3 Input parameter for Groundwater abstraction (Step 8)

The groundwater of the study area is abstracted for domestic as well as agricultural purposes. Well inventory data and pumping test data was collected from District lab Bhuj and discussed with the senior Geologist and chief engineer at Anjar and Bhuj divisions. Based on this data final Groundwater draft was estimated after discussions with the geologists.

6.3.1.4 Input parameter for Recharge (Step 9)

The recharge to the aquifer is never constant, due to the varying sub-surface geology, soil type, land use and topography it also varies depending on the amount of rainfall in a particular area at a particular time. The recharge was estimated from the soil infiltration tests performed at various locations through double ring infiltrometer. The results were correlated and any anomalies observed were rectified by re-testing that particular site location.

6.3.1.5 Assigning aquifer properties to the model (Step 10)

Hydro-Geological properties are the important factors in defining the physical framework of an aquifer and for governing the storage and movement of groundwater. The aquifer parameters such as hydraulic conductivity, specific yield and storage coefficient were taken from the pumping test data collected from various government departments like District Lab Bhuj, CGWB and GWSSB. Based on the data acquired from these departments, aquifer properties such as hydraulic conductivity, specific yield and initial head were assigned to observation wells with their respective co-ordinates. The aquifer was assumed to be horizontal by isotropic (kx=ky) and to have vertical conductivity of 0.1 times of kx, where kx is the hydraulic conductivity in the X-direction of the model, ky is the hydraulic conductivity in the Y-direction and kz is the hydraulic conductivity in the Z-direction. The distribution of hydraulic conductivity and storage propertieslike specific yieldwere assigned to each layer of the regional groundwater model. Hydraulic conductivity of the study area, is represented in Step 10.The specific yield of the study area ranges from 0.015 to 0.1.

6.3.1.6 Assigning elevation data (Step 11)

GPS survey was conducted in the study area and the elevation database was created for all the well locations. The elevations of each layer with respect to the coordinates (X, Y, Z) were created and updated with respected to ground level in the borehole manager. Step 11 shows the importing elevation data.

6.3.1.7 Assigning wells data (Step 12 & 13)

There are several observation wells monitored by the GWSSB and the details of these wells were added into the model by using create borehole option. The pumping data were given as negative values for the pumping wells. Monthly rates of groundwater withdrawal were applied for every stress period during the simulation. The locations of the observation wells and the refining grids on well locations are shown in step 12 and step 13.

6.3.1.8 Estimation of model input parameter-Evapotranspiration (Step 14)

The temperature data was collected from the Indian MeteorologicalDepartment (IMD). Since the weather data like solar radiation, wind speed, relative humidity etc. are absent, reference evapotranspiration was calculated using Hargreaves and Samani equation.

Hargreaves equation is according to recommendation of FAO. The alternative equation for a case that some data of radiation, water vapor pressure and wind speed are missing (Allen et al 1998) is; (Katarína Strelcová et al, 2009)

$$E = 0.0023(T_{mean} + 17.8)(T_{max}-T_{min})0.5\ R_a$$

where T_{mean} – Mean Temperature

T_{max} – Maximum Temperature

T_{min} – Minimum Temperature

R_a – Net Radiation

Using the above equation, evapotranspiration values were calculated for the study period and fed into the model to simulate the effects of plant transpiration, direct evaporation and seepage at the ground surface by removing water from the saturated groundwater regime.

6.3.1.9 Model Calibration (Step 15)

Before a groundwater model is used for any decision support or predictions, it is of utmost importance that it is calibrated in a way that it simulates the groundwater behavior satisfactorily. Hence the model was calibrated by modifying the input parameters to match with the field conditions within an established range of error. In boundary conditions, recharge and hydraulic conductivity are the major parameters that are predominantly modified in order to obtain a reasonable fit with observed values of hydraulic head and flow rate at outlet streams. However these input parameters were poorly known because of the unavailability of sufficient amount of data required for the calibration. The model is calibrated for transient state condition.

6.3.1.10 Model Validation (Step 16)

After the simulation of the model it is validated in order to have greater confidence in the calibrated model. In this study, a ten year period from January 2001 to December 2011 was used as model calibration process and the year 2011 data were used for validation process. The simulated regional groundwater head was compared with the observed data of wellsThe computed water level for the year 2011 is shown in Step 16 illustrates the comparison between observed and computed water levels. It was found that the computed values agreed well with the observed ones.

6.3.1.11 Future Prediction (Step 17)

After successful validation of the model, the model was then run to predict the response of the aquifer after the implementation of artificial recharge structures.

Steps (GMS Modflow Module)

1. To create a grid independent model we start with an imported georeferenced image displayed in the background showing our area of interest.

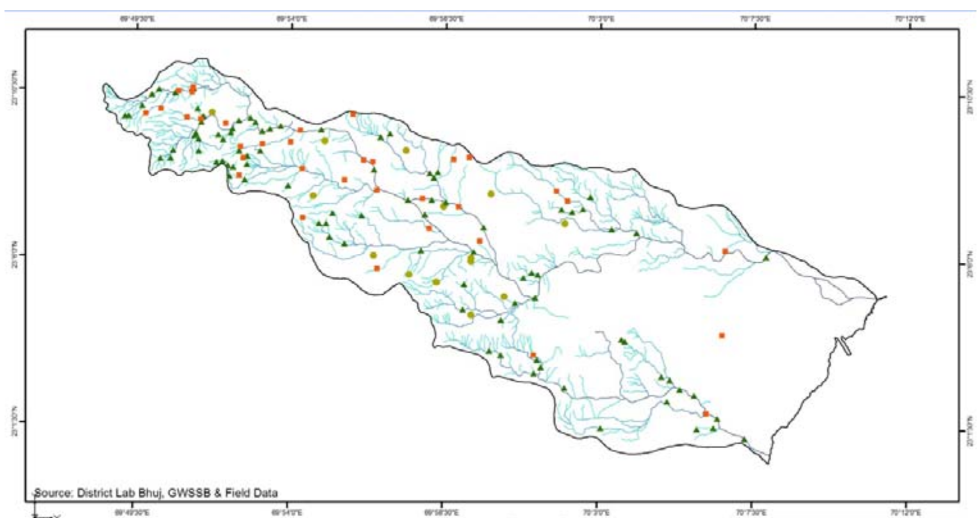


Fig. 6.1 Importing the Map of Study Area along with Recharge sites

2. We create a modflow conceptual model and within the model we create a new coverage that will be used for the coverage boundary. A coverage file is like a theme in ArcGIS or a layer in AutoCAD.

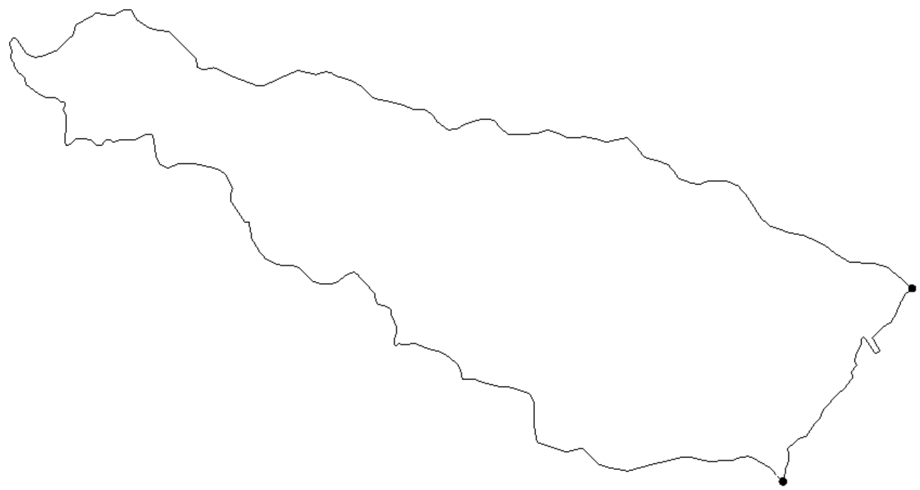


Fig. 6.2 Map showing the Boundary of Study Area

3. We digitize the model boundary in GMS. These can also be directly imported from ArcGIS or AutoCAD.

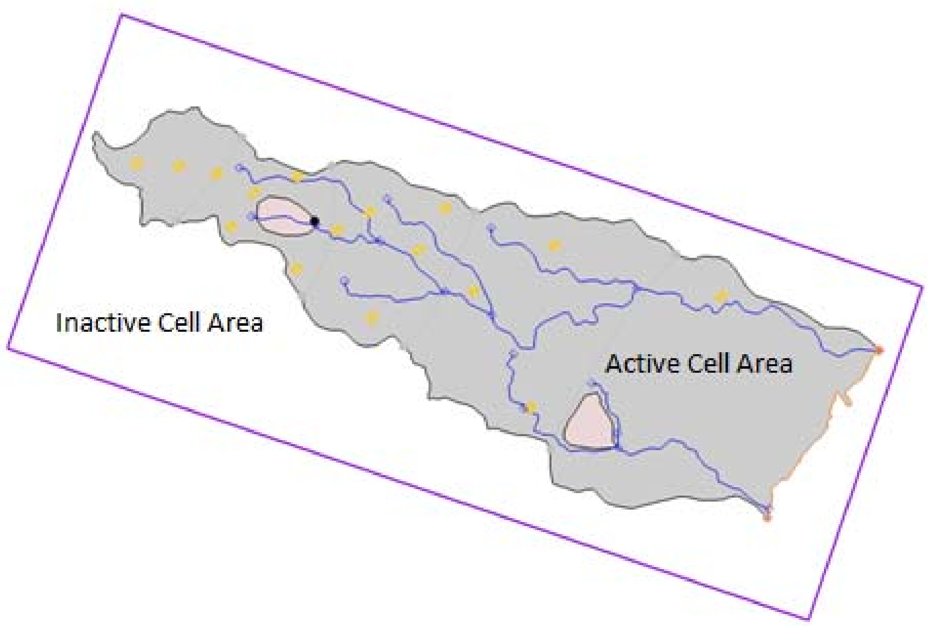


Fig. 6.3 Map of Active and Inactive Cells

4. We create a new coverage which will be used for demarcating the sources and sinks and turn on the attributes we need in the coverage like wells, specified Head, refinement points, general head, rivers etc.

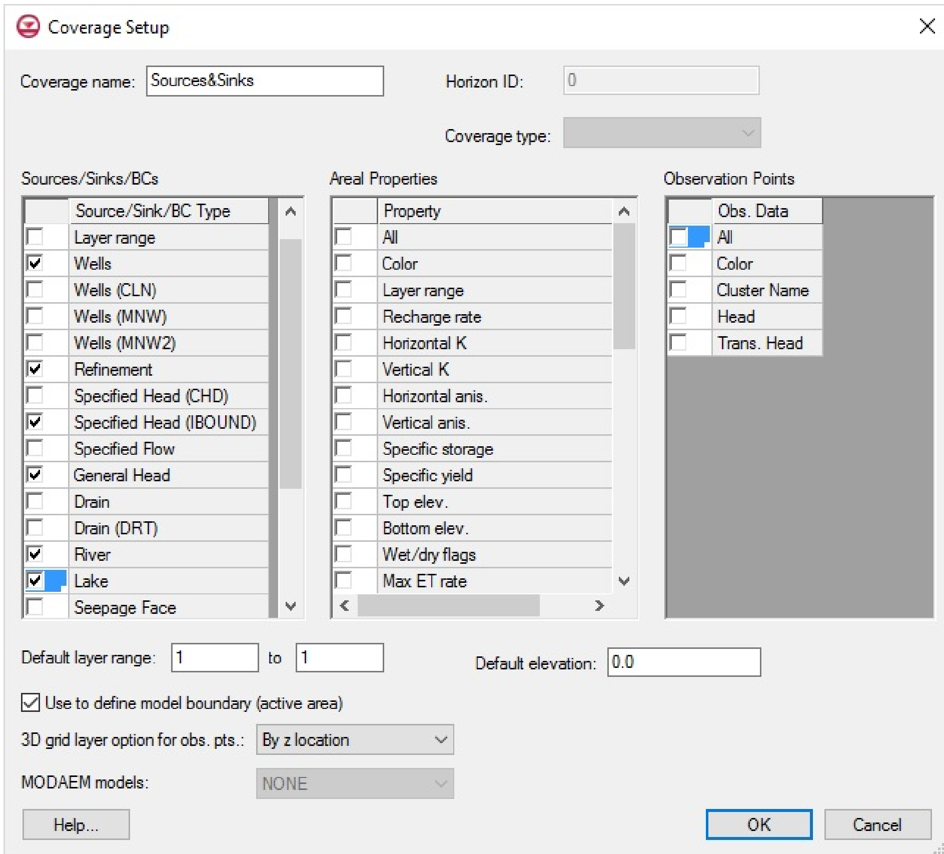


Fig. 6.4 Coverage Setup for Source and Sinks

5. The coastal boundary near the Gandhidham Taluka will be represented as specified head hence we will change the arcs near the coast boundary to specified head type.

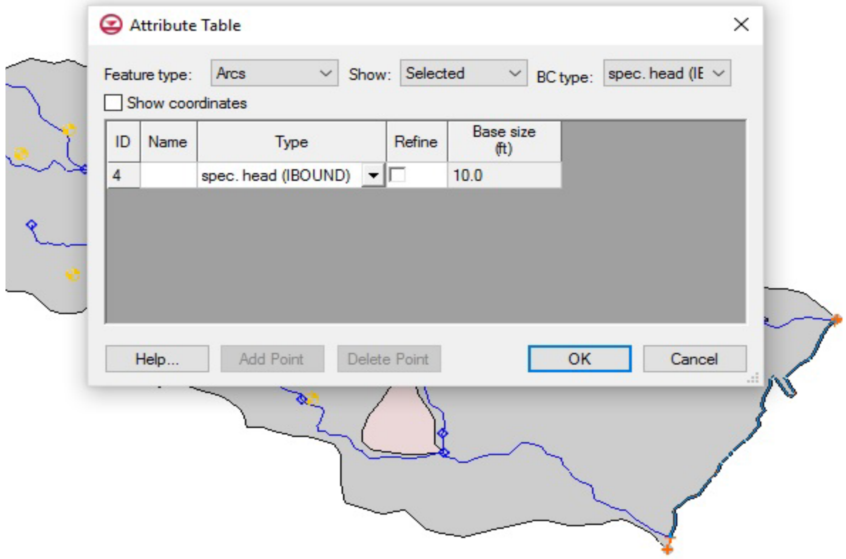


Fig. 6.5 Attribute Table for assigning Specified Head

6. Create arcs for the rivers and change the arc type to river and enter the same conductance for all of them. River stage and the bottom elevation are entered at the nodes so that they will be linearly interpolated along the length of the arcs

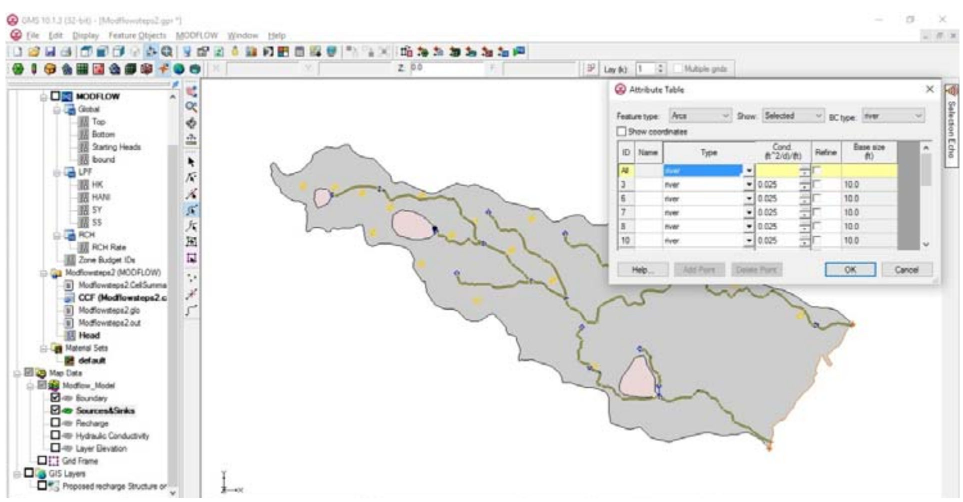


Fig. 6.6 Creation of Rivers and Assigning the Conductance Value

7. The lakes would be modelled using general head boundary conditions. We built polygons from the arcs and change the lake polygons type to general head and enter the head and conductance values.
8. Now create the points for the wells, check dams etc. and turn on the refinement option and specify the grid cell size because we want the grids to be refined around the wells. For each well we have to specify the flow rate in m3/day.

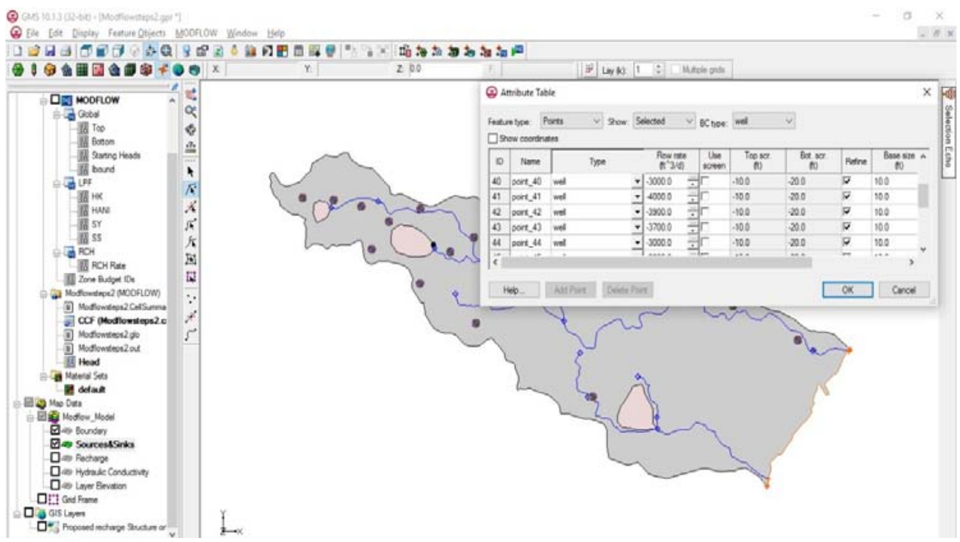


Fig. 6.7 Creation of Recharge Structures

9. Since it is the same study area, the boundary coverage is then duplicated to create a coverage boundary that will be used for the recharge. Built the polygons and inter the recharge rates.

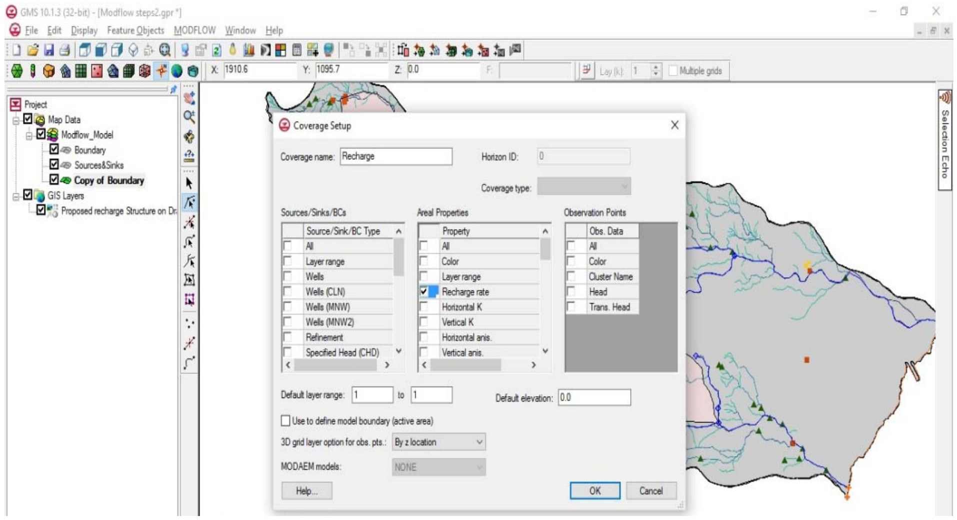


Fig. 6.8 Creation of Coverage boundary for Assigning the Recharge Rates

10. Another separate coverage is used for hydraulic conductivity. We create different zones of hydraulic conductivity using polygons and enter a hydraulic conductivity for each polygons.

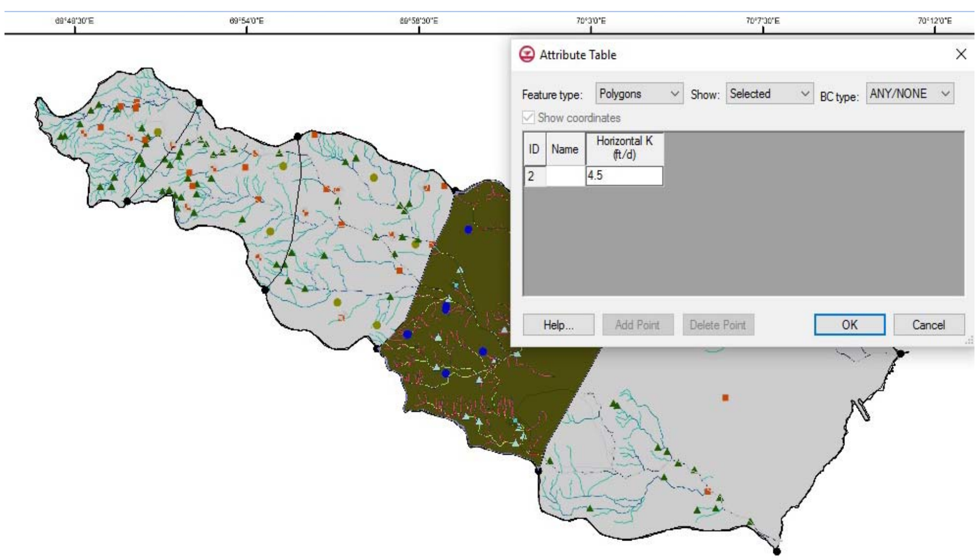


Fig. 6.9 Creation of Layer for Hydraulic Conductivity

11. Subsequently create a new coverage for layer elevations where we can define the top and bottom elevations of the study area.

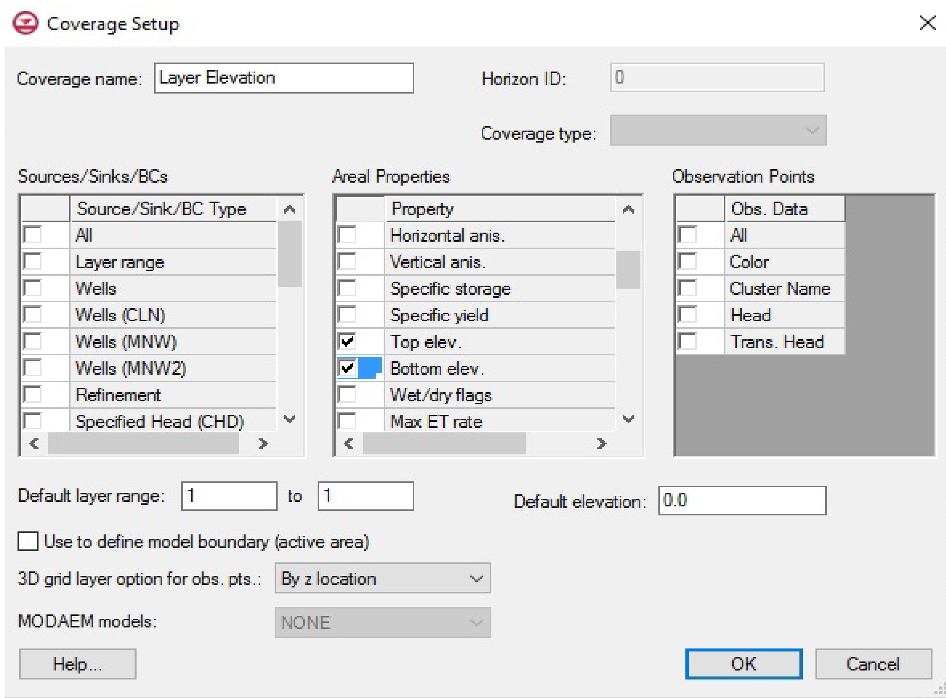


Fig. 6.10 Creation of Elevation layer

12. Now create a grid frame, this is automatically fitted to our conceptual model.

A 3D grid is also created that is refined around the wells.

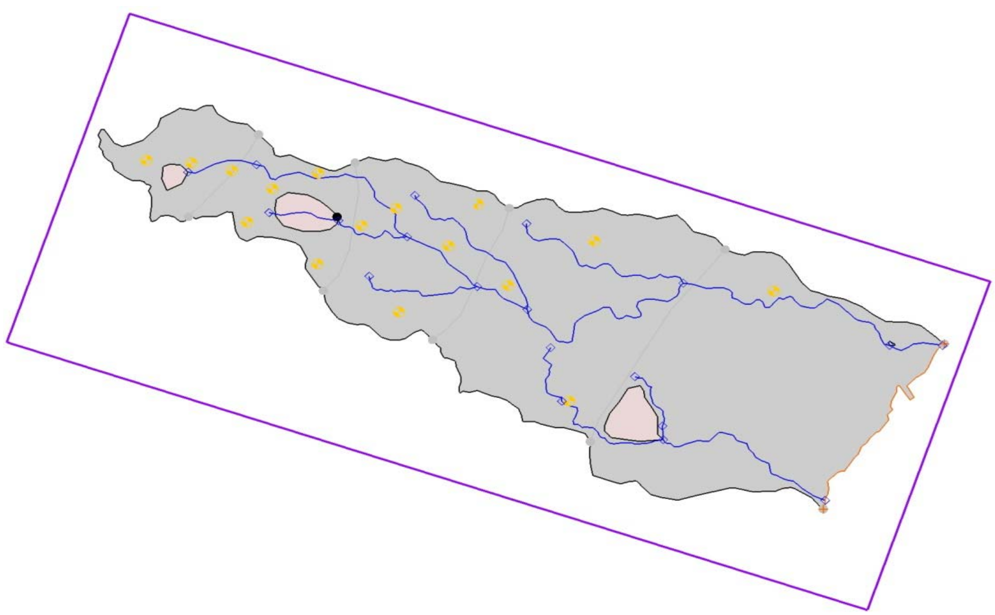


Fig. 6.11 Creation of Grid Frame for Model Simulation

13. We create a new modflow simulation and activate the grid cells inside our conceptual model and map our conceptual model to the grid.

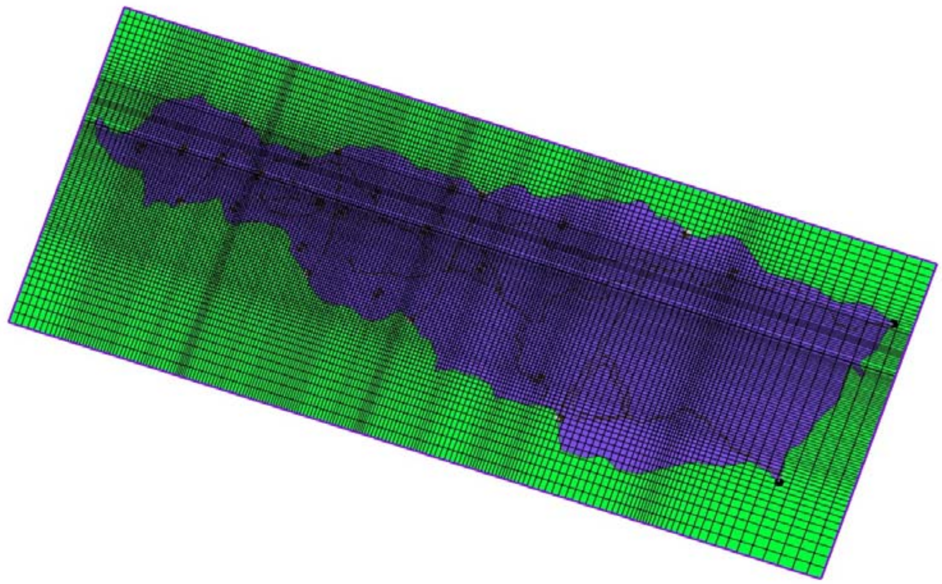


Fig. 6.12 Map showing the Active Grid Cells within the study area

14. Evaporation transpiration value was entered using EVT module of GMS.

    a. Set up ET conceptual model and assign max ET rate and extinction depth using the polygons. Map the values to the MODFLOW grid. Ignore the ET elevation for now.

    b. Create a "matching 2D grid" by selecting the Grid|Grid->2D Grid command in the 3D Grid Module.

    c. Go to the 2D Scatter Point module, select your 2D scatter point set representing the ground surface elevations and interpolate to the 2D Grid using the Interpolation- Interpolate->2D Grid command.

d. Go to the ET Package dialog in the MODFLOW interface and select the ET Surface array. Select the 2D Data Set -> Array button and select the 2D data set you created by interpolation.

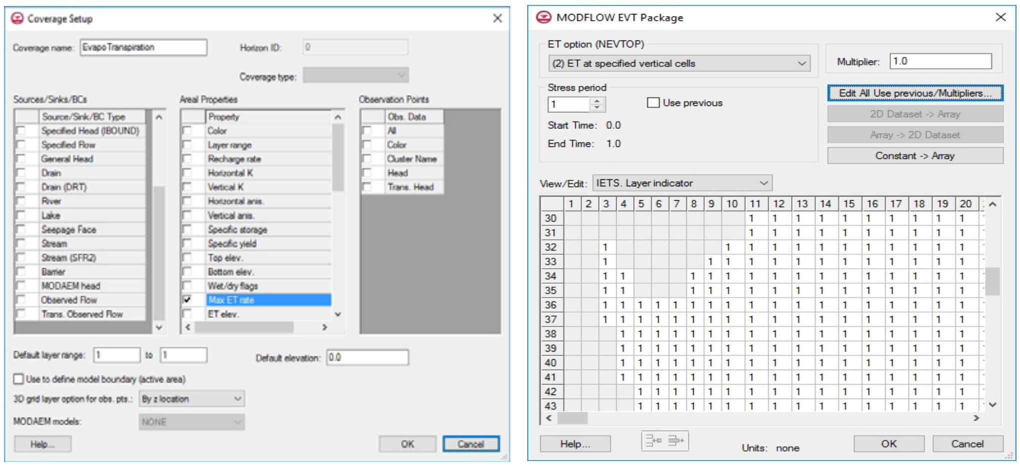


Fig 6.13 Assigning of Evaporation Values

15. Symbols will appear underneath our conceptual model objects. Starting head is then specified in the grid for our model. The modflow top and bottom elevation was mapped from our conceptual model and required data were calibrated.

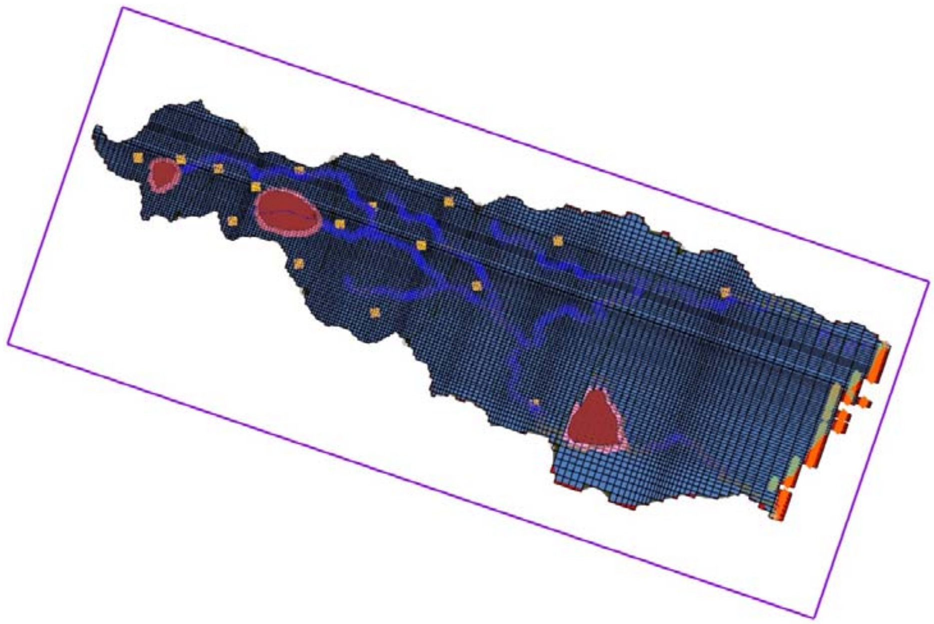


Fig. 6.14 Assigning of Starting head and Model Calibration

16. The model setup is complete and now we are ready to run our modflow. We can also import the modflow solutions and examine the contours of the head solution.

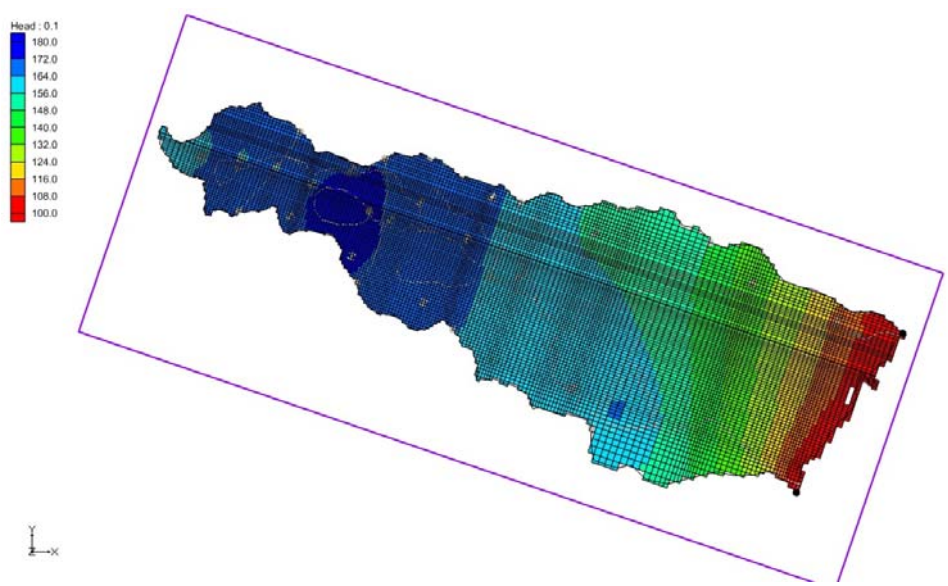


Fig. 6.15 Modflow Outputfor Present Scenario

17. After the detailed analysis of the demarcation of groundwater recharge zone in the study area, suitable recharge structures were located using GIS approach. Then the model was run to predict the response of the aquifer after the implementation of artificial recharge structures and the changes in flow rate, the head values in the observation wells and the water table were identified. Fig.6.16 shows the computed water level contours for 2035.

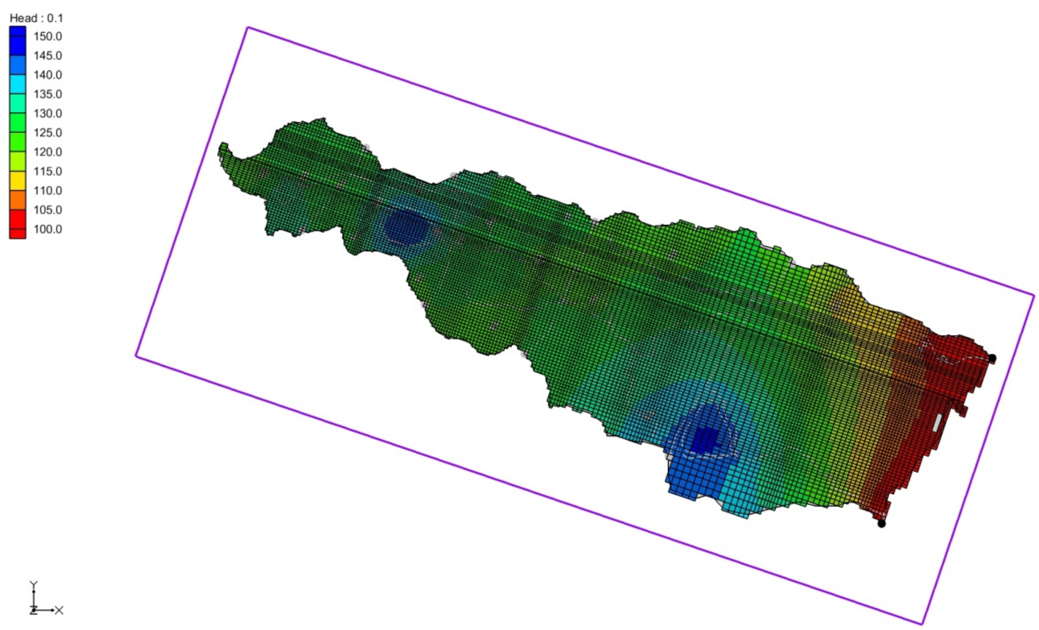


Fig. 6.16 Modflow Output for Future Secnario (2035)

6.3.2 Conclusion:

From the above map it can be predicted that if proper recharge structures are implemented along with well thought-out water management plans for the current usages, there are high chances of revival of the water level in catchment area of Sakar and Sang river basin (study area). According to the model considered for coming 20 years, around 25-40 mtr rise in the water level can be expected. The major positive impact are mostly in the taluka of Anjar followed by Bhuj and lastly Gandhidham. Owing to the proximity to the coast, no major changes visible near the coastal part of Gandhidham taluka.

6.4 GROUNDWATER VULNERABILITY ASSESSMENTS AND INTEGRATED WATER RESOURCE MANAGEMENT (DRASTIC MODEL)

6.4.1 Introduction

Surface water quality can be determined by hydrological responses that vary geographically. The sub-surface hydrologic environment, however, has a primary influence on groundwater movement and hence pollutant migration to the sub-surface water. Maps of aquifer vulnerability to pollution are becoming more in demand because on one hand groundwater represents the main source of drinking water, and on the other hand high concentrations of human/economic activities, e.g. industrial, agricultural, and household represent real or potential sources of groundwater contamination. There is a need to conduct studies on groundwater pollution.

GW pollution is artificially brought degradation of natural GW quality. In contrast with surface water pollution, sub-surface pollution is difficult to detect, is even more difficult to control, and may persist for years, decades, or even centuries (Todd, 1980).

GW vulnerability is a function of the geologic setting of an area, as this largely controls the amount of time, i.e. the residence time of the GW that has passed since the water fell as rain, infiltrated through the soil, reached the water table, and began flowing to its present location (Prior, Boekhoff, Howes, Libra, & VanDorpe, 2003). In any given area, the GW within an aquifer, or the GW produced by a well, has some vulnerability to contamination from human activities. This concept exists since the 1960s, yet there is no standard definition of aquifer vulnerability. The most common definition comes from Vrba and Zaporotec (1994), who described aquifer vulnerability as a concept representing the intrinsic properties of aquifer systems as a function of their sensitivity to human and natural activities. Vulnerability mapping is defined as a technique for quantifying the sensitivity of the resource to its environment, and as a practical visualization tool for decision-making. GW vulnerability is also defined as the tendency and likelihood for general contaminants to reach the water table after introduction at the ground surface (SNIFFER, 2004). In fact the term "vulnerability of GW to contamination" was first used by Margat (1968). "GW vulnerability" is used in the opposite sense to the term natural protection against contamination. GW vulnerability to contamination was defined by the National Research Council (1993) as "the tendency or likelihood for contaminants to reach a specified position in the GW system after introduction at some location above the uppermost aquifer."

With the rising importance of underground water resources, efforts are increasing to prevent, reduce, and eliminate GW pollution.

The DRASTIC model can be a valuable tool for identifying GW supplies that are vulnerable to contamination using basic hydro-geologic variables believed to influence contaminant transport from surface sources to GW.

- One of the tools created in order to protect the groundwater in the United States is a methodology known as "DRASTIC," created in partnership by National Water Well Association (Linda Aller, 1987). The main objective of this methodology was to assure a new and systematic tool of groundwater -pollution potential in any hydrogeologic setting. This method wasn't completely accepted in the past, presenting two main inconveniences: subjectivity as well as the difficulty to asses some important hydrogeological characteristics ore some specific properties of contaminants. Today the DRASTIC method, is a standardized system for evaluating groundwater pollution potential. DRASTIC has been widely used in many countries because the inputs required for its application are generally available or easy to obtain from public agencies. The main nitrate sources in groundwater are fertilizer applications on cultivated land, manure from livestock, and factory and domestic wastewater.

- The intended use of the vulnerability assessment process is the most obvious and important factor to consider in selecting a vulnerability assessment approach. Uses and needs for vulnerability assessments can be grouped into four broad categories. First, assessments can be used in the policy analysis and development process to identify potential for ground water contamination and the need for protection and to aid in examining the relative impacts of alternative ways to control contamination. Second, when scarce resources prevent uniform and high levels of spending, vulnerability assessments can be used in program management to guide allocation and targeting of resources to areas where the greatest levels of effort are warranted. Third, vulnerability assessments can be used in some instances to inform land use decisions such as alteration of land use

> activities to reflect the potential for ground water contamination, or voluntary changes in behaviors of land owners as they become more aware of the ground water impacts of their land-based activities. Finally, and perhaps most important, is the use of vulnerability assessments to improve general education and awareness of a region's hydrologic resources. Groundwater vulnerability assessments are a means to synthesize complex hydrogeologic information into a form useable by planners, decision and policy makers, geoscientists, and the public.

In recent years, groundwater contamination has been discussed continuously by water quality agencies of all levels of government (Dixon, 2005). Groundwater may be a reliable resource in many places today, but to keep the groundwater supply sustainable, risk assessments need to be conducted to keep groundwater a renewable resource (Twarakavi and Kaluarachchi, 2006). Determining how to delineate areas susceptible to contamination is difficult due to the many variables that may or may not affect groundwater contamination in certain areas (Dixon, 2005). Hydrogeologic factors are used to determine groundwater susceptibility. These factors are integrated into groundwater models using multiple methods to predict likely susceptible areas.Combining the DRASTIC model with GIS creates a powerful tool. (Watkins, McKinney, Maidment, and Lin ,1996) suggest ground water models integrated into GIS can visually represent the spatial aspects of ground water data as well as execute spatial calculations on data enabling further inferences to be made about susceptible areas.

6.4.2 Data Base and Methodology

The data used for this project was retrieved from multiple sources. Shape files of well points were generated from the GPS locations collected from the field as well as from the records of District Lab, Bhuj. The water quality data for the respective well was obtained from various govt. agencies like district lab, Bhuj, CGWB, Ahmedabad, GWSSB, Ahmedabad and also from the primary survey done on the field and the samples collected from the field for water quality analysis. The well points were prepared with two different types of data sets, i.e 1. Wells that were located with a Global Positioning System (GPS) and 2. well locations that were calculated from the description on the well logs. The CGM supplied a geology maps for Anjar, Bhuj and Gandhidham. The files consisting of a 30-meter digital elevation model (DEM) from ASTER was downloaded from USGS site and updated with the elevation data obtained from the field where ever necessary.

The soils layer was collected from the Natural Bureau of soil science (NBSS). Lastly, the precipitation information was obtained from Data centre, Gandhinagar, GSDMA.

All data was converted, when necessary, into spatial layers that were further viewed and processed using Environmental Systems Research Institute's (ESRI) ArcGIS Suite, version 10.1. A 30-meter cell size was used for all raster manipulation in the project. Thirty meter cell size was the scale of the DEM. This best fit the scale of the study area based on the accuracy of the 30-meter DEM, which was the smallest cell size of available data.

6.4.3 DRASTIC Model

According to Aller et al., in 1987, an EPA funded effort to research and develop a method for evaluating pollution potential anywhere in the United States successfully produced the DRASTIC model. DRASTIC was used to evaluate the relative vulnerability of areas to groundwater contamination by focusing on hydrogeologic factors that influence pollution potential. The hydrogeologic factors include Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity that make up the acronym DRASTIC. A combination of ratings and weights were assigned to these factors based on how significantly they influenced pollution potential. Each DRASTIC factor was assigned a DRASTIC weight ranging from 1 to 5. Each DRASTIC factor was further assigned a rating, typically from 1 to 10, based on a range of information within the parameter. Higher ratings and weights indicated higher risk of vulnerability.

Table 6.1 DRASTIC parameters with the associated DRASTIC weights

Parameter	DRASTIC Weight
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of Vadose Zone	5
Hydraulic Conductivity	3

The values of the ratings and weights for each parameter are plugged into an equation to determine the pollution potential known as the DRASTIC Index. The equation for the DRASTIC Index is as follows (Aller et al., 1987):

DRDW + RRRW + ARAW + SRSW + TRTW + IRIW + CRCW = Pollution Potential

where:

R = Rating

W = Weight

The DRASTIC index is the computed value that makes it possible to identify areas more susceptible to groundwater contamination. The higher the DRASTIC index means the higher the susceptibility.

DRASTIC were developed using the following assumptions (Aller et al., 1987):

1) the contaminant is introduced at the ground surface;

2) the contaminant is flushed into the groundwater by precipitation;

3) the contaminant has the mobility of water and;

4) the area evaluated is 100 acres or larger.

Deviations from the assumed characteristics would need to be determined with furtherstudies and were not included in the scope of this project.

6.4.4 The Modified DRASTIC Model

The Modified DRASTIC Model consisted of using the same methods for assigning ratings and weights to each of the parameters. The ranges for some factors were modified to more closely relate to local hydrogeologic settings.

6.4.4.1 Depth to Water

The depth to water factor refers to the actual depth of water table from the ground surface. The depth of water is important as it help us determine the thickness of material that a contaminant would have to pass through to reach the aquifer. In general, thicker material between the surface and the water table provides a higher chance of the contaminant breaking down before it can affect the aquifer.

It took many steps to determine the depth to water with the available data involving the creation of stream layer, location of the wells and its log files along with the topography data. The well data were queried to get the depth of the unconfined aquifer / uppermost aquifer or the uppermost bedrock was same as the aquifer from where it was fed.

The streams layer was studied to find the perennial streams and rivers, in other words where the water table is continuously contributing water at the surface. Both the streams and wells layers were converted to rasters and combined into one raster layer. This raster was then used to extract the elevation values from the DEM using the Extract by Mask command in Spatial Analyst. The raster was converted to elevation points in order to interpolate a raster surface. The Inverse Distance Weighted technique was used to interpolate the depth to water raster.

The Inverse Distance Weighted (IDW) interpolation uses a linearly weighted method of assigning values based on the inverse distance from the actual data value (ESRI, 2007). Simply, values closer together have more influence on the values assigned to a raster than values farther away. Although multiple interpolation methods were available and some even recommended for creating certain surfaces, the IDW technique provided better fitting data for use in this research by producing only the value ranges found within the data attributes. The IDW raster was then subtracted from the DEM using the Minus function in Spatial Analyst resulting in the depth to water raster. The values were then reclassified into values based on the ranges set in the Modified DRASTIC model as shown in Table 6.2

Table 6.2 Depth to water table with the associated DRASTIC weights

Depth to Water (Feet)	
Range	Rating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1

Depth to water table ranges, in feet, and associated ratings according to the Modified DRASTIC model.

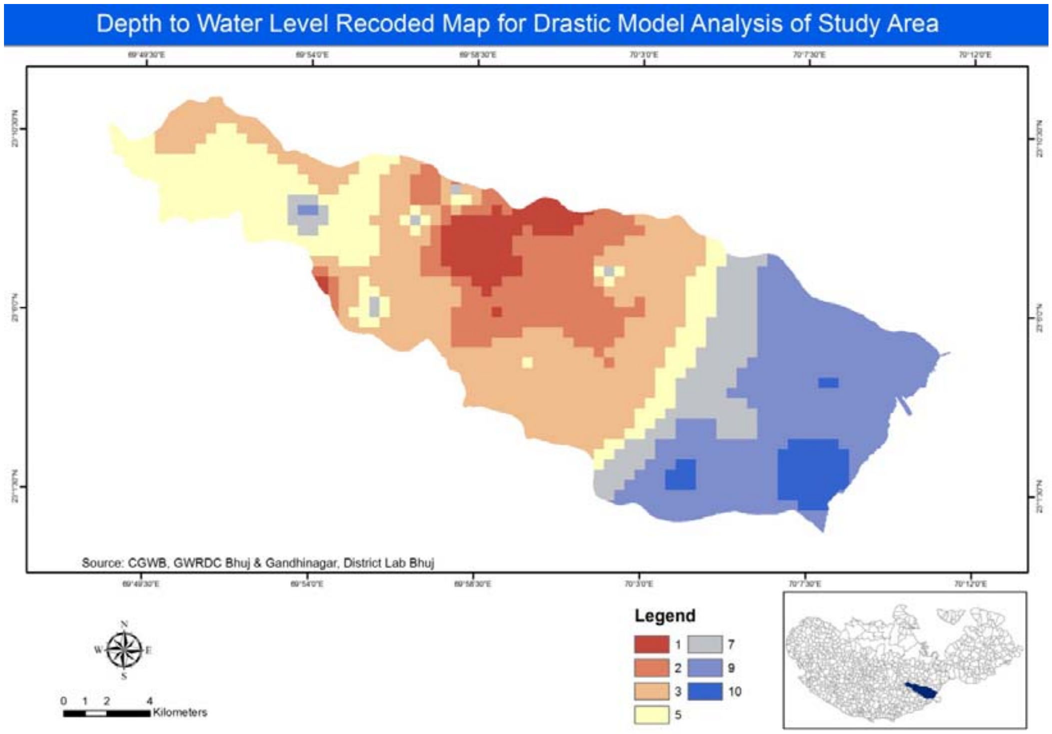


Fig. 6.17 Depth to water table Map of the study area recoded for Drastic Model

6.4.4.2 Net Recharge

"The primary source of groundwater typically is precipitation which infiltrates through the surface of the ground and percolates to the water table. Net recharge represents the amount of water per unit area of land which penetrates the ground surface and reaches the aquifer" (Aller et al., 1987). Net recharge is calculated by the following equation:

Net Recharge = Precipitation – Evaporation – Run Off

Precipitation data from the Data centre, gandhinagar was available, run off data was calculated.

The annual precipitation was calculated for each location. The net recharge was then calculated by taking 25% of the annual precipitation for each location and the net recharge points were applied to the map. The IDW interpolation technique was again used to create a raster of net recharge values. The values were reclassified based on the ranges set in the Modified DRASTIC model and are shown in Table 6.3.

Table 6.3 Net Recharge with associated DRASTIC Weightages

Net Recharge (Inches)	
Range	Rating
8-9	3
9-10	5
10-11	7
11+	9

The net recharge, in inches, was estimated as 25% of annual precipitation to account for runoff and evaporation. The range and ratings were established by the Modified DRASTIC model.

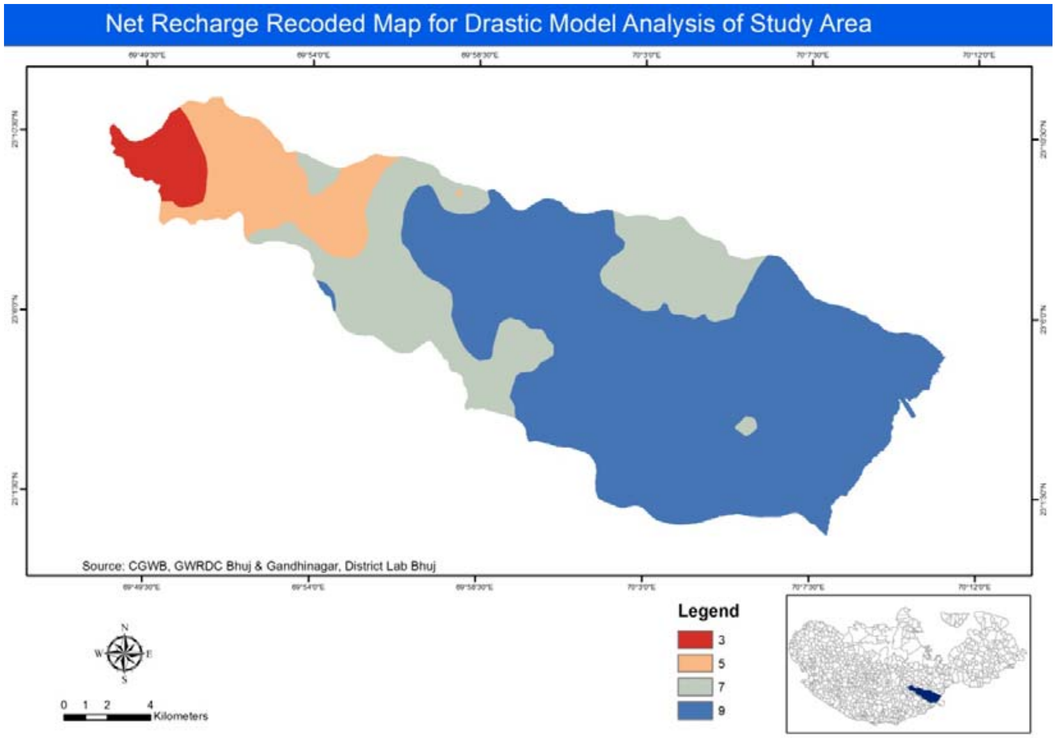


Fig. 6.18 Recoded Net Recharge Map

6.4.4.3 Aquifer Media

Aquifer media refers to the characteristics of the bedrock that serve as an aquifer. An aquifer is rock below the surface that has capacity to hold water for use. The water is contained within pour spaces and cracks in the rock layer. The media of the rock affects the flow of water through the rock which also affects the rate and direction that a contaminant flows. (KlugJ, 2009)

Well information and the bedrock geology files which were obtained from the district lab, Bhuj and Geological map available from the data centre were the sources used to generalize what aquifers were used and therefore, determine the media of each aquifer.

The geology of Kutch is unique in that it ranges Deccan trap basalts within and around Anjar taluka to quarternary alluvial near the coast of Gandhidham. Discussions with the chief engineer, Bhuj and senior Hydrogeologist at Bhuj division provided the background information necessary to generalize media types and aquifer usage to influence the Modified DRASTIC ratings (Table 6.4).

Many of the well attributes contained aquifer information from where they were pumping water. Although many wells were listed as operational and using water from various aquifers, there was no way to determine aquifer boundaries based on well information. To determine general boundaries for aquifer media, an assumption was made that the majority of the wells would determine the source aquifer. That said, wells were grouped by location within the bedrock geology layer.

The DRASTIC ratings were modified to better fit local hydrogeologic settings and the major rock characteristics within each aquifer were very similar and therefore were rated with little difference. Group 1 characteristics represented basaltic rocks and some of the intrusive rocks were assigned the weightage of 9. Group 2 characteristics represented fine to medium grained sandstone and was assigned a rating of 6. Group 3 characteristics represented very fine to fine grained sandstone or sand dominant alluvial was assigned a rating of 4. Group 4 characteristics represented clayey alluvial was assigned a rating of 2.

Table 6.4 Aquifer Media with associated DRASTIC Weightages

Aquifer Media	
Range	Rating
Basalts, Dyke, Sills, fault plains and other Intrusions	9
Sandstone	6
Alluvial – Sand Dominant	4
Alluvial - Clay dominant	2

The properties of the materials within the aquifer are known as the aquifer media and were rated by movement of water through the materials according to the modified DRASTIC model.

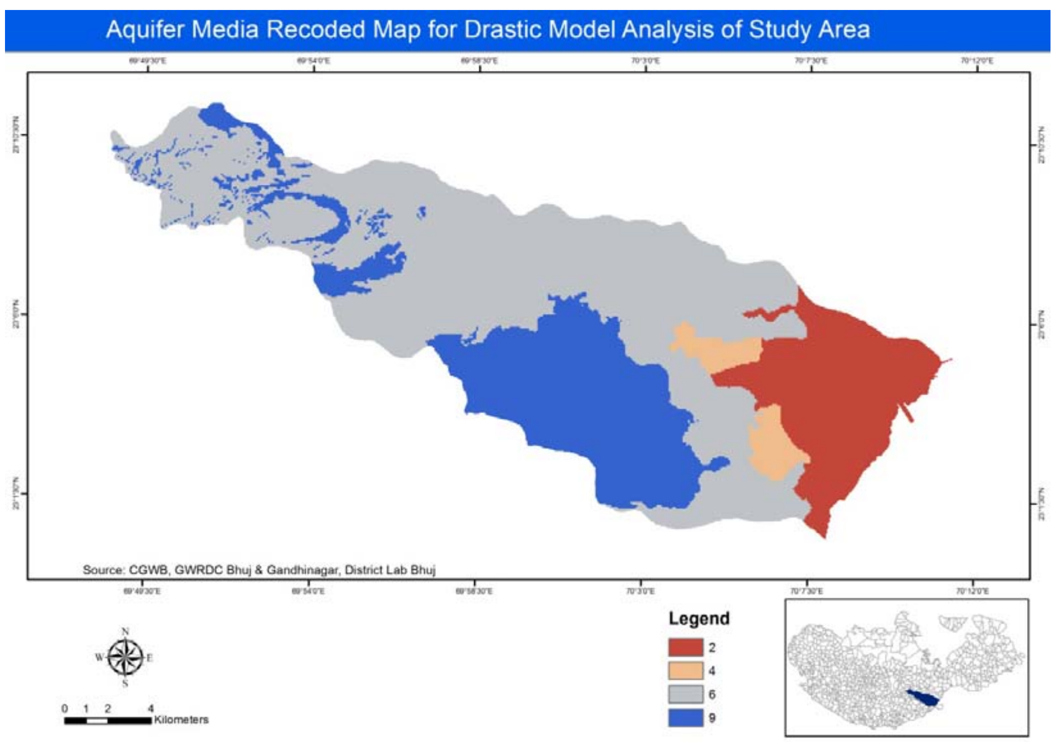


Fig. 6.19 Recoded Aquifer Media Map

6.4.4.4 Soil Media

The portion of the earth located between the surface and the uppermost bedrock is refered to as Soil media . This area contains significant biologic activity and organic material at the surface. The type and size of the soil media directly affects the rate of infiltration of pollution (Aller et al., 1987).

Soil data was initially obtained from the NBSS database. However the soils were later classified in regards to local soil characteristics which were surveyed on the field and were rated accordingly within the Modified DRASTIC model (Table 6.5).

Table 6.5 Soil Media with associated DRASTIC Weightages

Soil Media	
Range	Rating
Fine	2
Fine to loamy	3
Loamy	4
Mixed (Loamy to coarse)	5
Medium to coarse	6

The type and size of the soil media directly affects the rate of infiltration and is rated according to the modified DRASTIC model

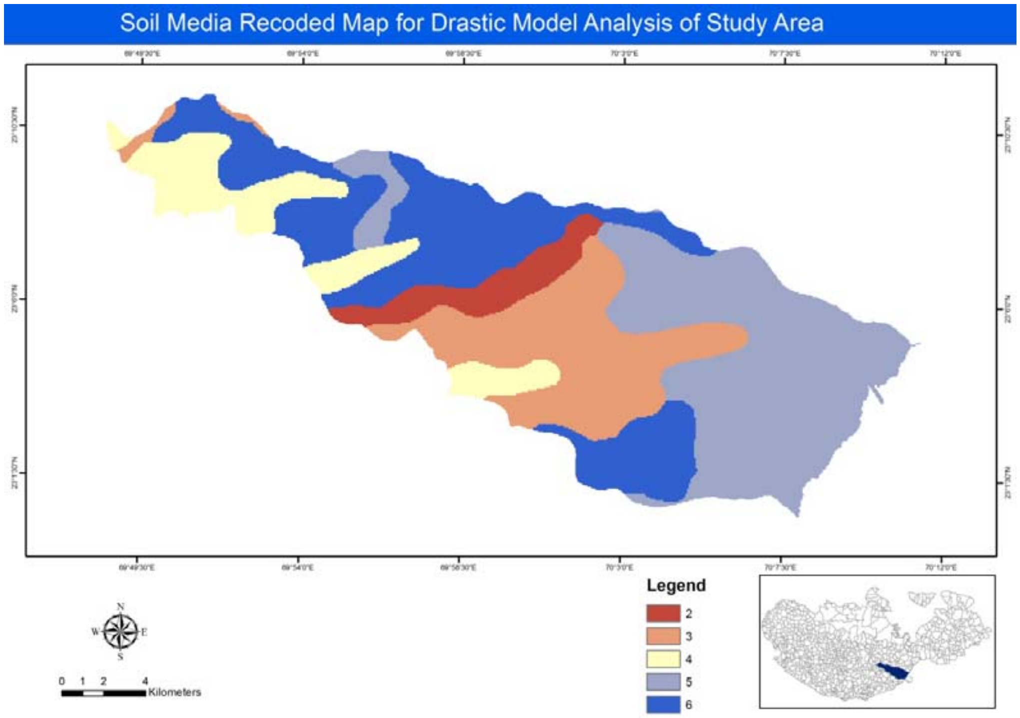


Fig. 6.20 Recoded Soil Media Map

6.4.4.5 Topography

Topography is variability of the slope, or gradient, of the ground surface. Slope affects the type and amount of soil at the surface of the land as well as the rate and quantity of runoff. A contaminant introduced on a steep slope has less chance of infiltrating into the surface and would likely flow downward leaving concentrated pollution at the base of the slope near a groundwater source. Slope is also used to determine gradient and flow of the water table since the water table similarly follows the contour of the surface (Aller et al., 1987).

The Slope tool from the Raster Surface toolset in the 3DAnalyst extension was used to generate the slope of study area. 30-meter DEM was used to calculate a grid layer showing percent slope. The slope layer was then reclassified to rating values according to the percent ranges recommended in the DRASTIC model (Table 6.6)

Table 6.6 Topography with associated DRASTIC Weightages

Topography (Percent Slope)	
Range	Rating
0-2	10
2-6	8
6-12	5
12-18	3
18+	1

Topography is the variability of slope of the ground surface. The slope affects the rate and quantity of runoff and was rated accordingly by the modified DRASTIC model.

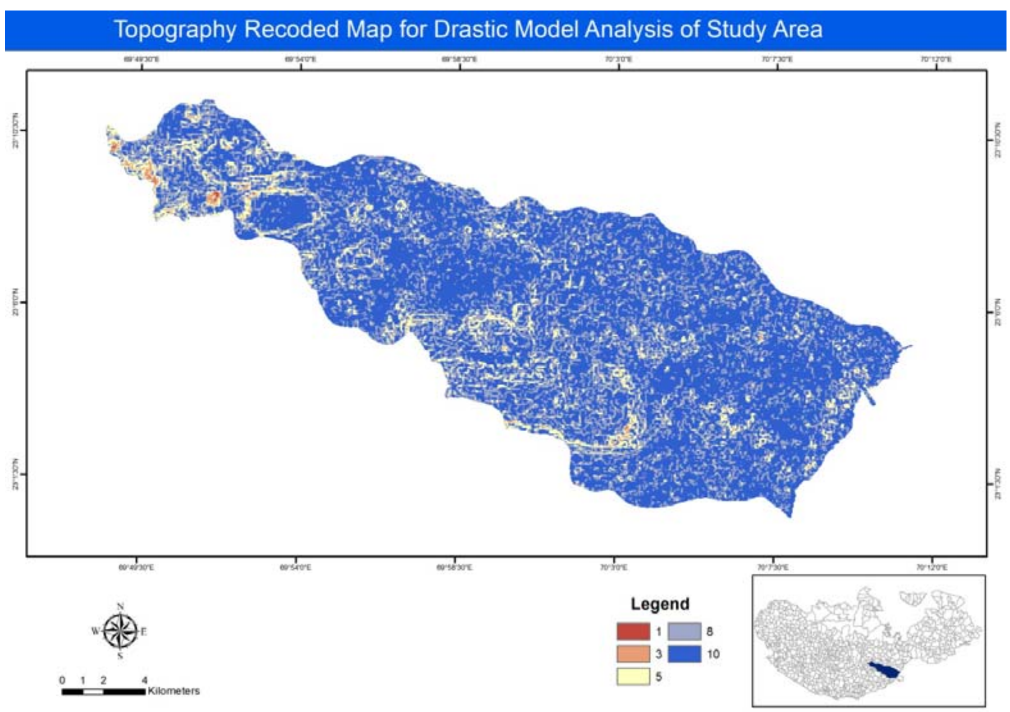


Fig. 6.21 Recoded Topographic Map

6.4.4.6 Impact of the Vadose Zone

The vadose zone is the layer of sub-surface found between the aquifer and the soil cover in which pores or joints are unsaturated; its influence on aquifer pollution potential is similar to that of soil cover, depending on its permeability, and on the attenuation characteristics of the media (S. Kaliraj et al, 2014)

The data used was in combination of the data collected from the field regarding the soil and the geological maps obtained from the GSI and CGM.

Table 6.7 Vadose Zone with associated DRASTIC Weightages

Vadose Zone	
Range	Rating
Mesozoic Deccan trap Basalt and intrusion	10
Bhuj formation sandstone	8
Jhuran sandstone	6
Tertary Kantavati sandstone	4
Quarternary Alluvial – Sand Dominant	2
Quarternary Alluvial - Clay dominant	1

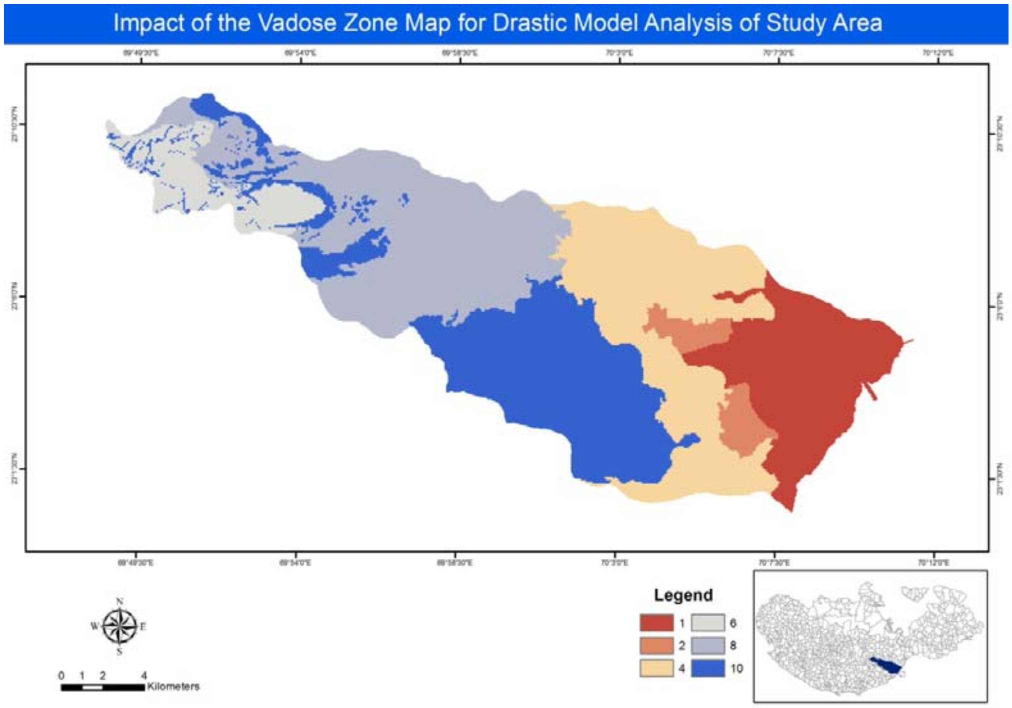


Fig. 6.22 Recoded Map of Vadose Zone

6.4.4.7 Hydraulic Conductivity

This refers to the ability of the aquifer materials to transmit water that controls the rate at which ground water will flow under a given hydraulic gradient. The rate of groundwater flow controls the rate at which a contaminant moves away from the point at which it enters the aquifer (S. Kaliraj et al, 2014)

Table 6.8 Hydraulic Conductivity with associated DRASTIC Weightages

Hydraulic Conductivity	
Range	Rating
100-300	1
300-700	2
700-1000	3
1000-2000	4
2000+	5

The hydraulic conductivity was calculated from the data obtained from the district lab, Bhuj and from the discharge or Pump test data and soil properties data collected from the field

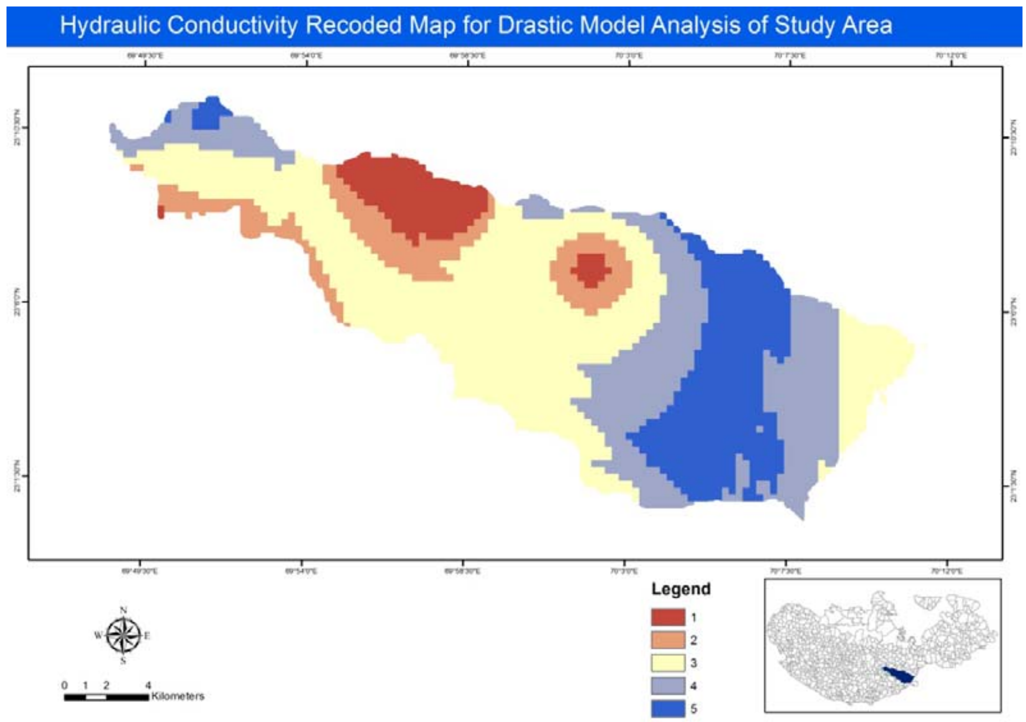


Fig. 6.23 Recoded Hydraulic Conductivity Map

6.4.5 DRASTIC Index

The final step in the modified DRASTIC model was to apply the weight factors to each of the seven parameters. Each parameter was weighted by multiplying the rating of each cell value and the DRASTIC weight using the Math toolset's Times tool in the Spatial Analyst extension. The resulting cell values for all parameters were added together using the Plus tool from the same toolset (Fig. 6.25). The final raster represented the DRASTIC Index showing the risk of susceptibility to contaminants in study area.

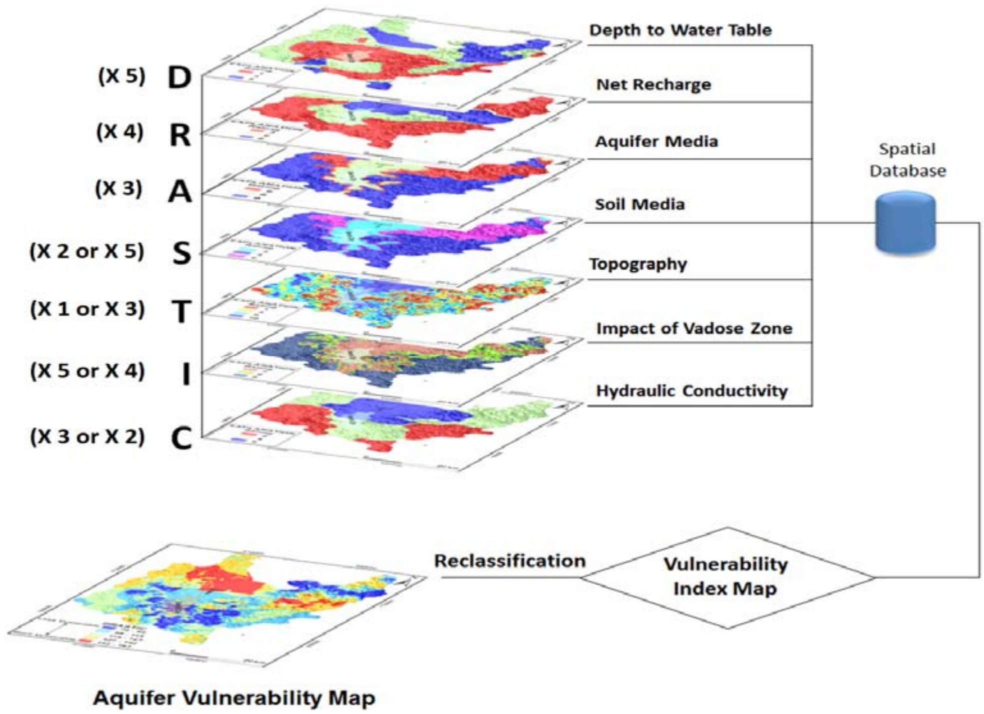


Fig. 6.24 Drastic Index (Source: Yahia Alwathaf et al (2011).

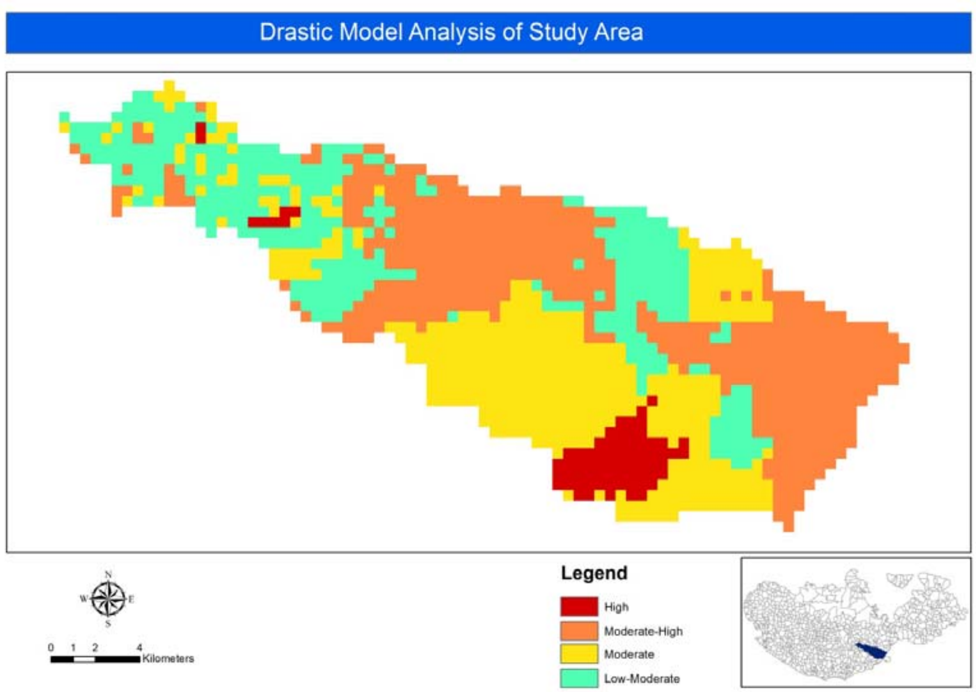


Fig. 6.25 Output Map of Drastic Model

6.4.6 Conclusions

The DRASTIC map showed higher risk areas mostly in the southern part of the study area with some dispersed moderate to high risk areas throughout the study area. Few of the area in the southern portion of the Gandhidham Taluka are in the high risk as shown in the map in red colour where there are agriculture fields. This area is also adjacent to the major water body of Anjar Taluka. A little portion on North and some region of the south of Anjar Taluka fall in moderate risk, whereas the upper areas near Bhuj and few portion towards the north in the Anjar Taluka area at comparatively lower to moderate risk.

Depending on the weightage applied to the parameters of the drastic model the ultimate output is supposed to vary. Hence it is of utmost important to take care in applying the weightages to them. The weightages applied here has been carefully worked out with the help of local geologists.

The research was planned to study the risk of groundwater contamination in study area. Modifying the DRASTIC model to accommodate local hydrogeological settings and combining the use of GIS made it possible to create a visual tool representing areas of risk. Many of the methods used for calculating the DRASTIC parameters typically rely on information provided by a geology, soil and Groundwater map. The maps produced, though reliable to the level of information used, should be used only as reference for further research. This study serves as a foundation to build upon and provide techniques that may be used for future groundwater research.

In this particular application it is to be noted that the area is a coastal zone and hence sea water ingression cannot be avoided due to the presence of various industries at the coast as well as Kandla port and also due to over exploitation of the groundwater resources due to the rising demand. Sea water ingression is also to be considered here as an additional factor.

6.5 MORPHOMETRIC ANALYSIS

6.5.1 Introduction

The drainage basin analysis is important in any hydrological investigation like assessment of groundwater potential and groundwater management. Various important hydrologic phenomena can be correlated with the physiographic characteristics of drainage basins such as size, shape, slope of drainage area, drainage density, size and length of the tributaries etc. (Rastogi et al., 1976). Remote sensing data can be used in conjunction with conventional data for delineation of ridgelines, characterization, priority evaluation, problem identification, assessment of potentials and management needs, identification of erosion prone areas, evolving water conservation strategies, selection of sites for check dams and reservoirs etc.,(Dutta et al.,2002). The present study describes the drainage characteristics of Sakar and Sang River obtained through RS and GIS based morphometric analysis. This type of studies are useful in understanding hydrological behavior of basin.

6.5.2 Methodology:

In present study, morphometric analysis and priorization of basin is based on the integrated use of remote sensing and GIS technique. The remotely sensed data is geometrically rectified with respect to Survey of India (SOI) topographical maps at 1:50000.The digitization of dendritic drainage pattern is carried out in Arc GIS 10.1 software. For stream ordering, Horton's law is followed by designating an un-branched stream as first order stream, when two first order streams join, it is designated as second order. Two second order steams join together to form third order and so on. The number of streams of each order are counted and recorded. The drainage map along with basin boundaries are digitized as a line coverage giving unique id for each order of stream. Morphometric parameters under linear and shape are computed using standard methods and formulae (Horton 1945; Smith 1950; Strahler, 1964).The fundamental parameter namely; stream length, area, perimeter, number of streams and basin length are derived from drainage layer. The values of morphometric parameters namely; stream length, bifurcation ratio, drainage density, stream frequency, form factor, texture ratio, elongation ratio, circularity ratio and compactness constant are calculated based on the formulae suggested by Horton (1945), Miller (1953), Schumn(1956), Strahler(1964), Nookaratm et al (2005) .

6.5.3 Morphometric Parameters of basin

The following paragraphs describe the physical meaning of various morphometric parameters. Further values of these parameters are obtained as per methods proposed by various researchers for the study area and indicated in respective descriptions. The formulae used for evaluating morphometric parameter are tabulated in Table 6.9.

Table 6.9 Method of Calculating Morphometric Parameters of Drainage basin

	Morphometric Parameters	Formula/Defination	References
LINEAR	Stream order (U)	Hierarchical order	Strahler,1964
	Stream Length (LU)	Length of the stream	Hortan, 1945
	Mean stream length (Lsm)	Lsm=Lu/Nu; Where, Lu= stream length of a given order (km), Nu=Number of stream segment.	Hortan, 1945
	Stream length ratio (RL)	RL= Lu / Lu-1 Where, Lu= Total stream length of order (u), Lu-1=The total stream length of its next lower order.	Hortan, 1945
	Bifurcation Ratio (Rb)	Rb = Nu / Nu+1 Where, Nu=Number of stream segments present in the given order Nu+1= Number of segments of the next higher order	Schumn,1956
RELIEF	Basin relief (Bh)	Vertical distance between the lowest and highest points of basin.	Schumn,1956
	Relief Ratio (Rh)	Rh = Bh / Lb Where, Bh=Basin relief, Lb=Basin length	Schumn,1956
	Ruggedness Number (Rn)	Rn=Bh×DdWhere,Bh= Basin relief, Dd=Drainage density	Schumn,1956
AERIAL	Drainage density (Dd)	Dd=L/A Where, L=Total length of stream, A= Area of basin.	Hortan, 1945
	Stream frequency (Fs)	Fs=L/A Where, L=Total number of stream, A=Area of basin	Hortan, 1945
	Texture ratio (T)	T=N1/P Where, N1=Total number of first order stream, P=Perimeter of basin.	Hortan, 1945
	Form factor (Ff)	Ff=A/(Lb)2 Where, A=Area of basin, Lb=Basin length	Hortan, 1945
	Circulatory ratio (Rc)	Rc=4πA/P2Where A= Area of basin,π=3.14, P= Perimeter of basin.	Miller,1953
	Elongation ratio (Re)	Re=2(√(A/π))/ Lb Where, A=Area of basin, π=3.14, Lb=Basin length	Schumn 1956
	Length of overland flow (Lg)	Lg=1/2Dd Where, Drainage density	Hortan, 1945
	Constant channel maintenance(C)	Lof=1/Dd Where, Dd= Drainage density	Hortan, 1945

6.5.3.1 Linear Aspects

The linear aspects of morphometric analysis of basin include stream order, stream length, mean stream length, stream length ratio and bifurcation ratio.

Stream Order (U)

There are four different system of ordering streams that are available [Horton (1945), Strahler (1952)]. Strahler's system, which is a slightly modified of Hortons system, has been followed because of its simplicity, where the smallest, un-branched fingertip streams are designated as 1st order, the confluence of two 1st order channels give a channels segments of 2nd order, two 2nd order streams join to form a segment of 3rd order and so on. When two channel of different order join then the higher order is maintained. The trunk stream is the stream segment of highest order. It is found that most river tributaries are of 4th order. Drainage patterns of stream network from the basin have been observed as mainly of dendritic type which indicates the homogeneity in texture and lack of structural control. The properties of the stream networks are very important to study basin characteristics.

Stream Length (Lu)

The stream length (Lu) has been computed based on the law proposed by Horton. Stream length is one of the most significant hydrological features of the basin as it reveals surface runoff characteristics. The stream of relatively smaller length is characteristics of areas with larger slopes and finer textures. Longer lengths of streams are generally indicative of flatter gradient. Generally, the total length of stream segments is maximum in first order stream and decreases as stream order increases. The numbers of streams are of various orders in a watershed are counted and their lengths from mouth to drainage divide are measured with the help of GIS software. The length of first order stream is 210.66 Km, second order stream is 123.32 Km, third order stream is 82.63 Km, fourth order stream is 68.87 Km and fifth order stream is 60.77 km. The change may indicate flowing of streams from high altitude, lithological variation and moderately steep slopes.The observation of stream order verifies the Horton's law of stream number i.e. the number of stream segment of each order forms an inverse geometric sequence with order number.

Mean Stream Length (Lsm)

The mean stream length is a characteristic property related to the drainage network and its associated surfaces (Strahler, 1964), .The mean stream length (Lsm) has been calculated by dividing the total stream length of order by the number of stream. The mean stream length of study area is 0.4 for first order, 0.377 for second order, 0.578 for third order, 0.76 for fourth order and 0.74 for the fifth order. In general it can be said that the mean stream length of stream increases with increase of the order.

Stream Length Ratio (RL)

The stream length ratio can be defined as the ratio of the mean stream length of a given order to the mean stream length of next lower order and has an important relationship with surface flow and discharge (Horton, 1945). The RL values between streams of different order in the basin reveal that there are variations in slope and topography. It ranges from 1.13 to 1.7 for the study area.

Bifurcation Ratio (Rb)

Bifurcation ratio (Rb) may be defined as the ratio of the number of stream segments of given order to the number of segments of the next higher order (Schumn 1956).

Horton (1945) considered the bifurcation ratio as an index of relief and dissections. Strahler (1952) demonstrated that the bifurcation ratio shows a small range of variation for different regions or different environmental conditions, except where the geology dominates. It is observed that Rb is not the same from one order to its next order. In the study area mean Rb varies from 1.098 to 1.59; the mean Rb of the entire basin is 1.64.

6.5.3.2 Relief Aspects

The relief aspects determined include relief ratio, relative relief and ruggedness number.

Relief Ratio (Rh)

The relief ratio, (Rh) is ratio of maximum relief to horizontal distance along the longest dimension of the basin parallel to the principal drainage line (Schumn, 1956). The Rh normally increases with decreasing drainage area and size of watersheds of a given drainage basin (Gottschalk, 1964). Relief ratio measures the overall steepness of a drainage basin and is an indicator of the intensity of erosion process operating on slope of the basin (Schumn, 1956). The value of Rh in basin is 7.33 indicating moderate relief and moderate slope.

Basin Relief (Bh)

This term was given by Melton (1957). In the present study area it is obtained by visual analysis of the digital elevation model prepared from ASTER data. The elevation varies from 0.0 m near the coastal area of gandhidham to 286 m around the villages of Bhuj taluka within the study area which represent the land has moderate slope.

Ruggedness number (Rn)

It is the product of maximum basin relief (H) and drainage density (Dd), where both parameters are in the same unit. An extreme high value of ruggedness number occurs when both variables are large and slope is steep. (Schumm, 1956). The value of ruggedness number in present basin is 481.84.

6.5.3.3 Aerial Aspects

It deals with the total area projected upon a horizontal plane contributing overland flow to the channel segment of the given order and includes all tributaries of lower order. It comprises of drainage density, drainage texture, stream frequency, form factor, circularity ratio, elongation ratio and length of overland flow.

Drainage density (Dd)

Horton (1932), introduced the drainage density (Dd) is an important indicator of the linear scale of land form elements in stream eroded topography. It is the ratio of total channel segment length cumulated for all order within a basin to the basin area, which is expressed in terms of Km/Km2.The drainage density, indicates the closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin. It has been observed from drainage density measurement made over a wide range of geologic and climatic type that a low drainage density is more likely to occur in region and highly resistant of highly permeable subsoil material under dense vegetative cover and where relief is low. High drainage density is the resultant of weak or impermeable subsurface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine drainage texture (Strahaler, 1964).The drainage density (Dd) of study area is 1.685 Km/Km2 indicating moderate drainage densities. The Moderate drainage density indicates the basin is highly permeable subsoil and vegetative cover.

Stream Frequency (Fs)

Stream frequency (Fs), is expressed as the total number of stream segments of all orders per unit area. It exhibits positive correlation with drainage density in the watershed indicating an increase in stream population with respect to increase in drainage density. The Fs for the basin is 3.58. (Horton, 1932)

Texture Ratio (T)

Drainage texture ratio (T) is the total number of stream segments of all orders per perimeter of that area (Horton, 1945). It depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development. In the present study the texture ratio of the basin is 4.78 and categorized as moderate in the nature.

Form Factor (Ff)

Form factor (Ff) is defined as the ratio of the basin area to the square of the basin length. This factor indicates the flow intensity of a basin of a defined area (Horton, 1945). The form factor value should be always less than 0.7854 (the value corresponding to a perfectly circular basin). The smaller the value of the form factor, the more elongated will be the basin. Basins with high form factors experience larger peak flows of shorter duration, whereas elongated watersheds with low form factors experience lower peak flows of longer duration. The Ff value for study area is 0.213, indicating elongated basin with lower peak flows of longer duration than the average.

Circulatory Ratio (Rc)

Circularity Ratio is the ratio of the area of a basin to the area of circle having the same circumference as the perimeter of the basin (Miller, 1953). It is influenced by the length and frequency of streams, geological structures, land use/ land cover, climate and slope of the basin. The Rc value of basin is 0.344 indicating the basin is characterized by moderate to low relief and drainage system seems to be less influenced by structural disturbances. The high value of circularity ratio shows the late maturity stage of topography.

Elongation Ratio (Re)

Schumn (1956) defined elongation ratio as the ratio of diameter of a circle of the same area as the drainage basin and the maximum length of the basin. Values of Re generally vary from 0.6 to 1.0 over a wide variety of climatic and geologic types. Re values close to unity correspond typically to regions of low relief, whereas values in the range 0.6–0.8 are usually associated with high relief and steep ground slope (Strahler 1964). These values can be grouped into three categories namely (a) circular (>0.9), (b) oval (0.9-0.8), (c) less elongated (<0.7). The Re values in the study area is 0.52 indicating moderate to slightly steep ground slope and area when collaborated with Strahler's range seem to suggest an elongated shape.

Length of overland flow (Lg)

The Length of Overland Flow (Lg) is the length of water over the ground surface before it gets concentrated into definite stream channel (Horton, 1945). Lg is one of the most important independent variables affecting hydrologic and physiographic development of drainage basins. The length of overland flow is approximately equal to the half of the reciprocal of drainage density. This factor is related inversely to the average slope of the channel and is quiet synonymous with the length of sheet flow to a large degree. The Lg value of study area is 0.297.

Constant channel maintenance (C)

Schumm (1956) used the inverse of drainage density as a property termed constant of stream maintenance C. This constant, in units of square feet per foot, has the dimension of length and therefore increases in magnitude as the scale of the land-form unit increases. Specifically, the constant C provides information of the number of square feet of watershed surface required to sustain one linear foot of stream. The value C of basin is 0.59.It means that on an average 0.59 sq.ft surface is needed in basin for creation of one linear foot of the stream channel.

6.5.4 Results and Interpretation

Bifurcation ratio, length ratio and stream order of basin indicates that the basin is fifth order basin with dendritic type of drainage pattern with homogeneous nature. Relief ratio, Ruggedness number and visual interpretation of DEM of study area indicate moderate and high relief, moderate run off and moderate to high infiltrations. Drainage density, texture ratio, circulatory ratio and elongation ratio shows that texture of basin is moderate and shape of basin almost elongated. The complete morphometric analysis of drainage basin indicates that the given area is having good groundwater prospect. Results of this analysis are tabulated in Table 6.10 (a) and Table 6.10 (b).

Table 6.10 (a) Result of morphomatric analysis

Stream order	Number of stream Nu	Bifurcation ratio	Mean Stream Length	Stream length ratio	Total length of stream Lu (Km)	Mean of Bifurcation ratio
1	520	1.590	0.405	1.708	210.667	
2	327	2.287	0.377	1.492	123.329	
3	143	1.589	0.578	1.200	82.639	
4	90	1.098	0.765	1.133	68.877	
5	82	---	0.741	----	60.772	1.640

Table 6.10 (b) Result of Morphomatric Analysis

Sr. no	Parameter	Value
1	Basin Area (Km)2	324.250
2	Perimeter (Km)	108.800
3	Basin order	5.000
4	Drainage density(Dd) (Km/Km2)	1.685
5	Stream frequency (Fs) (Km)2	3.584
6	Relief Ratio (Rh)	7.333
7	Texture ratio(T) (Km)	4.779
8	Basin Length(Lb) (Km)	39.000
9	Basin Relief(Bh) (m)	286.000
10	Ruggedness number (Rn)	481.841
11	Mean Bifurcation ratio (Rb)	1.640
12	Form Factor (Rf)	0.213
13	Circulatory ratio (Rc)	0.344
14	Elongation Ratio (Re)	0.521
15	Length of overland flow (Lg) (Km)	0.297
16	Constant channel maintenance (C) (Km)	0.594

6.5.5 Conclusion

This chapter helped in understanding the overall Drainage pattern and hydrological behavior of the study area. Correlation between different physiographic characteristics of drainage basins such as size, shape, slope of drainage area, drainage density, size and length of the tributaries etc was very useful in hydrological investigation for assessment of groundwater potential and groundwater management.

6.6 DELINIATING GROUND WATER SUITABILITY (AHP)

6.6.1 Introduction

The dependability of groundwater is very much increasing day by day and was already high on account of unreliable water supplies from the surface water reservoirs due to vagaries of monsoon. Further, in general 85 % of the total rainfall is confined to south-west monsoon i.e between June and September. Much of the 4000 billion cu.m of the rain in the country falls in just 100 hrs out of the 8760 hrs in a year. Under such erratic rainfall conditions, the natural recharge to the groundwater becomes highly erratic. At this juncture, the artificial recharge to groundwater is vital and needs the attention of the Government and the awareness of the common man.

Artificial recharge is a process of augmenting groundwater through infiltration of rainwater or surface run-off into the underground formation by artificial methods. Wherever the demand of groundwater is more than its availability, augmentation of the resource is required by construction of percolation tanks, check dams and other type of recharge structures. Though the augmentation of the resource is possible at many places, the prioritisation of the zones is essential. Further, the identification of suitable zones with favorable hydrogeological conditions is a primary requisite to implement the construction of artificial recharge structures.

The zone is confined to the part of shallow weathered pediplains, inselbergs, and dissected Plateau. These zones lack either primary or secondary porosity. Hence, this zone is not suitable for any kind of new artificial recharge structures. However, the existing tanks may be de-silted, which can help in supplementing the recharge to groundwater in these zones to some extent.

6.6.2 Scope of the Study

Potential zones can be easily identified with the help of ground water prospect maps in the concerned areas. Selection of the suitable site for artificial recharge to improve sustainability of water resources can be more improved with the help of ground water prospect maps.

Groundwater data along with the remote sensing data can be of immense use for the generation of the thematic layers like geomorphology, geological structures, hydrological parameter and also for the base map details.

These thematic layers are then integrated in GIS environment with suitable technique and weightings for hydro-geomorphic units.

The ground water prospects are expected to be uniform in a given hydrogeomorphic unit. In conjunction with the well data collected during the field work these hydro-geological units can give better estimates of ground water prospects.

Suitable well type, its depth in a particular formation that can be drilled and expected yield range can be estimated based on these technology. In addition, water quality and ground water irrigated area can also be estimated. Sufficient recharge is essential to improve the ground water regime, particularly the sustainability of both drinking as well as irrigation. Accordingly, the types of recharge structures that are suitable in each hydro-geomorphic unit are identified. The tentative locations for their construction are also suggested.

6.6.3 Modeling-The Decision Making Process

Outputs from process models of both human and physical systems are raw information that will be required to assist various types of decision making, output from a site allocation model might show potential locations for Artificial recharge site selection. This would need to be integrated with other data to ensure that the site is developed inline with regional strategic planning objectives. As each theme will have different effect on the environment it may be necessary to evaluate what these will be to help decide which of the selection options should be pursued.

To be integrated with other environmental parameter to determine priority areas for recharge, Map overlay is the traditional technique for integrating data for use in spatial decision making. For example in finding solid waste dumping site the criteria defining the geological suitability and conservation area status can be combined. However overlay analysis suffers from certain limitations when dealing with decision-making problems of a less defined nature. To summarize these:

Digital map overlays are difficult to comprehend when more than four or five factors are involved. Most overlay procedures in GIS do not allow for the fact that variables may not be equally important. When mapping variables for overlay analysis decisions about threshold values are important.

One way to address these problems is to use Multi-Criteria Evaluation (MCE) techniques to either supplement or replace standard map overlay in GIS. MCE techniques allow map layers to be weighted to reflect their relative importance and unlike polygon overlay in vector GIS they do not rely on threshold values. Therefore MCE provides framework for exploring solutions to decision-making problems, which may be poorly defined. MCE is a method of combining data according to their importance in making a decision. At a conceptual level, MCE methods evolve qualitative or quantitative weighting, coring or ranking of criteria to reflect their importance to either a single or a multiple set objectives. It is not the intention to introduce the full range of MCE techniques, however key concepts are presented here to appreciate it in GIS context. In essence MCE techniques are numerical algorithms that define the suitability of a particular solution on the basis of input criteria and weights together with some mathematical or logical means of determining tradeoffs when conflicts arise. The MCE techniques within a GIS permit the limitations of standard map overlay to be addressed.

The first step in MCE is to define a problem. In artificial recharge study the criteria that will influence the decision must then be defined. The criteria can be thought as a data layers in GIS. In artificial recharge study the main criteria that will influence the recharge would be average rainfall, Local Geology, Geomorphology, Slope, Runoff, Drainage pattern, Soil types, Depth of water level, Land use and landover.

6.6.3.1 Selection of criterion

Most MCE analyses in GIS start with the identification of the criteria that are important to the problem. These criteria's are represented as separate raster data layers in the GIS.

6.6.3.2 Standardization of the criterion scores

MCE analyses especially those using quantitative or mixed data sources, require some form of standardization of the scales of measurement used by the data layers. This is necessary to facilitate the comparison of factors measured during the different units and the scales of measurement. Therefore, standardization of the scales will enable meaningful comparisons between the data layers. Standardization can be done in a different ways, but it is normal to apply linear stretch routine to rescale the values in raster map between the maximum and minimum values present. Care needs to be taken to observe polarity such that the beneficial factors are represented in a way that gives a high value to high benefit and low value to low benefit. Another common method is to bring all the values on a data layer to an interval value between 0 and 10. For example weights are allocated in a manner in which it reflects the relative importance of data layers. Weighting of 80% may be expressed as 8.

6.6.3.3 Applying the MCE algorithm

An MCE Algorithm then multiplies these standardized scores by the data weights for each of the data layers to allocate a score to each pixel on the output map. The map produced will be a surface with values ranging from 0 to 10. In the case of artificial recharge; areas with a value close to 10 represent those areas where maximum recharge is possible. Ranking the values of the results in map and reclassifying the ranked map to show the top ranked sites may carry out further evaluation of the results.

6.6.4 Analytical Hierarchy Process

Decision analysis involves the use of a rational process for selecting the best of several alternatives. The "goodness" of a selected alternative depends on the quality of data used in describing the decision situation. The analysis that has to be carried out for selecting the site for the Artificial Recharge of groundwater has several benefits in decision-making 'under certainty in which the data are known deterministically', i.e. we can assign each of the spatial data a certain relative rank points over the other members in a particular map data set based entirely on knowledge and experience.

Following are the rank matrices for various criterions taken into account for analysis.

6.6.4.1 Weightages Assigned to Individual Parameters of the Thematic Maps

Geomorphology

Geomorphology exercises a significant control over groundwater regime, especially in hard rock terrain. The relief, slope, depth of weathering, type of weathered material, thickness of deposition and the nature of deposited material play an important role in defining the groundwater regime (Reddy, 2000). There is an increasing trend in the use of geomorphology in location, evaluation and proving of groundwater resources. The technique of Morphological mapping is first developed by Savigear (1952), Waters (1958) and (King, 1976).

Table- 6.11 Weightage Assigned to Geomorphological units

SI.No.	Class	Code
1	Valley Fill (VF)	7
4	Deeply weathered buried pediplain	6
2	Pediplain Moderate (PPM)	5
3	Pediplain Shallow (PPS)	4
5	Coastal Plain	3
6	Dissected Plateau	2
8	Denudo structural Hill	2
7	Structural Hill	1
9	Inselberg	1
10	Linear ridges (LR)	1

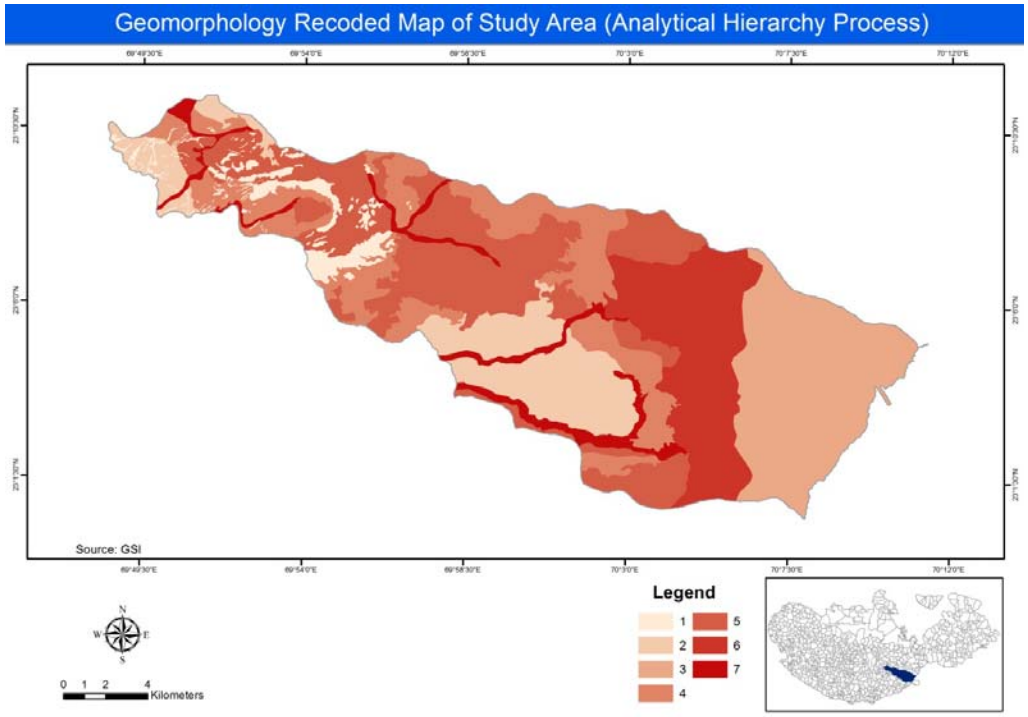


Fig. 6.26 Recoded Geomorphology Map

Geology

The regional geological maps indicate the location of different geological strata, their geological age sequence, boundaries/contacts of individual formations and the structural expressions like Strike, Dip, Faults, Folds, Flexures, Intrusive bodies etc. These maps also bring out correlation of topography and drainage to geological contacts.

Table 6.12 Weightage Assigned to Geololgical units

SI.No.	Class	Code
1	Mesozoic Bhuj sandstone	6
2	Tertiary kankavati formation	5
3	Mesozoic Jhuran sandstone	4
	Quartinary Alluvial (Sand Dominated)	3
5	Quartinary Alluvial (Clay Dominated)	2
4	Basaltic intrusion	1
6	Mesozoic deccan trap basalt	1

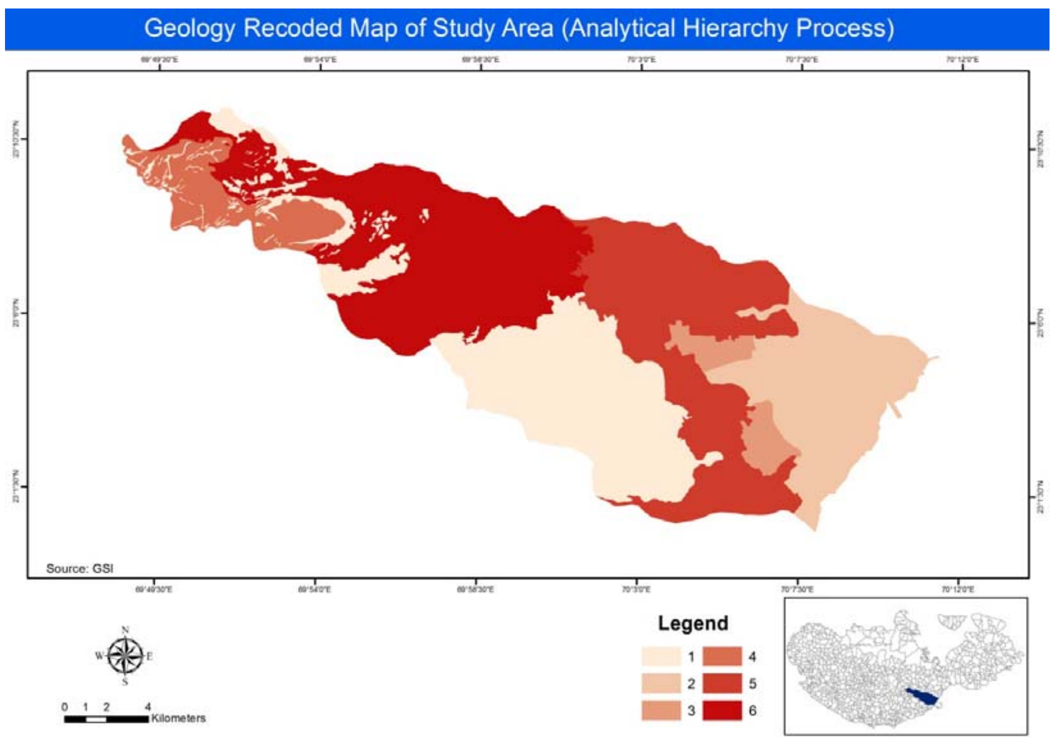


Fig. 6.27 Recoded Geology Map

Water Table

Recharge is the process through which water enters an aquifer. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface. For this purpose it is important to consider the water table for any kind of artificial recharge.

Table 6.13 Weightage Assigned to Static Water Level in Mtr.

SI.No.	Class	Code
1	150.1 - 175	9
2	135.1 – 150	8
3	120.1 – 135	7
4	105.1 – 120	6
5	90.1 – 105	5
6	75.1 – 90	4
7	60.1 – 75	3
8	45.1 – 60	2
9	< 45	1

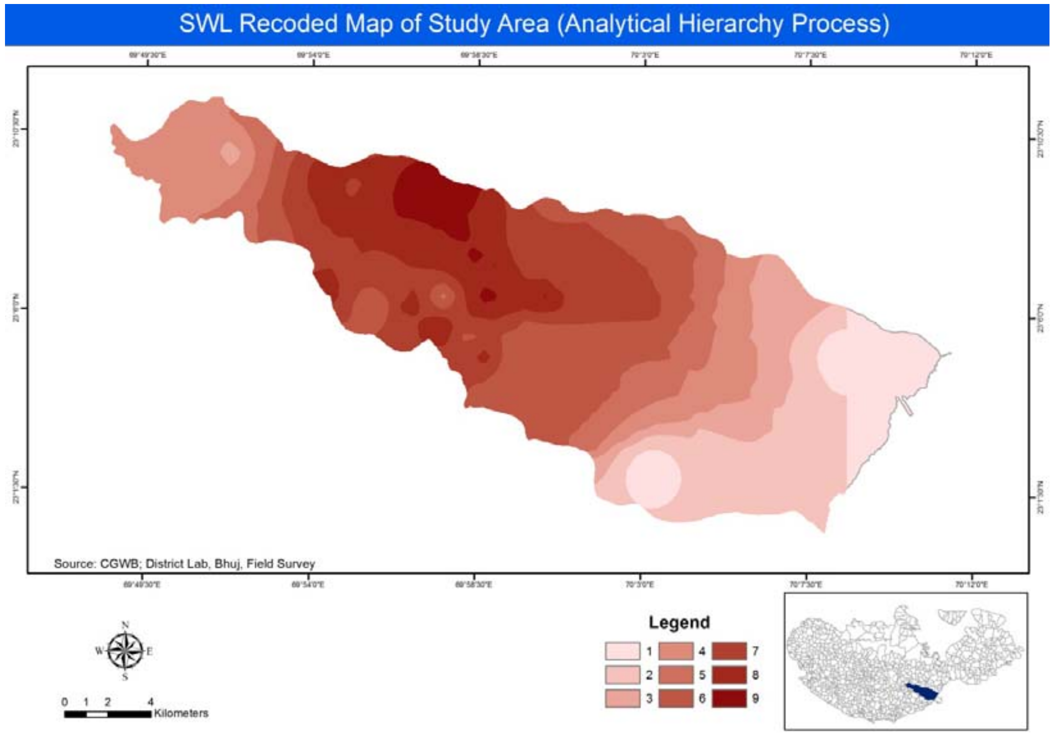


Fig. 6.28 Recoded SWL Map

Slope

Slope has a direct control on the surface runoff and infiltration processes. Infiltration is inversely related to slope. Gentle slopes coupled with vegetative cover will have higher infiltration and less runoff. The general slope of the area is towards East. The slope of more than 60 ° is found near to Jhuran, while villages like Sapeda, Malingna, Sinugra, Khirsara are showing the trend of gentle slope. Villages like Anjar and Vidi have moderate slope of 10 to 20°.

The northern boundary of upper Jurassic constitute a ridge running along the northern edge of the Jurassic outcrop. The southern island of lower Jurassic in the Bhuj-Anjar region constitutes a low range of hills running east-west south of Bhuj. Between these two ridges lies the broad mass of upper Jurassic a mass of qquiferous formations favorably placed for entry and preservation of water in them-which forms a trough as it were. The surface slopes in this trough are towards the north so that rivers flow northwards through this trough. These rivers have cut passes through the lower Jurassic formations of the northern range of hills and flow towards the great Rann. While the surface slopes in this region are towards the north the strata dip southward in the vicinity of the east-west fault. (more or less along the latitude of Bhuj 23° 14')(Chablani, 1949)

Table 6.14 Weightage Assigned to Slope (in degree)

SI.No.	Class	Code
1	0.0 – 0.5	6
2	0.5 – 2.0	5
3	2.0 – 5.0	4
4	5.0 – 10.0	3
5	10.0 – 15.0	2
	15.0 – 22.0	1

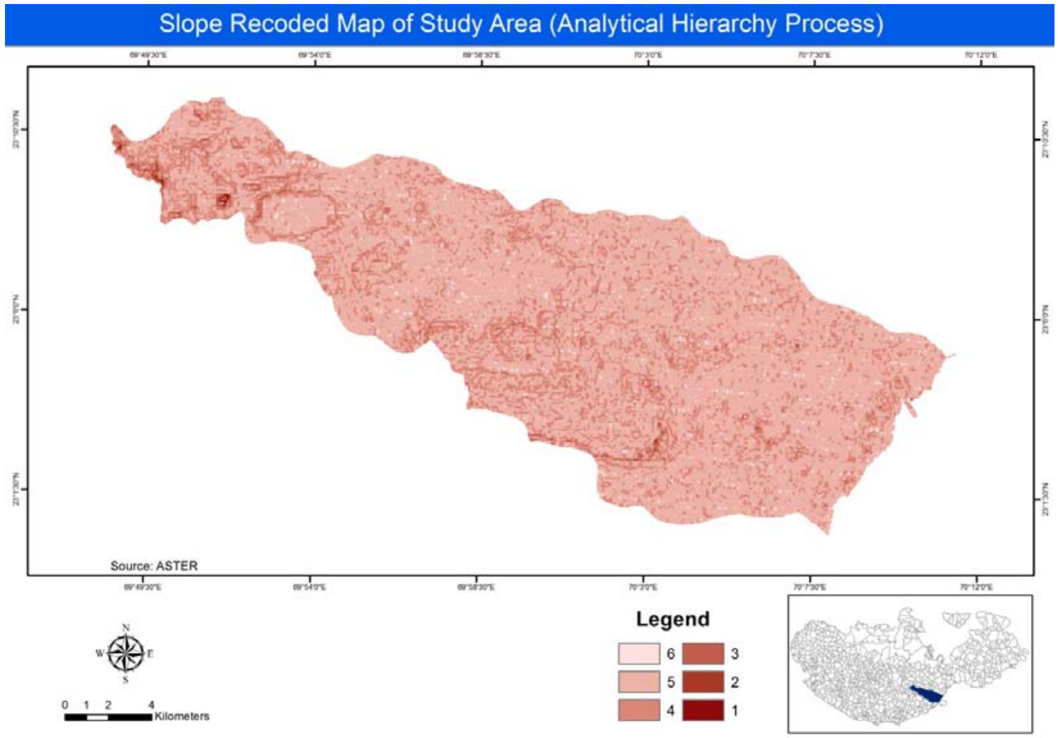


Fig. 6.29 Recoded Slope Map

Land Use /Land Cover

Groundwater is intimately connected with the landscape and land use that it underlies, and most of the landscape and is vulnerable to the anthropogenic activities on the land surface above. Land use affects groundwater resources through changes in recharge and by changing demands for water. (David N. Lerner, 2009)

As seen from the image large percentage of the area comes under agriculture in form of uncultivated and cultivated land. Agriculture is mostly seen in the central and SE portion of the study area in particular Anjar and Ghandhidham the area that falls under Bhuj formation in Anjar and tertiary and kankavati formation near to Gandhidham. Agriculture is done extensively in the areas of Bhuj sandstone.

Gandhidham Taluka due to its vicinity of sea coast is mostly saline towards the coast

Build-up areas like township, villages and industrial are also present.

Quarry's of Basalt rocks are also seen in the Anjar Taluka due to the occurrence of Mesozoic Deccan trap Basalt in the southern side of the Anjar Taluka.

Table 6.15 Weightage Assigned to Landuse and Landcover

SI.No.	Class	Code
1	River	9
2	Waterbodies	9
3	Flood Plains	9
4	Agriculture/Cultivated Land	8
5	Fallow Land/Uncultivated Land	7
6	Tree Clad Area	6
7	Wasteland	5
8	Saline land	4
9	Salt Pan	4
10	Industries	3
11	Settlement	3
12	Quarries	2
13	Rocky Terrain	2
14	Major Roads (Road Network)	1
15	State HW (Road Network)	1
16	National HW (Road Network)	1

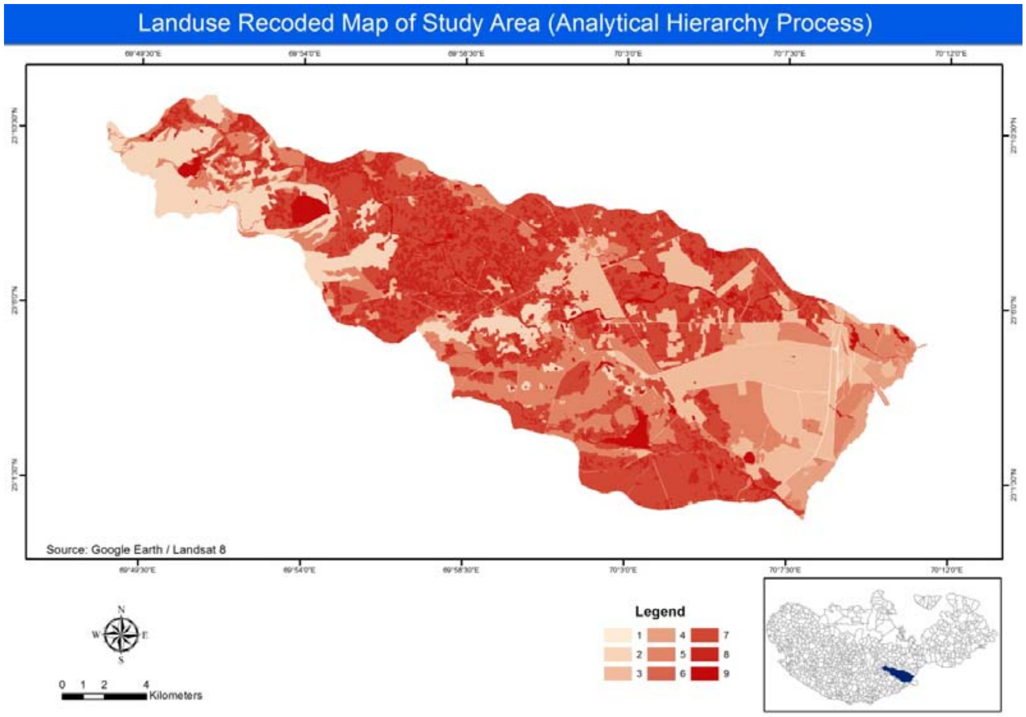


Fig. 6.30 Recoded Land Use Map

Drainage

The trend of groundwater movement in the study area is from E-W. Groundwater moves from the areas of Jhuran sandstone to the coastal plains. From the field survey, govt. report and local interactions it is found that the groundwater potential in general is much better near the 4^{th} and 5^{th} order drainage, for these reasons we have given buffer of 300 m and 240 m to the 5^{th} and 4^{th} order drainage respectively for artificial recharge of groundwater.

Katrol ranges may occur at the depth of 900 m below ground surfaces in the deepest parts of the synclines. These conditions implies that permeable member of the Katrol and Bhuj series should all be exposed on the surface and should be able to receive water which falls on them, either as direct precipitation or by influent seepages from runoff in streams as they pass over the permeable members. The conditions also imply that there should be succession of permeable beds confined by overlying shale members containing water under artesian conditions. (Auden, 1949)

Table 6.16 Weightage Assigned to Drainage

SI.No.	Class	Code
1	5th order (Buffer of 300 m)	5
2	4th order (Buffer of 240 m)	4
3	3th order (Buffer of 180 m)	3
4	2th order (Buffer of 120 m)	2
5	1th order (Buffer of 60 m)	1

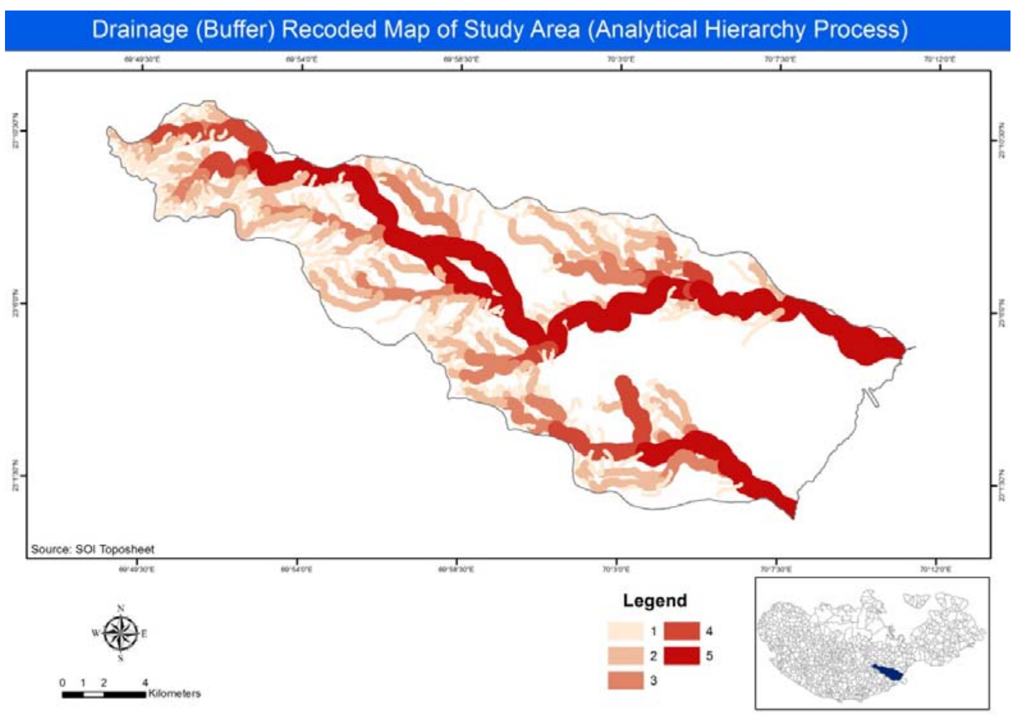


Fig. 6.31 Recoded Drainage Buffer Map

Rainfall Runoff

Surface runoff is the flow of water that occurs when excess storm water, melt water, or other sources flows over the Earth's surface. This might occur because soil is saturated to full capacity, because rain arrives more quickly than soil can absorb it or because impervious areas (roofs and pavement) send their runoff to surrounding soil that cannot absorb all of it. Surface runoff is a major component of the water cycle and must not be ignored while considering artificial recharge of groundwater.

Table 6.17 Weightage assigned to Rainfall Runoff Map

SI.No.	Class	Code
1	16.1 – 18.0	5
2	14.1 – 16.0	4
3	12.1 – 14.0	3
4	10.1 – 12.0	2
5	08.0 – 10.0	1

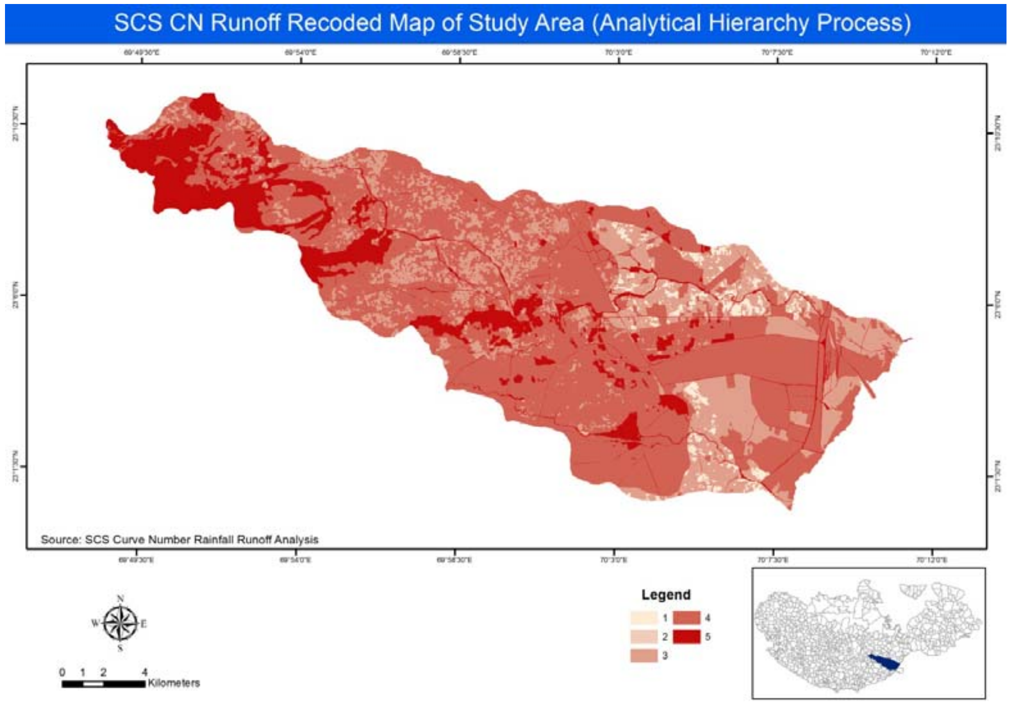


Fig. 6.32 Recoded SCS Rainfall Runoff Map

Soil

Soil and Land use conditions that control the rate of infiltration and downward percolation of the water applied on the surface of the soil assume special importance. Higher correlation coefficient of water level and precipitation implies significant groundwater recharge characteristic or most favorable recharge zone.

Table 6.18 Weightage assigned to Soil Map

SI.No.	Class	Code
1	Moderately Deep, Somewhat excessively Drained, Coarse soil, on very gently sloping pediment	6
2	Moderately Deep, Somewhat excessively Drained, Sandy Soil, on very gently sloping arid plain with slight erosion	5

3	Moderately Deep, Well Drained, Fine loamy Soil, on undulating pediment (with isolated hillocks)	4
4	Moderately Shallow, Well Drained, Fine loamy Soil	3
5	Shallow, well drained, loamy soils on very gently sloping elongated ridges with moderate erosion and moderate stoniness	2
6	Very shallow, somewhat excessively drained, sandy soils on undulating pediment (with isolated hillocks) with severe	1

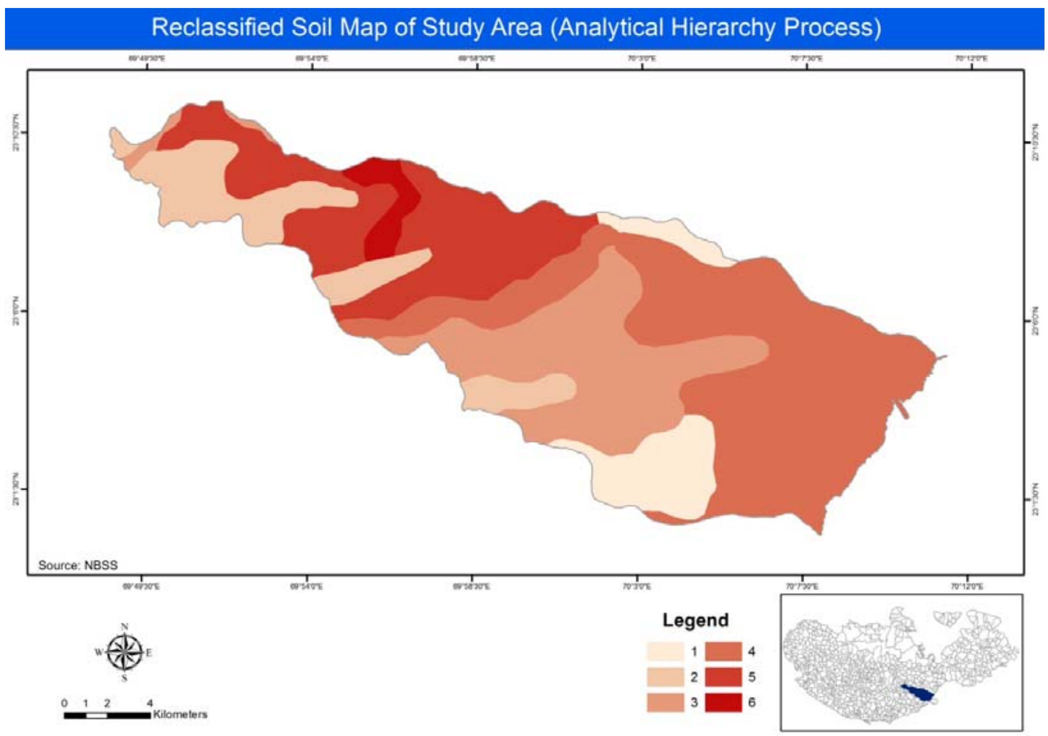


Fig. 6.33 Recoded Soil Map

Average Rainfall

These shall be undertaken to decipher the rainfall pattern, evaporation losses and climatological features. This is particularly helpful for determining the source water availability for artificial recharge.

Table 6.19 Rainfall

SI.No.	Class	Code
1	Bhuj	3
2	Anjar	2
3	Gandhidham	1

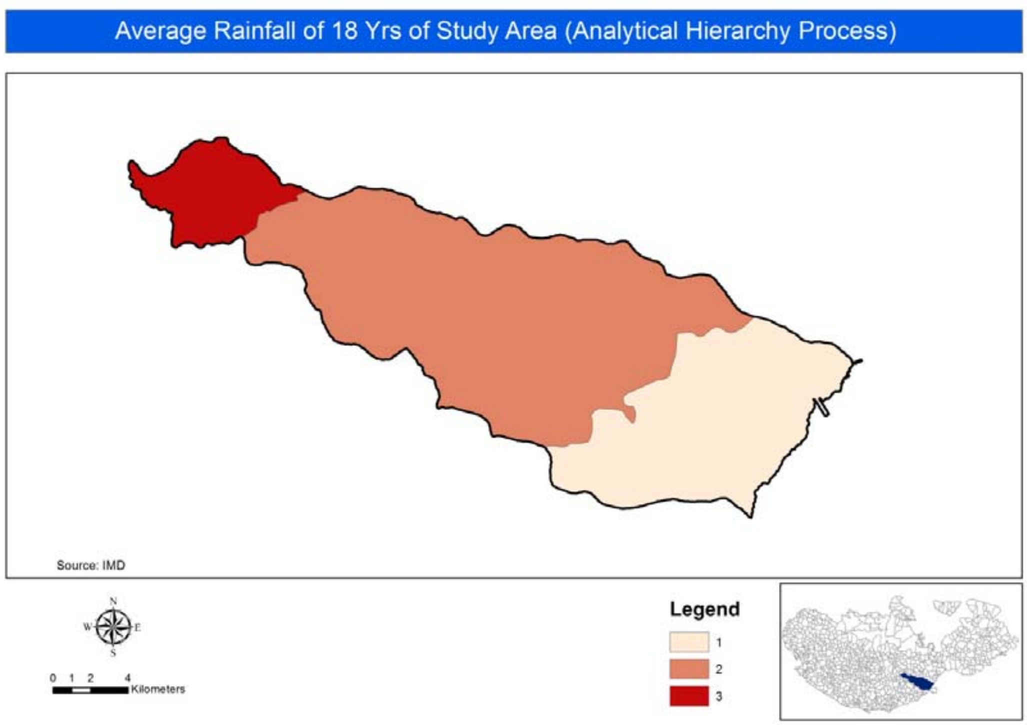


Fig. 6.34 Recoded Average Rainfall Map

Table 6.20 Problem solving: Assignment of ranking to the spatial data:

Judgement Scale for Pairwise Matrix	
Equally Preferred	1
Equally To Moderately	2
Moderately Preferred	3
Moderately To Strongly	4
Strongly Preferred	5
Strongly Preferred	6
Very Strongly Preferred	7
Very Strongly To Extremely	8
Extremely Preferred	9

6.6.4.2 Weightage assigned to the Themes

The evidential themes considered for the analysis of groundwater prospective zones are: Rainfall, Runoff, Geology, Geomorphology, Depth to water table, Drainage, Land use/Land cover, Soil, Slope.

Table 6.21 Weightages given to input themes

SI.No.	Input Parameters	Weightage
1	Rainfall	9
2	Runoff	8
3	Drainage (Buffer)	7
4	Soil	6
5	Slope	5
6	Depth to water level (MSL)	4
7	Geology	3
8	Land use/Land cover	2
9	Geomorphology	1

Table 6.22 Corellation Matrix

	Rainfall	Runoff	Drainage (Buffer)	Soil	Slope	Water Level	Geology	Land Use	Geo-morphology
Rainfall	1	2	3	4	5	6	7	8	9
Runoff	1/2	1	2	3	4	5	6	7	8
Drainage (Buffer)	1/3	1/2	1	2	3	4	5	6	7
Soil	1/4	1/3	1/2	1	2	3	4	5	6
Slope	1/5	1/4	1/3	1/2	1	2	3	4	5
Water Level	1/6	1/5	1/4	1/3	1/2	1	2	3	4
Geology	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
Land Use	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
Geo-morphology	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1

Table 6.23 Judgement Matrix

DECISION MATRIX AFTER PAIR WISE COMPARISION									
	Rainfall	Runoff	Drainage (Buffer)	Soil	Slope	Water Level	Geology	Land Use	Geo-morphology
Rainfall	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Runoff	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Drainage (Buffer)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Soil	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Slope	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Water Level	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Geology	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Land Use	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02
Geo-morphology	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

N=9	Judgement Matrix = Row Average				
JUDGEMENT MATRIX	N*ROW AVG	CI=(Nmax-N)/N-1	RCI=1.98(N-2)/N	CR=CI/RCI	CR<0.1
0.306	2.762	-0.004	1.54	0.002	<0.1
0.218	1.963				
0.150	1.356				
0.108	0.979				
0.076	0.687				
0.053	0.479				
0.0370	0.333				
0.025	0.233				
0.018	0.170				
Nmax	8.967				

CR value less than 0.1 (i.e. 0.002) indicates that the ranks assigned are consistent for analysis.

6.6.5 Recharge Site & Structures

6.6.5.1 Prospective Zones for Artificial Recharge Structures

Site Suitability Zones

The prospective zones for groundwater recharge mapped based on integration of different thematic data layers are shown in Fig. 6.35. This map resulted by combining the thematic layers are classified into 5 categories, which are shown below:

- High
- Moderate-High
- Moderate
- Low-Moderate
- Low

Highly Suitable zone

These zones are mainly associated with the valley fill zones, deep water table areas, and deeply weathered and fractured zones. These zones have high porosity and permeability developed due to the fracturing and weathering. These zones are very suitable for constructing the percolation tanks and check dams. The depth to the geo-electrical basement is also providing the information about the sub-surface weathering and the fracturing.

Moderately Suitable zone

This zone is existed in the moderately weathered pediplains and some part of shallow weathered pediplains, and along the minor lineaments, where the porosity and permeability are developed because of the weathering and at places due to fractured zones. The construction of check dams and at few places where the fractures traverse, this zone is suitable for percolation tanks.

Low Suitable zone

This zone is found in the shallow weathered and buried pediplains where the rate of infiltration and porosity are very low. This zone is not suitable to take-up the massive scale artificial structures. However, some of the artificial recharge structures such as farm ponds can be taken up in these zones. Keeping in view, the stage of groundwater development, some farm ponds and de-siltation of the existing tanks have been recommended in this zone.

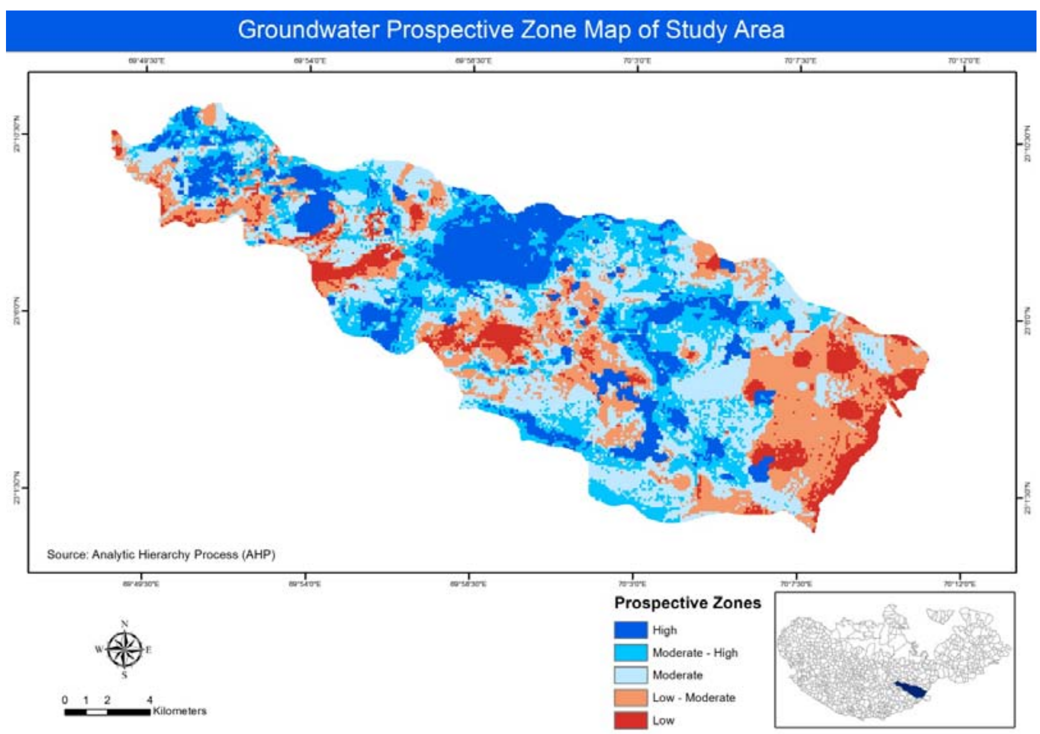


Fig. 6.35 Groundwater Prospect Zone Map

6.6.5.2 Recharge Structures

The following categories of recharge structures are considered for suggesting in each hydrogeomorphic unit. Besides this roof top harvesting is also suggested however since it is recommended for the entire study area and is not based on the prospective zone, it has not been included in this section.

1. Percolation Tank / Ponds (PT)

2. Check Dam (CD)

3. Recharge Wells (RW)

Assessment of Recharge Structures & Conditions

The main sources of recharge to the aquifers are rainfall, water bodies, return flow from the irrigation, etc. The amount of water available has been taken in to account for assessing the recharge condition from all these sources. However, the total available water may not percolate in to the ground. It depends on the infiltration capacity of the soil and the hydro-geological properties of the underlying rock formations. Hence, the actual recharge is assessed not only based on the water available from different sources but also the hydro-geological properties of geological material. The recharge conditions are classified as High, Moderate or Low.

Estimation of Ground Water Prospects

The ground water prospects are estimated based on the analysis of hydro-geological characteristics of all the parameters controlling the occurrence and movement of ground water in conjunction with the observation well data collected during the field work. The ground water prospects of the aquifers are estimated in terms of type of wells suitable, depth range of wells that can be drilled and expected yield range. In addition, water quality and ground water irrigated area are also considered. The ground water prospects however, are considered as anomalous with reference to surrounding lithology-landform controlled units. The fault/fracture zones generally acts as conduits for movement of ground water. The yields are significantly higher and wells are likely sustainable for longer duration. The linear intrusive units generally act as barriers for ground water movement. But the fractured portions may form as good aquifers and give high yields. The criteria for suggesting type of wells is given in Table 6.24 Based on this criteria, a suitable type of well has to be suggested in each hydrogeomorphic unit.

Table 6.24 Criteria for Suggesting Type of Well

Tube Well (TW)	In the areas where transmissivity of the upper strata is poor, e.g. in shale's underlain by sandstones, in buried pediplains with top soil having low permeability, in Deccan Traps where vesicular basalt is overlain by massive basalt or thick black cotton soil or impervious zone etc. or in other words where the water table is deep or a thick column of weathered / fractured rocks, loose unconsolidated and semi-consolidated rocks with fairly good transmissivity are present.
Check Dam (CD)	On 1st to 4th order streams along the foot hill zones and in the areas with 0-5% slops. Especially where there are more than 2 kms gap between the existing check dams or where a major maintenance of the existing check dam is required.
Percolation Tanks (Ponds)	On the 1st to 3rd order streams located in the plains and valleys having sufficient weathered zone / loose material / fractures.

Depth Range of wells: The depth range of the wells is estimated based on the depth to water table or SWL, the water table fluctuation, the depth at which the productive aquifer occurs.

Expected Yield range: Initially, considering the hydro-geological characteristics of the controlling factors, the potential yield of the hydrogeomorphic unit is evaluated. Then the yields or discharge of the existing wells located in the unit are considered for calibration. While doing so

1) The average yield of the wells is taken in to account,

2) The wells with abnormally low and abnormally high yields should be avoided and the reasons also should be verified and possibility of its occurrence on fracture zones was checked by examining the satellite imagery. If any fracture/lineament is inferred on the satellite data, some more wells are observed along such zone to confirm the existence of fracture and represent the same on the map as 'confirmed fracture' with appropriate line symbol). Finally, based on the correlation study, the expected yield range of wells in LPM or cu.m/day has been estimated for each unit. In those hydrogeomorphic units, where no observation wells are available, a tentative yield range has given based only on hydro-geological considerations or interpolation the data available from the surrounding areas.

Table 6.25 Type of well and its depth range

Type of Suitable	Suggested Depth Range of Recharge Wells	Expected Yield range of wells
TW	100-150 m	800-1500 lpm

Water Quality: The ground water quality, i.e. Potable (P) or Non-Potable (NP) is also evaluated for each unit. This information is provided mainly based on the existing maps / information, ground truth data and to some extent from the study of the composition of the aquifer material. Wherever the water is non-potable, the reasons for non-pot ability (e.g. high TDS, high fluoride, high nitrate content, saline etc.) are given in their respective Maps.

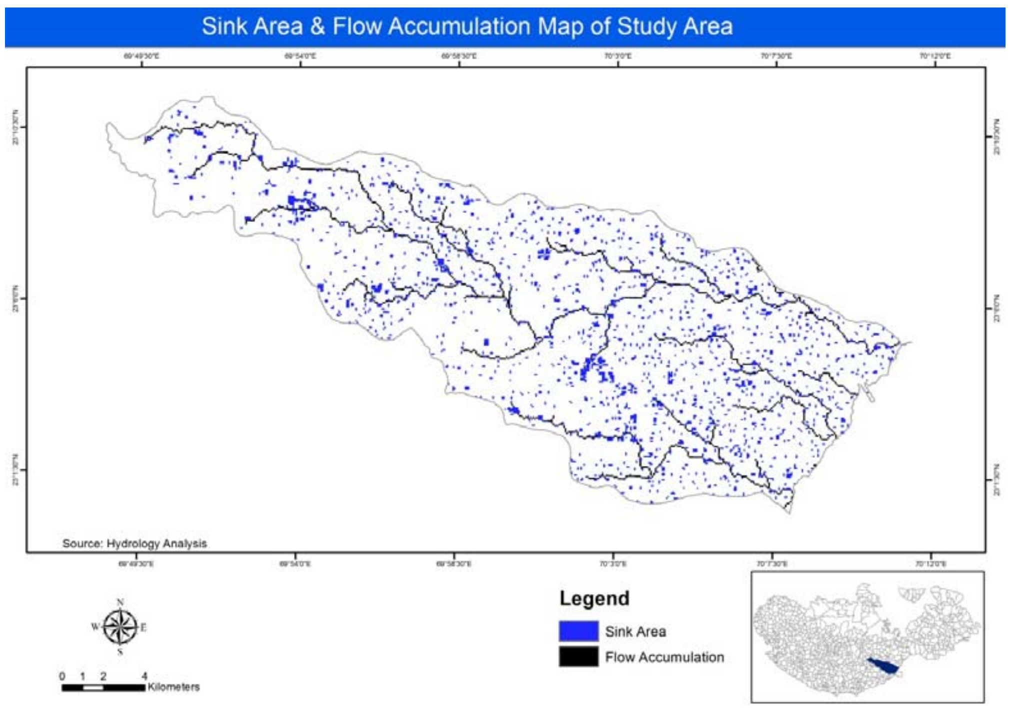


Fig. 6.36 Sink Area and Flow Accumulation Map

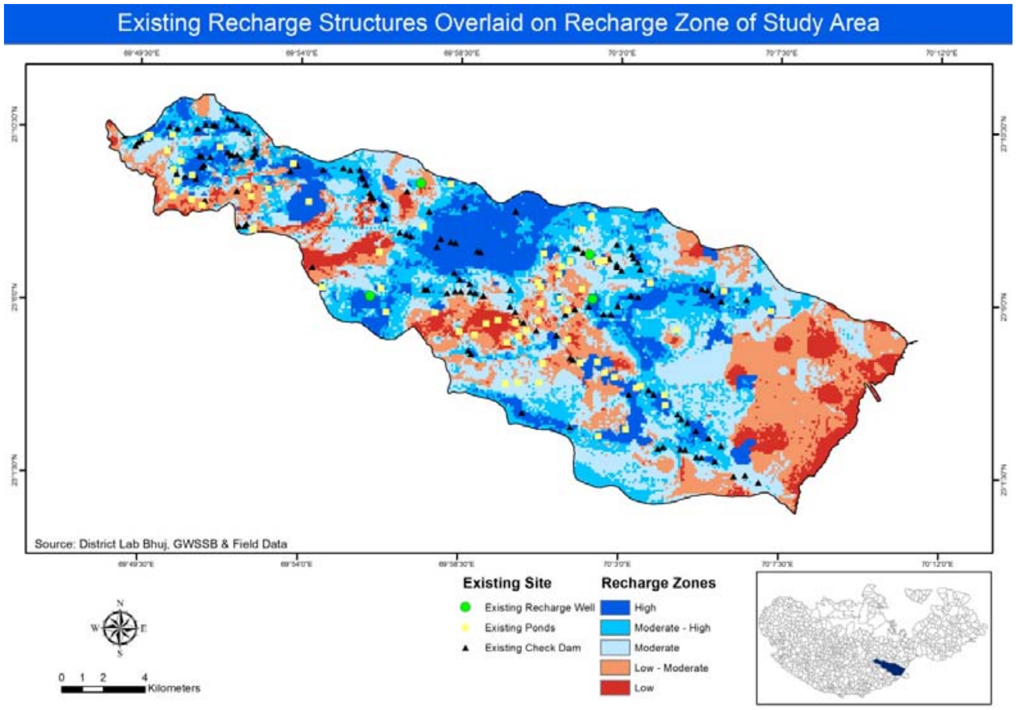


Fig. 6.37 Existing Recharge Structure overlaid on Recharge Zone Map

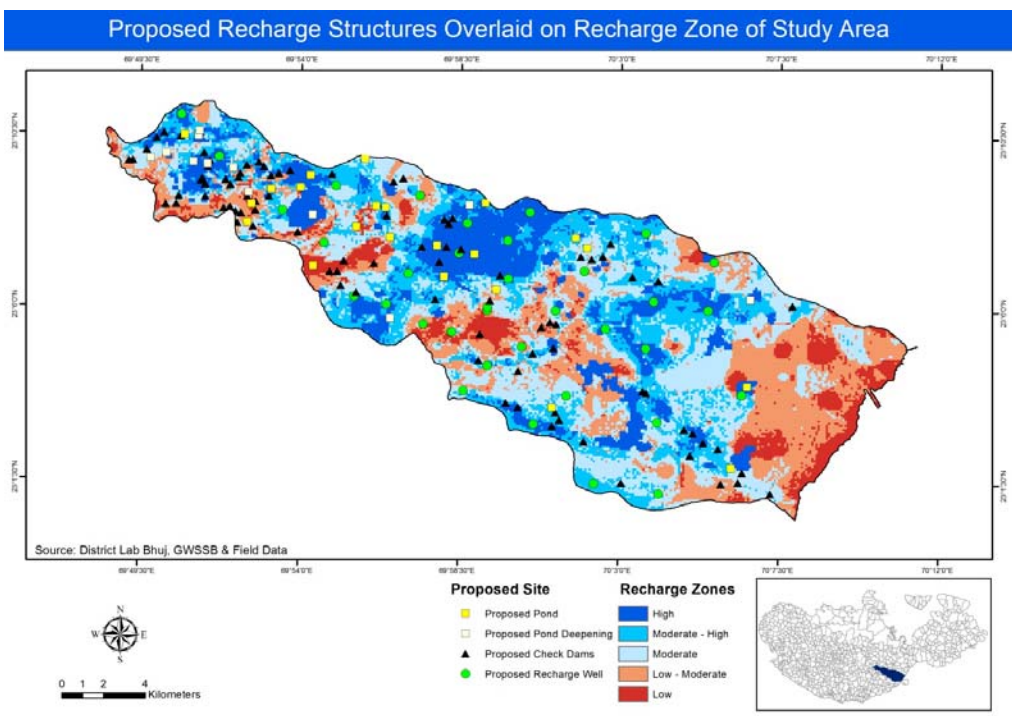


Fig. 6.38 Proposed Recharge Structure Map overlaid on Recharge Zone Map

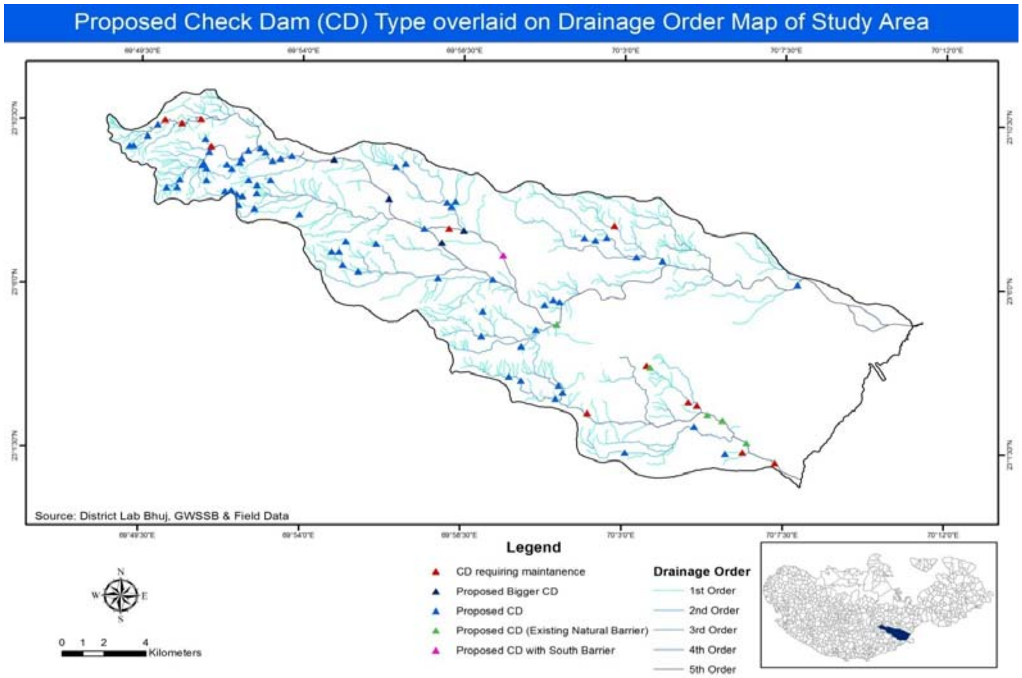


Fig. 6.39 Proposed Check Dam type overlaid on Drainage Map

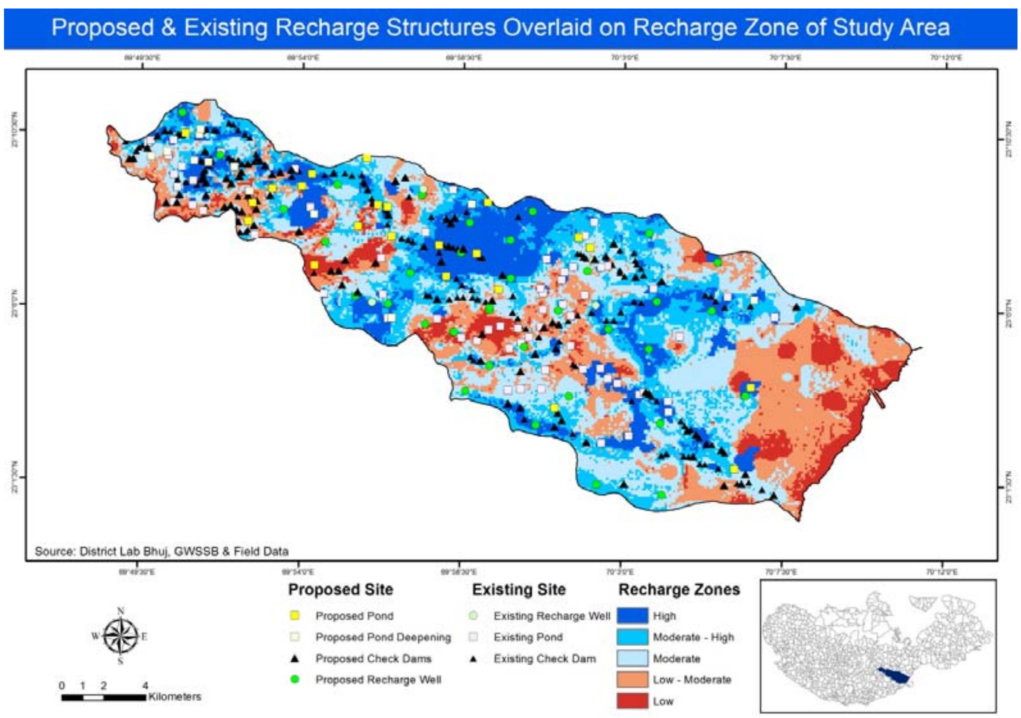


Fig. 6.40 Proposed & Existing Recharge structures overlaid on Recharge Zone Map

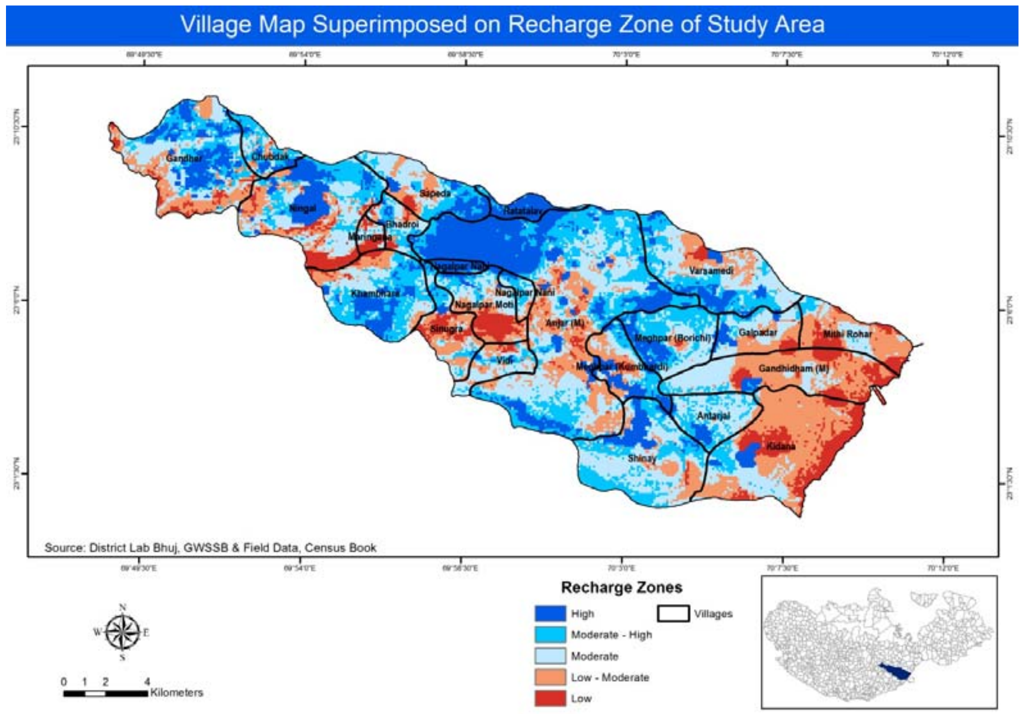


Fig. 6.41 Village Map overlaid on Recharge Zone Map

Table 6.26 Village Wise Proposed Recharge Structure and Area of Prospective Zone

Village Wise Zone	Area (SqKm)	Area in Percentage	Proposed Recharge Structures	Total Recharge Structures
Anjar (M)	**67.126**	20.72%		35
Low	1.261	0.39%	Proposed CD	1
Low - Moderate	10.907	3.37%	Proposed CD	2
Moderate	18.015	5.56%	Proposed CD	2
			Proposed Pond	3
			Proposed Recharge Well	2
Moderate - High	16.989	5.24%	CD requiring maintanence	1
			Proposed CD	7
			Proposed Recharge Well	1
High	19.954	6.16%	CD requiring maintanence	2

			Proposed Bigger CD	2
			Proposed CD	5
			Proposed Pond	2
			Proposed Recharge Well	5
Antarjal	**8.318**	2.57%		3
Low	0.035	0.01%		
Low - Moderate	0.348	0.11%		
Moderate	4.353	1.34%		
Moderate - High	2.734	0.84%	CD requiring maintanence	1
High	0.847	0.26%	CD requiring maintanence	1
			Proposed CD	1
Bhadroi	**4.616**	1.42%		3
Low	0.481	0.15%		
Low - Moderate	0.69	0.21%		
Moderate	1.731	0.53%	Proposed Pond	1
Moderate - High	1.326	0.41%	Proposed Pond	1
High	0.388	0.12%	Proposed Bigger CD	1
Chubdak	**5.01**	1.55%		6
Low	0.06	0.02%		
Low - Moderate	0.614	0.19%		
Moderate	1.161	0.36%	Proposed CD	1
Moderate - High	2.189	0.68%	Proposed CD	2
High	0.987	0.30%	Proposed CD	3
Galpadar	**8.215**	2.54%		1
Low	0.482	0.15%		
Low - Moderate	2.334	0.72%		
Moderate	3.445	1.06%		
Moderate - High	0.974	0.30%	Proposed CD	1
High	0.979	0.30%		
Gandher	**25.444**	7.85%		36
Low	1.531	0.47%		
Low - Moderate	5.931	1.83%	Proposed CD	6
			Proposed Pond Deepening	1
Moderate	6.803	2.10%	Proposed CD	5
			Proposed Pond Deepening	2

Moderate - High	5.235	1.62%	CD requiring maintanence	1
			Proposed CD	5
			Proposed Pond	1
			Proposed Pond Deepening	3
High	5.943	1.83%	CD requiring maintanence	3
			Proposed CD	5
			Proposed Pond Deepening	2
			Proposed Recharge Well	2
Gandhidham (M)	**19.274**	5.95%		2
Low	3.904	1.20%		
Low - Moderate	8.444	2.61%		
Moderate	5.568	1.72%		
Moderate - High	0.872	0.27%	Proposed Recharge Well	1
High	0.487	0.15%	Proposed Pond	1
Khambhara	**17.376**	5.36%		7
Low	0.845	0.26%		
Low - Moderate	2.199	0.68%	Proposed CD	1
Moderate	4.162	1.28%	Proposed CD	2
Moderate - High	6.458	1.99%	Proposed Recharge Well	2
High	3.712	1.15%	Proposed Pond Deepening	1
			Proposed Recharge Well	1
Kidana	**28.525**	8.80%		6
Low	7.244	2.24%		
Low - Moderate	14.552	4.49%	Proposed CD	1
Moderate	4.367	1.35%	CD requiring maintanence	2
			Proposed CD	2
			Proposed Pond	1
Moderate - High	1.29	0.40%		
High	1.072	0.33%		
Maringana	**1.948**	0.60%		1
Low	0.908	0.28%		

Low - Moderate	0.251	0.08%	Proposed Pond	1
Moderate	0.611	0.19%		
Moderate - High	0.156	0.05%		
High	0.022	0.01%		
Meghpar (Borichi)	**11.76**	3.63%		1
Low	0.09	0.03%		
Low - Moderate	0.45	0.14%		
Moderate	3.851	1.19%		
Moderate - High	5.015	1.55%		
High	2.354	0.73%	Proposed Recharge Well	1
Meghpar (Kumbhardi)	**8.26**	2.55%		3
Low	0.31	0.10%		
Low - Moderate	2.12	0.65%		
Moderate	1.664	0.51%		
Moderate - High	1.709	0.53%	CD requiring maintanence	1
			Proposed CD	1
High	2.457	0.76%	Proposed Recharge Well	1
Mithi Rohar	**10.303**	3.18%		0
Low	2.261	0.70%		
Low - Moderate	4.919	1.52%		
Moderate	2.524	0.78%		
Moderate - High	0.599	0.18%		
Nagalpar Moti	**9.512**	2.94%		6
Low	2.355	0.73%		
Low - Moderate	2.248	0.69%	Proposed CD	1
			Proposed Recharge Well	1
Moderate	2.945	0.91%	Proposed CD	1
			Proposed Recharge Well	1
Moderate - High	1.192	0.37%		
High	0.772	0.24%	Proposed Pond	2
Nagalpar Nani	**3.669**	1.13%		2
Low	0.043	0.01%		
Low - Moderate	0.257	0.08%		
Moderate	0.851	0.26%		

Moderate - High	0.96	0.30%		
High	1.558	0.48%	Proposed CD	1
			Proposed Recharge Well	1
Ningal	**24.733**	7.63%		22
Low	2.907	0.90%	Proposed CD	5
			Proposed Pond	2
Low - Moderate	4.502	1.39%	Proposed CD	2
Moderate	6.844	2.11%	Proposed CD	2
			Proposed Pond	2
			Proposed Recharge Well	2
Moderate - High	5.181	1.60%	Proposed Recharge Well	1
High	5.299	1.64%	Proposed Bigger CD	1
			Proposed CD	1
			Proposed Pond	3
			Proposed Pond Deepening	1
Ratatalav	**3.214**	0.99%		2
Moderate	0.016	0.00%		
Moderate - High	0.381	0.12%		
High	2.817	0.87%	Proposed Pond	1
			Proposed Recharge Well	1
Sapeda	**10.962**	3.38%		7
Low	0.414	0.13%	Proposed Recharge Well	1
Low - Moderate	1.924	0.59%		
Moderate	3.77	1.16%	Proposed CD	2
			Proposed Pond	1
Moderate - High	2.556	0.79%	Proposed CD	1
High	2.298	0.71%	Proposed Pond Deepening	1
			Proposed Recharge Well	1
Shinay	**21.972**	6.78%		5
Low	0.17	0.05%		
Low - Moderate	2.734	0.84%		
Moderate	9.313	2.87%	Proposed Recharge Well	1

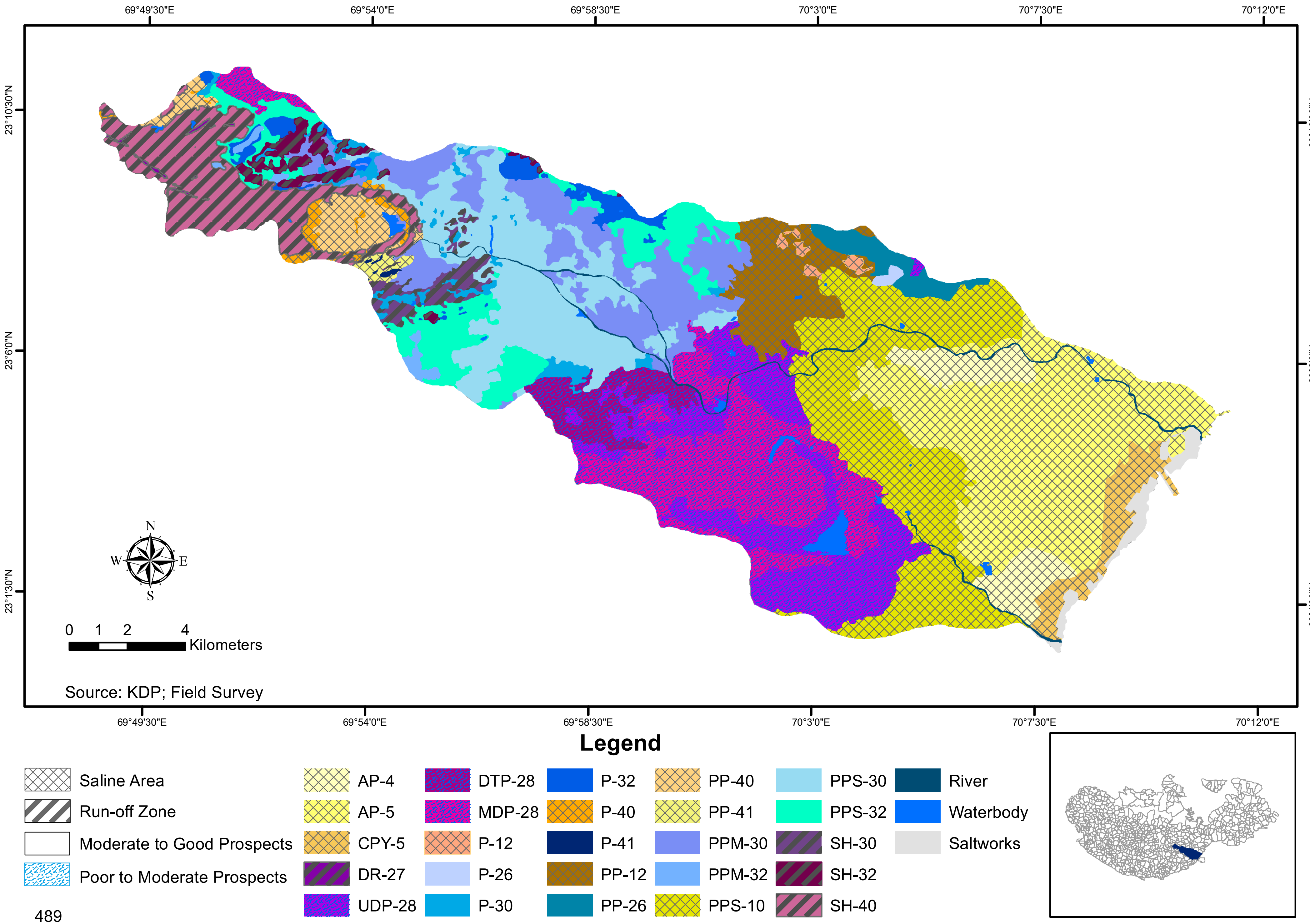
Moderate - High	6.947	2.14%	Proposed CD	2
			Proposed Recharge Well	2
High	2.807	0.87%		
Sinugra	**8.165**	2.52%		4
Low	1.604	0.50%	Proposed Recharge Well	1
Low - Moderate	3.024	0.93%	Proposed Recharge Well	1
Moderate	1.709	0.53%		
Moderate - High	1.39	0.43%	Proposed CD	1
High	0.438	0.14%	Proposed Recharge Well	1
Varsamedi	**20.131**	6.21%		5
Low	0.471	0.15%		
Low - Moderate	3.285	1.01%		
Moderate	7.446	2.30%	Proposed CD	1
			Proposed Pond Deepening	1
Moderate - High	5.801	1.79%	Proposed Recharge Well	1
High	3.127	0.97%	Proposed Recharge Well	2
Vidi	**5.437**	1.68%		8
Low	0.271	0.08%		
Low - Moderate	1.388	0.43%	Proposed Recharge Well	1
Moderate	2.718	0.84%	Proposed CD	2
Moderate - High	0.853	0.26%	Proposed Recharge Well	5
High	0.206	0.06%		
Grand Total	**323.969**	100.00%		165

Table 6.27 Groundwater Prospect Based on Hydro Geomorphic Unit

Map Unit (Hydrogeomorphic Unit) represented in a map with alphanumeric code (Colours indicate groundwater prospects)	Geological Sequence / Rock Type Represented in a Map with Numeric Code			Geomorphic Unit / Landform Represented in a Map with Alphabetic Code	Ground water Prospect (2015)	Quality of Water	Remarks (Limitations/ Variations)	Village	Taluka
					Depth in Mtr. - Yield in LPM	Potable (P); Non-Potable (NP)			
PP-12	Tertiary	Khari Formation	Shale (12)	Pediplain (PP)	Moderate to Poor ; Depth 160-190 ; Yield 10-30	NP	Marine formation, sediment deposits, yields brakish water	North Anjar, Varsamedi	Anjar
P-12	Tertiary	Khari Formation	Shale (12)	Pediment (P)	Poor; Depth 160-200; Yield <10	NP	Poor aquifer formation, wells not found, depth and yields are inferred from field observations	Anjar (North), Varsamedi	Anjar
DR-27	Mesozoic	Deccan Traps	Basalt Intrusive (27)	Dyke Ridge (DR)	NOT APPLICABLE	NOT APPLICABLE	Mainly Runoff Zone	Gandher	Bhuj
DTP-28	Mesozoic	Deccan Traps	Basalt (28)	Dissected Plateau (DTP)	Moderate to Poor; Depth >80; Yield 10-50	P	wells not found, depth and yields are inferred from field observations and discussions with the locals	Sinugra, vidi, Nagalpar Moti	Anjar
MDP-28	Mesozoic	Deccan Traps	Basalt (28)	Moderately Dissected Plateau (MDP)	Moderate to Poor; Depth 30-80; Yield 10-60	P	wells not found, depth and yields are inferred from field observations and discussions with the locals	Anjar, Vidi, Meghpar (Khumbardi), Shinay	Anjar
PPS-30	Mesozoic	Bhuj Formation	Sandstone (30)	Pediplain shallow Weathered (PPS)	Good to Moderate; Depth 120-170; Yield 50-100	P	Better prospects along fractures and lineaments	Sapeda, Bhadroi, Khambra, Nagalpar Nani. Nagalpar Moti, Ningal	Anjar
P-30	Mesozoic	Bhuj Formation	Sandstone (30)	Pediment (P)	Moderate; Depth >100; Yeild 50-100	P	wells not found, depth and yields are inferred from field observations and discussions with the locals	Small parts in Sinugra, Nagal Moti, Khambra, Ningal, Maringna, Bhadroi, Chubdak, Gandher	Anjar, Bhuj
SH-32	Mesozoic	Bhuj Formation	Shally Sandstone (32)	Structural Hill (SH)	NOT APPLICABLE	NOT APPLICABLE	Mainly Runoff Zone	Gandher, Chubdak	Bhuj
PPM-32	Mesozoic	Bhuj Formation	Shally Sandstone (32)	Pediplain Moderately Weathered (PPM)	Good to Moderate; Depth 150-180; Yield 100-200	P	Shale intercalation affects the water quality and Quantity. (Iron Problem)	Khambra, Gandher	Anjar, Bhuj
PPS-32	Mesozoic	Bhuj Formation	Shally Sandstone (32)	Pediplain shallow Weathered (PPS)	Moderate; Depth 100-150; Yield 50-100	P	Generally a moderate zone. Shale intercalations affect the water quality and quantity	Khambra, Ratatalav, Anjar	Anjar
P-32	Mesozoic	Bhuj Formation	Shally Sandstone (32)	Pediment (P)	Moderate; Depth 120-180; Yield 50-100	P	wells not found, depth and yields are inferred from field observations and discussions with the locals	Sapeda, Ratatalav, Chubdak, Gandher	Anjar, Bhuj

Map Unit (Hydrogeomorphic Unit) represented in a map with alphanumeric code (Colours indicate groundwater prospects)	Geological Sequence / Rock Type Represented in a Map with Numeric Code			Geomorphic Unit / Landform Represented in a Map with Alphabetic Code	Ground water Prospect (2015)	Quality of Water	Remarks (Limitations/ Variations)	Village	Taluka
					Depth in Mtr. - Yield in LPM	Potable (P); Non-Potable (NP)			
PP-40	Mesozoic	Jhuran Formation	Sandstone (40)	Pediplain (PP)	Moderate; Depth 120-180; Yield 50-100	NP	Brakish water. wells not found, depth and yields are inferred from field observations.	In and around Ningal Lake	Anjar
P-40	Mesozoic	Jhuran Formation	Sandstone (40)	Pediment (P)	Moderate to Poor; Depth 180-190; Yield 10-50	NP	Brakish water. wells not found, depth and yields are inferred from field observations.	Surrounding Ningal Village Lake	Anjar
SH-40	Mesozoic	Jhuran Formation	Sandstone (40)	Structural Hill (SH)	NOT APPLICABLE	NOT APPLICABLE	Mainly Runoff Zone	Ningal, Gandher	Anjar, Bhuj
PP-41	Mesozoic	Jhuran Formation	Shale (41)	Pediplain (PP)	Moderate; Depth 120-180; Yield 50-100	NP	Brakish water. wells not found, depth and yields are inferred from field observations and discussions with the locals	South of Ningal Village Lake	Anjar
PP-26	Tertiary	Madh Formation	Clayey Sandstone (26)	Pediplain (PP)	Good to Moderate; Depth 180-190; Yield 100-200	P	Water available at shallow depth upto 10 mtr is Brakish due to clay domination. The underlain shale yield potable water. A proper well design will be required to tackle the problem of brakish water	Varsamedi (North) small part	Anjar
AP-5	Holecene	Varahi	Alluviam (Clay Domenent) (5)	Alluvial Plain (AP)	Moderate to Poor; Depth 100-120; Yield 100-200	NP	Brakish water zone	Kidana, Galpadar, Varsamedi, Mithi Rohar, Gandhidham, Meghpar (Borichi)	Gandhidham
PPS-10	Tertiary	Kankavati	Sandstone (10)	Pediplain Shallow Weathered (PPS)	Moderate; Depth 120-140; Yield 50-100	NP	Brakish water occurs predominently. Overexploitation may lead to saline water intrusion. Better prospects alond fractures and lineaments	Varsamedi, Meghpar (Borichi), Meghpar (Kumbhardi), Gandhidham, Antarjal, Bharapar,	Gandhidham, Anjar
P-26	Tertiary	Madh Formation	Clayey Sandstone (26)	Pediment (P)	Moderate; Depth >100; Yield 50-100	P	wells not found, depth and yields are inferred from field observations and discussions with the locals	Varsamedi (North) small part	Anjar
PPM-30	Mesozoic	Bhuj Foramtion	Sandstone (30)	Pediplain Moderately Weathered (PPM)	Good; Depth 170-200; Yield 200-400	P	saturated and friable sandstone acts as a good aquifer. Groundwater exploitation is high	Anjar, Nagalpar Nani, Nagalpar Moti, Sapeda, Ningal, Chubdak	Anjar, Bhuj
UDP-28	Mesozoic	Deccan Trap	Basalt (28)	Undissected Plateau (UDP)	Moderatev to Poor; Depth 30-80; Yield 50-100	p	Better prospects can be expected along fractures and lineaments	Anjar, Vidi, Shinay	Anjar
SH-30	Mesozoic	Bhuj Formation	Sandstone (30)	Structural Hill (SH)	NOT APPLICABLE	NOT APPLICABLE	Mainly serves as a runoff zone	Bhadroi, Maringna, Khambra, Ningal	Anjar
AP-4	Quarternary	Recent Formation	Alluviam (Sand Dominant) (4)	Alluvial Plains (AP)	Good; Depth 120-150; Yield 200-400	NP	Brakish water zone but limited potable possible towards the river	Kidana, Galpadar, Varsamedi, Gandhidham, Meghpar (Borichi)	Gandhidham
CPY-5	Recent	Recent Deposits	Alluvium Clay Dominated	CPY	Good; Depth <70; Yield 200-400	NP	Mostly saline due to proximity to coast. wells not found, depth and yields are inferred from field observations and discussions with the locals	kidana, Gandhidham	Gandhidham

Fig. 6.42 Hydro Geomorphic Map with Prospective Recharge Zones



Field Photographs:

Fig. 6.43 Bore Cum Recharge Well at Anjar

Fig. 6.44 Recharge Tank with Check Dam

Fig. 6.45 GWSSB Groundwater Recharge Site

Fig. 6.46 Recharge Bore inside the GWSSB recharge site

Fig 6.47 Newly constructed Check Dam Site

Fig 6.48 Check Dam (Requiring Maintenance)

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GUIDANCE MANUAL FOR RAPID RECONNAISSANCE OF GROUNDWATER RESOURCES IN ARID AND SEMI-ARID ENVIRONMENTS

OBJECTIVE

The prime objective of the guidelines for rapid reconnaissance of ground water resources is to look into the variations of availability of water in different climatologically regions and diverse hydro geological conditions in various states of the country to ensure sustainability of ground water both in terms of quantity & quality and also focus on land based management of ground water resources.

While a detailed study has been done in the previous chapters for aquifer mapping, site suitability analysis and selection of recharge structures, this quick manual can be considered as a summary of the processes considered for the present study. For details kindly refer to the respective chapters.

Chapter:

1. **Introduction**: Identification of the need for Rapid Reconnaissance of Groundwater: for any study it is important to understand all the aspects of the existing problem. In case of the groundwater Conceptualization of the processes is required for rapid reconnaissance. For this purpose identification of the data required for the processes, Sources available for the procurement of the data and identifying the processes required for data generation needs to studied.

2. **Regional Set up: Physical and Socio-Economic:** A study based on the Census data available online and through various government authorities can provide a major insight on the type of land as well as the type and amount of living beings that might be affected due to the prevailing problems of ground water. For prioritizing the study area this study can be very useful.

   This studies when done through GIS will provide the data in a visual format which can later be correlated with other spatial and non-spatial data like Bore hole Log with GPS locations providing sub-surface geological strata and/or groundwater quality data with their respective sample locations. Such type of correlation can also help us in finding various health problems prevailing in a particular area. Correlation of Land use and Landcover maps generated based on the satellite images of Landsat, LISS V, CartoSAT or even Freely available Google Earth Historic images with the Socio-Demographic and Agriculture Census data can provide the insight of the reason for the changes in the trend of population growth.

3. **Hydro Geological Studies-** India has a large rural and semi-literate population, demystification of the Science of Hydrogeology will be very crucial to enable them to understand the dynamics of ground water availability and its sustainable utilization. (CGWB). The regional Geological and Geomorphology provide information related to different

geological strata, their geological age sequence, boundaries/contacts of individual formations and the structural expressions like Strike, Dip, Faults, Folds, Flexures, Intrusive bodies etc. These maps also bring out correlation of topography and drainage to geological contacts.

Soil Infiltration Studies - Soil and Land use conditions that control the rate of infiltration and downward percolation of the water applied on the surface of the soil assume special importance. Higher correlation coefficient of water level and precipitation implies significant groundwater recharge characteristic or most favorable recharge zone.

Remote Sensing and GIS based Studies: Satellite Imagery provides useful data on geomorphic units and lineaments that govern the occurrence and movement of ground water, while GIS provide a constructive platform for integration of the spatial and non-spatial data for generation of maps and datasets that can be used for decision making process.

Hydrological Studies: When hydrological data are integrated in GIS it provides a useful information regarding the local hydrology of the area. Information regarding the existing water level, changes in the water level in pre and post monsoon, draw down and pumping levels, specific capacity of the aquifer can now be visualized for better management and planning.

4. **Hydro Geo Chemical Studies:** Problem which arise due to over exploitation of groundwater and/or local geological setup especially coastal area are mainly related to the quality of water. A study focused on the hydro-chemistry can provide additional insight to the local geological setup as well and modification in the current practices for management and improvement of the water quality.

5. **Hydro Meteorological Studies** : These shall be undertaken to decipher the rainfall pattern, evaporation losses and climatological features. These can bring out the extent of evaporation losses in post monsoon period that would be helpful in designing the storages of particular capacity with a view to have minimum evaporation losses. Hydro Meteorology is an important part of artificial recharge projects as it provide a vital information regarding the total amount of water available for recharge and the amount of water can act as a ran off in a area under investigation.

6. **Hydro Geological Modelling:** For determining the source water availability for artificial recharge, possible pollutants and augmentation of the groundwater resources for the future, hydrological investigation based on GIS modeling shall be carried out in the Watershed/Sub-basin/basin where the artificial recharge schemes are envisaged.

Important studies that can be considered under this heading are

a. MODFLOW
b. DRASTIC
c. Morphometric Analysis
d. Multi Criteria Analysis like AHP and
e. 3D model for visualization of hydro geological framework of the study area.

These methods have been explained in details in their respective chapters and can be referred as a rapid reconnaissance and augmentation of any groundwater studies.