AN INTEGRATED APPROACH OF GROUNDWATER MANAGEMENT IN WAKAL RIVER BASIN USING REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEM

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ASHOK KUMAR SINHA

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MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

UDAIPUR (RAJASTHAN) 313 001 (INDIA)

MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
COLLEGE OF TECHNOLOGY AND ENGINEERING, UDAIPUR -313 001

Dated: 27/02/2012

CERTIFICATE -I

This is to certify that **Mr. Ashok Kumar Sinha** has successfully completed the preliminary examination held on 24/01/2011 as required under the regulation for the degree of **Doctor of philosophy** in **Agricultural Engineering** (Irrigation Water Management Engineering).

(**Dr. S.R. Bhakar**)
Head
Department of Soil and Water Engineering,
C.T.A.E., Udaipur

MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
COLLEGE OF TECHNOLOGY & ENGINEERING, UDAIPUR - 313 001

Dated: 27/02/2012

CERTIFICATE -II

This is to certify that this thesis entitled "**An Integrated Approach of Groundwater Management in Wakal River Basin using Remote Sensing and Geographical Information System**" submitted for the degree of **Doctor of Philosophy** in the subject of **Agricultural Engineering** (Irrigation Water Management Engineering), embodies bonafide research work carried out by **Mr. Ashok Kumar Sinha,** under my guidance and supervision and that no part of this thesis has been submitted for any other degree. The assistance and help received during the course of investigation have been fully acknowledged. The draft of the thesis was also approved by the advisory committee on date 28/01/2012.

(Dr. P.K. Singh)
Major Advisor

(Dr. S.R. Bhakar)
Head
Department of Soil and Water Engineering,
C.T.A.E., Udaipur.

(Dr. Narendra S. Rathore)
Dean
Collage of Technology and Engineering,
Udaipur.

ABSTRACT

Groundwater is a precious resource of limited extent. A systematic planning of groundwater exploitation using modern techniques is essential for the proper utilization and management of this precious but shrinking natural resource. Wakal river basin (study area), situated in the hard-rock terrain of Udaipur district in Rajasthan, suffers from water scarcity. Present study aimed at in-depth hydrogeologic and geochemical investigations in the study area for efficient management of scarce groundwater resources. It was analysed in the process of study that use of GIS can make the cumbersome geomorphological analysis and prioritization of sub-basin as an easy task. The Wakal river basin is maximum seventh order basin. The total drainage area of Wakal river basin is divided into seven sub-basins for the analysis. The determination of geomorphological characteristics included area and perimeter, stream number (order wise), stream length, basin length, stream frequency, bifurcation ratio, stream length ratio, form factor, circulatory ratio, elongation ratio, drainage density, constant of channel maintenance, length of overland flow, relief ratio, relative relief and ruggedness number. The prioritization of the basin was carried out on the basis of the geomorphological parameters and based on this the first priority is given to sub-basin-3 for soil and water conservation measures. The groundwater quality of the Wakal river basin was also analyzed. The different water quality parameter map was prepared under GIS environment and the spatio-temporal variations of groundwater quality parameters were analyzed. The highest EC, TDS, Na, SO_4 was found in village Kotra and Ca, Mg, Cl in village Bira of Jhadol block during pre monsoon period. During post monsoon period the highest EC, TDS, Ca, Mg, Na, K, Cl and SO_4 was found in village Kotra. The suitability of groundwater for irrigation use was evaluated on the basis of Sodium Absorption Ratio (SAR), Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), Soluble Sodium Percentage (SSP) and Permeability Index (PI) and found that most of the study area groundwater is suitable for irrigation purpose during both pre and post monsoon period. The aquifer parameters i.e. transmissivity and specific yield were determined by pumping test and it ranges from 132.82 to 343.94 m^2/day and from 0.00176 to 0.0245, respectively, suggesting strong heterogeneity.

In the present study, Geographical Information System (GIS) is used to integrate multiparametric data to generate several thematic maps, delineate

groundwater potential zones and identify sites of artificial recharge in the Wakal river basin. The thematic layers considered to delineate groundwater potential zones are geomorphology, soil, slope, topographic elevation, land use/land cover, recharge, post-monsoon groundwater depth and transmissivity, which were prepared using conventional maps and data. All these themes and their individual features were then assigned weights according to their relative importance in groundwater occurrence and the corresponding normalized weights were obtained based on the Saaty's analytical hierarchy process. The thematic layers were finally added using Arc GIS software to yield groundwater potential zone map of the study area. The study area is classified into four groundwater potential zones, 'good', 'moderate', 'poor', and 'very poor', which encompass 20, 31.17, 34.19, and 14.64 per cent of the study area, respectively. The thematic layers used in this study to determine artificial recharge zones are transmissivity, recharge, groundwater level (post-monsoon), topographic elevation, soil and slope. These layers were combined using boolean logic analysis to delineate zones of suitability for artificial recharge structures. The area suitable for artificial recharge is 174.39 km^2, which is 9.2 per cent of the total study area.

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I – INTRODUCTION

1.1 General

"Water" is a prime natural resource and is considered as a precious national asset. It is a major constituent of all living beings. Water is available in two basic forms i.e. Surface water and Ground water. Water is used for various purposes ranging from domestic, agricultural, industrial and allied purposes. Water is probably the only natural resource to touch all aspects of human civilization from agricultural and industrial development to cultural and religious values embedded in society. It existed on the earth from the very beginning of the 'Srishti' and will remain until the end of it. That is why, among all the planets and stars of our universe, our planet is known as the watery planet. Water, no doubt, is a boon of nature for the whole living world and is essential for variety of purposes to human beings as well as to plants and animals. Its many uses include drinking and other domestic uses, irrigation, power generation, transportation, industrial cooling, fishing, mining and fire fighting etc.

Earth is also called as 'blue planet' because 70 per cent area of it has been covered by water resource. The total water amount on the earth is about 1.35 billion cubic kilometers. About 97.1 per cent has been locked into oceans as saltwater. Ice sheets and glaciers have arrested 2.1 per cent. Only 0.2 per cent is the fresh water present on the earth, which can be used by human for variety of purposes. Remaining 0.6 per cent is in underground form (Status Report, 2007). But unfortunately, it has been getting polluted day by day due to different anthropogenic activities. The effects of water pollution are not only devastating to people but also to animals, fish, and birds. Polluted water is unsuitable for drinking, recreation, agriculture and industrial purposes. It diminishes the aesthetic quality of lakes and rivers. More seriously, contaminated water destroys aquatic life and reduces its reproductive ability. Eventually, it is a hazard to human health and nobody can escape the effects of water pollution. Therefore, it is burning need, to conserve the water and prevent it from every type of pollution.

Availability of water is highly uneven in both space and time. Precipitation is confined to only about three or four months in a year and varies from 100 mm in the western parts of Rajasthan to over 10000 mm at Cherrapunji in Meghalaya. Rivers and under ground aquifers often cut across state boundaries. Water, as a resource is one and indivisible: rainfall, river waters, surface ponds, lakes, and ground water are all part of one system. It is one of the most crucial elements in developmental planning. The country has entered the 21st century, efforts to develop, conserve, utilize and manage this important resource in a sustainable manner, have to be guided by the national perspective.

Water is the basic requirement for the survival of lives and considered as a socio-economic resource. The main source of livelihood of the communities i.e. agriculture is totally dependent on the availability of water. Agriculture production will be enhance with the availability of sufficient water for irrigation and therefore, improved the economic condition of the communities. Improved agriculture production and better economic condition will ensure food security, reduce outside migration and also improve education status of children. Availability of potable drinking water will reduce health hazard and women drudgery.

The need to increase agricultural production in order to provide necessary quantum of food grains and fiber to the ever-increasing population of the country has been well recognized and is a concern of policy makers, administrators and scientists all over the country. Since the land resources are limited, the increase in the production can be achieved only by augmenting the productivity per unit area. Water, in absence of which all growth-promoting packages of practices fail, is the critical determinant to accomplish the challenging task of enhancing the productivity.

The occurrence and distribution of rainfall in India are highly uneven in both time and space. Thus inadequate amount and uncertain and erratic distribution of short-spell monsoon rainfall remain one of the major constraints for low productivity and call for supplemental application of water artificially to soil to meet the moisture requirement of crop at various growth stages and facilitate its proper growth for higher yield. This supplemental water, known as irrigation water, may be made available either by storing surface runoff or lifting groundwater or by the combination of both.

Water, the source of life on earth, supports all our agricultural, industrial, urban and recreational activities. The sheer of wastage, misuse and mismanagement of the available water have created scarcity in many areas. Demand of supplies of limited freshwater are growing rapidly worldwide, making it an increasingly scarce resource. India has 16 per cent of world’s population, 2 per cent of world’s land area and 4 per cent of world’s water resources. Therefore, this limited amount of water resources is to be utilized efficiently to meet the increasing need of our growing population.

Rajasthan has always been a water deficit area. The rainfall is erratic and there is a large variation in the rainfall pattern in the state. The average annual rainfall ranges from 100 mm in Jaisalmer to 800 mm in Jhalawar. Average annual rainfall of the state is 531 mm. For the 22 eastern districts, it is 688 mm whereas for the remaining western districts, the rainfall is only 318 mm. Rainfall in large parts of the state is not only inadequate but also varies sharply from year to year and place to place. The rainfall occurs only during two months of monsoon and the actual rainy days are numbered. The state has also to depend largely on the water allocated through inter state water sharing agreements, which depends upon inflows in rivers. The state has witnessed frequent drought and famine conditions in the past fifty years. Groundwater is not available in many parts of state even for drinking purpose. Sometimes water is being transported by trains, trucks and other means. Total surface water available in the state is 21.71 BCM, out of which 16.05 BCM is economically utilizable. State has so far harnessed 11.84 BCM, which is 72 per cent of economically utilizable portion. In addition to it 17.89 BCM is allocated through Inter-State agreements (State Water Policy, Rajasthan, 2010).

1.2 Groundwater

Groundwater is the most important natural resource of our planet. It is an important resource for human existence and economic development. Amazing growth of population, agriculture and industry has compelled an indiscriminate exploitation of this resource. The depletion of groundwater resource is a matter of great concern for human society. However, groundwater is a renewable resource but it has reached to critical stage of exploitation in many regions. Therefore, its appropriate management has assumed great significance.

Groundwater is dynamic resource, but it is not unlimited. Its quantity and quality both varies from place to place and season to season. The water table shows rise and fall in response to changes in water storage. Increment in the storage due to recharge from rainfall and seepage from tanks, canal and irrigation water is reflected by the rise of water level, whereas withdrawals through pumping out, outflow and other losses are reflected by the decline of water levels. In the recent past, the annual rainfall cycle has undergone surprising changes. The season of rainfall, its distribution over areas, intensity and duration have all changed in irregular way. The result is shrinking of groundwater resources because of which well are getting dry.

India has been facing increasingly severe water scarcity in several parts of the country, especially in arid and semi-arid regions. The overdependence on groundwater to meet ever-increasing demands of domestic, agriculture, and industrial sectors has resulted in overexploitation of groundwater resources in several states of India such as Gujarat, Rajasthan, Punjab, Haryana, Uttar Pradesh and Tamil Nadu (CGWB, 2006; Garg and Hassan 2007; Rodell et al. 2009). Out of 53.5 million hectare net irrigated area in the country, only 32 per cent is irrigated through surface water supplies while groundwater accounts for about 56 per cent irrigated area. The groundwater extraction ranges from 98.3 per cent in Punjab, 75.6 per cent in Haryana, 72.1 per cent in Rajasthan, 62.6 per cent in Tamil Nadu, 49.3 per cent in Gujarat, 41.9 per cent in Uttar Pradesh to almost negligible in north-eastern states. Further, nearly 90 per cent of drinking water requirements of India are also met from groundwater resources (CGWB, 2006).

Groundwater is one of the most valuable natural resources, which supports human health, socio-economic development, and functioning of ecosystems (Zektser 2000; Humphreys 2009; Steube et al. 2009). Out of the 37 Mkm^3 of freshwater estimated to be present on the earth, about 22 per cent exists as groundwater, which constitutes about 97 per cent of all liquid freshwater potentially available for human use (Foster 1998). However, the worldwide groundwater overdraft, declining well yields, drying up of springs, stream flow depletion, and land subsidence due to overexploitation of groundwater as well as the growing degradation of groundwater quality by natural and/or anthropogenic pollutants, is threatening our ecosystems and even the lives of our future generations (Bouwer 2000; Shah et al. 2000; Zektser 2000). Inferior quality of groundwater with high salinity, fluoride and nitrate contents limits the availability of fresh water. Industrial and urban pollution has caused to deterioration in quality of groundwater. It is the major source of drinking water, besides it is an important source for the agricultural and industrial sector. Compared to surface water, groundwater offers better insurance against drought because of the long lag between changes in recharge and response to groundwater levels. Thus, groundwater can be a prospective source of future freshwater supplies. Recent research has highlighted the alarmingly high rate at which groundwater levels in various parts of the India are falling. Studies conducted by WHO-UNICEF (2002) indicate that the rate, at which the groundwater reservoirs are being emptied in India, is at least 10 times faster than the rate at which it can be naturally recharged. Therefore, the water table is rapidly falling with unregulated over-exploitation of groundwater. By 2025, water scarcity in India will be acute. Big dams, Mega River linking projects or privatized water distribution may not help to solve water scarcity problem (Surface Water Resources Assessment Report, 2008). Since water is one of the key inputs into agricultural production, this will have very serious consequences for the political economy of the region where a large section of the population still derives its income from agriculture or related economic activities.

1.2.1 Status of groundwater in Rajasthan

Rajasthan is the largest state of the country whose geographical area is more than the area of 128 countries in the world but the status of water in the state is most critical. Rajasthan with more then 10.40 per cent of the countries geographical area, supporting more then 5.5 per cent of the human population and 18.70 per cent of livestock has only 1.16 per cent of the total surface water and 1.70 per cent of total groundwater availability of the country (IDWR, 2005). The two third part of the state is a part of the great thar desert which is bigger than most of the states except Madhya Pradesh, Uttar Pradesh, Andhra Pradesh and Maharashtra. Out of the total 142 desert blocks in the country, 85 blocks are in the state of Rajasthan (State Water Policy, Rajasthan, 2010). It is one of the driest state in the country, has recently faced recurrent droughts and increased rate of groundwater abstraction further intensified the problem. Rajasthan's economic growth is largely affected by availability of water, more specifically of groundwater. Rathore, 2003 reported that 71 per cent of irrigation and 90 per cent of the drinking water supply source is through groundwater. Presently, there is tremendous pressure to exploit groundwater by users. Over exploitation and excess use of groundwater has led to substantial decline in water levels, which may ultimately result to drying up of aquifers in larger areas of the state. Therefore, the groundwater condition is quite alarming. The condition has deteriorated very fast in the last two decades. The stage of groundwater exploitation, which was just 35 per cent in 1984, has reached a level of 138 per cent in the year 2008. Out of 237 blocks in the state, only 30 blocks are in safe category (State Water

Policy, Rajasthan, 2010). This calls for immediate remedial measures to address the critical water resources situation in the state.

With increase in population and water demand for various purposes, the state is heading towards absolute water scarcity. The availability of water in the state does not commensurate with the requirement of water. The deficit between demand and supply is 8 BCM at present and likely to increase to 9 BCM by the year 2015. The per capita annual water availability in the state is about 780 cubic meters based on projected population in July 2009 against minimum requirement of 1000 cubic meter. It is feared that the availability would fall below 450 cubic meters by the year 2045 (State Water Policy, Rajasthan, 2010). As per international accepted norms, the availability of water below 500 cubic meters is considered as absolute water scarcity. There is a sharp increase in drinking water demand with increase in population and greater consciousness about sanitary facilities. Correspondingly, non-agricultural water demand, which was 3.28 BCM in the year 1995, is expected to reach 8.07 BCM in the year 2045 (State Water Policy, Rajasthan, 2010). The causes of groundwater depletion and pollution are rooted in population growth, economic expansion, decline in groundwater recharge and over-abstraction caused by rapid increase in the number of open wells and tube wells and the progress in pumping technology. The first groundwater potential estimates in Rajasthan were made during 1983-84. Despite an increase in the area of groundwater potential due to more exploratory studies, there has been a total decline of 39.89 per cent in the groundwater potential from 1984 to 2001. As a result, 'safe' water zones (i.e., those safe for exploitation) declined from 86 per cent in 1984 to 10.6 per cent in 2004. Also in the year 2001, 70.3 per cent of total groundwater potential zones were classified as 'dark' and 'gray' (Rathore, 2005). Therefore, there is an urgent need to manage the available groundwater resources of Rajasthan to meet the future demands.

The main source of recharge to groundwater is rainfall. The rainfall in the state gradually decreases from South East towards North East. However, rainfall pattern is very uneven and erratic marked by prolong rainless days which leads to occurrence of frequent droughts. Consecutive drought spell of 2 to 3 years often occurs in the state. The rainfall fails especially at the time when it is required most. Lack of rainfall at critical stage of crop growth is a common phenomena in the state which adversely affect the sustainable crop production. It is important to realize that in Rajasthan food security will depend heavily on a large scale rainwater harvesting and groundwater recharge programme. About two third agricultural lands are rainfed, which is totally depending on vagaries of monsoon. Under such conditions for ensuring availability of water in sub-strata, artificial recharging is only an alternative to save the crop under adverse climatic condition. Further inferior quality of groundwater with high salinity, fluoride and nitrate contents limits the availability of fresh water. Besides, the groundwater is being polluted in many areas due to indiscriminate disposal of industrial waste urban wastewater and solid waste. Excess use of chemical fertilizers is also detrimental of water quality (Ghosh et al., 2010). Cumulative effects of all these factors have made Rajasthan as the most water severe state in the country.

1.3 Remote Sensing and GIS

Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation. Remote sensing is largely concerned with the measurement of electromagnetic energy from the sun, which is reflected, scattered or emitted by the objects on the surface of the earth. Different objects on the earth surface reflect different amounts of energy in different wavelengths of the electromagnetic spectrum. Detection and measurement of these spectral response and spectral signature enables identification of surface objects both from airborne and space borne platforms. Satellite remote sensing provides multispectral, multispatial and multitemporal data useful for resources inventory, monitoring and their management by both visual interpretation and digital (computer) analysis.

Geographical Information System (GIS) has multiple meanings and the widely accepted views are the effectiveness of map processing, databases and spatial analysis with the help of human expertise. GIS integrates geographically referenced spatial and non spatial data required at different scales and times, and in different formats. GIS provides a digital representation of the watershed/basin characterization used in the hydrologic modeling. During the systematic survey of watershed/basin, factors like physiography, soils, vegetation, land use, slope, drainage pattern etc. are considered simultaneously and huge amount of attribute data are required to be collected. There are difficulties in data management with conventional methods. Further, the presentation of results through maps, charts, diagrams, texts etc. handling of voluminous data and its storing, manipulation, retrieving and updating is also cumbersome, tedious and plenty of time is required to manage the database. With the advent of advanced computerized technology, the above said problems are best handled through GIS techniques. One of the major advantages of GIS is its capability to overlay multithematic data, which could be used in hydrological models, integrated watershed management planning and groundwater assessment study. The results thus obtained are much more realistic, comprehensive and less time consuming.

The main advantages of using remote sensing and GIS techniques for groundwater exploration are the reduction of cost and time needed, the fast extraction of information on the occurrence of groundwater and the selection of promising areas for further groundwater exploration (Toleti et al., 2001). Unlike surface water hydrology, the application of remote sensing and GIS in groundwater studies is limited (Jha and Peiffer, 2006). It implemented lately as very useful tools by a number of researchers in the field of hydrogeology for groundwater study. The need for application of modern approaches such remote sensing and GIS techniques has been emphasized for the efficient management of groundwater resources (Jha et al., 2007). For delineating the groundwater potential/prospective zones, GIS has been found to be an effective tool. In recent years, use of satellite remote sensing data along with GIS, topographical maps, collateral information and limited field checks, has made it easier to establish the base line information on groundwater prospective zones (Saraf and Jain, 1993; Krishnamurthy et al., 2000; Agarwal et al., 2004). Therefore, remote sensing and GIS techniques are considered the most appropriate new alternative tools for groundwater exploration.

1.4 Need of the study

The situation of groundwater availability in the state is very crucial due to overexploitation of groundwater resources. The water table is depleting at an alarming rate and deteriorating the quality of groundwater in several areas. Large number of wells, hand pumps and tube wells have become dry in many areas causing acute shortage of irrigation and drinking water supply in the state. Depletion in water levels is directly associated with deterioration in quality of groundwater. Salinity increases as low quality water is drawn into heavily pumped fresh water aquifers. In urban and industrial areas, problems of pollution of groundwater due to heavy contamination is also a major threat for the people. This situation calls for the necessity for management, conservation and regulation of groundwater resources. Sustainable management on the state's groundwater resources is thus of fundamental importance to the state's future.

Morphometric analysis of a watershed provides a quantitative description of the drainage system, which is an important aspect of the characterization of watersheds (Strahler, 1964). Morphometric analysis requires measurement of linear features, areal aspects, gradient of channel network and contributing ground slopes of the drainage basin (Nautiyal, 1994). Drainage characteristics of many river basins and sub basins in different parts of the globe have been studied using conventional methods (Horton 1945; Strahler 1952, 1957, 1964; Morisawa 1959; Krishnamurthy et al. 1996). The remote sensing technique is a convenient method for morphometric analysis as the satellite images provide a synoptic view of a large area and is very useful in the analysis of drainage basin morphometry. In India, some of the recent studies on morphometric analysis using remote sensing technique were carried out by Nautiyal (1994), Srivastava (1997), Nag (1998), Srinivasa et al. (2004) and Chopra et al. (2005).

The Wakal river basin, situated in southern part of Rajasthan is a rainfed river basin. Total area of the basin is1914.32 km^2 whereas maximum length of basin is 71.22 km which is draining to Sabarmati river in Gujarat. About 2 per cent of the entire catchment area of this basin falls in Gujarat. The extreme seasonal rainfall to drought and flood conditions; long-term records suggest that region has experienced 41 drought conditions during past 50 years. Most of the rivers or streams in this basin are ephemeral, therefore, groundwater provides the main source of supply for human as well as livestock. In Wakal river basin, water quality is one of the major regions of acquiring water born diseases to the tribal peoples. Health hazard due to poor quality water is becoming a major issue in the area. The scientists of CTAE, Udaipur during the year 2008, carried out study on assessment of surface water resources of Wakal river basin. In Wakal river basin 90 per cent drinking water supply depends on groundwater resources which is depleting at an alarming rate. There is urgent need for argumentation of water table through identification of potential recharge zones and managing aquifer recharge system. Looking to the magnitude of the problem of declining trend of water table and water scarcity in the Wakal river basin, efforts have made to conduct groundwater resources study of the basin which will provide a guide line to mitigate the drought and also to enhance the crop yield of the area through sustainable interventions of groundwater management.

Remote Sensing and Geographical Information System (GIS) with their advantages of spatial, spectral and temporal availability and interpolation of data covering large and inaccessible areas within a short time have become very handy tools in accessing, monitoring and conserving groundwater resources (Sener et al. 2005). In the prospect of prevailing groundwater crisis the proposed study "An Integrated Approach of Groundwater Management in Wakal River Basin using Remote Sensing and Geographical Information System" is proposed for preparation of sustainable groundwater management for Wakal river basin.

1.5 Objectives

(i) To analyze geomorphological characteristics of different sub-basins of Wakal river basin.

(ii) To collect groundwater sample of Wakal river basin and analyze its spatio-temporal variability in groundwater quality.

(iii) To delineate groundwater potential zones and recommend suitable strategies for sustainable groundwater resource management.

II - REVIEW OF LITERATURE

An extensive review of literature has been made on the lines of objectives contemplated to facilitate devising an appropriate methodology towards accomplishing the entire research topic. The latest review of literature for the proposed study has been collected in the following headlines.

1. Geomorphological parameters of the basin
2. Groundwater quality
3. Pumping test data analysis and
4. Groundwater potential zoning

2.1 Geomorphological Parameters of the Basin

Quantitative Measurement of drainage basin was proposed during nineteenth century for the specific area, but by the early twentieth century, methods of stream ordering were conceived. R.E. Horton made a great step forward in 1932 when he crystallized previous work, added new measures and proposed general methods for the description of drainage basin characteristics. Such characteristics according to Horton included morphologic, soil, geologic or structural and vegetation factors. Horton proposed the way in which examples of each factor could be expressed in a way relevant to the functions of the drainage basin. These parameters have been used in various studies of geomorphology and surface-water hydrology, such as flood characteristics, sediment yield and evolution of basin morphology. Few geomorphologists began to work on quantification of land from description of the drainage basins. Strahler (1957) made revisions to these techniques and attempted to base a system of quantitative geomorphology on dimensional analysis and principles of scale model similarity. If two drainage basins are geometrically similar, all corresponding length dimensions will be in a fixed ratio. Maxwell (1955) and Morisawa (1957) also added numerous concepts to this view of quantitative geomorphology.

Nautiyal (1994) showed that remote sensing techniques using satellite images and aerial photographs are convenient tools in morphometric analysis of the drainage basin. He worked out morphometric parameters of Kharikuli drainage basin, district Dehradun, using aerial photographs. The computed parameters suggested that the peak flow generated from the basin were likely to be moderately high and of short duration.

Agarwal (1998) analyzed basin characteristics in term of basin morphology and related parameters. The drainage system of the region is composed of 3 perennial rivers with 7 sub-basins (K_1, K_2, K_3, K_4, C_1, C_2 and G_1). In the six sub-basins (K_I, K_2, K_3, C_1, C_2, G_1) the trunk stream is of Vth order and in K_4 sub-basin, the trunk stream is of VIth order. A total of 1223 streams of 1^{st} to 6^{th} order exist, out of which 761 are of 1^{st} order and 350 of 2^{nd} order, which hold sufficient amount of water during the peak monsoon period. The value of mean bifurcation ratio (R_b) shows only a small variation between the sub basins. The bifurcation ratio for the sub-basins fall in the range of 2.638 to 4.07 indicating that the geological structure did not distort the drainage pattern in all these watersheds. The low values of drainage density (D_d), stream frequency (F_s) and infiltration number (I_f) for K_2 sub-basin suggests that it is covered mostly with colluvium as compared to the higher values of drainage density, stream frequency and infiltration under for the six sub-basins with hard rock area, clearly indicate the possibility of higher infiltration and low runoff in K_2 sub basin. The values of all the 3 shape factors i.e. elongation ratio (R_e), form factor (R_f) and circulatory ratio (R_c) for K_3 sub-basin indicate that this sub-basin is more elongated as compared to the other six sub-basin which are relatively more circular. The detailed morphometric analysis finally concludes that sub-basin K_1, K_2 and K_3 of Karamnasha basin are having better scope for artificial recharge scheme and deep groundwater exploration, as the infiltration is more with less runoff. The water table in the area varies from 1.70 to 16.40 m (bgl) with number of springs, which can be utilised for artificial recharge scheme.

Nag (1998) carried out morphometric analysis using Remote Sensing techniques in Chaka river sub-basin of Manbazar Block, Purulia district, West-Bengal, which is one of the most drought affected area in West-Bengal. The parameters worked out include Bifurcation ratio (R_b), Stream length (L_u). Form factor (R_f), Circulatory ratio (R_c), and Drainage density (D_d). The morphometric analysis suggests that the area was covered by fractured, resistant, permeable rocks, the drainage network not so affected by tectonic disturbances.

Biswas et al. (1999) studied the morphometric characteristics of the nine sub watersheds of the major part of Nayagram Block in the Midnapure District, West

Bengal using Remote Sensing and Geographic Information System (GIS) techniques. They determine the morphometric parameters - stream length, bifurcation ratio, drainage density, stream frequency, texture ratio, form factor, circulatory ratio and elongation ratio and prioritized all the sub watersheds under study. The results suggest that the ratio between cumulative stream length and stream order is constant throughout the successive orders of a basin. The morphometric parameters - bifurcation ratio and drainage density, confirm that the area was under dense vegetative cover and virtually the drainage was not affected by structural disturbances. The form factor values indicate that the basin was moderately high and short duration peak flows. It was observed from the prioritization of sub watersheds that the sub watershed 8 has the highest priority because of high erosion intensity considering the above mentioned morphometric parameters.

Patel and Thakur (2000) analyzed morphometric and geomorphological characteristics of the Markanda Basin of Haryana. The study revealed that, there was a distinct geomorphological control for development of the Markanda basin. The development of Markanda basin is divided into two stages i.e. the youth stage in the Shivalik Mountain and old stage or mature stage in the plane. In the youth stage, the steep gradient, the lower order stream, maximum number of low order streams, smaller length low order streams, the dendritic drainage pattern, gully shape valley and consolidated rock types signify that the region is less porous and permeable. All these factors indicates that the upper reaches of the basin were not suitable for groundwater exploration. The mature and old stage of the basin is characterized by river meander deposits, piedoment deposits, buried channel deposits, high order stream, more length but few lower order streams. All these factor indicates that the lower reaches of the Markanda Basin were highly porous and permeable.

Dutta et al. (2001) used Remote Sensing techniques, tailored with GIS to study the major hydro-geomorphic variables of seven sub-watersheds having area ranging between 53 to 170 Km^2, belonging to the sub catchments of lower and middle Parbati and Kuno rivers, to analyze potential soil erodibility and effects of surface condition on erosion. Some of the hydro geomorphic variables were found to be significantly correlated with each other. Based upon the hydro-morphic and morphometric characteristics and their influence on sediment and transport potential, the sub-watersheds were classified into 5 categories (very high to low priority category), and the nature of flood discharge pattern was compared.

Kumar et al. (2001) evaluated geomorphological characteristics, which are commonly used in the various hydrological studies using the GIS package, Integrated Land and Water Information System (ILWIS) for the Ajay basin upto the Sarath gauging site of South Bihar. It has been experienced that manual estimation of the geomorphological parameters is a tedious and cumbersome process and often discourages the field engineers from developing the regional methodologies for solving various hydrological problems of the ungauged basins or in limited data situations. At times, it also leads to erroneous estimates. On the other hand, modern techniques like the GIS serve as an efficient approach for storage, processing and retrieval of large amount of database. The database created and stored in GIS system may be updated as and when required.

Kumari et al. (2001) conducted morphometric analysis to study the drainage pattern of Chittar sub-basin in Thiruvanayhapuram district of Kerla. Chittar sub-basin consists of five small watersheds. Stream order for these watersheds ranges from second to third order. Shape of the three watersheds were elongated, one oval and the other one is less elongated. The study revealed that four watersheds were in the youthful stage and the other one was early matured.

Wodeyar et al. (2001) made geological, geomorphological and hydrogeologyical studies in Kandra basin of the Panhale Taluka, Kolhapur District, Maharashtra State. The lateritic bauxites are found on the hill tops of the Panhala Township. The western and the southern part of the basin were occupied by the flat topped hill ranges with steep hill slopes. The basin is of 5th order. The bifurcation ratio is 3 to 4.8. The homogenous nature of the litho units is supported by circulatory ratio value. The drainage density value is 1.2 per km^2 indicating coarse drainage density. The hard and compact basalts possess only secondary opening by virtue of joints, fractures and fissures. The groundwater occurs in unconfined conditions and it is developed by either dug or bore wells. The dug wells are shallower while the bore wells are deeper and serve the local people in the dry season. The quality of the groundwater is suitable for both domestic and agriculture use.

Bhaskaran et al. (2002) analyzed fourteen geometric parameters for 34 minor basins of Bhavani sub-basin of the Cauvery basin. They grouped the parameters into four factors, which were closely inter-related. For better interpretability, the varimax had been used, resulted in a four rotated matrix. The first factor explains the basin size, second factor explains the runoff characteristics of sub basin, the third one spells out the drainage parameters and the last one describe the shape of the sub basin.

Mittal (2002) evaluated various geomorphological characteristics of Cheerwa and Losing watersheds of Udaipur, Rajasthan, and reported that both the watershed are 3^{rd} order. The value of bifurcation ratio for these watersheds was found to be 2.84 and 2.80 respectively, which shows that these basins are normal basins. The elongation ratio at both study sites suggests that watersheds are under moderate slopes. The study also shows that value of drainage density of Cheerwa watershed is 3.71 as compared to 2.44 for Losing watershed. Further, related to drainage density another morphological property of drainage basin is constant of channel maintenance, which was found to be 0.27 and 0.40 km^2 per km in Cheerwa and Losing watershed respectively. The lower value of drainage density in Losing watershed as compared to Cheerwa was due to the fact that former watershed was under denser vegetation than the later and also having low relief. This is also evident from the values of relief ratio i.e. 4.2 per cent and 3.6 per cent in Cheewa and Losing watershed respectively.

Muley et al. (2002) studied the geomorphological and hydrological characteristics of Kuranwadi watershed of Ambajogi Tehsil of Beed district of Maharastra. The geomorphological approach involves the study of drainage pattern, linear and aerial aspects of watershed, basin configuration, drainage density, stream frequency and length of overland flow. The hydrological studies involve the characteristics of basalt flow and effects of check dams on the groundwater condition of the area. The study of morphometric parameters indicates that the area is suitable for rainwater harvesting and conservation. Geological and hydrological characteristics of the watershed area were suitable for increasing groundwater potential when water harvesting structure was constructed on middle portion of the basalt flow.

Pakhmode et al. (2003) reveal that a combination of drainage analysis and hydrogeological mapping form an important tool for planning of watershed-development programmes. They Studies on the Kurzadi watershed from the Deccan volcanic province in west-central India, which is a part of the Yashoda River flows through the Kurzadi village. The Kurzadi river basin includes three third-order sub-basins (IIIA, IIIB and IIIC) and one-fourth order sub basin (IVA). The Kurzadi basin was analyzed for stream-order analysis, bifurcation ratio (R_b), length ratio (R_l), drainage density (D_d), constant of channel maintenance ($1/D_d$), length of overland flow (L_g) and stream frequency (F). The analysis reveal that the third-order basin III B is more permeable to infiltration than the third-order basins III A and III C, as indicated by the higher values of the constant of channel maintenance ($1/D_d$) and length of overland flow (L_g), and the lower values of drainage density (D_d) and stream frequency (F). Moreover, larger areas of basin III B are likely to be permeable since length ratio (R_L) data indicate more homogeneous surfaces for basin III B as compared to surfaces in basins III A and III C where the permeable rock surfaces would be restricted only to areas through which the third-order stream flows.

Singh et al. (2003) analyzed the morphometric parameters of a watershed, which plays an important role in deciding the hydrological behavior such as runoff, soil erosion, sediment delivery ratio etc. of a watershed. The Nana Kosi watershed in Kumaun Lesser Himalayas was considered for such study. Remote Sensing data were used for land use information. Various linear, aerial and relief parameters of the study area were determined using GIS. It was observed that first order streams constitute 63.52 per cent of the total stream length whereas remaining 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} order stream constitute 18.52, 7.19, 7.12 and 3.78 per cent respectively.

Dabral and Dabriyal (2004) studied 7 morphological parameters viz. form factor, drainage texture, time of concentration, bifurcation ratio, relief ratio, average slope and drainage density of 35 watersheds for fixation of priority. Priority was given based on the rank number (Lowest to Highest). The number of watersheds under very high priority, high priority and low priority were found 9, 16 and 10 respectively

Gopalkrishna et al. (2004) analyzed morphometric characteristics of Yagachi and Hemavati River Basins of Karnataka. They showed that the drainage system is dendritic and sub dendritic and the geomorphology of the area controls the geometric configuration of the aquifer media. The study indicates that the occurrence, movement and availability of groundwater in the region were controlled by the geology of the area.

Gowd (2004) analyzed morphometric and relative parameters for the Peddavanka basin Anantpur district, Andhra Pradesh. He showed that the basin is of 6^{th} order with dendritic drainage pattern. The basin length decreases as the order stream increases and it is lowest in case of the highest stream orders. The elongation ratio of Peddavanka basin was 0.45 showing extremely elongated nature. The drainage density revealed that the nature of subsurface strata is permeable. The mean bifurcation ratio lies between 3 to 5 indicating the homogeneous character and geologic structure with mature topography.

Pandey et al. (2004) studied the distinct characteristics of watershed, which govern the amount of runoff and soil loss produced by a rainfall event. The morphological analysis of a watershed coupled with land use and soil information can play a vital role in predicting the hydrological behavior of a watershed. The morphological parameters such as stream order, stream length, bifurcation ratio, form factor, circulatory ratio, elongation ratio, drainage order, drainage frequency, rugged number etc. were computed in the study using ARC/INFO GIS. GIS tool were used for the integration of various thematic maps, viz., land use/cover, soil and drainage information with morphometric parameters to delineate the area suitable for adopting soil and water conservation measures.

Prasad et al. (2004) studied the drainage pattern of Valagalamanda river basin of Chittor district, Andhra Pradesh by analyzing morphometric characteristics. The drainage pattern is dendritic. It is 6^{th} order basin and elongated in East-West direction. The bifurcation ratio (3.8) and hypsometric analysis indicated mature stage of development. The stream ratio was 0.87, area ratio 4.04, drainage density 2.41 km per km^2 and stream frequency of the basin was 2.78 per km^2.

Sriniwas (2004) conducted morphometric analysis for Peddavanka basin of Anantpur district of Andhra Pradesh. The quantitative analysis of the morphometric characteristics of the basin includes stream order, stream length, bifurcation ratio, drainage density, drainage frequency, relief ratio, elongation ratio and circulatory ratio. He concluded that the mean bifurcation ratio of all the sub-basin lies between 3 to 5 indicating the homogenous character and geologic structure. The higher value of bifurcation ratio indicates a mature topography which is the result of the process of drainage integration.

Vittala et al. (2004) analyzed morphometric characteristics of the area, which covers 570 km^2 comprising of 9 sub-watersheds (Dalavayihalli, Maddalenahalli, Talamaradahalli, Puluvalli tank, Nagalamadike, Gowdatimmanahalli, Naliganahalli, Devadabetta and Byadanur) range from 49 to 75 km^2 forming a part of Pennar river basin around Pavagada, using GIS softwares - Arclnfo and Arc View. The drainage network of 9 sub-watersheds was delineated using remote sensing data - Geocoded FCC of bands - 2 3 4 of IRS 1 C and 1 D (LISS III+PAN merged) on 1:50,000 scale and SOI topomaps were used as reference. The drainage network shows that the terrain exhibits dendritic to sub-dendritic drainage pattern. Stream orders ranges from fourth to fifth order. Drainage density varies between 1.55 and 2.16 km/km^2 and has very coarse to coarse drainage texture. The relief ratio range from 0.006 to 0.021. The mean bifurcation ratio varies from 3.21 to 4.88 and falls under normal basin category. The elongation ratio shows that Devedabetta sub-watershed possesses circular shape while remaining sub-watersheds mark elongated pattern. Hence, from the study it was concluded that Remote Sensing techniques proved to be a competent tool in morphometric analysis.

Chopra et al. (2005) carried out morphometric analysis of two sub-watersheds using remote sensing and GIS techniques. Detailed drainage map prepared from aerial photographs and SOI toposheets was updated using latest IRS-1D PAN sharpened LISS-III analog data. Updated drainage maps were used for the morphometric analysis of the two sub-watersheds. The parameters, namely stream order, stream length, bifurcation ratio, relief ratio, drainage density, stream frequency, drainage texture, form factor, circulatory and elongation ratio, area, perimeter, length and width of both the sub-watersheds were carried out. Both sub-watersheds were designated as fifth order sub watersheds having a total of 552 and 442 stream segments of different orders respectively. The total length of stream segments decrease with stream order. Both the sub-watersheds shows dendritic to sub-dendritic drainage pattern with moderate drainage texture. High bifurcation ratio indicates a strong structural control on the drainage. Logarithm of number of stream vs. stream order shows deviation from straight line indicating regional upliftment. In spite of mountainous relief, low drainage density values indicate that the area is underlain by impermeable sub-surface material. Circulatory and elongation ratios shows that both the sub watersheds have elongated shape.

Gupta et al. (2005) conducted GIS based study for the selected watersheds of Banas river catchment of southeast Rajasthan and reported that the geomorphological parameters directly or indirectly reflect almost the entire watershed based causative factors affecting runoff and sediment loss. The study revealed that hypsometric integral, which is geologic component of geomorphology, is useful in classifying the watersheds into highly eroded, moderately eroded and stabilized stages. They also summarized the various geomorphologic parameters and identified the priority rating of watersheds for soil and water conservation measures.

Nookaratnam et al. (2005) had attempted for check dam positioning by prioritization of micro-watershed using SYI model and morphometric analysis using Remote Sensing and GIS. Morphometric parameters such as bifurcation ratio, drainage density, texture ratio, length of overland flow, stream frequency, compactness coefficient, circulatory ratio, elongation ratio, shape factor and form factor were computed. Automated demarcation of prioritization of micro-watershed was done by using GIS overlaying technique by assigning weight factors to all the identified features in each thematic map and ranks were assigned to the morphometric parameters. Five categories of priority viz. very high, high, medium, low and very low were given to all the watersheds. Sixty-two micro-watersheds using SYI method and twenty-three micro- watersheds using morphometric data were prioritized under very high priority. Twenty-four suitable sites were identified for check dam construction in 21 highly prioritized watersheds.

Sahoo et al. (2005) conducted study for Nagaria nala micro watershed in Nayagarh district of Orissa. Different morphological parameters such as circulatory ratio, elongation ratio, drainage density, bifurcation ratio, form factor, number of streams of 1^{st}, 2^{nd}, 3^{rd} order, breadth, length and area of basin were determined. Form factor was found to be 0.558, which shows that watershed produces a medium peak flow for certain duration and it can be managed by an appropriate adoption of control measures. Bifurcation ratio was obtained as 7.44 whereas drainage density was found to be 3.30, which is medium indicating that the area is covered by resistant permeable rocks and medium vegetative cover. On the basis of their study and ground truth data, an action plan for the watershed was prepared successfully.

Sreedevi[1] et al. (2005) determine the drainage characteristics of Pageru River basin of Cuddapah District, Andhra Pradesh using topographical maps on a scale of

1:50,000. The total area of the Pageru River basin is 480 km^2. It was divided into 10 sub-basins for analysis. The drainage patterns of the basin are dendritic and include a sixth order stream. The quantitative analysis of various aspects of a river basin drainage network characteristic reveals complex morphometric attributes. The streams of lower orders mostly dominate the basin. The development of stream segments in the basin area was more or less affected by rainfall. The elongated shape of the basin is mainly due to the guiding effect of thrusting and faulting. The erosional processes of fluvial origin were predominately influenced by the subsurface lithology of the basin.

Mesa (2006) carried out morphometric analysis to determine the drainage characteristics of Lules River basin in Argentina using land-sat imageries and topographical maps. This catchment was divided into seven sub basins for the analysis: Liquimayo, Hoyada, Cie´naga, De Las Tablas, Siambo´ n, Potrerillo and San Javier. The drainage patterns of the sub-basins are dendritic and parallel. The basin includes seventh order stream and lower streams order mostly dominate the basin. The development of stream segments was affected by slope and local relief. The mean bifurcation ratio indicates that the drainage pattern was not much influenced by geological structures. The shape parameters also reveal the elongation of the basin and sub-basins.

Narendra and Rao (2006) determined the drainage characteristics of the six sub watersheds (M-I, M-II, M-III, M-IV, N-I and NB-I). The ranking of streams was carried out based on the method proposed by Strahler (1964). Out of six sub-watersheds, M-IV was the trunk stream of 6^{th} order and M-III, NB-I were of 5^{th} order, while remaining sub-watersheds: M-I, M-II, N-I were of 4^{th} order. The mean bifurcation ratio values range between 2.93 and 4.93 for six sub-watersheds indicates that the geological structures were not disturbing the drainage pattern. The total length of stream segments was maximum in first order streams and decreases as the stream order increases. The drainage density (D_d) of the area varies between 1.77 to 2.70 km/km^2 indicating low drainage density. It was suggested that the low drainage density indicates the watershed is having highly permeable subsoil and thick vegetative cover. The values of stream frequency (F_s) for six sub watersheds exhibits positive correlation with the drainage density values of the area indicating the increase in stream population with respect to increase in drainage density The form factor (R_f)

values range between 0.27 to 0.48 for six sub-watersheds indicates lower values of form factor and thus represents elongated in shape. The elongated basin with low form factor indicates that the watershed will have a flatter peak of flow for longer duration. Elongation ratio and form factor values shows that watershed possesses elongated shape that indicates the low runoff and flatter peak of flow.

Binjolkar and Keshari (2007) obtained a number of geomorphological parameters defining the behavior of the catchment of the Tilaiya reservoir, constructed on Barakar River, a tributary of Damodar River, by using GIS. The considered geomorphological parameters characterize basin geometry, basin relief, drainage network and intensity of dissection, which was evaluated to assess the hydrologic response. Results of the study revealed that the catchment is elongated with low bifurcation ratio in the upper reaches. The upper reaches were less susceptible to erosion and lower reaches were influenced by some geological structures. Results reported in the study will be useful in developing functional relationships between geomorphological parameters and hydrological variables.

Thakkar and Dhiman (2007) carried out morphometric analysis and prioritization of the eight miniwatersheds (5F2B5a1, 5F2B5a2, 5F2B5a3, 5F2B5b1, 5F2B5b2, 5F2B5b3, 5F2B5c1 and 5F2B5c2) of Mohr watershed, located between Bayad taluka of Sabarkantha district and Kapadwanj taluka of Kheda district of Gujarat State using Remote Sensing and GIS techniques. The morphometric parameters considered for analysis are stream length, bifurcation ratio, drainage density, stream frequency, texture ratio, form factor, circulatory ratio, elongation ratio and compactness ratio. The Mohr watershed has a dendritic drainage pattern. The highest bifurcation ratio among all the miniwatersheds is 9.5, which indicates a strong structural control on the drainage. The maximum value of circulatory ratio was 0.1197 for the miniwatershed 5F2B5b3. The miniwatershed 5F2B5a2 was maximum elongation ratio (0.66). The form factor values were in range of 0.29 to 0.34, which indicates that the Mohr watershed has moderately high peak flow for shorter duration. The compound parameter values were calculated and prioritization rating of eight miniwatersheds in Mohr watershed was carried out. The miniwatershed with the lowest compound parameter value was given the highest priority. The miniwatershed 5F2B5b2 has a minimum compound parameter value of 3.12 is likely to be subjected to maximum soil erosion hence it should be provided with immediate soil conservation measures.

Angillieri (2008) analyzes various morphometric characteristics of the Colangüil river basin, Argentina, in order to evaluated flash flood hazards. For this purpose, the basin was divided into seven sub-basins and both the morphometric characterization and basin delineation were made using 1:100,000 topographic maps, 1:15,000 aerial photographs, and digital satellite imagery (Landsat 7-TM). The stream ordering of the basin was made after Strahler (1964). The morphometric parameters were divided in basic parameters: area (A), perimeter (P), length (L), width (W), river network (Rn), maximum and minimum heights (H, h), total channel length (Tcl), main channel length (Mcl); and derived parameters: the circulatory index (R_c), the elongation ratio (R_e), the form factor (R_f) and drainage density (D_d). The computed morphometric characteristics shows that lower order streams mostly dominated in the basin. The river network was fifth order. The general pattern of the basin was parallel dendritic. It is an elongated basin with highly dissected areas, and the D_d of the basin indicates that the general nature of rocks is impervious.

Rao (2008) used a combination of morphometric analysis coupled with hydrogeological information to prepare a generalized scenario for watershed development plans. An attempt was made, from the morphometrical studies of the Varaha watershed of the Precambrian Eastern Ghats basement terrain in Eastern India, to illustrate how the numerical scheme is helpful as a tool in watershed development planning. The quantitative analysis of the morphometric characteristics of a watershed basin covers two aspects: (1) linear aspects and (2) aerial aspects. The former includes stream orders, bifurcation ratio, stream lengths and stream length ratio, while the latter includes drainage density, constant of channel maintenance, length of overland flow, stream frequency, drainage texture, circulatory ratio and elongation ratio. These are the important drainage characteristics required for an assessment of a watershed development plan, in association with hydrogeological information.

Rudraiah et al. (2008) analyzed morphometric characteristic of the area, which is a part of Kagna river basin in the Gulburga district of Karnataka, India. It covers an area of 1320 km^2 and it has been subdivided into 4 sub-basins namely Wadi, Chitapur, Sedam and Kurkunta, which range in area from 184 to 537 km^2. The drainage pattern of these sub-basins was delineated using Geo-coded FCC bands 2, 3, 4 of IRS 1C and

1D (LISS III+PAN merged) on 1:50,000 scale and Survey of India toposheets as reference. The morphometric parameters were computed using Arc Info and ArcView GIS softwares. The drainage pattern of the study area was dendritic to sub-dendritic with stream orders ranging from IV to VII orders. Drainage density ranges from 1.40 to 1.86 km/km^2 suggesting coarse to moderate drainage texture. The change in values of stream length ratio indicates their late youth stage of geomorphic development. The values of bifurcation ratio ranging from 2.00 to 4.71, which indicates that all the sub-basins falls under normal basin category. The values of form factor and circulatory ratio, suggest that the Kurkunta sub basin was elongated and the remaining sub-basins were more or less circular in shape. Elongation ratio indicates that the Wadi sub-basin is a region of very low relief whereas the other sub-basins were associated with moderate to high relief and steep ground slopes. It was concluded that Remote Sensing and GIS have been proved efficient tools in drainage delineation.

Javed et al. (2009) attempted to prioritize sub-watersheds based on morphometric and land use characteristics using Remote Sensing and GIS techniques in Kanera watershed of Guna district, Madhya Pradesh. Various morphometric parameters, namely linear and shape were determined for each sub-watershed and assigned ranks on the basis of value/relationship, so as to arrive at a computed value for a final ranking of the sub-watersheds. Land use/land cover change analysis of the sub-watersheds was carried out using multi-temporal data of IRS LISS II of 1989 and IRS LISS III of 2001. The study demonstrates the significant land use changes especially in cultivated lands, open scrub, open forest, water bodies and wastelands from 1989 to 2001. Based on morphometric and land use/land cover analysis, the sub-watersheds were classified into three categories as high, medium and low in terms of priority for conservation and management of natural resources. Out of the seven sub-watersheds, two sub-watersheds viz., SW1 and SW6 qualify for high priority, whereas SW7 was categorized as medium priority based on the integration of morphometric and land use change analysis.

Pankaj and Kumar (2009) studied the Geographic Information System (GIS) analysis techniques to evaluate and compare linear, relief and aerial morphometry of the five sub watersheds of Song River (tributary of the Ganga River) with special reference to landslide incidences, for future development and planning of the watershed. Jakhan Rao, Song River, Bandal Nadi, Baldi Nadi and Suswa Nadi were the five major sub watersheds of the Song River basin. All the sub watersheds were basically of 5th to 6th order. Drainage patterns was mainly dendritic to sub dendritic. The drainage pattern of the Song River basin was mainly structurally controlled and the area was characterized by high to moderate relief. The asymmetric factor indicates that the tectonic rotation of the four sub watersheds was upward on the right side of the drainage basin and only one sub-watershed was downward. The numbers of the landslide incidences were also more in the upward side, than the downward side of the Song River basin.

Sreedevi et al. (2009) was attempted to study drainage morphometry and its influence on hydrology of Wailapalli watershed, South India. For detailed study they used Shuttle Radar Topographic Mission (SRTM) data for preparing Digital Elevation Model (DEM), aspect grid and slope maps. Geographical information system (GIS) was used in evaluation of linear, aerial and relief aspects of morphometric parameters. The study reveals that the elongated shape of the basin is mainly due to the guiding effect of thrusting and faulting. The lower order streams are mostly dominating in the basin. The development of stream segments in the basin area was more or less affected by rainfall. The mean R_b of the entire basin is 3.89, which indicate that the drainage pattern was not much influenced by geological structures. Relief ratio indicates that the discharge capability of these watersheds was very high and the groundwater potential was meager. These studies were very useful for planning rainwater harvesting structures and developing watershed management plan.

Ballukraya and Kalimuthu (2010) quantitatively correlated the hydrogeological and geomorphological parameters with groundwater availability. Weathered rock thickness was the highest control on availability of groundwater followed by lineament density whereas drainage density was seen to minimum influence. A poor correlation was noticed between bore well depth and yield. The amplitude of seasonal variations in groundwater levels was noted to be higher in the low-lying plains compared to the hilly regions. The groundwater potential zone map, prepared using data merging techniques and assigning weightages based on the quantitative analyses of parameters on a GIS platform shows that more than 45% of bore wells falling in the area under the category of excellent water availability are high-yielding.

Mishra and Nagarajan (2010) analyzed morphometric characteristics of the watersheds of Tel river, covering an area of 1515.45 km^2 and lies between 19° 17′ and 20° 00′ N latitude and 82° 30′ and 82° 59′E longitude in Bhawanipatna area of Kalahandi district, Orissa. The entire study area was further divided into 12 sub watersheds named SWS1 to SWS12, ranging in geographical area from 30 km^2 to 202 km^2 and taken up for prioritization based on morphometric analysis using GIS and Remote Sensing techniques. The drainage density of sub watersheds varies between 1.09 to 3.36 km/km^2 and low drainage density values of sub watershed SWS11 indicates that it was highly resistant, impermeable subsoil material with dense vegetative cover and low relief. The elongation ratio varies from 0.6 - 0.8 which indicates high relief and steep ground slope. The high value of circulatory ratio for SWS11 sub watershed (0.8) indicates the late maturity stage of topography. This anomaly is due to diversity of slope, relief and structural conditions prevailing in this sub watershed. The compound parameter values were calculated and the sub watershed with the lowest compound parameter was given the highest priority. The sub watershed SWS1 was a minimum compound parameter value of 4 is likely to be subjected to maximum soil erosion and susceptible to natural hazards. Hence, it should be provided with immediate soil conservation measures.

Rao et al. (2010) adopted GIS and image processing techniques for the identification of morphological features and analyzing their properties of the Lower Gostani River Basin (LGRB) area in Andhra Pradesh state. The basin morphometric parameters such as linear and aerial aspects of the river basin were determined and computed. The area is occupied by 96% khondalite group (quartz-feldspar-garnetsillimanite-gneiss) of rocks. It was 7th order drainage basin and drainage pattern mainly in subdendritic to dendritic type. It was observed that the drainage density value is low which indicates the basin is highly permeable subsoil and thick vegetative cover. The circulatory ratio value reveals that the basin was strongly elongated and highly permeable homogenous geologic materials.

Sharma et al. (2010) carried out quantitative morphometric analysis and prioritization of eight sub watersheds of Uttala river sub-basin, which is a tributary of Son River, using GIS techniques. The morphometric parameters considered for analysis was stream order, stream length, stream frequency, drainage density, texture ratio, form factor, circulatory ratio, elongation ratio, bifurcation ratio and compactness ratio. After analysis of morphometric parameters, compound parameter values were calculated and prioritization rating of eight sub watersheds was carried out. The sub watershed 2 was lowest compound parameter value of 2.63 which receives the highest priority (one) with the next in the priority was sub watershed 1 and 4 having the compound parameter value of 3.88. Highest priority indicates the greater degree of erosion in the particular sub watershed and it becomes potential condition for applying soil conservation measures. Thus, soil conservation measures can first be applied to sub watershed 2 and then to other depending on their priority.

Walia and Mipun (2010) carried out quantitatively morphometric and drainage basin analysis of the Umshing River using Remote Sensing and GIS techniques. The results were presented concerning the hydrological behavior of Umshing River in order to define multi-scale geomorphometric landform types. The Umshing basin shows a sub-trellis drainage pattern indicating the litho-structural control on the drainage. Lithological, structural and geomorphological features control the directions of flow of the tributaries. It was observed and inferred that the Umshing river catchment was under the stage of creep or tilting and hence it is vulnerable to geohazard.

2.2 Groundwater Quality

Janardhana (2006) develop models relating well water chemical quality parameters to a set of independent chemical variables in post and pre-monsoon seasons in the upper Gunjanaeru River basin, Cuddapah district, Andhra Pradesh. The correlation between the specific electrical conductance (SEC) and other parameters except potassium (K^+) was significantly positive, whereas Ca^{2+} + Mg^{2+}/Na^+ + K^+ was significantly negative for both post and pre-monsoon seasons. In predicting SEC for both post and pre-monsoon, the independent variables, viz. HCO_3, SO_4 and Cl^- in the model had a significant effect (from‘t’ test for partial regression coefficient at the 5% level of probability). The multiple R^2 values 0.982 and 0.997 indicate that 98.2 and 99.7 per cent of variability in the observed SEC could be described to the combined effect of Na^+, Cl^-, Ca^{2+} $^+$ Mg^{2+}, HCO_3, and SO_4 for post and pre-monsoon seasons, respectively.

Aris et. al. (2007) studied hydrochemistry of groundwater in Manukan island, Sabah in Malaysia. Geochemical data on dissolved major consituents in groundwater samples from Manukan island reveal the main processes responsible for their geochemical evolution. The results of analysis showed that the groundwater was chemical highly enriched with Na^+ and Cl^- an indication of seawater intrusion into the aquifer as also suported from the Na-Cl signature on the Piper diagram.

Asadi et al. (2007) monitors the ground water quality using Remote Sensing and GIS techniques for a part of Hyderabad in Andhra Pradesh. Thematic maps for the study was prepared by visual interpretation of SOI toposheets and linearly enhanced fused data of IRS-ID PAN and LISS-III imagery on 1:50,000 scale using AutoCAD and ARC/INFO software. Physico-chemical analysis data of the groundwater samples collected at predetermined locations forms the attribute database for the study, based on which, spatial distribution maps of major water quality parameters were prepared using curve fitting method in Arc View GIS software. Water Quality Index (WQI) was then calculated to find the suitability of water for drinking purpose.

Dahiya et al. (2007) applied the fuzzy set theory for decision-making in the assessment of physico-chemical quality of groundwater for drinking purposes. Application of fuzzy rule based optimization model was illustrated with 42 groundwater samples collected from the 15 villages of Ateli block of southern Haryana, India. These samples were analysed for 16 different physico-chemical water quality parameters. Ten parameters were used for the quality assessment using this approach. The analysis showed that four samples were in “desirable” category with certainty level of 35–58%, 23 samples were in “acceptable” category whose certainty level ranged from 37 to 75% and remaining 15 samples were in “not acceptable” category for drinking purposes with certainty levels from 44 to 100%. The results of the study concludes that about 64% water sources were either in “desirable” or “acceptable” category for drinking purposes.

Vijith and Satheesh (2007) crried out Geographical Information System (GIS) based assessment of spatio-temporal behaviour of groundwater quality in upland sub-watersheds of Meenachil river, parts of Western Ghats, Kottayam, Kerala, India. Twenty-eight water samples were collected from different wells and analysed for major chemical constituents both in monsoon and post-monsoon seasons to determine the quality variation. Physical and chemical parameters of groundwater such as pH, dissolved oxygen (DO), total hardness (TH), chloride (Cl), nitrate (NO_3) and phosphate (PO_4) were determined. A surface map was prepared in the ArcGIS 8.3 (spatial analyst module) to assess the quality in terms of spatial variation, and it showed that the high and low regions of water quality varied spatially during the study period. The influence of lithology over the quality of groundwater is negligible in this region because majority of the area comes under single lithology, i.e. charnockite, and it was found that the extensive use of fertilizers and pesticides influenced the groundwater quality of the region. According to the overall assessment of the basin, all the parameters analysed were found below the desirable limits of WHO and Indian standards for drinking water. Hence, considering the pH, the groundwater in the study area were not found suitable for drinking but can be used for irrigation, industrial and domestic purposes. The spatial analysis of groundwater quality patterns of the study area shows seasonal fluctuations and these spatial patterns of physical and chemical constituents are useful in deciding water use strategies for various purposes.

Abdulmohsen Saleh Al-Amry (2008) curried out hydrogeochemical investigations for the assessment of water quality in Al-Salameh Area in the lower part of Wadi Meifaah within the arid climate zone of Yemen . The study area lies between latitudes 14º 12' 00" and 14º 21' 00" N and between longitudes 47º 26' 2.4" and 47º 40' 1.2" E and covers a total geographical area of about 414 km^2. The data on chemistry of the groundwater were used for the evaluation of quality of water for drinking and irrigation purposes. Comparisons of data with the water quality standards indicate that, out of 25 groundwater samples from Al-Salameh area, 17 samples were suitable for drinking purposes. The suitability of groundwater for irrigation use was evaluated by calculating SAR, Kelly's Ratio (KR), Residual sodium carbonate (RSC), Soluble Sodium Percentage (SSP) and Permeability Index (PI) and it was concluded that, the water from the study area can thus, be graded as good for irrigation use.

Kannel et al. (2008) studied to examined the spatial–temporal variations and factors influencing the management of groundwater along a section of the Bagmati river corridor in the Kathmandu valley (Nepal). The results showed that rural areas were less polluted than urban areas. In urban areas, the Biochemical Oxygen Demand (BOD), Total Nitrogen (TN) and Total Phosphorus (TP) concentrations ranged from 8.41 to 29.74 mg/L, 6.7 to 128.96 mg/L and 0.06 to 1.5 mg/L, respectively. In rural areas, the BOD, TN and TP concentrations ranged from 0.78 to 18.25 mg/L, 4.8 to 11.56 mg/L and 0.07 to 0.65 mg/L, respectively. The level of organics was higher in the pre-monsoon season, while the level of nutrients was higher in post-monsoon season.

Pritchard et al. (2008) conducted a study to determine the quality of water from shallow wells in three districts in southern Malawi namely, Balaka, Chikwawa and Zomba districts from 2006 to 2007. Water samples from 21 covered and five open shallow wells were analysed for chemical, microbiological and physical parameters using a portable water testing kit. Sampling was carried out at four different times of the year i.e. in August and October 2006 (dry season) and February and April 2007 (wet season). Microbiological data indicated that around 80% of the samples, obtained from the covered wells, failed to meet safe drinking water limits, set by World Health Organisation guidelines and Malawi Bureau of Standards, of zero total and faecal colony forming units (cfu)/100 ml. Values in excess of 1000 cfu/100 ml were noted in 10% of the samples, indicating gross contamination and the probability of pathogens being present. Contamination levels were higher during the wet season than the dry season in all three districts. Arsenic, ammonia, nitrate and sulphate were all within the acceptable limits. Elevated levels of hardness, turbidity were noted in certain wells.

Sadashivaiah et al. (2008) collected Water samples of 269 stations during pre-monsoon and 279 locations during post-monsoon of the year 2006 from Tumkur Taluka which is located in the southeastern corner of Karnataka state between 13º 06'30" to 13º 31' 00" North latitude and 76º 59' 00" to 77º 19' 00" East Longitude, and were subjected to analysis for chemical characteristics. The Taluka spreads over an area of 1043 km^2 falling within the semi-arid region and frequently facing water scarcity as well as quality problems. The type of water that predominates in the study area was Ca-Mg-HCO_3 type during both pre and post-monsoon seasons of the year 2006, based on hydro-chemical facies. Besides, suitability of water for irrigation was also evaluated based on sodium adsorption ratio, residual sodium carbonate, sodium percent, salinity hazard and USSL diagram.

Fadoua et. al. (2009) studied groundwater quality in South-East of Tunisia has special significance and needs great attention of all concerned since it was the major alternate source of domestic, industrial and drinking water supply. Major elements and Fluoride concentrations as well as temperature, pH and salinity, were monitored from 2005 in 14 wells capturing the Triassic aquifer. Water of the Triassic aquifer was used unevenly by different economic sectors. The saline load of these waters was in first place controlled by sulphate, chloride, sodium and calcium concentrations. The chemical composition interpretation clearly evidences two main geochemical facies Na-Ca-Mg-ClSO_4 and Na-Ca-Mg-Cl-SO_4. All analyzed samples were fluoride concentration above the upper limit proposed by the WHO for human consumption.

Najah et al. (2009) attempted to predict water quality parameters at Johor River Basin utilizing Artificial Neural Network (ANN) modeling. This study proposed a prediction model for total dissolved solids, electrical conductivity, and turbidity. The results show that the proposed ANN prediction model was a great potential to simulate and predict the total dissolved solids, electrical conductivity, and turbidity with absolute mean error of 10% for different water bodies.

Pradhan et. al. (2009) investigated on physicochemical parameters (temperature, pH, salinity, dissolved oxygen), including dissolved nutrients (PO4-P, NO3-N, NO2-N, SiO4-Si) were carried out in the water of the mouth of the Devi estuary in Orissa, during different months of the summer and winter seasons in 2006–07. The results indicated the addition of phosphates and silicates to the coastal water by the Devi estuary from natural sources during both the seasons. The anthropogenic nitrogenous species, as fallout from modernization activities in the north, was more clearly observed of the mouth of the Devi estuary during the winter season. The study indicated that the Devi estuary adds sufficiently well-oxygenated, nutrient-rich water to the coastal region.

Rahman et al. (2009) illustrated the statistical evaluation of the arsenic polluted groundwater to identify the correlation of that arsenic with other participating groundwater parameters so that the arsenic contamination level can easily be predicted by analyzing only those parameters. Multivariate data analysis carried out with the collected groundwater from the 67 tubewells of the contaminated aquifer suggests that arsenic may have substantial positive correlations with Fe, Mn, Al, HCO_3 and PO_4 whereas noticeable negative relationships were observed with SO_4, Cl and NO_3. Based on these relationships, a multiple linear regression model was developed that incorporates seven most influential groundwater parameters as the independent predictor variables to estimate the as contamination level in the polluted groundwater.

Alhumoud et al. (2010) examined the interrelationships between the TDS, electrical conductivity (EC), sodium (Na+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-) to trace out the groundwater quality trends of the Dammam Formation aquifer of Al-Sulaibiya field, Kuwait during the period 1991–2005. Al-Sulaibiya field is the oldest and the largest groundwater well field producing brackish groundwater from the Dammam Formation aquifer. Total dissolved solids (TDS) values of the Dammam Formation aquifer of Al-Sulaibiya field are very high and found in the range of 3523–9460 mg/l.The study revealed that, the variable most strongly correlated with TDS was electrical conductivity (EC).

Bu et al. (2010) applied cluster analysis, discriminant analysis, and factor analysis techniques to analyze the physical and chemical variables in order to evaluate water quality of the Jinshui River, a water source area for an interbasin water transfer project of China. Cluster analysis classifies 12 sampling sites with 22 variables into three clusters reflecting the geo-setting and different pollution levels. Discriminant analysis confirms the three clusters with nine discriminant variables including water temperature, total dissolved solids, dissolved oxygen, pH, ammoniacal nitrogen, nitrate nitrogen, turbidity, bicarbonate, and potassium. Factor analysis extracts five varifactors explaining 90.01per cent of the total variance and representing chemical component, oxide-related process, natural weathering and decomposition processes, nutrient process, and physical processes, respectively. The study demonstrates the capacity of multivariate statistical techniques for water quality assessment and pollution factors/sources identification for sustainable watershed management.

Chatterjee et al. (2010) worked on the groundwater quality assessment of Dhanbad district, Jharkhand, India. Groundwater quality assessment is important to ensure sustainable safe use of water. The overall water quality in the Dhanbad coal mining area of India is difficult due to the spatial variability of multiple contaminants and wide range of indicators that could be measured. An attempt was made to study the spatial variation of groundwater quality based on an integrated analysis of physico-chemical parameters and use of Geographic Information System. Using GIS contouring methods spatial distribution maps of Hardness, pH, TDS, HCO_3, SO_4, NO_3, Ca, Mg, Cl, and F were created.

Gabrial and Donatus (2010) studied physicochemical parameters related to groundwater quality obtained from Yola area of Northeastern Nigeria. They developed linear regression equations to predict the concentration of water quality having significant correlation coefficients with electrical conductivity (EC). The TDS and EC have perfect correlation coefficients whereas Na and Cl, are highly correlated in all the water sources. Furthermore, while Ca and HCO_3 are highly correlated in both the shallow and deep groundwater it has relatively lower correlation coefficients in the surface water samples. It was equally observed that Mg, Ca, NO_3, Cl and Fe are highly correlated with EC in surface water samples. The data also indicated that apart from surface water bodies Ca, NO_3, Cl and HCO_3 are poorly related with electrical conductivity at 5 per cet level of significance.

Machiwal et al. (2010) focused on a GIS-based assessment and characterization of groundwater quality in a semi-arid hard-rock terrain of Rajasthan, western India using long-term and multi-site post-monsoon groundwater quality data. Spatio-temporal variations of water quality parameters in the study area were analyzed by GIS techniques. GIS analysis revealed that sulfate and nitrate ions exhibit the highest (CV>30%) temporal variation, but groundwater pH is stable. Hardness, EC, TDS, and magnesium govern the spatial pattern of the GWQI map. The groundwater quality of the study area is generally suitable for drinking and irrigation (median GWQI >74).

Ramkumar et al. (2010) attempted to determine the groundwater quality in parts of Vedaraniyam region, Tamilnadu. Totally, eighty groundwater samples were collected from open dug wells, covering three seasons (Post-monsoon, summer and pre-monsoon seasons) and analyzed for physicochemical parameters (pH, EC, TDS, TH, Na, K, Ca, Mg and Cl, SO_4, HCO_3, NO_3) in order to understand the hydro geochemistry of the water. The results of analysis were interpreted with geology and geomorphology of the area and by various geochemical diagrams such as Piper trilinear plot and USSL classification diagram. Suitability of this water for its utility was verified using Indian standards. The results of the study indicates that only one well was suitable for drinking purpose and remaining others were suitable for domestic and irrigation purpose. Further, the results indicates that most of the well water falls in Na-Cl type indicating the influence of seawater in these wells, which is confirmed by Piper plot.

Tank and Chandel (2010) studied the hydrochemistry of groundwater in Jaipur city to assess the quality of groundwater for determining its suitability for drinking and agricultural purposes. Groundwater samples were collected from eleven stations of Jaipur city during monsoon season and were analyzed for physico-chemical parameters such as pH, EC, TDS, sodium, potassium, calcium, magnesium, chloride, sulphate, carbonate, bicarbonate, nitrate and fluoride. Comparison of the concentration of the chemical constituents with WHO drinking water standards of 1983, the status of groundwater is better for drinking purposes. Results indicates that nitrate concentrations are in an alarming situation with respect to the use of groundwater for drinking purposes. The calculated values of SAR, RSC and percentage sodium indicate that the water is excellent for irrigation. US Salinity diagram was used for evaluating the water quality for irrigation which suggests that the majority of the groundwater samples were good for irrigation

Patil and Patil (2011) studied the groundwater samples (Three open wells, three tube wells) collected from six different locations around Amalner town and analyzed during November 2007-February 2008. Fifteen physicochemical parameters were analyzed and the results were compared with water quality standards prescribed by WHO and ISI 10500-91. The study revealed that two water samples (one open well, one tube well) showed high EC, TDS, TA, TH values indicating poor water quality. The correlation coefficients were also calculated.

2.3 Pumping Test Data Analysis

Papadopulos and Cooper (1967) presented a solution for the drawdown in a large- diameter well discharge at a constant rate from a homogeneous isotropic fully penetrating artesian aquifer which also took into consideration the water derived from storage within the well. A set of type-curves computed from this solution permits determination of transmissivity of an aquifer by analysis of drawdown observed in the pumped well.

Summel (1974) reviewed various methods for analyzing aquifer test data from large-diameter wells in hard-rocks of India and discussed them critically with various problems encountered during such tests. He recommended low pumping rates for avoiding the development of seepage face and to external pumping duration by recirculation of water into the large-diameter well. It was suggested that the dug-cum-bore wells should be tested as step test, i.e., pumping at a rate which will lower the water levels into the boreholes and continue pumping at the same rate while measuring draw-downs in all the bores until the sufficient data would be made available for the analysis. He also discussed the applicability of the Papadopulos and Cooper (1967) method to large-diameter wells in hard-rocks.

Rushton and Holt (1981) analyzed the response of large-diameter wells by curve-matching technique based on analytical solutions and numerical model. For an ideal situation the methods yielded the similar results. However, in case of unconfined aquifer where decrease in saturated depth is significant, the curve-matching technique was unreliable. In a confined aquifer with the diameter of the dug portion of the well being much larger than the diameter of the hole bored through the confined stratum, the response was found to be particularly sensitive to the ratio of these diameters. In unconfined aquifer test, an important feature was the reduction in abstraction rate as the well was pumped.

Sharma (1983) conducted six pumping tests in large-diameter wells in hard-rocks. It was found that water withdraws from aquifer as well as from storage was about 43.0 and 70.0 per cent respectively. Lower values of transmissivity (within 20 to 30 per cent variation) were obtained in the analysis of recovery test data when aquifer inflow rate was chooses. The transmissivity values were more erratic when actual pumping rate was considered.

Wikramaratana (1985) modified the Papadopulos and Cooper (1967) method and proposed new type-curves for the analysis of pumping tests in large-diameter wells in a confined aquifer. The effect of well storage was taken into account. The method eliminates the possible spurious match point by an introduction of the match lines. A convenient check was provided on the correct choice of match line by the existence of two transmisssivity values. It was reported that the two values of transmissivity estimated by Theis method should be within 1.0 per cent variation and two estimates of storage coefficient agreed within 0.5 per cent variation.

Jat (1990) observed pumping test to study the hydraulic characteristics of aquifer in an open well at Hawala and Amberi village in Badgaon panchayat samiti of

Udaipur district, Rajasthan. He analyzed the pumping test data by using Theis and Jacob's method and found that transmissivity and storage coefficient ranged as 8.13 to 570.69 m^2/day and 5.005×10^{-4} to 9.07×10^{-2} respectively.

Sathyamoorthy et al. (1992) reported that the groundwater quantification and modeling require the evaluation of aquifer parameters. Pumping test is one of the most useful means of not only evaluating aquifer characteristics but also in the determination of yield and drawdown, specific capacity and design of wells. The aquifer transmissivity (T), storage coefficient, specific capacities, optimum yield and time for full recovery of dug wells have been evaluated.

Raghunath and Singh (1999) evaluated for an aquifer parameter for Nethuravathi River Basin of Karnataka State using drawdown and recovery data of 16 dug wells. The minimum and maximum values of the aquifer transmissivity, storage coefficient, specific capacity, optimum yield and time of full recovery were found within the range of (6.12-331.22) m^2/day, (0.06-0.32), (17.14-1671.9) lpm, (2.3-60.3) m^3/day, (0.9-147.9) hrs, respectively.

Singh and Gupta (2003) presented a numerical method for the interpretation of pump test data for a large-diameter well situated near such a boundary as a river, a lake or a dyke which commonly occur in hard rock terrains. The technique considers the time-drawdown data for the pumping as well as for the recovery phase. A field example were presented to illustrate the use of the technique. The computer code for numerical modeling was given in BASIC language, which can easily be implemented on a portable microcomputer for the estimation of aquifer parameters in the field.

Verma (2005) estimated aquifer properties by conducting pumping test in hard rock area of Udaipur, Rajasthan. The data collected during pumping test in different hydrogeological formations were analyzed by various methods viz, Papadopulos & Cooper, modified Papadopulos & Cooper, Boulton & Streltsova and Cooper & Jacob for estimating transmissivity and specific yield. The values of transmissivity ranged from 56.5 to 101.73 m^2/day and specific yield from 0.000503 to 0.00360.

Rushton and Holt (2006) carried out study on two alternative methods of analyzing the response of large-diameter wells. The curve matching technique based on analytical solutions and the use of a numerical model. For ideal situations the methods give the same results but for unconfined aquifers where the decrease in saturated depth is significant, the curve matching technique is unreliable. In a confined aquifer, where the diameter of the dug portion of the well was much larger than the diameter of the hole bored through the confined stratum, the response was found to be particularly sensitive to the ratio of these diameters. In an unconfined aquifer test, the important feature was the reduction in abstraction rate as the well get emptied.

Soupios et al. (2007) conducted study on combined use of geophysical method with puming test for the estimation of aquifer parameters. Knowledge of aquifer parameters is essential for the management of groundwater resources. Conventionally, these parameters were estimated through pumping tests carried out on water wells. Few boreholes may be available but conducting pumping tests at a number of sites may be costly and time consuming. The application of geophysical methods in combination with pumping tests provides a cost-effective and efficient alternative to estimate aquifer parameters. A geophysical method was used to obtain aquifer characteristics that are estimated through the pumping tests. A correlation was established between these parameters at other sites where pumping was not carried out. In this way, the entire investigation area could be covered to characterize an aquifer system. This study was carried out in the Keritis basin in Chania, where the aquifer characteristics were required for the management of groundwater in the region.

Mjemah et al. (2009) conducted study on determination of aquifer parameters by using pumping test for the evaluation of groundwater potential. The pumping tests in the study area were conducted in August 2004 and August 2005 and 39 selected boreholes were tested out of 400 listed boreholes. Total groundwater exploitation in the study area was estimated at 8.59×10^6 m^3/year, based on yield data collected during the 2004–2005 field campaigns. The pumping test analysis methods used include: Neuman type curve matching and Walton type curve matching, checked by specific well capacity assessment and Thiem–Dupuit/Thiem's method. The curve-matching results from the aquifer tests shows an average transmissivity and hydraulic conductivity of 34 m^2/day and1.58 m/day, respectively.

Nishtha (2009) conducted a pumping test in 19 selected wells of Ahar river basin and estimated transmissivity and specific yield by papadopulos & cooper method using curve matching technique. The results of the study revealed that the value of transmissivity ranging between 76-2239 m^2/day whereas the value of specific yield was found in the range of 0.0000051-0.211, which shows the large variations in the aquifer parameters of hard rock areas.

2.4 Groundwater Potential Zoning

Agarwal and Mishra (1992) attempted to delineate different hydrogeomorphological units in and around the immediate environs of Jhansi city with a view to attempt a correlation between the well yields and hydrogeomorphic units using satellite remote sensing technique. In general, a positive correlation is observed between the geomorphic units and the borewell yields with overlapping yields at the margin. The pediment residual hill complex is observed to provide wells with discharges ranging from 100 gallons per hour (gph) to 5000 gph, while the wells drilled in shallow weathered, buried pediplain has yields in the range of 2000 to 10000 gph. Moderately weathered, buried pediplain has discharges in the range of 8000 to 12000 gph, and deeply weathered, buried pediplain has discharges in excess of 12000 gph.

Krishnamurthy et al. (1996) demarcate the ground water potential zones of Marudaiyar basin. The different thematic maps such as, lithology, landforms, lineaments and surface water bodies at a 1: 50000 scale were prepared, using remotely-sensed data as well as drainage density and slope classes from Survey of India topographical sheets. In addition, a soil map at 1:50000 scale covering the study area was generated from a 1:250000 scale soil map prepared by the Soil Survey and Landuse Organization by regrouping the soil types based on their hydrological characteristics. All the thematic layers were integrated and analysed using a model developed with logical conditions in the Geographical Information System. The ground water potential zones map generated through this model was verified with the yield data to ascertain the validity of the model developed.

Ravindran and Jeyaram (1997) carried out hydrogeomorphological mapping using IRS-IB LISS II data and evaluated groundwater prospects of each hydrogeomorphologic unit on the basis of lithology, structure, landfrom and available aquifer data in the Shahbad tehsil, Baran district, Eastern Rajasthan. The study revealed that in the western parts of the area the Vindhyan sandstones is dominating in which groundwater occurs under unconfined to confined conditions along bedding planes and fracture zones have vast potential for groundwater development through deep bore-wells or dng-cum-barewells, while in the eastern parts where shales dominate, large diameter dug wells are suitable to tap the limited groundwater resources. Infiltration (or recharge) tube wells have been proposed to augment the sandstone aquifers.

Krishnamurthy et al. (2000) studied to demonstrate the capabilities of remote sensing and Geographic Information System (GIS) techniques for groundwater resources development in hard rock terrains, specifically for the demarcation of suitable sites for artificial recharge of groundwater aquifers in the Kallar Basin, which is located in parts of the Salem and Tiruchirapalli districts, Tamil Nadu, India. Thematic maps defining lithology, lineaments, landforms, landuse, drainage density, thickness of weathered zone, thickness of fractured zone, hydrological soils, and well yield were prepared from data collected by the Indian Remote Sensing Satellite (IRS) -1C and by conventional methods. All the thematic layers were integrated using a GIS-based model developed specifically for this purpose, enabling a map showing artificial recharge zones to be generated. The exact type of artificial recharge structure, eg, check dam, nallabund, gully plugging and percolation pond, suitable for replenishing groundwater was identified by superposing a drainage network map over an artificial recharge zones map.

Srivastava and Bhattacharya (2000) delineated various groundwater potential zones for the assessment of groundwater availability in a hard rock terrain with the help of hydrogeological parameters using satellite IRS- 1B-LISS-II digital data. Area selected for the study is a part of Bargarh district, Orissa, India covering an area of about 680 km^2. Satellite data was used to prepare geological-cum-lineaments, geomorphological, landuse and drainage maps. The various thematic maps were integrated with the help of Geographic Information System to demarcate the poor to excellent groundwater potential zones. Weightage was given to various groundwater controlling factors to the total groundwater potential in each segment of study area. Subsequently, several sites were selected to conduct the pumping tests in the area. The results show that among others, lineaments as well as drainage density are the most important contributory factors in the groundwater potential of various geomorphic units in the area of investigation.

Rao et al. (2001) investigated to identify groundwater favourable zones for development and exploration with the help of geomorphological units and associated features. The identified units and features by remote sensing technology with the integration of conventional information and limited ground truths are shallow weathered pediplain (PPS), moderately weathered pediplain (PPM), deeply weathered pediplain (PPD), residual hill (RH) and lineaments (L). The results show that the PPD, PPM and PPS are good, moderate to good and poor to moderate promising zones, respectively for groundwater prospecting. The RH is a poor geomorphological unit in respect to prospective zone as groundwater resource. However, adequate recharge source of groundwater can be expected surrounding the RH, as it acts as surface run-off zone. Lineaments parallel to the stream courses and intersecting-lineaments are favourable indicators for groundwater development. They can also be utilized to augment groundwater resource.

Sankar (2002) investigated to evaluate the potential zones for groundwater targeting of upper Vaigai river basin covering parts of Madurai and Theni Districts, in Tamil Nadu using IRS - ID LISS III geocoded data on 1:50,000 scale. The geology, geomorphology, lineament tectonic maps were generated and integrated to evaluate the hydrogeomorphological characteristics of the upper Vaigai river basin and demarcate the groundwater potential zones. A number of geomorphic units have been observed. Out of this, the more groundwater prospective units are buried pediment medium, buried pediment deep, flood plain, bajada and lineament and intersection of lineaments. Non-potential areas like pediment, pediment inselberg, shallow pediment and pediplain were identified.

Jaiswal et al. (2003) extracted information on lithology, geological structures, landforms, land use/land cover from remotely sensed data and drainage networks, soil characteristics and slope of the terrain using conventional methods and then integrated it in Geographical Information System environment to depict village-wise groundwater prospect zones. Thus, a GIS-based model which takes account of local condition/variations was developed specifically for mapping groundwater prospects. A pilot study was carried out for the Gorna sub-basin, a part of the Son watershed, Madhya Pradesh, India. Information from this study were used for effective identification of suitable locations for extraction of potable water for rural populations.

Jothi Prakash et al. (2003) delineated potential zones for artificial recharge in Agniar-Ambuliar- Southvellar river basins in Tamilnadu, India through integration of various thematic maps using Arc view GIS. The study area covers an area of 4566 km^2. Thematic maps pertaining to geology, permeability, effective soil depth, drainage intensity, soil texture, water holding capacity and physiography were prepared on 1: 50,000 scale using conventional methods. These maps were scanned and registered with reference to a base map and are prepared as separate layers or coverages using Arc view. GIS was used for the integration of various thematic maps to delineate the potential zones for artificial recharge. Each theme was assigned a weightage depending on its influence on groundwater recharge. Each class or unit in the map was assigned a knowledge based ranking from one to four depending on its significance in storage and transmittance of groundwater. The final map has been prepared showing four different categories of potential zones for artificial recharge.

Rao and Jugran (2003) studied the development and management of water resources based on advanced applications of remote sensing and geographical information systems for studying Chittoor area, comprised of a hard rock terrain, located in the drought-prone Rayalaseema region of Andhra Pradesh, India. Using remote sensing and GIS technology, groundwater potential zones, along with zones of water quality suitable for domestic purposes, were delineated and classified. Results indicated that, for the town of Chittoor, 1.64 per cent of the area was classified to have very high groundwater potential, with groundwater quality suitable or moderately suitable for domestic purposes; and 31.68 per cent of the area was classified as high potential, with over 31 per cent being suitable or moderately suitable. Most (62.05 per cent) of the area is of moderate groundwater potential, with groundwater quality mostly suitable or moderately suitable for domestic purposes.

Gopinath and Seralathan (2004) investigated the role of hydrogeomorphological units and lineaments in the storage of groundwater from the Muvattupuzha river basin using IRS ID LISS III data. Other than the usual water bodies such as river course, reservoirs and ponds, the major hydrogeomorphological units identified in this basin in the descending order of their groundwater potential were valley fills, moderately dissected plateau, pediments, residual mounts, residual mount complex, linear ridges, residual hills and structural hills. Majority of the lineaments trends in NW-SE and WNW-ESE directions. Even though the eastern part of the basin is characterized by moderate to high lineament density, the above area is found to be poor to moderate groundwater prospect zone because of high gradient and structural hills. The pump test analyses of dug wells from different hydrogeomorphic units also confirm that valley fills are the most promising unit for groundwater prospecting than the rest.

Rai et al. (2005) studied to evaluate the groundwater prospective zones in Jharia and Raniganj coalfields, Dhanbad district, Jharkhand. Landsat-5 Multi Spectral Scanner (MSS) data of band 2 and band 4 and false colour composite (FCC) of band 2, 3, 4 were interpreted visually to differentiate different hydromorphogeological units and to delineate the major trends of lineaments. The different geomorphic features identified are linear ridges, residual hills and pediplain, buried pediment and dissected pediplain, besides lineaments. The study shows that the pediplain and buried pediments are promising zones for groundwater prospecting. The occurrence and movement of groundwater is restricted to the unconsolidated material, weathered and fractured rocks. For the selection of tube well sites, geoelectrical resistivity investigations were carried out at the sites, which were found suitable based on hydrogeomorphological and hydrogeological studies. Twenty-six Vertical Electrical Soundings (VES) were carried out by using Schlumberger electrode configuration, which have brought out 3 to 7 layered sub-surface layers. The resistivity of water-bearing weathered/fractured rocks varies from 120–150 ohm m. The integrated studies revealed that the blue colour zones are most promising for groundwater exploration and dug wells may be dug up to depths of 30 ± 5 m.

Khan et al. (2006) prepared a ground water prospect map for a part of Jodhpur district in western Rajasthan through integrated analysis of four major controlling factors: geology, geomorphology, structure and hydrology. Through visual interpretation of satellite data and using Geographical Information System, twenty-five hydro-geomorphic units were delineated and mapped. Potential of each prospect unit have been discussed in reference to hydro-geomorphic units, their influence and well inventory like well yield, water table and quality of drinking water. The study revealed that 34 per cent of the area was classified to have high groundwater potential and 5.8 per cent area was classified into low potential categories. Most of the area (60.2 per cent) is of moderate ground water potential.

Ravi Shankar and Mohan (2006) evaluated groundwater potential and quality for designing suitable water management plans in the Bhatsa and Kalu river basins in the Thane district in the western Deccan volcanic province of India. A Geographical Information System platform is used to integrate and spatially analyse multiparametric data comprised of satellite, topographical, geological and hydrogeological information to generate several thematic maps, including groundwater potential zone map. The study reveals that 70 per cent of the area has medium to low groundwater potential, while only 10 per cent has high potential. The static and dynamic groundwater potentials were estimated to be 10.7 and 4.8 per cent of the annual rainfall. The groundwater quality in terms of hardness, total dissolved solids, salinity and chloride is suitable for domestic and irrigational purposes. A database was developed for sustainable water management program for the region and areas where suitable water conservation techniques need to be adopted were also identified.

Trivedi et al. (2006) studied to identification of geoenvironmental aspects on the Rajghat dam project situated in Lalitpur district of Uttar Pradesh, India, using the remote sensing techniques. In this IRS IA LISS II data was used. The various thematic maps were generated and integrated on 1:50,000 scale. Geology, geomorphology, Hydro-geomorphology, structure, soils and erosion, landuse / landcover helped in identification of the potential zones for developmental planning and forecasting limitations to their implementation with seasonal accuracy. Lineaments and their intersections appear to be potential sites for groundwater. Betwa drainage basin is suitable for surface reserviour and check dams. The study shows that the integration of all attributes provides more accurate results in identification of geoenvironmental characteristics.

Kumar et al. (2007) carried out integrated hydrogeological investigation to delineate the groundwater-potential zones of the Muvattupuzha river basin, Kerala, along the southwest coast of India. The integration of conventional and remote sensing data was made through Geographic Information System and it was found that about 50 per cent of the area could be identified as very good or good potential zones, whereas the remaining area falls under moderate and poor categories. Most of the Muvattupuzha sub-basin and the western part of the Kothamangalam and Kaliyar sub-basins were classified as good groundwater-potential zones, although the eastern upstream part of the basin has poor groundwater potential.

Dhakate et al. (2008) study a fast, cost effective and economical way of exploration of groundwater particularly in hard rock terrain and analyze remote sensing data. Interpreted remote sensing data was used to select sites for carrying out surface geophysical investigations. Various geomorphologic units were demarcated and the lineaments were identified by interpretation of remote sensing satellite images. The potential for occurrence of groundwater in the watershed areas was classified as very good, good, moderate and poor by interpreting the images. Sub-surface geophysical investigations, namely vertical electrical soundings, were carried out to delineate potential water-bearing zones. Integrated studies of interpretation of geomorphologic and geophysical data to prepare a groundwater potential map. The studies reveals that the groundwater potential of shallow aquifers is due to geomorphologic features and the potential of deeper aquifers is determined by lineaments such as faults and joints.

Kumar et al. (2008) identified potential sites for construction of rainwater harvesting structures in the Bakhar watershed of Mirzapur District, Uttar Pradesh, India by using remote sensing and GIS techniques. Various thematic maps such as Landuse/Landcover, geomorphology and lineaments, etc. were prepared using remote sensing. These layers along with geology and drainage were integrated using GIS techniques to derive suitable water harvesting sites. Each theme was assigned a weightage depending on its influence on ground water recharge (for example weightages 20,18,15,25,25 and 0 were assigned to geomorphology, landuse, geology, lineament, drainage and road and villages respectively). Each class or unit in the map was assigned a knowledge based ranking of one to four depending on its significance in storage and transmittance of groundwater, and these values were multiplied with layer weightage to form score. The average score for excellent region is greater than 200, for good 121 to 200, for moderate 81 to 121 and the other polygon having value less than 80 (excluding zero) were assigned to poor category. The final map showing different categories of suitable sites of water harvesting structures such as check dams, contour bunding, recharge pits, wells and contour trenching have been suggested.

Prasad et al. (2008) used Remote Sensing and Geographical Information System (GIS) techniques to delineate groundwater potential zones in hard rock terrain. The remotely sensed data at the scale of 1:50,000 and topographical information from available maps, were used for the preparation of ground water prospective map by integrating geology, geomorphology, slope, drainage-density and lineaments map of the study area. Further, the data on yield of aquifer, as observed from existing bore wells in the area, was used to validate the groundwater potential map. The result depicts the favorable prospective zones in the study area which is quite helpful in better planning and management of groundwater resources especially in hard rock terrains.

Chowdary et al. (2009) generated a specific watershed development plans for Mayurakshi watershed, India using remote sensing and GIS techniques. Adopting Integrated Mission for Sustainable Development (IMSD) guidelines, decision rules were framed. Using the overlay and decision tree concepts water resource development plan was generated. Indian Remote Sensing Satellite (IRS-1C), Linear Imaging Self Scanner (LISS-III) satellite data along with other field data on lithology, soil, slope, well inventory, fracture have been utilized for generating land use/land cover and hydro geomorphology of the study area, which are an essential prerequisites for water resources planning and development. Spatial data integration and analyses was carried out in GIS environment.

Ganapuram et al. (2009) used Remote Sensing data and Geographic Information System to locate potential zones for groundwater in the Musi basin. Various maps (i.e., base, hydrogeomorphological, geological, structural, drainage, slope, land use/land cover and groundwater prospect zones) were prepared using the remote sensing data along with the existing maps. The groundwater availability of the basin is qualitatively classified into different classes (i.e., very good, good, moderate, poor and nil) based on its hydrogeomorphological conditions. The land use/land cover map was prepared for the Kharif season using a digital classification technique with the limited ground truth for mapping irrigated areas in the Musi basin. The alluvial plain in filled valley, flood plain and deeply buried pediplain were successfully delineated and shown as the prospective zones of groundwater.

Nishtha (2009) used Geographical Information System (GIS) to integrate multiparametric data to generate several thematic maps, delineate groundwater potential zones and identify sites of Artificial Recharge in the Ahar River Basin, Rajasthan, India. The thematic layers considered to delineate groundwater potential zones are Geomorphology, recharge, Depth to groundwater level, Soil, Slope, Topographic Elevation and Transmissivity, which were prepared using conventional maps and data. All these themes and their individual features were then assigned weights according to their relative importance in groundwater occurrence and the corresponding normalized weights were obtained based on the Saaty's analytical hierarchy process. The thematic layers were finally added using ILWIS software to yield groundwater potential zone map of the study area. Thus, three different groundwater potential zones were indetified viz., 'good', 'moderate' and 'poor'. The area having 'good' groundwater potential is about 152.6 km^2 which is about 44 per cent of the total study area. The southern and southwestern portion of the study area falls under moderate groundwater potential zone. It encompasses an area of 102 km^2 which is 29.5 per cent of the total area. However, the groundwater potential along the boundaries of the study area is poor. It covers an area of 93.3 km^2, which is 26.8 per cent of the total area. The thematic layers used in this study to determine artificial recharge zones are Transmissivity, Recharge, Groundwater level (post-monsoon), Topographic elevation, Soil and Slope. These layers were combined using Boolean Logic analysis to delineate zones of suitability for artificial recharge structures. The area suitable for artificial recharge is 44.6 km^2, which is 12.7 per cent of the total study area.

Saha et al. (2009) studied for demarcating groundwater development potential zone of the Gangetic Alluvial Plain covering 2,228 km^2 in the state of Bihar. The area is mainly agrarian and experiencing intensive groundwater draft to the tune of 0.12 million cubic metre per square kilometres per year from the Quaternary marginal alluvial deposits, unconformably overlain northerly sloping Precambrian bedrock. Multiparametric data on groundwater comprising water level, hydraulic gradient (pre- and post-monsoon), aquifer thickness, permeability, suitability of groundwater for drinking and irrigation and groundwater resources vs. draft were spatially analysed and integrated on a Geographical Information System platform to generate thematic layers. By integrating these layers, three zones were delineated based on groundwater development potential. It is inferred that about 48 per cent of the area covering northern part has high development potential, while medium and low development potential category covers 41 per cent of the area. Further increase in groundwater extraction is not recommended for an area of 173 km^2, affected by over-exploitation.

Dar et al. (2010) studied the groundwater conditions in Mamundiyar basin, Tamilnadu through remote sensing, evaluation of digital elevation models (DEM), geographic information systems (GIS) and fieldwork techniques. Several digital image processing techniques, including standard color composites, intensity-hue-saturation (IHS) transformation and decorrelation stretch (DS) were applied to map rock types. Remote sensing data were interpreted to produce lithological and lineament maps. DEM was used for lineament and geomorphologic mapping. All thematic layers were integrated and analyzed in a GIS. The overall results demonstrate that the use of remote sensing and GIS provide potentially powerful tools to study groundwater resources and design a suitable exploration plan.

Singhal et al. (2010) attempted to delineate aquifers in the piedmont zone of Himalayan foothill region in Pathri Rao watershed, district Haridwar, Uttarakhand, India by using integrated hydrogeologic and geophysical techniques. The geophysical techniques included vertical resistivity soundings, two-dimensional resistivity image profiling and electromagnetic surveys. Nuclear isotope studies have been carried out to estimate groundwater recharge and its relative age. An assessment of groundwater availability and stage of groundwater development has also been made from the available and generated field data. On the basis of the study, it was found that the rate of recharge into the aquifers is of the order of 19 per cent and the stage of groundwater development in the watershed is 164 per cent indicating critical over-exploitation of groundwater. Based on the findings, possibilities of artificial recharge of groundwater have been looked into in the study area for augmentation of groundwater resources by proposing a few check dams at the suitable sites in the upstream areas of the watershed.

Machiwal et al. (2011) delineated groundwater potential zones using integrated RS, GIS and multi-criteria decision making (MCDM) techniques for Udaipur district of Rajasthan, western India. Initially, ten thematic layers, viz., topographic elevation, land slope, geomorphology, geology, soil, pre- and post-monsoon groundwater depths, annual net recharge, annual rainfall, and proximity to surface water bodies were considered in the study. These thematic layers were scrutinized by principal component analysis technique to select influential layers for groundwater prospecting. Selected seven thematic layers and their features were assigned suitable weights on the Saaty's scale according to their relative importance in groundwater occurrence. The assigned weights of the thematic layers and their features were then normalized by using AHP (analytic hierarchy process) MCDM technique and eigenvector method. Finally, the selected thematic maps were integrated by weighted linear combination method in a GIS environment to generate a groundwater potential map. Thus, four groundwater potential zones were identified and demarcated in the study area, viz., 'good', 'moderate', 'poor' and 'very poor' based on groundwater potential index values. The area falling in the 'good' zone was about 2,113 km^2 (17 per cent of the total study area), which encompasses major portions of Sarada, Salumber, Girwa, Dhariawad, and Mavli blocks of the study area. The northeast and southwest portions along with some scattered patches was fall in the 'moderate' zone, which encompasses an area of 3,710 km^2 (about 29 per cent of the total area). The 'poor' zone was dominant in the study area which covers an area of 4,599 km^2 (36 per cent of the total area). The western portion and parts of eastern and southeast portions of the study area were characterized as 'very poor' groundwater potential, and this zone covers an area of 2,273 km^2 (18 per cent of the total area).

III - MATERIAL AND METHODS

This chapter encompasses the methodology adopted in achieving the set of objectives in light of the basic ground data, the location of the study area and its characteristics features and other relevant component of the study. The determination of aquifer parameters by pumping test, estimation of groundwater recharge, assessment of groundwater quality and procedures for delineating groundwater potential zones using Remote Sensing and GIS technique are also described in this chapter.

3.1 Description of Study Area

3.1.1 Location

Wakal river is one of the tributaries of Sabaramati river basin. It is a rainfed river basin lies on the west coast of India between 24° 46' 34.65" N to 24° 8' 49.41" N latitudes and 73° 6' 23.41" E to 73° 35' 54.18" E longitudes and spread across the states of Rajasthan and Gujarat. The entire Wakal river basin is falling in 5 tehsils i.e. Gogunda, Girwa, Jhadol, Kotra tehsil of Udaipur district of Rajasthan and Khedbrahma tehsil of Sabarakanta district of Gujarat. The 98 per cent area of total basin falls in the Udaipur district of Rajasthan. The study area falls in Survey of India (SOI) toposheets of 45H/2, 45H/3, 45H/4, 45H/5, 45H/6, 45H/7, 45H/8, 45H/10 and 45H/11. The location map of the Wakal river basin is shown in Fig.3.1.

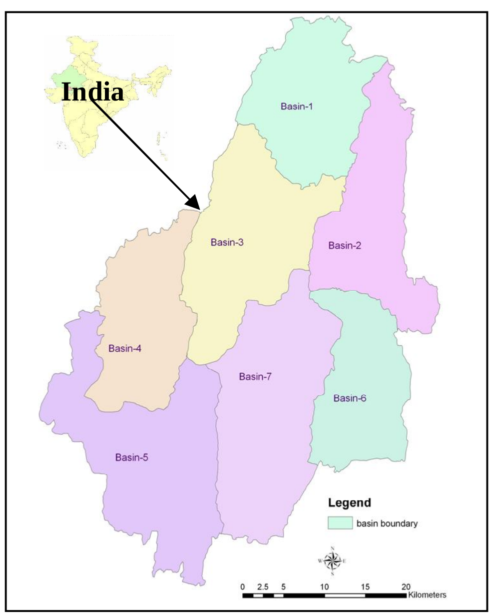


Fig. 3.1 Location map of Wakal river basin

3.1.2 Geographical area

Total geographical area of Wakal basin drain is 1914.322 Km^2, of which 1867.478 Km^2 lies in the state of Rajasthan and 46.844 Km^2 in Gujarat. In Rajasthan state, the basin completely falls under Udaipur district though it occupies only 13.1 per cent of total area of the district. The distribution of total area of Wakal river basin in different tehsils are highlights in Table 3.1.

Table 3.1 Distribution of basin areas in different tehsils

Tehsil	Area (Sq. Km)		%
	Total	Wakal	
Gogunda	907.73	268.733	29.6
Girwa	1887.46	48.415	2.56
Jhadol	1441.00	715.401	49.64
Kotra	2422.37	834.929	34.47
Khedbrahma	1111.70	46.844	4.21

The geographical spread of Wakal basin is mainly in Udaipur district of Rajasthan. The 98 per cent area of the basin is coming under Udaipur district of Rajasthan, where as the remaining 2 per cent area is in Sabarkanta district of Gujarat state. Major part of the Wakal basin (81 %) falls under Kotra and Jhadol tehsil of Udaipur district.

3.1.3 Drainage pattern

Wakal river originates northwest of Udaipur district near Sran village in Gogunda tehsil of Udaipur districts. On the way of its draining to Sabarmati river, tributaries like Mansi and Pamri rivers joins wakal river. The maximum length of the basin is 71.22 km (N-S) and the maximum width is 41.01 km (E-W). Mansi is the main tributaries of Wakal river which merge into Wakal near Birothi village of Jhadol tehsil. Wakal river drains out to Sabaramati near Delwada village in Khedbrahma tehsil of Sabarkanta district of Gujarat.

3.1.4 Climate

The Indian Meteorological Department has divided Rajasthan into two meteorological sub divisions i.e. West Rajasthan and East Rajasthan, with the Wakal basin falling within the East Rajasthan sub division. There is no any existing meteorological station in Wakal basin. The nearest station being Udaipur located outside the basin. The raingauge station is located in all the tehsil headquarter of Wakal river basin.

3.1.4.1 Temperature

The period from March to June is marked by a continuous increase in temperatures. May is generally the hottest month of the year with a mean daily maximum and minimum temperature of 39.5°C and 27.3°C respectively. The summer is milder than in the desert regions. January is the coldest month with daily maximum and minimum temperature of 22.2°C and 5.4°C respectively.

3.1.4.2 Humidity

Relative Humidity during the southwest monsoon is generally about 70 per cent or more. During the rest of the year, air is normally dry.

3.1.4.3 Cloudiness

Skies are generally moderately to heavily clouded during the southwest monsoon season especially in July and August, being overcast on some days. During the rest of the year, skies are normally clear to highly clouded.

3.1.4.4 Winds

Winds are generally light to moderate except in the latter half of summer and during the southwest monsoon season. In summer, winds blows from directions running from west to south. Mean wind speed is highest in June (8.8 km/hr) and lowest in November (2.6 km/hr).

3.1.4.5 Rainfall

The area is characterized by sub-humid climate with an average annual rainfall of 630 mm. Kharif crops are mainly dependent on the rainfall and thereby subjected to either complete or partial failures in either case of excessive or shortage of rainfall during monsoon. More than 95 per cent of the rainfall received during monsoon months of June to September. Uneven and erratic rainfall distributions marked by prolong rain less days is a common phenomena in entire Wakal river basin.

3.1.5 Soils of the basin

Most of the area of the basin falls under rocky soil group, in which soil depth and slope are the limiting factors. The soil group falls under hydrologic soil group D that indicates the high runoff potential. In some valleys, fine loam and clay soils are dominating, which are having moderate slope of less than 8 per cent and soil depth up to 100 cm.

3.1.6 Topography

The General topography of the area is hilly and undulating. Most of the cultivated lands are located in the valleys. Surface drainage of the area is generally good due to slight undulations in the topography. Water flows through seasonal nala with high velocity, which is a main cause of erosion in the area. Small and scattered land holding situated on varying slope gradient is also a measure cause of soil erosion in the area.

3.1.7 Problems and need of the area

Problems and needs of agricultural land is specially related to soil and water conservation and dry farming practices, great degree of variations in the slope, poor depth of soils, profile characteristics, infiltration rates, water holding capacity of controlled section of soil, rainfall distribution, intensity of rainfall, traditional practices, small and scattered holding and lack of financial resources.

Problems

- Erosion Problem – Due to high intensity of rainfall in monsoon season, variations in slope gradients and scarce vegetative cover, the problem of soil erosion by water is severe to acute in the basin.
- Crop Management Problem – Small and scattered land holding situated on varying slope gradients is one of the main hurdles for the better management practices and use of improved implements and other agricultural machines.
- Water Management Problem – Due to lack of soil and water conservation measures in the basin, most of the rain water is lost through surface runoff, very little amount of rainwater enters into the soil profile and is used by the plants.

Need

- Suitable soil and water conservation measures.
- Timely supply of better quality of seeds and fertilizers.
- Financial assistance for purchase of improved agricultural implements, tools and seasonal agriculture inputs.
- Suitable agro technique for dry land agriculture.
- Knowledge of plant protection measures.

3.2 Data Collection and Software Used

The distinct information and data required for the present study were procured from different sources, which were then imported to GIS environment. A brief rerview of data collection and GIS software is given in ensuing section.

3.2.1 Data acquisition

(a) Extent of Wakal river basin and geomorphologic features were extracted from Geodetic Toposheets at 1:50,000 scale, which were procured from Survey of India (SOI), Dehradun.

(b) Soil information and soil map of the study area at 1:250,000 scales were gathered from the Regional Centre of National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Udaipur, Rajasthan.

(c) Digital elevation model (DEM) for the study area was downloaded from the ASTER database.

(d) Pre and post monsoon groundwater depth in meter below ground surface (m bgs) in year 2011 were monitored in 63 selected open dug wells of the Wakal river basin.

(e) Aquifer characteristics (i.e., transmissivity and specific yield) were determined by conducting ten pumping tests in selected wells of Wakal river basin.

3.2.2 Software used

Present study deals with use of GIS for preparation, handling, and processing of different thematic layers. All the GIS related works were carried out by using Arc GIS 9.3.1 software. Arc GIS software is a PC-based GIS and Remote Sensing software, developed by the ESRI. ArcGIS desktop software products allow users to analyze, map, manage, share, and publish geographic information. At all levels of licensing, ArcMap, ArcCatalog and ArcToolbox are the names of the applications comprising the desktop package. ArcGIS Explorer, ArcReader, and ArcExplorer are basic freeware applications for viewing GIS data.

3.3 Geomorphological Analysis

Geomorphological analysis is the systematic description of watershed’s geometry and its stream channel system to measure the linear aspects of drainage network, aerial aspects of watershed and relief aspects of channel network. The morphological parameters directly or indirectly reflect the entire watershed based causative factors affecting runoff and sediment loss. The parameters have been conveniently worked out from the toposheet using GIS tools. The dimensionless geomorphological parameters are presented under different groups as shown in Table 3.2.

Table 3.2 Grouping of geomorphological parameters

S. No.	Groups	Geomorphological Parameters
1	Linear Aspects of Drainage Network	stream order, stream number, bifurcation ratio, stream length and stream length ratio.
2	Aerial Aspects of Watershed	drainage density, form factor, circulatory ratio and elongation ratio.
3	Relief Aspects of Channel Network	relief ratio, relative relief and ruggedness number

3.3.1 Linear aspects of drainage network

Linear aspect of the basins are related to the channel patterns of the drainage network wherein the topographical characteristics stream segments in terms of open links of the network system (streams) are analysed. Thus, the linear aspect includes the discussion and analysis of stream order (u), stream number (N_u), bifurcation ratio (R_b), stream lengths (L_u), stream length ratio (R_L), length of overland flow (L_g) etc.

3.3.1.1 Stream order (u)

The first step in a drainage basin analysis is numbering of stream order, following a system introduced in the United States by Horton (1945). The smallest fingertip tributaries having no branches are designated as first order streams, where two first order streams join, a channel segment of second order is formed and so on. The highest order stream is also called as trunk stream, through which all discharge of watershed passes to the outlet.

3.3.1.2 Bifurcation ratio (R_b)

The bifurcation ratio is defined as the ratio of number of streams of any order (N_u) to the number of streams of next higher order (N_{u+1}). It can also be determined by slope of regression line relating stream order and corresponding number. It is given by the formula

$$R_b = \frac{N_u}{N_{u+1}} \qquad \text{……….. 3.1}$$

Where,

N_u = No. of streams of order u

N_{u+1} = No. of streams of order u+1.

3.3.1.3 Stream length (L_u)

All lengths of the drainage lines are measured with the help of statistical function of Arc/INFO software. Stream lengths are defined in meter (m). To find out the mean length of the channel of order u, the total length is divided by the number of segments (N_u) of that order. Thus,

$$\overline{L}_u = \frac{\sum_{i=1}^{N} L_u}{N_u} \qquad \ldots 3.2$$

Where,

$\overline{L}_u$ = Average length of stream of order u

L_u = Length of stream of order u

3.3.1.4 Stream length ratio (R_L)

Horton (1945) defined the stream length ratio, R_L as the ratio of mean length, L_u of segments of order u to mean length of segments of the immediate lower order, L_{u-1}.

$$R_L = \frac{\overline{L}_u}{\overline{L}_{u-1}} \qquad \ldots 3.3$$

Where,

$\overline{L}_u$ = Average length of stream of order u

$\overline{L}_{u-1}$ = Average length of stream of order u-1

3.3.1.5 Length of overland flow (L_g)

The length of overland flow, considered as a dominant hydrologic and morphometric factor is the mean horizontal length of flow-path from the divide to the stream in a first order basin and is a measure of stream spacing and degree of dissection and is approximately one-half the reciprocal of the drainage density. Length of overland flow is one of the most important morphometric variables, which affects the hydrological and topographic development of the basins. It is generally related to the stage of basin development, but no definite parameter or limit or scale of the length of overland flow has been suggested so far and thus qualitatively it is generally observed that the early stage is marked with maximum length of overland flow and mature and old stages register marked reduction in length of overland flow.

3.3.2 Aerial aspects of basin

3.3.2.1 Form factor (R_f)

It is defined as the ratio of the basin area (A) to the square of basin length (L_b).

$$R_f = \frac{A}{L_b^2} \qquad \text{…3.4}$$

Where,

A =Area of basin

L_b =Length of basin

3.3.2.2 Basin shape factor (S_b)

Horton (1932) defined the basin shape factor S_b, as the ratio between the square of the maximum length of basin and the area of the basin.

$$S_b = \frac{L_b^2}{A} \qquad \text{… 3.5}$$

3.3.2.3 Circulatory ratio (R_c)

Circulatory ratio is defined as the ratio of basin area (A) to the area of circle (A_c) having equal perimeter as the perimeter of basin.

$$R_c = \frac{A}{A_c} = \frac{4A\pi}{P^2} \qquad \text{…3.6}$$

Where,

A_c =Area of circle having equal perimeter of basin

P = Perimeter of basin

3.3.2.4 Elongation ratio (R_e)

Elongation ratio, R_e, is defined as the ratio of the diameter of a circle (D_c) with the same area as the basin to the maximum length of the basin (L_{bm}). This parameter is used to assess whether the shape of the basin approaches a circle or not.

$$R_e = \frac{D_C}{L_{bm}} = \frac{2X\sqrt{\frac{A}{\pi}}}{L_b} \qquad \text{…3.7}$$

Where,

D_c =diameter of circle with the same area as the basin

3.3.2.5 Drainage density (D_d)

The drainage density (D_d) is defined as the ratio of the total length of all streams of all orders within a basin to the total area of basin (A).

$$D_d = \frac{\sum_{i=1}^{K} \sum_{i=1}^{N} L_u}{A} \quad \dots 3.8$$

Where,

D_d = Drainage density

K = Principal order stream

3.3.3 Relief aspects of channel network

3.3.3.1 Maximum basin relief (H)

Maximum basin relief (H) is the elevation difference between basin mouth (discharge point) and the highest point on the basin perimeter. Maximum basin relief is obtained from the available contour maps of the basin. It is expressed in meter.

3.3.3.2 Relative relief (R_R)

Melton (1957) defined relative relief, R_R as the ratio of the maximum basin relief to the perimeter length. It is computed using following expression.

$$R_R = \frac{H}{L_p} \times 100 \quad \dots 3.9$$

Where,

H =Basin relief

L_p =Length of perimeter

3.3.3.3 Relief ratio (R_r)

Schumm (1956) defined the relief ratio (R_r) as the ratio of maximum basin relief divided by the maximum basin length. It is computed using following expression.

$$R_r = \frac{H}{L_b} \quad \dots 3.10$$

Where,

L_b =Basin Length

3.3.3.4 Ruggedness number (R_N)

The product of relief (H) and drainage density (D_d) is called ruggedness number.

$$R_N = H \times D_d \qquad \text{....3.11}$$

Where,

D_d =Drainage density

For morphometric analysis, area, perimeter, maximum length, drainage map, stream length of each order, numbers of stream of each order and basin relief values are generally required. These inputs are derived under GIS environment and then by making use of the mathematical formulae as discussed above, all the necessary parameters for morphometric analysis were computed.

3.3.4 Prioritization of sub–basins

Basin prioritization is the ranking of different sub basins according to the order in which they have to be taken for treatment and soil conservation measures. The resource considerations for implementation of basin management program or various other reasons pertaining to administrative or even political consideration may limit the implementation to few sub basins. Even otherwise, it is always better to start management measures from the highest priority sub basins, which makes it mandatory to prioritize the sub basins available. Hence, it was necessary to evolve suitable mechanism for prioritizing the sub basins. Morphometric analysis is a significant tool for prioritization of sub basins. The morphometric parameters i.e., bifurcation ratio (R_b), basin shape factor(S_b), compactness coefficient (C_c), drainage density (D_d), stream frequency (F_s), drainage texture (T), form factor (R_f), circularity ratio (R_c), and elongation ratio (R_e) are also termed as erosion risk assessment parameters and have been used for prioritizing sub-basins for treatment and conservation measures (Biswas *et al.*, 1999). The linear parameters such as drainage density, stream frequency, bifurcation ratio, texture ratio have a direct relationship with erodibility, higher the value, more is the erodibility. Hence, for prioritization of sub basins, the highest value of these linear parameters was rated as rank 1, second highest value was rated as rank 2 and so on, and the least value was rated last in rank. Shape parameters such as elongation ratio, compactness coefficient, and circularity ratio and form factor have an inverse relationship with erodibility (Nookaratnam *et al*., 2005), lower the value, more is the erodibility. Thus the lowest value of these shape parameters was rated as rank 1, next lower value was rated as rank 2 and so on and the highest value was rated last in rank. The ranking of the sub basins have been determined by assigning the highest priority/rank based on highest value in case of linear parameters and lowest value in case of shape parameters. After completion of rating based on every single parameter, the rating values for every sub basins were averaged to arrive at a compound value. Based on these compound rating values, the sub basin having the least rating value was assigned highest priority number of 1, next higher value was assigned priority number 2 and so on. The sub basin which received the highest compound value was assigned the last priority number.

3.4 Groundwater Quality Analysis

Analyzing the groundwater quality of the basin, pre and post monsoon groundwater samples were collected in sampling bottles by dividing the entire basin into 6km x 6km grid. The village map of the Wakal river basin is divided into 66 systematic square grids (6km x 6km) as shown in Fig.3.2. The water samples were collected from 63 sites during pre monsoon and 60 sites during post monsoon period. These samples were analyzed in the laboratory to find out different water quality parameters such as pH, EC, TDS, CO_3, HCO_3, SO_4, Cl, Ca, Mg, Na and K. On the basis of the results of the analysis the different water quality parameter map of the Wakal river basin was prepared under GIS environment.

3.4.1 Water sampling techniques

Water samples for quality assessment are analysed for chemical constituents. Therefore, more attention were given to avoid the possibility of any external contamination. The samples were collected in plastic bottles thoroughly cleaned and sterilized. The samples were collected using rope and bucket. The water surface were disturbed a little to remove any floating material before collection of the sample. The sampling site in the study area is shown in Fig. 3.3.

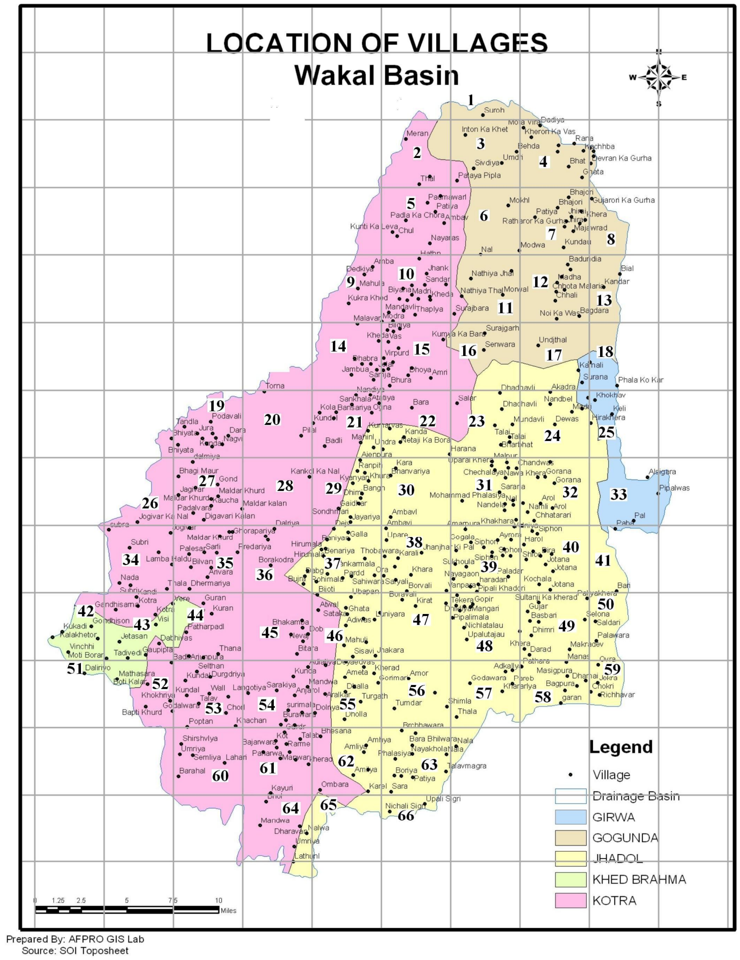


Fig. 3.2 Map of Wakal river basin with square grid pattern.

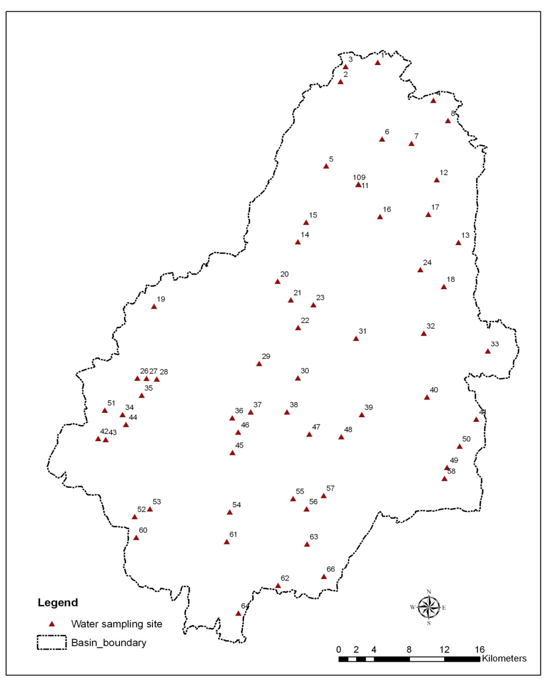


Fig. 3.3 Sampling site in Wakal river basin.

3.4.2 Analysis of water samples

The physicochemical parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Bicarbonate (HCO_3), Carbonate (CO_3), Chloride (Cl^{-}), and Sulphate (SO_4) were determined using standard methods. AR grade reagents were used for the analysis and double distilled water was used for preparation of solutions. The methods used for estimation of various physicochemical parameters are given in Table 3.3. The water samples were analyzed in the laboratory of AICRP on groundwater utilization as shown in Plate 3.1.

Table 3.3 Methods used for estimation of physiochemical parameters.

S.No.	Parameters	Method	References
1	pH	Using Glass Electrode pH meter	Jackson (1973)
2	Electrical Conductivity	Using EC meter	Wilcox (1950)
3	Total Dissolved Solids	Using TDS meter	Singh and Kalra (1975)
4	Calcium and Magnesium	EDTA titration	Cheng & Bray (1951) and Diehl et. al. (1950)
5	Sodium	Flame Photometric method	Toth et. al. (1948)
7	Potassium	Flame Photometric method	Stanford and English (1949)
8	CO_3 and HCO_3	Titration with standard H_2SO_4	A.O.A.C. (1950)
9	Chloride	Silver Nitrate method	A.O.A.C (1950)
10	Sulphate	Titrimetric method	Munger et. al. (1950)

Plate 3.1 Testing of water quality in laboratory

3.4.3 Residual sodium carbonate (RSC)

The residual sodium carbonate was calculated simply by subtracting the quantity of Ca + Mg from the sum total of carbonates and bicarbonates determined separately in a given sample and expressed in meq/l. Thus,

$$RSC = (CO_3^{2-} + HCO3^{-}) - (Ca^{2+} + Mg^{2+}) \qquad \text{…3.12}$$

3.4.4 Sodium adsorption ratio (SAR)

Sodium adsorption ratio was calculated using the formula given below.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad \text{…3.13}$$

Where, all ionic concentrations are expressed in meq/l.

3.4.5 Soluble sodium percentage (SSP)

Wilcox (1955) has proposed classification scheme for rating irrigation water on the basis of soluble sodoum percentage (SSP). The SSP was calculated by using following formula:

$$SSP = \frac{Na \times 100}{Ca + Mg + Na} \qquad \text{---3.14}$$

Where, the concentration of ions are expressed in meq/l.

3.4.6 Permeability index (PI)

The permeability index was calculated by the following formula:

$$PI = \frac{Na + \sqrt{HCO_3}}{(Ca + Mg + Na)} \times 100 \qquad \text{---3.15}$$

Where, all the values are in meq/l.

3.4.7 Kelly's ratio (KR)

Kelly's ratio was calculated by using the following expression:

$$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}} \qquad \text{---3.16}$$

Where, concentrations are expressed in meq/l

3.5 Determination of Aquifer Parameters

The aquifer parameter of Wakal river basin was not available and no study in this respect were conducted by any organization in the study area. Therefore, efforts were made to determine aquifer parameters through pumping test.

3.5.1 Determination of aquifer parameters by pumping test

Evaluation of aquifer characteristics is the prime task for harnessing an aquifer for optimum results yielding information about how much groundwater is available for development and what will be the consequences of withdrawing a certain quantity of groundwater.

Aquifer parameters, i.e. transmissivity (T) and specific yield (S_y) are often determined by means of pumping test. Scientifically planned pumping tests provides information for solution of many regional, as well as local, groundwater flow problems. It also provide information about the yield and drawdown of the well, which in turn is essential for selecting the type of pump, estimating cost of pumping, well efficiency etc. Minimum spacing requirement between two wells to avoid mutual interference can also be determined with these parameters.

In a pumping test or an aquifer test, a well is pumped at constant/variable rate for a certain period. The effect of pumping on the water level is measured in the pumped well and in one or more observation wells, penetrating the aquifer in the vicinity of the pumped well with the help of stage gauge recorder or a measuring tape. Type of an aquifer is identified by plotting time-drawdown curve on double-logarithmic scale and comparing with standard drawdown curve on double-logarithmic scale. Aquifer parameters (T and S_y) are then found by substituting the measured drawdown, discharge and the well function by use of a graphical technique called ‘curve matching’.

In present study, a total of ten pumping tests were performed in selected wells (Fig. 3.4) of the Wakal river basin. Wells selected for pumping tests were large diameter shallow open dug wells, which while pumped extract groundwater from the unconfined aquifer. The pumping test of selected well and measurement of water level using Acoustic water level indicator is shown in Plate 3.2 and Plate 3.3 respectivelly.

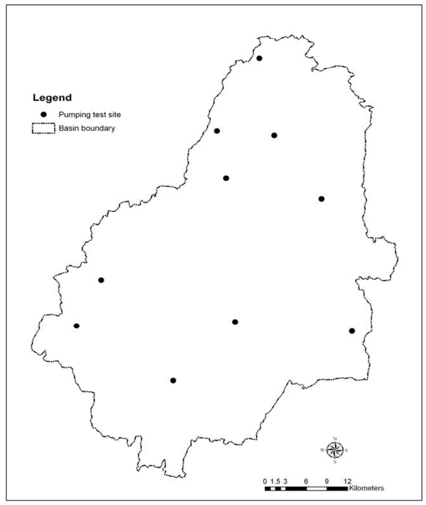


Fig. 3.4 Map showing location of pumping test sites

Plate 3.2 Pumping test of selected well

Plate 3.3 Measurement of water level by using Acoustic Water Level Indicator

3.5.2 Analyzing pumping test data by curve-matching technique

Plentiful techniques are available for analyzing pumping test data depending upon the type of aquifer (e.g., confined, semi-confined, unconfined, etc.), type of pumping well (e.g., infinitesimal or large diameter), well penetration (full or partial), and discharge rate (constant or variable). A chart with a list of available techniques for analyzing pumping test data depending upon the test conditions is shown in Table 3.4.

Table 3.4: Techniques for analyzing pumping test data

Type of Aquifer	Available Technique for Analyzing Pumping Test Data
Confined	Theis (1935)
	Theis (1935) residual drawdown/recovery
	Theis (1935) step-drawdown test
	Cooper-Jacob (1946)
	Butler (1988) nonuniform aquifer
	Papadopulos-Cooper (1967)
	Dougherty-Babu (1984)
	Dougherty-Babu (1984) step-drawdown test
	Hantush (1962) wedge-shaped aquifer
	Murdoch (1994) trench
	Daviau et al. (1985) uniform-flux horizontal well
	Daviau et al. (1985) infinite-conductivity horizontal well
	Barker (1988)
Leaky	Hantush-Jacob (1955)/Hantush (1964) without aquitard storage
	Hantush-Jacob (1955) step-drawdown test
	Hantush (1960) with aquitard storage
	Hantush (1960) early-time solution
	Neuman-Witherspoon (1969) confined two-aquifer system
	Moench (1985) Case 1: constant head
	Moench (1985) Case 2: no-flow
	Moench (1985) Case 3: both

Unconfined	Theis (1935)
	Cooper-Jacob (1946)
	Neuman (1974)
	Moench (1997)
Fractured	Moench (1984) slab-shaped blocks
	Moench (1984) spherical blocks
	Barker (1988) slab-shaped blocks
	Barker (1988) spherical blocks
	Gringarten-Witherspoon (1972) uniform-flux vertical fracture
	Gringarten et al. (1974) infinite-conductivity vertical fracture
	Gringarten-Ramey (1974) uniform-flux horizontal fracture

In the present study, pumping tests were performed in large diameter open dug wells in shallow unconfined aquifer situated in hard rock area of Wakal river basin. It can be seen from Table 3.4 that only a single technique (i.e., Moench method) is available for analyzing the pumping test data of large diameter wells in unconfined aquifer. However, solution of Moench method is very complex for practical application. Moench method is available in commercial software (e.g., AquiferTest and AQTESOLV), however, non-availability of any of these software posed a hurdle in pumping test data analysis. Some of the past studies conducted in Udaipur by Jat (1990) and Verma (2005) reported that Papadopulos and Cooper (1967) method can successfully be used for analyzing pumping test data of large diameter wells in unconfined aquifers after converting unconfined aquifer drawdown into equivalent confined aquifer’s drawdown

Therefore, Papadopulos and Cooper (1967) curve-matching technique was adopted for determining aquifer properties in this study. The Papadopulos and Cooper solution accounts for well bore storage effects in a large-diameter (finite-diameter) pumping well. Papadopulos and Cooper method is described below.

3.5.2.1 Papadopulos and Cooper method

The following assumptions apply to the use of the Papadopulos and Cooper solution:

- Aquifer has infinite areal extent.
- Aquifer is homogeneous, isotropic and of uniform thickness.
- Flow to pumping well is horizontal.
- Aquifer is confined.
- Flow is unsteady.
- Water is released instantaneously from storage with decline of hydraulic head.

The governing second order partial differential equation is:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial t} \qquad r \geq r_w \qquad \text{......3.17}$$

Where,

s = drawdown in the aquifer at a distance r at time t,

S = storage coefficient of the aquifer,

T = transmissivity, and

r_w = effective radius of well screen

r = radial distance of the pizometer from the centre of the pumped well.

The geometry of large diameter wells in a non-leaky confined aquifer is shown in Fig.3.5.

The initial conditions are:

$$s(r,0) = 0 \qquad r \geq r_w \qquad \text{......3.18}$$

$$s_w(0) = 0 \qquad \text{......3.19}$$

And the boundary conditions are

$$s_w(r_w, t) = s_w(t) \qquad \text{....3.20}$$

$$s(\infty, t) = 0 \qquad \text{....3.21}$$

$$2\pi r_w T \frac{\partial s(r_w, t)}{\partial t} - \pi r_c^{\,2} \frac{\partial s_{w(t)}}{\partial t} = -Q \qquad \text{...3.22}$$

Where,

s_w (t) = drawdown in the well at time t and

r_c = radius of the well casing in the interval over which the water level declines.

With the initial and boundary conditions stated above, Eqn. (3.17) was solved using Laplace Transform method, and the following solution was obtained (Papadopulos and Cooper, 1967; Papadopulos, 1967; Reed, 1980):

$$s(r,t) = \frac{Q}{4\pi T} F(u,\alpha,\rho) \qquad \text{…3.23}$$

Where,

$$F(u,\alpha,\rho) = \frac{8\alpha}{\Pi} \int_0^\infty \frac{C(\beta)}{D(\beta)\beta^2} \partial\beta \qquad \text{…...3.24}$$

and

$$C(\beta) = \left\{1 - \exp\left(-\beta^2 \frac{\rho^2}{4u}\right)\right\}\left[J_0(\beta\rho)A(\beta) - Y_0(\beta\rho)B(\beta)\right] \qquad \text{….3.25}$$

Where,

$$A(\beta) = \beta Y_0(\beta) - 2\alpha Y_1(\beta) \qquad \text{…3.26}$$

$$B(\beta) = \beta J_0(\beta) - 2\alpha Y_1(\beta) \qquad \text{…3.27}$$

$$D(\beta) = \left[A(\beta)^2\right] + \left[B(\beta)\right]^2 \qquad \text{…3.28}$$

$$u = \frac{r^2 S}{4Tt} \qquad \alpha = \frac{rw^2 S}{r_c^{\ 2}} \qquad \rho = \frac{r}{r_w} \qquad \text{….3.29}$$

J_0 (and Y_0), and Y_1 represent zero-order and first-order Bessel functions of the first and second kind, respectively.

The drawdown inside the pumped well is obtained at $r = r_w$ and expressed as:

$$s_w(t) = \frac{Q}{4\pi T} F(u,\alpha,\rho) \qquad \text{…3.30}$$

Where,

$$F(u_w,\alpha) = F(u,\alpha,1) \qquad \text{…..3.31}$$

and

$$u_w = \frac{r_w^{\ 2} S}{4Tt} \qquad \text{…3.32}$$

Values of $F(u,\alpha,\rho)$ are computed by numerical integration of Eqn. (3.24). Papadopulos and Cooper (1967) generated a family of type curves of $s_w / \frac{Q}{4\pi KD}$ versus $\frac{1}{u_w}$ with one curve for each α.

Aquifer parameters are determined by fitting observed drawdown data to one of the families of type curves and finding a match point. The Family of Type Curves for Papadopulos and Cooper Method is shown in Fig. 3.6.

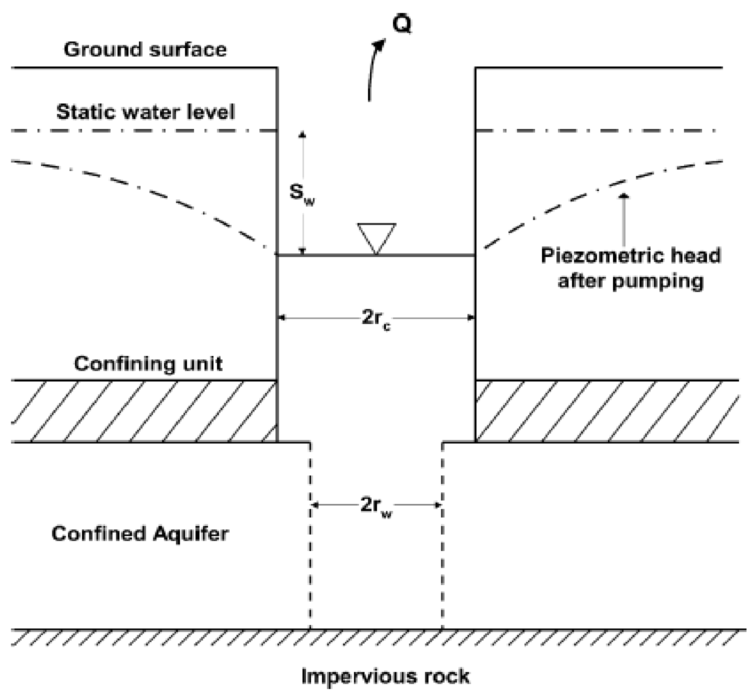


Fig. 3.5 Ideal large diameter well in a confined aquifer

(Source: Papadopulos and Cooper, 1967)

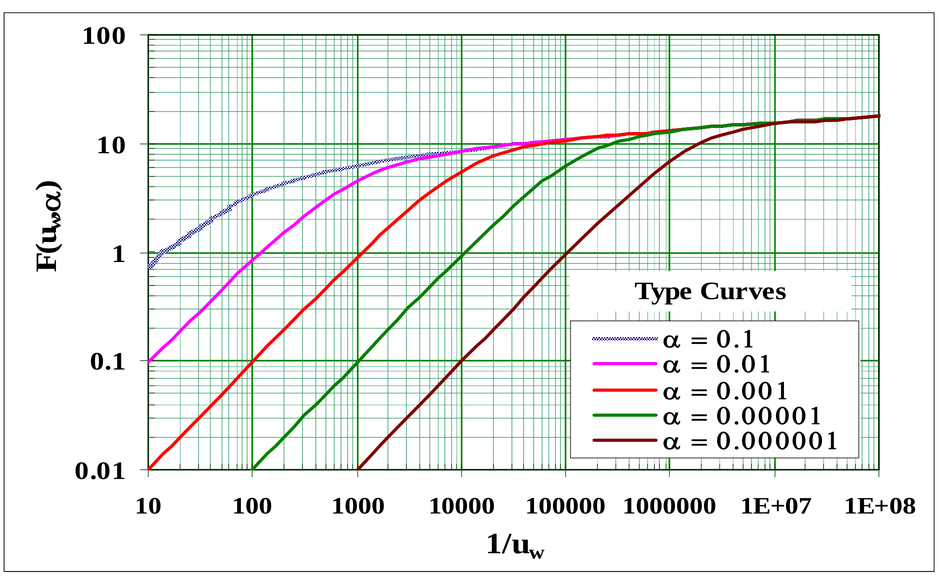


Fig. 3.6 Family of type curves for Papadopulos and Cooper method

Before plotting the observed time-drawdown curve, measured drawdown values of the unconfined aquifer were converted into the equivalent drawdown of confined aquifer by using the transformation as suggested by Jacob (1944).

$$S_c = S_{uc} - \frac{S_{uc}^{\ 2}}{2m} \qquad \text{....3.33}$$

Where,

S_c = equivalent drawdown in a non-leaky confined aquifer, m

S_{uc} = drawdown observed in an unconfined aquifer, m

m = initial saturated thickness of the aquifer, m.

Initial saturated thickness was obtained by adding average depth of impervious layer below the bottom of the well (D_{IL}) to water column depth (D_{WC}) in the well before start of the test. Average depth of impervious layer was computed from the following equation (Jat, 1990).

$$D_{IL} = \frac{K_H}{K_V} \times D_{WC} \qquad \text{... 3.34}$$

Where,

K_H = horizontal hydraulic conductivity, m/day.

K_V = vertical hydraulic conductivity, m/day.

The ratio K_H/K_V was found to be 2.2 (Acharya, 1988) for the study area.

Furthermore, partial penetration correction was applied by using the following expression as suggested by Hantush (1964).

$$S_{fc} = S_c - \frac{S_c^{\ 2}}{2L} \qquad \text{....3.35}$$

Where,

S_c = equivalent drawdown in a non-leaky confined aquifer, m

S_{uc} = drawdown observed in an unconfined aquifer, m

S_{fc} = equivalent fully penetrating well drawdown in a confined aquifer, m

m = initial saturated thickness of the aquifer,

L = penetration depth of the pumped well.

3.6 Computation of Net Groundwater Recharge

Groundwater recharge is the process by which water percolates down the soil and reaches the water table, either by natural or artificial methods. Quantification of the rate of natural groundwater recharge is a pre-requisite for efficient groundwater resource management. It is particularly important in regions with large demands for groundwater supplies, where such resources are the key to economic development. The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the groundwater recharge. However, the rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources. Estimation of recharge, by any method is normally subject to large uncertainties and errors. The following methods are commonly in use for estimating groundwater recharge.

(i) Soil water balance method

(ii) Zero flux plane method

(iii) One-dimensional soil water flow model

(iv) Inverse modelling technique

(iv) Ground water level fluctuation method

(v) Hybrid water fluctuation method

(vi) Ground water balance method

(viii) Isotope and solute profile techniques

In the present study, net groundwater recharge in Wakal river basin is computed by using Water Table Fluctuation (WTF) Method. This method linked the change in groundwater storage ΔS with resulting water table fluctuation Δh. Net recharge is equal to change in groundwater storage ΔS .

$$\Delta S = S_y \times \Delta h \qquad \text{......3.36}$$

Where,

Δh = difference in water level, and

S_y = specific yield or the fillable porosity of the unconfined aquifer.

Because the water level measured in an observation well is representative of an area of at least several tens of square meters, the WTF method can be viewed as an integrated approach and less a point measurement than methods based on very local data in the unsaturated zone for example. Techniques based on groundwater levels are among the most widely applied methods for estimating recharge rates (Healy and Cook, 2002). This is likely due to the abundance of available groundwater level data and the simplicity of estimating recharge rates from temporal fluctuations or spatial patterns of groundwater levels.

The WTF method, applicable only to unconfined aquifers, is best applied to shallow water tables that display sharp water level rises and declines. Deep aquifers may not display sharp rises because wetting fronts tend to disperse over long distances. The basic assumption is that the rise in the water table is primarily due to the rainfall recharge. There must be a distinct rainy season with the remainder of the year being relatively dry. It is recognized that other factors such as pumping or irrigation during the rainy season do not have an influence.

3.7 Groundwater Potential Assessment by using Remote Sensing and GIS

The remote sensing (RS) technique provides synoptic coverage and accurate spatial information, which enable economical utilization over conventional methods of hydrogeological surveys. Rapid advances in the development of geographical information system (GIS), which provides spatial data integration and tools for natural resources management, have enabled integrating the data in an environment which has been proved to be an efficient and successful tool for groundwater studies (e.g., Meijerink, 1996; Edet et al., 1998; Rao and Jugran, 2003; Jha and Peiffer, 2006; Madrucci et al., 2008).

This study utilized RS and GIS techniques for generating thematic layers of different factors influencing groundwater occurrence. The multi-criteria decision-making technique coupled with GIS have been used to identify groundwater potential zones in the study area. The procedures adopted to identify and delineate groundwater potential zones using RS, GIS and MCDM techniques are illustrated in Fig. 3.7 and are described in the subsequent sub-sections.

3.7.1 Selection of thematic layers

In past groundwater studies concerning combined use of RS and GIS techniques, various thematic maps for delineating groundwater favorability zones were selected believing that all the thematic parameters have some influence on the occurrence of groundwater (e.g., Rao and Jugaran, 2003; Solomon and Quiel, 2006; Ettazarini, 2007; Ganapuram *et al.*, 2009). The number of thematic layers used depends on the availability of data in an area. In the present study, eight thematic layers (viz., geomorphology, soil, slope, topographic elevation, land use/land cover, post monsoon groundwater depth, recharge and transmissivity) have been consider for the delineation of groundwater potential zones.

3.7.2 Generation of thematic layers

In order to assess groundwater potential in the study area, eight thematic maps, viz., geomorphology, soil, slope, topographic elevation, land use/land cover, post monsoon groundwater depth, recharge and transmissivity were generated using remote sensing and conventional data. Out of these thematic maps, topographic elevation and slope maps were generated from ASTER data, whereas the remaining maps were generated using conventional data. These thematic maps were developed using Arc GIS software.

3.7.2.1 Geomorphology map

Geomorphology is the science of landforms (Thornbury, 1986) and has a direct relation with the occurrence and movement of groundwater. The geomorphology of a particular area deals with the rock type, soil type, drainage pattern, etc. and hence geomorphic units and associated features indirectly control the groundwater prospect of an area (Brown, 1996). In the present study, earlier-mentioned SOI toposheets were scanned, rectified, and then digitized in the Arc GIS software to prepare a thematic layer on geomorphology. Thereafter, different geomorphology classes were identified, which were then assigned weights according to their relative importance in groundwater occurrence or recharge in the study area following the Saaty's analytical hierarchy approach.

3.7.2.2 Soil map

Soil is defined as the residual material, which has been modified and acted upon by physical, chemical and biological agents. The influence of soil on groundwater occurrence mainly depends on its retention capacity or texture. The texture of a soil can be defined as the relative proportion of silt, sand and clay present in it. The clay soil having smaller pores induces more runoff and less infiltration, whereas the sandy soil induces more infiltration and thereby recharge the groundwater reserve (Todd, 1980; Raghunath, 1987; Fetter, 1994).

As mentioned earlier, the soil map of the study area was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Udaipur at 1:250,000 scale. The map was scanned, rectified and then digitized using Arc GIS software. Thereafter, different soil categories were identified and assigned weights according to their contribution to groundwater.

3.7.2.3 Slope map

The slope of a particular terrain is an important factor in groundwater studies, because it determines the time required for the water to accumulate at a given location. The slope gradient directly influences the infiltration of rainfall. The lesser the slope, the lesser will be the runoff, and hence infiltration and recharge will be more thereby making a flat terrain more promising for groundwater availability.

The slope map for the study area was prepared from the Digital Elevation Model (DEM). The DEM was subjected to two directional gradient filters (one in x-direction and another in y-direction). The filtering was done by using in-built linear filters (dfdx and dfdy) available in the Arc GIS software. Then, the resultant maps were used to generate a slope map of the study area by computing slope using following equation:

$$\text{Slope} = 100 \times \sqrt{\text{DX}^2 + \text{DY}^2} \Big/ \text{Pixel Size(DEM)} \qquad \text{.....3.37}$$

Where,

DX = filtered DEM with x-gradient filter, DY = filtered DEM with y-gradient filter, and Pixel Size (DEM) = pixel size of the DEM.

The slope map was divided into different classes and suitable weights were assigned to each class based on its contribution to groundwater occurrence.

3.7.2.4 Topographic elevation map

As topography (land surface elevation) is one of the factors, which influence groundwater potential, topographical elevation map was considered as one of the themes for the present study. The higher the elevation, the lesser will be the groundwater availability. Sener et al. (2005) reported relation of topographic elevations with groundwater occurrence. In present study, topographic elevation layer is generated from the topographic data downloaded from USGS (2004). The ASTER obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. ASTER consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. The topographic data are available in GeoTIFF raster file format at 30 m pixel resolution. The obtained topography file was imported to Arc GIS software and DEM was generated for the study area. Suitable weights to different elevations were given based on their contribution to groundwater occurrence/recharge.

3.7.2.5 Land use/Land cover map

The land-use/land cover thematic map of the study area was prepared using satellite imagery. IRS-1D LISS-III data at 23.5 m spatial resolution were used for preparation of the land use/land cover thematic map. The raw satellite images were digitally processed in a series of image processing operations: geometric rectification**,** image enhancement, image interpretation and multispectral classification. Further, supervised image classification was carried out to classify land use classes. Different land use/land cover classes define the rate of infiltration of rainfall and water to the ground.

3.7.2.6 Post monsoon groundwater depth map

The post-monsoon groundwater depth map for the study area was prepared based on 60 monitoring sites data using Arc GIS software. The developed map was divided into suitable classes and weights were assigned according to their relative importance from groundwater viewpoint.

3.7.2.7 Groundwater recharge map

Recharge is broadly defined as water that reaches an aquifer from any direction. It can be classified as direct, localized and indirect. The term direct recharge refers to the recharge derived from precipitation or irrigation that occurs fairly uniformly over large areas, whereas the term localized recharge refers to the concentrated recharge from depressions in surface topography such as streams and lakes. Point estimates of the net recharge at 60 sites for the study area was estimated using Water Table Fluctuation method as mentioned earlier in Section 3.6. Using this point recharge values, a recharge map of the study area was prepared.

3.7.2.8 Transmissivity map

Aquifer transmissivity is very important factor as it governs groundwater movement and recharge process. The higher value of transmissivity increases the suitability of an area for artificial recharge. In this study, transmissivity values obtained in pumping test were used to prepare a thematic layer on transmissivity using Arc GIS software. Different transmissivity classes in the study area were identified and then assigned weights according to their transmissivity values using the Saaty's analytical hierarchy approach.

3.8 Delineation of Groundwater Potential Zones

The thematic layers on geomorphology, soil, slope, topographic elevation, land use/land cover, post monsoon groundwater depth, recharge and transmissivity were used for the delineation of groundwater potential zones in the study area. To demarcate the potential zones, all these thematic layers were assigned weights and then were integrated using Arc GIS software. The weights of thematic map and their individual features were decided based on the experts' opinions and local field experience (Nishtha, 2009; Jha et al. 2009; Machiwal et al 2011). The weights of the different themes were assigned on a scale of 1 to 5 based on their influence on the groundwater potential. Different features of each theme were assigned weights on a scale of 1 to 9 according to their relative influence on groundwater potential. Based on this scale, the qualitative evaluation of different features of a given theme was performed as poor, moderate, good, very good and excellent. The relative influence of the individual themes and features on groundwater potential was decided based on the experts' opinion, information and local knowledge. Thereafter, a pair-wise comparison matrix was constructed using the Saaty's analytical hierarchy process to calculate normalized weights for individual themes and their features. To demarcate groundwater potential zones, all the eight thematic layers after assigning weights were vb added (overlaid) using Arc GIS software. The total weights of different polygons in the integrated layer were derived from the following equation to obtain groundwater potential index (Rao and Briz-Kishore, 1991).

$$GWPI = (GM_w GM_{wi} + SO_w SO_{wi} + SL_w SL_{wi} + TE_w TE_{wi} + LU_w LU_{wi} + WD_w WD_{wi} + RE_w RE_{wi} + TR_w TR_{wi}) \quad \ldots 3.38$$

Where,

GWPI = groundwater potential index

GM = geomorphology

SO = soil type

SL = slope

TE = topographic elevation

LU = land use/land cover

WD = post monsoon groundwater depth

RE = groundwater recharge

TR = transmissivity

w = normalized weight of a theme and

wi = normalized weight of the individual features of a theme.

GWPI is a dimensionless quantity that helps in indexing probable groundwater potential zones in the area. The range of GWPI values was divided into four equal classes (called zones) and the GWPI of different polygons falling under different range were grouped into one class. Thus, the entire study area was qualitatively divided into four groundwater potential zones and a map showing these zones was prepared using Arc GIS software. The entire process of groundwater potential zoning is shown in Fig. 3.7.

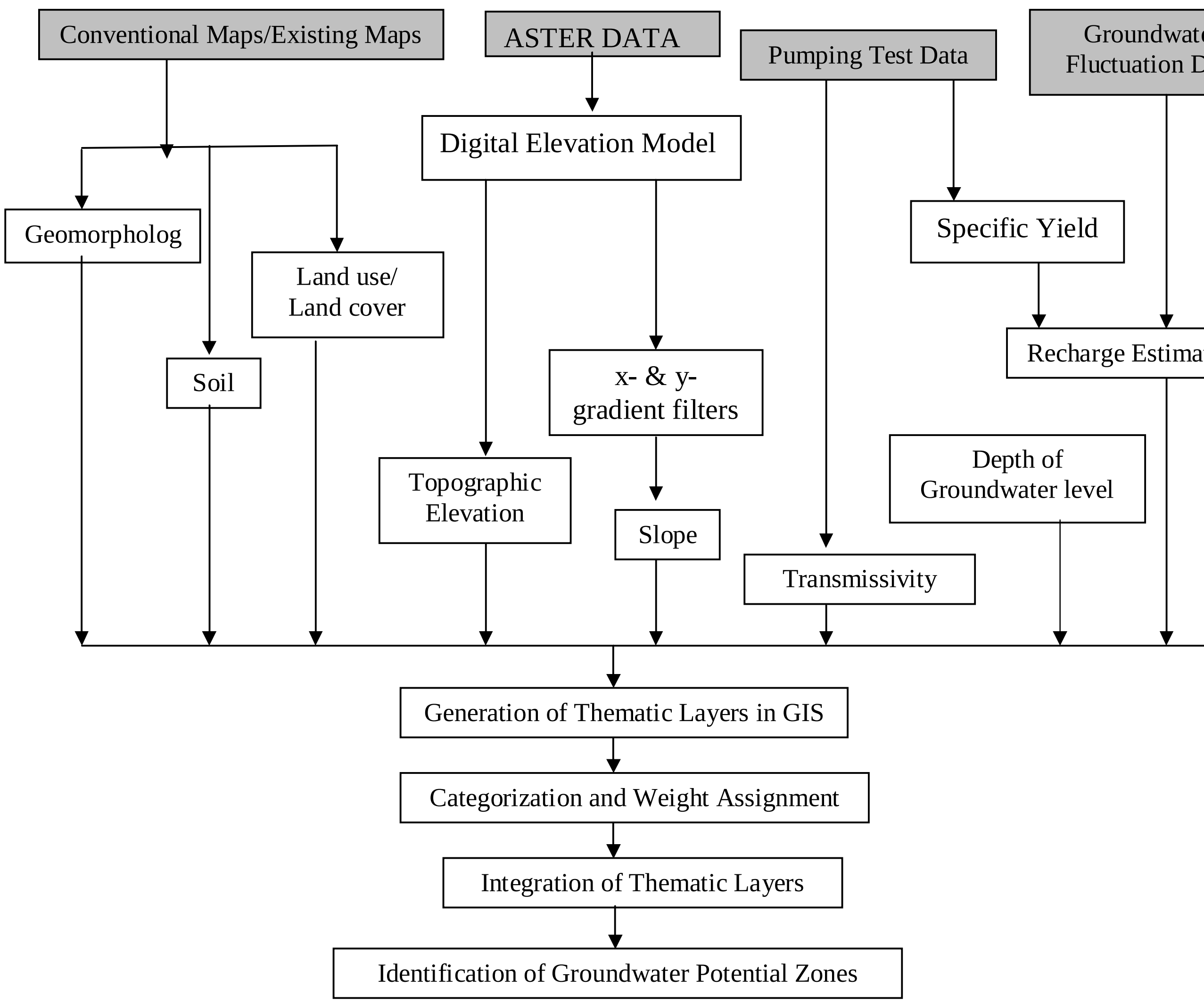


Fig. 3.7 Flowchart for groundwater potential zoning using GIS

3.9 Suitable Strategies for Sustainable Groundwater Resources Management

For the management of groundwater resources, artificial recharge is a very important factor. Artificial recharge is the process of augmenting the natural movement of surface water into underground formations by some artificial means. This is accomplished by constructing infiltration facilities or by inducing recharge from surface water bodies. In hard rock areas, the underlying lithological units do not have sufficient porosity and permeability. In these areas, groundwater recharge falls short of the water that is being taken out of the aquifers. Hence groundwater cannot suffice the requirement for agriculture or drinking water. Thus additional recharge by artificial methods becomes necessary to meet the water deficit. The performance of artificial recharge efforts can be immensely increased if they are performed through proper scientific planning. A remote sensing and GIS based method is found to be very useful in suitability analysis for artificial recharge sites in the hard rock terrain (Saraf and Choudhary, 1998). For such analysis, the first task is to identify the factors facilitating recharge to take place. In this study, the thematic layers used for determining recharge zones are: (a) Transmissivity, (b) Recharge, (c) Groundwater Level (post-monsoon), (d) Topographic Elevation, (e) Soil, and (f) Slope. All the six thematic layers were combined using Boolean Logic Analysis to delineate to zones of suitability for artificial recharge structures. The prime task in this method is to identify the criterion and to formulate the set of logical conditions to extract the suitable zones. With this criterion, the output has only two classes: suitable or unsuitable. The areas in which the defined conditions of the information layers are fulfilled together, a value of 1 is given whereas the remaining part will have a zero value. The criteria considered in this study for demarcating suitable zones for artificial recharge are mentioned in Table 3.5. A flowchart showing steps for delineating artificial recharge zones is presented in Fig. 3.8.

Table 3.5 Criteria for demarcating suitable artificial recharge zones

Thematic Layer	Suitability Criteria
Slope	<5%
Groundwater level (post monsoon)	>4 m bgs
Transmissivity	200-300 m^2/day
Recharge	2-4 cm/year
Topographic elevation	<600 m
Soil	Coarse loamy and rock outcrop to loamy skelton

Note: bgs = below ground surface

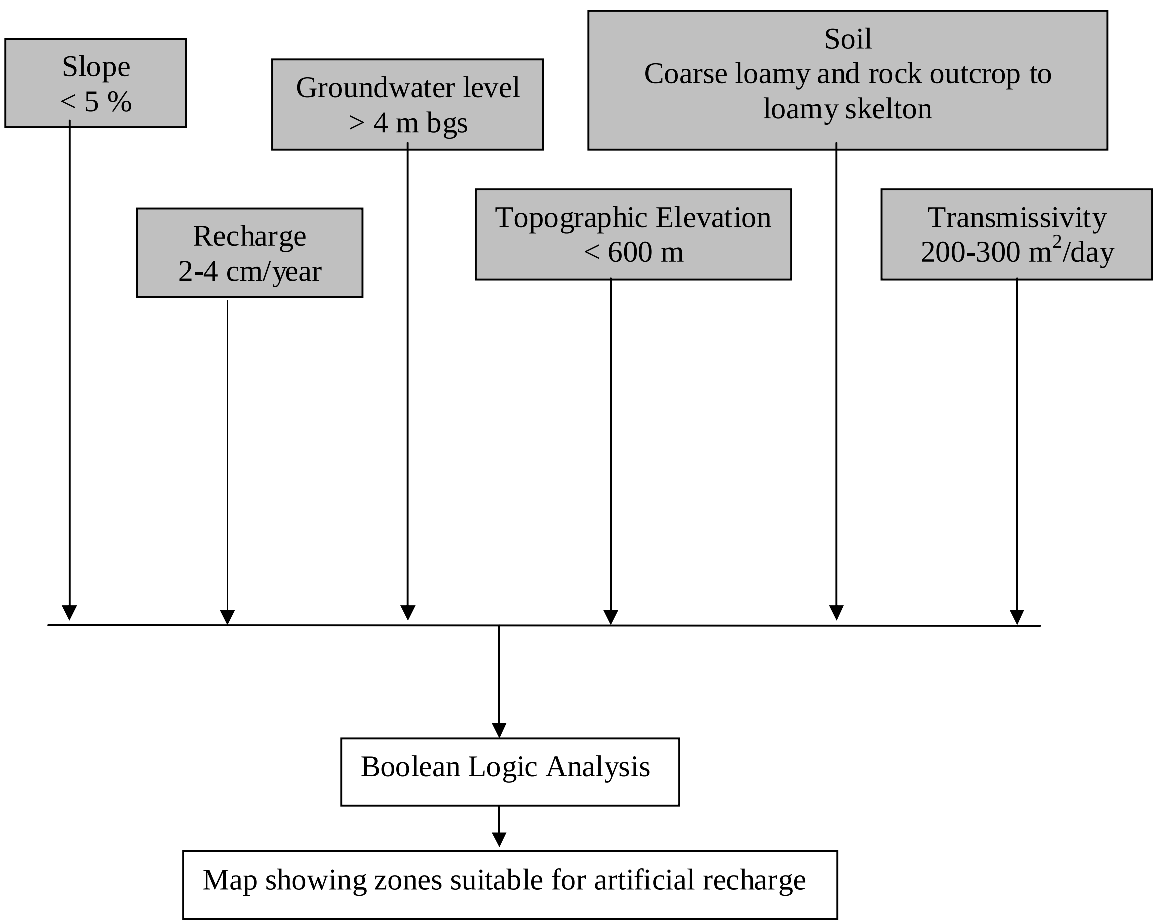


Fig. 3.8 Flowchart showing steps for delineating artificial recharge zones

IV - RESULTS AND DISCUSSION

This chapter deals with the results obtained from the present study and their discussion. The methodology adopted has already been systematically given in the previous chapter. The present study reported in this dissertation consists of three parts. In first part, geomorphological parameters of the basins were analyzed using Remote Sensing and GIS. In second part, the results of groundwater quality assessment and its spatio-temporal variation are discussed. Finally, the results and discussion of the assessment of groundwater potential using Remote Sensing and GIS technique in the study area are presented.

4.1 Geomorphological Analysis

For the geomorphological analysis the measurement were made from the digitized drainage pattern and basin boundary.

In the present study, the map showing drainage details have been prepared from digital data of LISS III and extracted by digitizing boundary of the basin from the geometrically rectified toposheet. The figure also shows digitized stream network. The drainage pattern for delineated basin of Wakal river was exported to ARC/INFO software for morphometric analysis. The parameters computed in the present study includes stream order, stream length, stream frequency, bifurcation ratio, drainage density, stream frequency, form factor, circulatory ratio, elongation ratio, relief ratio and ruggedness number by standard methods and formulae as given in previous chapter. The input parameters for the present study such as area, perimeter, elevation, stream length etc. were obtained from digitized coverage of drainage network map in GIS environment. Basin boundary and digitized drainage pattern of Wakal river basin is shown in Fig 4.1.

The total drainage area of Wakal river basin is 1914.32 km^2 and it is divided into seven sub-basins for the analysis. The drainage pattern of the basin ranges from dendritic to subdendritic at higher elevations and parallel to sub-parallel in the lower elevations. The drainage characteristics of the seven sub-basins of the study area were determined and are summarized in Tables 4.1 to 4.3. The drainage maps of sub-basins of Wakal river are shown in Fig. 4.2.

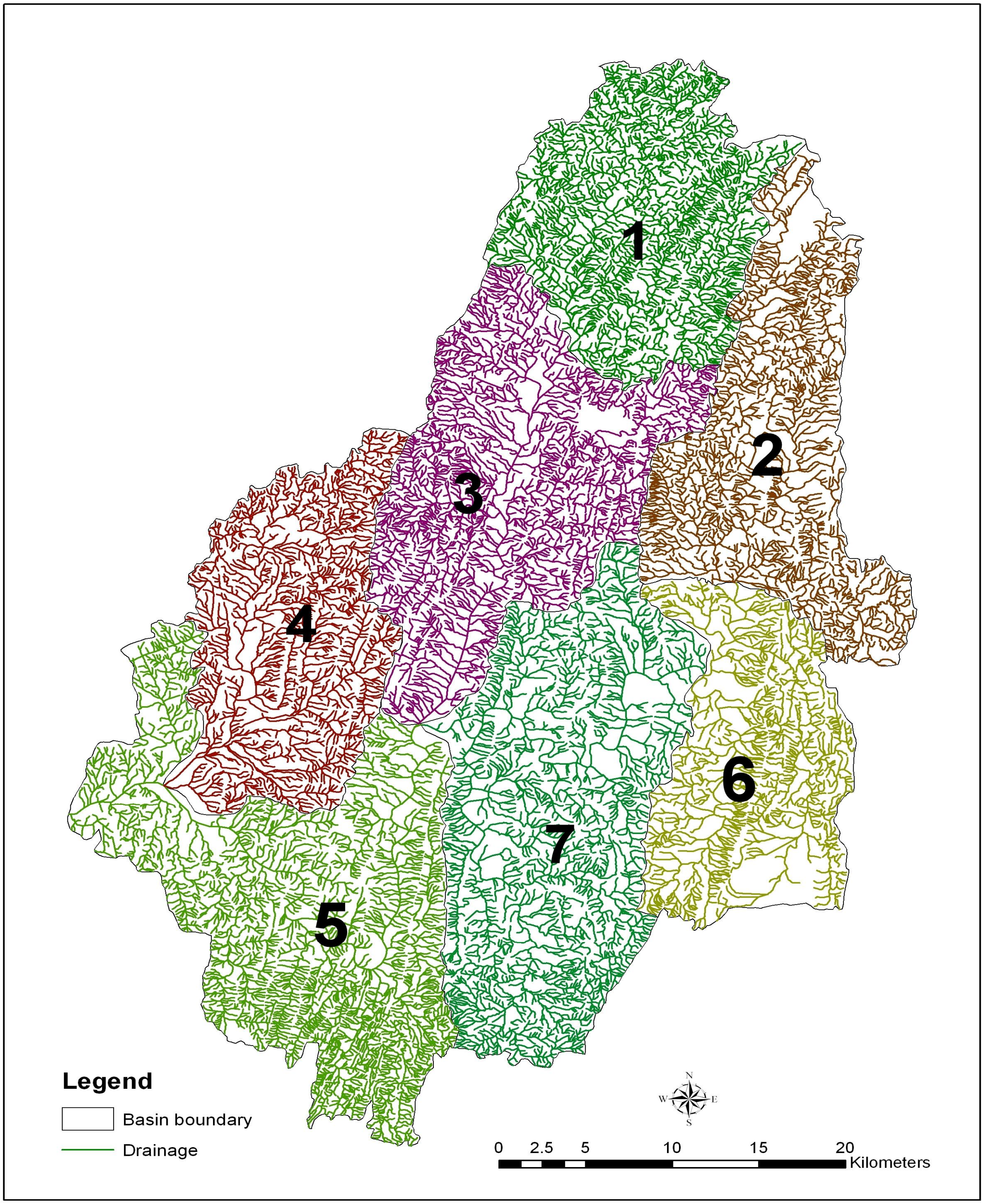
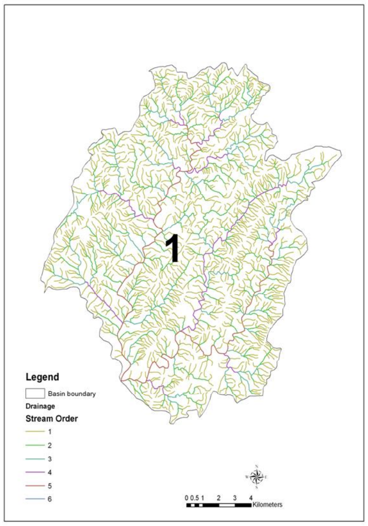
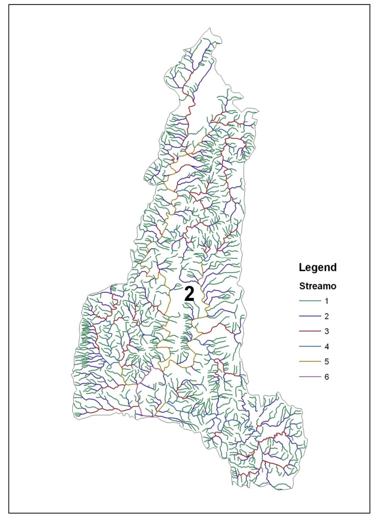


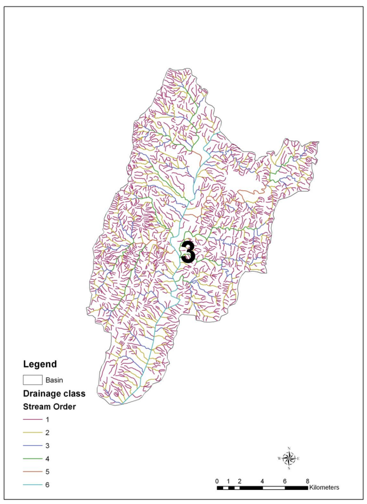
Fig. 4.1 Drainage map of Wakal river basin



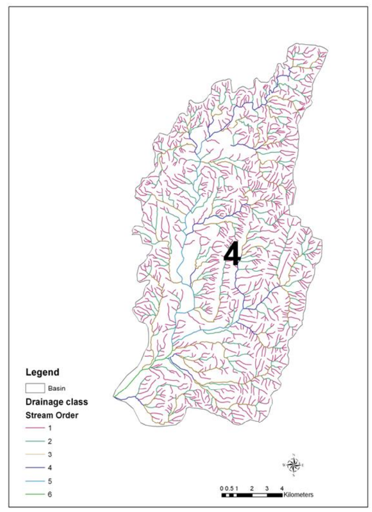
Sub-Basin 1



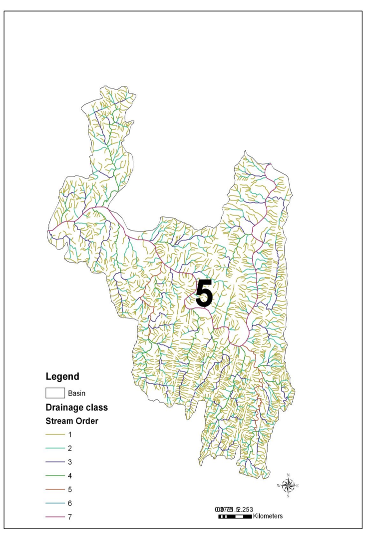
Sub-Basin 2



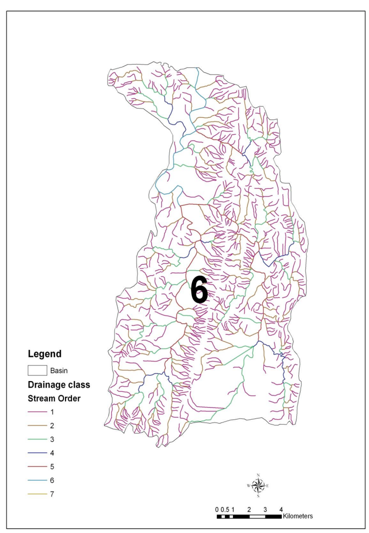
Sub-Basin 3



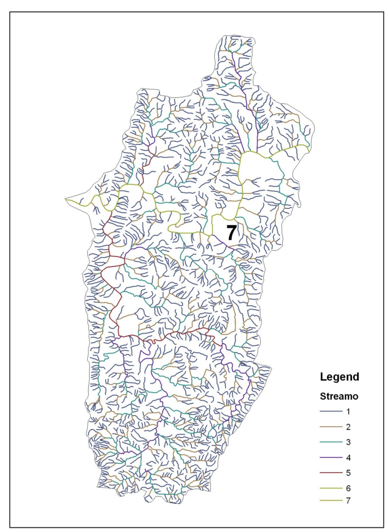
Sub-Basin 4



Sub-Basin 5



Sub-Basin 6



Sub-Basin 7

Fig. 4.2 Drainage map of sub-basins of Wakal river

4.1.1 Linear aspects

The linear aspects of the basin such as stream order (N_u), stream length (L_u) and bifurcation ratio (R_b) were determined and results have been given in Table 4.1 (a & b). In the present study ranking of streams has been carried out based on the method proposed by Strahler (1964). Out of these seven sub-basins, sub-basin 1, 2, 3 and 4 are sixth order basin whereas sub-basin 5, 6 and 7 are of seventh order basin. Table 4.1 also shows that the maximum stream frequency was found in case of first order streams and there is a decrease in stream frequency as the stream order increases. The order wise total number of stream segment is known as the stream number. Horton's (1945) laws of stream numbers states that the number of stream segments of each order form an inverse geometric sequence with plotted against order, most drainage networks show a linear relationship, with small deviation from a straight line. The plotting of logarithm of number of streams against stream order is given in Fig.4.3 according to the law proposed by Horton gives a straight line. It means that the number of streams usually decreases in geometric progression as the stream order increases.

The stream lengths for all sub-basins of various orders were measured on digitized map with the help of GIS. The total length of stream segments is maximum in first order streams and decreases as the stream order increases. The total stream length in the Wakal river basin is 6919.1 km and that of the seven sub-basins are 976.9 km, 849.6 km, 1153.0 km, 792.5 km, 1372.8 km, 629.9 km, and 1147.4 km respectively (Table 4.1 a). The stream length ratios (R_L) are changing haphazardly at the basin and sub-basins level. The values of the stream length ratio (R_L) vary from 0.01 to 155 for sub-basins, while it ranges from 1.3 to 5.7 for the whole Wakal river basin (Table 4.1 b). It is noticed that the R_L between successive stream orders of the basin vary due to differences in slope and topographic conditions (Sreedevi[2] et al. 2005). The Stream Length Ratio (R_L) has an important relationship with the surface flow discharge and erosional stage of the basin.

In the present study, it was observed that the plot of logarithm of the cumulative stream length as ordinate vs. stream order as abscissa is almost a straight line fit. The straight-line fit indicates that the ratio between cumulative length and order is constant throughout the successive orders of a basin (Fig.4.4).

Table 4.1(a) Linear aspects of Wakal river sub-basins

Basin/ Sub-basin	Area (km^2)	Peri-meter (km)	Stream number of different orders								Order wise total stream length(km)							
			1	2	3	4	5	6	7	Total	1	2	3	4	5	6	7	Total
Sub-basin-1	232.87	80.91	1260	269	51	12	2	1	-	1595	643.7	167.2	84.6	39.2	42.2	.03	-	976.9
Sub-basin-2	248.05	101.83	943	229	45	12	4	1	-	1234	526.5	157.4	80.5	33.6	45.8	5.8	-	849.6
Sub-basin-3	302.41	95.16	1351	290	56	12	3	1	-	1713	732.1	218.1	94.8	56.5	21.7	29.8	-	1153.0
Sub-basin-4	224.43	81.32	923	209	48	12	3	1	-	1196	473.9	154.7	99.6	36.1	22.7	5.5	-	792.5
Sub-basin-5	360.22	135.94	1786	381	85	17	2	1	1	2273	881.8	234.4	126.4	62.9	20.5	.3	46.5	1372.8
Sub-basin-6	203.46	74.48	617	166	44	10	3	2	1	843	380.7	117.0	66.5	19.7	29.8	13.1	.09	626.9
Sub-basin-7	342.88	95.64	1202	289	67	13	2	1	1	1575	694.5	197.0	121.9	46.7	25.4	29.3	32.6	1147.4
Wakal river basin	1914.32	256.70	8082	1833	396	88	19	6	1	10425	4333.1	1245.9	674.2	294.7	208.1	83.9	79.2	6919.1

Table 4.1(b) Linear aspects of Wakal river sub-basins

Basin/ Sub-basin	Average stream length (km)								Stream length ratio(R_L)							Bifurcation ratio(R_b)						
	1	2	3	4	5	6	7	Total	2/1	3/2	4/3	5/4	6/5	7/6	Mean R_L	R_b 1	R_b 2	R_b 3	R_b 4	R_b 5	R_b 6	Mean R_b
Sub-basin-1	0.5	0.6	1.7	3.3	21.1	0.03	-	27.2	1.2	2.8	1.9	6.4	.001	-	2.5	4.7	5.3	4.3	6.0	2.0	-	4.4
Sub-basin-2	0.6	0.7	1.8	2.8	11.4	5.8	-	23.1	1.2	2.6	1.6	4.1	0.5	-	2.0	4.1	5.1	3.8	3.0	4.0	-	4.0
Sub-basin-3	0.5	0.8	1.7	4.7	7.2	29.8	-	44.7	1.6	2.1	2.8	1.5	4.1	-	2.42	4.7	5.2	4.7	4.0	3.0	-	4.3
Sub-basin-4	0.5	0.7	2.1	3.0	7.6	5.5	-	19.4	1.4	3.0	1.4	2.5	0.7	-	1.8	4.4	4.4	4.0	4.0	3.0	-	4.0
Sub-basin-5	0.5	0.6	1.5	3.7	10.3	0.3	46.5	63.4	1.2	2.5	2.5	2.8	0.03	155	27.3	4.7	4.5	5.0	8.5	2.0	1.0	4.3
Sub-basin-6	0.6	0.7	1.5	2.0	9.9	6.6	0.09	21.4	1.2	2.1	1.3	5.0	0.7	0.01	1.7	3.7	3.8	4.4	3.3	1.5	2.0	3.1
Sub-basin-7	0.6	0.7	1.8	3.6	12.7	29.3	32.6	81.3	1.2	2.6	2.0	3.5	2.3	1.1	2.1	4.2	4.3	5.2	6.5	2.0	1.0	3.9
Wakal river basin	0.5	0.7	1.7	3.3	11.0	14.0	79.2	110.4	1.4	2.4	1.9	3.3	1.3	5.7	2.7	4.4	4.6	4.5	4.6	3.2	6.0	4.6

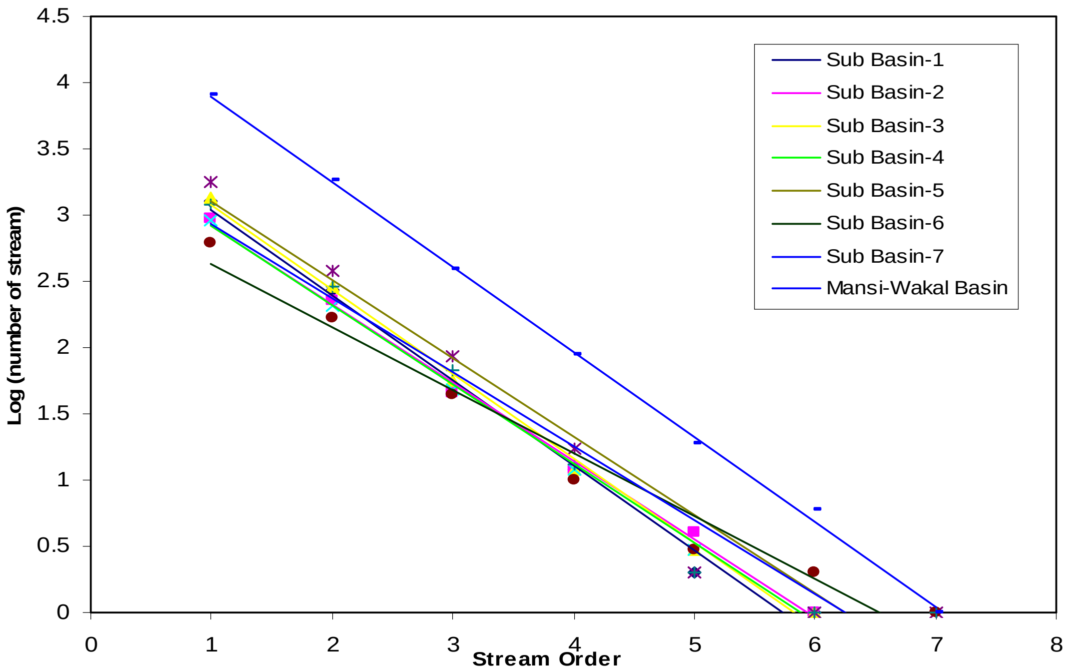


Fig. 4.3 Relationship between log(number of stream) and stream order

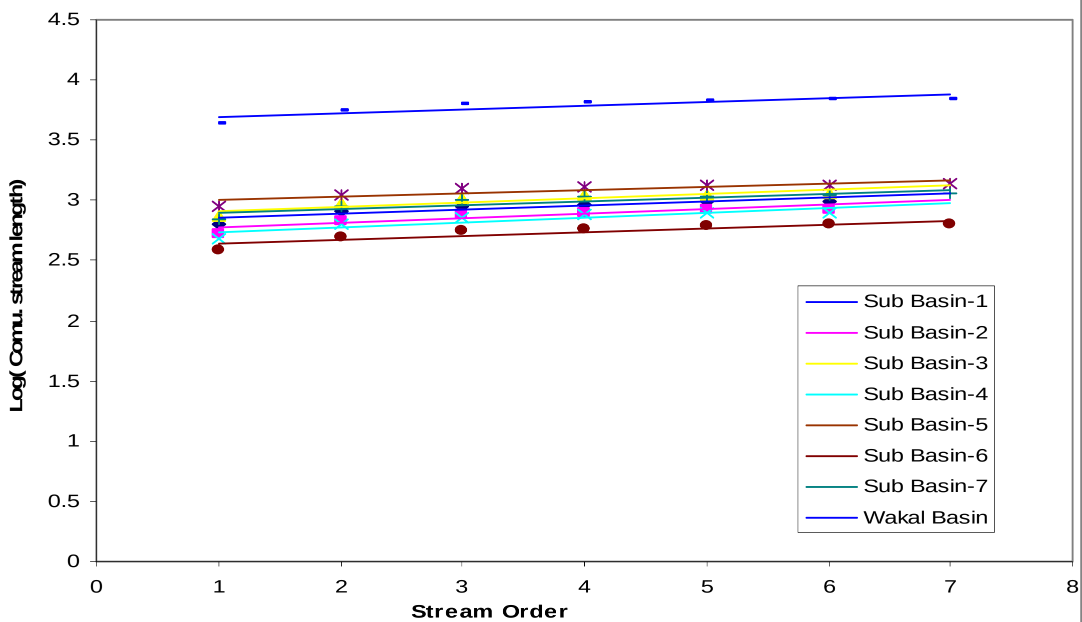


Fig. 4.4 Relationship between log(comu. stream length) and Stream order

The mean bifurcation ratio values range between 3.12 to 4.56 for the basins of the study area indicating that all the basins are falling under normal basin category (Strahler, 1957). The bifurcation ratio is also an indicative tool of the shape of the basin. Elongated basins have low R_b value, while circular basins have high R_b value (Morisawa, 1985). In this study area, the higher value of R_b indicates a strong structural control in the drainage pattern whereas the lower value indicates that the sub-basins are less affected by structural disturbances (Stahler, 1964; Vittala et al., 2004 and Chopra et al., 2005).

4.1.2 Aerial aspects

The aerial aspects of the basin like drainage density (D_d), stream frequency (F_s) elongation ratio (R_e), circularity ratio (R_c), form factor (R_f), were calculated and results have been presented in Table 4.2. The drainage density in the whole basin and sub-basins of the study area shows variation from 3.08 to 4.20 km per km^2 suggesting high drainage density. It indicates that the region is composed of weak or impermeable subsurface materials, sparse vegetation, mountainous relief and fine drainage texture (Reddy et al. 2004). The stream frequency (F_s) mainly depends on the lithology of the basin and reflects the texture of the drainage network. The stream frequency (F_s) values of the basin and sub-basins of the study area are varying from 4.14 to 6.85. It is also seen that the drainage density values of the sub-basins exhibits positive correlation with the stream frequency, suggesting that there is an increase in stream population with respect to increasing drainage density. Generally, High value of stream frequency (F_s) is related to impermeable sub-surface material, sparse vegetation, high relief conditions and low infiltration capacity (Reddy et al. 2004).

Form Factor (R_f) proposed by Horton (1945) to predict the flow intensity of basin of a defined area. The index of R_f shows the inverse relationship with the square of the axial length and a direct relationship with peak discharge. The value of form factor would always be greater than 0.78 for a perfectly circular basin. Smaller the value of form factor, more elongated will be the basin. Form Factor (R_f) values of whole basin and sub-basins of the study area vary from 0.23 to 0.54, which indicate that they are sub-circular and elongated in shape. The elongated basin with low form factor indicates that the basin will have a flatter peak of flow for longer duration. Flood flows of such elongated basins are easier to manage than of the circular basin (Nautiyal, 1994).

The circularity ratio (R_c) is affected by the lithological character of the basin. Its values approaching one indicates that the basin shapes are like circular and as a result, it gets scope for uniform infiltration and takes long time to reach excess water at basin outlet, which further depends on the prevalent geology, slope and land cover. The ratio is more influenced by length, frequency (F_s) and gradient of various orders rather than slope conditions and drainage pattern of the basin. The R_c of the whole basin and sub-basins of the study area vary from 0.24 to 0.47, which indicates the dentritic stage of a basin.

The elongation ratio (R_e) is a very significant index in the analysis of basin shape, which helps to give an idea about the hydrological character of a drainage basin. Elongation ratio (R_e) for the study area varied from 0.54 to 0.83 as shown in Table 4.2. The value near 1 is typical of regions of very low relief, whereas values in the range of 0.6 to 0.8 are generally associated with strong relief and steep ground slopes (Strahler, 1968).

Schumm (1956) used the inverse of drainage density as a property known as the constant of channel maintenance (C). It is the area of basin surface needed to sustain a unit length of stream channel and is dependent on the rock type, permeability, climatic regime, vegetation cover as well as duration of erosion. In areas of close dissection, its value will be very low. The value of constant channel maintenance (C) of the study area varied from 0.24 to 0.32, which indicates that these basin and sub-basins are under the influence of high structural disturbance, low permeability, steeps to very steep slopes and high surface runoff.

The length of overland flow (L_g) is the length of water over the ground before it gets concentrated into definite stream channels. It is approximately equals to half of the reciprocal of drainage density (Horton, 1945). This factor relates inversely to the average slope of the channel and is synonymous with the length of the sheet flow to a large degree. The length of overland flow (L_g) is one of the most important independent variables, affecting both the hydrological and physiographical development of the drainage basins (Horton 1945). The computed value of L_g for all sub-basins and basin varies from 0.12 to 0.16 km^2/km. The low L_g values indicate to short flow paths, with steep ground slopes, reflecting the areas associated with more run-off and less infiltration.

Table 4.2 Aerial aspects of Wakal river sub-basins

Basin/ Sub-basin	Form factor	Shape factor	Circulatory ratio	Elongattion ratio	Texture Ratio	Compactness Constant	Drainage density	Stream frequency	Constant of channel maintenance	Length of overland flow, km.
Sub-basin-1	0.54	1.87	0.45	0.83	19.71	1.49	4.20	6.85	0.24	0.12
Sub-basin-2	0.23	4.35	0.30	0.54	12.12	1.82	3.42	4.97	0.29	0.15
Sub-basin-3	0.35	2.86	0.42	0.66	18.00	1.54	3.81	5.66	0.26	0.13
Sub-basin-4	0.31	3.27	0.43	0.62	14.17	1.53	3.53	5.33	0.28	0.14
Sub-basin-5	0.38	2.64	0.24	0.69	16.72	2.02	3.81	6.31	0.26	0.13
Sub-basin-6	0.48	2.08	0.46	0.78	11.32	1.47	3.08	4.14	0.32	0.16
Sub-basin-7	0.32	3.13	0.47	0.64	16.47	1.45	3.35	4.50	0.30	0.15
Wakal river basin	0.38	2.65	0.37	0.69	40.61	1.66	3.61	5.45	0.28	0.14

4.1.3 Relief aspects

Relief aspect of the watershed plays an important role in drainage development, surface and sub-surface water flow, permeability, landform development and associated features of the terrain. Relief is the maximum vertical distance between the lowest and the highest points of a basin. The maximum height of the Wakal basin is 1060 m and the lowest is 275 m. Therefore, the relief of the basin is 785m. The relief of sub–basins of the study area is varying from 446m to 752m. The high relief value indicates the gravity of water flow, low infiltration and high runoff conditions of the study area. Relief ratio has direct relationship between the relief and channel gradient. The relief ratio normally increases with decreasing drainage area and size of the watersheds of a given drainage basin. The relief ratio of the Wakal river basin is 0.011, while that of the seven sub-basins vary from 0.014 to 0.028 as given in Table 4.3. The relief ratio of the basin as well as the sub-basins of the study area are low which are characteristic features of less resistant rocks of the area (Sreedevi, 1999).

Ruggedness number, R_N is the product of relief and drainage density in order to define the slope steepness and length. It is a dimensionless term and indicates the structural complexity of the terrain. The Wakal river basin displays the ruggedness number as 2.83 and indicate that the area is extremely rugged with high relief and high stream density. The ruggedness number of sub–basins varies from 1.48 to 2.65 as given in Table 4.3.

Table 4.3 Relief aspects of Wakal river sub-basins

Basin/ Sub-basin	Elevation (m)		Relief (m)	Relief ratio	Ruggedness number
	Max.	Min.			
Sub-basin-1	1060.0	560.0	500.0	0.024	2.10
Sub-basin-2	1001.0	555.0	446.0	0.014	1.53
Sub-basin-3	1042.0	427.5	614.5	0.021	2.34
Sub-basin-4	1037.0	285.0	752.0	0.028	2.65
Sub-basin-5	858.0	275.0	583.0	0.019	2.22
Sub-basin-6	1015.0	533.0	482.0	0.023	1.48
Sub-basin-7	1001.0	433.0	568.0	0.017	1.90
Wakal river basin	1060.0	275.0	785.0	0.011	2.83

4.1.4 Prioritization of sub–basins

All of these morphometric parameters are compounded and a final rating scale was generated for the study area as shown in Table 4.4. Sub-basins were prioritized according to these rating. Based on the average value of compound parameters, the sub-basins having the lowest rating value is assigned the highest priority number of 1, next higher value was assigned second priority number of 2 and so on. The sub-basin, which got the highest compound parameters value, was assigned last priority. It was found that the lowest compound parameters value is 3.13 occurred in the sub-basin number 3 that is given high priority for conservation measures. The next priority is given to sub-basin 1, sub-basin 4, sub-basin 5, sub-basin 2, sub-basin 7 and sub-basin 6 respectively (Table 4.4). Thus, soil and water conservation measures can first be applied to sub-basin number 3 and then to other depending on their priority.

Table 4.4 Prioritization result of sub- basins based on morphometric analysis

Sub-basin No.	Bifur-cation Ratio	Drainage Density	Stream Frequ-ency	Texture Ratio	Circul-atory Ratio	Form Factor	Elong-ation Ratio	Compact-ness Constant	Compound Parameter	Final Priority
Sub-basin-1	1	1	1	1	5	7	7	3	3.25	2
Sub-basin-2	3	4	5	6	2	1	1	6	3.50	4
Sub-basin-3	2	2	3	2	3	4	4	5	3.13	1
Sub-basin-4	3	3	4	5	4	2	2	4	3.38	3
Sub-basin-5	2	2	2	3	1	5	5	7	3.38	3
Sub-basin-6	6	7	7	7	6	6	6	2	5.88	6
Sub-basin-7	4	5	6	4	7	3	3	1	4.13	5

4.2 Groundwater Chemistry of the Study Area

The different physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), calcium (Ca^{+}), magnesium (Mg^{+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3), carbonate (CO_3), chloride (Cl^{-}), and sulphate (SO_4) present in pre and post monsoon samples of the study area were determined using standard methods as given in Appendix A1 and Appendix A2 respectively. The maximum and minimum values of these parameters of the study area present in the groundwater during pre and post monsoon is presented in Table 4.5. The variations in individual groundwater quality parameters map are prepared in GIS environments and shown in Fig.4.5a to Fig.4.5k for pre monsoon and Fig.4.6a to Fig. 4.6k for post monsoon period.

Table 4.5 Maximum and minimum value of water quality parameters in groundwater samples

Parameters	Pre-monsoon samples (meq/l)			Post-monsoon samples (meq/l)		
	Min.	Max.	Weighted Mean	Min.	Max.	Weighted Mean
pH	6.0	8.0	6.98	6.5	7.6	7.11
EC	0.40	3.20	0.96	0.30	2.90	0.81
TDS	223	2600	641.38	200	2020	575.17
Ca	1.6	7.0	3.10	1.1	15.0	3.40
Mg	0.8	14.0	3.25	0.0	7.4	1.94
Na	0.2	12.1	2.98	0.2	6.4	2.47
K	0.0	1.2	0.13	0.0	0.6	0.06
HCO_3	0.0	5.2	1.58	0.4	5.5	1.65
CO_3	0.0	4.2	0.24	0.0	2.0	0.05
Cl	2.8	19.5	4.92	1.5	13.5	3.69
SO_4	0.0	17.2	2.75	0.0	14.2	2.52

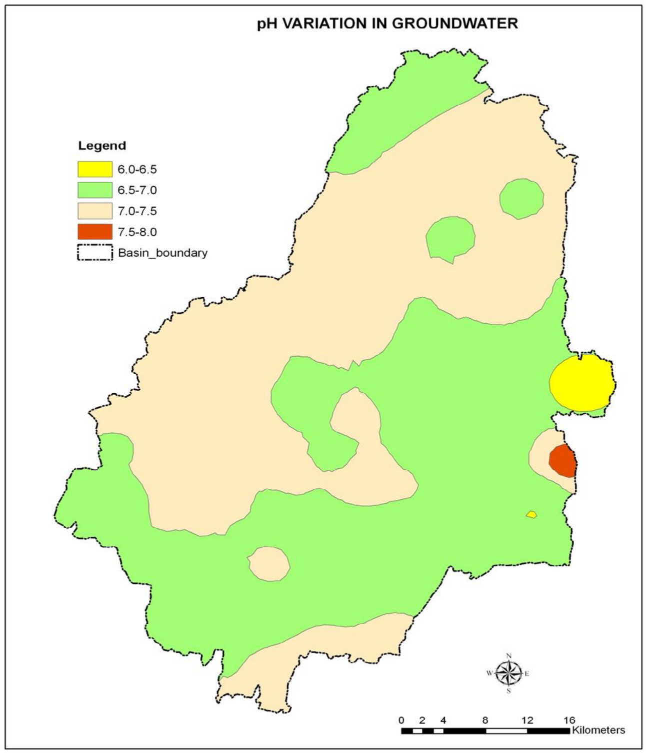


Fig. 4.5a Variation of pH in Wakal river basin during pre-monsoon

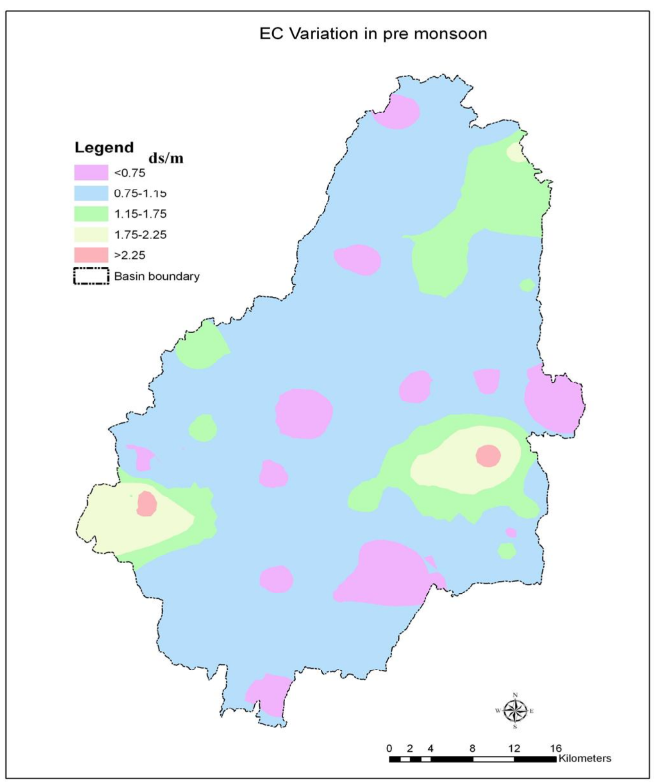


Fig. 4.5b Variation of EC in Wakal river basin during pre-monsoon

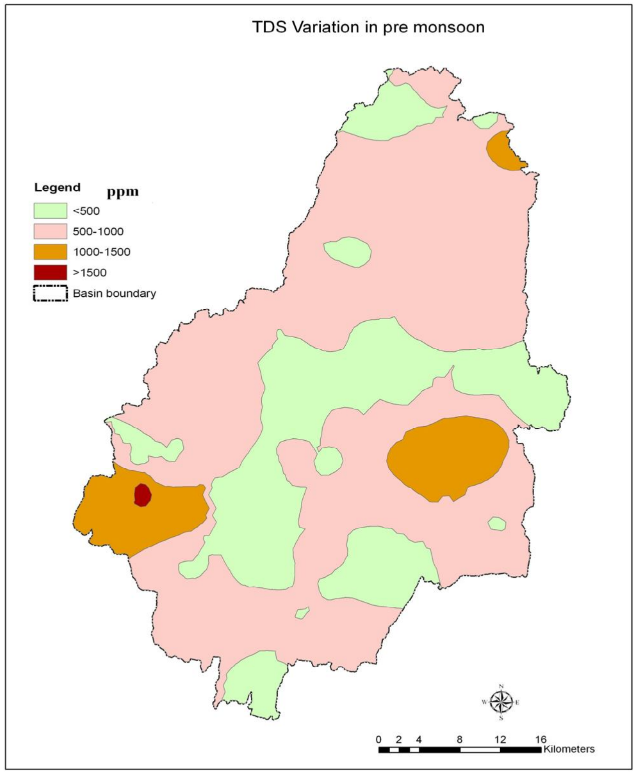


Fig. 4.5c Variation of TDS in Wakal river basin during pre-monsoon

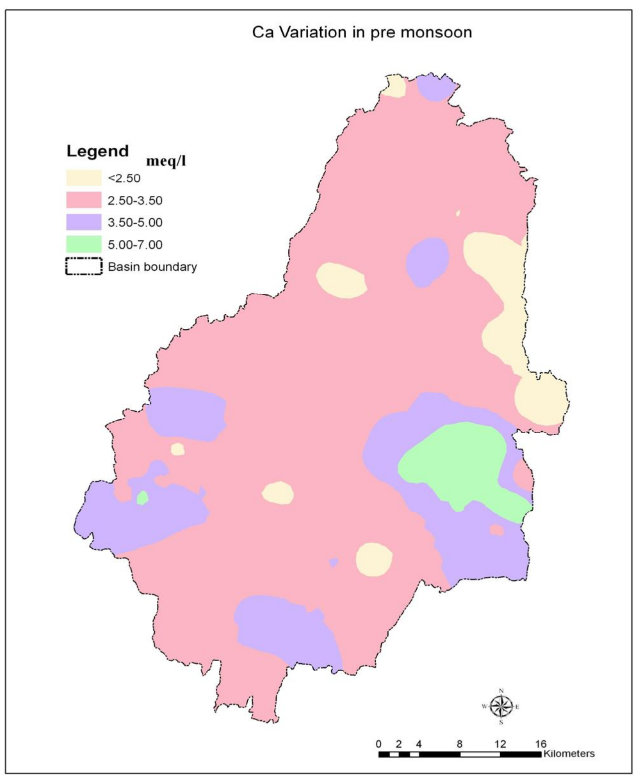


Fig. 4.5d Variation of Ca in Wakal river basin during pre-monsoon

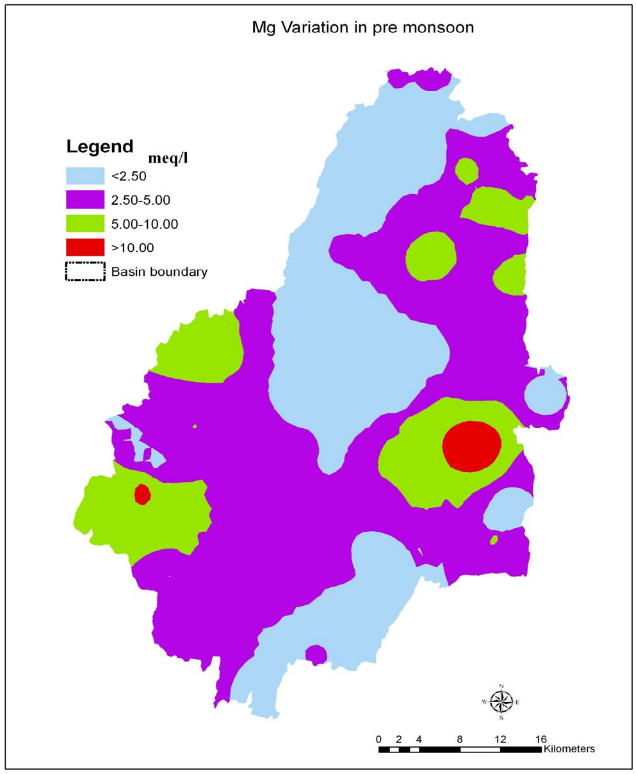


Fig. 4.5e Variation of Mg in Wakal river basin during pre-monsoon

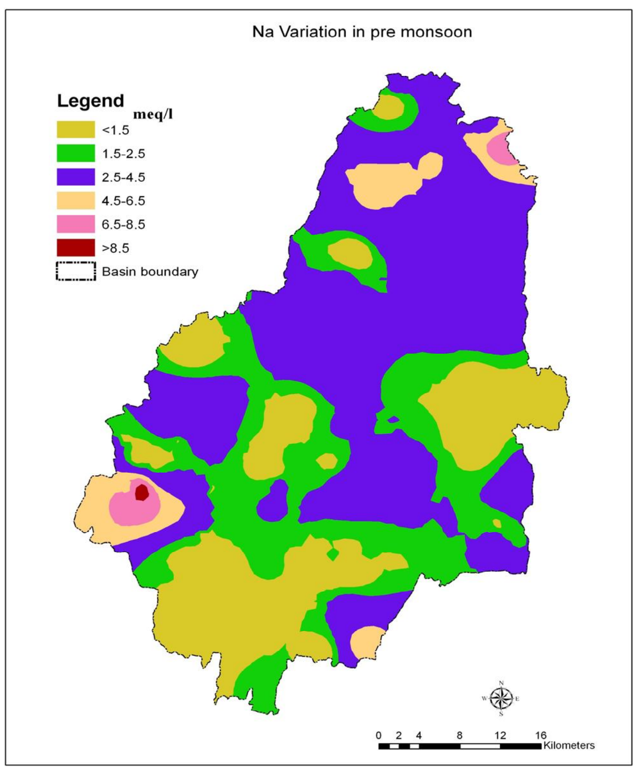


Fig. 4.5f Variation of Na in Wakal river basin during pre-monsoon

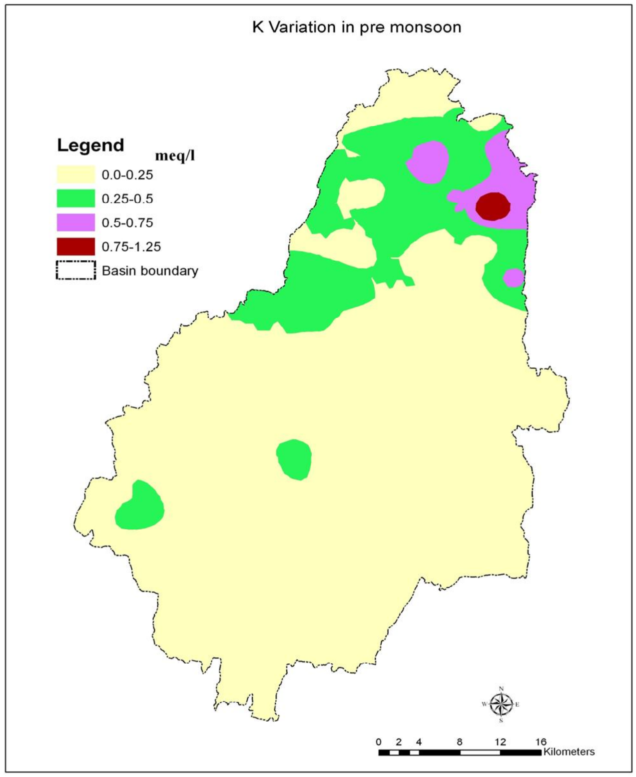


Fig. 4.5g Variation of K in Wakal river basin during pre-monsoon

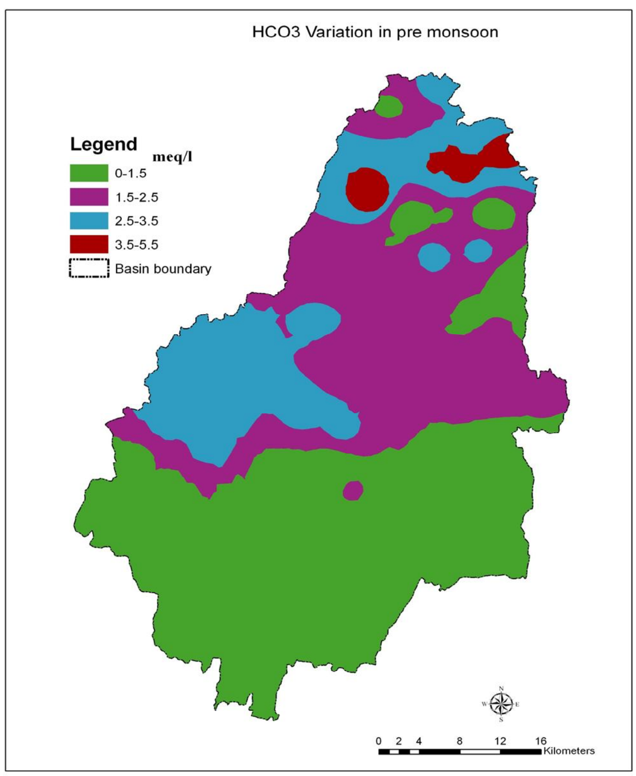


Fig. 4.5h Variation of HCO_3 in Wakal river basin during pre-monsoon

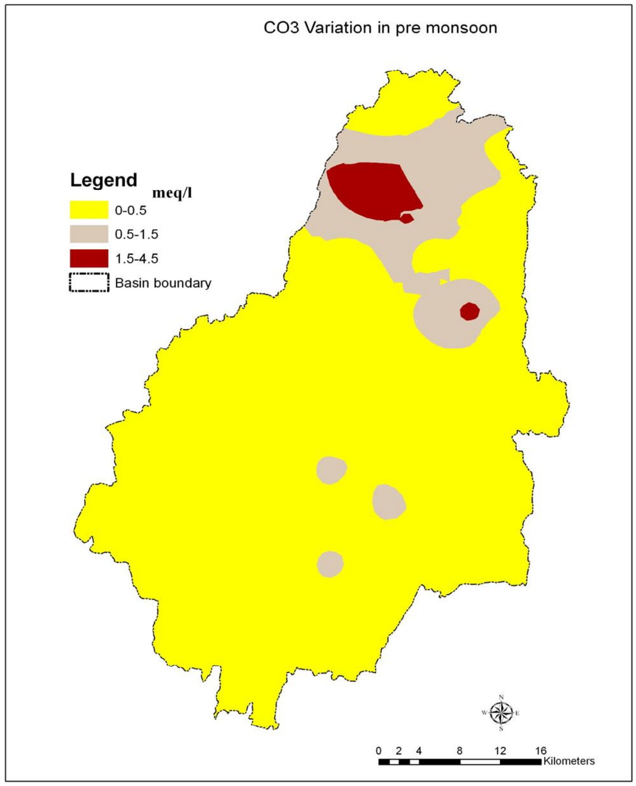


Fig. 4.5i Variation of CO_3 in Wakal river basin during pre-monsoon

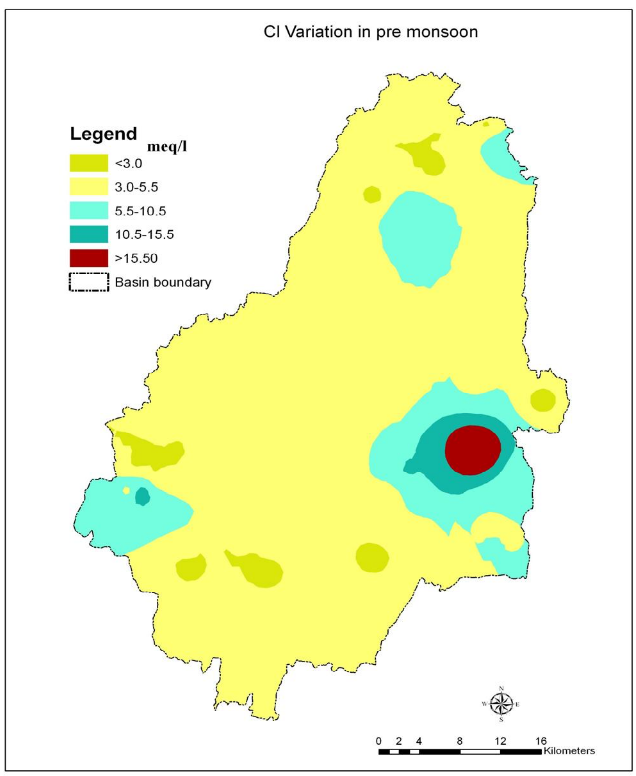


Fig. 4.5j Variation of Cl in Wakal river basin during pre-monsoon

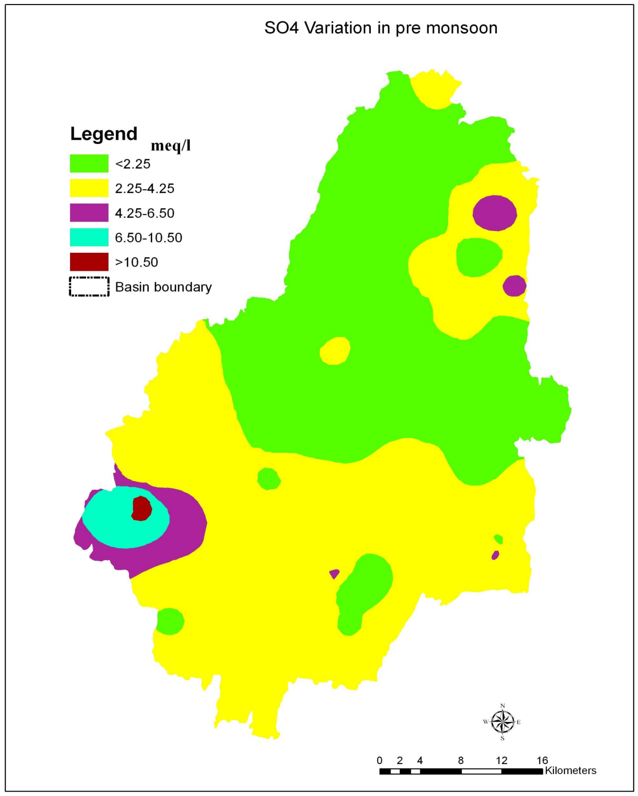


Fig. 4.5k Variation of SO_4 in Wakal river basin during pre-monsoon

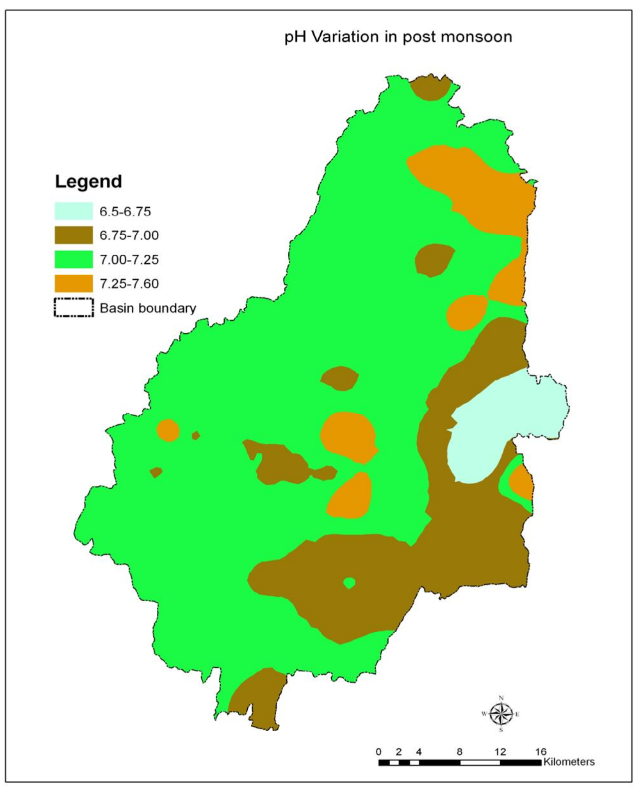


Fig. 4.6a Variation of pH in Wakal river basin during post-monsoon

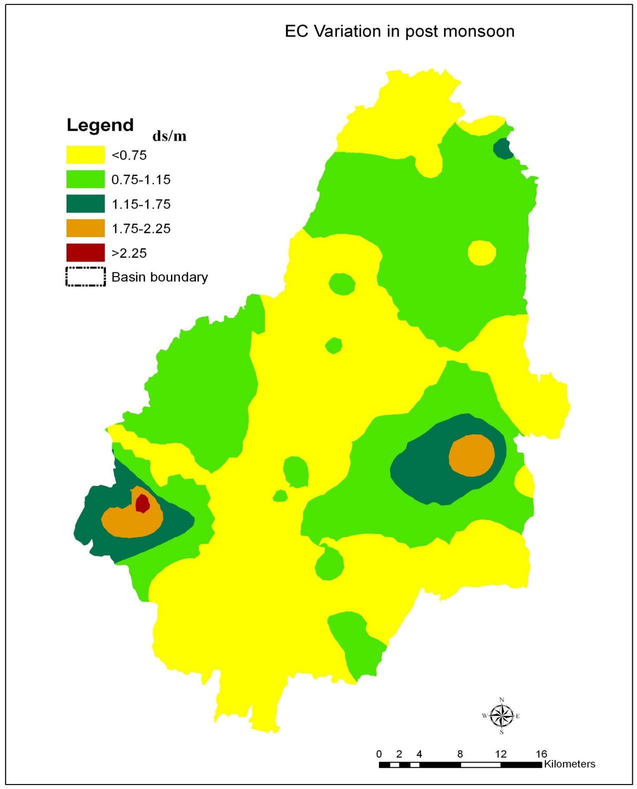


Fig. 4.6b Variation of EC in Wakal river basin during post-monsoon

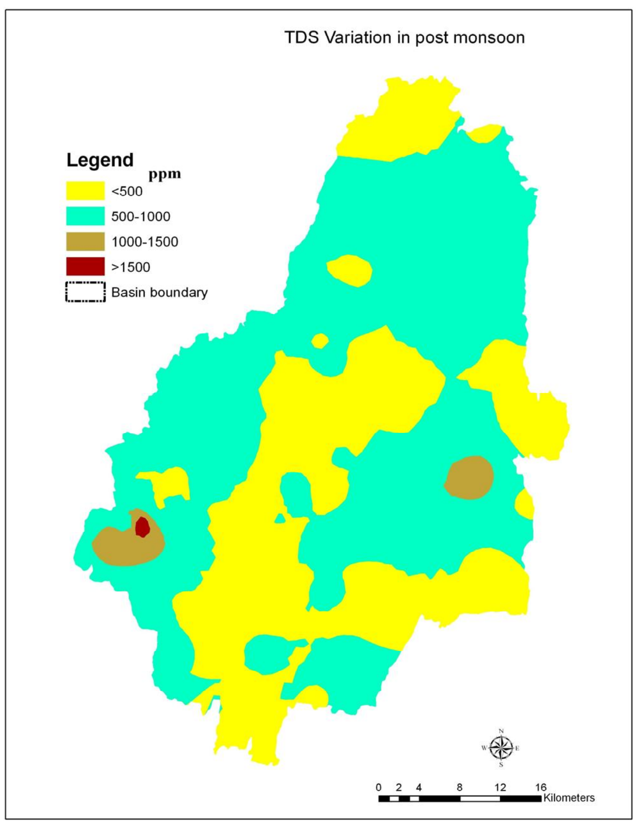


Fig. 4.6c Variation of TDS in Wakal river basin during post-monsoon

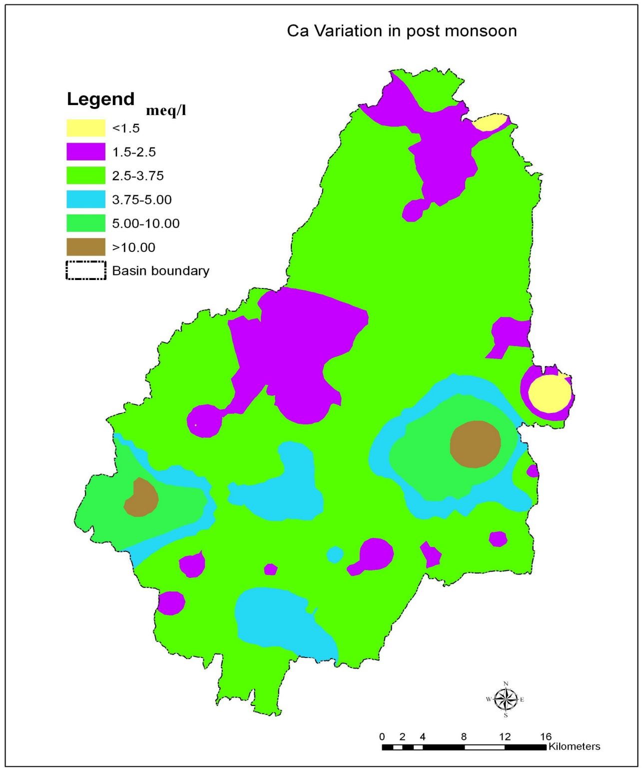


Fig. 4.6d Variation of Ca in Wakal river basin during post-monsoon

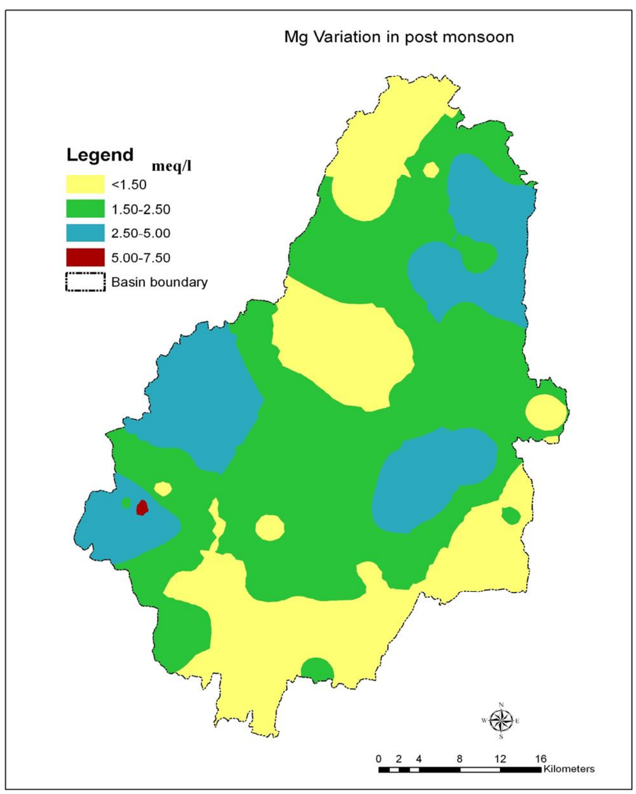


Fig. 4.6e Variation of Mg in Wakal river basin during post-monsoon

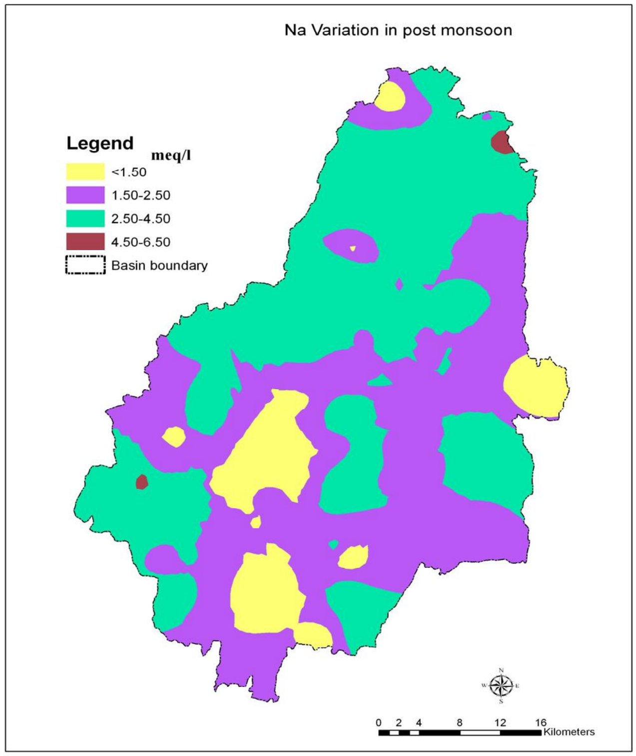


Fig. 4.6f Variation of Na in Wakal river basin during post-monsoon

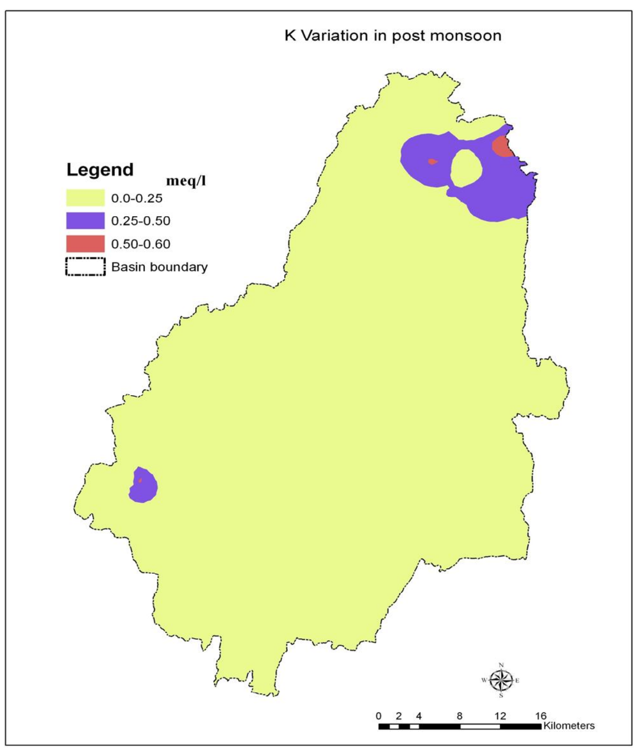


Fig. 4.6g Variation of K in Wakal river basin during post-monsoon

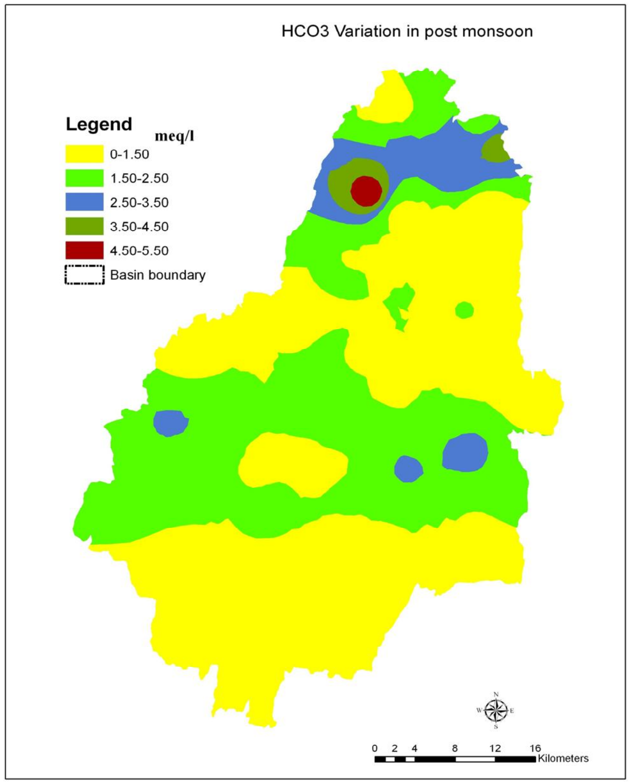


Fig. 4.6h Variation of HCO_3 in Wakal river basin during post-monsoon

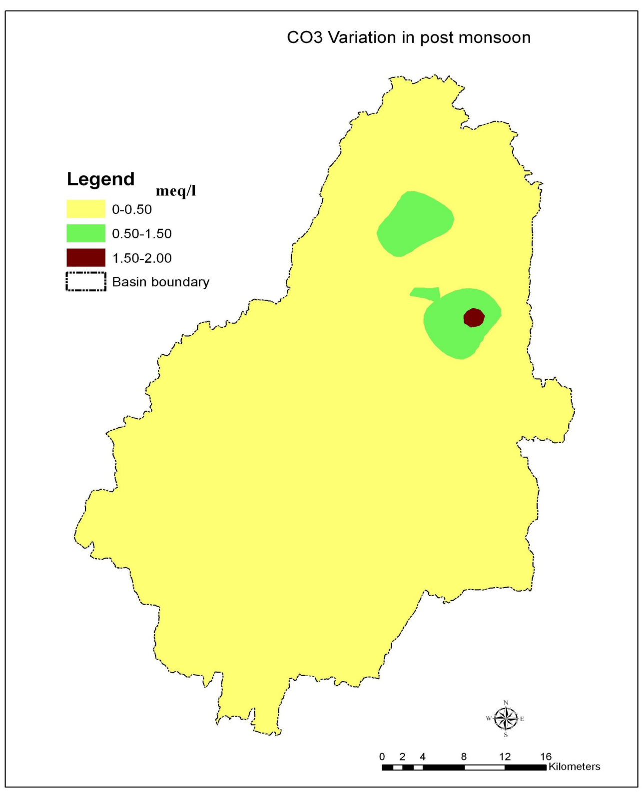


Fig. 4.6i Variation of CO_3 in Wakal river basin during post-monsoon

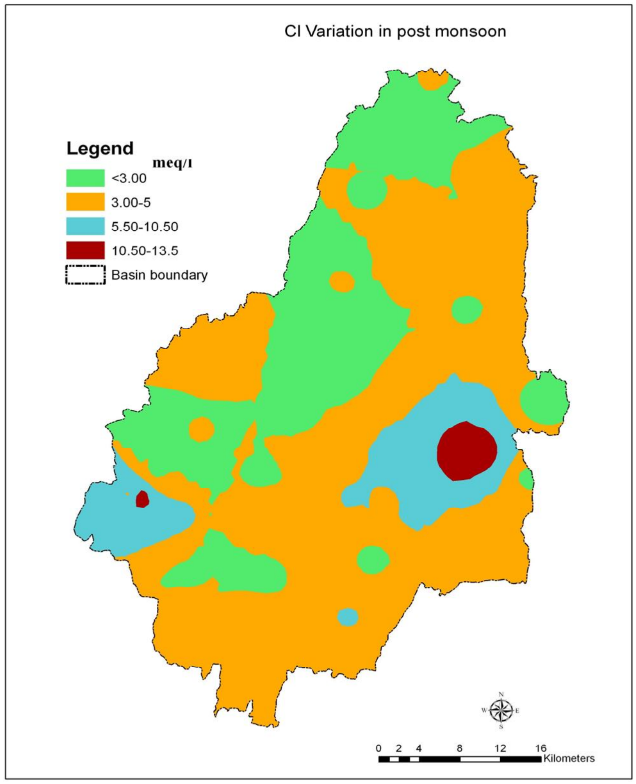


Fig. 4.6j Variation of Cl in Wakal river basin during post-monsoon

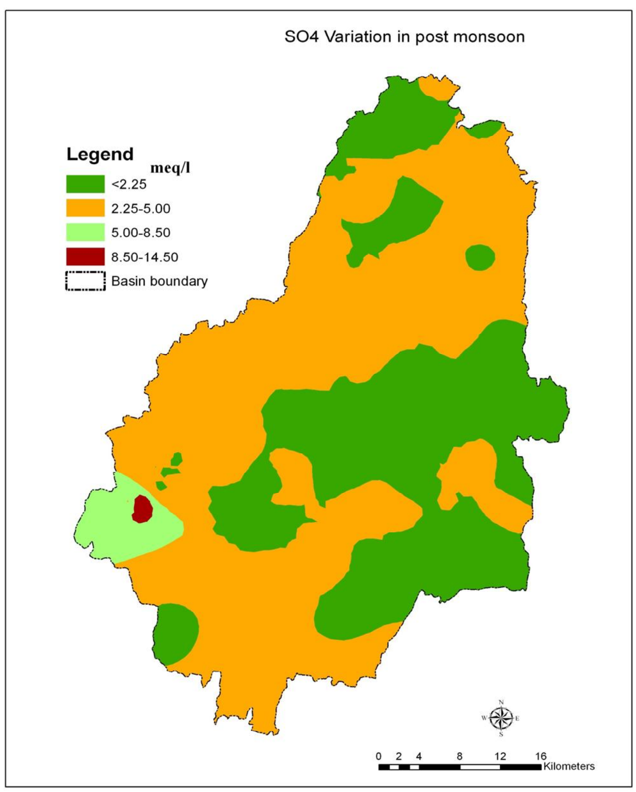


Fig. 4.6k Variation of SO_4 in Wakal river basin during post-monsoon

4.2.1 Spatio-temporal variations of groundwater quality parameters

Eleven groundwater quality parameters, viz., pH, EC, TDS, Ca, Mg, Na, K, HCO_3, CO_3, Cl, and SO_4 were analyzed for determining their spatial and temporal variations. The pH of groundwater varied from 6.0 to 8.0 with a mean of 6.98 in pre monsoon period and 6.5 to 7.6 with a mean of 7.11 in post monsoon period. About 91.36 per cent area of Wakal river basin has pH ranges between 6.75 to 7.25 during post monsoon period (Fig. 4.5a) and 97.2 per cent area ranges between 6.5 to 7.5 during pre monsoon period (Fig. 4.6a). The highest pH was observed near the village Bari in Jhadol block during both pre and post monsoon period.

Concentration of TDS, a measure of quality, ranged from 223 to 2600 mg/l with a mean of 641.38 mg/l during pre monsoon and 200 to 2020 mg/l with a mean of 575.17 mg/l in post monsoon period. Fig. 4.5c and Fig. 4.6c shows that concentration of total dissolved solids remains within its maximum permissible limit (500-1500 mg/l) in most of the study area for both pre and post monsoon period. The western part of the study area, namely Kotra village recorded more than 1500 mg/l TDS in both pre and post monsoon period.

The electrical conductivity (EC) varies from 0.40 to 3.20 ds/m with an average of 0.96 ds/m during pre monsoon and 0.30 to 2.90 ds/m with an average of 0.81 ds/m during post monsoon period. Fig. 4.5b and Fig.4.6b reveals that about 94.4 per cent of the study area during pre monsoon and about 47 per cent area during post monsoon groundwater is not even good to be used for drinking purposes because its EC is more than 0.75 ds/m. The western part of the study area particularly Kotra village found more EC (>2.25 ds/m) during post monsoon period and further it is found in scattered patches during pre monsoon period.

The mean concentration of major ion in groundwater is in the following order: cation:- magnesium>calcium>sodium>potassium during pre monsoon period and calcium> sodium>magnesium>potassium during post monsoon period and Anions:-chloride> sulphate> bicarbonate >carbonate during both pre and post monsoon period. Among the cations, the concentrations of Ca, Mg, Na, and K ions ranged from 1.6 to 7.0, 0.8 to 14.0, 0.2 to 12.1 and 0.0 to 1.2 meq/l with a mean of 3.10, 3.25, 2.98 and 0.13 meq/l, respectively during pre monsoon period and 1.1 to 15.0, 0.0 to 7.4, 0.2 to 6.4 and 0.0 to 0.6 meq/l with a mean of 3.40, 1.94, 2.47 and

0.06 meq/l, respectively during post monsoon period. The major ion chemistry data revealed that Mg and Ca are the most predominant cationic constituents followed by Na during pre monsoon period whereas calcium and sodium are dominated in post monsoon period. The dissolved anions of HCO_3, CO_3, Cl and SO_4 ions ranged from 0.0 to 5.2, 0.0 to 4.2, 2.8 to 19.5 and 0.0 to 17.2 meq/l with a mean of 1.58, 0.24, 4.92 and 2.75 meq/l respectively during pre monsoon period and 0.4 to 5.5, 0.0 to 2.0, 1.5 to 13.5 and 0.0 to 14.2 meq/l with a mean of 1.65, 0.05, 3.69 and 2.52 meq/l respectively during post monsoon period. For the major anions (SO_4, Cl, HCO_3, and CO_3), the chloride and sulphate are found to be the most predominant anions followed by bicarbonate and carbonate during both pre and post monsoon period. Fig. 4.5d and Fig. 4.6d reveals that some part in southeast and southwest of the study area has high calcium content during both pre and post monsoon period. The highest Ca and Mg were found near the village Bira in Jhadol block during pre monsoon period and near the village Kotra during post monsoon period. Figure also reveals that 99 per cent of the study area is within the permissible limit of Ca and Mg during both pre and post monsoon period. The highest Na was found in the village Kotra during both pre and post monsoon period. Most part of the study area was found negligible K and CO_3 during both pre and post monsoon period. The highest HCO_3 was found in the village Nayawas in Kotra block during both pre and post monsoon period. Figure also reveal that about 99 per cent of the study area, the HCO_3 has less than 3.5 meq/l for both pre and post monsoon period. The highest Cl was found in the village Bira in Jhadol block during pre monsoon period and village Kotra during post monsoon period. The highest SO_4 was found in the village Kotra during both pre and post monsoon period.

4.2.2 Correlation

The correlation coefficients (r) among eleven water quality parameters namely pH, EC, TDS, Ca, Mg, Na, K, HCO_3, CO_3, Cl and SO_4 were calculated for correlation analysis and given in Table 4.6 and 4.7 for pre and post monsoon period respectively. Interpretation of correlation gives an idea of quick water quality monitoring method. The EC and TDS shows highly significant and good positive correlation with Ca, Mg, Na, K, Cl and SO_4 during both pre and post monsoon period. It is suggested that presence of calcium, magnesium, sodium, potassium, chloride and sulphate in the study area greatly influence the TDS and EC. The EC also shows highly significant and good positive correlation with TDS during both pre and post monsoon period. The chloride and sulphate also shows highly significant and positive correlation with calcium, magnesium and sodium. Potassium also exhibit highly significant and positive correlation with carbonate and chloride during pre monsoon period and with sulphate during post monsoon period. Chloride is also significant and positive correlation with sulphate during both the period. It is observed that pH, CO_3 and HCO_3 exhibit negative or poor correlation with most of the variable during both pre and post monsoon period (Table 4.6 and 4.7).

4.2.3 Groundwater quality for irrigation purposes

The suitability of water for irrigation depends upon TDS (salinity) and the sodium content in relation to the amounts of calcium and magnesium or SAR. (Alagbe, 2006). The suitability of groundwater for irrigation use was evaluated by calculating SAR, Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), Soluble Sodium Percentage (SSP) and Permeability Index (PI) and given in Appendix B1 and Appendix B2 for pre and post monsoon period respectively.

The waters having SAR values less than 10 are considered excellent, 10 to 18 as good, 18 to 26 as fair, and above 26 are unsuitable for irrigation use (USDA, 1954). In the present study, the SAR values are less than 10 for all samples during both pre and post monsoon and therefore it is graded as excellent for irrigation use (Table 4.8).

Table 4.6 Correlation matrix for different water quality parameters in pre-monsoon

parameter	pH	TDS	EC	Ca	Mg	Na	K	HCO_3	CO_3	Cl	SO_4
pH	1.000	0.044	0.080	-0.076	-0.023	0.248*	-0.012	0.246*	0.066	-0.075	0.070
TDS	0.044	1.000	0.980**	0.598**	0.786**	0.707**	0.414**	0.015	0.124	0.781**	0.758**
EC	0.080	0.980**	1.000	0.614**	0.811**	0.702**	0.423**	0.065	0.165	0.828**	0.699**
Ca	-0.076	0.598**	0.614**	1.000	0.516**	0.131	-0.051	-0.052	-0.104	0.611**	0.408**
Mg	-0.023	0.786**	0.811**	0.516**	1.000	0.226*	0.173	-0.105	-0.091	0.791**	0.568**
Na	0.248*	0.707**	0.702**	0.131	0.226*	1.000	0.507**	0.231*	0.371**	0.407**	0.535**
K	-0.012	0.414**	0.423**	-0.051	0.173	0.507**	1.000	0.054	0.434**	0.294**	0.236*
HCO_3	0.246*	0.015	0.065	-0.052	-0.105	0.231*	0.054	1.000	0.081	-0.078	-0.295**
CO_3	0.066	0.124	0.165	-0.104	-0.091	0.371**	0.434**	0.081	1.000	0.062	-0.102
Cl	-0.075	0.781**	0.828**	0.611**	0.791**	0.407**	0.294**	-0.078	0.062	1.000	0.317**
SO_4	0.070	0.758**	0.699**	0.408**	0.568**	0.535**	0.236*	-0.295**	-0.102	0.317**	1.000

Table 4.7 Correlation matrix for different water quality parameters in post-monsoon

parameter	pH	TDS	EC	Ca	Mg	Na	K	HCO_3	CO_3	Cl	SO_4
pH	1.000	0.041	0.037	-0.105	0.109	0.167	0.157	0.224	0.040	-0.195	0.206
TDS	0.041	1.000	0.994**	0.846**	0.739**	0.639**	0.552**	0.319*	0.108	0.836**	0.792**
EC	0.037	0.994**	1.000	0.865**	0.734**	0.635**	0.535**	0.329*	0.096	0.848**	0.789**
Ca	-0.105	0.846**	0.865**	1.000	0.519**	0.275*	0.337**	0.186	-0.074	0.840**	0.652**
Mg	0.109	0.739**	0.734**	0.519**	1.000	0.262*	0.326*	0.162	0.037	0.582**	0.669**
Na	0.167	0.639**	0.635**	0.275*	0.262*	1.000	0.541**	0.434**	0.312*	0.406**	0.482**
K	0.157	0.552**	0.535**	0.337**	0.326*	0.541**	1.000	0.224	0.241	0.299*	0.544**
HCO_3	0.224	0.319*	0.329*	0.186	0.162	0.434**	0.224	1.000	0.004	0.028	0.087
CO_3	0.040	0.108	0.096	-0.074	0.037	0.312*	0.241	0.004	1.000	0.082	-0.090
Cl	-0.195	0.836**	0.848**	0.840**	0.582**	0.406**	0.299*	0.028	0.082	1.000	0.466**
SO_4	0.206	0.792**	0.789**	0.652**	0.669**	0.482**	0.544**	0.087	-0.090	0.466**	1.000

**Correlation is significant at the $p<0.01$ level (2-tailed), *Correlation is significant at the $p<0.05$level (2-tailed)

Table 4.8 Sodium hazard classes based on USSL classification

SAR	Sodium hazard class	Remark on quality	Pre-monsoon samples	Post-monsoon samples
<10	S1	Excellent	0.126-5.060 (all 63 samples)	0.138-4.071 (all 60 samples)
10-18	S2	Good	Nil	Nil
18-26	S3	Doubtful	Nil	Nil
>26	S4	Unsuitable	Nil	Nil

The Kelly's ratio of unity or less than one is indicative of good quality of water for irrigation whereas above one is suggestive of unsuitability for agricultural purpose due to alkali hazards (Karanth, 1987). The map of the variation of Kelly's Ratio was prepared in GIS environment and shown in Fig. 4.7a and Fig. 4.7b for pre and post monsoon period respectively. From these figures, it is observed that, during pre monsoon period about 94 per cent area has good quality water and 6 per cent area has unsuitable for irrigation due to alkali hazards, but in post monsoon period 99.85 per cent area has good quality of water for irrigation purposes.

The Residual Sodium Carbonate (RSC) value exceeds 2.5 meq/l, the water is generally unsuitable for irrigation. If the value of RSC is between 1.25 and 2.5 meq/l, the water is marginally suitable, while a value less than 1.25 meq/l indicates safe water quality (USDA, 1954). It is evident from Table 4.9 that, RSC values for all the samples of the study area are less than 1.25, (except one sample in pre monsoon) suggesting that whole study area are under safe limit for irrigation use during both pre and post monsoon.

Table 4.9 Groundwater quality based on RSC (Residual sodium carbonate)

RSC	Water class	Pre-monsoon samples	Post-monsoon samples
<1.25	Good	0-1.00 (62 samples)	0-0.90 (all 60 sample)
1.25-2.5	Doubtful	Nil	Nil
>2.5	Unsuitable	3.00 (1 sample)	Nil

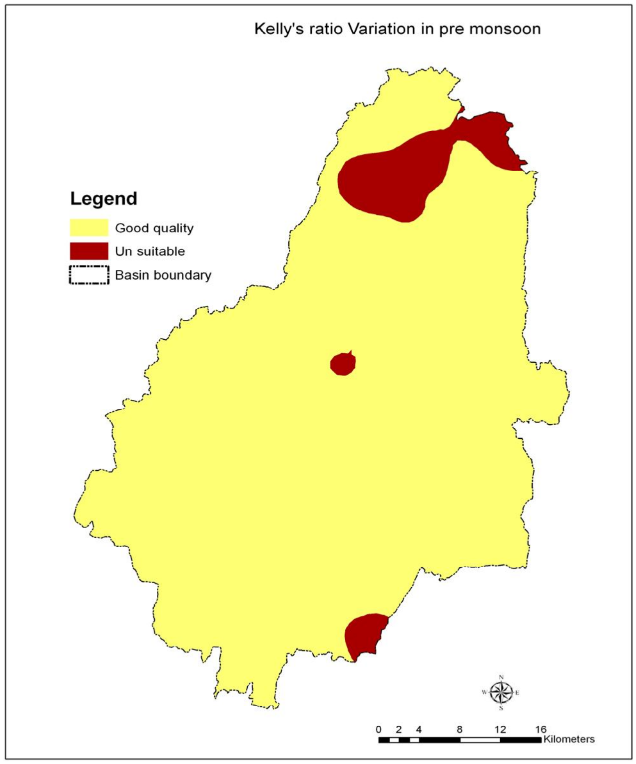


Fig. 4.7a Variation of Kelly's ratio in Wakal river basin during pre-monsoon

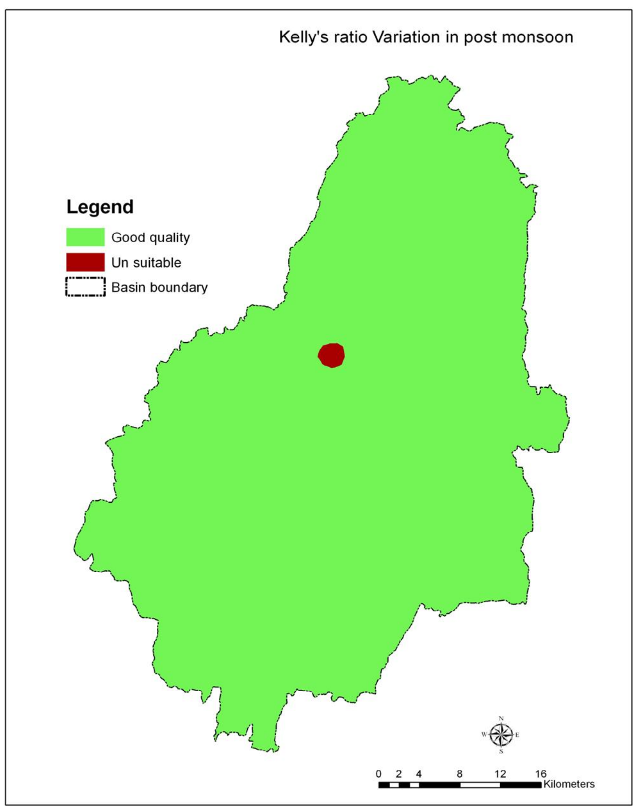


Fig. 4.7b Variation of Kelly's ratio in Wakal river basin during post-monsoon

Wilcox (1955) has proposed classification scheme for rating irrigation waters on the basis of soluble sodium percentage (SSP). The values of SSP less than 50 indicate good quality of water and higher values (i.e. > 50) shows that the water is unsafe for irrigation (USDA, 1954). The map of the variation of SSP was prepared in GIS environment and shown in Fig. 4.8a and Fig. 4.8b for pre and post monsoon period respectively. From these figures, it is observed that, during pre monsoon period about 95 per cent of basin area has good quality water and 5 per cent area is unsafe for irrigation but in post monsoon 99.5 per cent area has good quality of water for irrigation purposes.

The Permeability Index (PI) values > 75 indicate excellent quality of water for irrigation. If the PI values are between 25 and 75, it indicates good quality of water for irrigation. However, if the PI values are less than 25, it reflect unsuitable nature of water for irrigation. The map of the variation of PI was prepared in GIS environment as shown in Fig. 4.9a and Fig. 4.9b for pre and post monsoon period respectively. From these figures, it is observed that about 98 per cent of basin area has good quality water for irrigation purposes in both pre and post monsoon period.

For the purpose of diagnosis and classification, the total concentration of soluble salts (salinity hazard) in irrigation water can be expressed in terms of specific conductance. Classification of groundwater based on salinity hazard is presented in Table 4.10. It is revealed from the EC value that only 2 samples during pre-monsoon and 1 sample during post-monsoon were found to be unsuitable for irrigation purposes.

Table 4.10 Salinity hazard classes

Salinity hazard class	EC in ds/m	Remark on quality	Pre-monsoon samples	Post-monsoon samples
C1	0.100-0.250	Excellent	Nil	Nil
C2	0.250-0.750	Good	0.4-0.75 (16 samples)	0.3-0.75 (34 samples)
C3	0.750-2.250	Doubtful	0.8-1.55 (45 samples)	0.80-1.80 (25 samples)
C4	>2.250	Unsuitable	2.22-3.20 (2 samples)	2.90 (1 sample)

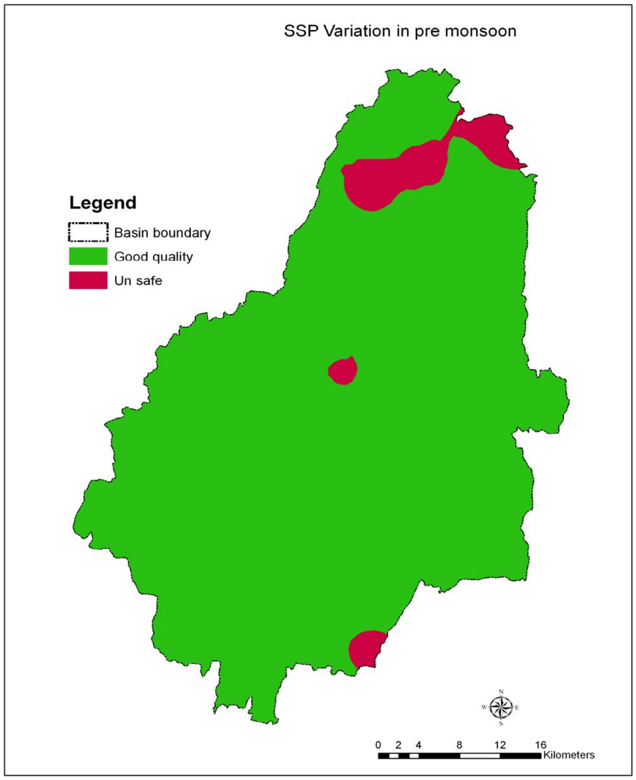


Fig. 4.8a Variation of SSP in Wakal river basin during pre-monsoon

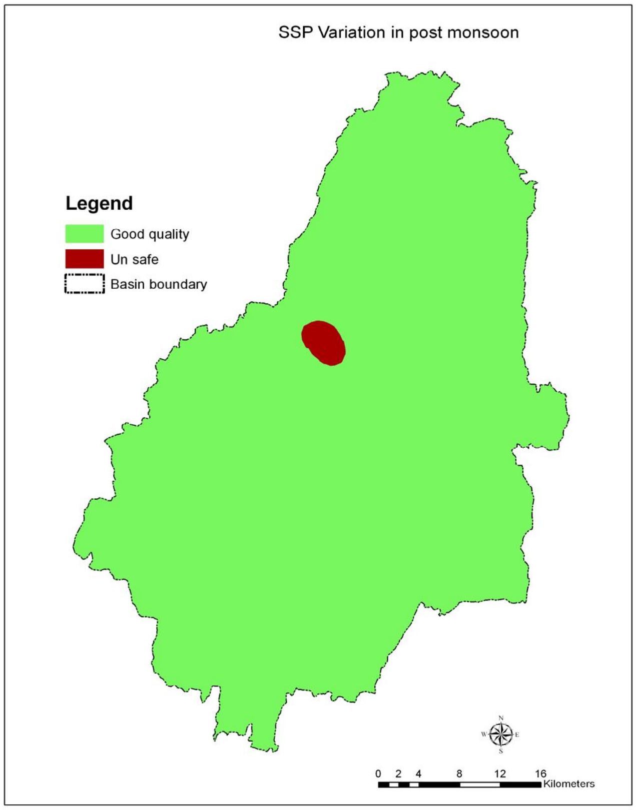


Fig. 4.8b Variation of SSP in Wakal river basin during post-monsoon

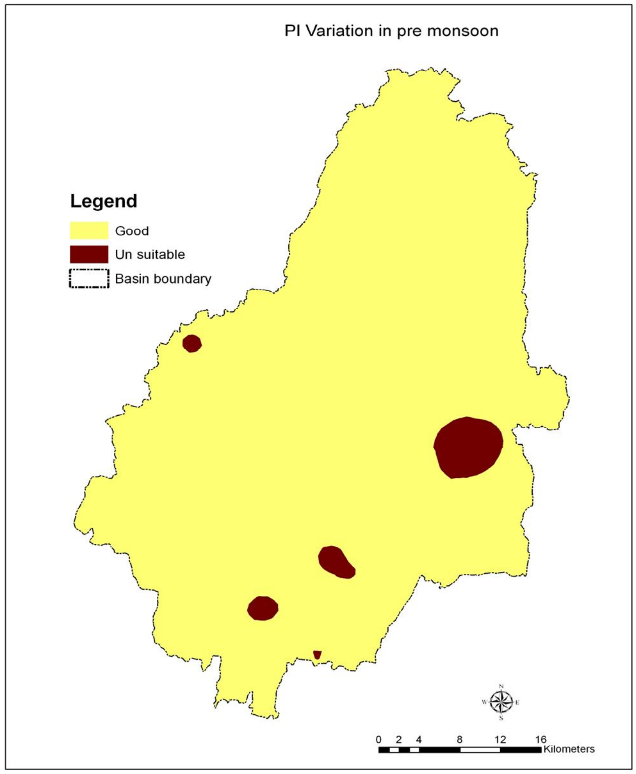


Fig. 4.9a Variation of PI in Wakal river basin during pre-monsoon

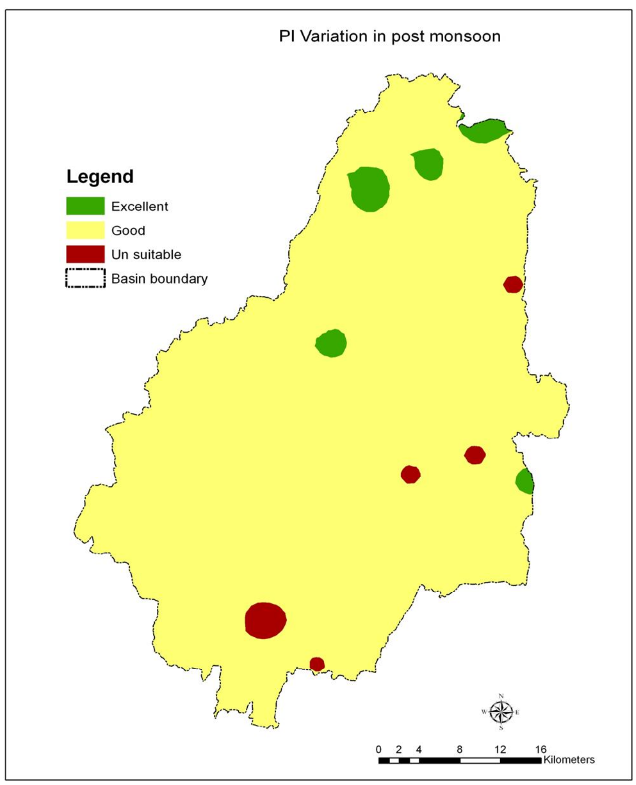


Fig. 4.9b Variation of PI in Wakal river basin during post-monsoon

4.3 Aquifer Parameters

Evaluation of aquifer parameters i.e. transmissivity and specific yield is an important task in groundwater assessment leading to an optimal development. Pumping test is the main field test for determining these parameters. Special significance of these tests are enhanced particularly in dealing with replenishable natural resources for optimum utilization, location of recharge/barrier boundaries, prediction of drawdown and well yields for efficient use of groundwater. The results of pumping tests are discussed in the ensuing section. The tests are analysed, especially, in view of hard-rock formations, and large diameter wells existing at the sites were tested during the course of investigations.

4.3.1 Estimation of aquifer parameters

Pumping test data of ten sites over the different geological formation of the study area of Wakal river basin were analyzed by Papadopulos and Cooper type curve-matching technique. Matching of the observed time-drawdown curve with the type curves of the Papadopulos and Cooper for one test site is illustrated in Fig 4.10 as an example. The pumping test data of different sites of the well are given in Appendix E. Results of the pumping test data analysis along with the details of pumping tests are summarized in Table 4.11. It is apparent from Table 4.11 that the aquifer transmissivity varies from 132.82 to 343.94 m^2/day and the specific yield ranges from 0.00176 to 0.0245 in the basin. It is also evident from Table 4.11 that the transmissivity and specific yield are highly site-specific and vary significantly over small distances. This wide variation in hydraulic parameters of the aquifer suggests strong heterogeneity, which is most likely in fractured subsurface formations of the study area (NABARD, 2006). These point estimates of transmissivity, a raster map is prepared which is used as one of the thematic layer for delineating groundwater potential zones for the Wakal river basin as discussed ahead.

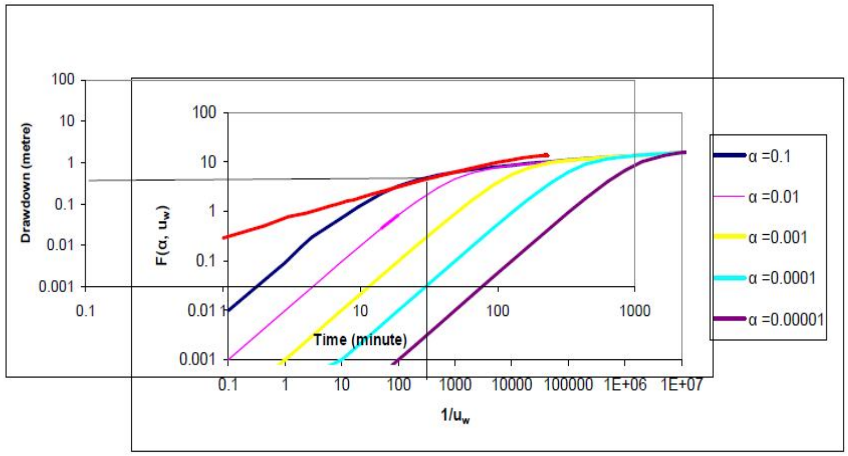


Fig. 4.10 Matching of observed time-drawdown curve with standard Papadopulos-Cooper type curve for well of grid no. 2

Table 4.11 List of wells where pumping tests were conducted and their corresponding aquifer properties

Geological Formation	Site/ Grid No.	Well dia(m) /Area(m^2)	Depth of well (m)	Test duration (min)	Transmissivity (m^2/day)	Specific Yield
Quartizite	9	3.70 x 2.30	8.15	242	174.69	0.00176
	14	4.25	14.60	418	159.52	0.00214
	47	4.20	9.40	410	155.35	0.00958
	54	5.20	14.00	280	343.94	0.00452
Phyllite & Schist	2	5.80	5.00	232	334.39	0.00636
	11	5.50 x 3.50	7.50	284	300.82	0.0163
	24	5.00 x 3.50	11.00	335	343.94	0.00247
	50	5.75 x 2.70	14.35	395	236.72	0.02113
Cal Schist & Gneiss	26	5.00	14.05	404	132.82	0.0245
	43	6.20	12.00	333	343.94	0.00981

4.4 Groundwater Recharge

Groundwater recharge for 60 sites were estimated by using Water Table Fluctuation Method explained earlier in methodology. The average value of specific yield estimated at various locations is taken for different geological formations in computation of groundwater recharge. The minimum computed recharge is 0.15 cm/year and the maximum value is 12.02 cm/year. Average value of groundwater recharge for the study area is found to be 3.05 cm. Computed groundwater recharge values for 60 sites along with location coordinates (longitude and latitudes) in the study area are shown in the Table 4.12. These point estimates of the groundwater recharge were used to prepare a point map of the groundwater recharge for Wakal river basin by using ArcGIS software. Furthermore, this point map was interpolated by using IDWMA technique to generate a raster map of groundwater recharge. This raster map was used as one of the thematic layer for delineating groundwater potential zones for the Wakal river basin.

Table 4.12 Recharge in the well by Water Table Flctuation Method

Well/Grid No.	Location		Groundwater Fluctuation (m)	Recharge (cm/year)
	Latitude	Longitude		
1	24^0 45’ 53.30’’ N	73^0 27’ 15.20’’ E	3.25	1.20
2	24^0 45’ 51.30’’ N	73^0 23’ 51.10’’ E	3.17	1.17
4	24^0 43’ 28.70’’ N	73^0 30’ 39.80’’ E	4.55	1.68
5	24^0 39’ 16.10’’ N	73^0 24’ 05.60’’ E	4.88	1.81
6	24^0 41’ 0.61’’ N	73^0 27’ 30.87’’ E	1.98	2.44
7	24^0 40’ 44.00’’ N	73^0 29’ 19.70’’ E	2.30	2.83
8	24^0 42’ 32.30’’ N	73^0 32’ 24.00’’ E	2.40	2.95
9	24^0 38’ 04.70’’ N	73^0 26’ 04.30’’ E	4.20	1.55
10	24^0 38’ 04.52’’ N	73^0 26’ 05.02’’ E	3.00	1.11
11	24^0 38’ 04.62’’ N	73^0 26’ 04.06’’ E	3.13	3.85
12	24^0 38’ 23.20’’ N	73^0 30’ 52.40’’ E	3.10	3.81
13	24^0 34’ 23.60’’ N	73^0 32’ 12.40’’ E	4.40	5.41
14	24^0 34’ 26.20’’ N	73^0 22’ 21.70’’ E	1.33	0.49
15	24^0 35’ 40.80’’ N	73^0 22’ 52.00’’ E	1.10	1.35
16	24^0 36’ 2.30’’ N	73^0 27’ 23.60’’ E	6.93	8.52
17	24^0 36’ 10.70’’ N	73^0 30’ 21.60’’ E	3.70	4.55
18	24^0 31’ 34.60’’ N	73^0 31’ 18.60’’ E	1.60	1.97
19	24^0 30’ 19.30’’ N	73^0 13’ 32.10’’ E	3.70	1.37
20	24^0 31’ 54.80’’ N	73^0 21’ 06.61’’ E	3.55	1.31
21	24^0 30’ 43.20’’ N	73^0 21’ 55.70’’ E	2.75	1.02
22	24^0 28’ 57.70’’ N	73^0 22’ 22.20’’ E	0.12	0.15
23	24^0 30’ 25.00’’ N	73^0 23’ 18.60’’ E	1.65	2.03
24	24^0 32’ 39.50’’ N	73^0 29’ 52.00’’ E	0.55	0.68
26	24^0 25’ 42.20’’ N	73^0 12’ 30.90’’ E	3.34	5.71
27	24^0 25’ 41.60’’ N	73^0 13’ 04.70’’ E	5.48	2.03
28	24^0 25’ 39.30’’ N	73^0 13’ 42.80’’ E	6.37	2.36
29	24^0 26’ 38.31’’ N	73^0 19’ 58.92’’ E	0.70	0.26
30	24^0 25’ 43.02’’ N	73^0 22’ 21.29’’ E	6.10	7.50
31	24^0 28’ 16.90’’ N	73^0 25’ 55.70’’ E	2.15	2.64
33	24^0 25’ 23.80’’ N	73^0 33’ 02.90’’ E	5.30	6.52
34	24^0 23’ 23.00’’ N	73^0 11’ 36.50’’ E	4.24	7.25
35	24^0 24’ 36.80’’ N	73^0 12’ 47.00’’ E	3.15	1.17
36	24^0 23’ 10.96’’ N	73^0 18’ 20.18’’ E	3.55	1.31
37	24^0 23’ 32.84’’ N	73^0 19’ 27.89’’ E	3.40	1.26
38	24^0 23’ 33.40’’ N	73^0 21’ 41.47’’ E	3.25	4.00
39	24^0 23’ 23.35’’ N	73^0 26’ 16.10’’ E	2.75	3.38

40	24^0 24’ 30.38’’ N	73^0 30’ 15.99’’ E	5.15	6.33
41	24^0 23’ 5.50’’ N	73^0 33’ 17.20’’ E	3.60	4.43
42	24^0 21’ 52.00’’ N	73^0 10’ 06.70’’ E	7.03	12.02
43	24^0 21’ 47.40’’ N	73^0 10’ 34.30’’ E	5.00	8.55
44	24^0 22’ 45.60’’ N	73^0 11’ 49.40’’ E	2.90	1.07
45	24^0 20’ 58.36’’ N	73^0 18’ 20.69’’ E	2.80	1.04
46	24^0 22’ 16.32’’ N	$73^0$18’ 41.97’’ E	1.25	1.54
47	24^0 22’ 8.35’’ N	73^0 23’ 03.45’’ E	1.45	1.78
48	24^0 21’ 58.40’’ N	73^0 25’ 01.20’’ E	1.80	2.21
49	24^0 20’ 0.90’’ N	73^0 31’ 30.00’’ E	2.40	2.95
50	24^0 21’ 22.00’’ N	73^0 32’ 16.20’’ E	3.25	4.00
52	24^0 16’ 53.50’’ N	73^0 12’ 21.30’’ E	4.91	8.40
53	24^0 17’ 22.60’’ N	73^0 13’ 16.90’’ E	3.53	1.31
54	24^0 17’ 11.10’’ N	73^0 18’ 11.00’’ E	3.10	1.15
55	24^0 18’ 2.30’’ N	73^0 22’ 03.70’’ E	1.95	2.40
56	24^0 17’ 22.50’’ N	73^0 22’ 53.80’’ E	2.75	3.38
57	24^0 18’ 13.50’’ N	73^0 23’ 56.50’’ E	2.90	3.57
58	24^0 19’ 19.20’’ N	73^0 31’ 20.90’’ E	2.90	3.57
60	24^0 15’ 31.50’’ N	73^0 12’ 26.60’’ E	2.70	1.00
61	24^0 15’ 15.90’’ N	73^0 17’ 59.50’’ E	2.80	1.04
62	24^0 12’ 29.00’’ N	73^0 21’ 08.20’’ E	1.20	1.48
63	24^0 15’ 06.70’’ N	73^0 22’ 54.90’’ E	2.35	2.89
64	24^0 10’ 43.60’’ N	73^0 18’ 42.60’’ E	3.20	1.18
66	24^0 13’ 3.20’’ N	73^0 23’ 57.10’’ E	5.70	7.01

4.5 Features of Different Thematic Maps

The eight thematic layers i.e. geomorphology, soil, slope, topographic elevation, land use/land cover, post monsoon groundwater depth, recharge and transmissivity were generated for the Wakal river basin. The areal extent of different features of these thematic layers is given in Table 4.13.

4.5.1 Geomorphology

Based on the physiographic characteristics, the landforms of the study area have been classified into four different units namely: (i) pediment, (ii) buried pediment, (iii) valley fills, and (iv) structural hills as shown in Fig. 4.11. The characteristic features of these geomorphic units are described below.

4.5.1.1 Pediment

The study area has pediment, encompassing an area about of 554.14 km^2, which is 28.95 per cent of the total study area. It is mainly broad gently sloping rock flooring, erosional surface of low relief between hills and plains. The pediment is comprised of varied lithology, criss crossed by fractures and faults. This type of geomorphology mainly occurs in middle and southeast portion of the study area along with small scattered patches in the entire area. It is poor for groundwater occurrence.

4.5.1.2 Buried pediment

Buried pediment is pediment covered essentially with relatively thicker alluvial, colluvial or weathered materials. A pediment is a gently inclined slope of transportation and/or erosion that truncates rock and connects eroding slopes or scarps to the areas of sediment deposition at lower levels (Oberlander, 1989). The study area has buried pediment mainly in south, southeast and southwest portions encompassing an area of 461.83 km^2, which is 24.13 per cent of the total study area. It is moderate to good for groundwater occurrence.

4.5.1.3 Valley fills

The study area has valley fills, encompassing an area about of 412.34 km^2, which is 21.54 per cent of the total study area. The valley fills are formed by fluvial activity usually at lower topographic locations and comprised of boulders, cobbles, pebbles gravels, sand slit, and clay. The unit has consolidated sediment deposits and is usually good for groundwater occurrence. This type of geomorphology is mainly in southwest portion of the study area.

4.5.1.4 Structural hill

About 486 km^2 area, which is 25.39 per cent of the total study area is falling under this geomorphologic feature. Structural hills are linear to arcuate hills showing definite trend lines with varying lithology associated with folding, faulting, etc. This type of geomorphology mainly occurs in north portion and boundary of the study area.

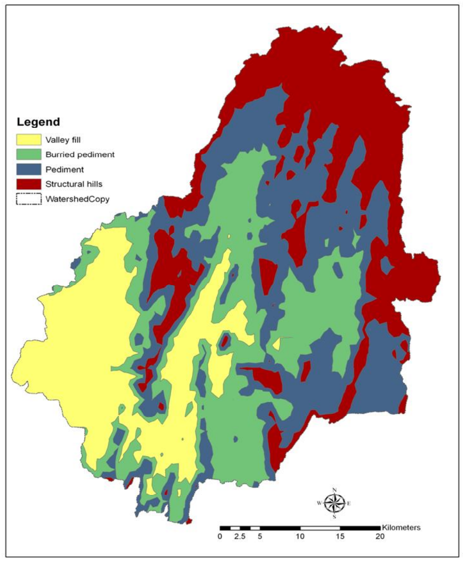


Fig. 4.11 Thematic layer of Geomorphology

4.5.2 Soil map

The thematic layer of soil for the study area reveals six main soil classes viz., Loamy to Coarse loam, Loamy skelton to Fine loam, Fine to Loamy skelton, Loamy skelton to Coarse loam, Rock outcrop to Loamy, Rock Outcrop to Fine loam. It is apparent from Fig.4.12 that the majority of the study area is dominated by loamy to coarse loam and rock outcrop to loamy soil, which is about 86 per cent of the total study area. These six soil classes can be categorized into five classes namely ‘very good’, ‘good’, ‘moderate’, ‘poor’ and ‘very poor’ according to their influence on groundwater occurrence.

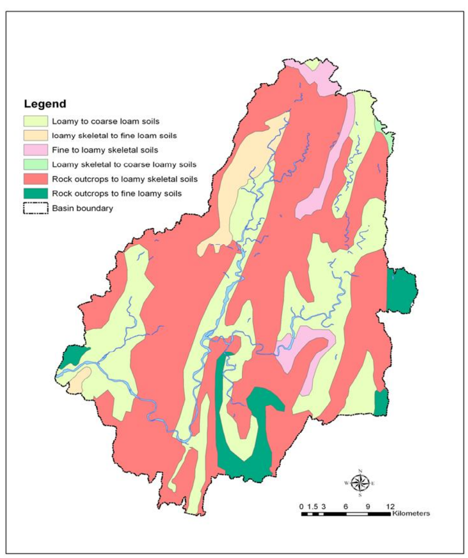


Fig. 4.12 Thematic layer of Soil

4.5.3 Slope map

The slope percentage in the area varies from 0 to 50 per cent. Based on the slope, the study area were divided into six slope classes: (i) 0-3%, (ii) 3-5%, (iii) 5-8%, (iv) 8-15%, (v) 15-30% and (vi) >30%. The area having 0 to 3% slope falls in the ‘very good’ category due to the nearly flat terrain and relatively high infiltration rate. It covers 398.76 km^2 areas, which is about 21 per cent of the total study area. The area with 3 to 5% slope is considered as ‘good’ for groundwater storage due to slightly undulating topography with some runoff, which is about 14 per cent area of the total study area. The area having a slope of 5 to 8% causes relatively high runoff and low infiltration, and hence categorized as ‘moderate’, which is about 27 per cent area of the total study area. The fourth (8-15%), fifth (15-30%) and sixth (>30%) category are considered as ‘poor’ and ‘very poor’ due to higher slope and runoff, which is about 39 per cent area of the total study area. A slope map prepared from Digital Elevation Model is shown in Fig. 4.13.

4.5.4 Topographic elevation map

The topographic elevation map has been divided into five classes: (i) <400 m, (ii) 400-600 m, (iii) 600-800 m, (iv) 800-1000 m and (v) >1000 m. The highest topographic elevations (about >1000 m MSL) exist in small scattered patches in the north and northeastern portions of the study area. The topographic elevation is usually low in the southwest and south portions of the study area. The study area is dominated by topographic elevations of 400-600 m in 703 km^2 areas, which is about 37 per cent of the study area and 600-800 m in 557 km^2 areas, which contributes 29 per cent of the study area, located in middle, south, southwest and southeast portions of the study area. The topographic elevation map is shown in Fig. 4.14.

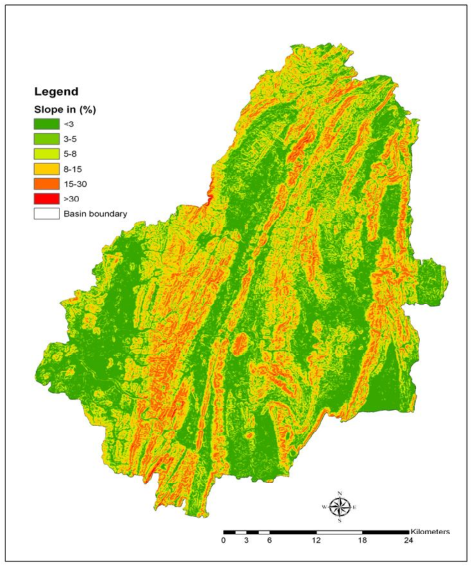


Fig. 4.13 Thematic layer of Slope

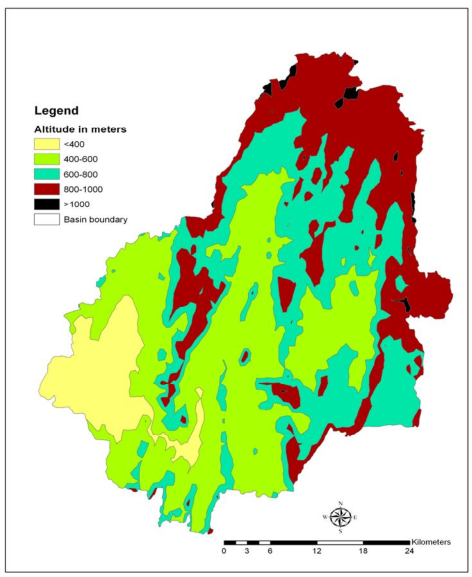


Fig. 4.14 Thematic layer of Topographic Elevation

4.5.5 Land use/ Land cover map

A land use/land cover thematic map was distinguished into four different classes: (i) agricultural land, (ii) fairly dense forest, (iii) degraded forest and (iv) open scrub, as shown in Fig. 4.15. Different land use/land cover classes were ranked according to their water requirement. Agricultural lands were given the highest rating over other land use features because it requires more water for irrigation, resulting in groundwater recharge. Dense forest was assigned a higher rating than degraded forest, because vegetation prevents direct evaporation of water from the soil, and the roots of a plant also absorb water, thus preventing water loss. Open scrub was assigned the lowest rating, because it allow less time for the infiltration of water.

4.5.6 Post-monsoon groundwater depth map

The post-monsoon groundwater depth in the study area ranges from 0.28 m to 14.45 m below the ground surface. Post-monsoon groundwater depth map for the study area is shown in Fig. 4.16, which reveals that the groundwater depth ranges from 0 to 4 m in 34 per cent of the total study area and from 4 to 6 m in 54.26 per cent of the total study area. The deeper groundwater levels in the east portion of the study area along with small scattered patches are due to excessive pumping of groundwater for irrigation.

4.5.7 Recharge map

The annual net groundwater recharge in the study area varies from 0.15 to 12.02 cm. Based on these recharge estimates, the area has been divided into 5 recharge zones: (i) 0-1 cm/year, (ii) 1-2 cm/year, (iii) 2-3 cm/year, (iv) 3-4 cm/year, and (v) >4 cm/year as shown in Fig. 4.17. It is apparent from the figure that a net recharge of 1-4 cm/year is dominant in the study area, which is about 82 per cent of the total study area. Some patches in the north and middle portions of the study area have very low recharge rate (<1 cm/year). A high recharge rate (>4 cm/year) is confined to five patches in the east, southeast and southwest portions of the study area.

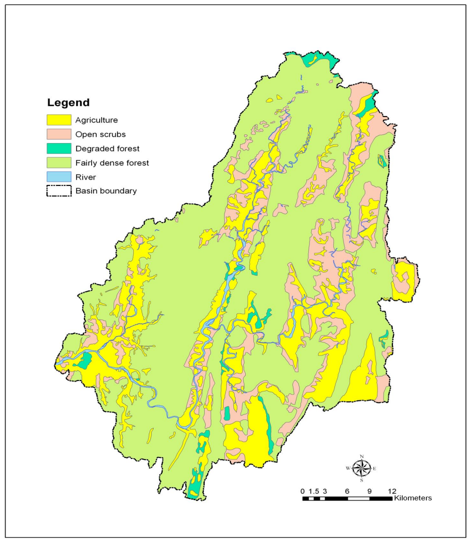


Fig. 4.15 Thematic layer of Land use/Land cover

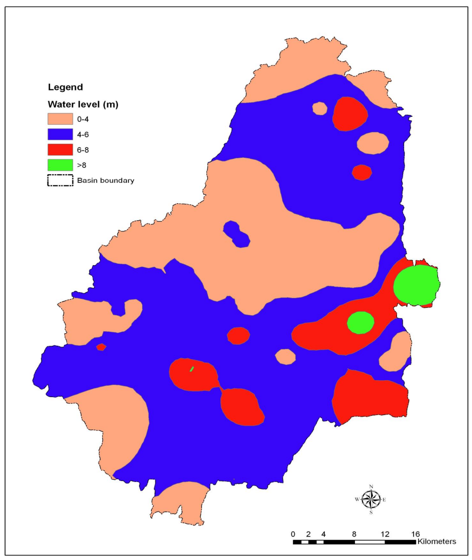


Fig. 4.16 Thematic layer of Post-monsoon Groundwater Depth

4.5.8 Transmissivity map

Transmissivity values obtained from the pumping tests have been used to prepare point map of transmissivity. Further, this point map was interpolated by using IDWMA method to generate a raster map of transmissivity. It is seen that the transmissivity in the study area varies from 132.82 m^2/day to 343.94 m^2/day. Based on these transmissivity values, the area was divided into five transmissivity classes namely 'extremely low' (<150 m^2/day), 'very low' (150-200 m^2/day), 'low' (200-250 m^2/day), 'moderate' (250-300 m^2/day) and 'high' (>300 m^2/day) as shown in Fig.

4.18. It is apparent from the map that a very low transmissivity (150-200 m^2/day) is confined to three patches in the west and southeast portions of the study area. The transmissivity ranges of 200-250 m^2/day is dominant in the study area, which is about 50 per cent of the total study area.

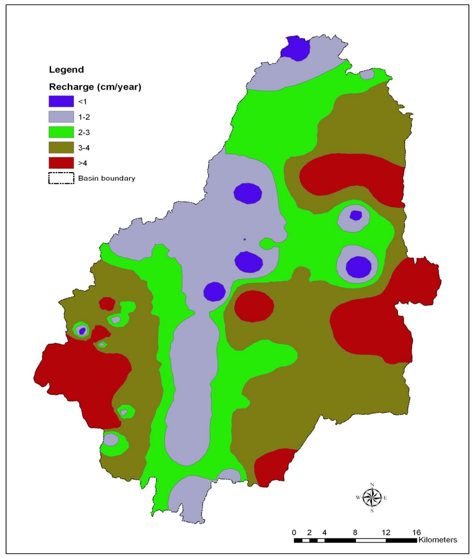


Fig. 4.17 Thematic layer of Recharge

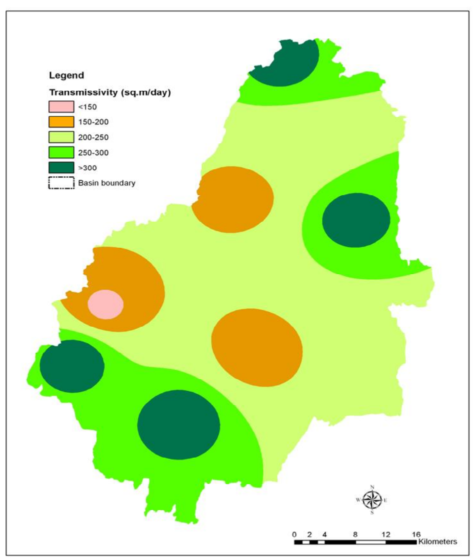


Fig. 4.18 Thematic layer of Transmissivity

Table 4.13 Areal extent of different features of the eight thematic layers

Features of thematic layers	**Area (km^2)**	**% Area**
1. Geomorphology classes		
(i) Vally Fill	412.34	21.54
(ii) Buried Pediment	461.83	24.13
(iii) Pediment	554.14	28.95
(iv) Structural Hill	486.01	25.39
2. Land use/Land cover classes		
(i) Agriculture	434.70	22.71
(ii) Fairly Dense Forest	1146.27	59.88
(iii) Degraded Forest	37.25	1.95
(iv) Open Scrub	296.10	15.47
3. Soil classes		
(i) Loamy to Coarse loam	560.90	29.30
(ii) Loamy skelton to Fine loam	78.94	4.12
(iii) Fine to Loamy skelton	81.83	4.28
(iv) Loamy skelton to Coarse loam	4.99	0.26
(v) Rock outcrop to Loamy skelton	1083.88	56.62
(vi) Rock Outcrop to Fine loam	103.78	5.42
4. Slope classes (%)		
(i) <3	398.76	20.83
(ii) 3-5	267.04	13.95
(iii) 5-8	511.58	26.72
(iv) 8-15	251.53	13.15
(v) 15-30	284.70	14.87
(vi) >30	200.71	10.48
5. Topographic elevation classes		
(i) <400 m	168.77	8.82
(ii) 400-600 m	702.99	36.72
(iii) 600-800 m	556.63	29.08
(iv) 800-1000 m	473.82	24.75
(v) >1000 m	12.11	0.63
6. Recharge classes		
(i) <1 cm/year	40.78	2.13
(ii) 1-2 cm/year	440.15	22.99
(iii) 2-3 cm/year	480.58	25.11
(iv) 3-4 cm/year	641.15	33.49
(v) >4 cm/year	311.66	16.28
7. Post monsoon groundwater depth classes		
(i) 0-4 m	650.62	33.99
(ii) 4-6 m	1038.79	54.26
(iii) 6-8 m	190.18	9.93
(iv) >8 m	34.73	1.82
8. Transmissivity classes		
(i) <150 m^2/day	14.31	0.74
(ii) 150-200 m^2/day	261.08	13.64
(iii) 200-250 m^2/day	961.11	50.21
(iv) 250-300 m^2/day	466.28	24.36
(v) > 300 m^2/day	211.54	11.05

4.6 Groundwater Potential Zoning

The eight thematic maps namely geomorphology, soil, slope, topographic elevation, land use/land cover, post monsoon groundwater depth, recharge and transmissivity described in the previous section were considered for identifying groundwater potential zones in the study area. The assignment of weights to the themes and their features and the integration of different themes in a GIS environment are discussed in the following sections.

4.6.1 Weights for thematic maps

After understanding the behaviour of different thematic features with respect to groundwater control in the study area, the different themes and their individual features of these themes were assigned suitable weights. The weights assigned to all the thematic layers are presented in Table 4.14.

Table 4.14 Weights of eight themes for groundwater potential zoning

S.No.	Themes	Weight
1	Geomorphology	5
2	Land use/Land cover	4
3	Soil	3.5
4	Slope	3.5
5	Topographic Elevation	3
6	Recharge	4.5
7	Post-monsoon Groundwater Depth	4
8	Transmissivity	1

The derivation of the normalized weights for individual themes using Saaty's analytic hierarchy process (AHP) and eigenvalue technique is shown in Table 4.15 as an example. Similarly, the assigned weights of different features of individual themes were normalized by AHP and eigenvalue technique and are presented in Tables 4.16 to Table 4.23.

Table 4.15 Pair wise comparison matrix and normalized weights of the themes

Themes	Themes								Normalized Weight
	GM	LU	Soil	Slope	TE	RE	WD	TR	
GM	5/5	5/4	5/3.5	5/3.5	5/3	5/4.5	5/4	5/1	0.173
LU	4/5	4/4	4/3.5	4/3.5	4/3	4/4.5	4/4	4/1	0.145
Soil	3.5/5	3.5/4	3.5/3.5	3.5/3.5	3.5/3	3.5/4.5	3.5/4	3.5/1	0.121
Slope	3.5/5	3.5/4	3.5/3.5	3.5/3.5	3.5/3	3.5/4.5	3.5/4	3.5/1	0.121
TE	3/5	3/4	3/3.5	3/3.5	3/3	3/4.5	3/4	3/1	0.105
RE	4.5/5	4.5/4	4.5/3.5	4.5/3.5	4.5/3	4.5/4.5	4.5/4	4.5/1	0.156
WD	4/5	4/4	4/3.5	4/3.5	4/3	4/4.5	4/4	4/1	0.145
TR	1/5	1/4	1/3.5	1/3.5	1/3	1/4.5	1/4	1/1	0.034
						Column Total =			1.000

Note: GM = Geomorphology, LU = Land use/Land cover, TE = Topographic Elevation, RE = Recharge, WD = Post-monsoon Groundwater Depth, TR = Transmissivity.

Table 4.16 Normalized weights of the geomorphology classes for groundwater potential zoning

Geomorphology Classes	Groundwater Prospect	Weight Assigned	Normalized Weight
Water Body	Very good	8	0.348
Vally Fill	Good	7	0.305
Buried Pediment	Moderate	4	0.173
Pediment	Poor	3	0.131
Structural Hill	Very Poor	1	0.043

Table 4.17 Normalized weights of the land use/land cover classes for groundwater potential zoning

Land Use/Land Cover Classes	Groundwater Prospect	Weight Assigned	Normalized Weight
Agriculture	Good	6	0.375
Fairly Dense Forest	Good	5	0.313
Degraded Forest	Moderate	3	0.188
Open Scrub	Poor	2	0.125

Table 4.18 Normalized weights of the soil classes for groundwater potential zoning

Soil Classes	Groundwater Prospect	Weight Assigned	Normalized Weight
Loamy to Coarse loam	Very good	8	0.308
Loamy skelton to Fine loam	Good	6	0.231
Fine to Loamy skelton	Moderate	5	0.192
Loamy skelton to Coarse loam	Moderate	4	0.154
Rock outcrop to Loamy	Poor	2	0.077
Rock Outcrop to Fine loam	Very Poor	1	0.038

Table 4.19 Normalized weights of the slope classes for groundwater potential zoning

Slope Classes (%)	Groundwater Prospect	Weight Assigned	Normalized Weight
<3	Very good	7	0.269
3-5	Good	6	0.231
5-8	Moderate	5	0.192
8-15	Poor	4	0.155
15-30	Poor	3	0.115
30-50	Very poor	1	0.038

Table 4.20 Normalized weights of Topographic Elevation for groundwater potential zoning

Topographic Elevation Classes	Groundwater Prospect	Weight Assigned	Normalized Weight
<400 m	Very good	6	0.30
400-600 m	Good	5	0.25
600-800 m	moderate	4	0.20
800-1000 m	Poor	3	0.15
>1000 m	Very poor	2	0.10

Table 4.21 Normalized weights for the recharge classes for groundwater potential zoning

Recharge Classes	Groundwater Prospect	Weight Assigned	Normalized Weight
<1 cm/year	Very Poor	1	0.053
1-2 cm/year	Poor	2	0.105
2-3 cm/year	Moderate	3	0.158
3-4 cm/year	Good	6	0.316
>4 cm/year	Very good	7	0.368

Table 4.22 Normalized weights of Post monsoon groundwater depth classes for groundwater potential zoning.

Post monsoon groundwater depth classes	Groundwater Prospect	Weight Assigned	Normalized Weight
0-4 m	Very good	8.5	0.378
4-6 m	Good	7	0.311
6-8 m	Moderate	5	0.222
>8 m	Poor	2	0.089

Table 4.23 Normalized weights of Transmissivity classes for groundwater potential zoning

Transmissivity classes	Groundwater Prospect	Weight Assigned	Normalized Weight
<150 m^2/day	Very poor	1	0.087
150-200 m^2/day	Poor	1.5	0.130
200-250 m^2/day	Poor	2	0.174
250-300 m^2/day	Moderate	3	0.261
> 300 m^2/day	Moderate	4	0.348

4.6.2 Groundwater potential zones

The groundwater potential map of the study area (Fig. 4.19) reveals four distinct zones representing ‘good’, ‘moderate’, ‘poor’ and ‘very poor’ groundwater potential in the area. The ‘good’ groundwater potential zone mainly encompasses valley fill and buried pediment areas around the river systems. It demarcates the areas where the terrain is most suitable for groundwater storage and also indicates the availability of water below the ground. The area covered by ‘good’ groundwater potential zone is about 382.94 km^2 (20 per cent). Parts of Khed Brahma, Kotra and Jhadol blocks of villages Jura, Dalmiya, Subri, Guran, Boti Kalar, Kotra, Thana, Ora etc. are mainly fall under this zone. The southeastern portion and some small patches in the south, central, northeastern and southwestern portions of the study area of villages Pipalimala, Adkaliya, Pipali Khadri, Khara, Richhavar, Bagpura, Virpura, Dhabra, Majawad etc. fall under ‘moderate’ groundwater potential zone. It encompasses an area of 596.61 km^2, which is about 31.17 per cent of the total study area. The ‘poor’ groundwater potential zone mainly dominant in the study area and encompassing an area of 654.48 km^2, which is 34.19 per cent of the total area. The groundwater potential in the north portion and some small patches in the central, northeastern and northwestern portions of the study area of villages Suroh, Meran, Thal, Inton Ka Khet, Sivdiya, Behda, Mokhi, Bhat, Kankal Ka Nal etc. are very poor covering an area of 280.29 km^2, which is 14.64 per cent of the total study area. The ‘very poor’ groundwater potential in the study area is most likely due to the presence of hillocks, rock outcrops and steep slopes.

The use of strategic documents, such as the map of groundwater potential zoning, allows the ability to predict sites favourable for well positioning and to optimize expenses of new water resources research (Ettazarini, 2007). The method can thus be used as a first estimate of the groundwater potentiality that goes parallel with probability of drilling success, but local studies in favorable zones should provide precisions for drilling location. Good groundwater potential zones are the most favourable for installing new production wells. It is most likely that well yields will be high in the good potential zones. Whereas, low well yields occur in poor groundwater potential zones.

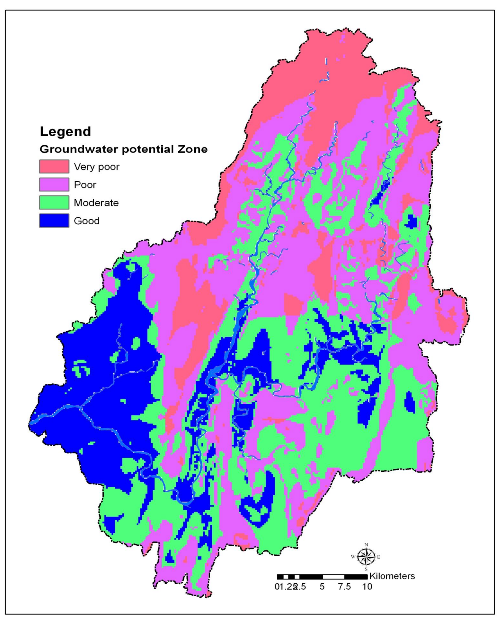


Fig. 4.19 Groundwater potential zone map of Wakal river basin

4.6.3 Groundwater resources management

The favourable artificial groundwater recharge zone for the study area is delineated using RS and GIS technique. In this map green colour indicates the favourable zone for artificial recharge. It was found in the southern part of the basin which includes villages of Guran, Thana, Dhermariya, Lahari, Ombara, Sisavi, Mahuli, Siphon, Amarpura, Khachan, Khakhar etc. For artificial recharge, suitable recharge structures such as percolation ponds, check dams and earthen dams are recommended for construction. The area, which is favorable for artificial recharge is 174.39 km^2, which contributes only 9.2 per cent of the total study area. Similar study was also carried out for the Ahar river basin of Udaipur district. The results of the study revealed that the favourable artificial recharge zone for the study area was found to be 44.6 km^2, which was 12.7 per cent of the total study area (Nishtha, 2009). Map of the suitable zones for artificial recharge of the study area is shown in Fig. 4.20.

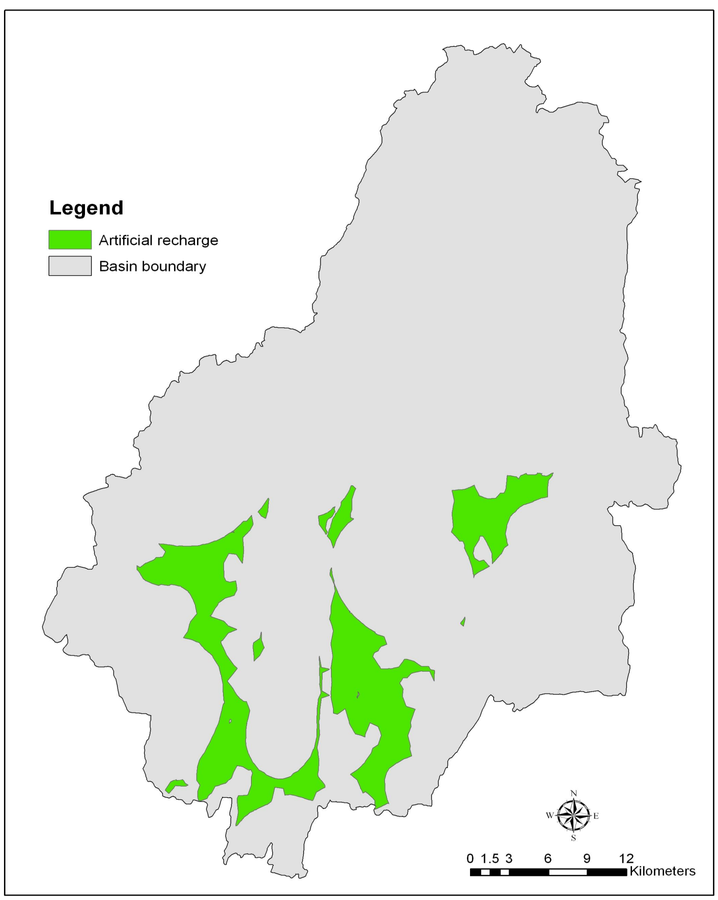


Fig. 4.20 Map showing zones favourable for artificial groundwater recharge

V- SUMMARY AND CONCLUSIONS

Groundwater is an important and a dependable source of water supplies in all climatic regions including both urban and rural areas of developed and developing countries. Unfortunately, lowering of groundwater table and aquifer depletion due to overexploitation and increasing pollution are threatening our ecosystems and even the life of our future generations. Rajasthan has always been a water deficit area. The deficit between demand and supply is 8 BCM at present and likely to increase to 9 BCM by 2015 (State Water Policy, Rajasthan, 2010). The stage of groundwater exploitation, which was just 35 per cent in year 1984, has reached a level of 138 per cent in 2008. Out of 237 blocks in the state, only 30 blocks are in safe category (State Water Policy, Rajasthan, 2010). This calls for immediate remedial measures to address the critical water resources situation in the state.

The Wakal river basin, in Rajasthan state of India's is most water scarce regions. It is located between 24° 46' 34.65" to 24° 8' 49.41" N latitude and 73° 6' 23.41" to 73° 35' 54.18" E longitude with an area of 1914.32 km^2, of which 1867.47 km^2 (98 per cent) falls in Udaipur district of Rajasthan and 46.84 km^2 in Gujarat. The maximum length of the basin is 71.22 km (N-S) and the maximum width is 41.01 km (E-W). Mansi is the main tributaries of Wakal river, which joins Wakal river near Birothi village in Jhadol tehsil. The entire Wakal river basin is hard-rock terrain situated in southern part of Rajasthan. It suffers from growing water scarcity, which is aggravated by frequent droughts. The groundwater level in the study area gradually declines with the advancement of dry season. Particularly, in summers, surface water sources dry up and groundwater level falls below the economic lift of pumping. Thus, water scarcity poses significant threat to the sustainable water supply and livelihoods in the study area. In the study area no scientific study has been conducted to date by any agency for sustainable groundwater management. The detailed hydrogeologic and geochemical investigations using modern tools and techniques are necessary for the efficient planning and management of groundwater resources. Looking to the severity of the problem and also considering these facts the Wakal river basin has been selected for the study and effective planning for sustainable groundwater management were carried out. The overall objective of the present study was to groundwater resource management and to assess groundwater quality in the hard-rock aquifer systems of study area using Remote Sensing and GIS techniques. In this study, an effort has been made for ensuring sustainable groundwater management, using Remote Sensing and GIS.

It was analysed in the process of study that use of GIS can make the cumbersome geomorphological analysis and prioritization of sub-basin as an easy task. The total drainage area of Wakal river basin is divided into seven sub-basins for the analysis. The drainage pattern of the basin ranges from dendritic to subdendritic at higher elevations and parallel to sub-parallel in the lower elevations. The drainage characteristics of the seven sub-basins of the study area were determined. The determination of geomorphological characteristics included area and perimeter, stream number (order wise), stream length, basin length, stream frequency, bifurcation ratio, stream length ratio, form factor, circulatory ratio, elongation ratio, drainage density, constant of channel maintenance, length of overland flow, relief ratio, relative relief and ruggedness number. The calculated values of geomorphological characteristics were interpreted in terms of drainage basin characteristics.

The groundwater quality of the Wakal river basin was also analyzed. For this purpose entire Wakal river basin is divided into 66 grid considering size of one grid as 6km x 6km. The water samples were collected from 63 sites during pre monsoon and 60 sites during post monsoon period. These samples were analyzed in the laboratory to find out different water quality parameters such as pH, EC, TDS, Ca, Mg, Na, K, CO_3, HCO_3, Cl and SO_4. The different water quality parameter map of the Wakal river basin was prepared under GIS environment and the spatio-temporal variations of groundwater quality parameters were analyzed. The suitability of groundwater for irrigation use was evaluated by calculating Sodium Absorption Ratio (SAR), Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), Soluble Sodium Percentage (SSP) and Permeability Index (PI).

In the Wakal river basin, aquifer parameters were also determined because previously it was never computed by any organization. The study deals with the determination of aquifer parameters i.e. transmissivity and specific yield. These aquifer parameters were determined by pumping tests method. In the basin total of ten pumping tests were conducted in large-diameter dug wells at different sites. The pumping test data were analyzed by Papadopulos and Cooper (1967) method using curve-matching technique. These point estimates of transmissivity, a raster map was prepared which was used as one of the thematic layer for delineating groundwater potential zones for the Wakal river basin. Groundwater recharge was computed at 60 sites of Wakal river basin by water table fluctuation (WTF) method. The average value of estimated specific yield is taken for different geological formation in computation of groundwater recharge. These point estimates of the groundwater recharge were used to prepare a point map of the groundwater recharge for Wakal river basin using Arc GIS software. Furthermore, this point map was interpolated by using IDWMA technique to generate a raster map of groundwater recharge. This raster map was used as one of the thematic layer for delineating groundwater potential zones in the Wakal river basin.

Finally, groundwater potential in the study area was identified by considering eight thematic maps, viz., geomorphology, soil, slope, topographic elevation, land use/land cover, recharge, post-monsoon groundwater depth and transmissivity. These maps were prepared using conventional and remote sensing data with the help of Arc GIS software. These themes and their features were assigned suitable weights as suggested by Saaty (1980) according to the relative importance of theme/feature in groundwater occurrence. The weights of the thematic maps and their individual features were then normalized by using Saaty's analytical hierarchy process. The selected thematic maps after assigning weights were integrated in a GIS environment to generate a groundwater potential index (GWPI) map, based on which groundwater potential zones were identified in the study area. The thematic layers used in this study to determine suitable artificial recharge zones are transmissivity, recharge, groundwater level (post-monsoon), topographic elevation, soil and slope. These layers were combined using Boolean Logic analysis to delineate zones of suitability for artificial recharge structures.

Specific conclusions drawn based on the results of the study are listed below.

1. The Wakal river basin has maximum seventh order basin. The sub-basin-1 to sub-basin-4 are sixth order basin whereas sub-basin-5 to sub basin-7 are seventh order basin.
2. The graph between logarithm of stream number and stream order confirms the validity of the Horton's law. The mean bifurcation ratio value varies

from 3.12 to 4.56 for the basins of the study area, which indicates that all the sub basins are falling under normal basin category.

3. The drainage density values of the sub-basins exhibits positive correlation with the stream frequency and there is an increase in stream population with respect to increasing drainage density. High value of stream frequency (F_s) indicates availability of impermeable sub-surface material, sparse vegetation, high relief conditions and low infiltration capacity.

4. Form factor values of whole basin and sub-basins of the study area vary from 0.23 to 0.54, which indicates that basin is having sub-circular and elongated shape.

5. The value of constant of channel maintenance (C) of the study area varied from 0.24 to 0.32 indicates that all the sub-basins are under the influence of high structural disturbance, low permeability, steeps to very steep slopes and high surface runoff.

6. The low values of length of overland flow of basin and sub-basins indicate short flow paths, with steep ground slopes, reflecting the areas associated with more run-off and less infiltration.

7. The ruggedness number of Wakal river basin indicates that the area is extremely rugged with high relief and high stream density. Relief ratio of the basin is very less i.e. 0.011 which indicates that the basin need to be treated with soil and water conservation measures.

8. The prioritization of the basin was carried out on the basis of the geomorpho- logical parameters and based on this the first priority is given to sub-basin-3 for soil and water conservation measures followed by sub-basin 1, 4, 5, 2, 7 and 6.

9. The pH of groundwater varied from 6.0 to 8.0 with a mean of 6.98 in pre monsoon period and 6.5 to 7.6 with a mean of 7.11 in post monsoon period. The highest pH was recorded in the village Bari of Jhadol block during both pre and post monsoon period. TDS concentration in most of the study area was found within its maximum permissible limit (500-1500 mg/l) during both pre and post monsoon period.

10. In 94.4 per cent of the study area during pre monsoon and 47 per cent area during post monsoon, EC was found to be more than 0.75 ds/m which indicates that this water is not safe for regular drinking throughout the year and dangerous for the health.

11. The cations concentrations of Ca, Mg, Na, and K ions ranged from 1.6 to 7.0, 0.8 to 14.0, 0.2 to 12.1 and 0 to 1.2 meq/l with a mean of 3.10, 3.25, 2.98 and 0.13 meq/l, respectively during pre monsoon period and 1.1 to 15.0, 0 to 7.4, 0.2 to 6.4 and 0 to 0.6 meq/l with a mean of 3.40, 1.94, 2.47 and 0.06 meq/l, respectively during post monsoon period. The major ion chemistry data revealed that Mg and Ca are the most predominant cationic constituents followed by Na during pre monsoon period and calcium and sodium are dominated in post monsoon period.

12. The dissolved anions of HCO_3, CO_3, Cl and SO_4 ions ranged from 0.0 to 5.2, 0.0 to 4.2, 2.8 to 19.5 and 0.0 to 17.2 meq/l with a mean of 1.58, 0.24, 4.92 and 2.75 meq/l respectively during pre monsoon period and 0.4 to 5.5, 0.0 to 2.0, 1.5 to 13.5 and 0.0 to 14.2 meq/l with a mean of 1.65, 0.05, 3.69 and 2.52 meq/l respectively during post monsoon period. For the major anions (SO_4, Cl, HCO_3, and CO_3), the chloride and sulphate are found to be the most predominant anions followed by bicarbonate and carbonate during both pre and post monsoon period.

13. Some part in southeast and southwest of the study area in villages Bira, Nayagaon, Saldari, Kotra etc. has high calcium content during both pre and post monsoon period. The highest Ca and Mg were found in the village Bira of Jhadol block during pre monsoon period and in the village Kotra during post monsoon period. About 99% of the study area is within the permissible limit of Ca and Mg during both pre and post monsoon period. The highest Na was found in the village Kotra during both pre and post monsoon period.

14. Most part of the study area was found negligible K & CO_3 during both pre and post monsoon period. The highest HCO_3 was found near the village Nayawas in Kotra block during both pre and post monsoon period. The highest SO_4 was found near the village Kotra during both pre and post monsoon period.

15. The EC and TDS show highly significant and good positive correlation with most of the parameters except CO_3 and HCO_3 during both pre and post monsoon period. The EC also show highly significant and good positive correlation with TDS during both pre and post monsoon period.

16. The suitability of groundwater for irrigation use was evaluated on the basis of Sodium Absorption Ratio (SAR), Kelly's Ratio (KR), Residual Sodium Carbonate (RSC), Soluble Sodium Percentage (SSP) and Permeability Index (PI) and found that most of the study area groundwater is suitable for irrigation purpose during both pre and post monsoon period.

17. On the basis of study, the study area were divided into four groundwater potential zones, viz., 'good', 'moderate', 'poor', and 'very poor', which cover 20 per cent good groundwater potential, 31.17 per cent moderate, 34.19 per cent poor and 14.64 per cent very poor groundwater potential zone. About 48.83 per cent of the basin falls under poor potential zone. Therefore, immediate attention is required for ensuring sustainable groundwater management in the basin.

18. The parts of Khed Brahma, Kotra and Jhodol blocks are mainly fall under good groundwater potential zone. The groundwater potential in north portion of villages Suroh, Meran, Thal, Inton ka khet, Sivdiya, Behda, Mokhi, Bhat etc. and some small patches in the central, northeastern and northwestern portions of the study area are very poor.

19. In the study the suitable artificial recharge zone were also identified and it was found that the southern part of the basin which includes villages of Guran, Thana, Dhermariya, Lahari, Ombara, Sisavi, Mahuli, Siphon, Amarpura, Khachan, Khakhar etc. are suitable for artificial recharge. The area suitable for artificial recharge is 174.39 km^2, which is 9.2 per cent of the total area of the basin.

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