ASSESSMENT OF AQUIFER VULNERABILITY TO POLLUTION IN HARIDWAR DISTRICT USING OVERLAY INDEXING APPROACH

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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HYDROLOGY

By

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in this thesis, entitled **ASSESSMENT OF AQUIFER VULNERABILITY TO POLLUTION IN HARIDWAR DISTRICT THROUGH OVERLAY INDEXING APPROACH** in fulfillment of requirement for the award of the degree of Master of Technology, submitted in the **Department of Hydrology,** Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out during a period from June 2005 to July, 2006 under the supervision of **Dr.H.Joshi, Dr.S.Kumar, Dr.M.D.Nautiyal.** The matter presented in this thesis has not been submitted by me for the award of any other degree of this of any other institute university.

Dated: 29.06.06

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Ground water is an important source of drinking water. Ground water is believed to be free from pollution. But the fact is that, when water percolates through the opening inside the soil and substrata it will dissolve various mineral elements as well as pollutants. Hence, areas which are prone to such contamination have to be delineated. Aquifer vulnerability studies meant for identifying areas sensitive to pollution by studying the intrinsic characteristics of soil, unsaturated zone and saturate zone.

The Haridwar district of Uttaranchal state has taken up for the present study. Area is an upcoming industrial hub. Intensive agriculture is going on in the area. Haridwar district is one of the most populous districts of Uttaranchal. Combined effect of urbanization, industrialization and agricultural practices can produce contaminants.

In the present study DRASTIC method is applied to assess the vulnerability conditions of the area. All the parameters of the DRASTIC have been collected and Index is estimated. An index for water quality is also attempted. Then DRASTIC Vulnerability Index has validated with Index of Aquifer Water Quality. Sensitivity analysis has done to know the relative importance and variability among the parameters and DRASTIC Vulnerability Index. Also Vulnerability indices are correlated with aquifer resistivity and land use

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CHAPTER – I

INTRODUCTION

1.1 INTRODUCTION

Ground Water has been considered as an important source of drinking water due to its relatively low susceptibility to pollution in comparison to surface water and its large storage capacity. Increase in population and related anthropogenic impacts can contaminate the ground water resources, and the contaminated ground water may pose serious health hazards. Ground water quality remediation is prohibitively expensive and slow. Hence strategies are required to preserve an optimum ground water quality. Thus, management of this vital resource becomes a priority for an effective environmental management.

This has necessitated seeking ways for effective and efficient methods for protecting ground water resources from future contamination. Aquifer vulnerability assessment had been introduced in 1968, for identification of the areas likely to become contaminated as a result of activities at or near the land surface. Once identified, these areas could be targeted by careful land use planning, intensive monitoring and by suitable prevention and control measures to arrest contamination of the underlying ground water (Babiker et.al, 2005).

1.2 GENERAL CONCEPTS OF AQUIFER VULNERABILITY ASSESSMENT

As water moves from surface to the ground water regime concentration of its constituents gets enriched. The degree of attenuation depends up on the type of soil and aquifer characteristics and also, the nature and magnitude of contaminant. These physical, chemical and biochemical attenuation processes depend on site specific soil and aquifer characteristics as wells as on geochemical properties of each pollutant. Importance of these attenuation processes can be partially or completely bypassed by the physical conditions of the aquifer and infiltration conditions (Gogu et, al., (1999).

Vulnerability assessment of ground water is not a characteristic that can be directly measured in the field. The idea of vulnerability is based on the fundamental concept that "some land areas are more vulnerable to ground water contamination than others (Vrba and Zaporozec, 1994). Degree of ground water vulnerability to contamination is a function of type of soil, subsoil and other hydro-geological conditions and it varies from place to place.

Thus, vulnerability is distinct from pollution risk. Pollution risk depends not only on vulnerability but also on the existence of significant pollutant loading entering the subsurface environment. It is possible to have high aquifer vulnerability but no risk of pollution, if there is insignificant pollutant loading, and to have high pollution risk in spite of low vulnerability, if the pollutant loading is exceptional. The risk of pollution is determined not only by the intrinsic characteristics of the aquifer, which are relatively static and hardly changeable but also on the existence of potentially polluting activities, which are dynamic factors which can in principle be changed and controlled (Lobo – Ferreira, 1991)

It is important to recognize that the vulnerability of the aquifer would be different for different pollutants. It is a sound practice to evaluate vulnerability to pollution in relation to a particular class of pollutants such as organics, heavy metals, pathogens etc.

Aquifer vulnerability maps are required for implementation of management plans to prevent degradation of ground water quality. Vulnerability maps would be useful for implementation of ground water quality monitoring program. These maps would be useful for examining existing and potential policies for ground water protection vise, zoning and other programs that influence new development.

1.2.1 Definition

Before we assess ground water vulnerability to pollution, it is necessary to formally define the term vulnerability. Vulnerability means different things to different people. In the area of water resources, vulnerability has been defined within the context of system performance evaluation (Hashimoto et. al., 1982). Three fundamental concepts of system performances are (i) how likely the system is to fail, which is measured by its **reliability** (ii) how quickly the system returns to a satisfactory state once a failure occurred, is expressed by its **resiliency** and (iii) how severe the likely consequence of failure, may be measured by its **vulnerability**.

The concept can be defined in the context of ground water pollution, if "system failure" would be replaced by "pollutant loading" and severity of consequences can be measured in terms of water quality deterioration. It has a close similarity with risk of pollution.

In agreement with recommendations of international conference on "vulnerability of soil and ground water to pollutants" Duijvenbooden and Waegemish, (1987) have defined ground water vulnerability as "Sensitivity of ground water quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer".

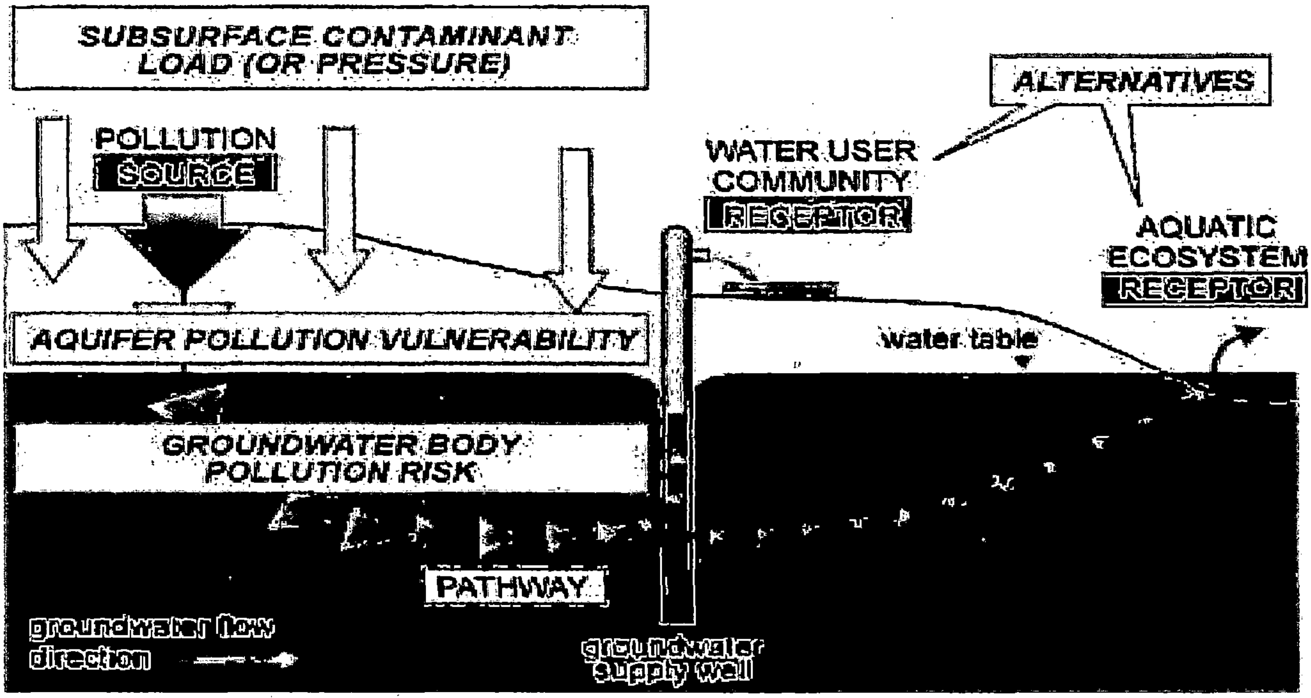


Fig.1.1 Conceptualization of aquifer vulnerability to pollution

Aquifer vulnerabilities are of two types

i. Intrinsic vulnerability

ii. Specific vulnerability

Intrinsic vulnerability is defined as vulnerability of ground water to contamination generated by human activities taking account of inherent geological, hydrological and hydro-geological characteristics of the area and, independent of the nature of contaminant.

Intrinsic vulnerability is a dimensionless and non measurable property (G.P.Panagopoulos et. al., 2005). The main attributes used for the assessment of intrinsic vulnerability are soil properties and characteristics of unsaturated and saturated zones. Attributes of secondary importance include topography, ground water-surface water relation and the nature of the underlying unit of the aquifer.

Specific vulnerability is a term used to defined vulnerability of ground water to a particular contaminant or a group of contaminants taking account their contaminant properties and their relationships with the various components of intrinsic vulnerability.

Contaminant loading is determined by quantity, the physiochemical property, and the way in which the various contaminants are released into the environment. Specific vulnerability is mostly assessed in terms of the danger for the ground water system becoming exposed to specific contamination. The most important parameters are specific contaminant travel time within the unsaturated zone and its residence time inside the aquifer medium; and also attenuation capability of the soil-rock-ground water system with respect to the properties of the individual contaminants.

1.2.2 Assessment

Three main approaches can be distinguished in the assessment of ground water vulnerability to contamination (R.C.Gogu et, al., 1999)

1. Vulnerability assessment considering only soil and unsaturated zone without taking into account the transport processes within the saturated zone, e.g., GOD method (Foster 1987), Irish Approach (Daly and Drew, 1999) and AVI method (Van Stemvoort et, al., 1993).
2. The approach based on delineation of protection zone for ground water supply systems where ground water flow and contaminant transport system processes within the saturated zone are considered to some extent.
3. An approach targeting soil, unsaturated zone as well as aquifer system.

Vulnerability assessment methods can be classified into three general strategies

a. Statistical methods

b. Process based contaminant transport models

c. Overlay index methods

Used alone, each of these methods has limitations for regional assessments. However these are capable to provide reasonably good insight into the complexities of regional ground water vulnerability if used together.

Statistical Methods: Statistical methods use response variables such as the frequency of contaminant occurrence, contaminant concentration or contamination probability. To determine significant relationships between intrinsic and specific explanatory and response variables, statistical methods may use known contaminant distributions and their spatial proximity to threshold values of explanatory variables. However, statistical relations can be extrapolated only to conditions similar to those used to develop the relations. One goal in applying statistical methods to vulnerability assessment is to identify variables that can be used to define the probability of ground water contamination.

Logistic regression can be used to relate a categorical response variable to independent exploratory variables. The logistic regression equation predicts the probability of a response in each category. This statistical approach has been successfully used in water analysis. The resulting list of variables and ranks may be useful to define weights and variables to estimate the probability of ground water contamination.

Contaminant Transport Model: Deterministic models use process-based equations to simulate containment transport. This method may be distinguished from the others in its potential to predict contamination transport in both space and time. Models range from one-dimensional, simulating transport through the unsaturated zone, to multiple phase, multi dimensional models. Work at regional scales is, however restricted by dependence on models developed for use at local scales (Burkart et al., 1999). Many of these local scale unsaturated zone models have data requirements that are not often available outside small research areas.

Comprehensive assessment of ground water vulnerability requires the application of multiple approaches because of the variety of questions posed by policy makers, the variety of data available for assessment, the variety of scales at which assessment is needed and the different levels of understanding the process affecting vulnerability and special variability in these processes. No single method is universally suited to address the full spectrum of questions that may be asked and to deal with the variety of hydrologic conditions that may be encountered in assessments over large areas.

Overlay and Index Methods: Overlay and index methods rely mainly on the quantitative or semi-quantitative compilation and interpretation of mapped data. Overlay and index methods involve examining the geographic distribution of intrinsic and specified vulnerability properties. These methods use geographic position as the framework in which variables are combined and directly define the spatial domains of specified vulnerability classes. Indexing of the resultant classes can range from assigning equal weights for all variables used in the index to sophisticated systems of scores and weights. While these methods can provide insight into causes of contamination, they do not completely incorporate the processes that ultimately affect vulnerability.

Use of a Geographic Information System (GIS) makes overlay methods particularly well suited to large geographic areas having a variety of hydrologic settings and corresponding specific vulnerability. Indexing allows the incorporation of knowledge obtained from previous research on contamination processes to classify and rank vulnerability. Indexing is necessary to classify and order the large number of variables that may be included and the large number of polygons that result from the combination of several thematic maps. Indexing provides a rating or scoring system for application at any scale where adequate information is available. Overlay and index methods rely mainly on quantitative or semi-quantitative compilation and interpretation of mapped data.

Existing methods of overlay index methods can be grouped into two categories as given below:

i. Qualitative Assessment based methods: This method implies a qualitative assessment of hydro-geological, hydrographical and morphological conditions that correspond to each class in a vulnerability scale. Large areas with various hydrographical and morpho-structural features are best suited for assessment through these methods.

ii. Parametric system methods: In these methods, certain parameters are selected and considered to be representative for ground water vulnerability assessment. Each parameter has a defined natural range divided into discrete hierarchical intervals. All the intervals are assigned specific values reflecting the relative degree of sensitivity to contaminants. The important parametric system methods are:

a. Matrix systems (MS): These methods are based on a fewer number of carefully chosen parameters. These parameters are combined based on research strategies to obtain quantified degree of vulnerability.

b. Rating systems (RS): These methods provide a fixed range to the parameters considered, which, is subjectively divided based on variation interval of each parameter. The sum of the ratings gives vulnerability of that point. The final numerical score is divided into intervals expressing a relative vulnerability degree (e.g. GOD system, AVI method, and ISIS method).

c. Point Count System Models: These models imply the same method as Rating System. However, in addition, a multiplier (as a weight) is assigned to each parameter to correctly reflect the relative importance of the parameters involved. Ratings of each parameter are multiplied with weight factor to get the vulnerability index. These scores provide a measure of relative vulnerability (e.g. DRASTIC, SINTACS, EPIK).

1.2.3 Drastic method

DRASTIC Point Count System Model was developed by US Environmental Protection Agency (EPA) (Aller et.al, 1987). DRASTIC is the acronym of the seven parameters involved which are **D**epth to water level, Net **R**echarge, **A**quifer media, **S**oil media, **T**opography in terms of percentage of slope, **I**mpact of vadose zone and hydraulic **C**onductivity.

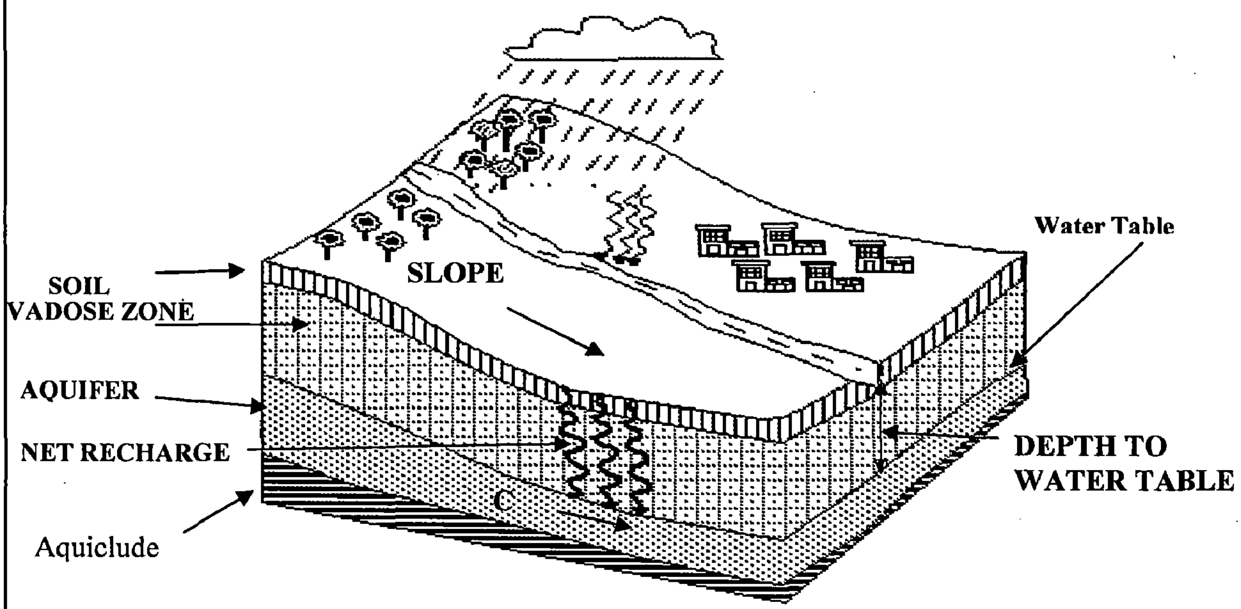


Fig.1.2 Visual explanation of Parameters of DRASTIC approach

Each mapped parameter has been are classified into ranges and the assigned rates rage from 1 to 10. Based on the physical significance, weight factors also have been assigned and final vulnerability index is evaluated using the formula:

$$D_i = \sum_{i=1}^{7}\left(W_j * R_j\right) \qquad \text{........1.1}$$

Where, Di = DRASTIC Vulnerability Index

W_j = Weight factor for the parameter j

R_j = Rating for parameter j

DRASTIC provides two weight classifications, one for normal conditions and other indicating a condition with intense agricultural activities. The later is called Pesticide DRASTIC or PDRASTIC index. Once DRASTIC index is computed for a given study area, it is possible to identify zones that are more susceptible to ground water contamination. Although DRASTIC concept is physically based, the final index has no physical meaning; rather it is a numerical index.

1.3 LITERATURE REVIEW

1.3.1 International Scenario

S.Fuest et al, (1998) in their study of **"Risk hazard mapping of ground water contamination using long term monitoring data of shallow drinking water wells"** have generated regionalized top aquifer contamination maps of Osnabruck county, Germany. Further, they prepared risk hazard maps of the area by overlying data regarding live stock figures; climatic factors etc. using **ARC/INFO.**

M.R.Bukart et al. (1999) have explained various method viz., statistical, overlay indexing and process based models for assessing ground water vulnerability.

R.C.Gogu et al., (1999) in their research paper entitled **"Current trends and future challenges in ground water vulnerability assessment using over lay and index methods"** have explained various concepts of vulnerability assessment, existing methods of assessment under overlay and index method and finally limitation and required improvements in methodology.

Diana Allen (2002) explained various DRASTIC parameters and prepared DRASTIC and pesticide DRASTIC (PDRASTIC) maps of Grand Forks area of Canada.

Ground water vulnerability mapping of Abu Dhabi area of UAE has been done by T.Al Zabet in 2002. In this study, the author prepared PDRASTIC maps and identified highly vulnerable areas.

R.A.N.Al-Adamat et al., (2003) have prepared DRASTIC vulnerability maps of Badia region of Jordan using GIS. The vulnerability map so prepared is integrated with land use to assess potential risk to ground water pollution in the area. The results are published in their research paper "**Ground water vulnerability and risk map for the Basaltic aquifers of the Azraq basin of Jordan using GIS, Remote Sensing and DRASTIC**".

I.S.Babiker et al., (2005) have prepared aquifer vulnerability maps of Central Japan using **DRASTIC** method by **GIS** techniques. This research group also conducted sensitivity analysis of **DRASTIC** parameters in their study entitled **"A GIS based DRASTIC model for assessing aquifer vulnerability in kakamigahara heights, Gifu Prefecture, Central Japan".**

B.Andreo et al., (2005) in their study entitled **"Karst ground water protection, first application of a Pan European approach to vulnerability, hazard and risk mapping in the Sierra De Liber, Spain"** prepared intrinsic vulnerability maps using PI and COP method (Pan European Approach) and specific vulnerability maps. By using a hazard map showing localization of potential contaminant sources when overlaid, a risk map for ground water contamination is prepared.

K.C.S.Naulkar and B.A.Angel (1999) in their study "**Predicting of special distribution of vulnerability of Indiana State aquifer systems to nitrate leaching using GIS** used DRASTIC and SEEPAGE methods for preliminary screening to vulnerability of ground water system. Results were evaluated with water quality data.

A miscellaneous publication entitled "**Evaluating AVI and DRASTIC for assessing ground water pollution potential in Frazer Valley**" used AVI and DRASTIC for ground water vulnerability assessment. AVI uses hydraulic resistance as a measure of vulnerability.

1.3.2 National Scenario

The hydro-geological conditions and recharge characteristics of the aquifers of Haridwar district is studied by **M.S.Rao et al, (1998)**. According to **Rao et al,** aquifers exists both in phreatic and confined conditions are not interconnected and recharge is mainly taking place at higher altitudes of Bhabar area.

Ground water vulnerability assessment of Goa case study area by Ferreira et al.., (2001) details various conceptual aspects of ground water vulnerability and its assessment and validation in Goa area.

D.Thirumalaivasan et al, (2003) developed a software package **AHP-DRASTIC** to derive ratings and weights of modified **DRASTIC** parameters for use in specific aquifer vulnerability assessment.

Hussain (2005) in his PhD studies has assessed the vulnerability conditions in inter fluve areas of Ganga and Yamuna. He has validated the vulnerability index with water quality index and modified the vulnerability index by using land as an eighth layer.

1.4 RATIONALE OF THE PRESENT STUDY

The present study area which is a part of gangetic basin administratively falls in Haridwar district of Uttaranchal State. A steep rise in population and sharp increase in floating population to the holy city of Haridwar has necessitated an increase in drinking water requirement. As surface water sources are more amenable to pollution, stress has shifted to ground water. Increase in population has resulted in an urban sprawl and increase in sewage and waste disposal. Many pockets of the district have become industrial hubs in the recent past. The area has an intensive agricultural history as it is a part of sugar cane producing region of the State. These developmental activities can facilitate ground water quality deterioration. So it is proposed to carry out an aquifer vulnerability study in the present area. The study will also provide safer sites for waste disposal and locating industries.

1.5 OBJECTIVES

- Characterization of hydro-geological system of the area.
- Preparation of a data base for assessment of ground water vulnerability through DRASTIC Indexing model.
- Evaluate, rank and map ground water vulnerability to pollution.
- Validate the index by comparing it with observed ground water quality parameters keeping in view of the hydro-geological conditions of the area.
- Modify the vulnerability map with other environmental parameters such as land use.

1.6 APPROACH

The approach followed for the present study is given below.

- Selection of the study area for the aquifer vulnerability studies.
- Characterisation of the hydro-geological set up of the area
- Selection of a suitable method for assessment of aquifer vulnerability after reviewing several methods of assessment.
- Preparation of a data base required for the methodology adopted.
- Field and laboratory studies for soil and water quality assessment.
- Assessment of aquifer vulnerability by employing the selected methodology
- Validation of the estimated aquifer vulnerability index with existing ground water quality scenario and its modifications if required.

CHAPTER – II

STUDY AREA

2.1 INTRUDUCTION

This chapter presents a summary of the main attributes of the study area. The study area forms part of Indo-Gangetic alluvial plain and administratively falls in Haridwar district in Uttaranchal State. The Holy City of Haridwar is situated in the north eastern part of the area. The Holy River of Ganga is flowing through Eastern and South Eastern boarder of the district. The study area is geographically bounded by North latitudes of 29^0 30’ and 30^0 15’ and East longitudes of 77^0 42’ and 78^0 21’ and has an aerial extent of 2360 sq.kms.

2.2 ADMINISTRATIVE SET UP

Administratively, the study area falls in Haridwar district of Uttaranchal State. Haridwar district is divided into 3 Tehsils and 6 Developmental Blocks. Further the district has 3 Muncipal Boards, 3 Nagar panchayats, 299 Gram Panchayats, 10 statutory towns, and 503 villages. The administrative setup of the area is given in Table 2.1.

Table 2.1 Administrative setup of the study area

State	Division	District	Tehsils	Blocks
Uttaranchal	Garhwal	Haridwar	Roorkee	Bhagwanpur
				Roorkee
			Laksar	Narsan(Kurhi)
				Khanpur
				Laksar
			Haridwar	Bahaderabad

(Source: Dainic Jagaran Survey, 2005)

No. of Municipal Boards 3

No. of Nagar Panchayats 3

No. of Gram Panchayats	299
No. of Statutory Towns	10
No. of Villages	503

2.3 LOCATION AND APPROACH

The study area is located in the Western part of the Uttaranchal State. The Haridwar district is bounded by Uttar Pradesh State on Western, Southern and South Eastern part, and by Dehradun district on the North Eastern part. The area falls in the Survey of India Degree sheet 53 K, 53 G and 53 F and toposheet numbers 53 K/1, 53 K/2, 53 G/13, 53 G/14 and 53 F/16. A location map is shown in Fig.2.1

2.4 DEMOGRAPHIC CHARACTERISTICS

Haridwar district is one of the densely populated districts of the State Uttaranchal. There is a sharp increase in population from 112448 in 1991 to 1444213 in 2001. Moreover, the district is receiving a sizable floating population from all over India, as Haridwar is a religious Holy City. Also, Haridwar is used as a base camp for tourists who are exploring the higher reaches of the Himalayas. The population density also shows an increasing trend. The Sex Ratio is 868 which is well below the national average of 927. However, decennial growth rate shows a decreasing trend. The demographic details are given in Table 2.2

Table 2.2 Demographic Characteristics of the District Haridwar.

Population	1991			2001		
	Male	Female	Total	Male	Female	Total
Urban	189080	159062	348142	241645	204018	445663
Rural	419974	356372	776346	531528	467022	998550
Total	609054	515434	1124488	773173	671040	1444213
Density	485			612		
Sex ratio	846			868		
Decennial growth	28.44 (1981-91)			26.30 (1991-01)		

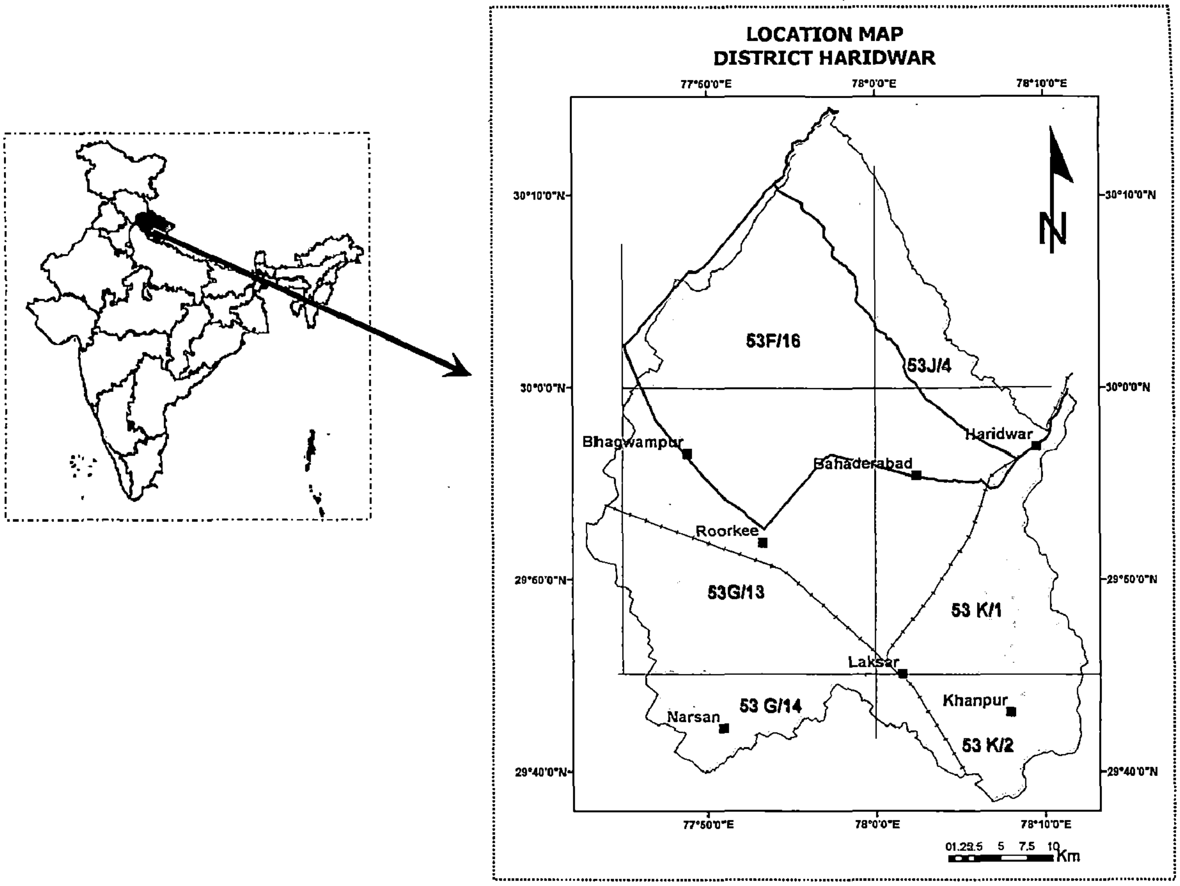


Fig.2.1 Location Map of the Study Area

2.5 OTHER SALIENT FEATURES

2.5.1 Literacy

The literacy rate of the district is 75.06% against the national average of 65%. Male literacy is more than female literacy. The details are shown in table 2.3.

Table 2.3 Literacy Rates of the District Haridwar

Literates	1991			2001		
	Male	Female	Total	Male	Female	Total
Urban	-	-	-	177400	125199	302599
Rural	-	-	-	299958	166245	466203
Total	-	-	-	477358	291444	768802
Literacy rate (%)	59.51	34.93	48.35	75.06	52.6	48.35

2.5.2 Source Wise Irrigated Area

The district has a network of canals, Government tube wells, and Private tube wells. The agricultural tract of this district is irrigated by these surface water and ground water resources. Table 2.4 details the source wise irrigated areas in district Haridwar.

Table 2.4 Source Wise Irrigated Area in District Haridwar

Source	Area in ha
Canals	16657ha
Government tube wells	5483ha
Private tube wells	76478ha
Total tube wells	81961ha
Other wells	919ha
Other sources	1756ha
Total irrigated area	101293ha

(Source: Dainic Jagaran Survey, 2005)

2.5.3 Major Crops

The major crops of the study area are shown in table 2.5.

Table 2.5 Major Crops in District Haridwar

Type	Major crops
Kharif crops	Rice, maize, bajra, jowar, ground nut, sugar cane, cereals, urd, pulses, til, soyabean, oil seed, cotton
Rabi crops	Wheat, barley, gram, pea, arhar, masoor, rape seed/mustard, tobacco, sunflower, potato, onion
Fruits	Mango, papaya, guava, melon

(Source: Dainic Jagaran Survey, 2005)

2.5.4 Consumption of Fertilizers

The district has a good agricultural history, so is the use of fertilizers. This is done for getting the maximum out put from agriculture. Among the inorganic fertilizers, nitrogenous fertilizers are most common. Table 2.6 gives details of consumption of various fertilizers.

Table 2.6 Consumption of Fertilizers in District Haridwar for the Year 2000-2001

Major fertilizers	Consumption in tones (2000-01)
Nitrogen	20085
Phosphates	6447
Potash	806
Total	27338

(Source: Dainic Jagaran Survey, 2005)

2.5.5 Industries

In the study area, rapid industrial growth has taken place in the last decade. Haridwar district has sizable industrial pockets. In the recent past, lot of industrial hubs have cropped up in the area. Haridwar, Roorkee, Ranipur, Bahaderabad, Laksar etc are some of these. The statistics shows that number of industries registered during 2003-2004 is 204, 2004-2005 is 345, and 2005-2006 is more than 401. The main industries are dairies, food processing, leather processing, sugar mills, pharmaceuticals, cosmetics, paper and pulp and electro plating.

2.5.6 Land Use

The main land use practices for the year 2000-2001 are listed out in Table 2.7

Table 2.7 Land Use categories of District Haridwar

Land Use category	Area in ha.
Total geographic area	233506
Forest	26320
Barren and uncultivable land	2107
Culturable waste land	49
Permanent pastures and other grazing land	281
Areas under other trees and groves not included in the new area sown	3173
Current fallow land	2554
Other fallow land	124503
Net area sown	55269
Area sown more than once	179772

(Source: Dainic Jagaran Survey, 2005)

2.5.6 Characteristics of Waste

The sources of waste generation in the study area can be divided into three categories, municipal, agricultural, and industrial. Sewage and solid waste are the main municipal wastes. Proper sewerage system is only available in few areas of the towns and treatment plants are scanty. So, observed to pollute land and surface water sources. Solid waste is also dumped resulting in degradation of soil and ground water quality.

With increase in population, agricultural production has also increased. This has necessitated extensive use of fertilizers and pesticides. In addition, sewage farming is extensively practiced in the area. Associated apparent environmental hazards are contamination of ground water by nutrients and toxic pesticide residues, accumulation of heavy metals and toxic organics.

There are large number of industries in the study area related to paper, milk products, distillery and small scale cottage industries pertaining to paperboard, electro plating, chemicals and rubber. The waste effluents generated from these industries are discharged either directly or after partial treatment into Solani River or its tributaries. Most of these effluents contaminate the receiving water as can be sensed from the foul odor, apparent colour, ill health symptoms and quality deterioration.

2.6 CLIMATE

The study area has a moderate to sub tropical monsoon climate with pronounced Rainy, Winter, and Summer seasons. Monsoon starts from mid June to mid September thereafter winter extends up to February – March and April to mid June period represents summer. Average annual rainfall is about 1000mm, of which 85% is received during monsoon season. January is generally the coldest month and May is the hottest month.

2.7 SOIL

The study area is a part of the vast Indo – Gangetic alluvial plain. The sediments of the alluvium are composed of sand, silt, and clay. These are reworked sediments brought by Himalayan Rivers. In general, the soil of the study area is sandy and sandy loam.

2.8 GEOLOGY

Geologically, the area is divided into Siwalik formations and Indo - Gangetic Alluvium (Fig.2.2). Further, Indo – Gangetic Alluvial plain can be divided into (i) Bhabar, (ii) Tarai and (iii) Alluvial plain (Taylor, 1959).

2.8.1 Siwalik Formations

These are the outer most foot hills of the Himalayas. The sediments of these Tertiary deposits were derived from the Himalayas. These can be further divided into Upper, Middle and Lower Siwaliks. The boulder beds of the Upper Siwaliks form moderate potential aquifers. These are constituted by pebbles, cobbles, boulders, sand and clay. At many locations sand and clay beds are intercalated within the boulders beds. In general, potential water bearing zones can be demarcated by boulder beds with sand as an interspacing material. Middle and Lower Siwaliks are devoid of ground water potential zones. These are constituted by compact sand stones and silt stones. Pebbly sandstones are the characteristics of the Middle Siwaliks. But, in these formations also, moderate ground water potential zones can be found along structurally weak planes such as faults and fractures.

2.8.2 Indo – Gangetic Alluvium

These are the vast alluvial deposits deposited in a fordeep basin south of the Himalayas and Siwalik ranges. Taylor (1959) divided these into the following:

Bhabar Formations: These are relatively dry terrains fringing Siwalik foot hills lying at a higher elevation than plains. Bhabar formations are geologically piedmont deposits by hill torrents. These are made up of alluvial and talus cons. The alluvial fans in these piedmont deposits are relatively wider and larger. The topography is generally bad land type wherever silt and clay deposits are thick. Spurs and depressions are common. The sediments brought by the Himalayan rivers, when debouches into plains, deposit its sediment load, coarser near and finer far off. The continuous depositions

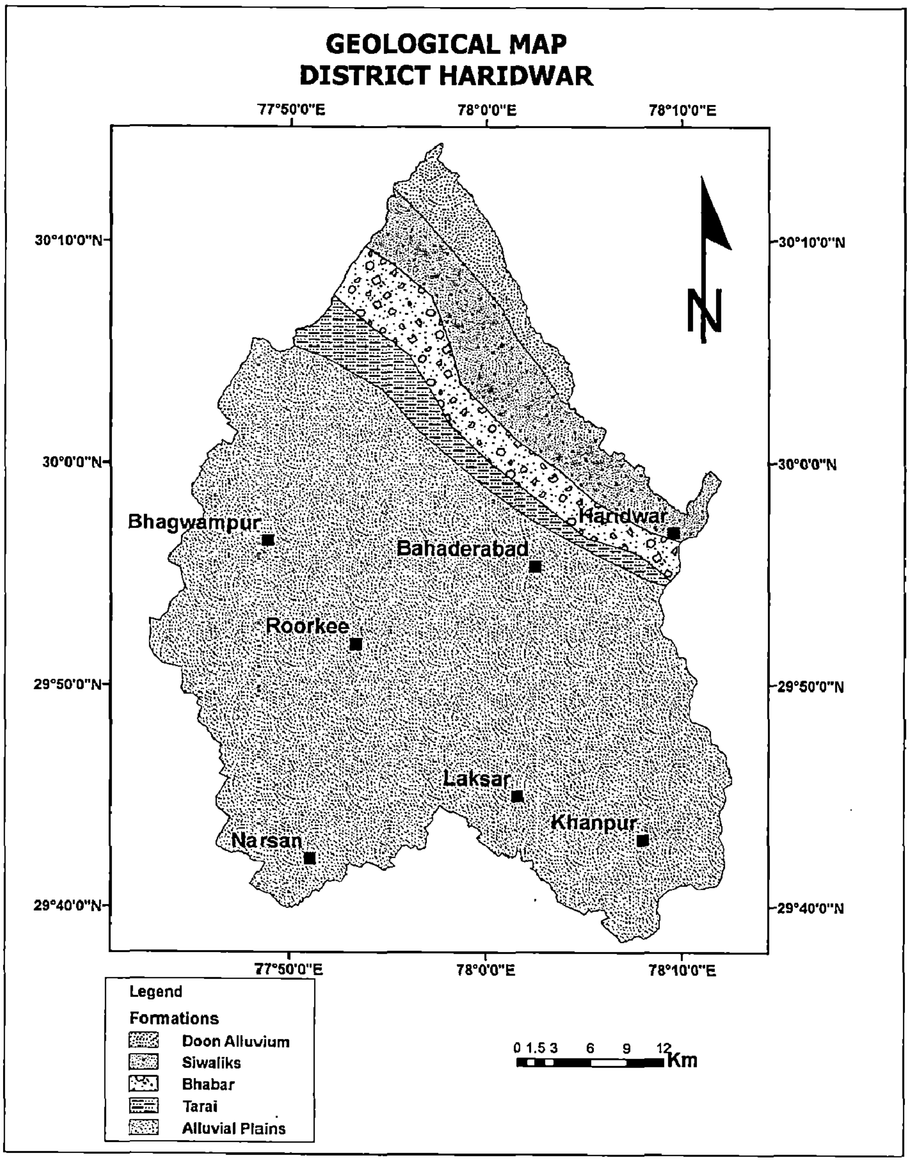


Fig.2.1 Geology of the Study Area

have built up alluvial cones and alluvial cones, and alluvial cones in turn have coalesced to form Bhabar piedmont zones between hills and plains. Bhabars are composed of boulders, pebbles, cobbles, gravel, sand and silt. These are generally recharge areas and rivers are influent.

Tarai: Tarai occupies a place between vast alluvial planes and Bhabar formations. Swampy conditions mark the break in topography. These are composed of finer materials like sand, silt and clay. Generally these are discharge areas composed of contemporaneous and heterogeneous sediments derived from Bhabar and hinder land areas. Clay content is appreciable. Tarai areas consist of alternating layers of sand, gravel, pebble having continuity with Bhabar belt.

Alluvial Plains: The region south of Tarai is occupied by these vast plains. These are one of the important ground water potential zones of North India. The Gangetic alluvial plains are composed of unconsolidated and semi consolidated deposits of sand, clay and Kankar.

2.8.3 Structure

The study area is a tectonically active zone. The area is underlined by Delhi – Haridwar Ridge (M.S.Rao et.al., 1998). The important tectonic features are (i) The Himalayan Frontal Fault that separates Siwalik Hills (Tertiaries) and Gangetic plains (Recent) (ii) NE –SW trending Meerut-Haridwar Fault that coincide with the Eastern boundary of Delhi Haridwar Ridge (iii) Solani Fault, along which the River Solani flows and (iv) Ratmau Fault.

2.9 HYDROGEOLOGY

In conformity with geology, hydrogeology of the area also has 3 divisions viz. Bhabar, Tarai and alluvial plain. In Bhabar, water levels are generally deep. Aquifers are both in phreatic and confined conditions. These are generally recharge areas, which comprise of boulders, cobbles, pebbles, gravel, sand, silt, and clay intercalations. On the contrary, in Tarai area, water levels are shallow to swampy conditions. Aquifers are in a confined condition. Bhabar – Tarai contacts are marked with springs and high yielding wells. Drainage of the Bhabar is influent in nature whereas rivers in Tarai are effluent in nature. Tarai and alluvial plains are generally discharge areas. The alluvial plains are composed of gravel, sand, silt, and clay. Aquifers are phreatic, leaky confined and in locally confined conditions. The summary of hydrgeological details are given in Table 2.8.

Table 2.8 Average Values of Aquifer Parameters

Aquifer Parameters	Range
Thickness of shallow aquifers	4 to 100m
Coefficient of permeability	2.16 to 28.8 m/day
Storativity	1×10^{-4} to 3.74×10^{-4}
Transmissivity	10 to 2880 m^2/day
Specific Yield	0.13 to 0.26

(Source Shakeel, 1997)

In order to know the aquifer disposition of the study area, lithological cross sections along P – P' (Ganeshpur –Shikarpur) were prepared. The section along P – P' (Ganeshpur – Shikarpur) reveals that aquifers are in confined or semi-confined in nature. The unconfined aquifers are not connected to deep seated aquifers. This is further validated by the study of Rao et al., (1998). Recharge is apparently taking place at higher altitudes. This also reveals that towards the southern part of the study area, aquifers are sandy.

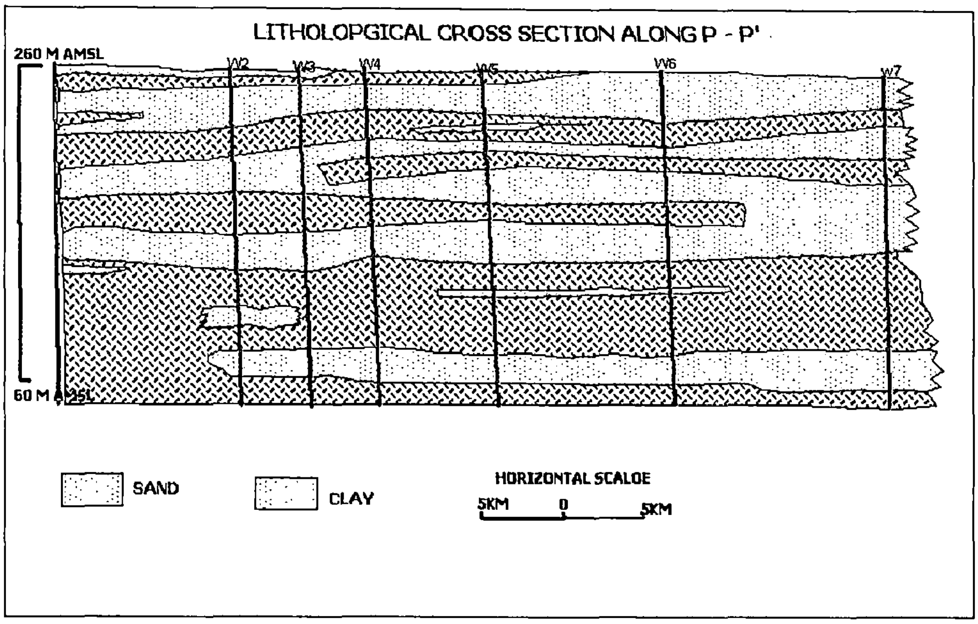


Fig.2.2 Lithological cross section along Ganeshpur – Shikarpur

CHAPTER – III

MATERIALS AND METHODS

3.1 INTRODUCTION

Water quality or soil data are only as good as the water or soil samples from which the measurements are made. Even most precise laboratory analysis of a water or soil sample cannot compensate for improper or poorly executed sampling procedures or for physical and chemical alteration of a sample due to inappropriate sample collection, transport or storage (Hussain, 2005). This chapter describes the monitoring program, selection of parameters, analytical methods employed, and methodology adopted for the present study.

3.2 SOIL MONITORING PROTOCOL

3.2.1 Collection of samples

In the present study, 72 number of soil samples were collected from different land use types, using hand augur from a depth up to 30cm and sealed in plastic bags before transportation. The samples were disaggregated and air dried and subsequently stored in clean sealed plastic bags for further analysis.

3.2.2 Soil Texture analysis

The most important piece of information to know about soil is the particle size distribution, often referred as texture. Particle size distribution has an important influence on soil's permeability, water storage capacity, its ability to aggregate and propensity for crusting, and chemical make up of the soil water (Trout et al., 1987). Textural analysis is a procedure to determine the relative proportions of the different particle sizes which make up the given soil mass. Two techniques are used in the present study to separate the soil particle into size ranges. The coarse particles (Sand and above) can be separated with mechanical sieves. The distribution of fine particle sizes (Silt and Clays) can be separated using wet analysis (Pipette method).

Sieve analysis: Sieve analysis involves passing a soil sample through sieves with successively smaller holes. Consequently, the method cannot determine individual particle sizes. It only divides the particles into size categories bracketed by the sieve opening sizes. All particles retained on a given sieve in a stack are larger than the holes in that sieve but smaller than the previous sieve's holes. By dividing the mass retained on each sieve by the total mass, the percent of the particles in each size range can be determined.

Preparation of the samples for textural analysis consisted of the following steps (Carver, 1971)

- Breaking all clumps and mashing with fingers
- Mixing sample thoroughly and splitting
- Coning and quartering
- Removing carbonates by adding 1N HCl with stirrer and rim washing, followed by decanting the HCl.
- Removing organic matter by adding 6% to 39% H_2O_2, stirring and rim washing
- Adding distilled water and heating on hot plate for 12 hours (at 40^0 C temp)
- Removing iron oxide by adding distilled water aluminum foil and 15gm oxalic acid with stirrer and heating on hot plate for 10 to 25 minutes followed by decanting excess clear water.
- Drying and weighing.

In the present study, the dried samples were mechanically sieved through stacks containing sieves of 2 mm and 63μm and collector pan. The sample retained in 63μm is the sand fraction and weighed. The fraction retained in the bottom collector pan is silt and clay and weighed together. By adding these two weights we get the total weight. Then, the sand percentage can be calculated using the formula

$$\text{Sand \%} = \frac{\text{Weight of sand fraction}}{\text{Total Weight}} \times 100 \qquad .....3.1$$

The silt and clay fraction is stored in clean plastic bags for further wet analysis.

Mechanical Analysis by Pipette Method: Mechanical analysis by pipette is based on stock's law of fluid mechanics. According to stock, settling velocity of a particle in a liquid of given density and viscosity is directly proportional to the square of it's radius. But Stoke's law is not valid for particles larger than 0.2mm, because they fall rapidly enough to create fluid turbulence, or for very small particles less than 0.0002mm, because they are affected by molecular forces of retraction and repulsion (Brownian movement). The pipette method of analysis depends on the premises that after a particular time all particles greater than a particular size would have settled below a certain depth. If a pipette is inserted in to the liquid at this depth, the sample will only contain particles of diameter smaller than this size.

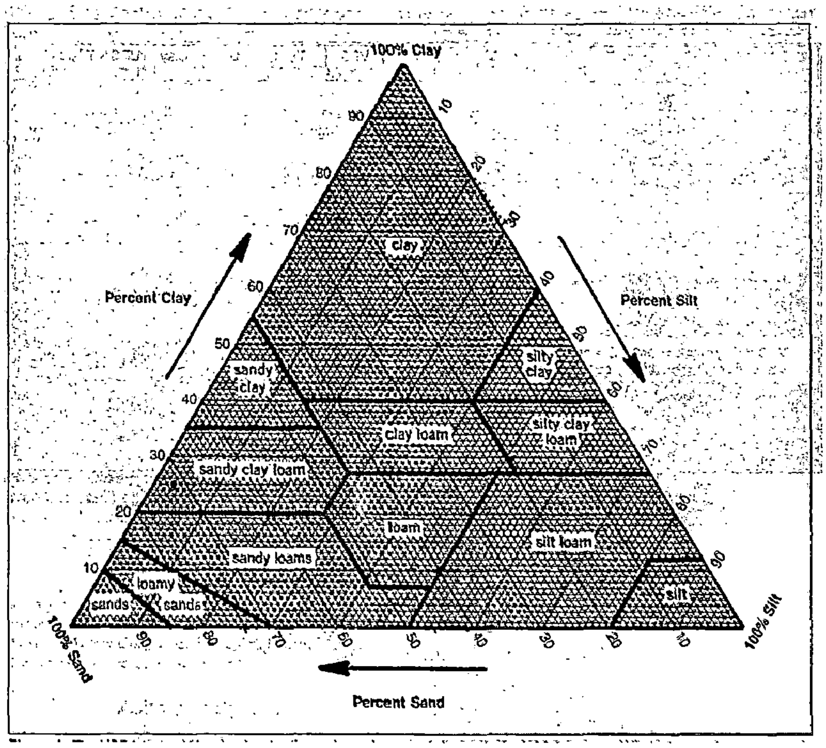
In the present study, the Silt and Clay portion was transferred to a beaker, moistened with little distilled water and transferred to a larger container. Thereafter, 300 ml of distilled water and 15 ml (10%) Calgon solutions were added. Stirring was done for 15 minutes to disperse the aggregates in the soil. The sample was then transferred to a 1000ml graduated measuring cylinder, and the volume up to 1000ml mark was made up with distilled water. The stem of a 20ml pipette was marked exactly 5 cm from its tip. The measuring cylinder suspension was vigorously stirred for about half a minute so that the sample got evenly distributed throughout the cylinder, care being taken to avoid introducing air bubbles into the suspension. The temperature of the suspension was noted and then stirring was done again for further 30 seconds. The timer was started as soon as the stirrer was withdrawn. 20ml of sample was withdrawn from 5cm depth after 3 hours 36 minutes into a previously cleaned and weighed (ED) silica crucible. The dispersant in this case was clay fraction. The sample was then placed in an oven, evaporated to dryness, cooled and weighed (DD).

Weight of dispersant (Clay) (DS) in 1000ml = (DD-ED)*50

Weight of Silt = (Weight of Silt +Clay) – DS; from which % of Silt and Clay were calculated using Equation 3.1.

3.2.3 Soil textural classification

After completing the laboratory analysis to obtain the percentages of sand, silt and clay, the soil textural classification was done using USDA textural triangle (Brown, 1990)



(Source: Brown, 1990)

Fig.3.1 USDA Textural Triangle

3.3 WATER QULITY MONITORING PROTOCOL

The modality of ground water sampling depends on the objectives of the study. In the present aquifer vulnerability assessment study, several shallow wells were selected for sampling because the contaminant would apparently pollute the top aquifer first. However, in order to asses the ground water quality of the deeper aquifers some of the deep tube wells also was selected. A total of 88 water samples from different land use types such as Agriculture, Forest, Urban and Rural areas were collected and analyzed. The ground water quality monitoring process involved preparation for sampling, purging of the well, and collection, transportation, preservation and storage of the samples, followed by the field and lab analysis of water samples.

3.3.1 Preparation for sampling

Prior to the commencement of sampling, field equipments were cleaned and calibrated. Field kits containing pH meter, conductivity meter, thermometers etc were checked for efficiency and calibrated. Sampling bottles were cleaned and preconditioned in the lab. Sample containers, necessary reagents, preservatives etc has to be made ready. Field sampling labels and formats were also designed for recording.

3.3.2 Purging the wells

Before collection of the water samples, the wells were purged to remove any stagnant water in the well in order to ensure that water sample is representative of the aquifer formation water. As a rule of thumb, three to four well volumes of water were purged to get a representative sample. Purging was continued until, temperature, conductivity and pH readings were stabilized.

3.3.3 Collection, Storage, and Field Analysis of samples

Immediately after purging ground water samples were collected in sampling bottles. Plastic bottles were used for collecting samples to determine the major ions and general analysis. Samples meant for heavy metal analysis were collected in Teflon bottles. Samples were filled completely, caped, and sealed. Necessary information was filled in the sampling forms. The 2ml preservatives (Con. HNO_3) were added in 1litre sample separately for heavy metal analysis. The bottles were kept in containers having thermal insulation and transported to the laboratory and stored at 4^0 C. A representative sample was taken separately for field measurements of electrical conductivity, field pH, and temperature of the sample.

3.3.4 Laboratory Analysis

All the 88 ground water samples were analysed in the laboratory for physical, major ions, Nutrients, and heavy metals and methods followed are tabulated in Table 3:1.

Table 3.1 Analytical methods used for water quality assessment

Sl.No.	Constituents	Methods
1.	**Physical**	
	pH	Potentiometric
	EC	Electrometric
	TDS	Electrometric
2.	**Major Ions**	
	Ca^{2+}	Titrimetric
	Mg^{2+}	Calculation
	N^{+}	Photometric
	K^{+}	Photometric
	Cl^{-}	Titrimetric
	SO_4^{2-}	Gravimetric
	HCO_3^{2-}	Calculation
	CO_3^{-+}	Calculation
3.	**Nutrients**	
	NO_3^{-}	Ion Selective Electrodes
	TOC	TOC Analiser
4.	**Heavy metals**	
	Cd	Voltametry
	Cu	Voltametry
	Pb	Voltametry
	Zn	Voltametry

3.4 DATA BASE

Data used in the present study were of two types: spatial data and attribute data. Spatial data were taken from maps, images, sketches etc. They could be directly digitized into GIS environment. Attribute data were taken from tables, points and lists. The data were acquired through field monitoring, laboratory analysis, and from other Government organizations. The collected data were in different formats, scales, levels of spatial completeness temporal resolution etc and is shown in Table 3.2.

Table 3.2 Data types and sources used in the present study

Data type	Source
Depth to water levels	CGWB, Dehradun, UP GWO, Roorkee, Former PhD studies, Field Measurements
Specific yield	Pumping test data, UP GWO, Roorkee, Former Studies
Rainfall	Department of Hydrology, IIT, Roorkee
Lithologs	Former studies, Field collection, CGWB, Dehradun, TW Division, Roorkee, Private Drilling Agencies.
Soil Texture	Former Studies, Field collection and Analysis
Elevation	Survey of India toposheets
Hydraulic conductivity	Long duration Pumping test data, Former Research Studies, CGWB, Dehradun
Land use	Survey of India toposheets
Resistivity data	Field soundings and analysis

3.5 METHODOLOGY

Predicting the degree of vulnerability to pollution of an aquifer using data from geological and anthropogenic environment constitutes an issue of priority and major practical importance (Panagopoulos et al., 2005). In the present study, intrinsic vulnerability was assessed using the DRASTIC method.

DRASTIC represents an acronym of 7 parameters involved in it as indicated in chapter II earlier; they include **D**epth to ground water, **R**echarge, **A**quifer material, **S**oil type, **T**opography, **I**mpact of the vadose zone and hydraulic **C**onductivity. Each parameter has a predetermined, fixed, relative weight that reflects its relative importance to vulnerability. The weighting coefficient is determined with a qualitative approach based on physical significance. Most significant factors have weights of 5 and least significant factors have weights of 1. DRASTIC weighting coefficients are given in table 3.3.

Table 3.3 DRASTIC Weighting Coefficient for Intrinsic and Specific Vulnerability

Parameters	DRASTIC weight	Pesticide (PDRASTIC)
Depth to water table	5	5
Net Recharge	4	4
Aquifer material	3	3
Soil type	2	5
Topography	1	3
Impact of vadoze zone	5	4
Hydraulic Conductivity	3	2

All the seven parameters have been reduced to a relative scale from their physical scale in a manner similar to assigning weighting coefficients. A value between 1 and 10 for each parameter is attributed as rating depending on local conditions. High values correspond to high vulnerability. The description of the parameters and its ratings are given in below.

The **D parameter** represents depth to water table. Water table is defined as a plane where hydrostatic pressure equally balances the atmospheric pressure. It is a level below which all the pore space is completely filled with water. Depth to water level may be directly taken from the water level records. Contaminants at the surface must cross this distance before reaching ground water, so it is an important parameter in determining aquifer vulnerability to contamination. So it has got a DRASTIC weighting coefficient of "5." Greater distance implies large distance to travel and greater attenuation and hence lower vulnerability. The ratings for the local conditions of depth to water level are given below in Table 3.4 (Aller et al., 1987b).

Table 3.4 Rating for Depth to Ground Water

Depth range (m)	Ratings
0.0 – 1.5	10
1.5 – 4.5	9
4.5 – 9.1	7
9.1 – 15.2	5
15.2 – 22.9	3
22.9 – 30.5	2
>30.5	1

R parameter represents net recharge to the aquifer. Recharge is the principle parameter which controls leaching and transportation of contaminants to the water table. So, it has been assigned a DRASTIC weight of "4". The ratings are given below in Table 3.5.

Table 3.5 Ratings for Ranges of Net Recharge

range (mm)	Ratings
0.0-50.8	1
50.8-101.6	3
101.6-177.8	6
177.8-254.0	8
>254	9

A parameter represents nature of aquifer medium. Larger the fractures and openings within the aquifer, vulnerability would be high. This parameter is assigned a weight of "3" in DRASTIC model. Coarser grained material has been assigned higher rating and fine grained material has got a lower rating. Since geological conditions are extremely complex to put under certain limits, this parameter has got both variable and typical ratings. The ratings can be assigned as per the field conditions. Table 3.6 describes the variable and typical ratings assigned for aquifer media parameter.

Table 3.6 Variable and Typical Ratings for Aquifer Media

Aquifer media	Variable rating	Typical rating
Massive shale	1-5	2
Metamorphic/igneous rocks	2-5	3
Weathered metamorphic/igneous rocks	3-5	4
Thin bedded sandstone, limestone shale sequences	5-9	6
Massive sandstone	4-9	6
Massive limestone	4-9	6
Sand and gravel	4-9	8
Basal	2-10	9
Karstic limestone	9-10	10

S parameter represents influence of soil material on the over burden contaminant. It has got a DRASTIC weight of "2." Soil media have significant impact on recharge and hence vertical movement of contaminant. Attenuation process of filtration, decomposition, sorption, and vitalization may be significant in thick soils. In general less the clays in soil shrink and swell and smaller the grain size of soil, the less permeable the soil will be and less likely the contamination will reach the ground water. The ratings for this parameter are given below in Table 3.7.

Table 3.7 Rating for soil type

Soil type	Ratings
Thin or absent	10
Grave	10
Sand	9
Peat	8
Shrinking/aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	4
Clay loam	3
Muck	2
Non shrinking and non aggregated clay	1

T parameter represent surface topography and hence the slope. On steeper slope, runoff will be high and chances of contaminant reaching ground water are rare. In DRASTIC method, this parameter has been assigned a weighting coefficient of "3". The DRASTIC ratings for this parameter are given in Table 3.8. The T parameter is used in this method as percentage of slope.

Table 3.8 Ratings for the slope percentage

Slope range (%)	Ratings
0.0-2.0	10
2-6	9
6-12	5
12-18	3
>18	1

I parameter represents the impact of vadose zone which indicates an overall infiltration capability of the ground. The texture of vadose zone material would influence the movement of contaminants passing through it. The vadose zone material determines attenuation characteristics of the material below the soil horizons and above the water table. Fine grained vadose zone material inhibits movement and implies lower aquifer vulnerability. It has great influence on contamination attenuation and movement. So it has got the highest weight of "5." The ratings are given below in Table 3.9.

Table 3.9 Rating for I Parameter

Nature of vadose zone media	Variable rating	Typical rating
Silt/clay	1-2	1
Shale	2-5	3
Limestone	2-7	6
Sandstone	4-8	6
Bedded sandstone, limestone, shale	4-8	6
Sand gravel with significant silt and clay	4-8	6
Metamorphic/igneous rocks	2-8	4
Sand and gravel	6-9	8
Basalt	2-10	9
Karstic limestone	8-10	10

C parameter represents hydrologic conductivity K of the aquifer. Higher K value implies greater aquifer vulnerability. This parameter is responsible for contaminant distribution within the aquifer. C parameter is having a DRASTIC weight of "3." Ratings are given below in Table 3.10.

Table 3.10 Ratings for Hydraulic Conductivity

Hydraulic conductivity (m/day)	
Range	**Ratings**
0.005-0.50	1
0.50-1.5	2
1.5-3.5	4
3.5-5.0	6
5.0-10.0	8
>10.0	10

Local index of vulnerability is computed through multiplication of rating and weight of each parameter and adding up all seven parameters through a simple linear equation.

DVI = 5*Dr+4*Rr+3*Ar+*2Sr+1*Tr+5*Ir+3*Cr 3.1

where

DVI	DRASTIC Vulnerability Index and
Dr, Rr, Sr, Tr, Ir, Cr	Assigned Ratings of DRASTIC Parameters.

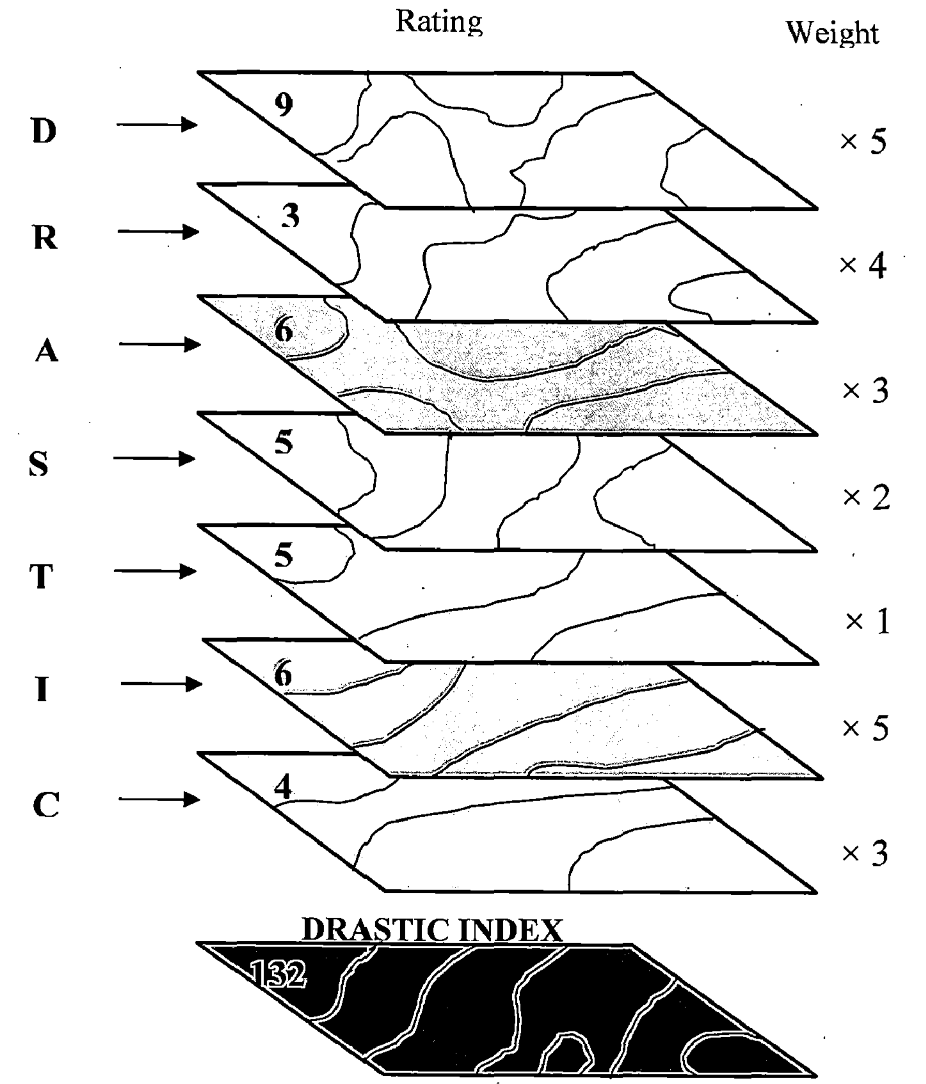
Minimum DRASTIC index is 23 and maximum is 226. Such extreme values are rare, commonly ranging between 50 and 200. Fig.3.2 shows the conceptual view of DRASTIC Vulnerability Index estimation.

The vulnerability map thus obtained is further classified and colour code is assigned as per the Table 3.11 given below (Aller et al., 1987).

Table 3.11 Classification of vulnerability index developed by Aller et al., (1987)

Class	DVI Index	Colour code
1	<79	Violet
2	80-99	Indio
3	100-119	Blue
4	120-139	Dark Green
5	140-159	Light Green
6	160-179	Yellow
7	180-199	Orange
8	>200	Red

A further step in the methodology was the interlayer and intra-layer statistical analysis and modifications of weighting coefficients and ratings if required. Both DRASTIC Vulnerability Index and Modified Vulnerability Index were then validated with water quality index. After the validation, pollution potential map was prepared by overlaying Land use parameter.



+DRASTIC Index = (9×5) + (3×4) + (6×3) + (5×2) + (5×1) + (6×5) + (4×3) = 132

Fig.3.2 Estimation of DRASTIC Vulnerability Index

3.5.1 Advantages of DRASTIC Method

There are many advantages of the DRASTIC method in assessing aquifer vulnerability, and these are:

- The method has a low cost of application and can be applied in extensive regions, because of the relatively few, easy to collect, and common data required.

- The selection of many parameters and their interrelationship decrease the probability of ignoring some important parameters, restrict the effect of an incidental error in the calculation of a parameter and so enhance the statistical accuracy of the model (Rosen, 1994).
- This method gives relatively accurate results for extensive region with a complex geological structure, despite the absence of measurements of specific parameters that the most specialized methods would require.

3.5.2 Disadvantages of DRASTIC Method

- So many variables are factored into the final index that sometimes critical parameters in ground water vulnerability may be subdued by other parameters that have no bearing on vulnerability for a particular setting.
- The selection of the parameters is based on qualitative judgment and not quantitative studies.
- Many important scientifically defined factors e.g., sorption capacity, travel time and dilution are not taken directly into account.
- The system tends to overestimate the vulnerability of porous media aquifers compared to aquifers in fractured media.
- A test of the accuracy of the model is very difficult to carry out, because it required that pollutant with properties assumed by the model (introduced into the ground surface flushed into the ground water via precipitation and mobility of water) be deposited all over the test area with uniform concentration and for a considerable time period of several years to allow the hydro-geological setting to respond.

CHAPTER – IV

PREPARATION OF THEMATIC LAYERS

4.1 INTRODUCTION

The Assessment of ground water vulnerability involves usage of various geo environmental parameters. In overlay indexing approach, these environmental parameters have to be converted to thematic layers. Moreover overlay indexing requires a working platform to enter, store, retrieve, edit, and manipulate the data. So, Geographic Information System (GIS) has been used as a tool in the present study to perform all these operation. This chapter describes generation of various thematic layers depicting all the geo environmental parameters and their classification therein.

4.2 GEOGRAPHIC INFORMATION SYSTEM

Geographic Information System is defined as a collection of information on geographic norms. It is a computer based capability for the manipulation of large volume of geographic information. The components of the GIS are the real world situations, data, computer hardware, software, and users (Fig 4.1).

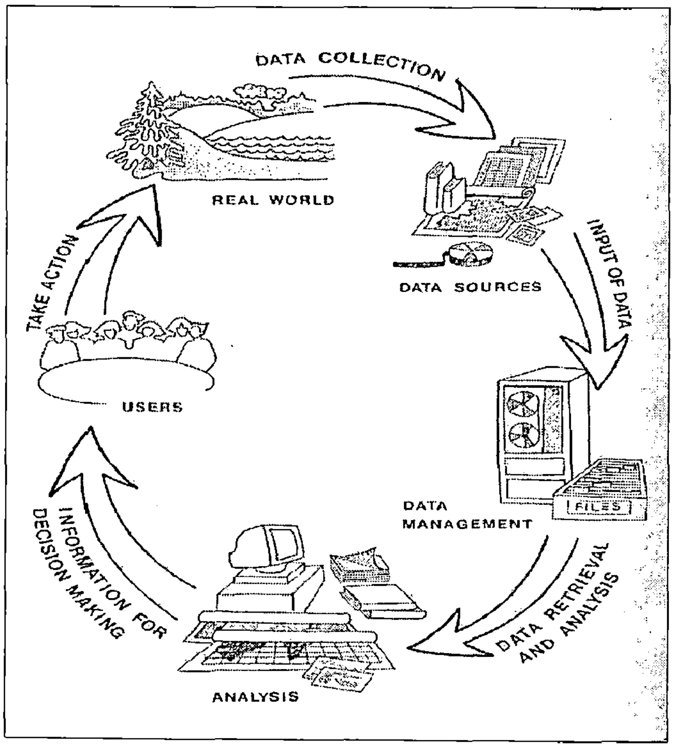


Fig.4.1 Working of Geographic Information system

In the present study, ARC GIS 8.3 and ARC GIS 9.0 are used for the generation of thematic layers. ERDAS 8.5 is used for geo referencing the spatial data sources. ARC MAP, along with its sub modules has been used for the data analysis and classification. ARC Catalog has been used for data base management and ARC TOOL is used for data projections and various statistical analyses.

4.3 GENERATION OF THEMATIC LAYERS

Before the generation of thematic layers, the source data (spatial) has to be geo-referenced. ERDAS 8.5 has been used for the purpose. Any scanned image (file) can be geo-referenced using data preparation module of ERDAS. Polynomial projection was taken for the present study using set geometric model sub module. Reference map information was added using GCP Tool Reference Set Up. This was followed by Set Automatic Transformation matrix to calculate RMS error. Datum used was Everest. Using the Projection Chooser, the file was re-sampled and using inquiry cursor, the accuracy was checked. In a similar manner, all the source data has been geo-referenced.

4.3.1 Base Map

A Base map has been prepared using geo-referenced toposheets. Items in base map include study area boundary, important locations, main cultural features like roads, rail roads, major rivers, main canal etc. All the shape files have geographic coordinate system as India-Nepal.prj and projection is taken as Polyconic. For all other themes projection were imported from the base map files.

4.3.1 Depth to Ground Water

Data on Depth to ground water were collected from 1994 to 2003 for 54 from Central Ground Water Board, Dehradun and UP Ground Water Department, Roorkee. Besides direct field observations were also made. Data sets are collected Both pre monsoon and Post monsoon water levels were collected separately and Post monsoon water levels were taken up for the present study. Water levels have been observed to be ranging from 0.17 m bgl to 17.25 m bgl, the average water level being 4.9 m bgl.

In order to obtain the spatial distribution of depth to ground water levels, the decadal mean post monsoon water levels were calculated and stored in an excel file. This was then converted to a data base file using MS Access. Then locations were plotted using tools in ARC MAP.

The geographic coordinates and projections were imported from the base map to convert this into a shape file by using ARC TOOLBOX.

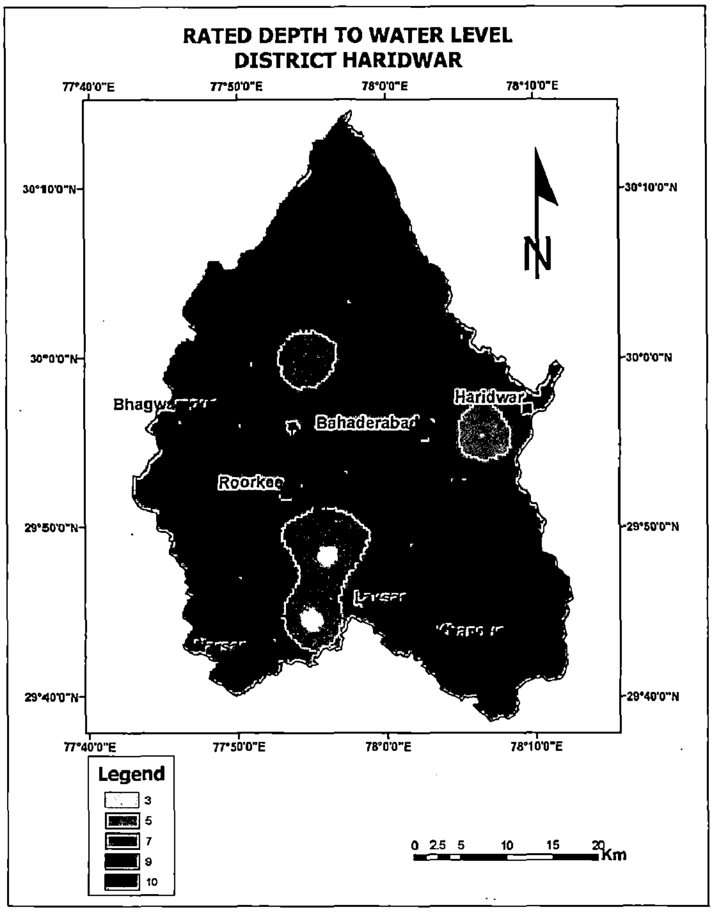


Fig.4.2 Rated Depth to Water Level

Later, using Spatial Analyst Module of ARC MAP the data was extrapolated using Inverse distance method. The raster output was then classified as per the DRASTIC norms. Finally, the data was reclassified to get depth to water level thematic map. Water level distribution is shown in Fig.4.2. The ratings adopted for the present study are given in Table 4.1 The Figure 4.2 shows that in the South Western, South Eastern, North Western and North Eastern parts of the district, was observed a shallow depth of 1.5 to 4.5 m bgl.

Majority of the central portion had deeper water levels of up to 9.1 m bgl. Both very shallow and very deep water levels are observed in discrete pockets, where prevailing local conditions apparently controls the depth to water levels.

Table No.4.1 Local Ratings adopted for the 'D' Parameter.

Depth range (m)	Ratings
0.0 – 1.5	10
1.5 – 4.5	9
4.5 – 9.1	7
9.1 – 15.2	5
15.2 – 22.9	3

4.3.2 Net Recharge

The net recharge is defined as the amount of water per unit area that percolates to the ground water. Precipitation is the primary source of recharge. In the present study estimation of net recharge was done following GEC 97 norms. For the monsoon season, ground water level fluctuation method was used. For this, water level fluctuation was plotted in Spatial Analyst module of ARC GIS. Similarly, specific yield was also plotted.

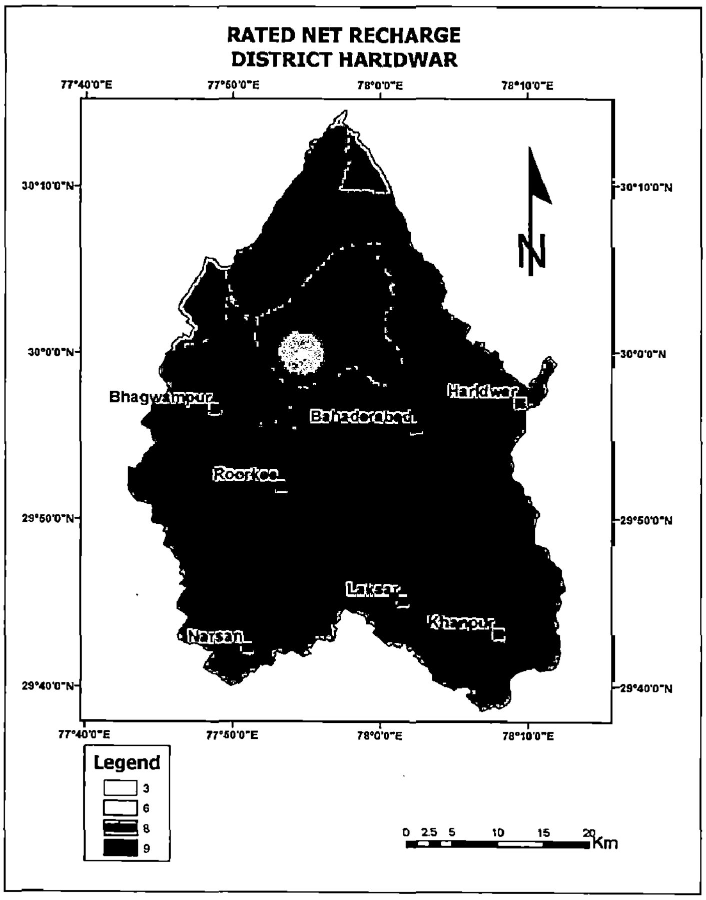


Fig.4.3 Rated Net Recharge

Recharge for the monsoon season is plotted using the formula given in Equation 4.1

$$\mathbf{R = h * Sy * A * + D_G} \quad \text{.........4.1}$$

Where R = possible recharge due to precipitation

h = rise in ground water level (pre-monsoon water level in m bgl – post monsoon water level in m bgl)

S_Y = Specific Yield in m/day

A = Area in ha (this term is not included in the calculation since the recharge data is required in mm)

D_G = Gross ground water draft

Since the normal non monsoon rainfall is greater than 10% normal monsoonal rainfall, 22% of it has been taken as recharge during non monsoon season. The total of monsoonal and non monsoonal recharge gives the net recharge to ground water. This has been rated as given in Table 4.2

Table 4.2 Ratings for 'R' parameter

Net Recharge Range (mm)	Ratings
0.0-50.8	1
50.8-101.6	3
101.6-177.8	6
177.8-254.0	8
>254	9

4.3.3 Aquifer Media

Aquifer media refers to unconsolidated or consolidated medium, which serves as an aquifer. Present study area is a part of vast alluvial deposits. So in general aquifer medium is sandy.

Table 4.3 Rating Assigned to Aquifer Media

Aquifer media	Rating
Sand	8
Sand, Gravel, Pebble, Cobble, Boulders	6
Sand, Clay	5
Gravel, Pebble	9
Sand, Gravel	9
Sand, Kankar	7
Boulder, Sand	8

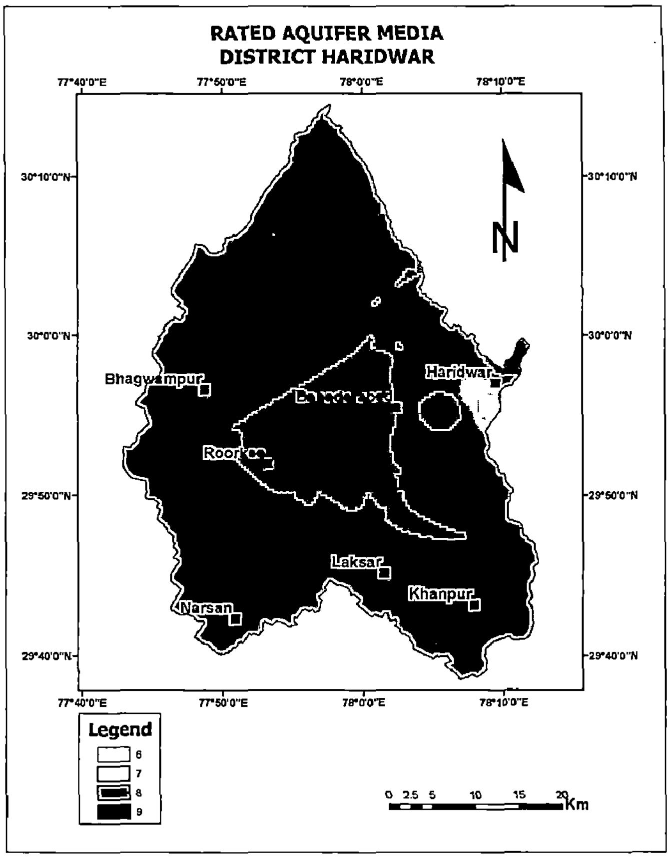


Fig.4.4 Rated Aquifer Media

The extrapolation of data has been done as explained in section 4.3.1. Fig. 44 Shows the distribution of aquifer media in the study area. It is inferred from the map that aquifers of the district are generally sandy or have a mixture of sand and gravel. However, in the middle of the district, sand is associated with pebbles, cobbles boulders etc. In Haridwar area, aquifer has observed to be mixed with Kankar and clay in a small patch.

4.3.4 Soil

The soil media has a significant impact on the amount of recharge, which can infiltrate into the ground water and influence the ability of contaminants to move vertically into the vadose zone.

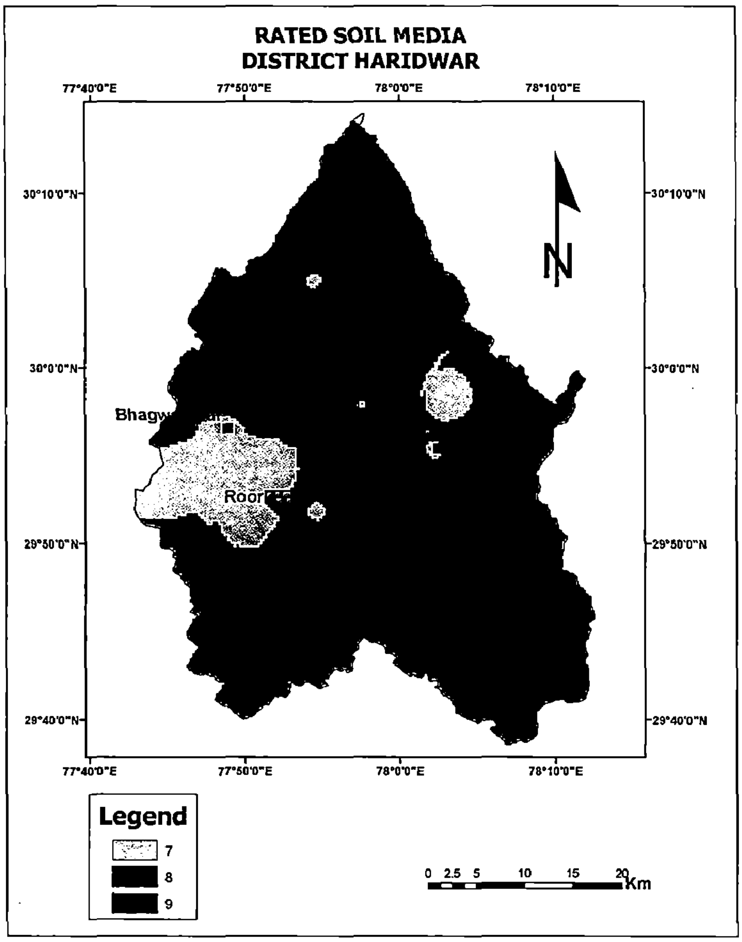


Fig.4.4 Rated Soil Media

Moreover, if the soil zone is fairly thick, the attenuation process of filtration, biodegradation, sorption, and volatilization may be quite significant. The textural classes prepared in the section 3.2.3 have been reclassified in the GIS environment as explained in section 4.3.1 by assigning DRASTIC rates. The assigned DRASTIC rates are given in Table.4.4

Table 4.5 Ratings Assigned to 'S' Parameter

Soil type	Ratings
Sand	9
Sandy loam	8
Silty Loam	6

Fig. 4.5 shows that 3 classes of soil occur in the study area. In majority of the study area, soil is sandy. Only the North Eastern and Western parts have sandy loam and silty loam soil.

4.3.5 Slope

The thematic layer of slope has been prepared using elevation data. 950 elevation data were picked up from topographic sheets. These data locations are plotted as explained in section 4.3.1. By using 3D analyzer of ARC MAP, a Digital Elevation Model has been prepared. Digital elevation model generally refers to a regular array of elevations and is represented as a raster map. Each cell in the grid has its own elevation value.

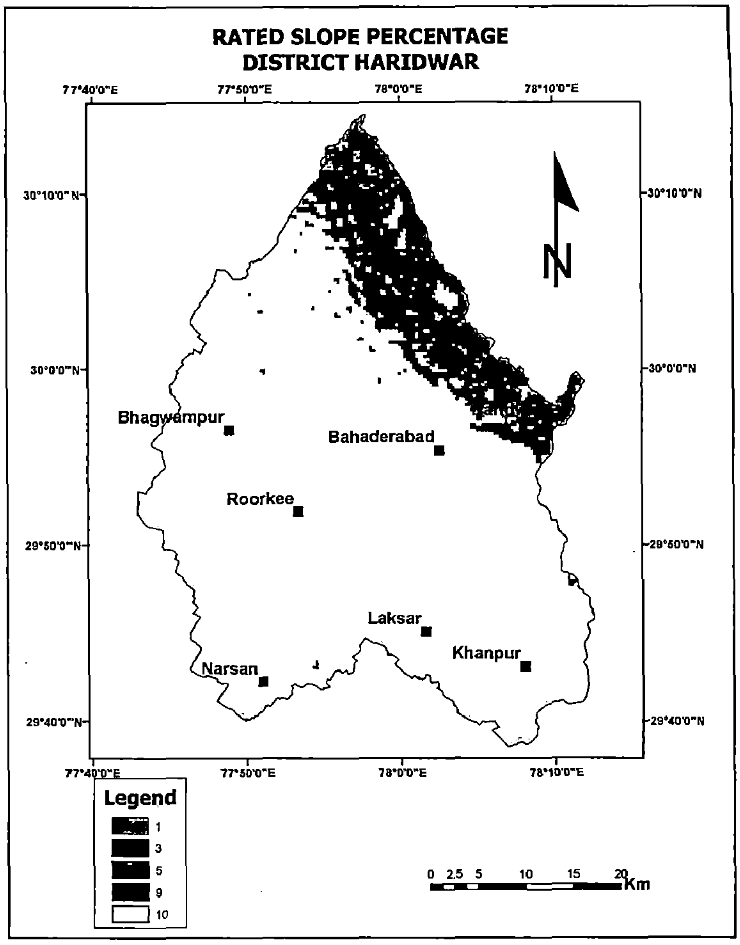


Fig.4.6 Rated Slope

Using the surface analysis, slope percentage was calculated and mapped. This raster layer was reclassified by assigning DRASTIC ratings. Table 4.5 shows the assigned rating for slope percentage.

Table 4.5 Ratings for Slope Percentage

Slope range (%)	Ratings
0.0-2.0	10
2-6	9
6-12	5
12-18	3
>18	1

All the DRASTIC rating categories are available in the present study area. Fig 4.6 shows the final slope map prepared. It shows that the majority of the area slope is 0 to 2%. Only in the North Eastern part, the slope is high.

4.3.6 Impact of Vadose Zone

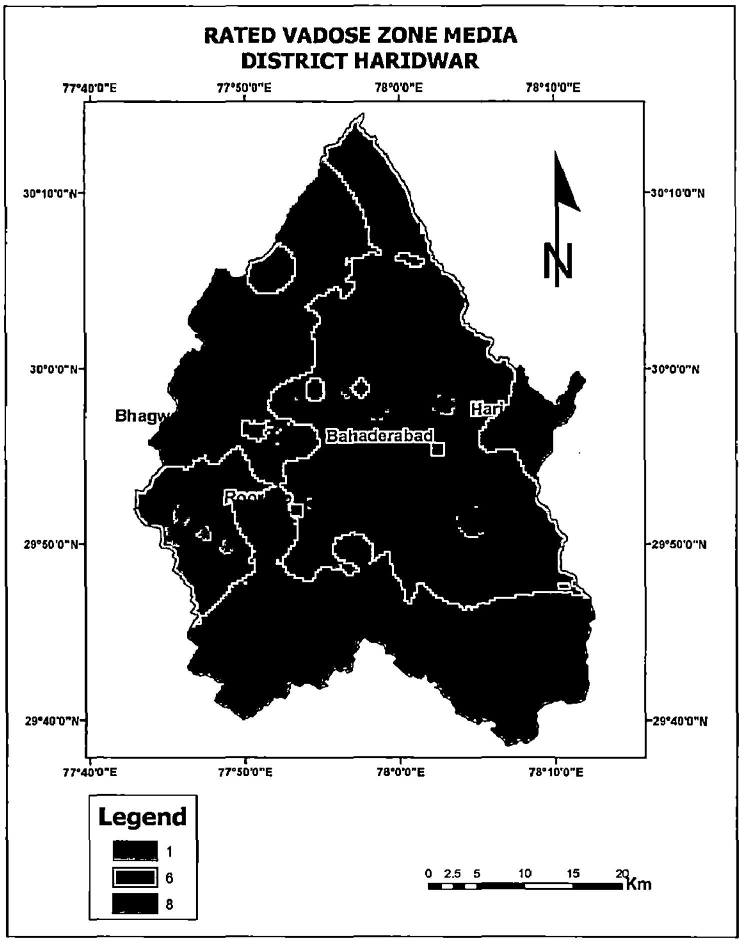


Fig.4.7 Rated Vadose Zone Media

Vadose zone is defined as the zone above water table and is unsaturated. The type of vadose zone media determines the attenuation characteristics of the material below the top soil. A total of 59 lithologs were analyzed to infer the material of vadose zone. Based on the perusal of lithological logs it was found that vadose zone material consists of varying proportions of sand, silt, clay, boulders etc. As in DRASTIC method, this parameter has got both variable ratings and typical ratings. A variable rating system of 4 to 8 was adopted for the present study, since the material is an admixture of different kind of materials. Table 4.6 shows the assigned rating for the vadose zone.

Table4.6 Ratings of I Parameter for the Present Study

Nature of vadose zone media	Rating
Clay	1
Sand gravel with significant silt and clay	6
Sand and gravel	8

Fig.4.7 shows the distribution of vadose zone materials in the study area. Sandy and gravely vadose zone has been observed in the southern Parts. Only in the isolated pockets, vadose zone is clayey. In rest of the area vadose zone is made up of sand, gravel, boulders, pebbles etc.

4.3.7 Hydraulic Conductivity

Hydraulic conductivity refers to the ability of the aquifer material to transmit water which in turn controls the rate at which the ground water would flow under a given hydraulic gradient. The rate at which ground water flow also controls the rate at which a contaminant would be moved away from the point at which it enters the aquifer. Table 4.7 shows the ratings assigned for the 'C' parameter for the present study area.

Table 4.7 Rating of 'C' parameter for the study area

Hydraulic conductivity (m/day)	
Range	Ratings
5.0-10.0	8
>10.0	10

From long duration pumping test data of 13 wells in the study area, the hydraulic conductivity was calculated. Plotting and classification have been done as given in section 4.3.1. Fig. 4.8 shows the distribution of hydraulic conductivity in the a

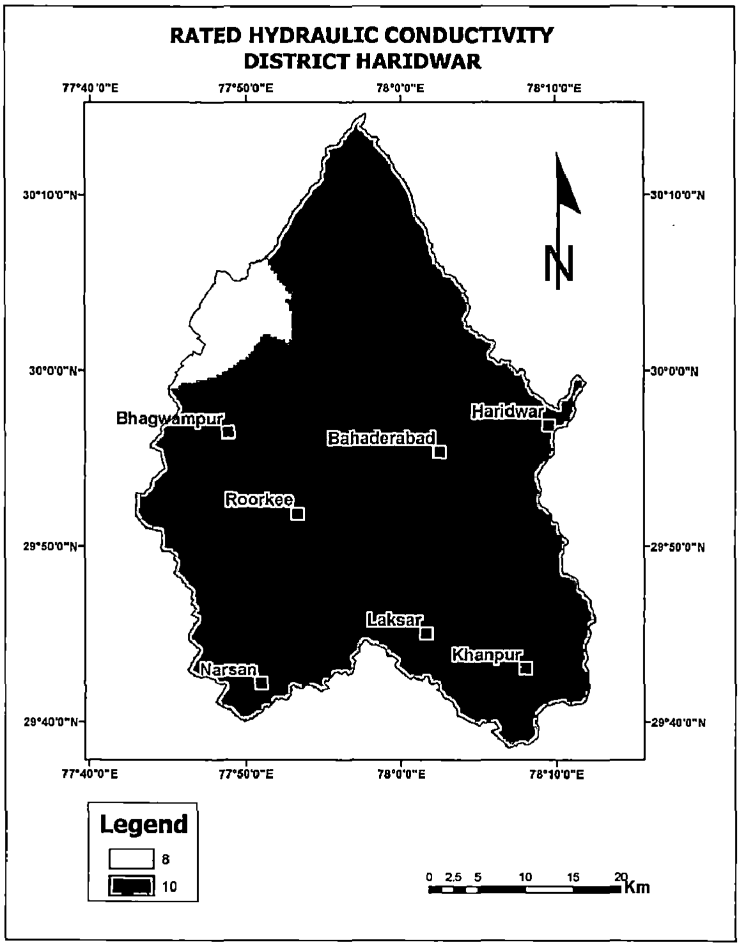


Fig.4.8 Rated Hydraulic Conductivity

4.3.7 Land Use

A level 1 classification of the study is done using SOI topographic sheets and other collateral data. Primary division like Urban, Agriculture, Rural, and Forest were done for the study area. These data were digitized and converted to a raster layer for further analysis.

The ratings considered are given in Table 4.8 and map is shown in Fig.4.9

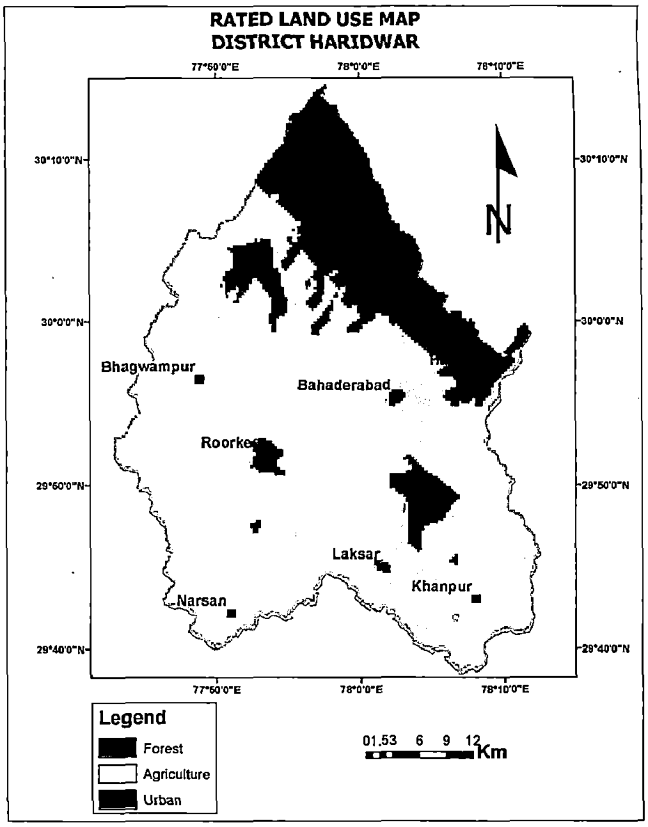
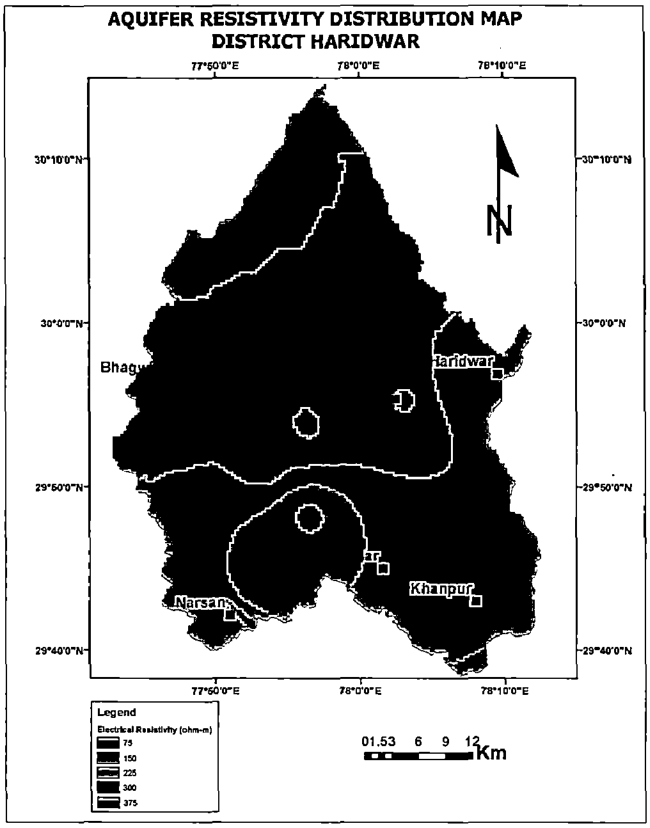


Fig.4.9Rated Land Use

4.3.8 Electrical Resistivity



The vertical electrical sounding was done at few locations in the study area. The field data was plotted in log-log sheet of same size as the master curves. Field curves are matched with master curves and interpreted. After a detailed study of interpreted zones and available lithologs, resistivities of aquifer media are delineated. This was plotted in ARC GIS and shown in Fig.4.10. It is inferred from the Fig.10 that there is gradation of resistivities from NE to SW.

Fig.4.10 Aquifer Resistivity

CHAPTER – V

WATER QUALITY ASSESSMENT

5.1 INTRODUCTION

Ground water is gaining attention as a source of drinking water owing to its low susceptibility to pollution in comparison to surface water and its relatively large storage space (US EPA, 1985). The degree of vulnerability of ground water to pollution can be expressed in different ways. One way is sensitivity of ground water quality to anthropogenic activities. The findings emerging analysis of water quality data along with along with general discussion on the ground water quality are presented in this chapter. An attempt has been made to compute a numerical index on overall ground water quality using hydro-chemical data are also presented in this chapter.

5.2 GROUND WATER QUALITY ASSESSMENT

In the present study, a total of 88 ground water samples from different locations of district Haridwar, were collected and analyzed for pH, TDS, Major ions, Nutrients and Heavy metals. A statistical summary of the results of analysis is given in Table 5.1. It is noticed from the table that ground water quality is exhibiting a very large range indicated by large standard deviations. Water quality parameters were compared with Indian Drinking Water Quality Standards (BIS 10500, 1991) as ground water is consumed by a sizable population residing in the study area.

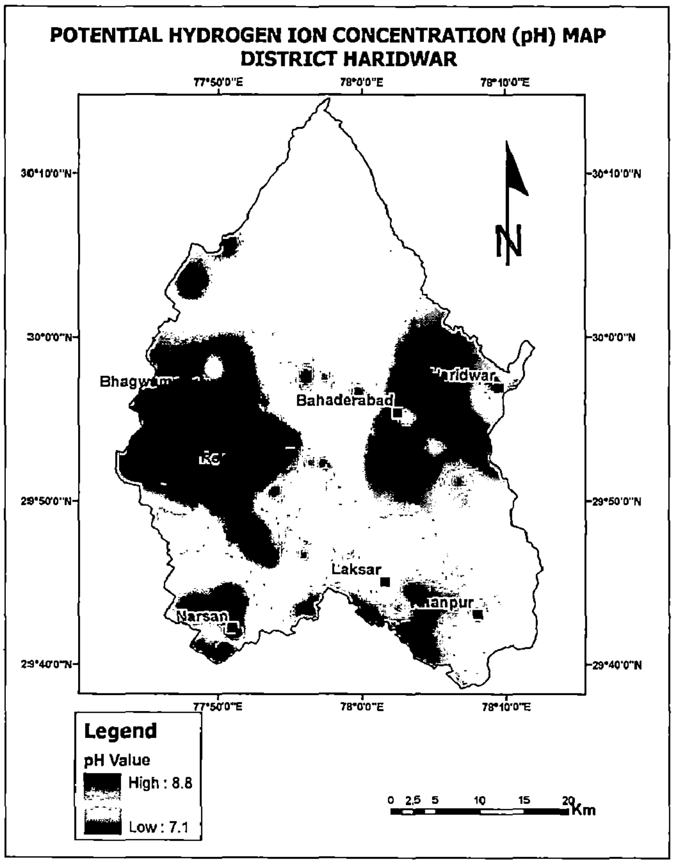


Fig.5.1 Distribution of pH

5.2.1 Physical Properties

pH: The observed pH values range from 7.1 to 8.8 against the pH occurrence inside the prescribed limits is expected to. Most of the samples lie with in the prescribed limits. Low and high pH will

cause corrosion in water supply lines and house hold plumbing fixtures due to its increased acidity and

Table 5.1 Statistical summary of groundwater quality data

Parameters	Min	Max	Mean	SD	Indian Water Quality Standard
Physical properties					
pH	7.1	8.8	7.7	0.35	6.5-8.5
Specific conductance (μmhos/cm)	234	1562	673.8	282.26	-
Total dissolved solid (mg/l)	1547	1020	448.8	184.7	500
Major ions (mg/l)					
Calcium (Ca^{2+})	61.6	408	178.5	74.21	75
Magnesium (Mg^{2+})	15	99.1	43.59	17.94	-
Potassium (K^{+})	nd	66.8	7.33	17.35	-
Sodium (Na^{+})	nd	259.6	30.87	59.45	-
Bicarbonate (HCO_3^-)					[TA=200]
Sulphate (SO_4^{2-})	64	358	188.8	62.26	200
Chloride (Cl^-)	1	144.9	22.96	29.88	250
Fluoride	Trace				1.0
Nutrients (mg/l)					
Nitrate (NO_3^-)	1.6	230	34.95	38.09	45
Phosphate (PO_4)	Trace				-
Heavy Metals (mg/l)					
Cadmium (Cd)	nd	0.008	0.005	0.001	0.01
Lead (Pb)	0.001	0.028	0.004	0.0056	0.05
Zinc (Zn)	0.001	3.442	0.295	0.61	5
Copper (Cu)	nd	0.061	0.009	0.0117	0.05

alkalinity respectively. In case of shallow wells deriving waters with high and low pH; the well machinery will get corroded easily. In rural house holds the storing vassals will get corroded due to high or low pH. Fig.5.1 shows pH distribution.

Total Dissolved Solids (TDS): Both organic and inorganic materials are dissolved in ground water right from its inception in hydrological cycle as precipitation. Later additional solids are dissolved in water through out the zone of saturation. TDS is generally used as a water quality indicator or as a salinity indicator. Water with high TDS can produce scaly deposits, and cause staining, wear, or corrosion of pipes, fittings, and storage devices. Excessively large concentration of TDS is objectionable in drinking water because of possible psychological effect, unpalatable mineral taste, and higher cost of additional treatment. Fig 5.2 shows TDS distribution in the present study area. The distribution is within the desirable limits in most of the agricultural, rural, and forest areas.

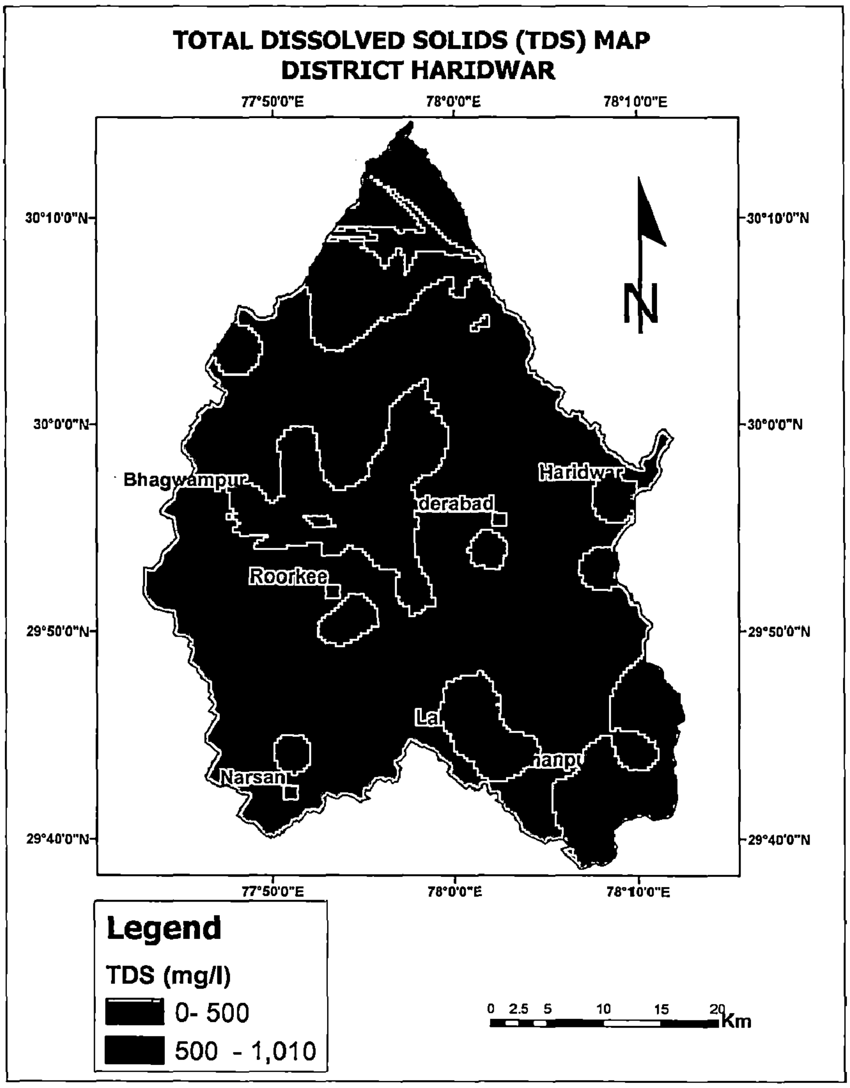


Fig.5.2 Distribution of TDS

However in the Urban areas like, Bahaderabad, Haridwar, Roorkee, Laksar, and Narsen shows a high TDS. Other areas showing high TDS are Southern most and Northern most areas. The distribution shows that the lowest TDS is

154 mg/l and the highest is 1020 mg/l. The desirable Indian Drinking Water Standard set by BIS is 500 mg/l. The average TDS is 448 mg/l. The Standard Deviation of 184 shows that there is great variation in TDS distribution as evidenced in the map. About 27% of the samples analysed high TDS than the desired Indian Standard.

5.2.2 Major Ions

Calcium (Ca^{2+}): Calcium is the dominant cation present in the water samples of the study area reflecting chemical maturity of the ground water of the area with the rock matrix. Majority of the samples (57%) show a high value of Ca^{2+} as compared to the Indian Drinking Water Standard of 75 mg/l. This may be a result of a number of interrelated geochemical processes like the dissolution and precipitation of calcite and dolomite minerals, which are present in the study area as impure calcium carbonate nodules

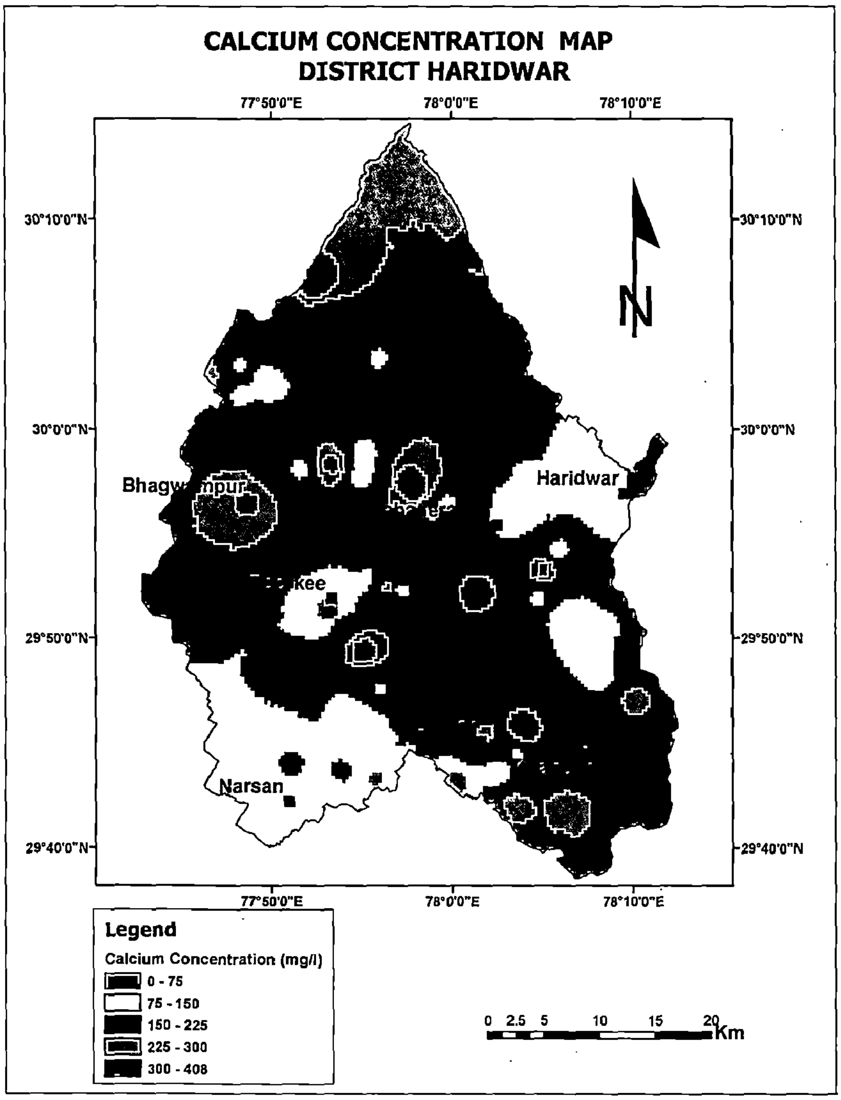


Fig.5.3 Distribution of Calcium

viz Kankar. High calcium is generally associated with Urban centers. Highest concentration of Calcium is observed in isolated pockets. The lowest value of calcium is 61.6 mg/l and height is 408 mg/l with an average of 178 mg/l. A standard deviation of 74 indicates wide variation in calcium content in ground water of the area.

Magnesium (Mg^{2+}): Magnesium is ranges from 15 mg/l to 99 mg/l. Average magnesium content is 43 mg/l and the Indian Drinking Water Standard has a desirable amount of 30 mg/l.

Both calcium and magnesium together account for the hardness of the ground waters of the area. The ground water of the area can be considered to be in medium hardness category. Hardness can cause scaling in vessels, and washing problems. Majority of the study area shows a magnesium concentration double than the desired limit. Isolated pockets are showing very high concentrations.

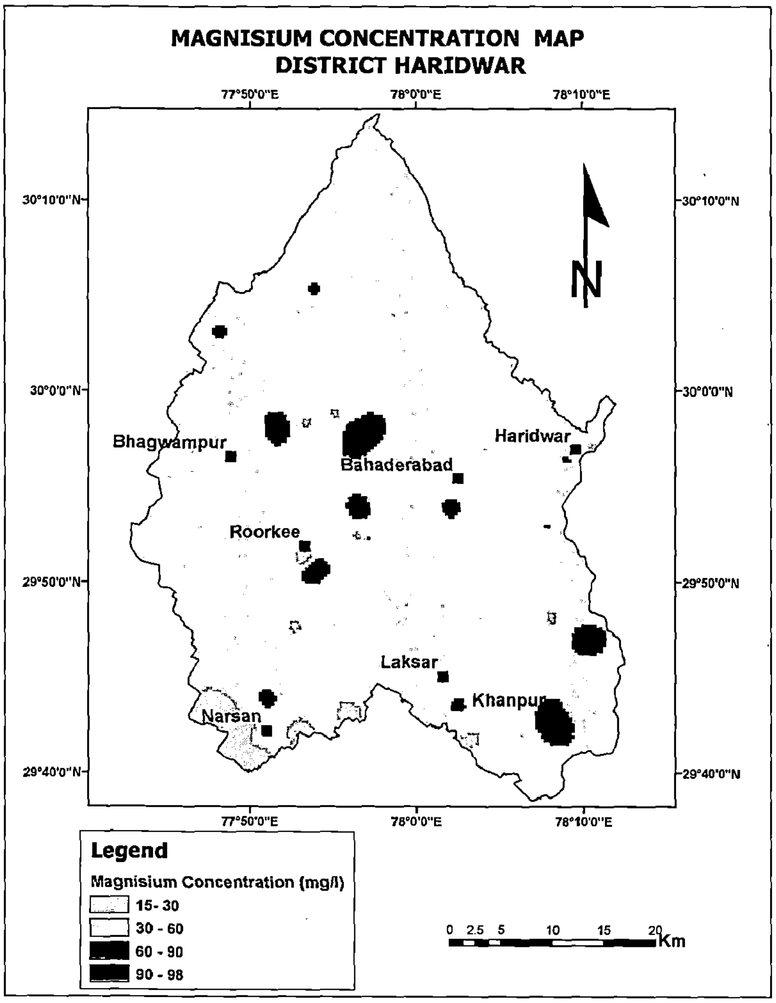


Fig.5.4 Distribution of Magnesium

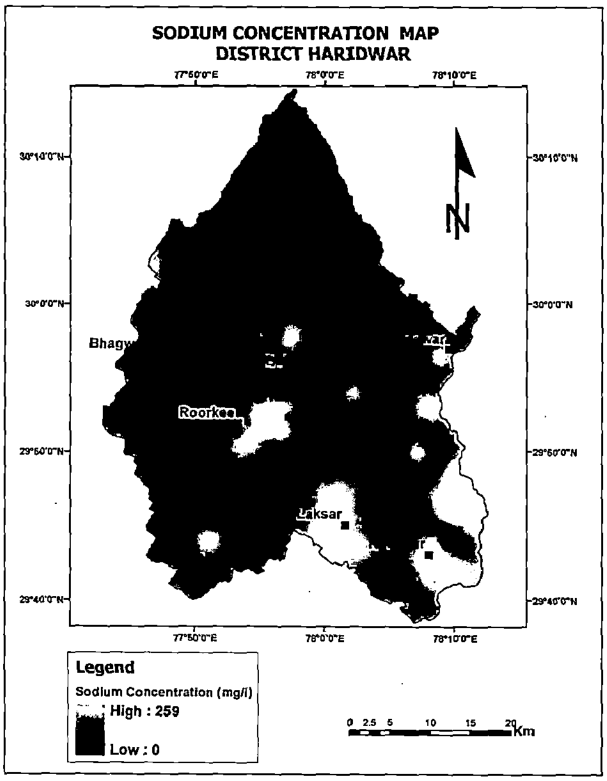
Sodium (Na^{+}): Sodium shows wide variations in the study area. In the ground waters of the study area, Sodium ranges from trace amount to 259 mg/l.

The average value of sodium is 30.87 mg/l. Excess sodium can cause salinity and can affect taste of the water. In contrast to the general behavior sodium is showing low values around urban clusters. That indicates that sodium is closely associated with agricultural practices in the study area.

Potassium (K^+): Another major cation is Potassium. In South Eastern and North Eastern portions potassium is showing a low values. Rest of the study area potassium is showing relatively high values. From many of the samples potassium, is in below detectable amount. However, in certain pockets, it ranges up to 66.8 mg/l. The average potassium content is 7.33 mg/l.

Sulphate (SO_4^{2-}): Sulphate is one of the major anions of the ground waters of the area. It is also showing wide variations. The values range from 64 to 358 mg/l. 32% of the samples show excess of sulphate than BIS desirable limits. Fig.5.8 shows that sulphate is within the limits in majority of the area. However, in Haridwar and its southern portions, it shows a high value.

Chloride (Cl^-): Distribution of chloride is displayed in fig.5.6 In the present study area, chloride is well within the permissible limits. However wherever intense canal irrigation and intense agricultural practices exist chloride shows relatively high concentration. The canal command area of Narsen block and Bahaderabad block show a high chloride distribution.



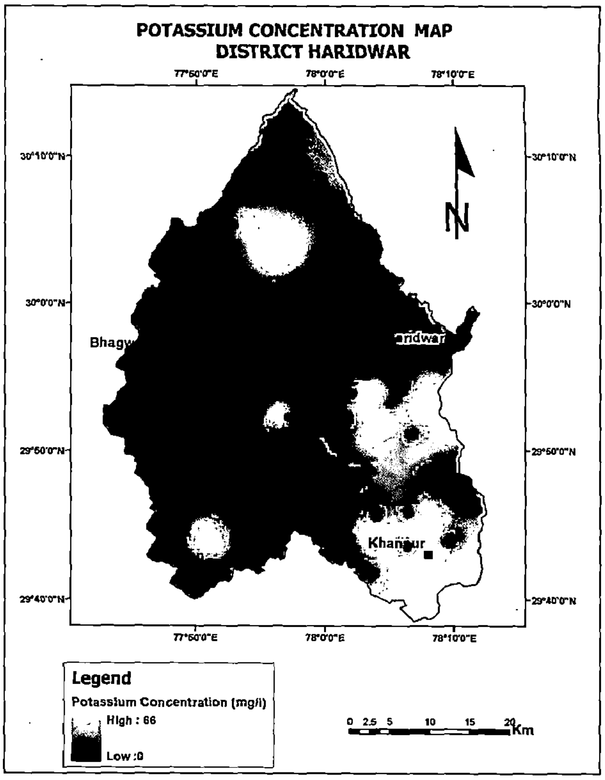
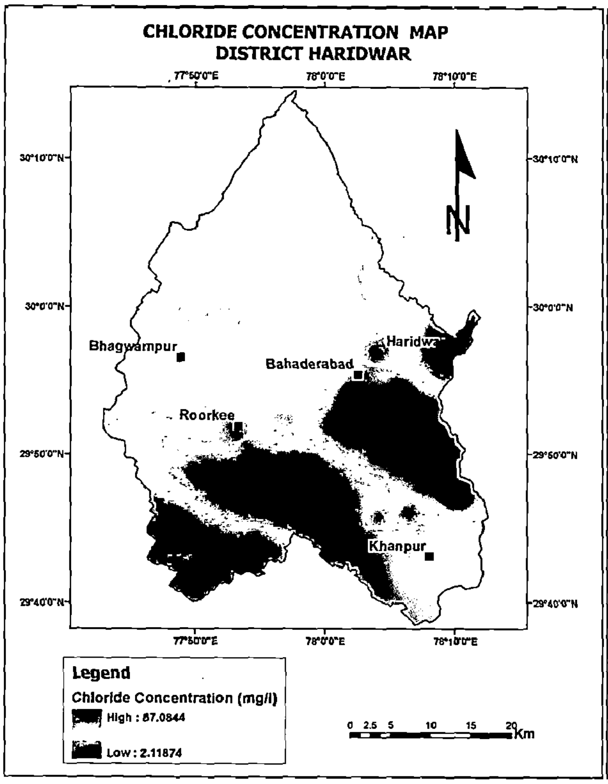


Fig. 5.5 and Fig. 5.6 Distribution of Sodium and Potassium



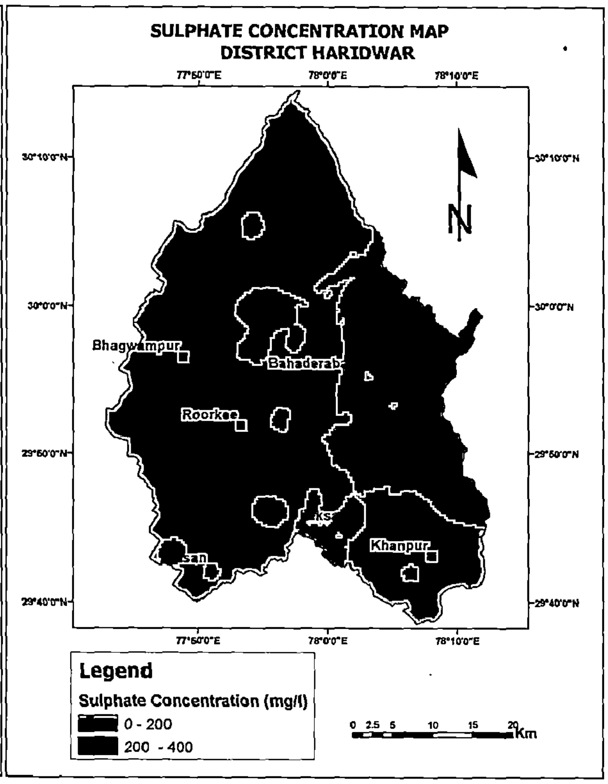


Fig.5.7 and Fig.5.8 Distribution of Chloride and Sulphate

Bicarbonate (HCO_3^-): Bicarbonates are the dominant anions in the ground water samples. 66% of the samples show a violation of Indian Drinking Water Standards.

The high concentration of bicarbonate in ground waters may be explained by the following process (i) the natural process such as dissolution of carbonate mineral and (ii) dissolution of atmospheric and soil carbon dioxide gas contributed by natural and anthropogenic sources in ground water.

$$CaCO_3 + CO_2 + H_2O \longleftrightarrow Ca^{2+} + 2HCO_3$$

$$CO_2 + H_2O \longleftrightarrow H^+ + HCO_3^-$$

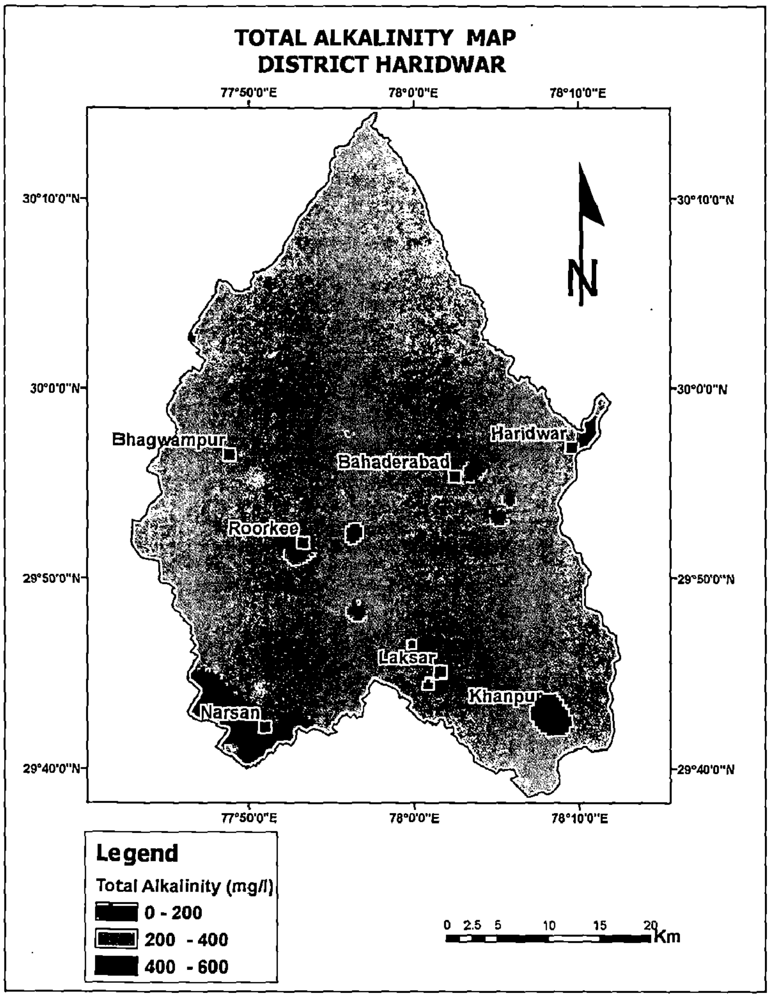


Fig.5.9 Distribution of Total Alkalinity

The bicarbonates were determined from total alkalinity empirically using Moore's Equation.

$$HCO_3^- = \{A + 1000 * (H^+) - 1000 * K_W * (H^+)\} / (1 + 2 * K_Z) / (H^+) \qquad ......5.1$$

Where ,

A = Alkalinity of titrate

H^+ = H^+ mole/liter

K_W = Ionisation constant for HCO_3^- = $4.69 * 10^{-11}$

K_Z = Ionic product of water = 10^{-14}

Carbonate (CO_3^-): Carbonates are derived by subtracting bicarbonates from total alkalinity and shows medium occurrence in the study area. Fig.5.9 shows that in majority of the study area alkalinity is high. Very high concentrations are observed at Khanpur area.

5.2.3 Nutrients

Nitrate (NO_3^-): Nitrates in ground water represent a pollution concern all over the world. They are perhaps the most ubiquitous of all ground water contaminants. Natural and human induced sources of nitrates in ground water are a result of irrigation, excessive application of commercial fertilizers, and waste disposal practices associated with sludge or waste water effluents, municipal or industrial landfills and septic tank systems. These sources can be natural, waste materials, and agriculture.In the study area nitrate values ranges from 1.6 mg/l to 230 mg/l with an average of 24.75 mg/l. Only 15% of the samples show

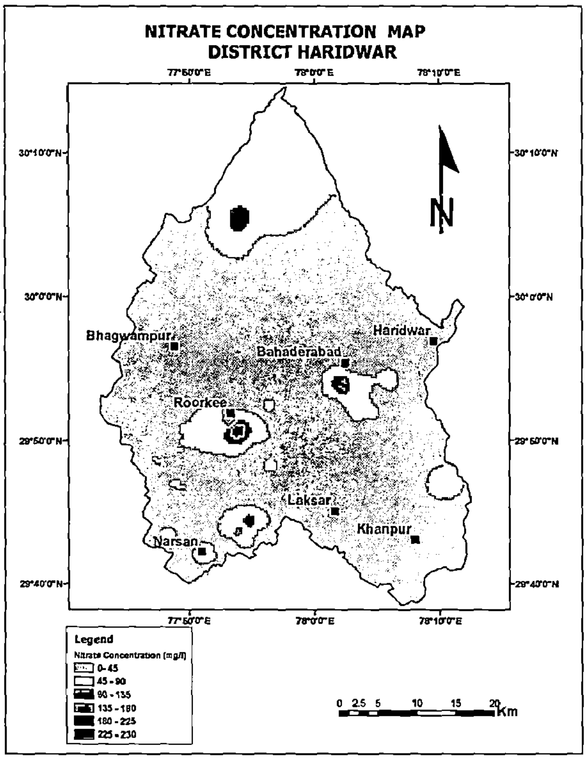


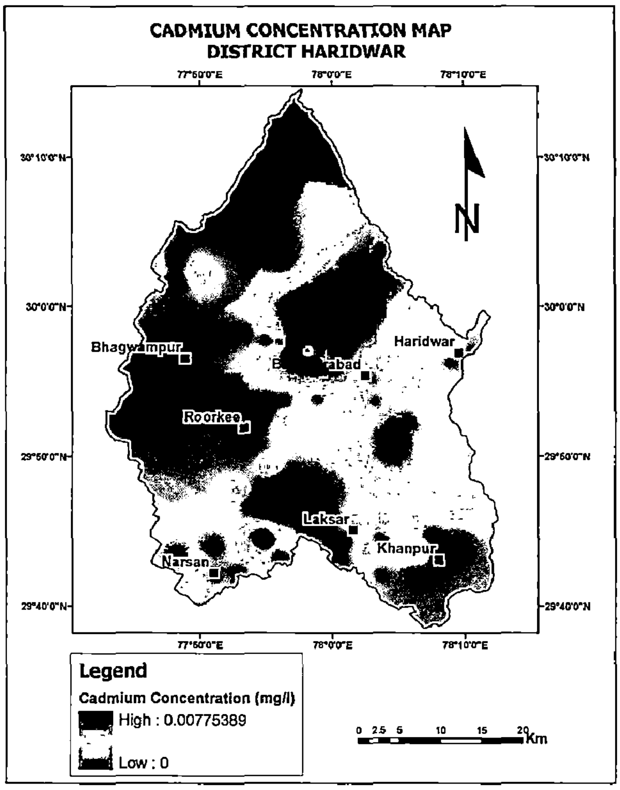
Fig.5.10 Distribution of Nitrate

higher nitrates than proposed desirable limit of 45mg/l. The Fig.5.10 shows that nitrates is within the limits in majority of the area. High nitrates are associated with urban areas and towns which are due to decomposition of urban waste and sewages.

Phosphates and TOC are available only in trace amounts, so it is not considered for the study.

5.2.4 Heavy Metals

In general, Heavy metals are found in the ground water as geogenic impurities. Ground water



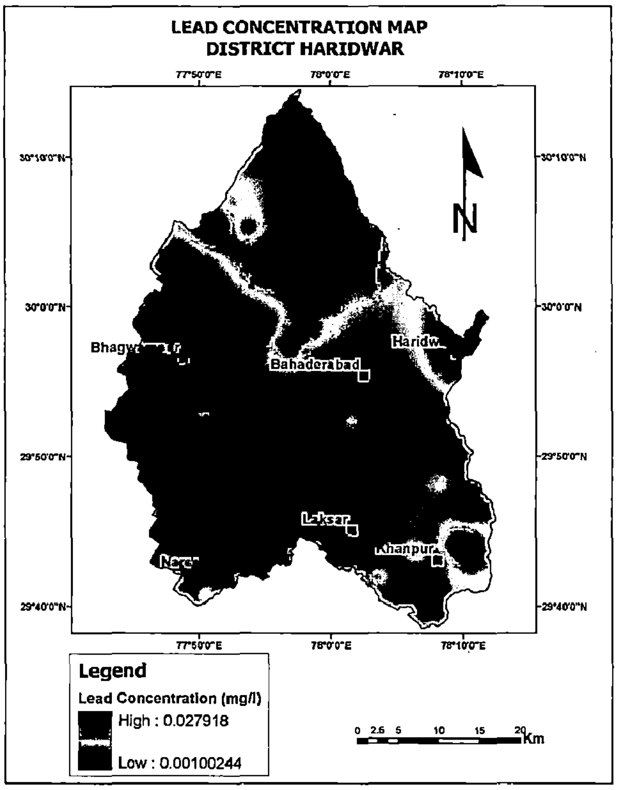


Fig.5.11 and Fig.5.12 Distribution of Cadmium and Lead

during its course through pores of soil and rock matrix acquires such impurities. However, anthropogenic activities can also contribute heavy metals to ground water. During the present study cadmium, lead, copper and Zinc were analyzed. Most of these heavy metals are found to be within the standards set by BIS.

Cadmium (Cd): Cadmium is highly toxic to man and animals (Friberg et al., 1974). In the present analysis, cadmium has been found to range from non detectable quantities to 0.008 mg/l against Indian Standards of 0.01mg/l. Cadmium distribution shows a high values near urban and industrialized areas like Bahaderabad, Roorkee, Haridwar etc.

Lead (Pb): The Pb in the ground water of the study area is mainly through anthropogenic activities such automobile industry, pesticides such as lead arsenate etc. However, lead is observed in all water samples analysed and results show a minimum value as 0.001 mg/l to a maximum value of 0.028 mg/l. Indian desirable limit is 0.05mg/l. Standard deviation of 0.0056 indicates a uniform occurrence in the study area. Distribution of lead also is in conformity with other heavy metals and high concentrations observed near urban centers and nearby industrial areas.

Zinc (Zn): Zinc is essential for plant and animal metabolism. Average Zn concentration in the

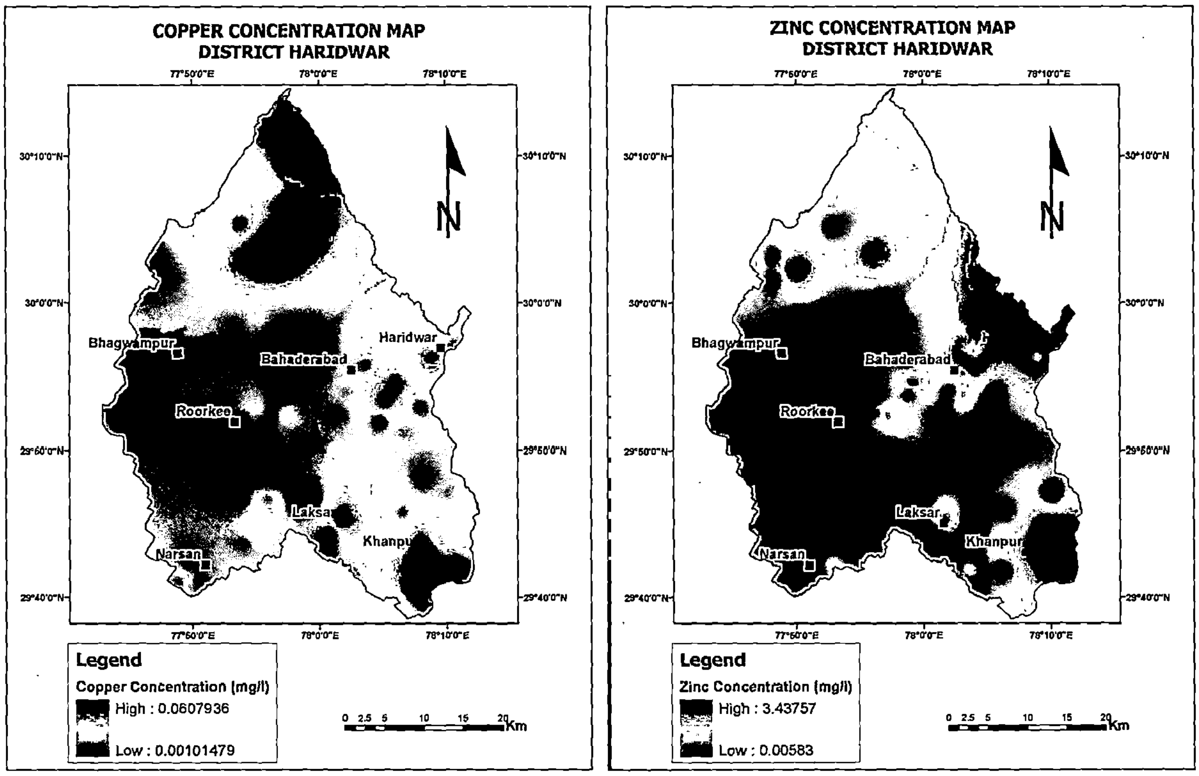


Fig.5.13 and Fig.14 Distribution of Copper and Zinc

present study area is 0.298 mg/l. Desirable Indian standard is 5 mg/l. Zink is also showing high values near urban and southern areas.

Copper (Cu): Copper concentration in ground water of the area is ranging from non detectable amount to 0.061 mg/l. Desirable Indian Standard is 0.05mg/l. Only 2 of the samples shows ranges above desirable limits. So it can be concluded that copper concentration in present study area is well within the desirable limits set by BIS. High Copper values near urban centers.

5.3 GROUND WATER FACIES

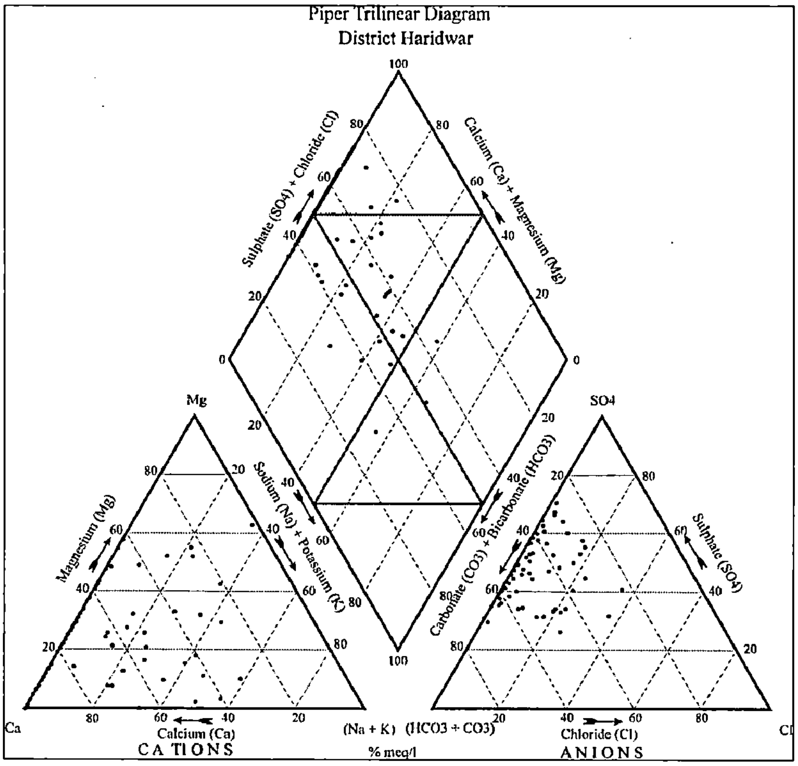


Fig.5.15 Piper Trilinear diagram for the study area

The concept of hydro-chemical facies was developed by Back (1966). The term hydro-chemical facies is used to describe the bodies of ground water in an aquifer that differ in their chemical composition. The facies are a function of lithology, solution kinetics and flow pattern of ground water through the aquifer.

The chemical data obtained during chemical analysis is plotted on a Piper trilinear diagram to know the facies of ground waters of the study area. The plot of anions shows that majority of the samples are bicarbonates and sulphates. Cationic facies shows that a quite number of samples fall in Calcium and Magnesium category, rest of the samples showing a non dominant classes. Further it is inferred from the diagram that the ground water of the study area falls in calcium sulphate facies.

5.4 GROUND WATER QUALITY INDEX

The DRASTIC vulnerability assessment gives only a relative assessment of aquifer vulnerability to pollution by utilizing seven environmental parameters in context of an empirical indexing system. However, data scarcity, inexactitude as regards the soil zone which is rich in biological activity, the lithology, the grade of consolidation and fissuring in the unsaturated zone, the physical – chemical character of percolating pollutants and the initial hydraulic loading associated with the pollutant event, require all ground water vulnerability assessment to be validated by accurate empirical field testing (A.J.Melloul and M.Collin, 1998).

So it is imperative to formulate a ground water quality index using hydro - chemical data. In the present study the **Index of Aquifer Water Quality (IAWQ)** proposed by A.J.Melloul and M.Collin, 1998 was selected because (i) it gives overall ground water quality status and (ii) its preparation is in a manner parallel to the DRASTIC vulnerability assessment method (weighing and rating system), and (iii) it can form a basis for validating vulnerability assessment. So that, together these two models can assess the relative vulnerability potential to pollution and the actual situation of ground water quality for any particular aquifer.

The Index of Aquifer Water Quality (IAWQ) is an empirical relation simultaneously utilizing data values of a number of chemical parameters characterizing pollution. This index can act as a means of relating theoretical DRASTIC results to field realities. The procedure for obtaining is given below.

In order to standardize the field data, each value of a parameter P_{ij} (field data value) is related to P_{id} (Indian desirable drinking water standard) by the relation

$$X_{ij} = P_{ij} / P_{id} \qquad \text{............5.2}$$

To relate X_{ij} as a corresponding index rating value, related to ground water quality, Y_i has been assigned to each X_{ij} value as follows.

(i) For high water quality, with X_{ij} equal to 0.1, the corresponding index rating value would be around 1.

(ii) For acceptable water quality, with X_{ij} equal to 1(the raw field value is equal to standard desired value), the corresponding index rating value of such water would be 5.

(iii) For unacceptable ground water quality with X_{ij} equal to or higher than 3.5 (the initial value of the field data is equal or higher than 3.5 times its standard desired value), corresponding index rating would be 10.

Now, for X1 = 0.1, Y1 = 1, for X2 = 1, Y2 = 5 and for X3 = 3.5, Y3 = 10. The for any parameter i in any cell j an adjusted parabolic function of rates $Y_{ij} = f(X_{ij})$ can be determined and converted to a polynomial

$$\mathbf{Y_i = -0.712 * X_i^2 + 5.228 * X_i + 0.484} \qquad \text{.................5.3}$$

From this Equation the corresponding rating Y_i can be estimated for any value of X_i. After this transformation of the field data, the index formula would involve only Y values representing input data.

The IAWQ selected for the study is the summation of weights multiplied by ratings of various parameters i for each cell j by using the formula

$$\mathbf{IAWQ = C / n} \left[\sum_{i=1}^{n} (Wri * Yri)\right] \qquad \text{................5.4}$$

Where

C Constant (in the present case 10)

n No. of parameters involved (i = 1,2,........n), in the present study major ions and heavy metals are taken up for the study. Heavy metals being toxic to human and animals, considered for the calculation of IAWQ. Among the major ions, those ions for which more than 10% of the sample shows higher values than the Indian Drinking Water Standard were selected for the estimation of IAWQ.

Table 5.2 Percentage and Violation of samples exceeding the Indian standards

Parameters	Percentage of samples exceeding Indian standard	Indian Drinking Water Standard
TDS	27	500
Ca^{+2}	57.47	75
TA	66	200
SO_4^{-2}	32	200
$NO3^-$	15	45

$W_{ri} = W_i / W_{max}$ and

$Y_{ri} = Y_i / Y_{max}$

Where

W_i is weight for any given parameter. In the present study the weight is ranging from 1 to 5. Weight is a numerical value assigned to a parameter to characterize its relative anticipated pollutant impact. Lower numeric value designates lower pollution potential and vise versa. W_i would be larger if a given parameter is toxic or hazardous to ground water. Table 5.3 gives classification and assignment of weight to water quality parameters on the basis of human health significance.

W_{max} is maximum weight assigned, i.e., 5

Y_i is the rating derived from Equation 5.3

Y_{max} is the maximum rate i.e., 10

Table 5.3 Classification of water quality parameters on the basis of human health significance

Group	Parameter	Water quality criteria	Weight
I	Cd	Biologically cadmium is a non essential, non beneficial element recognized to be a high toxic potential. It is deposited and accumulated various tissues and is found in varying concentration throughout all areas where man lives. The Cadmium is toxic to man when ingested or inhaled. It is stored largely in the kidney and liver and is excreted at an extremely slow rate (Train, 1979)	5
	Pb	Most Lead salts are of low solubility and stable complexes result also from the interaction of Lead with the sulfhydryle group. It has no beneficial or desirable nutritional effects. It is a toxic metal that tends to accumulate in the tissues of man and other animals. Although seldom seen in the adult population, irreversible damage to the brain is a frequent result of lead intoxication in children. Such lead intoxication most commonly results from ingestion of lead-containing paint still found in older homes. The major toxic effects of lead include anemia, neurological dysfunction, and renal impairment (EPA, 1973).	5
II	NO_3^-	It becomes toxic only under conditions in which they are high nitrates concentration. Otherwise, at "reasonable" concentrations, nitrates are rapidly excreted in the urine. High intake of nitrates constitutes a hazard primarily to warm blooded animals (Specially the younger ones, blue baby syndrome) under conditions that are favorable to their reduction to nitrite.	4
III	TDS	Excess dissolved solids are objectionable in drinking water because of possible physiological effects, unpalatable mineral tastes. The physiological effects directly related to dissolved solids include laxative effects principally from sodium sulfate and magnesium sulfate and the adverse effect of sodium on certain patients afflicted with cardiac disease and women with toxemia associated with pregnancy.	3
IV	Ca^{2+}	There are no direct effects on the human health.	1
	TA	There are no direct effects on the human health.	1
	SO_4^{2-}	There is no direct effect on human health	1

5.4.1 Calculation of IAWQ using GIS

- Using Spatial Analyst module of ARC GIS, the geographic distribution of all 7 parameters were prepared
- X_{ij} values were calculated using Raster Calculator in Spatial Analyst by dividing field values with Indian desired drinking water standard value (All the values above 3.5 is taken as 3.5).
- Y_i values were calculated using Equation 5.3

- IAWQ is calculated using Equation 5.4 where C=10, n =7, W_i taken from Table 5.3, W_{max} = 5, Y_i obtained in former step and Y_{max} = 10

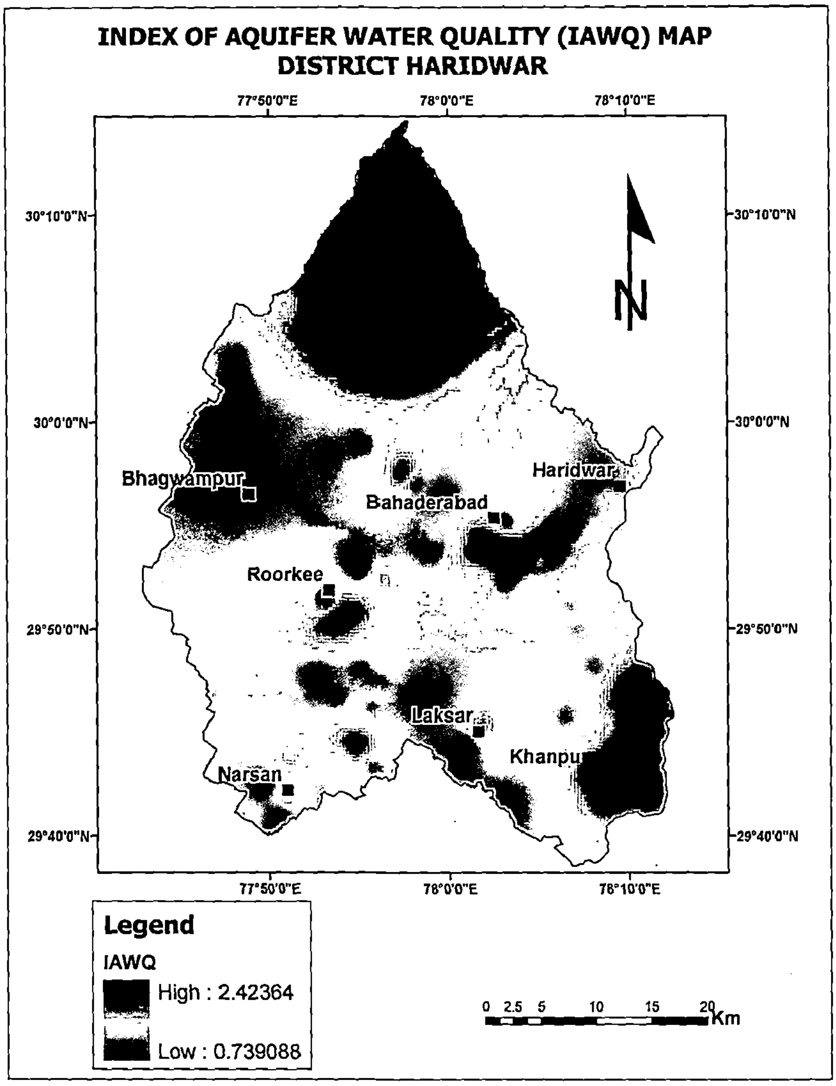


Fig.5.16 Index of Aquifer Water Quality

Index of Aquifer Water Quality ranges from 0.73 to 2.4. Water quality index map displays that northern part of the district has high water quality index. All the urban centers show high water quality index. Rest of the area shows lesser degree of contamination. A high water quality index indicates a high contamination concentration and low index value represent low contamination concentration.

CHAPTER – VI
ASSESSMENT OF AQUIFER VULNERABILITY

6.1 INTRODUCTION

This chapter describes the assessment of aquifer vulnerability using DRASTIC method. An attempt has also made to conduct sensitivity analysis of DRASTIC components. DRASTIC has also been slightly modified to suite the local controlling factors. Both DRASTIC Vulnerability Index and Modified DRASTIC Vulnerability Index has been validated with Water Quality Index, computed and presented in earlier section..

6.2 COMPUTATION OF DRASTIC VULNERABILITY INDEX

The DRASTIC Vulnerability Index (DVI) has been calculated as per the Equation 3.1 given in section 3.5. Fig.6.1 shows the schematic diagram of calculating DVI for the present study area. In order to understand the Vulnerability Index, it is necessary to choose a representation method which can expose the aquifer vulnerability in an appropriate fashion and simultaneously allows comparability between different areas. Table 6.1 shows the portion of common colour coding adopted by Aller et al., (1987) applicable in the present study area. Fig.6.2 shows the vulnerability index developed for the study area.

Table 6.1 Classification of DVI for the Study Area (Aller et al., 1987).

Class	DVI Index	Colour code
1	120-139	Dark Green
2	140-159	Light Green
3	160-179	Yellow
4	180-199	Orange
5	>200	Red

Figure shows that highest vulnerability (>199) is demonstrated in the southern parts of the district. Sandy soil, sandy aquifers, sandy vadose zone, flat topography, high recharge rates, high hydraulic conductivity and moderately deep ground water table are the reasons of the same. Isolated pockets near Bhagwanpur and North Western parts are also showing high vulnerability index. Majority of the area shows a vulnerability demonstrated by a index value of 179 to 199. Western part of the Roorkee, North of Bahaderabad and surroundings of Haridwar show a medium vulnerability with DRASTIC Index of 159 to 179. Isolated pockets in the district show still lesser vulnerability.

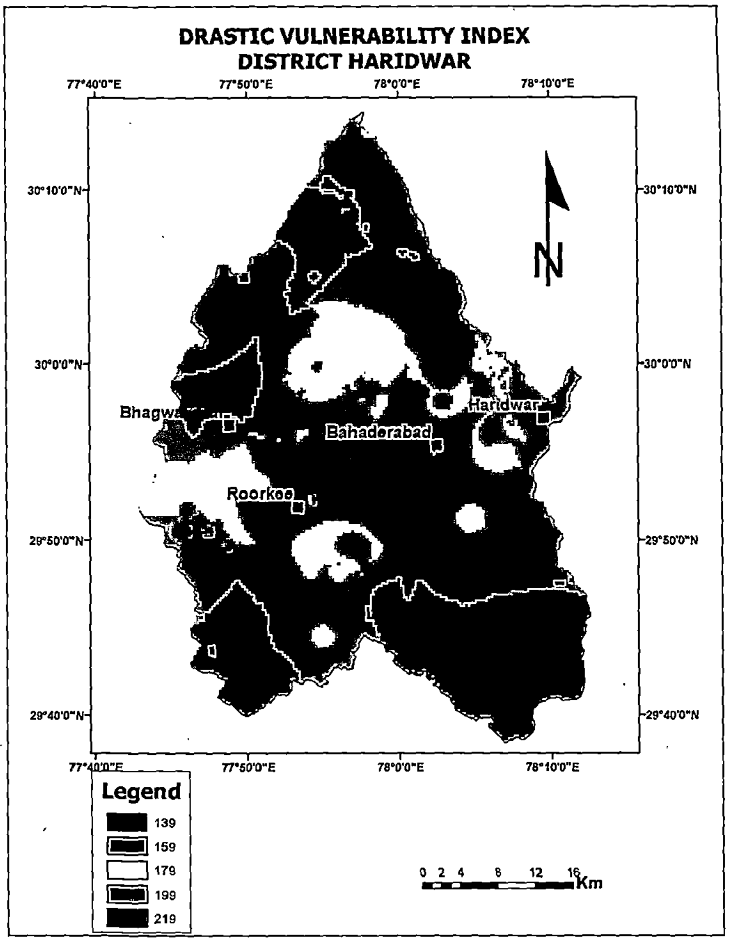


Fig.6.1 DRASTIC Vulnerability Index

6.3 SENSITIVITY ANALYSIS OF DVI

DRASTIC model employs a number of input layers which will limit the impacts of errors or uncertainties of the individual parameters on the final output. However, unavoidable subjectivity is associated with assigning the ratings and weighting coefficients to compute the Vulnerability Index. Sensitivity analysis is meant to evaluate whether it is a real necessity to use all the seven parameters and effectiveness of each parameter. The sensitivity analysis can be done through test of independency, single parameter sensitivity analysis, and map removal sensitivity analysis (Lodwick et al., 1990).

Test of Independency: was done using statistical summary of the parameters used in DRASTIC Index. Table 6.2 describes the statistical summary of the parameters of the present study. From the table it is inferred that hydraulic conductivity (with a mean of 9.9) poses highest risk of contamination. Net recharge, Aquifer media, Soil, and topography poses moderate risk of contamination and impact of vadose zone and depth to water table poses least risk of contamination.

Table 6.2 Statistical summary of rated DRASTIC parameters

Parameters	Min	Max	Mean	SD	Correlation Coefficient with DVI
D	3	10	7.8	1.33	0.599
R	3	9	8.8	0.44	0.322
A	6	9	8.1	0.38	-0.0857
S	7	9	8.7	0.63	0.354
T	7	9	8.7	0.63	0.0844
I	1	8	6.9	1.19	0.634
C	8	10	9.9	0.42	0.0276
DVI	139	219	200.7	12.64	1.0

Standard deviations indicate that, aquifer media is the least deviating parameter of the study area. So this parameter has lowest contribution to variations in vulnerability index across the study area. Next lesser variable parameter is the net recharge and hydraulic conductivity. Behavior of soil is in conformity with the topography. Maximum deviation is observed in depth to water level and impact of vadose zone. The study indicates that recharge is related to hydraulic conductivity and impact of vadose zone is related to depth to water table and soil is related to topography.

Correlation coefficients with DVI indicate that depth to water level and impact of vadose zone are the most effective layers in DVI. Net recharge and soil media shows moderate correlation. Topography and aquifer media have still lesser influence and hydraulic conductivity has least influence on DVI.

Table 6.3 Inter Layer Correlation Matrix

Layer	D	R	A	S	T	I	C	DVI
D	1	0.13439	-0.1912	0.13667	-0.15415	0.12237	-0.18769	0.59904
R	0.13439	1	0.08802	-0.1222	0.02462	0.07075	0.15144	0.32215
A	-0.1912	0.08802	1	-0.00491	0.11195	-0.25398	0.07935	-0.08572
S	0.13667	-0.1222	-0.00491	1	0.00905	0.1925	-0.11742	0.3541
T	-0.15415	0.02462	0.1119	0.00905	1	0.10868	-0.06834	0.08443
I	0.12237	0.07075	-0.25398	0.1925	0.10868	1	-0.16212	0.63432
C	-0.18769	0.15144	0.07935	-0.11742	-0.06834	-0.16212	1	0.02758
DVI	0.59904	0.32215	-0.08572	0.3541	0.08443	0.63432	0.02758	1

Inter layer correlation are given in Table 6.3. The analysis shows that the inter layer correlation is not good. Hence, all layers can be considered as independent.

Single parameter sensitivity: this analysis has done to know the impact of each of the DRASTIC parameters on vulnerability index. In this analysis, compare effective or real weighting coefficient of each parameter is compared with the theoretical weighting coefficients assigned in DRASTIC analytical model (Napolitano and Fabbri, 1996). The effective weighting coefficient is calculated using the formula

$$W = (P_r * P_w / V) * 100 \qquad \text{.......6.1}$$

Where W Effective weighting coefficient of each parameter

P_r Rating value of each parameter

P_w Weighting coefficient of each parameter (Theoretical)

V Vulnerability Index

The effective weighting coefficient is a function of the value of the single parameter with regard to the six other parameters as well as the weight assigned to it by the DRASTIC model. Table 6.3 details the statistics of single parameter sensitivity analysis. From the Table 6.3, it is inferred that effective weighting coefficients show some deviation from their original theoretical weights. Depth to water level (with effective weight percentage of 18.91) is still the dominant factor with maximum variation. Effective weighting coefficients of Net recharge, Aquifer media, Soil, and Topography are in proximity with their theoretical weighting coefficients. The effective weighting coefficient of impact of vadose zone (16.85%) shows much lesser value with its theoretical value (21.7 %). However, in case of hydraulic conductivity, effective weight is more than its theoretical values.

Table 6.3 Statistics of Single Parameter Sensitivity Analysis

Parameter	Min	Max	Mean	SD	Theoretical Weighting %	Theoretical Weight	Effective Weight
D	8	25	18.91	2.89	21.7	5	4.35
R	7	25	17.47	1.32	17.4	4	4.02
A	9	17	11.81	1.18	13.0	3	2.71
S	7	12	8.5	0.78	8.7	2	1.95
T	0	7	4.5	0.81	4.3	1	1.03
I	2	22	16.85	2.6	21.7	5	3.87

C	10	21	14.54	1.17	13.0	3	3.34

Map removal sensitivity: Map sensitivity analysis was computed by removing one or more data layers. Table 6.4 displays variation of vulnerability index by removing only one layer at a time sequencially.

Table 6.4 Statistics of Map Removal Sensitivity Analysis

Layers Removed	Min	Max	Mean	SD	% variation
DVI	**138**	**208**	**190.07**	**9.86**	
D	119	161	150.83	6.76	20.64
R	102	172	154.66	9.42	18.6
A	114	184	165.66	10.07	12.8
S	120	190	172.74	9.55	9.1
T	128	198	180.45	9.81	5.1
I	119	168	155.7	7.18	18.1
C	108	178	160.35	10.04	15.6

It is clear from the table that high variation in vulnerability index is expected upon removal of 'Depth to water level' layer. This is attributed to its high theoretical weighting coefficient and also its high local rating. As expected, net recharge and impact of vadose zone plays next potential contamination risk. Hydraulic conductivity is more influential than aquifer media, even though each has same theoretical importance. Topography is the least sensitive layers among the DRTASTIC layers.

A multi layer sensitivity analysis was done by removing successively least sensitive layers based on Table 6.4 and results are summarized in Table 6.5. Doing sensitivity analysis is done with multiple layers, it was inferred that variations are more or less uniform throughout the area for topography, soil, aquifer media, hydraulic conductivity and impact of vadose zone. Again it got confirmed that depth to water table and net recharge are the most varying factors for the study area.

Lodwick et al., (1990) developed sensitivity coefficient using the formula given in Equation 6.2. Sensitivity coefficient is a variation index. The results are summarized in Table 6.6.

Table 6.5 The Statistics of Multilayer Sensitivity Analysis.

Layers Used	Min	Max	Mean	SD
DRASTIC	138	208	190	9.86
DRASIC	128	198	180	9.81
DRAIC	110	180	163	9.51
DRIC	86	156	139	9.74
DRI	56	126	109	9.91
DR	37	86	75	7.15
D	15	50	39	6.69

S = {[(V / N) – (V' / n)] / V} * 100 **.......6.2**

Where S Sensitivity Coefficient

V Original DVI

N No. of parameters (7)

V' VI using lesser no. of parameters

n No. of parameters used

Table 6.6 Statistical Summary of Sensitivity Coefficient Estimation

Layers Used	Min	Max	Mean	SD	Inter layer difference
DRASTIC	0	0	0	0	0
DRASIC	2	3	2.04	0.2	2.04
DRAIC	2	5	3.44	0.51	1.4
DRIC	2	6	4.34	0.55	0.9
DRI	0	7	5.29	1.06	0.95
DR	0	11	5.73	1.32	0.44
D	0	14	6.9	2.85	1.17

It is inferred from the Table 6.6 that topography and soil are the parameters least variable and least sensitive. Impact of vadose zone is most variable and most sensitive. Hydraulic conductivity and aquifer media are the parameters moderately sensitive and moderately variable. Depth to water table is most variable but least sensitive.

6.4 MODIFICATION OF DVI

In DRASTIC vulnerability Index model, the ratings and weighting coefficients are taken subjectively based on their physical significance. An attempt has been made in the present study to remove the subjectivity in assigning the weighting coefficient through sensitivity analysis. Ratings of most of the DRASTIC parameters are suited to the present location conditions of the study area. However, most of the hydraulic conductivity data are surpassing the highest limit of the DRASTIC ranges. So the range of the hydraulic conductivity has to be modified.

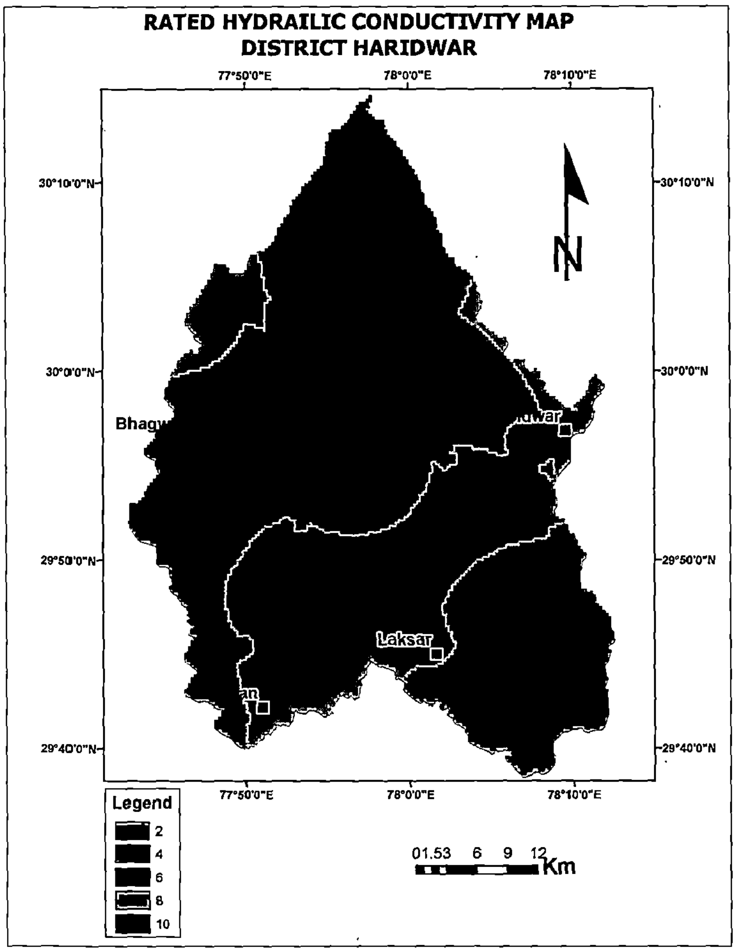


Fig.6.2 Rated Hydraulic conductivity

The modification is adopted from the work of Hussain et.al., (2005). The modified DRASTIC ranges and its ratings for hydraulic conductivity is given in Table 6.7. Hence it is imperative to modify the DRASTIC method, just to suit to the present field conditions. Fig. 6.3 shows the rated hydraulic conductivity distribution for the resent study area. Land use has got a good correlation with vulnerability index, so a separate modified index is developed by combing land use with modified DVI. The Weighting coefficient has been taken as 5 rating as given in Chapter IV.

Table 6.7 Original and modified ranges of hydraulic conductivity

Original Ranges	Modified Ranges	Ratings
0.005 – 0.5	0.03 – 3.0	1
0.5 – 1.5	3.0 – 9.0	2
1.5 – 3.5	9.0 – 21.0	4
3.5 – 5.0	21.0 – 30.0	6
5.0 – 10.0	30.0 – 60.0	8
>10.0	>60.0	10

(Source, Hussain, 2005)

6.5 VALIDATION OF DVI AND MODIFIED DVI

Validation of aquifer vulnerability is a difficult task. A high vulnerability does not imply a corresponding increase in ground water quality deterioration. However, it implies that the system is sensitive to contaminants, and risk of getting polluted is on a high level. In the present study, an attempt has been made to validate both DRASTIC and Modified DRASTIC (with theoretical weights and

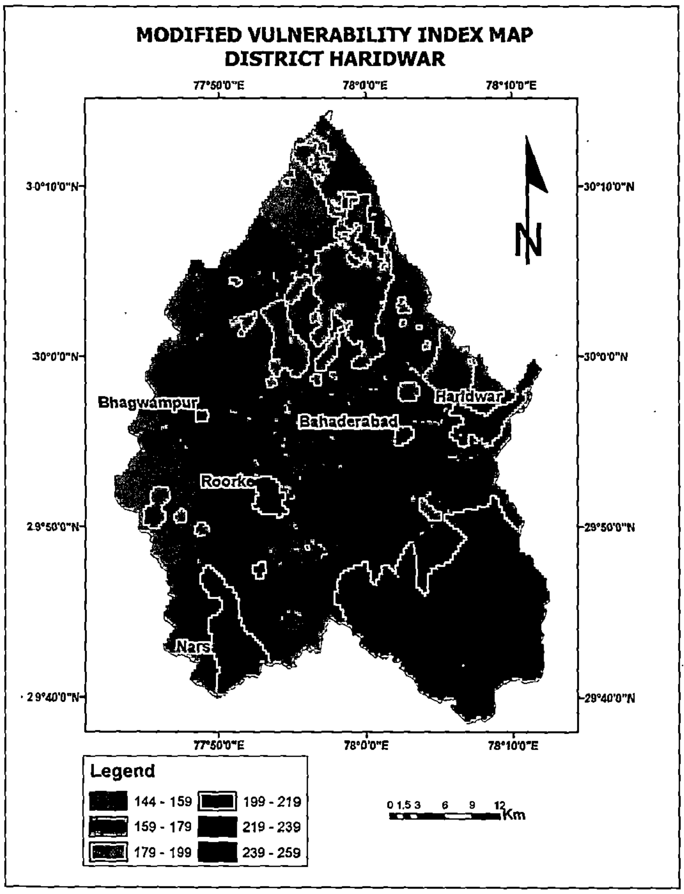


Fig.6.3 Modified Vulnerability Index

with effective weights) with IAWQ developed in Chapter V.

Validation was done through Spatial Statistical Analysis module of ARC GIS 9.1. In this band combination analysis, has been done to derive a correlation matrix of DVI, IAWQ, MOD DVI, and modified DVI + Land use. The table 6.8 shows a summary of the analysis. The results show that a negative correlation exists between IAWQ and various vulnerability indices. The values of -0.003, -0.108 and -0.423 is obtained for DVI, Modified DVI and Modified DVI with Land use respectively. The results are interpreted as follows.

- There may not be a clear cut relation ship between IAWQ and Vulnerability Indices.
- The area may be vulnerable to pollution but presence of polluting contaminants is not reflected in the water quality index.
- The low correlation coefficients indicate that Index of Aquifer Water Quality is not a parameter reckoned to validate aquifer vulnerability for the present study area.

Table 6.8 Correlation matrix of various indices with IAWQ

Layer	**Mod. DVI+ Land use**	**IAWQ**	**Modified DVI**	**DVI**
Mod. DVI+ Land use	1			
IAWQ	**-0.42367**	1		
Modified DVI	0.76728	**-0.10812**	1	
DVI	0.50065	**-0.00319**	0.71243	1

Another attempt has been made to correlate the vulnerability indices with resistivity data. The resistivity of the aquifer media is plotted. The rasterised data is correlated with vulnerability indices. Results are summarized in table 6.9. The table displays that a correlation of 0.13 and 0.48 is obtained for DVI and Modified DVI respectively. It is inferred from the study that aquifer media resisitivity can be used to validate vulnerability indices. But further detailed study is required in this field.

Table 6.9 Correlation Matrices of Vulnerability Indices with Aquifer Resistivity.

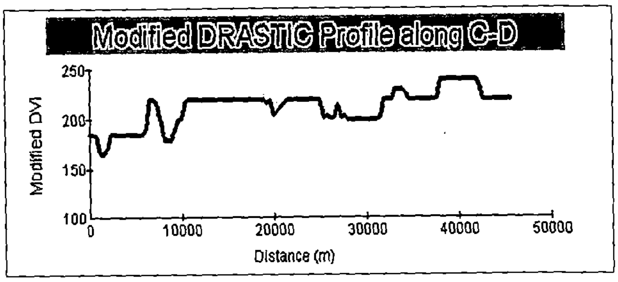
	Resistivity (ohm-m)	IAWQ	Mod DRASTIC	DRASTIC
Resistivity (ohm – m)	1	-0.33613	0.48394	0.1309
IAWQ	-0.33613	1	-0.42367	-0.00319
Mod DRASTIC	**0.48394**	-0.42367	1	0.50065
DRASTIC	**0.1309**	-0.00319	0.50065	1

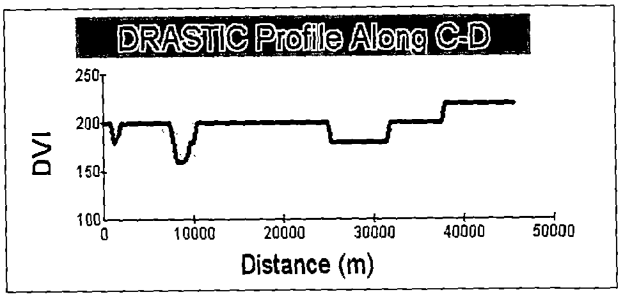
Land use is an ideal parameter to validate vulnerability indices. In the present study, when land use is used as an indicator of aquifer vulnerability, it is found that there exists a relatively good correlation with vulnerability indices (Table 6.10). A correlation coefficient of 0.05, 0.79, and 0.15 is obtained for DVI, modified DVI with theoretical weightings, and modified DVI with effective weights.

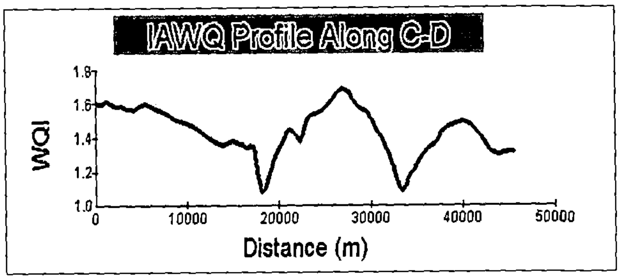
An attempt has been made to establish the validation through matching the profiles taken along A- B and C- D (Fig.6.4). The profiles Shows that there is much variations in indices when taken along the general ground water flow direction i.e., C – D. But much more uniform variations are observed along A – B. This analysis will provide only qualitative information on variations in different vulnerability indices with IAWQ.

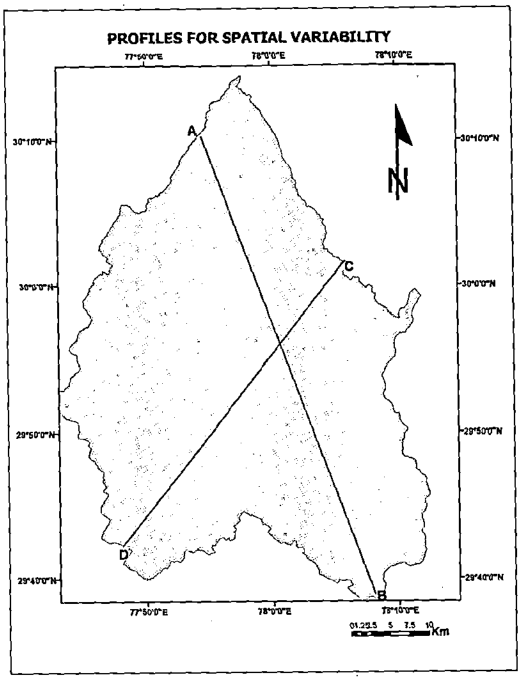
Table 6.10 Correlation matrix of Vulnerability Indices with Land Use.

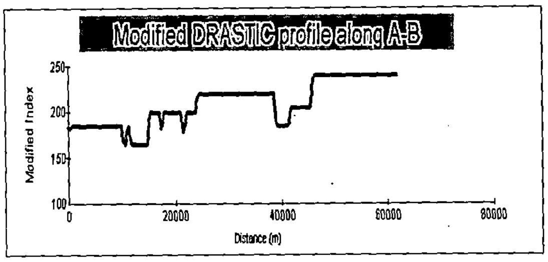
	WQI	DVI	MDVI	MDVIW	LU
WQI	1	0.14122	-0.36447	-0.01758	-0.48347
DVI	0.14122	1	0.43861	0.80325	-0.05993
MDVI	-0.36447	0.43861	1	0.6943	0.79639
MDVIW	-0.01758	0.80325	0.6943	1	0.15888
LU	-0.48347	-0.05993	0.79639	0.15888	1

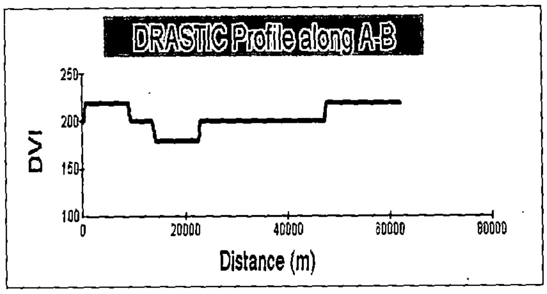












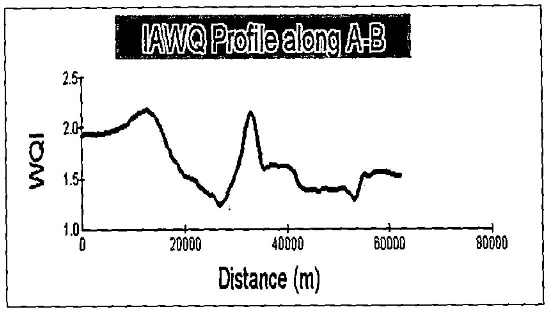


Fig.6.4 Profiles of Vulnerability Indices

6.6 POLLUTION POTENTIAL ASSESSMENT

Pollution potential of the present area has been prepared in ARC GIS by using Boolean logic in Raster Calculator. Both modified DVI map and IAWQ were used simultaneously for the purpose. Both the maps are classified into 4 categories, and matching pixels were delineated by combining high of DVI with High of IAWQ and so on. Fig.6.5 shows the obtained results. Majority of the area was not able to classify due to mismatching of water quality index and vulnerability index.

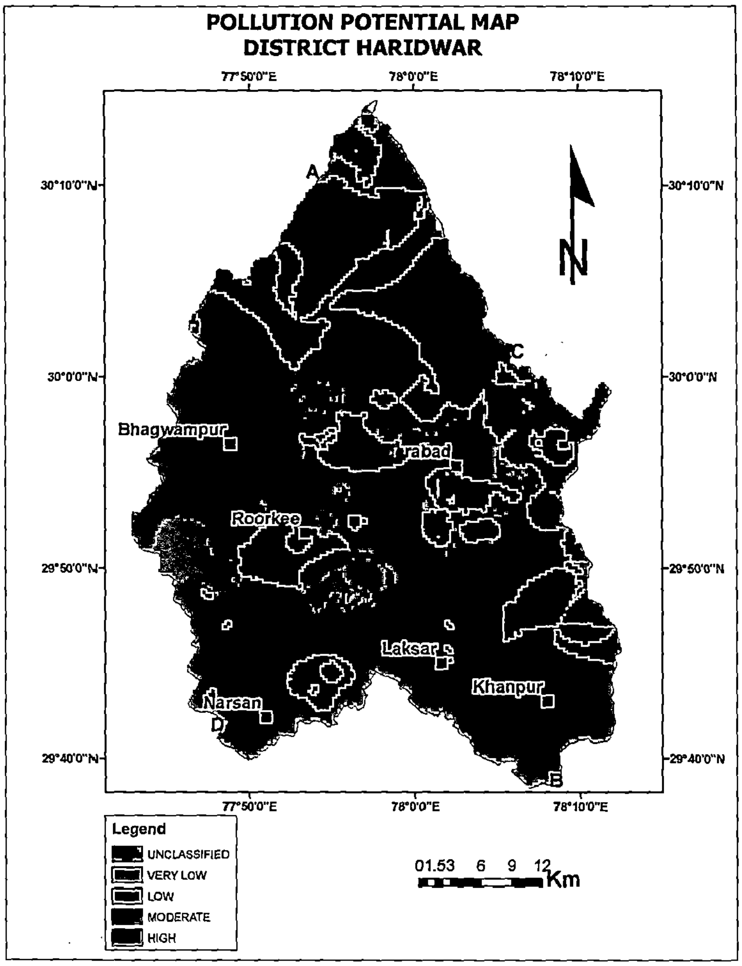


Fig.6.5 Pollution Potential Map

CHAPTER – VII

SUMMARY AND CONCLUSION

7.1 SUMMARY

- Ground water is a important source of drinking water. Anthropogenic impacts can produce contaminants and deteriorate ground water quality. For maintaining desirable ground water quality and for preventing future contamination, an assessment of aquifer vulnerability is desired.
- Aquifer Vulnerability is defined as the sensitivity of the ground water quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer.
- Aquifer vulnerabilities are of two types, Intrinsic and Specific. Intrinsic vulnerability is a function of soil, vadose and aquifer characteristics. In specific vulnerability, in addition to intrinsic vulnerability, characteristics of the contaminant is also dealt with.
- Haridwar district of Uttaranchal State has been taken for the present study. The study area is a populous area with several urban centers. More over this area is fast turning into an industrial hub. The study area is also one of the sugar cane producing part of the State. Impact of all these anthropogenic

activities are expected in terms of an increase in the amount of various contaminants. Hence the present study is planned for the area.

- Geologically the area is mainly divided into Siwaliks and Indo – Gangetic alluvium. Hydrogeology is in conformity with geology of the area and can be divided into Bhabar, Tarai and Alluvial plains. The characteristics of Bhabar are steep slope, and low yielding wells. Aquifers are both in phreatic and confined conditions. Tarai region is characterized by gentle slope, springs, high yield wells and auto flow conditions, fine sediments, swamps and water logged conditions. In alluvial plain, aquifers are both in phreatic and confined conditions and , wells are high yielding.
- Vulnerability can be assessed through (i) statistical, (ii) Simulation and (iii) Overlay indexing approach. For the present study, overlay indexing approach is selected, because through this processes vast geographical areas can be covered using the GIS Tool.
- Among the various methods of overlay indexing, DRASTIC method has been selected for the present study. DRASTIC is the acronym of 7 geo-environmental parameters. The method is selected because (i) the parameters involved are commonly and easily available in hydro-geological studies, (ii) it involves rating and weighting system which is highly suitable

to process in GIS environment, and (iii) many of the parameters are inter related so that error in one parameter can be eliminated by the other.

- GIS environment has been used for the model preparation and analysis. ARC GIS 8.3 and 9.1 versions were used for the purpose. Since most of the data required in the ARC GIS environment is .dbf and .mbd types, a data base has been created in MS Excel for easy conversion to the these file types.
- A total of 72 soil samples have been colleted from different land use categories. These samples were analyzed for particle size ranges through mechanical sieving and pipette method. The percentages of Sand, Silt and clay were calculated and plotted on a United States Department of Agriculture Textural Triangle. The study indicates that majority of the samples are sandy and loamy sands in nature. Very few samples fall in silty sand category.
- Thematic layers have been prepared for the DRASTIC parameters. Depth to water level ranging from 0.17m to 17.25m bgl. Water levels are shallow in Southern and Northern portions. Wells are moderately deep in central areas and in isolated pockets water levels are deep.
- Net recharge has been estimated in using GIS. For this, ground water fluctuation and specific yield maps have been prepared. These were added

using raster Calculator. Ground water draft and non monsoon rainfall contributions to ground water were added to each pixel and classified as per the DRASTIC norms. Recharge is generally high and uniform. Only in Northern and North Central portions, recharge is low. These are as generally come under Tarai region.

- Variable ratings were adopted for aquifer media. Aquifer media for the present study area is composed of sand with gravel, boulders, cobbles, pebbles and clay. In central portions between Roorkee and Haridwar, aquifer media is highly sandy.
- Soil categories are ranked and plotted. In West Central and East Central areas, soil is loamy, sandy or loamy silt. In rest of the area, soil is generally sandy.
- Slope of the study area is generally gentle. Only in northern portion, the of slope is steep.
- Vadose zone is sandy and gravelly in Southern and North Western portions and in Haridwar area. In rest of the study area, vadose zone has sand, gravel, silt and clay.
- Hydraulic conductivity is generally high. Only in North of Bhagawanpur, hydraulic conductivity is showing a low value.

- A level 1 classification of the study area shows forests, built up land and agriculture categories.
- 88 ground water samples were collected and field temperature, pH, and electrical conductivity were measured. These samples were later analysed for pH, conductivity, Total Dissolved Solid, major ions, nutrients, and heavy metals.
- pH of the study area is within limits and relatively high values are observed in the East Central portions of the area. Southern blocks of Laksar, Narsen, and Khanpur areas of the district showing high pH. High pH is indicative of slightly alkaline nature of the ground water. All the urban centers of the study area are showing high TDS. Rest of the area is showing TDS well within the desirable limit set by the BIS.
- Among the cations, Calcium is the dominant one. Majority of the area are showing a high calcium concentration. Isolated pockets in urban areas are showing a five fold increase than the desirable limits. In majority of the area Magnesium concentration is slightly more than the desirable limits. High concentration of Sodium and potassium have not been noticed in the area.
- Among the anions, sulphates are the dominant ones in the ground water samples of the area.32% of the sample showing excess of sulphates than desirable limit. Chloride distribution shows that high values are associated

with intensely cultivated and irrigated areas. Total alkalinity is high in majority of the area.

- Ground waters of the study area are calcium - sulphate type.
- Nitrate is thought to be generally associated with agricultural practices. But Nitrate distribution in the present study indicates that high nitrate is associated with urban centers. It is inferred from the study that high concentration of nitrates of the study area is due to decomposition of biological waste and sewages than usage of fertilizers.
- Among the heavy metals, Cadmium, Lead, copper and Zinc were analyzed. The heavy metals are within the desirable limits. Still their distribution shows a high value near industrial areas.
- An Index of Aquifer Water Quality is developed and distribution of index shows that deteriorating water quality is associated with urban centers and industrial areas than agriculture.
- The Distribution of DRASTIC indicates that high vulnerability areas are Laksar, Narsen, Khanpur and northern parts of the district. Urban centers are located next lower vulnerability index categories. There are only very few pockets were DVI is low.
- Sensitivity analysis has been done through test of independency, single parameter sensitivity and multi layer sensitivity.

- Intra layer Standard Deviations indicate that Depth to water table and Impact of vadose zone are the most variable parameters. Interlayer correlation coefficients indicate that there is no relation among DRASTIC parameters, that means all layers are independent. However, there is relatively good correlation exists between DVI and Depth to water table and impact of vadose zone.
- Effective weighting coefficients have been derived and analysis indicats that Depth to water table and impact of vadose zone both requires lower weighting coefficients than the theoretical weightings.
- Single layer map removal sensitivity analysis indicates that maximum variations are observed when depth to water level was removed. This is followed by net recharge, impact of vadose zone, aquifer media, soil and topography.
- Estimation of sensitivity analysis by computing sensitivity coefficients indicate that topography is the layer which is least variable and least sensitive. Impact of vadose zone is most variable and most sensitive. Hydraulic conductivity and quifer media are the parameters moderately sensitive and moderately variable. Depth to water level is most variable but lease sensitive.

- A modified DVI has been prepared by modifying the ratings of hydraulic conductivity and introducing the land use as an eighth parameter.
- An attempt has been made to validate the DVI, Modified DVI with land use and modified DVI without land use by using IAWQ. The correlation matrix indicate that aquifer vulnerability is not highly correlated to water quality index.
- An attempt has been made to validate these indices through aquifer resistivity and land use. It is found that relatively good correlation exist between these parameters and vulnerability indices.

7.2 CONCLUSION

- It is concluded from the above study that some areas of district Haridwar is vulnerable to ground water pollution.
- GIS is an apt tool in assessment of ground water vulnerability to pollution.
- Water quality is not reflected the way Vulnerability to pollution.
- Aquifer resistivity and land use are better parameters to validate the vulnerability indices in such cases.

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