SUSTAINABLE DEVELOPMENT OF WATER RESOURCES IN AN INTERMONTANE SUB-HIMALAYAN WATERSHED

A THESIS

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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **SUSTAINABLE DEVELOPMENT OF WATER RESOURCES IN AN INTERMONTANE SUB-HIMALAYAN WATERSHED** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Hydrology of the Indian Institute of Technology Roorkee is an authentic record of my own work carried out during a period from January, 2004 to March, 2010 under the supervision of Dr. D. C. Singhal, Professor, Dr. Ranvir Singh, Professor, Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee and Dr. Sudhir Kumar, Scientist E2, National Institute of Hydrology, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

(SANTOSH RANGRAO YADAV)

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The Ph. D. Viva-Voce Examination of **Mr. Santosh Rangrao Yadav,** Research Scholar, has been held on 08/10/2010.

Signature of Supervisors

Signature of External Examiner

DEDICATED TO

My late Grandmother and late Brother-in-law, for eternal blessings

My Beloved Parents, for support, encouragement and blessings

My Teachers, for encouragement and co-operation

My Wife, for her love and patience

Supporters in my village

ABSTRACT

Groundwater utilization has increased dramatically in developing cities of the world over last few decades. With the increasing urbanization, the need to protect water resources from different types of contamination has increased. Dehradun city, the capital of newly created Uttarakhand State, gets its major drinking water supplies from groundwater for use by the increasing population. Yet, indiscriminate construction of private tubewells by commercial enterprises and households has led to phenomenal increase in the density of tubewells in the city, over the last few years. The pressure is increasing due to large migration into the city from rural areas coupled with increased influx of visitors in the form of tourists and students. In view of these factors, water resources management in Dehradun city is believed to have become unsustainable.

The present study was aimed at assessing the sustainability of water resources development in the Suswa Watershed which also includes Dehradun city. The specific objectives of the study were as under:

1. To review available literature on sustainability indicators in terms of their applicability in the field of water resources development and their status in India,
2. To assess groundwater resources of the study area and evaluate its surplus surface runoff,
3. To assess and analyze the quality of available water resources in the study area,
4. To identify and evaluate available sustainability indicators vis-à-vis water resources development in the study area, and
5. To recommend suitable options for sustainable water resources development.

The Suswa Watershed is located in the eastern part of the Doon Valley, Dehradun District, Uttarakhand, India. It includes hills of Mussoorie to the north whereas Siwalik range forms the southern boundary. The watershed pertains to the Song river system which is a tributary of the Ganga river. The area, covering about 292 km^2, is situated approximately between 77° 57' and 78° 10' East longitudes and 30° 08' and 30° 27' North latitudes. The ground altitude varies between 420 m and 2000 m AMSL. The average annual rainfall varies from 1600 to 2200 mm, most of which falls in the monsoon (June to

August) months. Its land use is characterized by forest and agriculture besides urban area of Dehradun city. Main crops grown in the area are paddy, wheat, maize and sugarcane.

As per 1991 and 2001 census reports, total population of Dehradun city is 2,70,000 and 4,47,808 respectively, showing a high decadal growth rate of about 66 %. Although, it is difficult to give the precise population figures of the Suswa Watershed, above figures of Dehradun city reveal the magnitude of stress posed by the population in the area.

The analysis of land use-land cover changes was carried out by using satellite imageries in GIS environment for the years of 1972, 1990 and 2000. This analysis has indicated that the rate of urbanization has increased drastically in the recent decade, especially in Dehradun city where forest and agricultural land use has decreased. Surface runoff was estimated for the study area by employing the Natural Resources Conservation Services-Curve Number method. The estimates of annual storm runoff coefficient indicate that the annual runoff is around 22 % of annual rainfall in the study area. Thus, the minimum surface water resources availability is about 63 million-m^3. Hence, it appears that there is adequate scope for the development of surface water resources.

Groundwater estimation for 2005-06 was carried out by using the mass balance based methodology of groundwater budgeting practiced in India. The necessary data was collected from the concerned agencies and also monitored during 2005-06 from a number of wells distributed in the watershed. The annual groundwater recharge for the year was 11915 ha-m whereas the total draft was 4175 ha-m. The stage of groundwater development in the command and non-command areas was found to be 19 % and 38 % respectively, thus indicating the Suswa Watershed under 'Safe' category. However, within the Dehradun city, declining trend of groundwater table was recorded in the hydrograph stations. Therefore, during any further development of groundwater, there is an urgent need to arrest the declining trend of groundwater levels in the Dehradun city possibly through artificial recharge measures. Accordingly, it is imperative to construct water conservation structures in the study area especially rooftop rain water harvesting schemes in the Dehradun city.

Chemical analyses of 37 groundwater samples (including one river water sample) were carried out for determination of physico-chemical parameters (TDS, EC, pH, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}), nutrients (NO_3^- and PO_4^{3}) and heavy metals (Zn, Mn, Fe, Ni, Cu, Cd, and Cr) by using the standard methods with the objective of assessing the water quality for drinking purpose on the basis of standards laid down by regulatory agencies like Bureau of Indian Standards and World Health Organization. The major ionic composition of groundwater evaluated using the trilinear diagram showed the presence of non-carbonate hardness during pre-monsoon period whereas during post-monsoon period the water had dominant carbonate hardness. This change in nature of hardness can be probably explained due to the dilution caused by rainfall recharge. The overall groundwater quality in the study area was found to be suitable for drinking purpose. Although, groundwater from shallow aquifers was not fit for drinking at few places, it was found to be within the 'permissible' ranges of Indian standards and can thus be allowed for drinking in the absence of alternate drinking water sources.

A synoptic assessment of groundwater quality was also carried out by employing a groundwater quality index (GWQI). For estimating GWQI, seven water quality parameters were selected viz. cadmium, nickel, chromium, total hardness, sulfate, total dissolved solids and total alkalinity. The necessary weights of these parameters were computed by using an analytical hierarchy process. The cutoff value of GWQI for groundwater fit for drinking purposes was 2.0, with higher values indicating undesirable groundwater quality.

The indicators identified for application in the Suswa Watershed to assess the sustainability of water resources are deforestation rate, water barrier index (WBI) and integrated water stress score (IWSS). Water quality index based synoptic groundwater quality evaluation was used to assess the sustainability vis-à-vis water quality. It was observed that. the deforestation rate in the recent period of 10 years (from 1990 to 2000) was faster than that during the preceding period of 18 years (from 1972 to 1990), although it was not alarming. The WBI computations have put the Suswa Watershed in 'absolute scarcity' category whereas as per IWSS approach, the watershed can be classified as 'moderately stressed' to 'highly stressed'. Considering seven relevant chemical parameters in the groundwater quality assessment, GWQI values ranged between 0.42 and 3.30. Mapping of GWQI indicated that, barring few locations, the groundwater of the study area is fit for drinking purpose, and also showed the poor groundwater quality areas in the watershed. It is necessary to adopt adequate measures to remedy the groundwater in such problematic areas for which suitable steps should be taken by concerned agencies.

Based on the evaluation of sustainability indicators, this study has employed a viable approach which includes regular assessment of indicators in ensuring the sustainable management of water resources in the Suswa Watershed. It was found that the groundwater resources development, in the context of declining trend of groundwater levels, in the Suswa Watershed in general, and Dehradun city in particular, is becoming unsustainable. In this context, this study has resulted in formulation of guidelines for assessment of sustainability of water resources for the benefit of the planners, hydrologists and decision makers.

For future studies, it is essential to augment the existing groundwater monitoring network through construction of additional deep piezometers for enabling sustainable water resources management in the Suswa Watershed.

Keywords: sustainability indicators, groundwater resources, water quality, water quantity, safe yield, sustainability assessment, groundwater quality index, surface runoff, Dehradun, Suswa Watershed, India.

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(SANTOSH RANGRAO YADAV)

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LIST OF SYMBOLS

A	:	Area
AMC I	:	Antecedent moisture condition for dry condition
AMC II	:	Antecedent moisture condition for average/ normal condition
AMC III	:	Antecedent moisture condition for wet conditions
CN_I	:	Curve number for antecedent soil moisture condition I
CN_{II}	:	Curve number for antecedent soil moisture condition II
CN_{III}	:	Curve number for antecedent soil moisture condition III
$CN_{II\alpha}$	:	Slope-adjusted CN_{II}
e	:	Ion balance error
F	:	Actual infiltration
h	:	Water table fluctuation depth
I_a	:	Initial abstraction
Ma	:	Million years
meq/L	:	Milli-equivalent per litre
P	:	Total rainfall
pH	:	Negative base-10 logarithm of the hydrogen ion activity in moles/ litre
Q	:	Direct surface runoff
R^2	:	Coefficient of determination
S	:	Potential maximum retention
S_y	:	Specific yield
$	:	United States dollar
%	:	Percent
$^{\circ}C$	:	Degree Celsius
∞	:	Infinity
α	:	Soil slope (in m/m)
ΔS	:	Change in the groundwater storage
λ	:	Initial abstraction coefficient

LIST OF ABBREVIATIONS

AAS	:	Atomic Absorption Spectrophotometer
AHP	:	Analytical Hierarchy Process
AMC	:	Antecedent moisture condition
AMSL	:	Above mean sea level
APHA	:	American Public Health Association
ARS	:	Agricultural Research Service
ASCE	:	American Society of Civil Engineering
ASRC	:	Annual storm runoff coefficient
BCM	:	Billion cubic metre
bgl	:	Below ground level
BIS	:	Bureau of Indian Standards
BOD	:	Biological/ biochemical oxygen demand
CBIP	:	Central Board of Irrigation and Power
CCA	:	Culturable (cultivable) command area
CGWB	:	Central Groundwater Board
CHASDWR	:	Canadian Health Act Safe Drinking Water Regulation
CI	:	Consistency index
CN	:	Curve number
CPCB	:	Central Pollution Control Board
CR	:	Consistency ratio
DEM	:	Digital elevation model
DO	:	Dissolved oxygen
DR	:	Deforestation rate
DW	:	Dug well
e.g.	:	For example
EC	:	Electrical conductivity
ERDAS	:	Earth Resources Data Analysis System
et al.	:	And others
etc.	:	Etcetera
ETM	:	Enhanced thematic mapper
Fig.	:	Figure
GEC	:	Groundwater Estimation Committee

GeoTIFF	:	Geographic Tagged Image File Format
GIS	:	Geographical Information System
GNP	:	Gross National Product
GPS	:	Global Positioning System
GWQI	:	Groundwater quality index
HFT	:	Himalayan Frontal Thrust
HP	:	Hand pump
HPI	:	Heavy metal pollution index
HSG	:	Hydrologic soil group
http	:	Hypertext transfer protocol
i.e.	:	That is
IAWQ	:	Index of aquifer water quality
ICP	:	Inductively Coupled Plasma
IDPH	:	Illinois Department of Public Health
IIC	:	Institute Instrumentation Center
IIT	:	Indian Institute of Technology
ILWIS	:	Integrated Land and Water Information System
IMD	:	India Meteorological Department
INCOH	:	Indian National Committee on Hydrology
IRS	:	Indian remote sensing satellite
ISMM	:	Iowa Stormwater Management Manual
IWMI	:	International Water Management Institute
IWSS	:	Integrated water stress score
LISS	:	Linear imaging self scanner
LULC	:	Land use-land cover
MBT	:	Main Boundary Thrust
MCDM	:	Multi-criteria decision-making
MDGs	:	Millennium Development Goals
MoEF	:	Ministry of Environment and Forest
MSS	:	Multi-spectral scanner
ND	:	Not detected
NEH	:	National Engineering Handbook
NMR	:	Normal monsoon season rainfall
No.	:	Number

NRCS : Natural Resources Conservation Services
NSF : National Sanitation Foundation
NTU : Nephelometric turbidity unit
PD : Percentage difference
QI : Quality index
RCI : Random consistency index
RIF : Rainfall infiltration factor
SAR : Sodium adsorption ratio
SCS : Soil Conservation Services
Sl. No. : Serial number
TDS : Total dissolved solids
TM : Thematic mapper
TW : Tubewell
U.S.S.L. : United States Salinity Laboratory
UN : United Nations
UNESCO : United Nations Educational, Scientific and Cultural Organization
UNICEF : United Nations Children's Fund
URR : Use-to-resource ratio
US EPA : United States Environmental Protection Agency
USA : United States of America
USDA : United States Department of Agriculture
viz. : Namely
WBI : Water barrier index
WGS : World Geodetic System
WHO : World Health Organization
WQI : Water quality index
WRDM : Water resources development and management
WTF : Water table fluctuation
www : World wide web

Chapter 1

INTRODUCTION

1.1 GENERAL

The ever-growing demand of freshwater for human consumption has become a worldwide cause for concern. Over 2 billion people around the globe depend on groundwater for their daily supply. A large amount of the world's irrigation is dependent on groundwater, as are large numbers of industries. The local groundwater users, stake holders, decision makers and governments are realizing that the groundwater resource is getting scarcer, increasingly polluted and thereby affecting options for social and economic growth and development. Addressing groundwater management issues from a technical perspective alone- as has been tried unsuccessfully in a number of cases- is clearly not enough, and the need of improved groundwater management in addressing this situation is becoming increasingly obvious. Consequently, many countries are actively moving from liberal approaches where each individual could abstract from his or her source, at will, to managed approaches, involving groundwater users and developing a variety of instruments to improve aquifer management (Kemper, 2004).

India, with a population of 1.17 billion is the most populous country in the world after China. All its developmental sectors are in growing state; villages are being provided with basic amenities of water and electricity in recent years through several government-sponsored programs. Despite these efforts to improve rural facilities, there is a rapid migration of rural population to urban areas possibly for better work opportunities and living conditions. The urban areas are fast getting densely populated and are expanding rapidly to adjoining areas putting unwanted stress on the natural resources and declining the environmental health around these areas. Civic administrators and city planners are making all attempts to provide basic amenities to the growing urban population in a systemic manner. But, with the availability of the limited natural resources and fund constraints, their efforts are implemented at a very slow pace and are not in conformity with the rapid growth in population.

The demand on water is ever increasing and although attempts are being made to supply adequate quantity of water, the sewerage systems installed years back are inadequate to contain the increased volume of water converted to sewage. With the improvement in infrastructural facilities and increase in trained manpower, several small to large-sized industries are being rapidly established with inadequate disposal facilities for their effluents. Groundwater quality is thus getting deteriorated due to seepages from unlined sewerage lines and effluent channels. There is thus an environmental mess, especially in the rapidly expanding towns and cities across the country. Dehradun, the capital city of Uttarakhand State, is one such city where migration of rural people from hilly areas of the State is on the increase, especially after 2000, when this State was created.

Precise assessment and monitoring of water resources is of paramount importance in its management. Therefore, it is necessary to develop, improve and promote the use of new techniques for better assessment and sustainable management of water resources. It is now increasingly accepted that water resources management, aimed at such objectives as augmentation of water supply, reduction in freshwater demands, protection from water-related natural disasters, and ensuring a good ecological status of waters, needs an integrated approach, embracing different dimensions. Such an approach requires joint consideration of groundwater and surface water, and of water quantity and quality. This calls for the implementation of norms of sustainability in the development and management of water resources.

1.2 WATER RESOURCES DEVELOPMENT IN INDIA

In the field of water, development and management is crucial in view of mismatch between its natural availability and demand. India occupies 2 % of the world's area but has about 16 % of its population. The livelihood of almost 65 % of the population depends directly on agriculture. About 25 % of our gross national product (GNP) is derived from agriculture, which in turn depends on land and water resources (Singh, 2005). Therefore, in India water resources development has been given increasing importance with time as evident from increasing share given to water sector in the national five year plans. However, serious challenges emerge in the context of massive development needed in view of increasing population of a country like India and high economic growth required for its development. As quoted by Chaturvedi (2004), with the average GNP per capita of the developing and the industrialized world at about $ 1,000 and $ 21,000 respectively and doubling the population of the former, which accounts for about 85 % of the world population, environmental resources will have to be used about 36 times more efficiently. To meet such challenges, a revolution will be required in the concepts, policies, technology, planning, management and institutions.

In India, groundwater since long has been used for irrigation and domestic water supply. Optimum development and efficient utilization of groundwater resources, therefore, assumes great significance. At present, over 70 % of the country's population uses groundwater for its domestic needs and more than half of irrigation is provided from this source (Singh, 2005). The total utilizable groundwater potential of the country has been estimated as 432 billion cubic metre (BCM) per year. After making provision of 71 BCM for domestic, industrial and other higher priority uses, the potential available for irrigation is 361 BCM per year. About 90 % of it (or 325 BCM) can be considered utilizable for irrigation. Thus, total utilizable groundwater may be taken as 71 + 325 = 396 BCM (Singh, 2005). On an average, about 58 % of the net utilizable annual groundwater resources of 396 BCM have been actually developed in India and out of total 5723 blocks/ mandals/ talukas in the country, 839 units are over-exploited (CGWB, 2006). In spite of the overall satisfactory availability of groundwater, there are some areas in the country, which are facing acute scarcity of groundwater. The reason for this is the non-uniform development of groundwater in different areas of the country. Highly intensive development of groundwater in certain regions/ states in the country, like Punjab, Haryana to mention a few, has resulted in its over-exploitation leading to fall in the groundwater levels and salinity ingress in coastal areas.

The significance of groundwater in the agrarian economy of India is ascribed to the fact that crop yields are generally high in areas irrigated with groundwater than irrigated from other sources (Dhawan, 1995). If India's aspirations for continued economic growth and improved social and environmental conditions are to be met, fundamental changes in how water is captured, allocated, planned and managed must take place. To enable sustainability of the water resources, watershed should become the unit for all further water resources development and management activities by involving stake holders only. Technocrats, bureaucrats and politicians should act as facilitators in such endeavours (Sinha, 2002).

1.3 SUSTAINABILITY OF WATER RESOURCES DEVELOPMENT

The current thinking on sustainability of water resources systems shows that these systems need to be developed and managed to fully contribute to the objectives of society, now and in future, while maintaining their ecological, environmental and hydrological integrity, which in turn requires provision of environmental flows of the required quality in the rivers. An adaptive management regime, with adequate monitoring of the environmental outcomes in order to overcome the shortcoming of limited knowledge on the ecological requirement for environmental flows and its quality need to be adapted (Chander, 2005).

Water resource professionals have an obligation to design and manage water resource systems so that they can fully contribute to an improved quality of life for all humans. Water resource systems that are able to satisfy the changing demands placed on them, now and into the future, without system degradation can be called 'sustainable' (McMahon, 1999). Sustainability is a unifying concept that emphasizes the need to consider the long term future as well as present. This includes the future economic, environmental, ecological, physical and social impacts that will result from decisions and actions taken today. Anyone involved in water resources planning and management must contend with risk and uncertainty and this is especially so when required to look into a distant future.

While we cannot know with certainty what all these impacts will be, or what future generations of individuals or societies will want or value, we can attempt to predict what we think might happen and what future generations may want or value as we develop our current plans, designs and management policies. Admittedly, we can only guess at what future generations would like us to do now for them. We must take these guesses into account as we make our decisions or take actions to satisfy our immediate demands and desires, lest the posterity might blame the present generation for depletion of the invaluable natural resources.

Because sustainability is a function of various economic, environmental, ecological, social and physical goals and objectives, analyses must inevitably involve multi-objective tradeoffs in a multi-disciplinary and multi-participatory decision making process. No single discipline, and certainly no single profession or interest group, has the wisdom to make these tradeoffs. They can only be determined through a political process involving all interested and impacted stakeholders. The participants must at least attempt to take into account the likely preferences of those not able to be present in this decision-making process, those who will be living in the future and who will be impacted by current resource management decisions. Sustainability is intimately related to various measures of risk and uncertainty about a future we cannot know but which we can surely influence. Clearly our guesses about the future may, with certainty, be wrong. Hence they will need to be revised periodically. Recognizing that some management objectives will change over time, we must consider the adaptability or robustness of the systems we design and operate today to this management uncertainty and to the inevitable changes in the quantity and quality of the resources being managed (McMahon, 1999).

1.4 BACKGROUND AND SCOPE OF THE STUDY

1.4.1 Background

The review of literature on groundwater quantity and quality assessment indicates that in any study it is crucial to evaluate the sustainability of water resources; both surface water as well as groundwater, in terms of its quantity and quality keeping in mind the basic tenets of sustainability. Such a study, therefore, would also include consideration of re-use of waste waters generated by the increasing population and industrial activities in an area. The review also indicates that a watershed must be the basis for viable development of water resources. Sustainability indicators are the ideal means by which progress towards sustainable development can be measured. However, most indicator initiatives throughout the world have been aimed at state-of-the-environment reporting, with relatively few aimed at developing sectoral indicators (Walmsley et al., 2001) and water sector is no exception to this fact. In the present study, the Suswa Watershed which includes Dehradun city of north India has been taken up for carrying out an assessment of sustainability of its surface water and groundwater resources.

Lack of in-depth technical knowledge, sufficient data for decision making, planning and management creates a barrier for sustainable development of water resources in many regions worldwide, including India. Sustainable development is largely a replication of how people interact with the available natural resources and environmental degradation is due to over-population and poor socio-economic conditions. Therefore, the need for proper monitoring and management has arisen to fulfill the targets of achieving sustainable development.

Many studies have addressed the urgent need for sustainable water resources development but very few have talked about how to assess the sustainability. Particularly in India, only a little efforts have been made towards assessment of sustainability. In this context, in order to assess the sustainability of water resources development, it is necessary to identify the relevant parameters from amongst various sustainable development indicators developed worldwide, modify them to suit the Indian conditions and apply them at various stages of water resources development and management programmes starting from small scale to basin/ country wide scale. These observations form the background for this research work.

South Asia alone uses some 200 of the 800 BCM or so of groundwater used annually in the world (Llamas et al., 1992; Shah et al., 2000). Similarly, depending on climatic conditions (arid, semi-arid or humid), groundwater use for irrigation is 40 to 90 % of the total groundwater use (Mukherji and Shah, 2005). The case is not different in the Dehra Dun Valley which includes the Suswa Watershed wherein tremendous groundwater development is being carried out as evidenced by the drilling of large number of tubewells in the Dehradun city and adjoining areas in the recent years. This has necessitated greater attention on groundwater as compared to the surface water of the area.

1.4.2 Scope of the Study

The present study is aimed at attempting the assessment of sustainability of surface and groundwater resources development in the Suswa Watershed in Dehradun District of Uttarakhand State, India. The study includes identification and application of sustainability indicators vis-à-vis water resources development in the selected watershed. A framework of suggestions will also be presented for water resource management that can be applied for its sustainable management at the basin-wide scale.

The status of research on sustainability indicators in India may be characterized as being in its infancy because of very limited knowledge base. Efforts made by scientists in different parts of the world on sustainability indicators (frameworks, methodologies, approaches, themes and sub-themes) are applicable at a large scale like country or state. But very few efforts have been made in case of sustainability indicators applicable on watershed basis, besides emphasizing its need worldwide in general and in developing countries like India in particular.

In this context, there is a need to address the methods of assessment of sustainability of water resources through identification of various sustainability indicators applicable on the watershed basis. Such indicators are required to be identified so that one can have a check on whether the development and management of water resources in a particular watershed is sustainable or not. Therefore, focused studies aiming at the evaluation of sustainability indicators in the development of water resources on the watershed basis are required to be undertaken.

The major activity in watershed based water resources development and management is assessment of available water resources. The scope of the present study includes the following aspects:

1. Assessment of the surface water and groundwater resources of the Suswa Watershed of Uttarakhand State. The water resources assessment is divided into two parts: surface runoff estimation and groundwater estimation. The surface runoff has been arrived at by using the commonly employed approach of Natural Resources Conservation Services- Curve Number (NRCS-CN) method and groundwater estimation has been done by using groundwater estimation methodology based on general mass balance approach.
2. The water quality of the collected water samples has been evaluated by using standard methodologies for determination of physico-chemical parameters, nutrients and heavy metals.
3. Review of literature on available sustainability indicators vis-à-vis water resources development along with the concerned issues of sustainable development, and finally,

sustainability assessment of the Suswa Watershed through identification and evaluation of various indicators.

4. The Suswa Watershed includes the urban area of Dehradun, the capital city of Uttarakhand State. In this context, this study is likely to bring out the guidelines for sustainable development of water resources for the benefit of the planners, hydrologists, soil and water conservationists and decision makers.

1.5 OBJECTIVES

The specific objectives of the present study are to:

1. Review available sustainability indicators in terms of their applicability in the field of water resources development and their status in India,
2. Assess groundwater resources and evaluate surface runoff potential of the study area,
3. Assess and analyze the quality of available water resources in the study area,
4. Identify and evaluate viable sustainability indicators vis-à-vis water resources development in the study area, and
5. Recommend suitable options for sustainable water resources development.

1.6 ORGANIZATION OF THESIS

This thesis is arranged in eight chapters as described below:

Chapter one provides background for the proposed research and the objectives which are proposed to be achieved in this research work.

Chapter two presents the literature review related to the sustainable development of water resources with respect to their quantity and quality. This chapter also includes literature on assessment of groundwater and surface water resources.

Chapter three describes the study area. Its characteristics like topography, physiography, climate, etc. have been described in detail.

Chapter four gives the analysis of land use-land cover changes and details of assessment of surface water potential of the study area.

Chapter five gives the details of assessment of groundwater resources in the study area using the commonly employed approach of groundwater budgeting.

Chapter six presents the methodology used in the assessment of various quality parameters of water samples collected in the study area along with the data on their chemical quality.

Chapter seven gives a discussion on formulation of synoptic groundwater quality index for inclusion in the sustainability assessment.

Chapter eight includes the methodology used for identification and evaluation of sustainability indicators vis-à-vis water resources development.

Chapter nine presents the summary, important conclusions drawn from the study and recommendations for future work.

Chapter 2

REVIEW OF LITERATURE

2.1 GENERAL

This chapter deals with the available literature and varying perceptions of concept of sustainable development and carries a discussion on 'indicators for sustainable development'. Subsequently, the prevalent perceptions of concept of sustainable development of water resources have been discussed wherein emphasis has been placed on sustainability of groundwater resources development in view of increasing use of groundwater for various uses in the Suswa Watershed. The literature on the assessment of water quantity and quality has been reviewed. The part of the present research work also deals with the watershed study in Geographical Information System (GIS) environment. Therefore some studies which involved application of GIS have also been reviewed. Finally, research needs/ gaps have been discussed in brief.

2.2 SUSTAINABLE DEVELOPMENT: DEFINITIONS AND PERCEPTIONS

Sustainable development of water resources continued to move into the international spotlight amidst warnings that more than a third of the world's population will not have access to sufficient freshwater by 2025 (Gleiek, 2001). Sustainable development is a relatively recent concept that has grown out of concerns about the declining quality of the environment coupled with increasing resource needs as populations expand and living standards rise (Karki, 2008). In 1987, a report entitled, 'Our Common Future' (The Brundtland Report) was published by the United Nations (UN), and it defined sustainable development as: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. This is commonly accepted definition of sustainable development (also known as the Brundtland definition so named, after 'The Brundtland Commission' convened by the UN in 1983), and is used worldwide.

The underlying theme of sustainable development is the integration of economic, social environmental issues in decision and policy making at all levels. This integration implies the involvement of virtually all traditional sectors of economic and government activity, such as economic planning, agriculture, health, energy, water, natural resources, industry, education and the environment (UN, 2001).

The increasing demand for sustainable development will have a profound impact on all types of rural and urban infrastructures. It has now been recognized that every effort towards natural (including water) resources development and management should be such that the sustainability of the resources is ensured and it should not be carried out at the cost of deteriorating environment. In this regard Hydrology, as an applied science, should be used to ensure that the development and management of water resources and its use are carried out judiciously with the perspectives of sustainable development (Perumal et al., 2005).

However, there is a lack of knowledge of how sustainable development should be attained and how sustainability of various natural systems should be assessed. Tremendous research efforts have been made worldwide and in India to address the above-mentioned question of how sustainable development should be attained but little efforts have been made to answer the equally important question of how sustainability of various natural systems should be assessed. Laying down of viable sustainability indicators may provide a proper response to the question of assessment of sustainability of water resources development.

2.3 SUSTAINABILITY INDICATORS

2.3.1 Importance and Purpose of Sustainability Indicators

Although the Brundtland definition of sustainable development gained widespread acceptance, it provided little detail on what to sustain, to what extent and on what time scale (Bartelmus, 2003; Parris and Kates, 2003). Godfrey and Smith (2005) reported that in order to address the inadequate level of coverage of safe water supply in developing countries, the UN established various initiatives including the Millennium Development Goals (MDGs). The principal target of the MDGs is to ensure environmental sustainability by halving the proportion of people without access to safe water by 2015. The recent emphasis on the MDGs has brought attention to the need for indicators that monitor progress towards the goals individually and collectively.

Sustainability indicators can provide crucial guidance for decision-making in a variety of ways. They can translate physical and social science knowledge into manageable units of information that can facilitate the decision-making process. They can help to quantify and calibrate progress towards sustainable development goals. They can provide an early warning, sounding the alarm in time to prevent economic, social and environmental damage. They are also important tools to communicate ideas, thoughts and values because as one authority said, "We measure what we value, and value what we measure".

The 1992 Earth Summit (the UN Conference on Environment and Development, UNCED, held in 1992 at Rio de Janerio, Brazil) recognized the important role that the indicators can play in helping countries to make informed decisions concerning sustainable development. This recognition calls on countries at the national level, as well as international, governmental and non-governmental organizations to develop and identify sustainability indicators that can provide a solid basis for decision-making at all levels. In response to this call, the UN Commission on Sustainable Development approved in 1995, the 'Work Programme on Sustainability Indicators' and called upon the organizations of the UN system, intergovernmental and non-governmental organizations to implement the key elements of the work programme (UN, 2001).

2.3.2 Theoretical Background

- **Some definitions of sustainability indicators:**
  1. Local initiative to measure our 'quality of life' and our sustainability, not just our economic well being. (Available at: http://www.caspianenvironment.org/scripts/diction.pl)
  2. A set of goals which indicate our progress in the pursuit of sustainability. (Available at: http://www.citywestwater.com.au/about/glossary.htm)
- **Properties of sustainability indicators:** Sustainability indicators should possess the following properties (after UN, 2001). Indicators should be:

1. relevant to assessing sustainable development progress;
2. understandable, clear, and unambiguous, to the extent possible;
3. conceptually sound;

4. limited in number, but remaining open-ended and adaptable to future needs; and
5. dependent on cost effective data of known quality.

- **Uses of sustainability indicators:** Test results showed that the sustainability indicators can be used to (after UN, 2001):
  1. bring important issues to the political agenda;
  2. help to identify main trends in priority sectors;
  3. facilitate reporting on the state of sustainable development to decision-makers and the general public;
  4. promote national dialogue on sustainable development;
  5. help to assess the fulfillment of governmental goals and targets;
  6. facilitate the preparation and monitoring of plans;
  7. help to assess the performance of both policies and actions when implementing the plans; and
  8. state the concept of sustainable development in practical terms.

2.3.3 Sustainability Indicators in Water Resources Development

For water resources management, sustainability implies a notion of equilibrium that simultaneously satisfies water demands and the preservation of the water resources system. (Cai et al., 2001). In order to encourage regional authorities and institutions to apply sustainable development in their planning, the Ministry of Environment and Forest (MoEF, Government of India, 2002) published a manual on 'Carrying Capacity based Regional Developmental Planning' in 2002. It describes the content of sustainable development and the carrying capacity process, a scheme to analyze regions and case studies. Sowbhagya Rao et al. (2002) attempted to evaluate and compare the performance of three irrigation projects in Andhra Pradesh using the sets of indicators developed and suggested by the International Water Management Institute (IWMI). They used crop yields, irrigation system efficiency and the returns on the investment as the major indicators of the performance evaluation.

Crabtree and Bayfield (1998) described the development of local level sustainability indicators for the Cairngorms, Scotland by selecting them on the basis of feasibility of measurement and an informal cost benefit analysis of the contribution of information in a policy context and concluded that to improve the use of sustainability indicators for sustainability assessment, performance indicators need to be developed which incorporate a comparison of current state with policy defined capacity criteria. They indicated the difference between local indicators and those at national or international levels. At the local level the stakeholders are quite different, and indicators will generally be selected to inform on local sustainability issues particularly those amenable to local action (Williams, 1996).

Ngana et al. (2004) reported that the core problem in the water resources management of the Lake Manyara sub-basin in north-eastern Tanzania is unsustainable utilization and management of natural resources. The subsequent effects observed in the sub-basin are natural resource use conflicts, poverty, low productivity, overcrowding, high siltation in rivers and lakes, degraded environment, decreased river flows, polluted water sources, etc. In order to establish strategies to arrest this situation, they used a strategic planning process as a tool involving key stakeholders in the basin at various levels. Hellstroma et al. (2000) described the framework of a systems analysis project dealing with the sustainability assessment issues, which focus on urban water and wastewater systems. Rijsberman and Ven (2000) discussed and showed that different people use different approaches in sustainable urban water management and that these differences cannot be neglected. Therefore, a system of four basic approaches is presented, distinguishing so-called ecocentric, ratiocentric, sociocentric, and carrying capacity approaches. They concluded that this system can facilitate the process leading to a workable consensus on sustainable development.

Water resources carrying capacity is defined as “the maximum yield (exploitable amount of available surface water and groundwater of a certain quality) of a river basin under the condition that water allocation to subsistence and commercial functions is reasonable and feasible from a technological and economical viewpoint and the environmental function and ecological value are sufficiently sustainable” (Tambunan et al., 2002). Joardar (1998) used carrying capacities and standards as bases towards urban infrastructure planning vis-à-vis water supply and sanitation in India. He developed an array of indicator measures through which the natural and man-made resources and assimilative capacities of urban areas with respect to water supply, sewerage, drainage and solid waste disposal can be assessed in quantitative and qualitative terms. He suggested a framework for the use of these urban carrying capacity measures in spatial planning and highlighted the need of further research to test the applicability of these indicator measures through real-life case studies of Indian cities based on available environmental information base. From his research work, carrying capacity indicators relevant to the present study are: utilizable water (both groundwater and surface water), depth to water table, distance and altitude difference between water source and urban area, and ambient water quality.

Narula et al. (2001) addressed the emerging concerns regarding water resources sustainability through a case study for Yamuna river basin in India using an area-wide approach. An assessment of water resources development in the Yamuna river basin has been conducted by evaluating present and future water availability. The assessment of present water availability is done by an area-wide analysis of surface and groundwater quantity and quality, backed by data from various Indian governmental water agencies. They identified and evaluated three sustainability indicators for analyzing the water sustainability status of the basin. The sustainability indicators used by them were water barrier index (WBI), use-to-resource ratio (URR) and integrated water stress score (IWSS). The WBI calculated by them for Yamuna river basin was 1200 m^3/ capita, putting the basin in the 'stressed' category and the value of URR indicator was approximately 34 per cent, which again puts the basin in the 'stressed' category, confirming the view developed by the WBI approach. Analysis by using IWSS indicator showed that out of 80 districts in the basin, 20 districts face high water stress caused either due to depletion in water quantity or deterioration in water quality. A water development scenario is discussed, which examines the prospects for water sustainability in the year 2025 assuming business-as-usual. The scenario concludes that by the year 2025 the number of water-stressed districts will rise to approximately 40. Finally, options for shifting to a sustainable water resource management path in the Yamuna basin have been suggested.

Agrawal and Dikshit (2002) described the concept of strategic environmental assessment as a tool for providing the sustainable development with special reference to multipurpose reservoir projects. They concluded that such an assessment requires a change in approach of impact assessment by introducing environmental and social considerations from the beginning and incorporating sustainability criteria throughout the process.

Hiscock et al. (2002) discussed the importance of groundwater resources in industrialized and developing countries, and the associated problems of over-abstraction and groundwater pollution, with the objective of defining sustainable groundwater development. It was concluded that sustainable groundwater development at global and local scales is achieved through the maintenance and protection of groundwater resources balanced against economic, environmental and human (social) benefits. This interpretation of sustainable groundwater development is incorporated into the methodologies currently emerging in Europe and England. However, success in achieving future sustainable groundwater development will require a common understanding at the level of the individual based on information and education within a legislatory framework that promotes co-operation and self-responsibility.

Kulkarni et al. (2004) demonstrated a strategy to ensure the water well sustainability based on aquifer diffusivity and community participation at Neemkheda watershed in Madhya Pradesh State of India. They identified some simple and broad-based indicators which can be used to evaluate a groundwater management experiment as the one at Neemkheda watershed. These indicators were water levels in the wells at the end of summer (as compared to summer water levels in the pre-experiment scenario), increased period over which irrigation is possible, increased annual cultivated area and decreased variability of cropped area between the kharif and rabi seasons.

In United Nations publication viz. 'Indicators of Sustainable Development: Guidelines and Methodologies' (UN, 2001), 56 sustainability indicators [listed as per 4 core sets (of social, environmental, economic and institutional), 15 themes (like land, biodiversity, fresh water, economic structure, institutional capacity, etc.) and 38 sub-themes (like water quantity, water quality, forests, agriculture, ecosystem, etc.)] along with their respective methodologies have been discussed. Out of 56, four sustainability indicators have been identified for their possible application in the Suswa Watershed, the present study area, as per their relevance. These sustainability indicators are: forest area as a percent of land area, annual withdrawal of groundwater and surface water as a percent of total available water, biological oxygen demand (BOD) in water bodies and concentration of Faecal Coliform in freshwater.

Walmsley et al. (2001) reviewed trends in the development of indicators that assist in integrated water resource management. They concluded that identification of the themes and common indicators will be useful for the development of indicators for catchment management in South Africa. From the response to the survey by the 21 organizations approached, they found that not many had developed sets of indicators for catchment management purposes, which is unexpected as the need for integrated catchment and water resource management is recognized throughout the world, and indicators are the ideal means for tracking changes in catchment conditions, and thus providing information for decision making. They recommended that the selection of indicators should not rely on data availability, but should be guided by what is available, or what can be collected within reasonable cost, effort and timeframe.

Marechal et al. (2006) proposed to use bore-wells drilled by farmers for irrigation purposes in order to assess the quality and quantity of available groundwater. They compared water table depletion zone maps to water pumping locations and quantified groundwater over-exploitation at the watershed scale by associating quantity with quality. A groundwater electrical conductivity map revealed highly mineralized groundwater near the villages, and pollution plumes near the main populated areas. The absence of sewage or solid waste collection and treatment facilities threatened groundwater quality by increasing its chloride content, even in small rural villages. The overall analyses indicated increasing risk for sustainability of groundwater resources. They suspected salinization of groundwater due to irrigation practices at the regional scale.

2.4 SURFACE WATER RESOURCES DEVELOPMENT AND SUSTAINABILITY

Chander (2005) reviewed the current thinking on sustainability of water resources systems and concluded that these systems need to be developed and managed to fully contribute to the objectives of society, now and in future, while maintaining their ecological, environmental and hydrological integrity, which in turn requires provision of environmental flows of the required quality in the rivers.

Borah et al. (2005) examined some of the key aspects of water resources of the Brahmaputra- Barak system in the light of some recent concepts to enhance its role in the future sustainable development of the entire North East India. They emphasized that for the overall development of water resources in the Brahmaputra basin, it is essential to have a complete understanding of different components, which may encompass a wide spectrum of issues including geology, hydrology, climatology, environmental aspects, administrative and socio-economical issues, soil types, agriculture, irrigation, groundwater potential etc.

The integrated watershed management approach has been globally accepted as the best for natural resource management, but is rarely or partially implemented because of the lack of required framework and/or technical know-how. Gosain and Rao (2004) demonstrated the use of GIS-based modelling framework for local level planning and watershed prioritization, incorporating the sustainability aspects of watershed development in Bijapur District, Karnataka. They pointed out the urgent need of monitoring and evaluation of the watershed programmes which is an important but invariably missing component. Panda et al. (2005) undertook a study in an agricultural watershed in the Midnapore district of West Bengal, India, to develop an eco-friendly sustainable management strategy for control of non-point source pollution of natural resources like soil and water, on a watershed basis. They estimated runoff from the watershed by using composite curve number (CN) technique.

Bouwer (2000) suggested that water short countries can save water by importing most of their food and electric power from other countries with more water, so that in essence they also get the water that was necessary to produce these commodities and, hence, is virtually embedded in the commodities. Local water can then be used for purposes with higher social or economic returns or saved for the future. Rayar and Pande (2009) analyzed the present scenario of water resources management in Rwanda with emphasis on the problems and prospects of effective water management for sustainable agricultural production and environmental protection.

2.5 GROUNDWATER RESOURCES DEVELOPMENT AND SUSTAINABILITY

The concept of sustainability of water resources has quite varied perceptions to different professionals viz. hydrologists, hydrogeologists, water resources engineers, and sociologists. As in case of sustainability of groundwater resources, the concept is largely related to 'safe yield'. Kalf and Woolley (2005) described the progression of the concept of safe or sustainable yield in chronological order of the key authors with their yield concepts, definitions and comments (Table 2.1). Recently, Zhou (2009) has reviewed the concepts of safe yield and sustainability of groundwater.

Table 2.1: Author, yield concepts, definition and comments (Source: Kalf & Woolley, 2005)

Author	Concepts and definition	Comments
Lee (1915)	Safe yield: 'The limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve.'	Hydrologically based on something less than dangerous storage depletion. What does dangerous and regular mean? Yield available in perpetuity (i.e. sustainable)
Meinzer (1920)	Safe yield: '...the practicable rate of withdrawing water from the aquifer primarily for human use.'	Hydrologically based and a yield available in perpetuity (i.e. sustainable). 'Sensible, but overdraft not evident until after it has occurred'.
Meinzer (1923)	Safe yield: 'The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to the extent that withdrawal at this rate is no longer economically feasible.'	Hydrologically based but dependent on the pumping economics.
Theis (1940)	Perennial safe yield: [for non-artesian aquifers that are small and most artesian aquifers] 'there is a perennial safe yield equivalent to the amount of rejected recharge [induced recharge] and natural discharge it is feasible to utilize.'	Implies concept may not apply to large aquifer with low diffusivity (transmissivity/ storativity) and isolated abstraction.
Stuart (1945)	Safe yield: "is the maximum rate at which water may be withdrawn without impairing the quantity and quality of the supply."	Hydrologically based on the Meinzer concept with water quality constraint added
Conkling (1946)	Safe yield: 'Taken over 1 year should not: (1) Exceed average annual recharge; (2) Lower water table so that the permissible cost of pumping is exceeded; (3) Lower water table so as to permit intrusion of undesirable quality.'	Hydrologically based on natural recharge but production facility economics included in definition plus water quality constraint
Williams and Lohman (1949)	Perennial yield: 'has been regarded as the maximum rate at which water can be salvaged from the natural discharge or added to the (natural) recharge or both.	Return to a hydrologically based definition. However, no consideration of storage capacity.
Thomas (1951, 1955) Synder	Safe yield: suggests abandoning the term because of its indefiniteness. Overdraft/ overdevelopment: 5 types (1)	United States Geological Survey calls for abandonment of safe yield terminology about this time.

(1955)	Development overdraft- lowering of water table in areas of natural recharge/ discharge; (2, 3) Season or cyclic overdraft: zero net change in water levels over specific time period year to year; Cyclic, water levels over two or more seasons and then return; (4) Long- run overdraft: perennial pumping exceeding replenishment (i.e. mining); (5) Critical overdraft- pumping leads to irreversible undesirable result.	Definition of overdraft or overdevelopment in areas exceeding sustained yield. All overdraft yields are unsustainable.
Kazmann (1956)	Safe yield: suggests abandoning the term because of its indefiniteness	---
Todd (1959)	Safe yield: 'the amount of water which can be withdrawn from a groundwater basin annually without producing an undesirable result.'	Compact, but adds nothing to clarify the situation in that the 'undesirable results' include concern for available water, economics of pumping, quality and water rights.
ASCE (American Society of Civil Engineers) (1961)	Four concepts of safe yield: (1) Maximum sustained yield- maximum perennial abstraction; (2) Permissive sustained yield- maximum perennial abstraction legally and economically for beneficial use without undesirable result; (3) Maximum mining yield- total volume in storage that can be extracted and utilized; (4) Permissive mining yield- maximum volume in storage that can be extracted for beneficial purposes without undesired result.	Designed to remove ambiguity of safe yield concept. Definition is a mix between basin mass balance (water budget) and production facility response.
Freeze (1971); Freeze and Cherry 1979)	Demonstrates relationship between basin water balances using three dimensional variably saturated model. Simulation defines the 'Maximum stable basin yield.'	Illustrated variation of inflows and outflows and storage depletion over time.
ASCE (1972)	Two types: (1) Maximum mining yield- abstraction exceeds annual replenishment, (2) Perennial yield- rate at which water can be salvaged from the natural discharge, or added to the natural recharge or both.	(1) Exceeds natural plus induced recharge- unique value (2) based on changing values depending on groundwater levels in basin.
Domenico (1972)	'The question whether groundwater should be managed on a sustained or mining- yield basis is not yet fully resolved and is controlled by local conditions and demands than by policy	---

	decisions in advance of their absolute necessity. This is understandable in that there is likely to be little public sympathy for an announced depletion policy, whereas one of sustained use lends a ring of permanency. Whatever the merits of sustained and mining yield concepts, they are definitely ingrained in groundwater management.'	
Bouwer (1978)	Safe yield: Three types. (1) Normal safe yield- is equal to the average replenishment rate of the aquifer- limited by intrusion near coast; (2) Economic safe yield- rate at which groundwater can be withdrawn without danger of wells drying up before adequate tax base for more expensive water is established (i.e. mining); (3) Legal safe yield- 'rate at which a well owner can pump groundwater without getting involved in legal action.'	Mixes hydrological based recharge, production facility, maximum available drawdown and non-hydrological legal issues.
Bredehoeft et al. (1982, 1997, 2002)	Sustainable groundwater development is determined by capture of natural discharge. Basing groundwater development sustainability on natural recharge (i.e. safe yield) is a myth and irrelevant.	Focus is on production facility transient phase leading up to equilibrium. Implies sustainability means groundwater system must reach equilibrium. Numerical modelling required to determine response.
Brudtland (1987)	Sustainable development to take into account environmental and social issues and long-term protection of resource.	Not specifically related to groundwater but the origin of sustainability concept.
Sophocleous (1997, 1998, 2000)	Sustainable yield primarily derived from groundwater storage but ultimately from induced recharge (i.e. surface water depletion). Sustainable yield must allow for sustainability of environment and therefore should be less than safe yield.	States that numerical models are best to determine and distinguish between natural and induced recharge. Indicates 'irrelevance' of natural recharge. [Bredehoeft (2002) and Kendy (2003) have also stated that natural recharge is irrelevant]
Alley & Leake (2004)	Review differences between safe yield and sustainability.	No definition or methodology given but indicate ambiguities and complexities of concepts and usefulness of numerical models in determination.

Todd (1980) broadly defined the safe yield of a groundwater basin as 'the amount of water which can be withdrawn from it annually without producing an undesired result.' Similar to the safe yield, groundwater sustainability is defined in a broad context, and somewhat ambiguously, as 'the development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences' (Alley & Leake, 2004). Application of the concept of sustainability to water resources requires that the effects of many different human activities on water resources, and on overall environment, be understood and quantified to the extent possible (Sophocleous, 1998; Alley et al., 1999; Sophocleous, 2000). The conventional safe-yield approach is limited and restrictive. It fails to address the beneficial impacts of natural groundwater discharge on related groundwater dependent ecosystems, and on the surface water system in general (Sophocleous, 2000). In this respect, the importance of managing water at the basin scale, or watershed approach, has emerged along similar lines to the concepts of sustainable development.

When talking about sustainability, it is necessary to stipulate the period over which the use is planned and any assumptions about the future sources of water supply (Hiscock et al., 2002). In many situations, a long-term approach to water resources sustainability may involve withdrawals from groundwater storage during dry periods that are balanced by replenishment during intervening wet periods. Sustainable development encourages integrated water management approaches such as artificial recharge, conjunctive use of surface water and groundwater, and use of recycled water, all of which can profoundly affect the magnitude of development that can be sustained.

Alley and Leake (2004) discussed the difference between the concepts of safe-yield and sustainability vis-à-vis groundwater development. According to them safe-yield concepts historically focused attention on the economic and legal aspects of groundwater development whereas sustainability concerns have brought environmental aspects more to the forefront and have resulted in a more integrated outlook.

Kalf and Woolley (2005) reported that an increase in the ratio of groundwater usage to groundwater availability and the over-exploitation of groundwater worldwide resulted in a vigorous debate about the way in which the capacity of an aquifer to deliver water in a sustainable way should be defined and determined. The two prominent concepts developed to describe this are 'safe yield' and, much later, 'sustainable yield'. These latter concepts together with a variety of applied constraints constitute what has been called 'sustainable groundwater development' (Hiscock et al., 2002). If the concept of sustainable groundwater development is to be applied, then it is essential that both safe yield and sustainable yield be understood. Unfortunately, this is currently not the case and there are a variety of interpretations and often also confusion as to their exact meaning.

Wright and Xu (2000) applied the water balance approach for the sustainable groundwater management in South Africa prioritizing basic human needs and the needs of aquatic ecosystems over other inessential uses. Kendy (2003) emphasized the importance of distinguishing between water consumption and pumping when assessing sustainability by stating that, it is not pumping that depletes the groundwater storage but only that component of pumped water which evapotranspires.

Foster et al. (2004) showed how technical and institutional/ administrative knowledge can be combined to tackle groundwater depletion in an urban and densely populated, yet agriculturally vital area of North China Plain. They focused upon the hydrogeologic and socio-economic diagnosis of the groundwater resource issues, and identified strategies to improve groundwater resource sustainability. They recommended that groundwater in the deep fresh-water aquifer be treated as a strategic water supply reserve, which in the long-term should only be tapped for: (a) high-value, small-demand uses, where no other ready alternative resource exists, and (b) to alleviate water-supply shortages in extreme drought conditions. This recommendation is similar to the one given by Central Groundwater Board (CGWB) in case of development of 'static groundwater resources' in India, that they can be considered for development only during extreme drought conditions and that too probably only to meet the drinking water supply (CGWB, 1998).

Foster et al. (2004) also discussed a range of water resource management strategies, which could contribute to reducing (and eventually eliminating) aquifer depletion, and concluded that those on the demand-side are likely to make a larger and more critical contribution than those on the supply-side. They suggested that all the options given below can be applied at local (county or district) level but require varying degrees of facilitation and/or support:

1. Reducing groundwater abstraction for irrigation: They implied that such measures are capable of reducing the rate of decline in the deep confined aquifer and of making a contribution to the stabilization of the water table of the shallow aquifer;
2. Aquifer recharge enhancement with excess surface runoff;
3. Aquifer recharge with urban wastewater: Most urban wastewater should be regarded as a valuable water resource which, after primary/ secondary treatment, can be reused directly for the irrigation of certain agricultural crops. Such irrigation normally results in high rates of infiltration and recharge to aquifers when practiced on permeable soils (Foster et al., 1997).

Kemper (2004) hoped that the increasing emphasis on addressing groundwater as an important part of the global development agenda will lead to more active, and improved groundwater management worldwide, permitting long-term economic growth and social development.

Water resources cannot be developed without altering the natural environment; thus, one should not define basin yields, either as safe or sustainable, without carefully explaining the assumptions that have been made about the acceptable effects of groundwater development on the environment. More recently, concern about the long-term effects of groundwater development have been extended to lakes, wetlands, springs and estuaries. The tradeoff between the water used for consumption and the effects of withdrawals on the environment are increasingly the driving force in determining the sustainability of many groundwater systems (Alley et al., 1999).

According to Devlin and Sophocleous (2005) sustainability and sustainable pumping are two different concepts that are often used interchangeably. The latter term refers to a pumping rate that can be maintained indefinitely without dewatering or mining an aquifer, whereas the former term is broader that goes beyond sustainable pumping to include issues such as ecology, water quality, and human and environmental welfare. Another important distinction between them is that although groundwater recharge rates are not required for estimating sustainable pumping rates, they are required for the accurate assessment of sustainability. Due to the effects recharge is likely to have on water quality, ecology, socio-economic factors, it remains important in assessments of sustainability.

We now understand that the sustainable yield of an aquifer must be considerably less than recharge, if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and groundwater dependent ecosystems. Sustainable resource management is managing groundwater for both present and future generations, and providing adequate quantities of water for the environment. Quantifying what these environmental provisions are is presently an urgent research need (Sophocleous, 2000).

Mukherji and Shah (2005) provided a balanced view of the plus and the down side of groundwater use in agriculture by drawing examples from countries such as India, Pakistan, Bangladesh, China, Spain and Mexico- all of which make very intensive use of groundwater. They analyzed institutions and policies that influence groundwater use in order to understand how groundwater is governed in these countries and whether successful models of governance could be replicated elsewhere. They urged the need for expansion in the knowledge base in groundwater studies, especially through inclusion of soft sciences like economics and sociology. Finally, they argued that there is a need for a paradigm shift in the way groundwater is presently perceived and managed- from management to governance mode by simultaneous deployment of number of instruments such as direct regulation, indirect policy levers, livelihood adaptation and people's participation in a quest for better governance.

2.6 ASSESSMENT OF WATER RESOURCES

2.6.1 Surface Runoff Estimation by NRCS-CN Method

A multitude of methods/ models are available in hydrologic literature to simulate the complex process of rainfall-runoff in a watershed. In year 1954, the United States Department of Agriculture (USDA), Soil Conservation Services (SCS) (now called the Natural Resources Conservation Services, NRCS) developed a unique procedure known as SCS-CN method. Mishra et al. (2005) provided an extensive review of the method and subsequent improvements suggested by various researchers. The method, which is basically empirical, was developed to provide a rational basis for estimating the effects of land treatment/ land use changes upon runoff resulting from storm rainfall. According to Garen and Moore (2005) "...the reason for the wide application of CN method includes its simplicity, ease of use, widespread acceptance, and the significant infrastructure and institutional momentum for this procedure within NRCS. To this date, there has been no alternative that possesses so many advantages, which is why it has been and continues to be commonly used, whether or not it is, in a strict scientific sense, appropriate…"

2.6.1.1 Theoretical background

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of actual amount of direct surface runoff (Q) to the total rainfall (P) (or maximum potential surface runoff) to the ratio of actual infiltration (F) to the amount of the potential maximum retention (S). The second hypothesis relates the initial abstraction (I_a) to the S, also described as the potential post initial abstraction retention (McCuen, 2002). Expressed mathematically,

(a) Water balance equation

$$P = I_a + F + Q \tag{2.1}$$

(b) Hypothesis of proportional equality

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{2.2}$$

(c) Hypothesis of relation between I_a and S

$$I_a = \lambda S \tag{2.3}$$

The values of P, Q and S are given in depth dimensions, while the I_a coefficient λ is dimensionless. The first (or fundamental) hypothesis (equation 2.2) is primarily a proportionality concept (Mishra and Singh, 2003). Apparently, as $Q \rightarrow (P-I_a)$, $F \rightarrow S$. The parameter S of the SCS-CN method depends on soil type, land use, hydrologic condition, and antecedent moisture condition (AMC). The I_a coefficient λ is frequently viewed as a regional parameter depending on geologic and climatic factors (Boszany, 1989). The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications. Many other studies carried out in the United States and other countries report λ to vary in the range of (0, 0.3). A study of Hawkins et al. (2002) suggested that value of λ = 0.05 gives a better fit to data and would be more appropriate for use in runoff calculations.

The second hypothesis (equation 2.3) is a linear relationship between initial I_a and S. Coupling equation (2.1) and equation (2.2), the expression for Q can be written as:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad \text{for } P > Ia \qquad (2.4)$$

$$Q = 0 \qquad \text{for } P \le Ia$$

Equation (2.4) is the general form of the popular SCS-CN method. For $\lambda = 0.2$, the coupling of equation (2.3) and equation (2.4) results

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{for } P > 0.2S \qquad (2.5)$$

$$Q = 0 \qquad \text{for } P \le 0.2S$$

Equation (2.5) is the popular form of existing SCS-CN method. Thus, the existing SCS-CN method with $\lambda = 0.2$ is a one-parameter model for computing surface runoff from daily storm rainfall.

Since parameter S can vary in the range of $0 \le S \le \infty$, it is mapped onto a dimensionless CN, varying in a more appealing range $0 \le CN \le 100$, as:

$$S = \frac{25400}{CN} - 254 \qquad (2.6)$$

where, S is in mm. The difference between S and CN is that the former is a dimensional quantity (L) whereas the later is non-dimensional. CN = 100 represents a condition of zero potential maximum retention (S = 0), that is, an impermeable watershed. Conversely, CN = 0 represents a theoretical upper bound to potential maximum retention ($S = \infty$), that is an infinitely abstracting watershed. However, the practical design values validated by experience lie in the range (40, 98) (Van and Mullem, 1989). CN has no intrinsic meaning; it is only a convenient transformation of S to establish a 0-100 scale (Hawkins, 1978).

2.6.1.2 Curve number estimation and applications

Reliable estimation of parameter CN has been a topic of discussion among hydrologists and water resources community (McCuen, 2002; Springer et al., 1980; Simanton et al., 1996; Steenhuis et al., 1995; Bonta, 1997; Ponce and Hawkins, 1996; Sahu et al., 2007; and Mishra and Singh, 2006).

From the observed rainfall (P)-runoff (Q) data of a gauged watershed, the NRCS-CN parameter S can be determined by solving equation (2.4) for $\lambda = 0.2$, as follows (Hawkins, 1993):

$$S = 5\left[P + 2Q - \sqrt{Q(4Q + 5P)}\right] \quad (2.7)$$

For accuracy in runoff prediction using the popular NRCS-CN method, correct estimation of AMC-dependent CN-values is necessary. Mishra et al. (2008) proposed AMC-dependent runoff CN conversion formulae as given below in equation (2.8) and (2.9) and compared the same with the available four AMC-dependent runoff CN conversion formulae due to Sobhani (1975), Hawkins et al. (1985), Chow et al. (1988) and Neitsch et al. (2002) utilizing the (National Engineering Handbook-4) NEH-4 CN-values as target values. The Sobhani formula was found to perform the best in CN_I-conversion, and the Hawkins formula in CN_{III}-conversion. They concluded that when evaluated on a large data set of USDA- Agricultural Research Service (ARS), the newly proposed formulae (equation (2.8) and (2.9)) performed the best of all and therefore recommended for field use.

$$CN_I = \frac{CN_{II}}{2.2754 - 0.012754 CN_{II}} \quad (2.8)$$

$$CN_{III} = \frac{CN_{II}}{0.430 + 0.0057 CN_{II}} \quad (2.9)$$

A considerable amount of literature on the method has been published and the method has undergone through various stages of critical reviews (Rallison, 1980; Chen, 1982; Ponce and Hawkins, 1996; Mishra and Singh, 2003; Jain et al., 2006).

In one of the latest modifications available in the literature, Jain et al. (2006) proposed a new non-linear relation between I_a and S in the NRCS-CN methodology incorporating storm rainfall (P) and tested on a large set of storm rainfall-runoff events derived from the water database of USDA-ARS. Employing root mean square error, the performance of both the existing and proposed models was evaluated using the complete database, and for model calibration and validation, data were split into two groups: based on ordered rainfall (P-based) and runoff (Q-based). They concluded that a specific formulation of the proposed model as given below in equation (2.10), with $\lambda = 0.3$ and $\alpha = 1.5$, was found to generally perform better than the existing $I_a = 0.2S$, and therefore, was recommended for field applications.

$$I_a = \lambda S\ (P / (P+S))^{\alpha} \qquad (2.10)$$

Rallison (1980) provided detailed information about the origin and evaluation of the methodology and highlighted major concerns to its application to the hydrology and water resources problems it was designed to solve and suggested future research areas. Chen (1982) evaluated the mathematical and physical significance of methodology for estimating the runoff volume. A sensitivity analysis shows that the errors in CN have more serious consequences on runoff estimates than the errors of similar magnitude in initial abstraction or rainfall.

Though primarily intended for event-based rainfall-runoff modeling of the ungauged watersheds, the SCS-CN method has been applied successfully in the realm of hydrology and watershed management and environmental engineering, such as long-term hydrologic simulation (Knisel, 1980; Woodward and Gburek, 1992; Pandit and Gopalakrishnan, 1996; Rao et al., 1996; Choi et al., 2002; Mishra and Singh, 2004a; Geetha et al., 2007); prediction of infiltration and rainfall-excess rates (Aron et al., 1977; Bhattacharya and Sarkar, 1982; Mishra and Singh, 2004b); sediment yield modeling (Mishra and Singh, 2003; Mishra et al., 2006); and determination of sub-surface flow (Yuan et al., 2001). The method has also been successfully applied to distributed watershed modeling (White, 1988; Moglen, 2000; Mishra and Singh, 2003).

Sharma and Singhal (1989) used the satellite remote sensing data of Delhi region for deciphering supervised and unsupervised land use classifications for further use in estimation of urban runoff from the SCS CN method. Kumar et al. (1991) attempted to establish the CN from Indian Remote Sensing satellite (IRS)-1A LISS II digital database for the Kaliaghai river basin situated in the Midnapore district of West Bengal. They developed LULC map with hydrologically significant classes (cultivated, forest, fallow, waste land and impervious surface) with the help of IRS digital data. They used SCS model modified for Indian conditions for establishing the CN for Kaliaghai river basin.

2.6.2 Groundwater Recharge Estimation

Groundwater is a strategic resource due to its usually high quality and perennial availability. However, groundwater management all over the world often lacks sustainability as evident by falling water tables, drying wetlands, increasing sea-water intrusion and overall deterioration of water quality. As groundwater cannot be recharged naturally or artificially on a large scale, its sustainable management is vital. A number of scientific tools are available to assist in this task. They include methods for the determination of groundwater recharge, groundwater modeling including the estimation of its uncertainty, and the interfacing to the socio-economic field. Generally, the quality of groundwater management work can be largely enhanced with newly available tools, including remote sensing, digital terrain models, Global Positioning System (GPS), environmental tracers, automatic data collection, modeling and the coupling of models from different disciplines (Kinzelbach et al., 2003).

As defined by Rushton and Ward (1979), groundwater recharge is 'the amount of surface water which reaches the permanent water table either by direct contact in the riparian zone or by downward percolation through the overlying zone of aeration'. Lerner (1997) broadly defined recharge as 'water that reaches an aquifer from any direction-down, up, or laterally'. Quantification of the current rate of natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management, although it is one of the more difficult to infer. It cannot be measured directly and must be estimated from other measurements (Rushton and Ward, 1979; Simmers, 1988).

Kinzelbach et al. (2003) reported that groundwater recharge is not yet possible to measure with sufficient accuracy. Recharge is not directly measurable, and indirect methods introduce various uncertainties. To make things worse, rain and recharge events in dry climates are of an extremely erratic nature. Integral methods such as the Wundt method (which does not consider inter-flow, and usually lead to a significant over-estimation of base flow; Kling and Nachtnebel, 2009) based on low flow analysis of rivers are very useful in humid climates, but do not work in arid zones, where the low flow is usually zero. The method of hydrological water balance is notoriously inaccurate. The methods based on Darcy's law are inaccurate, as it is extremely difficult to find a representative effective value on the large scale for the usually abnormally distributed hydraulic conductivity. Better estimates can be obtained at least in sand gravel aquifers using environmental tracers like tritium.

Various techniques are available to quantify recharge; however, choosing appropriate technique is often difficult. Lloyd (1999), in a United Nations Educational, Scientific and Cultural Organization (UNESCO) publication, presented a critical review of various methods used for groundwater recharge estimation in hard rock areas. He, after comparing various methods, suggested preferring the use of combination of methods like chloride profile method, cumulative rainfall departure method and water balance techniques for recharge estimation. According to Scanlon et al. (2002), important considerations in choosing a technique include space/ time scales, range, and reliability of recharge estimates based on different techniques. The goal of the recharge study is important because it may dictate the required space/ time scales of the recharge estimates. Typical study goals include water resource evaluation, which requires information on recharge over large spatial scales and on decadal time scales whereas in studies on evaluation of aquifer vulnerability to contamination detailed information on spatial variability and preferential flow is required. They reported that the techniques based on surface water and unsaturated zone data provide estimates of potential recharge, whereas those based on groundwater data generally provide estimates of actual recharge. Uncertainties in each approach to estimating recharge underscore the need for application of multiple techniques to increase reliability of recharge estimates.

Misstear et al. (2009) estimated groundwater recharge in a major sand and gravel aquifer in Ireland by using multiple approaches like soil moisture budgeting, well hydrograph analysis, numerical modelling and a catchment water balance. They computed recharge coefficient between 81 and 85 %, which is considered a reasonable range for the aquifer in question, where overland flow is rarely observed. The well hydrograph analysis, using a previous estimate of specific yield of 0.13, gave recharge coefficients in the range of 40 to 80 %, which they considered low for the aquifer and hence they used a revised value of specific yield (0.19) which resulted in a more reasonable range of recharge coefficients of 70 to 100 %. They concluded that results from all approaches are sensitive to the input parameters, for example climate data in the case of soil moisture budgets or specific yield values in the case of well hydrograph analysis.

The common recommendation that recharge should be estimated from multiple methods is sound, but the inherent differences of the methods make it difficult to assess the accuracy of differing results (Scanlon et al., 2002). Sophocleous (1991) showed how unsaturated zone water balance monitoring could be combined with water table fluctuations to increase the reliability of recharge estimates. Scanlon et al. (2002) indicated that hydrograph analysis is best applied over short time periods in areas where the water table is shallow, and where the hydrographs display sharp rises and falls in groundwater levels. Techniques based on groundwater levels are among the most widely applied methods for estimating recharge rates (Healy and Cook, 2002). In India, the recharge estimation methodology given by CGWB includes combination of water table fluctuation (WTF) method (which is based on groundwater balance approach) and rainfall infiltration factor method to get a reliable estimate of groundwater recharge (CGWB, 1998).

Sophocleous (1991) pointed out that the WTF method can be misleading if the water level fluctuations are affected by those resulting from pumping, barometric, or other causes. Risser et al. (2009) compared the four methods (including the WTF method) for estimating groundwater recharge and two methods for estimating base flow (as a proxy for recharge) at two hydrologic research sites in east-central Pennsylvania, USA. All results from the multiple methods provided reasonable estimates of groundwater recharge that differed considerably. The estimates of mean annual recharge for the period 1994-2001 ranged from 22.9 to 35.7 cm. For individual years, recharge estimates from the multiple methods ranged from 30 to 42 % of the mean value during the dry years and 64 to 76 % of the mean value during wet years. They found that the WTF method gives lower estimates than other methods and produces anomalously small variability in results from year to year, possibly because specific yield is assumed to be constant in time.

Andreo et al. (2008) estimated the mean annual recharge in carbonate aquifers, expressed as a percentage of precipitation for eight regions in southern Spain, based on the variables like altitude, slope, lithology, infiltration landform, and soil type. They termed the method as APLIS, after the Spanish initials for these variables. They selected eight aquifers representing a wide range of climatic and geological characteristics for which the mean rate of annual recharge is already known. Then, they created layers of information corresponding to above-mentioned variables that influence the recharge. After subjecting these variables to multivariate analysis to determine which of the variables were the most influential, they developed a system of ratings and scores which, when appropriately combined and applied, using the GIS, enabled them to estimate the rate of recharge and its spatial distribution. They found that the recharge values computed by APLIS method are similar to those previously calculated by other conventional methods. The results obtained by them for the eight carbonate aquifers revealed that the mean annual recharge rates were approximately 33-55 % of the precipitation into the aquifer.

In another similar study in hard rock terrain of Bhandara District of Maharashtra State, India, Katpatal and Dube (2005) adopted 'weight average method' for recharge estimation in which they assigned weights to various classes of different parameters like geology, geomorphology, slope, lineament density, soil type and runoff, according to the importance of these classes supporting groundwater recharge. After assigning weights to different parameters mentioned above, they integrated all the parameters through overlay analysis and generated the final map of estimated recharge. They concluded that the methods of assigning weights to different parameters according to their importance in groundwater recharge and integration of various parameters proved to be more accurate for groundwater recharge estimation.

In India, studies related to estimation of groundwater recharge using environmental as well as injected tracers were initiated shortly after the successful demonstration of the tracer technique by Munnich (1968) (e.g. Datta et al., 1973; Sukhija and Shah, 1976). More recently, the tritium injection technique has been used by many workers in various geologic environs (e.g. Gupta and Sharma, 1984; Chandrasekharan et al., 1988; Rangarajan et al., 1989; Athavale and Rangarajan, 1988; Singhal et al., 2010).

Sukhija et al. (1996) measured natural direct groundwater recharge in the semi-arid/ arid regions of India using techniques that employ environmental, geochemical, and artificial tracers. In the arid sands of Western Rajasthan and the semi-arid alluvial tracts of Gujarat, recharge rate observed by them was 3-10 % of local average annual rainfall, whereas in the alluvial tracts of Uttar Pradesh, Punjab, and Haryana, recharge rates were about 12-20 %. According to them, the coastal semi-consolidated sandstone aquifers of Pondicherry and Neyveli have an average recharge rate of about 15-25 % whereas the consolidated aquifers, consisting of the basaltic and granitic-gneissic complexes, have a natural recharge rate of 3-15 %. In the basaltic regions they find intermediate recharge values (8-12 %).

Kalf and Woolley (2005) gave a comprehensive review of methodologies used for estimation of groundwater resources in various countries (Table 2.2). They also referred to the widely used methodology of Central Ground Water Board (Ministry of Water Resources, Government of India) which is based on the general mass balance approach involving safe yield. Yet, this approach does not account for groundwater in deep confined aquifers.

Table 2.2: Some examples of current water budget approaches (Source: Kalf & Woolley, 2005)

Country/ state	Water budget approach	Comments
Britain	Total abstraction, plus the required stream flow, must be less than recharge	Indirect limit applied to groundwater abstraction by community decisions on stream water quality. (Abstraction leads to loss of stream flow and possible degradation of quality)
India	Safe yield policy depending on a given percentage of rainfall. Target is to have abstraction less than recharge	Recharge rate for various aquifers is specified as a percentage of rainfall in Central Government publications. Calculations and administration by States. Inconsistently applied. May improve with implementation of recent legislation
China	New legislation is based on a safe yield policy	Aim is to reduce abstraction where it exceeds recharge, and to prevent increased abstraction where it balances recharge
Kansas, USA	Groundwater Management Districts (GMD) in east and northwest now have a safe yield policy, but introduced too late to prevent water level declines. Western GMDs have a planned depletion policy	Widespread falls in groundwater level of significant magnitude. Non-recoverable in large areas
Arizona, USA	Over-use and falling water levels addressed by legislation that mandates safe yield (balancing abstraction with recharge)	Not clear that targets will be met
California, USA	Courts have determined 'equitable distribution' over large areas	May not lead to sustainable use. San Gabriel has defined 'natural safe yield' (quantity that can be extracted from long-term

		average annual supply) and 'operating safe yield' (quantity determined by agency for use in a particular fiscal year)
Rhode Island, USA	Safe yield policy	Uses the Todd (1959) definition (see Table 2.1)
Indonesia	Implied target of reducing abstraction to less than recharge	Sub-optimal location of abstraction facilities has led to operational problems
Arabian Peninsula (Algeria, Oman, UAE, Syria, Jordan, Bahrain, Qatar, Kuwait, Saudi Arabia)	No specific yield policy. Abstraction is without volume limitation for individuals	Range of groundwater withdrawal as percentage of renewal 110 to 1,456 % (Young, 2002)
Mexico (Guanajuato State)	No specific yield policy. Efforts to set up groundwater management program	Sandoval (2004)
Western Turkey	Safe yield policy since 1960's. Now exploring groundwater development using various yield policies	Sakiyan and Yazicigil (2004)
Australia	Sustainable yield policy, based on keeping abstraction less than natural recharge, with specific allowance for groundwater dependent ecosystems (including rivers)	Use of time frame in definition of sustainable yield allows for some groundwater mining to be referred to as sustainable

Watershed with well-defined hydrogeological boundaries is an appropriate hydrological unit for estimation of groundwater resource and simulating other water balance components (Tripathi et al., 2006; Sharma, 1997). Gheith and Sultan (2002) estimated the groundwater recharge rates for alluvial aquifers within the major watersheds of the north eastern desert, Egypt from sporadic precipitation over the Red Sea hills. They estimated that during the November 1994 flood event, the groundwater recharge through transmission losses ranged from 21 to 31 % of the precipitated volume and the initial losses ranged from 65 to 77 % whereas only 3 to 7 % of the precipitation reached the watershed outlets.

Sharda et al. (2006) estimated groundwater recharge from water storage structures under semi-arid conditions of western India by employing WTF and chloride mass balance (CMB) methods. Groundwater recharge was estimated as 7.3 % and 9.7 % of the annual rainfall by WTF method for the years 2003 and 2004, respectively while the two years average recharge was estimated as 7.5 % using CMB method. Singhal et al. (2010) attempted delineation of aquifers of piedmont zone of Himalayan foothill region in Pathri Rao watershed in Haridwar District of Uttarakhand State (India), by using integrated hydrogeologic and geophysical techniques (vertical electrical soundings, 2-dimensional electrical resistivity tomography and electromagnetic surveys). From the tritium injection studies, they estimated the rate of recharge into the aquifers in the range of 9 % to 29 %.

2.7 ASSESSMENT OF WATER QUALITY

As water moves through the hydrologic cycle, its quality changes in response to the differences in the environment through which it passes. The changes may be either natural or human induced. Groundwater quality deterioration is a function of many factors. These include the ability of the intervening unsaturated zone and soil media to transfer pollutants from the ground surface to the water table aquifers. The role of regular monitoring of water quality is widely recognized in many parts of the world because of the increasing scarcity of safe water resources, a high competition between water uses and environmental degradation (Trefry, 2008). It is, therefore, accepted by all its users that water should be considered safe only if its quality is regularly monitored and considered acceptable by health officials. In this context the assessment of groundwater quality becomes imperative in order to initiate any further action in groundwater quality management and to identify problems and formulate measures to prevent deterioration in water quality.

The World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) estimated that at the beginning of the year 2000, one-sixth of the world's population lacked access to a safe water supply (WHO/ UNICEF, 2000). Despite global efforts made during 1980-1990, the majority of the worlds' population with access to safe water remains in developed countries. In a number of studies in India and abroad, poor water quality is considered as one of the reasons for unsustainable water consumption. Sustainable groundwater management must take into consideration pollution sources and the potential of percolating water carrying pollutants to the aquifer. Chapman (1996) has given the detailed guidelines for assessing quality of natural waters in environmental monitoring.

2.7.1 Water Quality Assessment

The quality of groundwater usually is evaluated in relation to chemical and physical criteria. Bacteriological parameters are frequently included in assessment of water quality. Godfrey and Smith (2005) discussed appropriate methods for assessing and managing the safety of the groundwater in developing countries. They acknowledged the increasing global importance of chemical contamination highlighting the significance of assessment of the vulnerability of groundwater to microbial contamination and emphasized the challenges faced by hydrogeologists in developing rapid risk assessment methods for localised pathways of shallow groundwater contamination in developing countries.

The decline in the utility of groundwater is due to its quality problems. Leaching from compost pits, animal refuse, dumping grounds for garbage, synthetic fertilizers and pesticide-enriched irrigation return flows, seepage from septic tanks, seepage of sewage, etc. have adversely affected the groundwater quality in several parts of India (Handa, 1994). Geogenic contaminants such as unsafe concentration of arsenic, fluoride and iron are related to excessive groundwater pumping (Sharma, 2009). In India, the higher concentration of fluoride in groundwater is associated with igneous and metamorphic rocks (Handa, 1988). Hem (1970) has summarized the natural sources and concentrations of the principal chemical constituents found in groundwater and their effects on the usability of the water. Matthess (1982) has elegantly described properties of groundwater in his monograph.

The incidence of groundwater pollution is high in urban areas, where large volumes of domestic and industrial wastewater are discharged into relatively smaller areas as point source. Several researchers have studied impact of urbanization and industrialization on groundwater resources in alluvial and hard rock regions (e.g. Foster, 1990; Handa, 1994; Lagerstedt et al., 1994; Zhou et al., 2007; Shankar et al., 2008).

Foster (1990), by drawing examples mainly from developing nations of Latin America and the Caribbean, showed that urbanization, coupled with almost inseparable industrial development, has profound impacts on groundwater quality. He concluded that administrators in the land and water sector need to take much fuller account of such impacts when making decisions on the choice of sewerage and drainage arrangements, and the location of certain industries, in new urban areas. He mentioned nitrates, some heavy metals (such as chromium), and the common synthetic industrial solvents (such as chloroform, trichloroethylene), as the principal groundwater contaminants of concern. If more positive controls over the impact of urbanization and industrialization on groundwater quality are not taken and dangerous effects on public health are to be avoided, then the groundwater from aquifers within urban areas will have to be restricted to non-potable use or complex treatment facilities will have to be provided at innumerable individual sources.

In India, groundwater pollution or contamination from the point, non-point and line sources has been observed by Handa (1994). According to him, the 'point sources of pollution' in India are bacterial contamination caused by indiscriminate siting of hand pumps, poor construction and improper maintenance of dug wells/ tubewells, occurrence of unhygienic conditions near extraction sites and discharge of untreated industrial waste effluents into the environment. The 'non-point sources of pollution' are the return irrigation flows which take with them their load of dissolved salts, plant nutrients, pesticides etc. to contaminate the receiving groundwater bodies. The 'line sources of pollution' observed in India are waste effluent discharges in unlined drains, or even beds of non-perennial streams, the seepage of polluted water affecting the quality of dug well water located along the banks of the streams (Handa, 1994).

Lagerstedt et al. (1994) observed the nitrate pollution from the perspective of the general nitrogen circulation in the eastern Botswana. They compared the three cases of nitrate pollution in groundwater where the resulting concentrations were of similar magnitude but the causes were different. Gallegos et al. (1999) determined the environmental effects of wastewater irrigation on the subsurface at two locations in Mexico; Leon and the Mezquital valley. The subsurface sediment samples and groundwater samples were collected from various depths by the authors and analyzed for a range of physicochemical and microbiological parameters. They concluded that wastewater irrigation has a negative impact on groundwater quality in the Mezquital Valley as fecal bacteria from the wastewater got transported through the subsurface into the underlying aquifer. The shallow aquifers were observed to be more affected by microbial contaminants than deep aquifers.

Atasoy et al. (2006) examined the impact of urbanization on water quality using disaggregate data from Wake county, North Carolina for a sub-river basin in an area where urban pressure dominates. They used total suspended solids, total nitrogen and total phosphorous as measures to link development to water quality. The study provided a strong evidence of the effects of urban residential construction and land use on water quality. Zhou (2007) summarized the groundwater pollution problems of three urban areas in Cordoba City (Argentina), Ramallah- Al Bireh District (Palestine) and Saharanpur City (India) under a project sponsored by UNESCO-IHE in order to assess, monitor and protect the groundwater pollution in these areas. Naik et al. (2008) studied the impact of urbanization on the groundwater regime in Solapur city, Maharashtra, India and reported that the water quality in the city has deteriorated during the last 10 years, especially in dug wells, mainly due to misuse and disuse of these structures and poor circulation of groundwater.

Nitrate is often seen as an agricultural pollutant of groundwater (Rajmohan & Elango, 2005) and so is expected to be at higher concentrations in the groundwater surrounding a city than in those beneath it. However the difference between rural and urban nitrate concentrations is often small, due to the non-agricultural sources of nitrogen that are concentrated in cities. The review carried out by Wakida & Lerner (2005) has shown that the major sources of the nitrogen in urban aquifers throughout the world are related to wastewater disposal (onsite systems and leaky sewers) and solid waste disposal (landfills and waste tips). In developing countries, a sewage collector system and treatment in conjunction with an appropriate solid waste disposal system will reduce much of the problem. However, it will not eliminate the risk of groundwater pollution through leaking sewers. Through a case study of nitrate loading, they further illustrated that the major sources of nitrogen in the Nottingham city area are mains leakage and contaminated land with approximately 38 % each of a total load of 21 kg N ha^{-1} $year^{-1}$.

Jeong (2001) investigated the chemical characteristics and the contamination of groundwater in relation to the land use in Taejon area, Korea. Groundwater samples collected at 170 locations showed a highly variable chemical composition of groundwater. Factor analysis used in this study indicated that the high levels of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), and sulphate (SO_4^{2-})

were derived from both pollution sources and natural weathering reactions. Trojan et al. (2003) studied and compared groundwater quality under irrigated and non-irrigated agriculture, sewered and non-sewered residential developments and industrial and, non development land use. The authors monitored 23 wells in upper layer of an unconfined sandy aquifer in the period from 1997 to 2000. They observed that there are no seasonal differences in water chemistry, but noted variations of water chemistry when land use changes occurred. So the land use is the dominant factor affecting shallow groundwater quality.

Seth and Singhal (1994) examined the status of groundwater quality in shallow aquifers of upper Hindon Basin, in the context of prolific industrial activity around Saharanpur town of Uttar Pradesh (India) and reported that the groundwater of the area is only marginally affected when compared to the quality criteria for drinking set by WHO. A report of National Institute of Hydrology (1999) presents the findings regarding the monitored physicochemical parameters of surface water, groundwater and wastewater of district Haridwar, Uttarakhand (India). The quality of groundwater upto 50 feet was not found to be good as it contained various inorganics and organics, while the quality of groundwater at deeper levels was good and safe. It could be due to the leaching of inorganics and organics in the aquifer till about 50 feet while the leaching of these contaminants upto 100 feet or more, though, not observed significantly, but could be possible after some time.

Kumar et al. (1995) studied the groundwater quality status of shallow aquifer in Saharanpur District (Uttar Pradesh State) and Haridwar District (Uttarakhand State), India. They collected 22 samples from various wells in the period (Jun 1987 to Nov 1987), and analyzed them for various physicochemical parameters viz. pH, electrical conductivity (EC), colour, odour, hardness, alkalinity (carbonates and bicarbonates), temperature, and major cations and anions. Hussain et al. (2006) evaluated the groundwater vulnerability in Ganga-Yamuna interfluve area in India. He analyzed groundwater samples for various physicochemical parameters, major ions, nutrients and heavy metals. The groundwater vulnerability mapping was carried out using two methods of DRASTIC and its modification (DRASTIC-MOD), based on inclusion of land use as an additional parameter.

Srivastava (2006) carried out physicochemical characteristics of groundwater in parts of Uttarakhand state including Doon valley (which includes the present study area of the Suswa Watershed) in order to study its suitability for domestic and irrigation uses. He analyzed groundwater samples collected from tubewells (hand pumps) and dug wells for pH, EC, Cl^-, bicarbonate, nitrate (NO_3^-), fluoride, total hardness, Ca^{2+}, Mg^{2+}, Na^+ and K^+ and observed that quality of groundwater of most of the area is suitable for both drinking and irrigation purpose.

2.7.2 Water Quality Indices

Subsequent to assessment, the groundwater quality needs to be represented in a suitable format for end users and decision makers for better comprehension and further action. A range of methods from graphical to numerical (employing water quality index (WQI)) have been reported in the literature (Matthess, 1982).

Graphical representations are intended to simplify comparison and evaluation of different analyses. They include pictorial diagrams (like bar graphs, circular- and radial-diagrams) and multivariate diagrams (like trilinear, square, rectangle, combination and parallel scale triangles). Piper (1944) developed one of the most useful trilinear diagrams for representing and comparing water quality. Stiff (1951) suggested the pattern diagrams for representation of chemical analysis by four horizontal parallel axes along which concentration of cations are plotted to the left of a vertical zero axis and anions to the right.

Water quality indexing system serves as a convenient means of holistic numerical representation of water quality data. It generally involves a mathematical framework used to transform large quantities of water quality data into a single number representing the consolidated water quality level, while eliminating the subjective assessment of water quality and bias of individual water quality experts.

The WQI is a mathematical instrument used to transform large quantities of water quality data into a single number which represents the water quality level. In fact, developing WQI in an area is a fundamental process in the planning of land use and water resources management. Water quality indices are developed as a tool to summarize and report on the monitoring data to the decision makers to be able to understand the status of the water quality in a water source and to have the opportunity for better use in future.

Despite the fact that the use of an index may not be the best way to understand large-scale water quality conditions, for specific use, it would still be the only viable method. Indices can also overcome communication problems between scientists and water managers or policymakers. Their application should always involve the necessary prudence, as standardization and aggregation of the variables are subjective procedures accompanied by a loss of information. Therefore, the index can never be considered as a final quantitative assessment of capability of groundwater to be used as a reliable source of drinking water but should be applied as a purpose-specific water management tool. The details regarding the major indices proposed by various researchers have been presented in the following paragraphs.

So far, many researchers gave indices to measure surface and groundwater quality. Horton (1965) suggested that the various water quality data could be aggregated into an overall index. Over the years, many water quality indices have been suggested for special purposes (Dalkey, 1968; Prati et al., 1971; Harkins, 1974; Walski and Parker, 1974; Inhaber, 1975; Shaefer and Janardan, 1977; Couillard and Lefebvre, 1985; Singhal et al., 1987; House and Ellis, 1987).

Backman et al. (1998) presented an index for evaluating and mapping the degree of groundwater contamination and test its applicability in Southwestern Finland and Central Slovakia. A simple WQI involving nine parameters is created by Soltan (1999) to indicate the quality of groundwater from ten artesian wells located near the Dakhla Oasis in the Egyptian Western. The work of S'tambuk-Giljanovic (1999) reported the creation of a WQI both for surface waters and groundwater and the results of its application for water evaluation in Dalmatia, Croatia. Coulibaly and Rodriguez (2004) developed utility performance indicators on the basis of operational, infrastructure, and maintenance characteristics of utilities for explaining surface water and groundwater quality as main source of drinking water in Quebec (Canada). Stigter et al. (2006) used groundwater quality index for evaluating influence of agriculture activities on several key parameters of groundwater chemistry and potability.

Shankar and Sanjeev (2008) assessed the WQI for the groundwater of K.R. Puram industrial area in Bangalore, India. They carried out physicochemical analysis for the 30 groundwater samples collected in and around the industrial area. For calculating the WQI, parameters considered by them were: pH, total hardness, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-}, NO_3^-, SO_4^{2-}, total dissolved solids (TDS), iron, and fluorides. Forty percent of their tested samples exceeded 100, the upper limit for drinking water. They concluded that the groundwater of the area needed some treatment before consumption.

Kaushik et al. (2002) assessed the groundwater quality in Hisar and Panipat cities of Haryana (India) for drinking purpose based on water quality parameters like pH, EC, turbidity, TDS, alkalinity, total hardness, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-, PO_4^- and fluoride with respect to different land-use areas viz. residential, industrial, commercial and agricultural. WQI based on 9 parameters showed that at Panipat, groundwater in all the land-use zones was fit for consumption (WQI < 50), whereas at Hisar, water in agricultural areas was good in quality, but that in other areas varied in magnitude of pollution (WQI > 50 to 100).

Prasad and Sangita (2008) collected groundwater samples from the periphery of a fly ash filled open cast mine, from within the mine property, and from a half kilometre away from the site at Dhanbad (India). They found that the concentrations of metals such as Cu, Zn, Cd, Pb, and Cr were consistently below the permissible limit for drinking water, but concentrations of Fe and Mn were above the permissible limit. They used the data to calculate a heavy metal pollution index (HPI). The HPI of the groundwater of the ash filled mine was 36.67, which was below the critical index limit of 100. The HPI of Dhanbad town groundwater, from very near to the mining area, was 11.25. They concluded that leachate from the fly ash filled mine has apparently contaminated the groundwater to a limited extent.

Horton (1965) proposed the first formal water quality index in the literature. Horton's Quality Index (QI) uses a linear sum aggregation function. It consists of the weighted sum of sub-indices divided by the sum of the weights and multiplied by two coefficients, M_1 and M_2, which reflect temperature and 'obvious pollution,' respectively:

$$QI = \frac{\sum_{i=1}^{n} w_i I_i}{\sum_{i=1}^{n} w_i} M_1 \times M_2 \qquad (2.11)$$

where W_i is the variable weight (range from 1 to 4), I_i is variable rating (range from 0 to 100). The Horton's index has an advantage that it is relatively easy to apply, although the coefficients M_1 and M_2 require some tailoring to fit individual situations.

Brown et al. (1970) presented a water quality index similar in structure to Horton's index. This effort was supported by the National Sanitation Foundation (NSF), and the resulting index is known as the NSF's Water Quality Index (NSF-WQI). The NSF-WQI was developed using a formal procedure based on the Rand Corporation's Delphi technique. A list of nine parameters (Table 2.3) was chosen as the most significant by Brown et al. (1970). In addition, they stated that if total content of detected pesticides or toxic elements (of all types) exceeds 0.1 mg/L, the WQI will be automatically registered to zero. The NSF-WQI is calculated as follows:

$$\text{NSF - WQI} = \sum_{i=1}^{n} w_i q_i \tag{2.12}$$

where,

q_i = the subindex value for the i^{th} parameter read from the appropriate subindex rating graphs (a number between 0 to 100) and

w_i = weight of the i^{th} parameter.

Table 2.3: Weights for parameters included in NSF-WQI

Parameters	Weights
Dissolved oxygen	0.17
Fecal coliform	0.16
pH	0.11
BOD (5-day)	0.11
Nitrates	0.10
Phosphates	0.10
Temperature	0.10
Turbidity	0.08
Total solids	0.07
Total	1.00

This WQI uses a scale from 0 to 100 to rate the quality of the water. The overall WQI score is compared against a standard scale (given in Table 2.4) to determine how sound the water is at a given time.

Table 2.4: NSF-WQI scale

Index value	Water quality	Suitability for activities involving direct human contact, recreation, bathing, etc.
91-100	Excellent	Suitable
71-90	Good	
51-70	Medium/ average	
26-50	Fair/ bad	Marginally suitable
0-25	Poor/ very bad	Not suitable, abundant quality problems

Use of NSF-WQI in evaluating groundwater quality may be considered questionable due to the fact that many of the parameters considered in this index (e.g. DO, BOD, fecal coliforms, turbidity, and total solids) have greater relevance in surface water quality characterization.

Dinius (1972) proposed a WQI to be used as possible water quality reporting system for the State of Alabama. This WQI includes 11 pollutant variables viz. dissolved oxygen (DO), 5-day BOD, fecal coliforms, total coliforms, specific conductance, chlorides, hardness, alkalinity, pH, temperature and colour. Like Horton's index and the NSF-WQI, it had a decreasing scale, with values expressed as a percentage of 'perfect water quality', which corresponded to 100 %. The weights (w_i) ranged from 0.5 to 5.0 on a basic scale of importance. The index was calculated as the weighted sum of the sub-indices.

$$I = \frac{1}{21}\sum_{i=1}^{11} w_i I_i \qquad (2.13)$$

The index was defined over the range from 0 to 100, although limits were required to be placed on the range of each variable to avoid values over 100.

Backman et al. (1998) developed an approach for assessment and visualization of areas characterized by hazardous concentration of defined elements and ionic species to calculate a contamination index. This index took into account both the number of parameters exceeding the upper permissible limit or guide values of the potentially harmful elements, and the concentrations exceeding these limit values. Calculation of the contamination degree, C_d, was made separately for each sample of water analyzed, as a sum of the contamination factors of individual components exceeding the upper permissible value. Hence, the contamination index summarized the combined effects of several quality parameters considered harmful. The scheme for the calculation of C_d is as follows:

$$C_d = \sum_{i=1}^{n} C_{fi} \qquad (2.14)$$

$$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1 \qquad (2.15)$$

where, C_{fi} = contamination factor for the i^{th} component, C_{Ai} = analytical value of i^{th} component and C_{Ni} = upper permissible concentration of the i^{th} component (N denotes the normative value).

In India, WQI given by Central Pollution Control Board (CPCB) is primarily based on the NSF-WQI (Abbasi, 2002). However, slight modifications were made in terms of assignment of weights so as to conform to the water quality criteria for different categories of water uses set by the CPCB. Four important water quality parameters- dissolved oxygen (DO), biochemical oxygen demand (BOD), pH and fecal coliform were selected. A weighted sum aggregation function was used to evaluate the overall WQI. This index was developed to evaluate the water quality profile of river Ganga in its entire stretch and to identify the reaches where the gap between the desired and the existing water quality is significant enough to warrant urgent pollution control measures (Sarkar and Abbasi, 2006).

The index has the weighted multiplication form:

$$\text{WQI} = \sum_{i=1}^{n} W_i I_i \qquad (2.16)$$

where,

I_i = subindex for i^{th} water quality parameter

W_i = weight associated with i^{th} water quality parameter and

n = number of water quality parameters

A list of four parameters was selected and sub-index values were obtained by using sub index equations as shown in Table 2.5. To assign weightages, significance ratings were given to all the selected parameters. A temporary weight of 1 was assigned to the parameter which received highest significance rating. All other temporary weights were obtained by dividing each individual mean rating with the highest. Each temporary weight was then divided by the sum of all weights to arrive at the final weights. These weights were modified to suit the water quality criteria for different categories of uses. The classification of water vis-à-vis final index values is given in Table 2.6 and the weights are illustrated in Table 2.7.

Table 2.5: Sub-index equations of the CPCB-WQI (Source: Sarkar and Abbasi, 2006)

Parameter	Range applicable	Equation	Correlation
DO	0–40% saturation	IDO = 0.18 + 0.66 (% sat)	0.99
	40–100% saturation	IDO = − 13.5 + 1.17 (% sat)	0.99
	100–140% saturation	IDO = 163.34 − 0.62 (% sat)	–0.99
BOD (mg/L)	0–10	IBOD = 96.67 – 7.00 × (BOD)	–0.99
	10–30	IBOD = 38.9 – 1.23 × (BOD)	–0.95
pH	2–5	IpH = 16.1 + 7.35 × (pH)	0.925
	5–7.3	IpH = − 47.61 + 20.09 × (pH)	0.99
	7.3–10	IpH = 316.96 – 29.85 × (pH)	–0.98
	10–12	IpH = 96.17–8.00 × (pH)	–0.93
Fecal coliform	$1–10^3$	Icoli = 97.2 – 26.80 × log (coli)	–0.99
	$10^3–10^5$	Icoli = 42.33 – 7.75 × log (coli)	–0.98
	$> 10^5$	Icoli = 2	

Table 2.6: Water class as per CPCB-WQI score

Sl. No	WQI	Description	Class
1	63 – 100	Good to excellent	A
2	50 – 63	Medium to good	B
3	38 – 50	Bad	C
4	< 38	Bad to very bad	D, E

Table 2.7: Weights assigned to water quality parameters in CPCB-WQI

Parameters	Weights
DO	0.31
Fecal coliforms	0.28
pH	0.22
BOD	0.19
Total	1.00

Said et al. (2002) defined some useful relationships between common water quality constituents, which were used in evaluating water quality situation using a new water quality index. This index was applied on the big lost watershed in Idaho and on some other data from different watersheds. The index has the formulation as given below

$$WQI = \log\left[\frac{(DO)^{1.65}}{50(TP)^{0.5} + (Turb)^{0.15} + 0.4(F.Coli)^{0.5} + 0.15(SC)^{0.5}}\right] \qquad (2.17)$$

where,

DO = Dissolved oxygen (% oxygen saturation)

Turb = Turbidity (NTU)

TP = Total phosphates (mg/L)

F.Coli = Fecal coliform bacteria (counts/100 ml)

SC = Specific conductivity (μS/cm at 25°C)

This index was developed for the purpose of providing a simple method for expressing the significance of water quality data, and was designed to aid in the assessment of water quality for general uses.

2.7.3 Groundwater Quality Indices

Groundwater quality index is a useful tool for monitoring the groundwater quality and for evaluating its potential to fit specific purpose. Saeedi et al. (2009) developed a simple methodology based on multivariate analysis to create a groundwater quality index, with the aim of identifying places with best quality for drinking water within the Qazvin province of Iran, based on the average values of eight cation and anion parameters (K^+, Na^+, Mg^{2+}, Ca^{2+}, SO_4^-, Cl^-, pH and TDS) for 163 wells during a 3-year period. They calculated the proportion of observed concentrations to the maximum allowable concentration as normalized value of each parameter in observing wells. Final indices for each well have been calculated considering weight of each parameter. In order to assess the groundwater quality of study area, the derived indices are compared with those of well-known mineral waters. Using developed indices, groundwater iso-index map for study area has been drawn which revealed that groundwater quality in many part of Qazvin plateau is near to mineral waters and is suitable to be used for drinking.

Melloul and Collin (1998) developed the index for chloride and nitrate parameters to assess salinity and pollution in groundwater of Israel's Sharon region, viz. Index of Aquifer Water Quality (IAWQ) which is given as:

$$IAWQ = C/n\left[\sum_{i=1}^{n}(W_{ri}.Y_{ri})\right] \quad (2.18)$$

where, C = a constant, used to ensure desired range of numbers (taken as 10); i, n = number of chemical parameters involved (i = 1, ..., n), which is incorporated in the denominator to average the data. W_{ri} is the relative value of W_i/W_{max}, where, W_i is a weight for any given parameter and W_{max} is the maximum possible weight (taken as 5). The weight is a numerical value given to a parameter to characterize its relative anticipated pollutant impact; lower numerical values defining lower pollution potential and vice-versa. Higher value of W_i indicates toxic groundwater quality. Y_{ri} = the value of Y_i/Y_{max}; where, Y_i is the rating value for the i^{th} chemical parameter and Y_{max} is the maximum possible rating for any parameter (taken as 10).

Hussain (2004) modified the framework given by Melloul and Collin (1998) and computed Modified Index of Aquifer Water Quality (MIAWQ) by using the parameters like TDS, Ca^{2+}, total alkalinity, NO_3^-, Cd, Mn, Pb and Fe estimated in Ganga- Yamuna interfluve area. He assigned the weights to the eight parameters as per their analytical hierarchy in the human health (effecting) significance and not in a subjective manner as attempted in the original work by Melloul and Collin (1998).

2.8 LAND USE-LAND COVER ESTIMATION BY USING REMOTE SENSING AND GIS

Land use and land cover (LULC) are significant dynamic parameters of a watershed as these are easily and directly influenced by human activities. Groundwater systems are also dynamic and adjust continually to short term and long term changes in climate, groundwater withdrawal, and land use (Taylor and Alley, 2001). It is necessary to study changes in LULC in a watershed for its effective management. Remote sensing and GIS techniques are being increasingly applied by researchers in India in various studies related to water resources development on watershed basis (Srivastava, 1997; Chopra et al., 2005; Suresh et al., 2004). Satellite remote sensing data have proved useful in assessing the natural resources and in monitoring the changes. Results that are obtained from integrating remote sensing and GIS can be effectively used to plan and monitor land based activities in a watershed. In this context, remote sensing and GIS based studies on LULC changes have been discussed in the following paragraphs.

Tiwari et al. (1997) extracted watershed parameters to develop an empirical model for seasonal runoff estimation using remote sensing and GIS techniques. Bauer et al. (1979) used Landsat Multi-spectral scanner (MSS) data covering an area of three counties in northern Illinois, USA to study the crop areas. Shrivastava et al. (1992) applied visual interpretation technique for preparation of land use map and geological map of Khargone district of Madhya Pradesh, India. The Landsat Thematic Mapper (TM) and Indian remote sensing satellite (IRS) 1A LISS-II imageries of false colour composite are used for extraction of land use and geological data. Superimposition of drainage map, geological map, LULC map and geomorphological map is done for assessment of recharge area, groundwater potential zone and location sites for reservoirs at various tributaries of river network.

Panigrahi et al. (1995) used visual interpretation technique for preparation of land use map of Athagarh block of the Cuttack district of Orissa, India from false colour composite of IRS 1B LISS-II with bands 2, 3 and 4. Classified land use map along with thematic layers of geomorphology and lineaments, drainage were used to prepare a groundwater potential zone map of the study area. Ratanasermpong et al. (1995) performed the natural resources assessment of Phuket Island (Thailand) using the integration of visual and digital analysis of Landsat-TM data. Using the method of overlays, changes in natural resources during 1987, 1990, 1992 and 1995 were assessed. Somporn (1995) detected land use changes due to rapid growth of Chiang Mai city in Northern Thailand. Landsat-5 TM imageries of years 1988 and 1991 were employed in this study.

Mendis and Wadigamangawa (1996) observed land use changes using existing land use survey data of year 1983, satellite TM data of year 1992 and aerial photograph of year 1994 for Nilwala River Watershed in the Southern Province of Sri Lanka. Lwin et al. (1998) monitored forest degradation of lower part of Myanmar. Forest degradation have been extracted from Landsat TM data sets of year 1989 and 1995 and annual forest change by using AVHRR time series images (1989 to 1995). The satellite imageries of different sensors and spatial resolution were classified using clustering and supervised classification. Dahal et al. (2002) assessed the land cover change in tropical rain forest of Labanan province of Berau regency, East Kalimantan, Indonesia using Landsat TM images. Two images, Landsat-7 ETM+ acquired on 26th August 2000 and Landsat-5 TM acquired on 12th April 1996 were used in this research. The color composites of band 4, 5 and 3 in RGB channels showed a comparative view of the land cover classes between the two images. Weicheng et al. (2002) detected land use changes in an arid and semi-arid region of North Ningxia, in Northwest China by utilizing the multi-temporal remotely sensed data (Landsat TM dated 1987, 1989 and ETM 1999). Indicator differencing technique utilizes seven bands information to transform into three indicators such as brightness, greenness and wetness.

Dontree (2003) detected land use changes using remote sensing data and aerial photographs of year 1972, 1989 and 2000. Remotely sensed data consisted of Landsat MSS of year 1972, Landsat TM of year 1989 and Landsat ETM+ of year 2000. The visual interpretation technique was used for aerial photographs while maximum likelihood classification technique was used for satellite image processing to obtain the land use maps of three different periods. Hietel et al. (2004) described the major spatial-temporal processes of land cover changes and identified the correlations between environmental attributes and land cover changes in a German marginal rural landscape. The role of potential environmental drivers to cause land cover changes was also identified. Land cover dynamics from 1945 to 1998 was correlated with the physical attributes (elevation, slope, aspect, available water capacity and soil texture) of the underlying landscape. Doorn and Correia (2007) derived land cover maps for a study area in southeast Portugal from aerial photographs and satellite image. These are usually categorical maps, in which the land cover was classified into discrete, non overlapping land cover classes. Fan et al. (2007) studied drastic LULC changes in Guangzhou municipality areas of China covering five counties over the past 30 years due to economic development, population growth, and urbanization. Liu et al. (2007) analyzed the eco-environmental changes of the Longdong region of the Chinese Loess Plateau during the period 1986-2004 and identified the controlling factors.

GIS has emerged as an effective tool for relating and integrating vast volumes of different data types (Dhiman and Keshari, 2006). It has been designed to restore, manipulate, retrieve and display spatial and non-spatial data, is an important tool in analysis of parameters such as LULC, soils, topographical and hydrological conditions. Remote sensing along with GIS application aid to collect, analyze and interpret the multidisciplinary data rapidly on large scale and is very much helpful for watershed planning. For ungauged watersheds accurate prediction of the quantity of runoff from land surface into rivers and streams requires much effort and time. Conventional methods of runoff measurements are not easy for inaccessible terrain and not economical for a large number of small watersheds. Remote sensing technology can augment the conventional method to a great extent in rainfall-runoff studies. Researchers (Slack and Welch, 1980; Tiwari et al., 1991; Pandey and Sahu, 2002) have utilized the satellite data to estimate the SCS runoff CN.

Recent studies (Sharda et al., 1993; Schumann et al., 2000; Saxena et al., 2000) illustrated that remote sensing and GIS techniques are of great use in characterization and prioritization of watershed areas. LULC is the category in which remote sensing has made its largest impact and comes closest to maximizing the capability of this technology (Garbrecht, et al. 2001; Pande et al., 2002). One of the options for use of remote sensing and GIS is to improve the estimation of watershed parameters such as CN for a watershed with widely used SCS model from its land use data and digitized soil map (Still and Shih, 1985; Kumar, 1991; Pande et al., 2002). However LULC accuracy is directly related to the spatial resolution of the sensors.

2.9 RESEARCH NEEDS/ GAPS

The review of above literature on groundwater quantity and quality assessment indicates that in any study it is crucial to evaluate the sustainability of water resources; both surface water as well as groundwater, in terms of its quantity and quality keeping in mind the basic tenets of sustainability as outlined in the above review. Such a study, therefore, would also include considerations of re-use of wastewater generated by the increasing population and industrial activities in an area. The use of sustainability indicators for assessing the sustainability of surface water and groundwater resources has proved crucial in decision making process. Therefore the need of the hour is to develop and apply sustainability indicators on watershed basis especially in a country like India where watershed has prevalently been taken as unit of all developmental activities and wherein degradation of available natural resources and environment due to over-population and poor socio-economic conditions has already taken its toll on natural resources in many areas (especially urban areas) of the country.

Many studies have addressed the urgent need for sustainable water resources development but very few have talked about how to assess the sustainability, especially in India. In this context, in order to assess the sustainability of water resources development, it is very necessary to identify various sustainable development indicators developed worldwide, modify them to suit the Indian conditions and apply them at various stages of water resources development and management programmes starting from small scale, basin wide to country wide scale. These observations form the background for this research work.

The review on groundwater recharge estimation shows the significant progress made in establishing methods that can be applied with greater confidence by practitioners and water planners to obtain reliable groundwater recharge estimates. In this respect, GEC-1997 methodology widely practiced in India has proved to be the most valuable and has made significant impact on groundwater resources assessment and development in the country. The use of this methodology at watershed scale needs to be taken up at national level to further rationalize its application.

In order to arrest water table declines beneath the groundwater irrigated areas the present day need is to ensure that the evapotranspiration is reduced by reducing the total irrigated area. Most urban waste-water, after primary/ secondary treatment, can be re-used directly for irrigating certain agricultural crops. In this context, it is essential to develop the high-tech irrigated agricultural systems incorporating the re-use of waste-water and reduction of irrigated area.

The quality of water resources have been given due consideration in its sustainable development as quantity of water without quality aspects is of no significance in terms of usage. Regular monitoring of water quality needs to be taken up by using water quality indices. GIS is an undeniably valuable tool for gathering and analyzing environmental information and helps in observing, measuring, mapping and monitoring of the earth's natural resources, therefore use of such techniques should be made mandatory in studies of sustainable development of natural resources.

Chapter 3

THE STUDY AREA

3.1 GENERAL

3.1.1 Location

The area under study, the Suswa Watershed, is a part of Doon Valley in the Dehradun District, Uttarakhand State, India (Fig. 3.1). It is bounded approximately between 30° 08' to 30° 27' North latitudes and 77° 57' to 78° 10' East longitudes and is included in the Survey of India topographical sheets Nos. 53J/3, 53J/4, 53F/15 and 53F/16 on the scale 1:50,000 (Fig. 3.2). The Watershed falls in the catchment of Song river system which is a tributary of the Ganga river. It includes the city of Dehradun towards north-west and hill ranges of Mussoorie towards north. The Siwalik hill range is situated on the southern boundary of the study area, whereas Nagsiddh Hill, a part of Lesser Himalaya, falls on the eastern boundary. The extent of the study area is about 292 km^2. It lies within the two developmental blocks of Dehradun District viz. Raipur block and Doiwala block.

3.1.2 Climate

The study area has sub-tropical monsoon type of climate which is characterized by hot summers and cold winters. Average annual temperature is around 20 °C with May and June being the hottest months. The climate of Dehradun is more temperate and humid than that of the adjoining districts, the maximum and minimum day and night temperature being 3 °C to 6 °C lower throughout the year. The daily air temperature at Dehradun varies between 4 °C in winter and 35 °C in summer. The relative humidity is higher during the south-west monsoon season, generally exceeding 70 % on the average. The mornings are comparatively more humid than the afternoons. The potential evapotranspiration observed at Dehradun varies from 35.3 mm in the month of December to 168.9 in the month of May. Wind in the summer blows from north to northeastern direction which is sometimes experienced during the winter too. The wind speed varies around a mean of 3.2 km/ hour in Dehradun city.

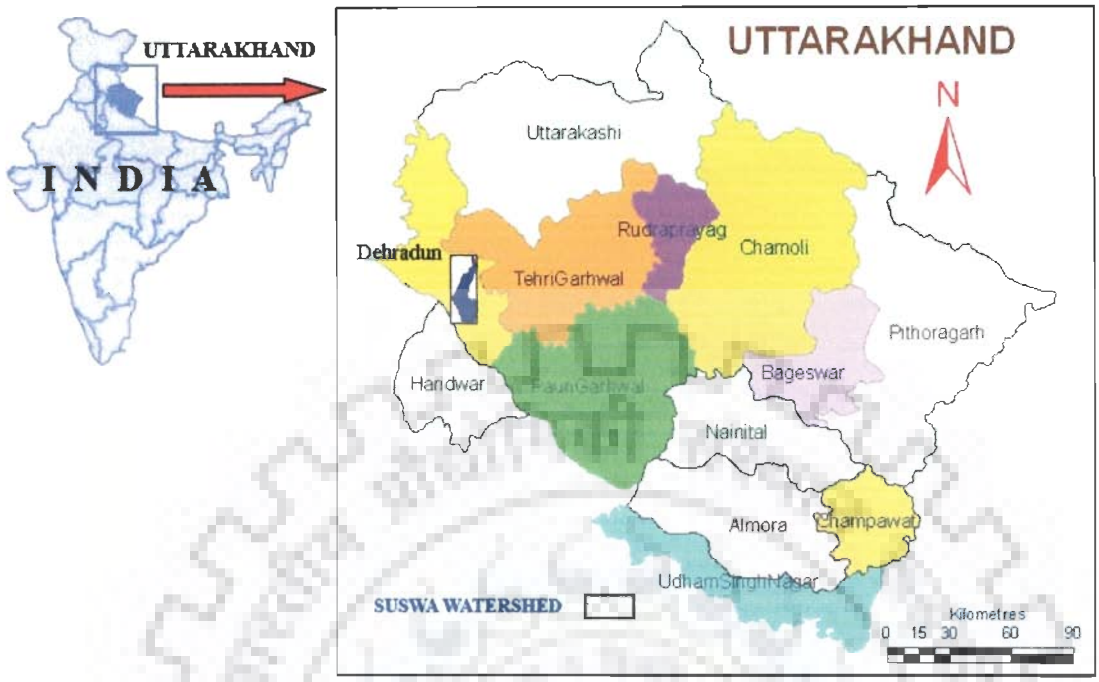


Fig. 3.1: Location map of study area

Climate varies greatly from tropical to severe cold depending upon the variations in the altitude. The district being hilly, temperature variations due to difference in elevation are considerable. In the hilly regions, the summer is pleasant, but in the Doon Valley, the heat is often intense, although not to such degree as in the plains of the adjoining districts. Climate data of Doon Valley for all the twelve months is given in Table 3.1 on the basis of mean of preceding 25 years.

3.1.3 Rainfall

The area receives an average annual rainfall of 2073 mm but it varies from 1600 mm to 2200 mm depending on elevation and most of the rainfall (about 85 % of annual) is received in the monsoon months of June to September, July and August being rainiest (Table 3.1). The monsoon generally arrives by the end of June and continues until about the middle of September. Occasional showers may continue in the end of September and October after which, there is usually little rain until about the end of December. Some rain usually falls in January and February. Few months pass without any rain at all; however, extreme drought years are rare in the area.

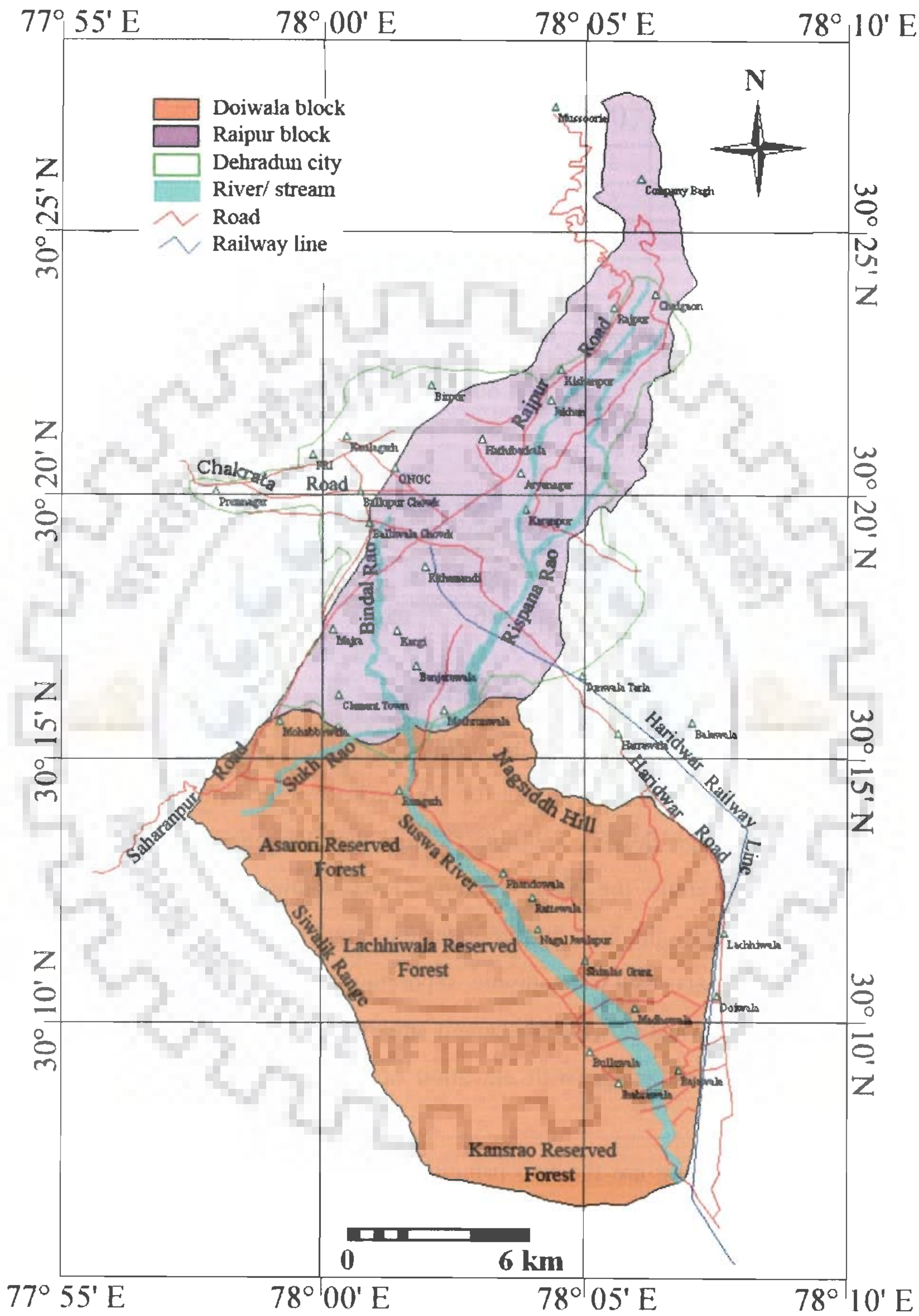


Fig. 3.2: Index map of the Suswa Watershed

Table 3.1: Climate data of Doon Valley

Month	Rainfall (mm)	Relative humidity (%)	Temperature (°C)		
			Maximum	Minimum	Average
January	46.9	91	19.3	3.6	10.9
February	54.9	83	22.4	5.6	13.3
March	52.4	69	26.2	9.1	17.5
April	21.2	53	32	13.3	22.7
May	54.2	49	35.3	16.8	25.4
June	230.2	65	34.4	29.4	27.1
July	630.7	86	30.5	22.6	25.1
August	627.4	89	29.7	22.3	25.3
September	261.4	83	29.8	19.7	24.2
October	32.0	74	28.5	13.3	20.5
November	10.9	82	24.8	7.6	15.7
December	2.8	89	21.9	4.0	12.0
Average annual	2051.4	76	27.8	13.3	20.0

3.2 GEOMORPHOLOGY AND DRAINAGE

The Doon Valley, lying along the northwest-southeast regional Himalayan strike, extends for 80 km in length and spreads for 20 km in average width. Along its eastern extremity the river Ganga flowing southwest enters the Gangetic plain at Haridwar and along its western extremity the river Yamuna flows southwest. The Doon Valley is bounded towards south by the high and younger topographic relief of the Siwalik ranges. This topographic relief acts as a water-divide, separating the north-east flowing consequent streams from the south-west flowing obsequent streams. To the north the Doon Valley is bounded by the Mussoorie range with elevation ranging from 1800-2800 m and rising abruptly from the valley.

The Asan and Song are the two principal rivers in the Doon Valley, the former joining the river Yamuna and the latter joining the river Ganga (Fig. 3.3). A water divide, running northeast-southwest from Clement Town to Rajpur, separates the northwest flowing river Asan from the southeast flowing river Song.

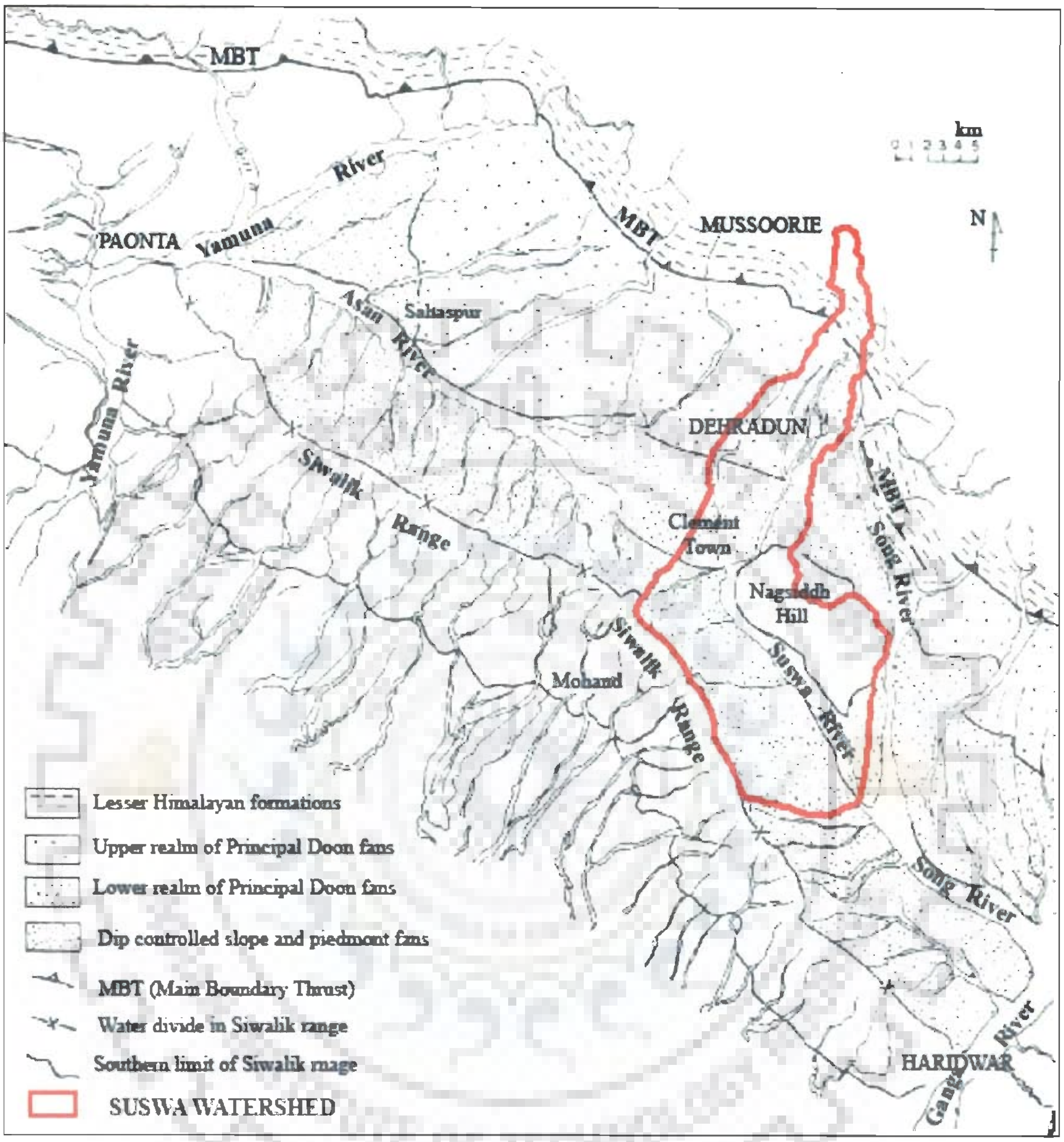


Fig. 3.3: Geomorphological map of Doon Valley (modified after Thakur, 1995)

The river Rispana flowing south-southwest takes right angle turn and joins the southwest flowing river Suswa which in its continued journey meets the river Song. The river Song emerges from the Mussoorie range flowing southward and is joined by southwest flowing tributaries. Subsequently, it changes its course to southeast and finally joins the river Ganga. Both the Asan and Song river systems and their consequent tributaries are tectonically controlled (Thakur, 1995). The river Suswa rises to the west of Saharanpur-

Mussoorie highway and flows in the south-eastern direction to discharge into the Song river (Fig. 3.4). The Raos (Rao is a local synonym for a 'stream') emerging from the Siwalik ranges in the southern part of study area carry immense volume of water and sediments during monsoon which continuously undermines the adjoining banks and as a result they have very wide and shallow beds. Most of the Raos are dry during the greater part of the year, but turn torrential during the monsoon carrying large volume of boulders and loose material along their beds.

The ground altitude in the Suswa Watershed varies from 420 to 2000 m above mean sea level (AMSL), as seen from the Table 3.2, which is based on the data derived from digital elevation model (DEM) of the Suswa Watershed (Fig. 3.5). It is also seen that 94 % of the study area has altitude of lesser than 900 m AMSL. The summary of the slope (Fig. 3.6) attributes for the Suswa Watershed is given in Table 3.3, which indicates that 27 % of the entire area has steep gradient (slope more than 10 %) whereas 62 % of the study area is gentle to level.

Stream frequency and drainage density in Doon Valley is low because of the poor development of drainage, possibly due to porous and permeable characteristics of the bed rocks (Jain et al., 2007). The Suswa river, with a stream order of five, is the main stream in the study area (Fig. 3.4). The drainage of the eastern half of the Doon Valley pertains to two major rivers viz. Suswa and Song. The Suswa river mainly receives discharge of two streams viz. Rispana Rao and Bindal Rao. These streams carry runoff resulting from monsoon rains, yet, for major remaining period of the year, their beds are usually dry.

In its lower reaches, the Suswa river also remains dry during the months of November and December after withdrawal of monsoon in September and recession of possible base-flow that feeds the river flow during October. However, Bindal Rao carries the sewage discharge of the entire Dehradun city area and discharges the load into the Suswa river near the Clement Town area. Although, this helps in maintaining the river flow throughout the year, the Suswa river was observed to be dry (which is visible in the photograph shown in Annexure 3.1) during the month of November (on 22.11.2006) at a location about 5.3 km upstream side of the outlet point of the Suswa Watershed. The exact location from where the river flow vanished is not clear, but it is apparent from the diminishing flow in the river at Ramgarh, a place about 16 km upstream of the outlet point

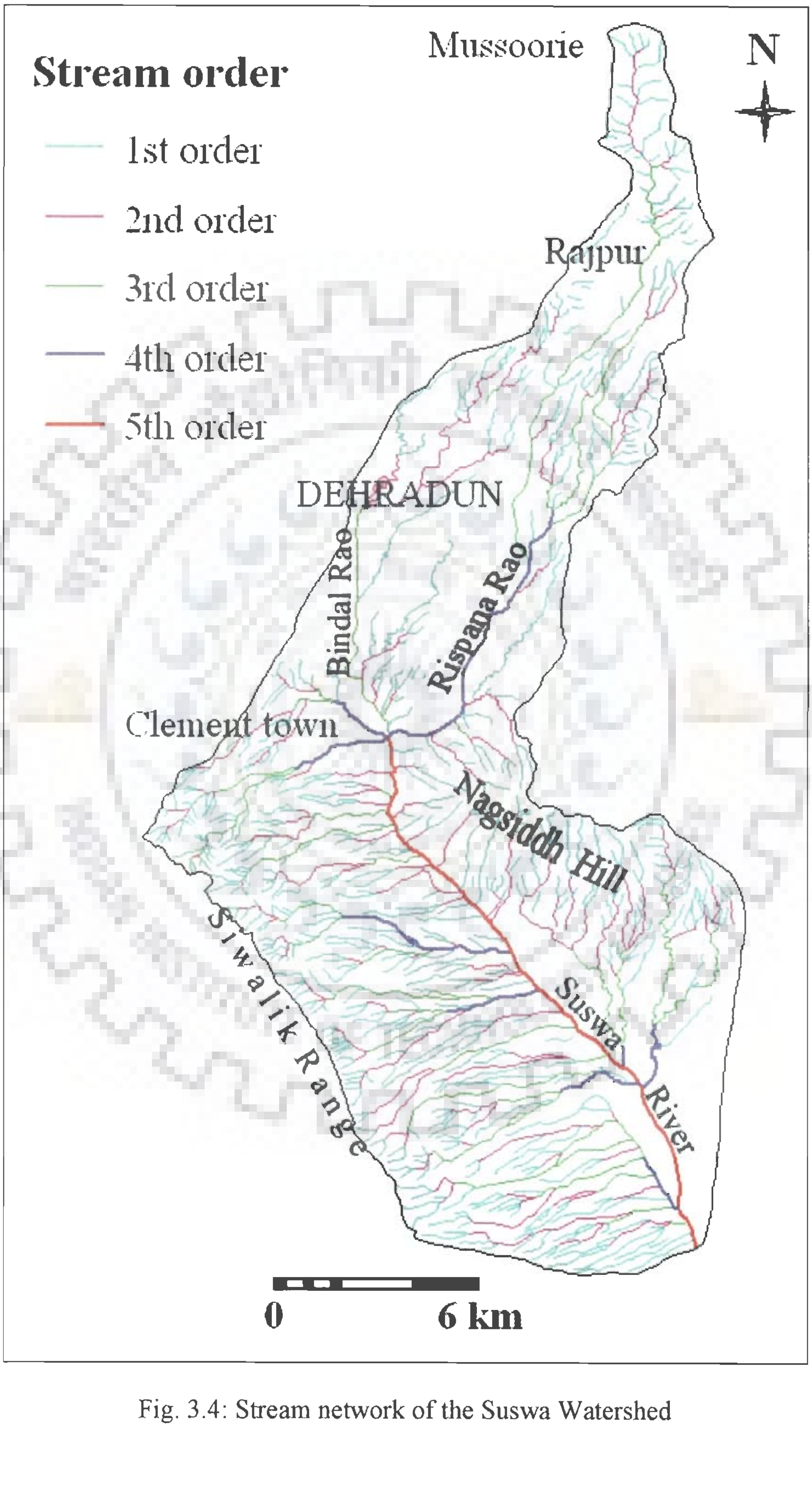


Fig. 3.4: Stream network of the Suswa Watershed

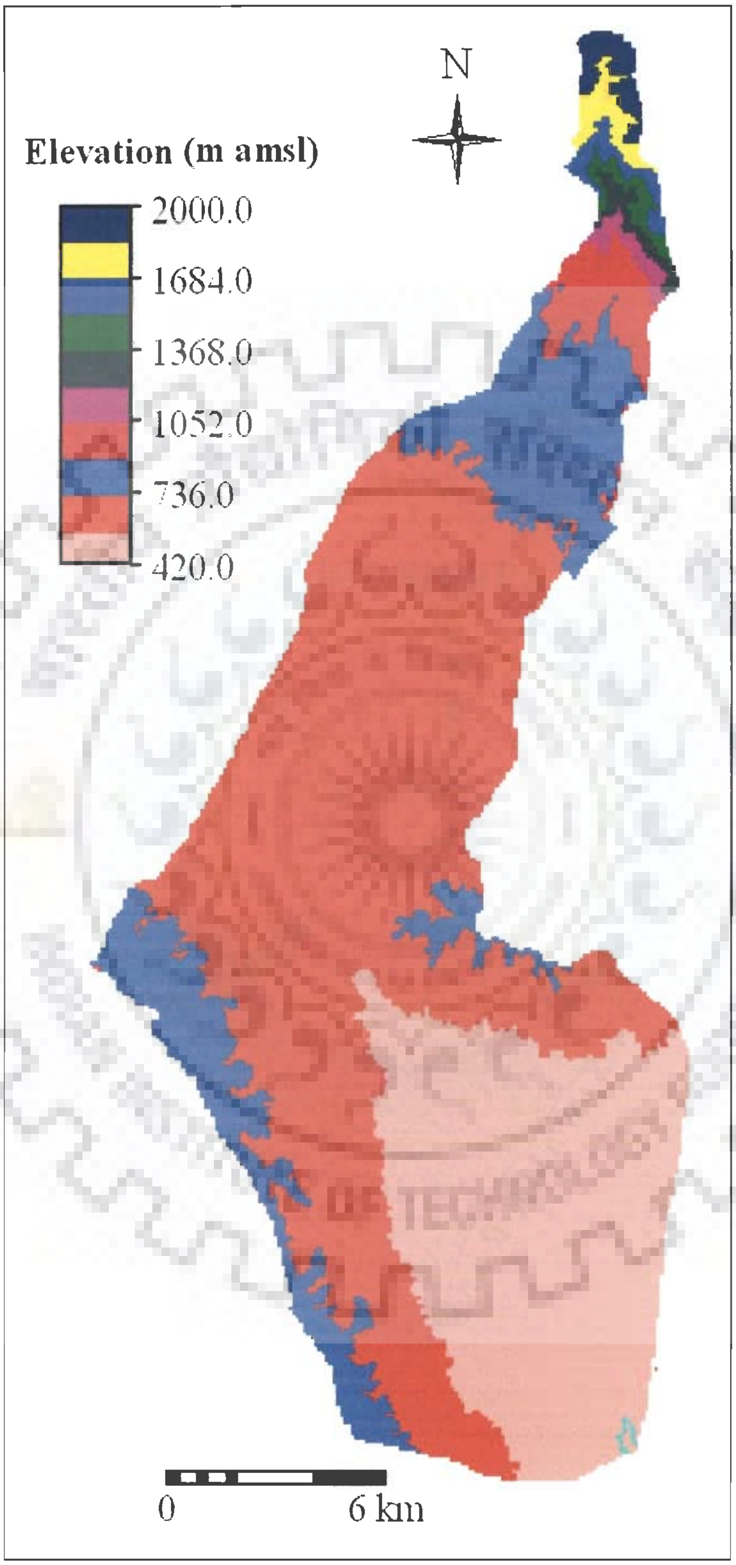


Fig. 3.5: Digital elevation model (DEM) of the Suswa Watershed

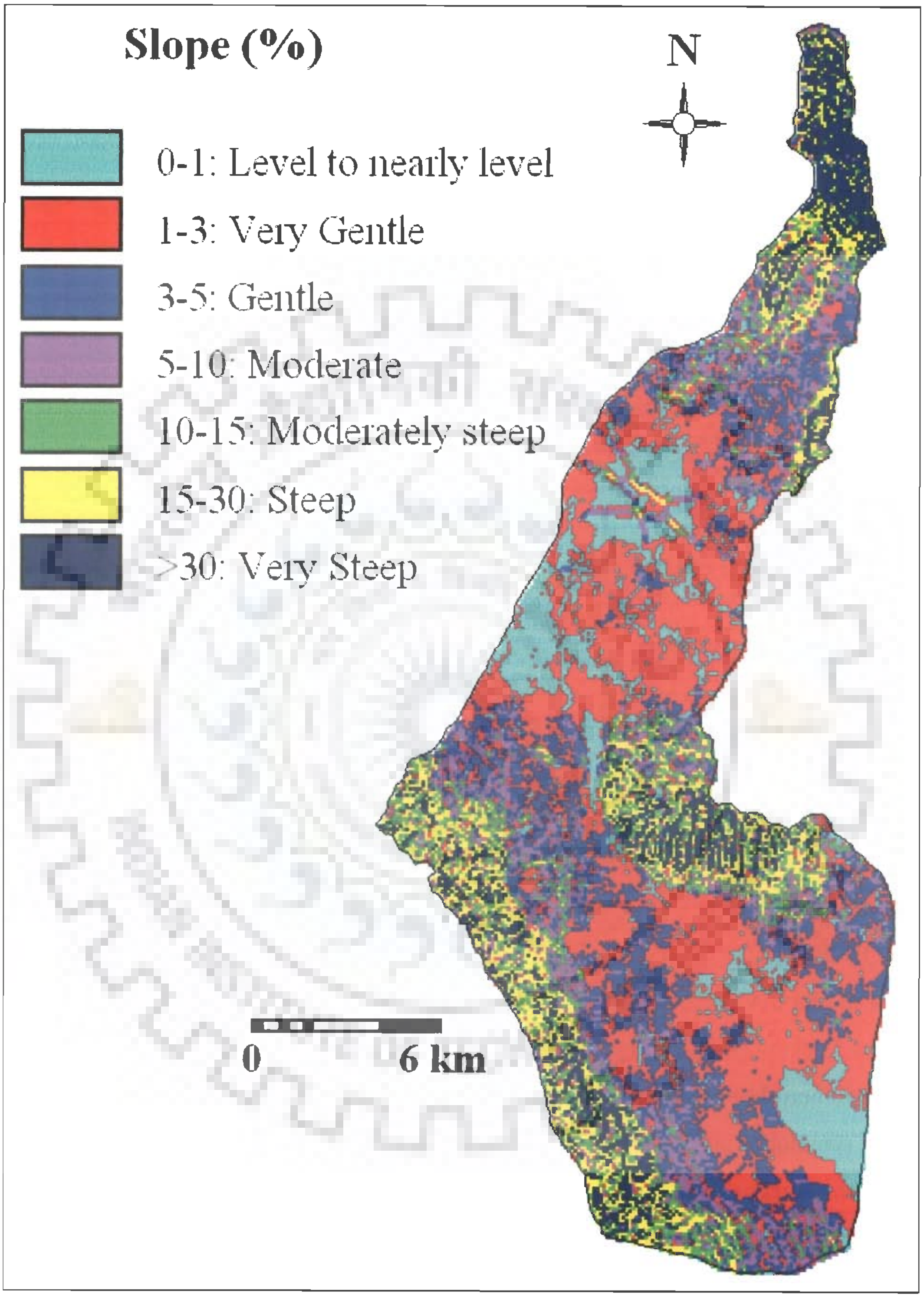


Fig. 3.6: Slope map of the Suswa Watershed

of the Suswa Watershed, that it can flow only for some distance downstream of Ramgarh. From the drainage network, it has been observed that the drainage pattern is mostly dendritic tending towards parallel in the study area.

Table 3.2: Altitude zones in the Suswa Watershed

Altitude zones (m)	Area (km^2)	Area (%)
420 – 600	117.59	40.3
600 – 900	157.72	54.1
900 – 1200	6.70	2.3
1200 – 1500	2.97	1.0
1500 – 1800	3.61	1.2
1800 – 2000	3.00	1.1
Total	291.59	100

Table 3.3: Land slope characteristics of the Suswa Watershed

Slope zones	Slope range (%)	Area (km^2)	Area (%)
Level to nearly level	0 – 1	33.00	11.3
Very Gentle	1 – 3	101.26	34.7
Gentle	3 – 5	46.63	16.0
Moderate	5 – 10	32.28	11.1
Moderately steep	10 – 15	22.52	7.7
Steep	15 – 30	30.92	10.6
Very Steep	> 30	24.98	8.6
	Total	291.59	100

3.3 GEOLOGY

The Doon Valley was formed as an intermontane valley within the Siwalik group rocks in a foreland propagating thrust system (Fig. 3.7). The Upper Siwaliks are exposed towards southern boundary of the Suswa Watershed and the Doon gravels occupy almost the entire remaining portion of the study area (Fig. 3.3). The stratigraphy of Doon Valley and adjoining region is summarized in Table 3.4. To the north, the rocks of the foreland basin are separated from the older formations of the Lesser Himalaya along the Main Boundary Thrust (MBT) (Karunakaran & Rao, 1979). The Lesser Himalaya is characterized by higher elevation (2000-4000 m) than the Siwaliks, and there is an abrupt change in relief north of Main Boundary Thrust. To the south, the sudden rise of Siwaliks from the Indian alluvial plains is demarcated by Himalayan Frontal Thrust (HFT) system,

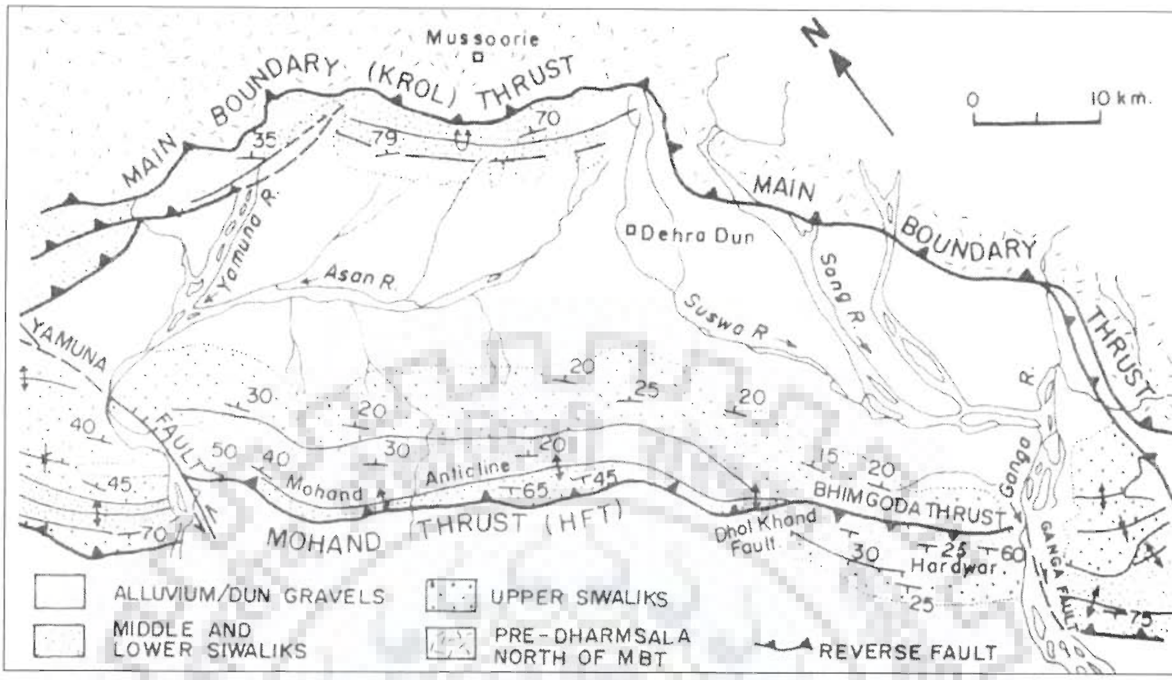


Fig. 3.7: Regional geological map of Doon Valley (after Thakur, 1995)

Table: 3.4: Stratigraphy of Doon Valley and Siwaliks

Formation	Lithology	Thickness (m)	Age
Doon gravel	Thickly bedded massive conglomerate embedded in sandy silty matrix	600	0.5 Ma and younger
Upper Siwalik	Thickly bedded massive conglomerate embedded in sandy matrix and interbedded sandstone	2000	0.5 Ma to 5 Ma
Middle Siwalik	Multistoried sandstone with pebbles and mudstone-siltstone. Grey sandstone with planar stratification	1800	10 Ma to 6.7 Ma
Lower Siwalik	Sandstone and interbedded mudstones	2000	14 Ma to 18 Ma

locally called Mohand Thrust (Fig 3.7). This fault system is considered to be the principal present day tectonic displacement zone (Thakur, 1995). An isolated hill named Nagsiddh is present in the eastern part of study area. It is composed of big broken boulders and pebbles with pockets of clay. These are known as old Doon gravel. Rest of the study area is occupied by loose stratified beds of pebbles, sand, clay, and gravel forming sub-recent fans and terraces. Geologically, the Doon Valley is divided into the Lesser Himalaya, a synclinal structural depression and the Siwalik range.

The Lesser Himalaya (Mussoorie mountain range in northwest and northeastern parts): It comprises rocks of the Jaunsar (Chandpur phyllites and Nagthat quartzites) and Mussoorie Group (Shales, sandstone, greywacks, calcareous slates, dolomite and limestone of Blaini-Krol-Tal sequence) of Proterozoic-Cambrian age. These formations are present at the northern boundary of the Suswa Watershed and are separated by Main Boundary fault/ Thrust (MBT) passing in the northern part.

Synclinal structural depression is filled with coarse clastic fan deposits of late Pleistocene and Holocene age known as Doon Gravels: The Doon Gravels have been further subdivided into Oldest, Younger and Youngest Doon Gravels (Nossin, 1971; Meijerink, 1974). The Oldest Doon Gravels rest over the Upper and Middle Siwalik rocks and at places directly over Chandpur phyllites and consist of poorly sorted pebbles and gravels set in sandy matrix and red clays. These consist partly of crushed Upper Siwaliks cobbles, angular pebbles of quartzites, slates and shales from the Nagthat, Chandpur and Tal formation and limestone pebbles from the Krol limestone alternating with clay beds. The Younger Doon Gravels, resting uncomfortably over the Oldest Doon Gravels in northern part are characterized by very large boulders present in debris flow and braided river deposits. The unit consists of poorly sorted mixture of clay, sands, gravels and large boulders. The major part of the Suswa Watershed is occupied by Younger Doon Gravels occurring in the form of large fans, formed by reworking of Oldest Doon Gravels, and are called Principal Doon fans. The Youngest Doon Gravels are the present day braided river deposits and sub-recent terrace deposits along the rivers, especially in the lower reaches of the Suswa river stretch of the present study area.

The Siwalik range: The hills in the southern part of the study area are comprised of Middle Siwalik and Upper Siwalik. The rocks of the Middle Siwalik consist of friable medium grained grey coloured sandstone rich in the micaceous minerals with mudstone. The rocks of the Upper Siwalik are characterized by alternate conglomerate and subordinate grey micaceous sandstone. They are exposed towards southern boundary of the Suswa Watershed while Middle Siwaliks are exposed just outside of the watershed divide. The conglomerates consist of well rounded to subrounded pebbles of quartzite, granite, phyllite and limestone.

Geological fence diagram of the study area:

The subsurface geological framework of Dehradun city is prepared as a fence diagram (Fig. 3.8) using the available lithological logs of 13 tubewells. These tubewells were drilled during different periods and have been selected out of the larger number of available lithologs of about 75 tubewells drilled in the recent past by Uttarakhand State Jal Sansthan, Dehradun for supplying water for drinking purpose. All these tubewells show presence of admixture of boulder and clay in the upper portion and down to the depth of about 40-60 m below ground level lying below the top soil of few metre thickness. The boulder clay layer seems to become more clay having greater amount of finer size sediment fraction especially at Patel Nagar, Indra Colony, Arya Nagar, Nalapani and Kaulagarh area (CGWB, 1995). However, towards north in Johrigaon tubewell, boulder and clay is persistent between the top soil layers. This boulder clay layer is present in the Prem Nagar tubewell upto a depth of about 60 m below which a thick layer of about 40 m thickness is present with increasing content of sand and boulder towards East in the Indra Colony and Patel Nagar tubewells. The presence of clay layer continues in the Indra Colony, Patel Nagar, Mothronwala, Badripur, and Nalapani tubewells towards east and northeast upto about 115 m in Patel Nagar/ Mothronwala and 205 m in the Nalapani tubewell. The granular material in the tubewells is observed in the depth interval between 65 m and 120 m at Patel Nagar, 77-154 m at Badripur, 61-111 m at Mothronwala, 61-109 m at Pathribagh, 13-147 m at Kaulagarh and 117-135 m at Prem Nagar (CGWB, 1995). However, it may be mentioned that the granular zones are characterized by presence of intervening clay zones which act as aquiclude and aquitard.

3.4 CROPPING PATTERN

Land use-land cover in the Suswa Watershed is characterized by forest and agriculture besides the urban area of Dehradun city. It will be discussed in detail in Chapter 4. Main crops grown in the area are paddy, wheat, maize and sugarcane. Paddy is one of the most important kharif (April to September) crop in the study area. Other important kharif season crops are maize, black gram, pigeon pea and sugar cane. Wheat is the principal rabi season (October to March) crop besides barley and mustard.

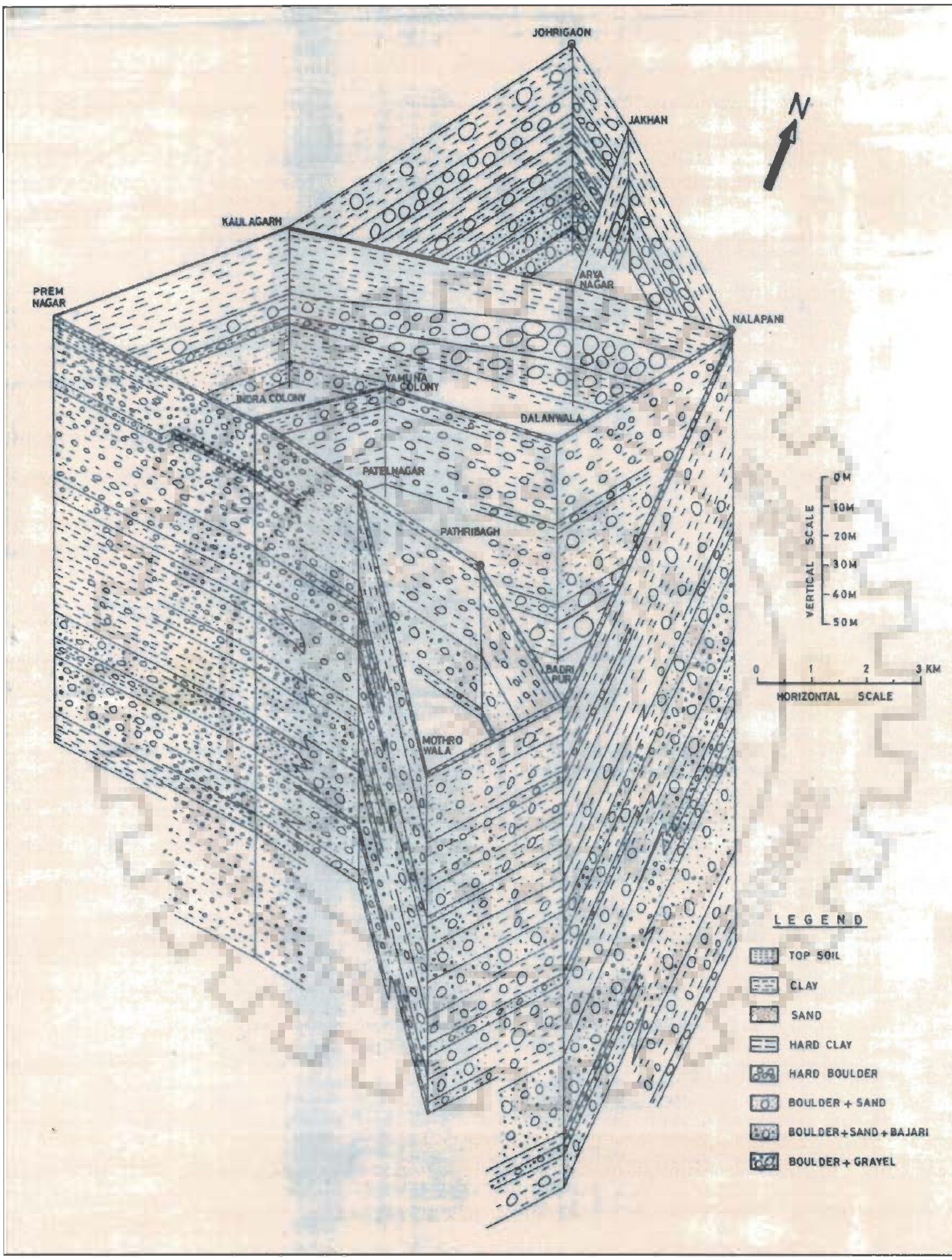


Fig. 3.8: Geological fence diagram of Dehradun city (modified after Sahu, 2009)

The important fruits grown in the area are mango, guava, peach, grape, strawberry, pear, lemon and litchi. Among vegetables, potato is the most important crop. Potato cultivation in the Mussoorie hills is an old and established industry. The plain area is readily cultivable due to intense irrigation mainly through tubewells and to lesser extent through canal irrigation system. Main source of water to meet the irrigation requirements in the study area is groundwater, although in northern parts of the study area, minor and medium canal irrigation schemes are also operational for shorter periods in the summer months. In the southern part of the study area tubewells tapping groundwater are the only source of irrigation.

3.5 SOILS

Soil types of the Doon Valley have been classified as Sandy loam, Sandy clay, Coarse sand, Silty clay loam, Silty loam, and Clay. The higher reaches of the area are found to have mostly coarse sand cover. The areas adjacent to rivers also mostly consist of sand. The remaining area is dominated by sandy loam. Soils on the gentle slopes of the Suswa Watershed are fine loamy. In general, soils are clay loam to silty loam in texture and acidic to neutral in reaction. The organic carbon percent ranges from 1.5 to 1.8 whereas the Ca:Mg ratio in upper horizon is higher in the Suswa Watershed.

3.6 DEMOGRAPHIC CHARACTERISTICS

It is difficult to give the precise population figures of the Suswa Watershed. Yet, the population of the two developmental blocks of Doon Valley viz. Raipur block and Doiwala block, where the Suswa Watershed falls, is 1,02,843 and 1,73,891 respectively as per 1991 census and 1,44,714 and 1,02,749 respectively as per 2001 census. According to 1991 census, the total population of the Dehradun district was 10,25,680 (population density of 332 persons/ km^2) whereas as per 2001 census the same has touched 12,82,143 (population density of 415 persons/ km^2), an increase of 2,56,463 in 10 years (growth rate of about 25 %). As per 1991 census, total population of Dehradun city is 2,70,000 and that as per the census report of 2001 is 4,47,808, thus giving a quite high overall decadal growth rate of 65.85 %.

3.7 SOCIO-ECONOMIC CONDITIONS

In the study area, rapid industrial and agricultural growth has taken place during last decade. After formation of the Uttarakhand State in 2000, Dehradun, its capital city, has undergone large urbanization in the adjoining areas. Tourist industry possesses tremendous possibilities of development in the area. Many institutions of national importance like the Forest Research Institute; Oil and Natural Gas Commission; Indian Military Academy; Indian Institute of Petroleum and Survey of India, etc. are located in Dehradun which makes it a place of national importance attracting tourists in large numbers.

3.8 WATER RESOURCES

3.8.1 Surface Water and Groundwater

The detailed discharge data of the different streams present in the study area is not available but scanty past data of discharge for the Suswa river, Bindal Rao and Rispana Rao is available for November 1970 and January 1971 as given in Table 3.5:

Table 3.5: Discharge of rivers at selected points in the Suswa Watershed (after CGWB, 1995)

Sl. No	Name of the river	Location of measurement	Average width of flow (m)	Depth range (m)	Gradient	Discharge (m^3/s)
1	Suswa River	1.6 km west-northwest of 2303 on Nagsiddh Hill	29.0	0.10-0.43	Gentle	3.63
2	Bindal Rao	Near Maldevata	13.0	0.15-0.25	Moderate	1.06
3	Rispana Rao	East of Rajpur	3.70	0.10-0.25	Moderate	1.00

Dehradun city and the surrounding area are endowed with very good coarse aquifer materials, geologically known as Doon gravels. The Doon gravel beds occur at different depths below the surface. These are separated by clay lenses and beds. These gravel-sand boulder aquifers are annually recharged by rain, but some of the underground water seeps out at the two ends of the valley along the Suwsa river in the east and the Asan river in the west. Groundwater in the lower parts of the valley also seep out as base flow along the rivers Asan, Suswa, Song and Jakhan which flow in the lower parts of the valley. Flows in the major tributaries in the lowest part of the valley are perennial while minor tributaries in the upper and lower parts of valley remain dry in all seasons except monsoon. There are many perched water bodies emerging out from both the hill ranges (Himalayan and Siwalik) in the form of springs and small water channels.

A number of tubewells have been constructed in the rapidly growing Dehradun city area. Tubewells tap aquifers up to a maximum depth of about 120 m to 140 m bgl and the dug wells between 15 m to 20 m bgl. The water table in the valley is affected by the semi-confined groundwater conditions. Water table depth ranges from about 20 m to 90 m. In the lowest valley areas the water table varies from 7 m to 15 m bgl. Doon gravels hold a very high prospect for groundwater recharge, storage and harvesting. Areas lying in the lower portion along the lengths of the valley are capable of yielding 300-480 m^3/hour. Away from this area, on both the northern and southern slopes, yield potential decreases, yet the areas are capable of supporting wells having discharge ranging from 4-9 m^3/hour.

Although groundwater is the main source of water supply for Dehradun city, there are various other sources of surface water from which about 8.96 million-m^3 of water is made available annually (Table 3.6). This water availability is provided through two water treatment plants working in the Dehradun city. The water treatment plant at Dilaram Bazar produces about 5.84 million-m^3 of water per year while the other at Shahnshahi Ashram produces about 3.12 million-m^3 per year of water after treatment. These plants receive water from various sources mentioned in Table 3.6. The water treatment comprises of settling tanks and rapid sand gravel filters followed by chlorination.

Table 3.6: Availability of surface water from other sources
(Source: Uttarakhand Urban Development Project, Dehradun)

Sl. No.	Name of source	Quantity of water available in	
		million-litre per day	million-m^3 per year
Water treatment plant at Dilaram Bazaar:			
1	Bijapur canal	10.00	3.65
2	Bindal Rao	6.00	2.19
Water treatment plant at Shahnshahi Ashram:			
3	Moussi fall	8.00	2.92
4	Kolhu-khet	0.54	0.20
	Total	24.54	8.96

3.8.2 Canal System

In the northern parts of the study area, minor and medium canal irrigation schemes were constructed in the past. The details of the canal segments included in the study area are given in Table 3.7. Eight numbers of canals are included in the Suswa Watershed (Fig. 3.9). The culturable (cultivable) command area (CCA) of all canals in the study area is 1996 ha. Some of the above canals have been demolished in the recent development works carried out in the Dehradun city.

Table 3.7: Canals in the command area of the Suswa Watershed

Sl. No.	Name of the canal	Length, (km)	Command area (ha)	Discharge (m^3/s)
1	Badripur branch canal	5.90	187	0.90
2	Rajpur canal	8.10	214	1.26
3	Kargi minor	6.07	374	0.41
4	Dharampur branch canal	9.00	180	0.72
5	Shimlas Grant canal	13.70	280	0.63
6	Bullawala canal	9.65	401	0.75
7	Banjarewala canal	4.80	184	0.45
8	Majra minor	2.60	176	0.33

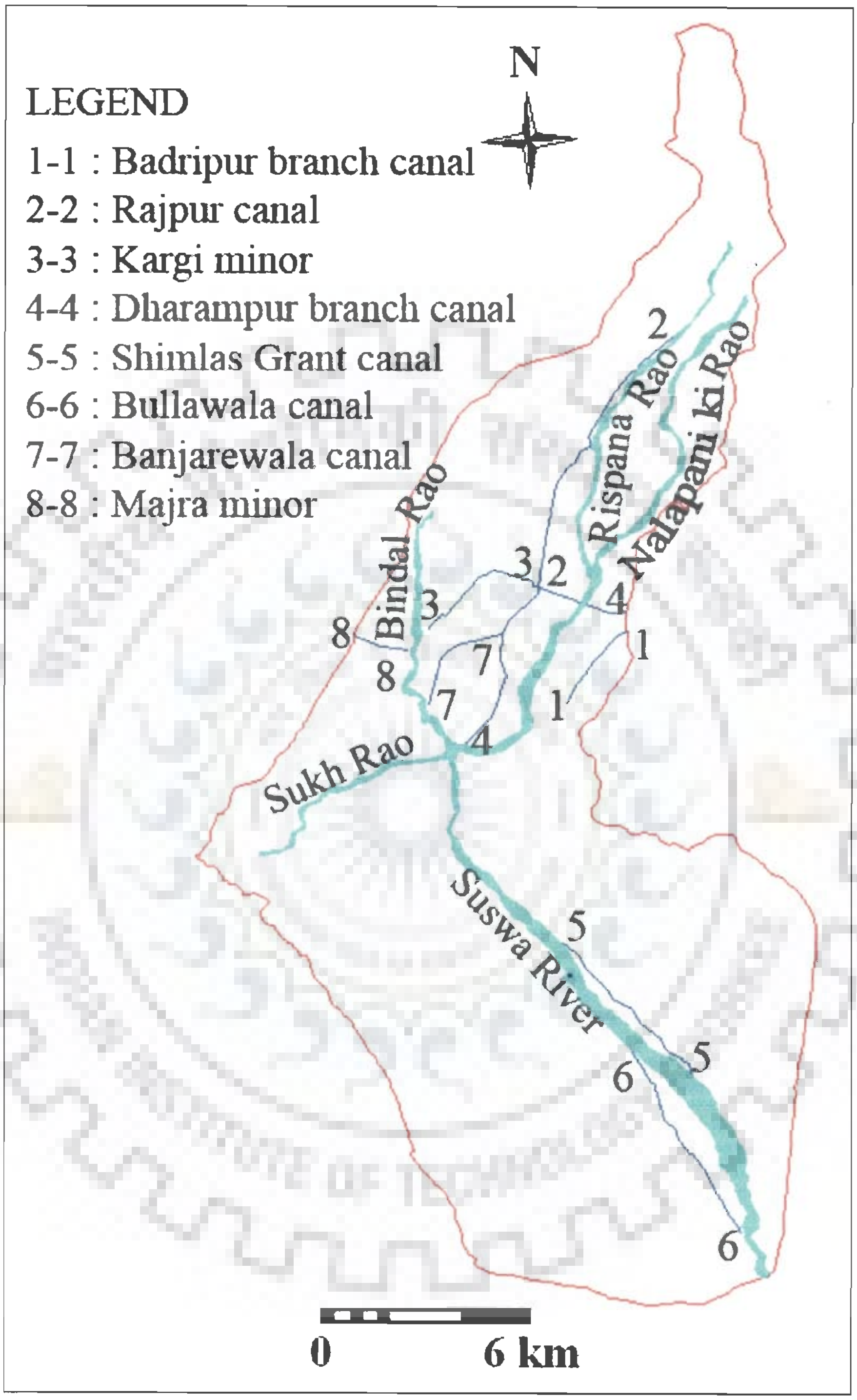


Fig. 3.9: Locations of canals in the Suswa Watershed

Chapter 4

ASSESSMENT OF SURFACE WATER RESOURCES

4.1 GENERAL

Rainfall generated runoff in a watershed is an important input in design of hydraulic structures and erosion control measures. On the long-term basis, change in runoff volume and its time distribution indicates dynamic changes occurring in a watershed. Poor land use planning and land management practices may adversely affect quantity and quality of surface runoff volume by changing land cover (Harr et al., 1975; Minner, 1998; Booth et al., 2002). Urbanization, deforestation, changes in agricultural practices, open grazing etc. are part of land use change. Thus, a hydrologic model that uses land use-land cover as input is useful to quantify the effect of land use-land cover changes on runoff volume. One such model is the Natural Resources Conservation Services- Curve Number (NRCS-CN) method which is widely used by engineers, hydrologists and watershed managers for runoff estimation.

This chapter deals with application of NRCS-CN method for assessment of surface water resources in the Suswa Watershed. The analysis of land use-land cover (LULC) changes has been carried out by using remote sensing imageries in GIS environment. The estimated parameters from this chapter (like amount of LULC changes and surface water resources availability) can then be used in the computations of sustainability indicators vis-à-vis water quantity.

4.2 ANALYSES OF LAND USE-LAND COVER CHANGES

Information on existing LULC and its spatial distribution forms the basis for any developmental planning. LULC changes over time have been studied by several researchers for different purposes. The aspects relevant in the context of sustainable water resources management are quantification of changes in LULC over time and effects of changes in LULC on surface runoff potential and groundwater recharge potential of a watershed, besides its effects on water quality. For sustainable development and management of natural resources in a watershed, it is required to identify and quantify the changes in LULC in terms of the area affected and rate of its change over the years. Review of literature on LULC has shown that research efforts are needed to analyze changes in LULC in response to activities carried out for development and management of water resources. Moreover, most of the developmental activities in a watershed are closely associated with the development and use of water resources. Therefore, dynamics of LULC and the driving factors for changes in LULC need to be analyzed to make water resources planning exercise more realistic and effective.

4.2.1 Remote Sensing Data Acquisition

To determine major LULC of the study area, the satellite imageries in various wave bands have been obtained from the Global Land Cover Facility Data Center of Maryland University, USA (Source: www.landcover.org). Landsat imageries are available for the period from 1972 onwards from six satellites of the Landsat series. These satellites have been a major component of Earth Observation Program of National Aeronautics and Space Administration (NASA) with three primary sensors evolving over thirty years viz. Multi-spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+). The Geo-Cover dataset provides global Landsat imagery of three years i.e. 1972, 1990 and 2000, utilizing the Landsat-MSS, TM and ETM+ sensors respectively.

All the data of satellite images is ortho-rectified i.e. corrected for terrain displacement and errors in image geometry. The Geo-Cover dataset is provided in a standard Geographic Tagged Image File Format (GeoTIFF) with a Universal Transverse Mercator (UTM) projection, using the World Geodetic System of year 1984 (WGS-84) datum. Each scene is provided with the bands as separate files. The characteristics of satellite remote sensing imageries obtained for the present study area are shown in Table 4.1.

4.2.2 Selection of Band Combinations

Popular band combinations for different type of sensors have been used in this study to recognize a land class from the available Landsat dataset. It is often selected on the basis of the types of land covers required to be classified. The most common and popular band combination for Landsat-MSS sensor is 4-2-1 shown by red green blue

(RGB) color combination which makes land and water boundaries more clear along with clear differentiation of agricultural and forest areas.

Table 4.1: Characteristics of satellite remote sensing imageries

Imagery of year	Date on which imagery taken	Sensor	Spectral rage (μm)	Available band numbers	Pixel size (m)
1972	14th November	MSS	0.50 – 1.10	1,2,3,4	57.0
1990	21st October	TM	0.45 – 2.35	1,2,3,4,5,6,7	28.5
2000	25th November	ETM+	0.45 – 2.35	1,2,3,4,5,7	28.5

In case of Landsat-TM sensor, the 4-5-3 band combination for RGB is found to be more clear than 1-2-3 band combination as the two shortest wavelength bands (bands 1 and 2) are not included. The 4-5-3 band combination makes different vegetation types more clearly defined and also the land/ water interface is clear. The Landsat-ETM+ sensor has extra panchromatic band in addition to other bands of Landsat-TM imageries. However, same band combination of 4-5-3 is used for LULC classification.

4.2.3 Land Use-Land Cover Classification Procedure

A widely used software having blend of both remote sensing and GIS analysis capabilities viz. Earth Resources Data Analysis System (ERDAS) IMAGINE 8.6 has been used for classification of satellite imageries. A combination of unsupervised and supervised classification methods has been used in identifying the different LULC classes. First, all the imageries have been classified for LULC classes of forest, agriculture, settlements and other (barren land and dry river/ stream bed) by supervised classification method. Again, the same imageries have been classified by unsupervised classification method for fifteen numbers of land use classes and subsequently, these classes have been reduced to four by manually merging them with visual interpretation with simultaneous comparison with already classified imageries by supervised method. Classification of satellite imageries has been carried out in reverse order of chronological time period. The method of classification in reverse of chronological order helps to classify the imagery of earlier years from the recent imagery as the base for which ground truth data is available.

The recent satellite imagery of 2000 has been selected first for classification. Band combination of 4-5-3 has been used to recognize the patches of forest, agriculture, settlement and other categories (which includes dry river bed and barren land). The recognized patches have been verified using spatial database information and high resolution real world images of recent years from Google Earth Launch Programme (www.earth.google.com and www.wikimapia.org). Intended LULC classes are also based on the information acquired and observed during the field visits.

Classified land use layer of year 2000 is superimposed over the imagery of 1990 with band combination of 4-5-3. This superimposition helps to identify the changes in shape and size of land classes besides confirming the identified LULC classes. Likewise, the satellite imagery of 1972 has been classified based on already classified LULC imagery of 1990.

4.2.4 Analysis of Land Use-Land Cover

Four major land use classes viz. forest, agriculture, settlements and other (which includes barren land and dry river/ stream bed) have been derived from the satellite imageries. The classified land use maps for the years 1972, 1990 and 2000 are shown in Fig. 4.1, whereas the areal extent of various LULC classes is given in Table 4.2.

Table 4.2: Area under various land use-land cover classes in the Suswa Watershed

Land use class	1972		1990		2000	
	km^2	%	km^2	%	km^2	%
Forest	187.33	64.24	182.83	62.70	167.22	57.35
Agriculture	55.42	19.01	42.69	14.64	30.77	10.55
Settlements	13.88	4.76	27.56	9.45	55.42	19.01
Other	34.97	11.99	38.53	13.21	38.19	13.10
Total	291.60	100.00	291.60	100.00	291.60	100.00

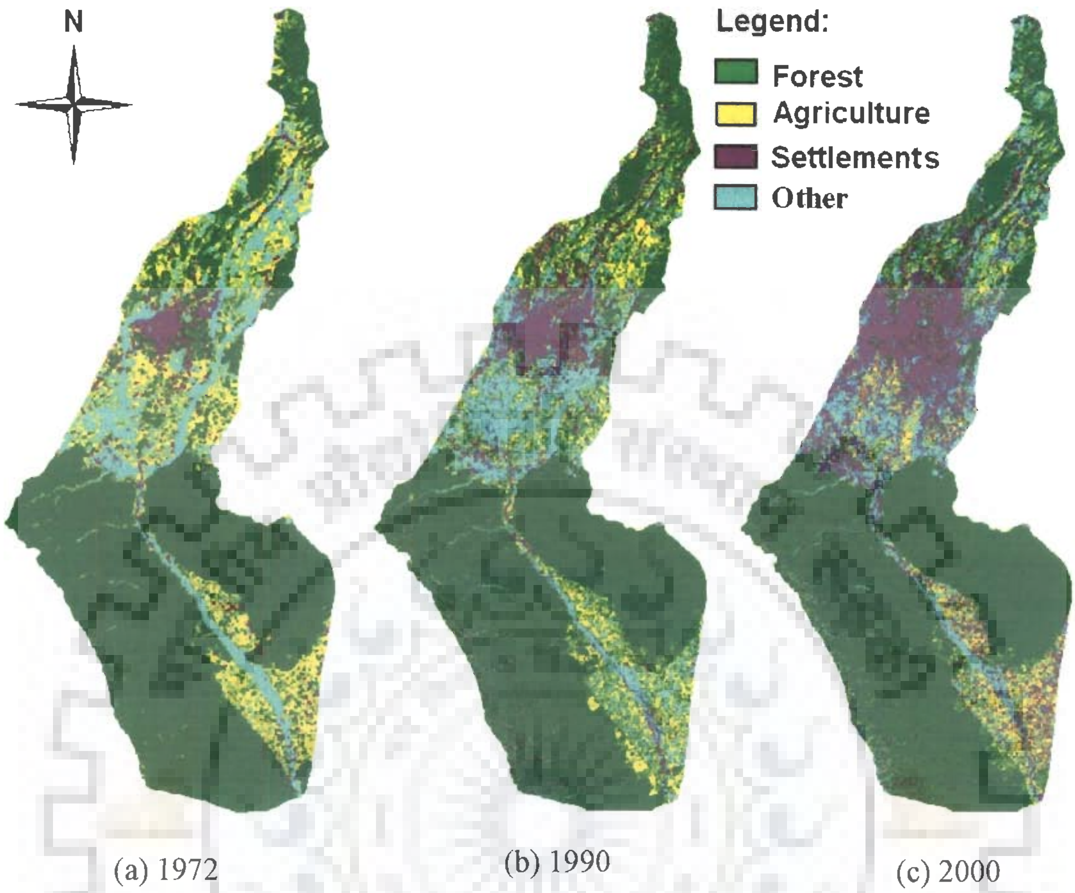


Fig. 4.1: Land use-land cover of the Suswa Watershed for 1972, 1990 and 2000

'Forest' is the dominant land use class with coverage of more than 57 % of total area of the Suswa Watershed. Forest area is mainly present on Siwalik hills in the form of reserved forests (as indicated in Fig. 3.2) of Asarori, Lachhiwala and Kansrao and also on Nagsiddh hill, besides its presence in scattered patches in the extreme northern Lesser Himalayan (southward from Mussoorie hills upto Kishanpur) region of the Suswa Watershed. The second LULC class (i.e. agriculture) exists mainly in the vicinity of the Suswa river course in the southern part and mostly around the courses of Rispana Rao and Bindal Rao in the northern part of the study area.

The major portion of the third LULC class viz. 'settlements' is occupied by the Dehradun city and adjoining areas like Clement Town area, besides the villages like Shimlas Grant, Madhowala, Balawala, Bullawala, to mention a few. The LULC class named 'other' consists of the barren land and dry river bed of the Suswa river and that of other mountain streams (Raos) emerging from the Siwalik ranges. The barren land is mostly found in between agricultural fields and on the hills with little vegetative cover on them especially, in recent years (Fig. 4.1 (c)). The water bodies in the form of river flow are not visible in the classified LULC maps because the images were taken during the dry months of October and November whereas small water bodies like canals are not recognized due to the limited ground resolution (pixel size of 57 m and 28.5 m) of the imageries. The northern part of the Suswa Watershed shows considerable visible increase in the settlements area (especially urban area) in recent years. Yet, this urban expansion over the years has mostly occurred around the Dehradun city and Clement Town areas as shown in Fig. 4.1 (c). Along with expansion of urban area, there is decrease in forest and agricultural areas indicating some deforestation and conversion of agricultural land into urban settlements. The 'other' class of LULC i.e. barren land and dry river beds appear to be largely unchanged over the years.

4.2.5 Extent and Rate of Land Use-Land Cover Change

Recognizable changes have taken place in land use classes in the study area during 18 years period from 1972 to 1990 and during 10 years period from 1990 to 2000. The change in land use (magnitude and percentage) and dynamic rate of land use change in the Suswa Watershed are given in Table 4.3. Change in LULC during the two periods of 1972 to 1990 and 1990 to 2000 are compared in Fig. 4.2.

Table 4.3: Land use-land cover change in the Suswa Watershed

Year	Forest	Agriculture	Settlements	Other
1972 (km^2)	187.33	55.42	13.88	34.97
1990 (km^2)	182.83	42.69	27.56	38.53
2000 (km^2)	167.22	30.77	55.42	38.19
Area change (km^2) during 1972-1990	−4.50	−12.73	+13.68	+3.56
during 1990-2000	−15.61	−11.92	+27.86	−0.34
Percent change during 1972-1990	−2.40	−22.97	+98.56	+10.18
during 1990-2000	−8.54	−27.92	+101.09	−0.88
Dynamic rate (%/year) during 1972-1990	−0.13	−1.28	+5.48	+0.57
during 1990-2000	−0.85	−2.79	+10.11	−0.09

The area under forest is decreased by 2.4 % during the period of 18 years (from 1972 to 1990) and by 8.54 % during the next 10 years (from 1990 to 2000). The negative dynamic rate of change in forest area shows the decrease in forest area with time. Although the overall rate of decrease in forest area is smaller, this decrease is faster (as shown by rate of 0.85 % per year) in the recent period of 10 years than that occurring during the preceding period of 18 years (rate of 0.13 % per year). Area under agriculture has also decreased by about 23 % in year 1990 over the agricultural area of year 1972 with dynamic rate of 1.28 % decrease per year. In the next period (1990 to 2000), the dynamic rate was more than double (2.79 % per year). The agricultural area in the year 2000 was about 11 % of the watershed area while it was 15 % and 19 % in year 1990 and 1972 respectively.

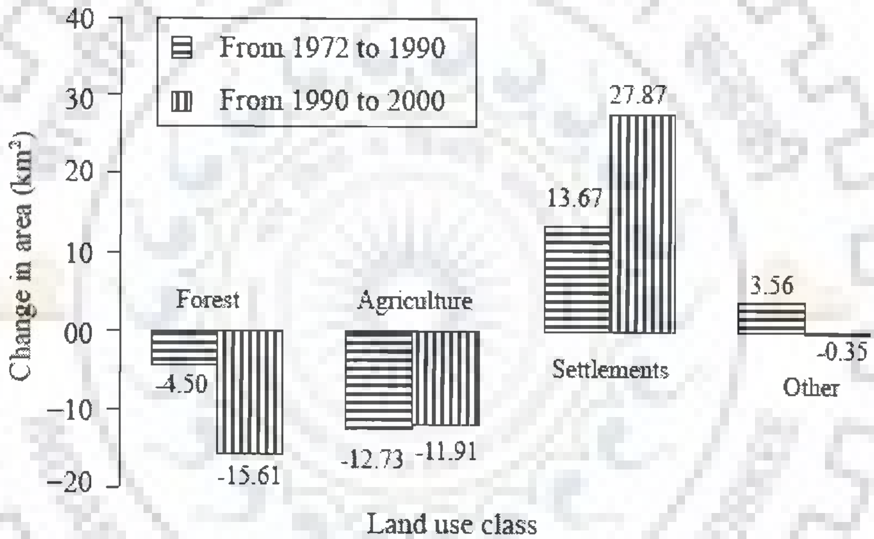


Fig. 4.2: Change in land use-land cover in the Suswa Watershed

The rate of increase in settlements area is around 100 % for both the periods under discussion. The increase in settlements area during 1972 to 1990 is about 14 km^2 while that in the next 10 years is about 28 km^2. The rate of increase in settlements area during period of 1972 to 1990 was slower (5.48 % per year) as compared to that (10.11 % per year) during recent period of 1990 to 2000, yet, both these rates are highest amongst the all LULC classes, which is attributed to the fast growing urban and industrial hub at Dehradun city, the capital of newly formed Uttarakhand State. The area under 'other' class i.e. barren land and dried beds of rivers/ Raos appears to be unchanged, although there is slight increase in area during the period of 1972 to 1990 which can be attributed to the progressive development of streams during this period [Fig. 4.1 shows the well developed streams, through increase in channel width, in (b) as compared to rather undeveloped streams in (a)]. The slight decrease in the area under this class in next 10 years period (from 1990 to 2000) may be attributed to the transfer of some land under this class to some other class like settlements.

4.3 SURFACE RUNOFF ESTIMATION

Modelling of the rainfall-runoff process has significant importance in Hydrology and it has been fundamental to a range of applications in hydrological practices e.g. in design of hydraulic structures and erosion control measures. One of the most commonly used methods to estimate the volume of surface runoff for a given rainfall event is the Soil Conservation Services- Curve Number (SCS-CN) method, which has now been renamed as Natural Resources Conservation Services- Curve Number (NRCS-CN) method. The method is simple, easy to understand, and useful for ungauged watersheds. It accounts for the major runoff producing watershed characteristics viz. soil type, land use, land treatment, surface condition and antecedent moisture condition (AMC). It computes the surface runoff volume for a given rainfall event from small agricultural, forest and urban watersheds (SCS, 1985). Curve number, which is descriptive of runoff potential of a watershed, is the most important factor in the method. The NRCS-CN method is widely used by engineers, hydrologists and watershed managers as a simple watershed model. This section deals with estimation of runoff potential of the Suswa Watershed by using the NRCS-CN method.

4.3.1 NRCS-CN Method

The NRCS-CN method has been reviewed in detail in Chapter 2 (section 2.6.1). The basic formula of the existing NRCS-CN method is:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad \text{for } P > I_a \tag{4.1}$$

$$Q = 0 \quad \text{for } P \leq I_a$$

where, P = total rainfall (in mm), Q = direct surface runoff (in mm), I_a = initial abstraction (in mm) and S = potential maximum retention (in mm).

S can be transformed to CN scale using the empirical equation (4.2):

$$CN = \frac{25400}{(254 + S)} \tag{4.2}$$

where, S is in mm and CN is non-dimensional.

Recently, for field applications Jain et al. (2006) recommended the non-linear relation between I_a and S incorporating storm rainfall (P) as given in equation (4.3), with $\lambda = 0.3$ and $\alpha = 1.5$.

$$I_a = \lambda S\,(P / P+S)^{\alpha} \tag{4.3}$$

The parameter S of the NRCS-CN method depends on soil type, land use, hydrologic condition and AMC.

AMC is defined as the initial moisture condition of the watershed prior to the storm event of interest. AMC II describes the watershed's 'average condition' in terms of wetness. AMC I and III describes the 'dry' and 'wet' conditions of watershed and thereby the lowest and highest runoff potential characteristics of a watershed respectively. In the present study, the AMC condition is determined by using previous 5-day antecedent rainfall and considering the growing season for the monsoon months and the dormant season for remaining months of a year. Table 4.4 is used for the purpose.

Table 4.4: Rainfall limits for estimating AMCs (after Geetha et al., 2007)

AMC	5-day antecedent rainfall (mm)	
	Dormant season	Growing season
I	< 13	< 36
II	13 to 28	36 to 53
III	> 28	> 53

Although the effect of the slope on runoff volume has been clearly established, very few attempts have been made to include a slope factor into the CN method. One of these is that of Sharpley and Williams (1990), for which a slope-adjusted CN_{II}, named $CN_{II\alpha}$, is obtained by

$$CN_{II\alpha} = \frac{1}{3}(CN_{III} - CN_{II})(1 - 2e^{-13.86\alpha}) + CN_{II} \tag{4.4}$$

where, CN_{II} and CN_{III} are the NRCS-CN for soil moisture conditions II (average) and III (wet), and α is the soil slope (in m/m). The $CN_{II\alpha}$ is then used, instead of CN_{II}, in the subsequent calculations of the runoff volume. This method assumes that CN_{II} obtained from the handbook table (SCS, 1985) corresponds to a slope of 5 %. The following criteria are used for classifying the soils in a watershed into various hydrologic soil group (HSG):

Table 4.5: USDA- SCS soil classification (after Amutha & Porchelvan, 2009)

Hydrologic soil group	Type of soil	Runoff potential	Infiltration rate (mm/ hr)	Rate of water transmission (permeability)
A	Deep, well drained sands and gravels	Low	> 7.5	High
B	Moderately deep, well drained with moderately fine to coarse textures	Moderately low	3.8 – 7.5	Moderate
C	Clay loams, shallow sandy loam, soils with moderately fine to fine textures	Moderately high	1.3 – 3.8	Low
D	Clay soils that swell significantly when wet and soils with a permanent high water table	High	< 1.3	Very low

4.3.2 Runoff Estimation Procedure

The surface runoff from daily rainfall data of meteorological observation station located at Dehradun have been estimated for the three years (1972, 1990 and 2000 for which LULC have been estimated in section 4.2) by using the NRCS- CN method as given below.

1. The AMC conditions corresponding to daily rainfall have been arrived at based on 5-day antecedent rainfall and considering the growing season for the four monsoon months of June to September and dormant season for remaining eight months of a year.
2. Using the LULC and soil characteristics based hydrologic soil group of the Suswa Watershed, the weighted CN for 'average condition' (CN_{II}) have been arrived at by reading the modified CN values applicable for the Indian conditions (Table 4.6).
3. Further, CN_I (CN for AMC I) and CN_{III} (CN for AMC III) values have been computed by using the conversion formulae (equations 2.8 and 2.9) given by Mishra et al. (2008).

4. The slope correction has been applied to the CN_{II} values by computing the weighted mean slope (average taken with respective areas under various slope categories) of the watershed. The $CN_{II\alpha}$ values have been arrived at by applying the approach of Sharpley and Williams (1990) (equation 4.4) and this $CN_{II\alpha}$ value has been then used, instead of CN_{II}, in the subsequent calculations of the runoff volume estimation.
5. The values of the parameter 'S' have been computed by using equation (4.2) and corresponding I_a values have been arrived at by employing equation (4.3).
6. Finally, the surface runoff from daily rainfall has been estimated by substituting these values of S and I_a in equation (4.1).

Table 4.6: Runoff curve numbers for AMC II condition for the Indian conditions (Source: Handbook of hydrology, 1972)

Sl. No.	Land use	Treatment/ practice	Hydrological condition	Hydrologic soil group			
				A	B	C	D
1	Cultivated	Straight row	-	76	86	90	93
		Contoured	Poor	70	79	84	88
			Good	65	75	82	86
		Contoured and terraced	Poor	66	74	80	82
			Good	62	71	77	81
		Bunded	Poor	67	75	81	83
			Good	59	69	76	79
		Paddy (rice)	-	95	95	95	95
2	Orchards	With under stony	-	39	53	67	71
		Without under stony cover	-	41	55	69	73
3	Forest	Dense	-	26	40	58	61
		Open	-	28	44	60	64
		Shrubs	-	33	47	64	73
4	Pasture	-	Poor	68	79	86	89
			Fair	49	69	79	84
			Good	39	61	74	80
5	Waste land	-	-	71	80	85	88
6	Hard surfaces	-	-	77	86	91	93

4.3.3 CN from Land Use-Land Cover and Soil Characteristics

The CN is a dimensionless runoff index based on hydrologic soil group, land use, land treatment, hydrologic conditions and AMC which counts on previous 5-day rainfall total. In the present study, LULC maps of three different years (1972, 1990 and 2000) have been derived from satellite imageries by visual interpretation. The classified land use maps showing four major LULC classes such as forest, agriculture, settlements and other (barren land and dry river bed) are given in Fig. 4.1 and the corresponding areas under these LULC classes given in Table 4.2 have been used for computing the weighted CN values. CN values for individual LULC class are obtained from reference table (Table 4.6) appropriate for Indian conditions and using land use and hydrological soil cover data (Handbook of Hydrology, 1972). The weighted CN of a watershed is computed by using equation (4.5).

$$CN = \frac{\sum (CN_i \times A_i)}{A} \tag{4.5}$$

where,

CN = Weighted curve number,

CN_i = Curve number of area i assigned on the basis of LULC and HSG,

A_i = Area having CN_i and

A = Total area of the watershed.

The soil types prevalent in the study area discussed in section 3.5 are used in classifying the hydrologic soil groups in the Suswa Watershed. Accordingly, the soils on the gentle slopes of the Suswa Watershed are fine loamy having moderate infiltration rate; therefore the soils under LULC of 'agriculture' and 'settlements' have been considered under hydrologic soil group– B. On the other hand, soils along the 'river bed' and 'barren land' are gravel and coarse sandy respectively, having very high infiltration rate whereas soils on the higher reaches of 'forest' are coarse sandy to sandy having high infiltration rate; hence these areas are considered under hydrologic soil group– A.

The CN values have been taken from Table 4.6, in which the CN values against 'hard surfaces' are selected for LULC of 'settlements' and those against 'waste land' are selected for the LULC of 'other' (which includes dominance of barren land area over dried river bed area). The CN values for the LULC of 'agriculture' are selected from Table 4.6 by reading values for 'cultivated' land use with the land use practice/ treatment of 'contoured and terraced' land with 'poor' hydrological condition, taking into account the average slope and prevalent agricultural practices in the study area. While reading the CN values for LULC of 'forest' the values are taken from those for 'open' forest.

The computation of weighted CN_{II} for three years is shown in Table 4.7. The CN_I and CN_{III} values corresponding to CN_{II} values for the years 1972, 1990 and 2000 estimated by using conversion formulae given by Mishra et al. (2008) are shown in Table 4.8. The average slope of the Suswa Watershed after taking weighted mean with the corresponding areas included in various slope zones (as shown in Table 3.3 of Chapter 3) has been computed as 9.43 %. Thus, by using this value of slope (i.e. α = 0.0943 m/m), the corresponding slope corrected CN values ($CN_{II\alpha}$) are estimated by using equation (4.4) and are shown in Table 4.8. These $CN_{II\alpha}$ values, instead of CN_{II}, have been used in all further calculations such as that of computing S (by using equation 4.2), I_a (by using equation 4.3) and finally the runoff.

Table 4.7: Estimation of weighted CN_{II} in the Suswa Watershed

Details	LULC class				Total
	Forest	Agriculture	Settlements	Other	
For 1972:					
Area, A_i (km²)	187.33	55.42	13.88	34.97	291.60
CN_i	28	74	86	71	-
$A_i \times CN_i$	4870.58	3879.4	1193.68	2482.87	12426.53
				Weighted CN_{II}	44.66
For 1990:					
Area, A_i (km²)	182.83	42.69	27.56	38.53	291.60
CN_i	28	74	86	71	-
$A_i \times CN_i$	4753.58	2988.3	2370.16	2735.63	12847.67
				Weighted CN_{II}	45.90
For 2000:					
Area, A_i (km²)	167.22	30.77	55.42	38.19	291.60
CN_i	28	74	86	71	-
$A_i \times CN_i$	4347.72	2153.9	4766.12	2711.49	13979.23
				Weighted CN_{II}	49.51

Table 4.8: Values of CN_I, CN_{III} and $CN_{II\alpha}$ in the Suswa Watershed

Year	CN_{II}	CN_I	CN_{III}	$CN_{II\alpha}$
1972	44.66	26.18	65.24	47.81
1990	45.90	27.16	66.36	49.03
2000	49.51	30.12	69.52	52.57

4.3.4 Variation in CN over the Years

Estimated CN values of three different years (Table 4.8) shows the gradual increase from 1972 to 1990 and from 1990 to 2000. The CN values have increased from 47.81 to

49.03 during 1972 to 1990 and from 49.03 to 52.57 during 1990 to 2000. Thus, the increase in CN values is more than about three times in the later period of 1990 to 2000 than that in the first period of 1972 to 1990. This increase in CN shows the increase in runoff potential of the Suswa Watershed in the recent years which can be attributed to the significant increase in the settlements area especially due to increase in urban area of Dehradun city. The obvious reduction in runoff potential of the Suswa Watershed due to decrease in forest area is not significant as compared to the quite high increase in the runoff potential due to increase in settlements area. This is because forest has very less CN of 28 as compared to that for settlements (CN = 86) and the decrease in forest area (about 1 % per year) is also quite less as compared to the increase in the area of settlements (about 10 % per year). Further, forest cover (CN = 28) and agricultural land (CN = 74) have been gradually replaced by settlements area (CN = 86) in the Suswa Watershed which has caused increase in CN values in the successive time period.

4.3.5 Estimation of Surface Water Resources

The annual runoff has been arrived at by adding the daily runoff values estimated from corresponding rainfall for years 1972, 1990 and 2000 by using above-discussed CN values. Additionally, the annual runoff has also been estimated for years 1973 and 2002 by using the estimated CN values of the years 1972 and 2000 respectively, with the assumption that notable changes will not occur in land use-land cover (and hence in CN) within one or two years. Out of 33 years (from 1972 to 2006), the lowest and the highest values of annual rainfall in the study area have been recorded in the years 2002 and 1973 respectively. Thus, the purpose of estimating the annual runoff for 1973 and 2002 is to get the lowest and the highest values of surface water availability in the study area. Here, the annual runoff for the year 2002 has been considered as dependable value (the minimum rainfall availability likely to be fulfilled every year) for assessing the surface water availability in the study area. The annual rainfall and estimated runoff values are given in Table 4.9.

Table 4.9: Estimated annual runoff and annual storm runoff coefficient

Year	Annual rainfall, P_a (mm)	Annual runoff, Q_a (mm)	ASRC (= Q_a/P_a)
1972	2120.90	501.50	0.237
1973	2914.90	788.90	0.271
1990	2898.40	648.70	0.224
2000	2564.00	586.30	0.229
2002	1573.90	185.80	0.118
Average	2414.42	542.24	0.216

From Table 4.9, it can be seen that the estimated lowest and highest annual runoff is about 186 mm to 789 mm respectively. By assuming uniform depth of runoff over entire area of the Suswa Watershed, the minimum annual runoff volume is of the order of 54.23 million-m^3 (291.6 km^2 × 0.186 m).

In addition to these figures, it will be necessary to add the figure (of 8.96 million-m^3) of existing surface water supplies from the other sources as detailed in Table 3.6 (section 3.8.1). This will make a minimum annual availability of surface water resources of 63.19 million-m^3.

4.3.6 Comparison of ASRC with Runoff Coefficient

The annual storm runoff coefficient (ASRC), defined as the ratio of annual runoff to annual rainfall (Pandit and Gopalkrishnan, 1996), has been estimated for five years of 1972, 1973, 1990, 2000 and 2002 (Table 4.9).

ASRC exhibits the runoff potential of watershed, which depends upon watershed characteristics (such as the land use-land cover, soil type, land slope, moisture condition) and rainfall characteristics (such as magnitude and duration of rainfall). Among these, rainfall is the most variable parameter influencing runoff magnitude by changing soil moisture condition when other watershed factors are constant.

The average ASRC estimated for the Suswa Watershed is about 0.22 indicating that the average annual runoff is about 22 % of annual rainfall (Table 4.9). The lowest and the highest values of ASRC (0.1181 and 0.2707 for 2002 and 1973 respectively) clearly indicate that the ASRC values are very much influenced by annual rainfall conditions as

2002 and 1973 are the years in which the lowest and the highest rainfall have been recorded.

The use of ASRC approach addressed a need for a simple and effective yet sufficiently rigorous method for estimating annual runoff volumes from the Suswa Watershed. One of the notable strengths of this approach includes its use for easily computing the effects of urbanization on annual runoff volumes and therefore, annual pollutant loads (Pandit and Gopalkrishnan, 1996). This is significant in view of increasing urbanization, especially in and around the Dehradun city area. The method is also cost-effective since computations can be made simply by using easily available daily rainfall data from nearby climatological station. On the other hand, the limitation of the runoff estimation for the present study is that the runoff values estimated by using NRCS-CN method have not been validated with measured ones due to absence of any gauging station monitoring the discharge of the Suswa river. Yet, comparison (as discussed in next paragraph) of estimated ASRC values with the runoff coefficient values available in literature (given in Annexure 4.1) shows that the method can make reasonable predictions and hence the estimated ASRC value may be recommended for field applications in the Suswa Watershed.

In the absence of observed data of discharge in the Suswa river, the comparison of ASRC and runoff coefficient (C) has been treated as some sort of validation of the estimated runoff values as the 'C' used in Rational method (of estimation of peak rate of runoff) cannot be exactly matched with the ASRC values. The 'C' used in Rational method is defined as the ratio of the peak runoff rate to the rainfall intensity and is expressed as a dimensionless decimal fraction which appears as a fraction of surface runoff from the contributing watershed area (ISMM, 2008).

To achieve the comparison of ASRC with 'C', the values of 'C' have been taken from standard tables (Annexure 4.1) available for the Dehradun and adjoining areas. The values of 'C' have been taken from Annexure 4.1 for the estimated LULC classes of three years of 1972, 1990 and 2000 in the Suswa Watershed. For this purpose the value of 'C' for 'forest' is taken 0.3 (the value for 10 to 30 % land slope with sandy loam soil) and that for 'agriculture' is taken as 0.3 (the value for cultivated land with slope of 0 to 5 % with sandy loam soil), whereas for LULC class 'other' (barren land and dry river bed) it is taken as 0.16 (the value for pasture land with 5 to 10 % land slope and sandy loam soil). Further, the value of 'C' for 'settlements' is taken as 0.4 by reading it against pasture land with slope of 5 to 10 % and stiff clay soil. Then the weighted 'C' values (given in Table 4.10) have been arrived at by taking weighted mean with corresponding areas under each LULC class in a similar way as shown in Table 4.7 by inserting 'C' values instead of CN_{II} values.

Table 4.10: Comparison of estimated ASRC with runoff coefficient (C)

Year	ASRC	C
1972	0.237	0.288
1990	0.224	0.291
2000	0.229	0.301

The comparison of values of ASRC and 'C' (Table 4.10) shows that the values of 'C' are increasing with increase in impervious ground surfaces through urbanization in the watershed thus indicating that the values of 'C' are more influenced by land use-land cover changes, whereas values of ASRC indicate their dependence on watershed as well as rainfall characteristics. Therefore, use of ASRC values for estimation of annual runoff volume seems to be more reasonable and reliable option.

4.4 CONCLUDING REMARKS

The spatial and temporal changes in LULC and thereby changes in runoff potential affect the sustainable development and management of surface water resources in a watershed. Appropriate methods for eco-environmental planning, and development of surface water and groundwater resources at micro level can be selected based on dynamic analysis of LULC changes presented in this chapter. Analysis of changes in LULC in the present study shows that the rate of urbanization has increased considerably in the recent period, especially in Dehradun city whereas forest and agricultural land use has decreased, which has probably resulted in increased runoff.

Estimated average ASRC value of about 0.22 indicates that the annual runoff in the study area is about 22 % of the annual rainfall. The estimated minimum annual availability of surface water resources is of the order of 63.19 million-m^3. Thus, it appears that there is adequate scope for the development of surface water resources through construction of water storage and rainwater harvesting structures. The limitation of this study is that the necessary validation of estimated runoff values with the observed discharge data of the Suswa river has not been carried out due to the lack of realistic field data and gauge discharge data in the study area.

Chapter 5

ASSESSMENT OF GROUNDWATER RESOURCES

5.1 GENERAL

Groundwater continues to be the main source for irrigation of agricultural crops and to meet domestic water requirements in urban as well as rural areas of the Suswa Watershed in the absence of substantial surface water storage schemes. A large number of deep tubewells tapping multiple aquifers have been drilled in the study area mainly for domestic and irrigation purpose. Accordingly, the net groundwater availability in the Suswa Watershed can be used as an input parameter in the estimation of the sustainability indicators vis-à-vis water quantity, to be discussed in a forthcoming chapter.

In this context, it is felt necessary to assess the present groundwater development scenario in the study area. This chapter deals with the assessment of groundwater resources using an available methodology of groundwater budgeting practiced by the State and Central Government agencies. This technique is largely based on the safe yield concept and employs the principle of mass balance and was recommended in 1997 by Groundwater Estimation Committee set up by Central Groundwater Board (CGWB), Ministry of Water Resources, Government of India. Subsequent to this, some modifications have also been made in their report for including groundwater in hard rock aquifers and in deeper confined aquifers.

5.2 GROUNDWATER ASSESSMENT UNIT

The groundwater resource estimation for the Suswa Watershed has been carried out for the year 2005-06 in accordance with the methodology given by Groundwater Resource Estimation Committee- 1997 (GEC-1997), Central Ground Water Board (CGWB), Ministry of Water Resources, Government of India. Total geographical area of the Suswa Watershed is about 291.6 km^2, out of which 44.8 km^2 (15.36 % of total area) is hilly area having slope of more than 20 %. The remaining area of 246.8 km^2 is considered suitable for groundwater recharge and it does not include any poor groundwater quality area. The recharge area has been divided into two parts viz. command area (19.96 km^2) and non-command area (226.84 km^2) based on the presence of canal irrigation system (section 3.8.2) having command area of more than 100 hectares (1 km^2). Also, the groundwater assessment has been made separately for the monsoon season (rainy months from July to October) and non-monsoon season (winter and summer months from November to June).

5.3 COLLECTION AND GENERATION OF DATA

5.3.1 Groundwater Structures Data

Details of various groundwater structures used for withdrawal of groundwater in the Suswa Watershed are given in Table 5.6. These structures, as identified in different villages of the Suswa Watershed, have been compared with the available data from various state and central governmental organizations (viz. Tubewell and Irrigation Divisions, Dehradun; CGWB, Dehradun) and their total number is suitably modified for the year 2005-06. Further, the distribution of groundwater structures within the command and non-command areas have been worked out based on prorata percentage taken out of the total area of command and non-command area units.

5.3.2 Groundwater Level Data: Monitoring Programme

Measurements of groundwater levels in wells provide a basic indicator of the status of the groundwater development. These are critical for meaningful evaluation of the quantity and quality of groundwater and its interaction with surface water. Groundwater level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how these stresses affect groundwater recharge, storage, and discharge. Long-term, systematic measurements of groundwater levels provide essential data needed to evaluate changes in the resource over time, to develop groundwater models and forecast trends, and to design, implement, and monitor the effectiveness of groundwater management and protection programs (Taylor and Alley, 2001).

In the present study area, groundwater level measurements are being made at few hydrograph stations by a national governmental agency viz. CGWB, Dehradun. However, the data collected from this agency seems to be inadequate for carrying out a meaningful groundwater assessment in the area. Accordingly, a few additional wells have been selected for monitoring the depth of groundwater levels and for having a more representative water level fluctuation data in the overall study area. The groundwater levels in all selected observation wells of the watershed have been monitored twice a year i.e. for pre-monsoon (May to June) and post-monsoon (October to November) periods. Thus, four cycles of groundwater level monitoring were carried out during the years 2005 and 2006, during pre-monsoon (i.e. before rainy season) and post-monsoon (i.e. after rainy season) periods. These data are given in Annexure 5.2.

Accordingly, during the field studies carried out for the present study in pre-monsoon- 2005, the depths to water table were initially measured at selected five hydrograph stations. However, after identifying additional observation wells in the study area, groundwater level measurements were taken at a total of 13 hydrograph stations (station numbers 1 to 13 in Fig. 5.1) from the subsequent season of post-monsoon- 2005. These additional wells included some private as well as government operated agricultural and domestic production wells. Further, besides the 13 observation wells in the watershed, additional 10 hydrograph stations (station numbers 14 to 23 in Fig. 5.1) were identified and monitored for recording groundwater levels data during post-monsoon- 2006. The locations of all the hydrograph stations in and around the study area are shown in Fig. 5.1 whereas their location details recorded with a hand held global positioning system (GPS) (latitude, longitude and altitude) are given in Annexure 5.1. Some of the new observation wells included production tubewells operated by State Government (Uttarakhand Jan Sansthan, Dehradun) whereas others are private owned tubewells used for irrigation and domestic uses.

It may be mentioned that most of the monitored dug wells have gone out of use because of unavailability of sufficient water or due to vandalism. Yet, in the area where tubewells were not available, the groundwater levels were measured in the abandoned dug wells and groundwater samples were collected from the nearby hand operated pumps available in their vicinity. These hand pumps tapped the unconfined aquifer in the study area. The tubewells were monitored by measuring groundwater level and by collecting groundwater samples from them. Before collecting groundwater samples, each well was purged for first few minutes in order to remove stagnated water in the well and to get representative water sample from the aquifer storage. The method of measurement of the depth to water table in the tubewells included use of an electrical water level indicator supplemented by a measuring tape carrying an electrode at its end. In order to measure the groundwater level in such tubewells, the tape of water level indicator was lowered inside the tubewell through the annular space available in between the suction pipe and the outer casing wall of the tubewell. However, this arrangement is not feasible in the newly constructed recent production tubewells fitted with vertical turbine and submersible pumps.

5.3.3 Rainfall Data

Recharge from the sources other than rainfall (known as 'other sources') are to a large extent the result of human interventions, and hence they are computed with reference to the current groundwater assessment year. Rainfall is however, a natural phenomenon showing considerable variation from year to year. The 'normal rainfall' obtained as the average rainfall over a sufficiently long number of groundwater years will be therefore the most appropriate basis for computing rainfall recharge (CGWB, 1998).

The rainfall data collected from India Meteorological Department (IMD), Dehradun for a period of 106 years (from 1901 to 2006) has been used for computing the normal rainfall during monsoon and non-monsoon seasons and the same is tabulated in Table 5.1. It is seen that the average annual rainfall in the area is 1668.2 mm, out of which 403.7 mm (24.2 %) is received during the non-monsoon season. The remaining 1264.5 mm (75.8 %) rainfall received in the monsoon season is known as 'Normal Monsoon Season Rainfall' (NMR). From the comparison (shown in Table 5.1) of the monthly rainfall for the year 2005-06 and the normal monthly rainfall for 106 years (from 1901 to 2006) it is seen that the total annual rainfall in 2005-06 (2044 mm) has had a surplus by an amount of 375.7 mm over the average annual rainfall. The non-monsoon rainfall received in the year 2005-06 is 15.4 % (304.6 mm) of the annual total rainfall (2044 mm).

5.4 GROUNDWATER LEVEL FLUCTUATION

The data of depth to water table monitored at various hydrograph stations are given in Annexure 5.2. The depth to water level data of the tubewells included in the Suswa Watershed and of tubewells for which the data have been continuously monitored from pre-monsoon- 2005 to post-monsoon- 2006 have been used for computation of groundwater recharge. Such data is given in the Table 5.2. A perusal of the water level data

Table 5.1: Rainfall data for Dehradun (Source: IMD, Dehradun)

Sr. No.	Month	Average monthly rainfall for 106 years (1901 to 2006) (mm)			Monthly rainfall for the year 2005-06 (mm)		
		Monsoon	Non-monsoon	Total annual (mm)	Monsoon	Non-monsoon	Total annual (mm)
2.1	January	-	42.8	42.8	-	62.74	62.74
2.2	February	-	47.2	47.2	-	88.66	88.66
2.3	March	-	39.2	39.2	-	29.21	29.21
2.4	April	-	23.4	23.4	-	5.33	5.33
2.5	May	-	41.1	41.1	-	21.84	21.84
2.6	June	-	183.2	183.2	-	96.27	96.27
2.7	July	490.3	-	490.3	747.54	-	747.54
2.8	August	500.5	-	500.5	606.56	-	606.56
2.9	September	235.3	-	235.3	382.76	-	382.76
2.10	October	38.4	-	38.4	2.54	-	2.54
2.11	November	-	8.1	8.1	-	0	0
2.12	December	-	18.7	18.7	-	0.51	0.51
2.13	Total	1264.5(**A**)	403.7(**B**)	1668.2(**C**)	1739.4(**D**)	304.6(**E**)	2044.0(**F**)
2.14	Percent	75.8	24.2	100.0	85.1	14.9	100.0

Table 5.2: Water table fluctuation data of observation wells

Stn No.	Location Name	Depth to water table for pre-monsoon 2005 (m bgl)	Depth to water table for post-monsoon 2005 (m bgl)	Seasonal water table fluctuation (Rise) in 2005 (m)	Depth to water table for pre-monsoon 2006 (m bgl)	Depth to water table for post-monsoon 2006 (m bgl)	Decline during dry season (m)
(1)	(2)	(3)	(4)	(5) = (4)–(3)	(6)	(7)	(8) = (6)–(4)
1	Siwalik Hills	9.50	8.78	0.72	9.57	7.26	0.79
2	Shewala Khurd	5.50	1.96	3.54	8.50	3.50	6.54
3	Kaonli	15.27	11.64	3.63	15.50	13.94	3.86
11	Kuanwala	15.64	3.68	11.96	17.34	7.10	13.66
			Average	= 4.96		Average	= 6.21

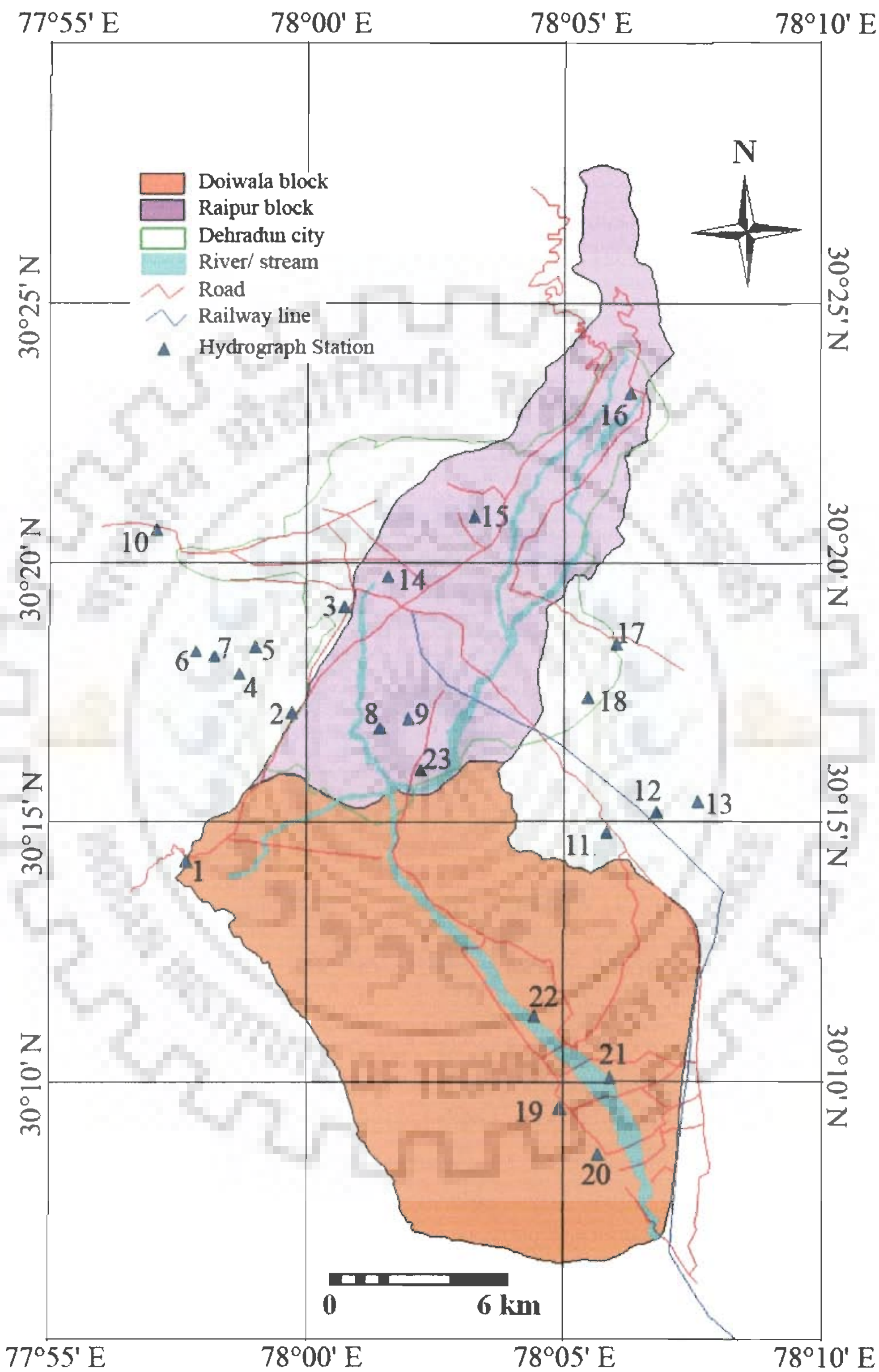


Fig. 5.1: Locations of hydrograph stations

Table 5.3: Average seasonal rise in groundwater level and annual rainfall from 1998 to 2006

Year	Average seasonal rise in groundwater level (m)	Annual rainfall (mm)
1998	7.15	2828.0
1999	5.68	2562.7
2000	6.21	2564.0
2001	6.17	2306.3
2003	6.89	1884.6
2005	4.48	2044.0
2006	4.14	1745.0

in this table shows that the average annual decline in the groundwater level recorded is 6.21 m during the dry season of 2005-06, whereas the rise observed in water level due to monsoon season rainfall is 4.96 m. The average seasonal rise in groundwater level in response to the monsoon season rainfall has been computed from the seasonal rise recorded for each hydrograph station and has been compared with the annual rainfall of corresponding years in Table 5.3. This historical data was collected from various state and central governmental agencies like Irrigation and Tubewell Divisions, Dehradun and CGWB, Dehradun etc. It is observed that the average seasonal rise in the groundwater levels in the Suswa Watershed in the recent years (from 1998 to 2006) exhibits a declining trend against the observed annual rainfall (Fig. 5.2).

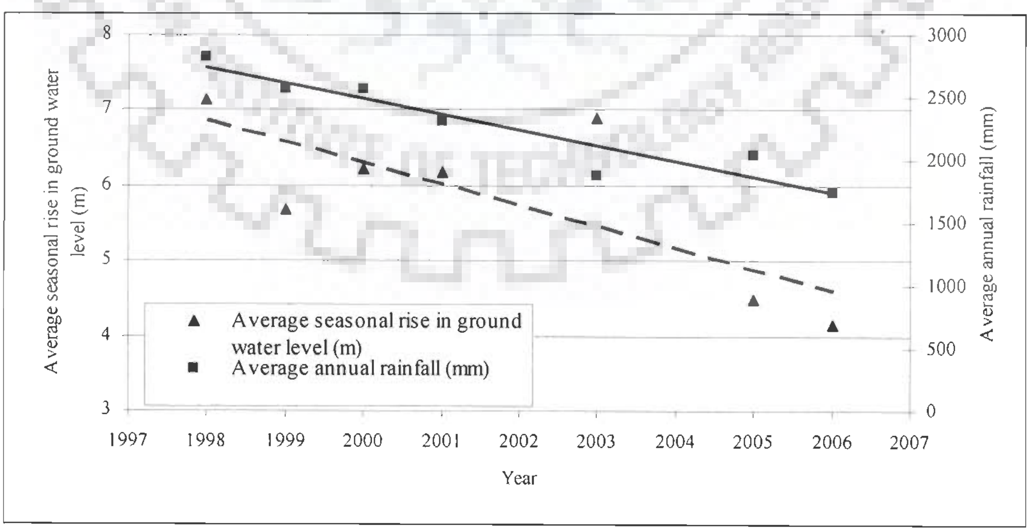


Fig. 5.2: Average seasonal rise in groundwater level (m) and average annual rainfall (mm)

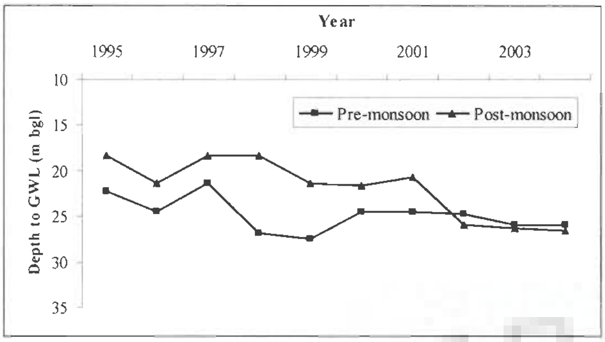
5.5 LONG-TERM GROUNDWATER LEVEL TRENDS

Long-term depth to groundwater level data was available for seven hydrograph stations (shown in Fig. 5.1) for the period of 10 years (between 1995 and 2004) which have been used to assess the rising (or declining) trend of groundwater levels. The trend of water table has also been estimated for pre-monsoon and post-monsoon periods by using depth to water table data for linear regression analysis (GEC-1997). Annexure 5.3 provides a sample calculation demonstrating the linear regression procedure used for estimating the trend of pre-monsoon depth to water table for 'Harbhajawala' station. Long-term trend (rise/ decline in cm per year) in groundwater levels for various hydrograph stations is shown in Table 5.4 and corresponding groundwater level fluctuation plots are shown in Fig. 5.3.

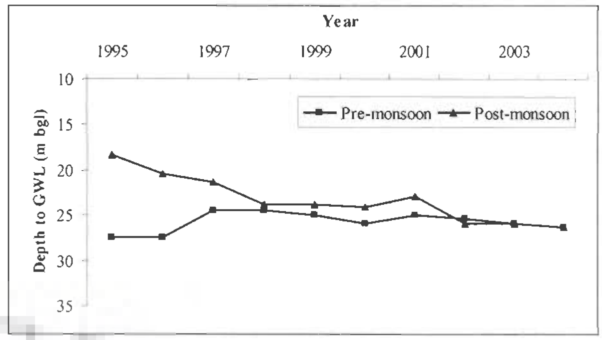
Table 5.4: Long-term trend in groundwater levels

Stn. No.	Location Name	Groundwater level trend (cm/ year)		Groundwater level trend (Rising/ Declining)	
		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
5	Mehuwala Arkediya	30.30	93.31	Declining	Declining
4	Mehuwala Mafi	–8.68	79.05	Rising	Declining
7	Harbhajwala	54.76	89.69	Declining	Declining
12	Nakrounda	56.40	35.93	Declining	Declining
13	Balawala	–34.48	–0.24	Rising	Neither rising nor declining
23	Mothronwala	52.85	39.63	Declining	Declining
-	Harrawala	68.27	93.14	Declining	Declining
	Mean	31.34	61.50	Declining	Declining

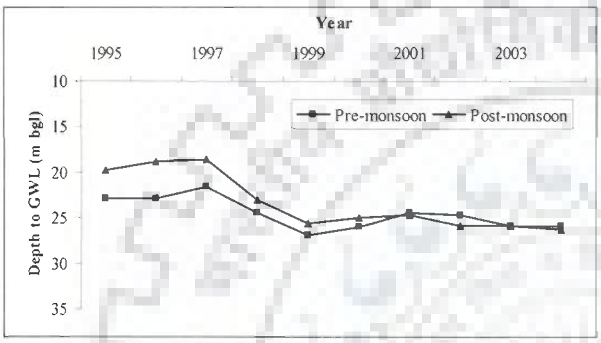
It can be observed from Table 5.4 and Fig. 5.3 that the long-term trend analysis in groundwater levels at seven hydrograph stations shows that in general, the groundwater levels are declining at the rate of about 0.31 m to 0.62 m per year in pre-monsoon and post-monsoon periods respectively. The maximum rate of decline in the groundwater level in pre-monsoon period has been observed at Harrawala (68.27 cm/ year) whereas that in post-monsoon has been observed at Mehuwala Arkediya (93.31 cm/ year). The lowest rate of decline of groundwater level in pre-monsoon and post-monsoon periods has been observed at Mehuwala Arkediya (30.30 cm/ year) and Nakrounda (35.93 cm/ year) respectively.



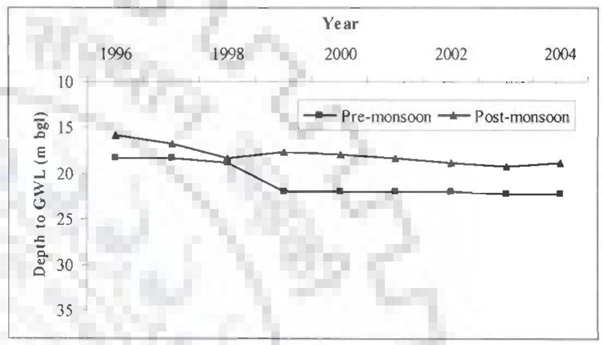
(A) Mehuwala Arkediya



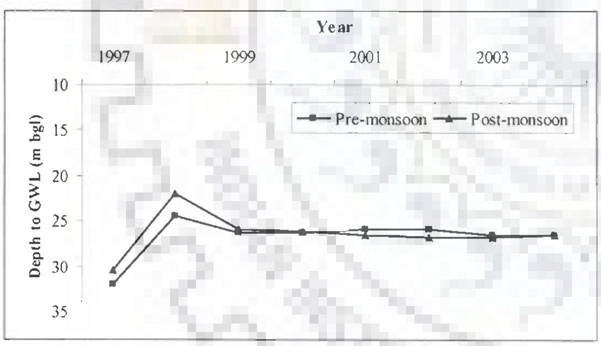
(B) Mehuwala Mafi



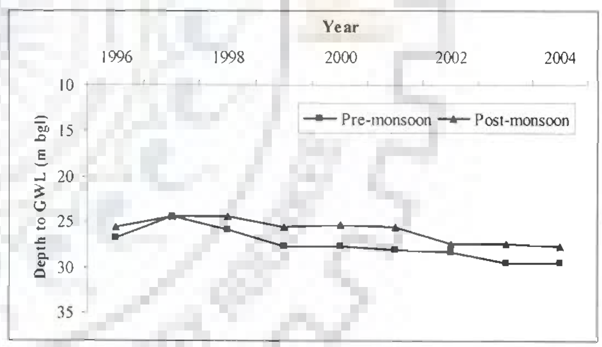
(C) Harbhajawala



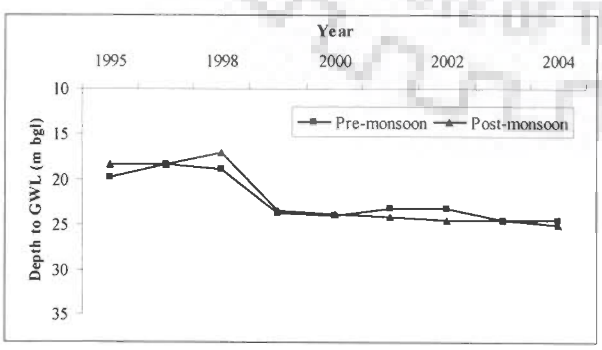
(D) Nakrounda



(E) Balawala



(F) Mothronwala



(G) Harrawala

Fig. 5.3: Groundwater level (GWL) fluctuation over the years

In contrast to the above, a rising trend of groundwater level has been observed at Balawala and Mehuwala Mafi in pre-monsoon periods but the water table at Balawala has been neither rising nor declining in post-monsoon period. The significant rate of rise in groundwater level at Balawala (about 34 cm/ year) in pre-monsoon period may probably be attributed to the possible recharge from the nearby Song river flowing towards west of the hydrograph station at about 700 m distance.

It may be pointed out that all the above seven hydrograph stations are located in areas dominated by agriculture. The overall falling trend in groundwater level indicates that exploitation of groundwater is high in these areas (which is inevitable in the absence of surface water storage schemes and as groundwater is the only source to meet the irrigation requirements of agricultural crops in these areas). Further, the average rate of decline in the groundwater levels in post-monsoon period is quite high as compared to the rate in pre-monsoon period which may be attributed to the high rate of withdrawal of groundwater for meeting the crop water irrigation requirement in the months of October and November. The usual time for harvesting the paddy (Basmati) in the Dehradun and adjoining areas is at the end of the September after which the Rabi season (winter season; October to March) crops are being grown. Therefore, after the end of the monsoon season rainfall in the month of September, the requirement of water for irrigating the Rabi crops of paddy, sugarcane and wheat besides some pulses and oil-seed crops is mainly met from groundwater.

In addition to the above-mentioned seven hydrograph stations, the recent (2005-06) groundwater level data of four hydrograph stations have also been considered for trend analysis. This also corroborates the declining trend in the groundwater levels at all the four stations during both the pre-monsoon as well as post-monsoon periods except the well at Siwalik Hills for the post-monsoon period (Table 5.2).

5.6 GROUNDWATER FLOW DIRECTION

The data (given in Annexure 5.2) obtained during groundwater monitoring (discussed in section 5.3.2) in the study area has been used for drawing the water table elevation contour maps. The water table elevation contour maps for pre-monsoon and post-monsoon periods of 2005 and 2006 are shown in Figures 5.4 to 5.7. These maps clearly show that the general flow of groundwater in the Suswa Watershed varies towards east to south-east direction, whereas in the area outside the western boundary of Suswa Watershed, the flow is in the north-west direction. The western boundary of Suswa Watershed almost coincides with the water divide which separates two major river basins of Doon Valley viz. Song in the eastward and Asan in the westward direction.

The highest water table elevation (of 749 m AMSL) recorded in the Suswa Watershed during all the four cycles of data monitoring was observed in the well at Siwalik hills, a station located near the western boundary of the Suswa Watershed. The lowest water table elevation (of 437 m AMSL) recorded in the Suswa Watershed has been in the well at Bullawala village located at about 4 km away from the outlet point and at the south-eastern boundary of the Suswa Watershed.

The depth to water table data (given in Annexure 5.2) for the pre-monsoon periods of 2005 and 06 shows a wide variation between less than 10 m bgl at Shewala Khurd to more than 50 m bgl at Balawala and Nakrounda villages. However, the water table is found to be shallow (less than 5 m, bgl) at Bullawala village and Shewala Khurd during the post-monsoon periods of 2005 and 2006. The maximum depths to water table during post-monsoon periods were observed at Yamuna Colony (22 m bgl) and at Mehuwala Mafi village (27.4 m bgl), which can be attributed to the heavy pumping of water for meeting the domestic needs of densely populated area of Yamuna Colony. The maximum depths to water tables occurring at various villages like Mehuwala Mafi, Balawala, Nakrounda, etc. can be attributed to the heavy pumping of groundwater for meeting irrigation needs of agricultural crops in addition to the fulfillment of domestic needs at these villages.

It may be clarified that to arrive at a clear picture of groundwater depths and its flow, data from a well distributed network of hydrograph stations covering entire the Suswa Watershed is essential which is presently not available. Further, it appears that the deeper aquifers in the area are mostly semi-confined in nature and thus are, in all probability, connected to the upper (unconfined) aquifers through intervening clayey aquitards. As such, the groundwater level configuration in this area seems to represent a manifestation of both the piezometric levels (pertaining to the semi-confined aquifers) and the water table (pertaining to the unconfined aquifers).

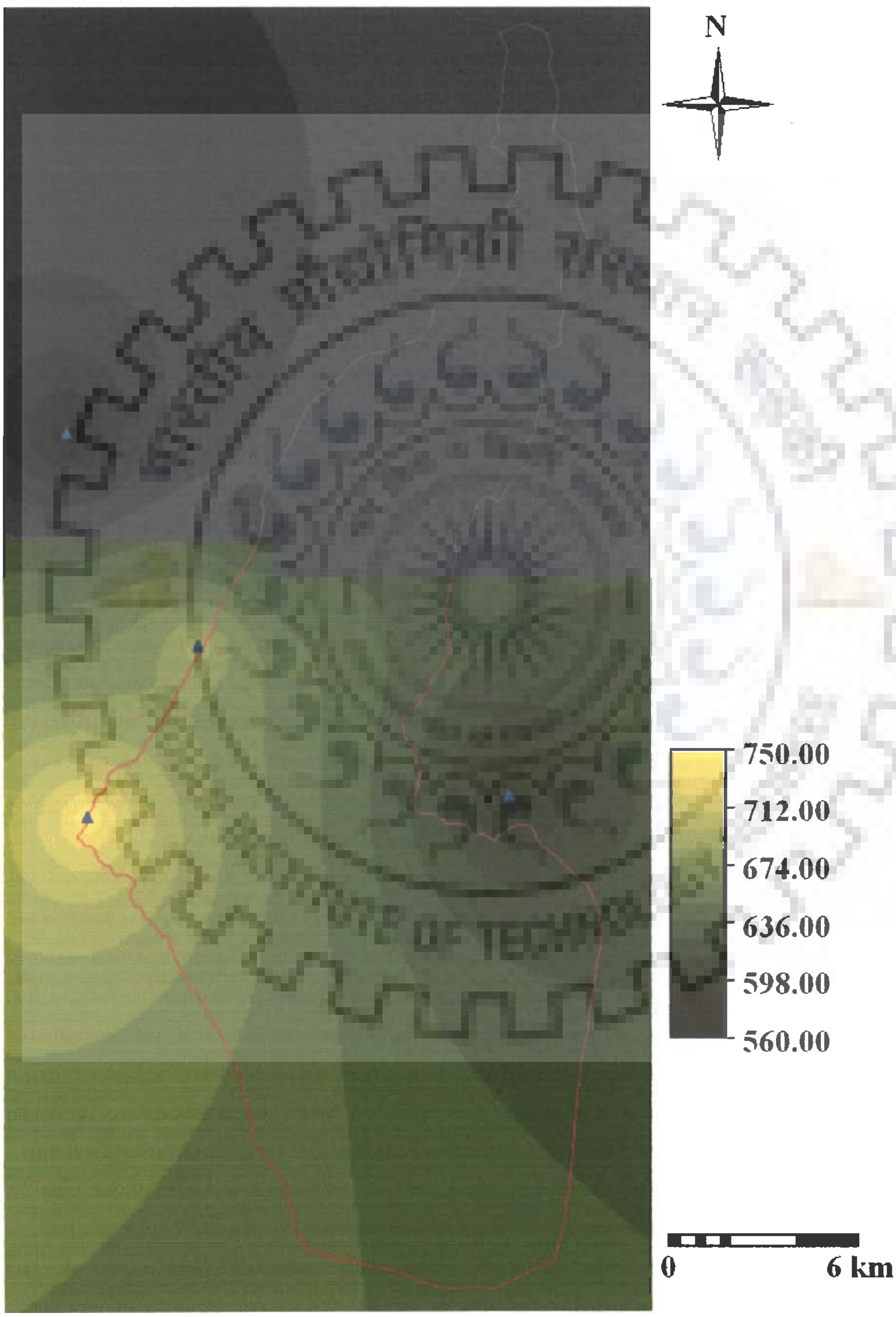


Fig. 5.4: Water table elevation (m AMSL) contour map (Pre-monsoon 2005)

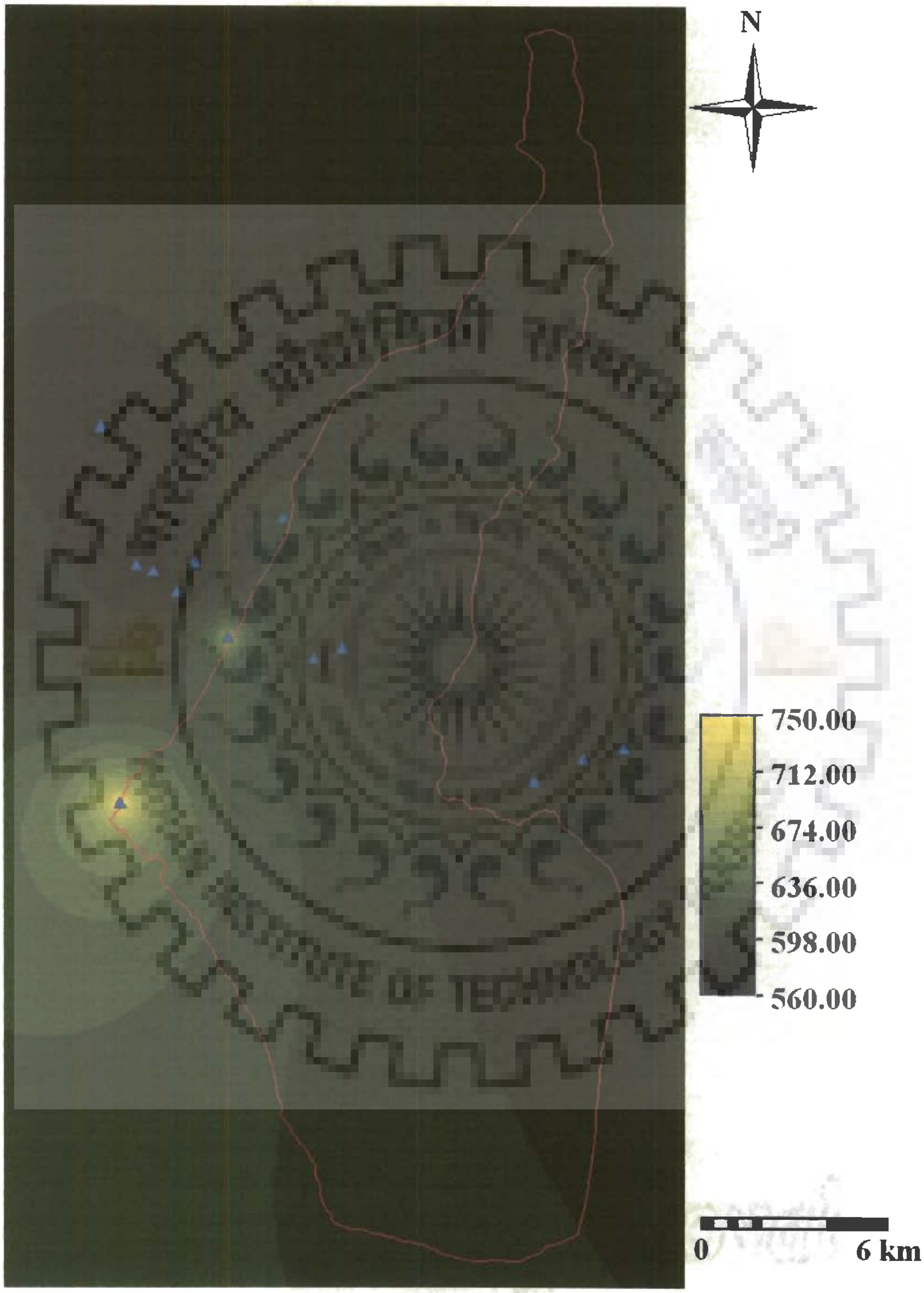


Fig. 5.5: Water table elevation (m AMSL) contour map (Post-monsoon 2005)

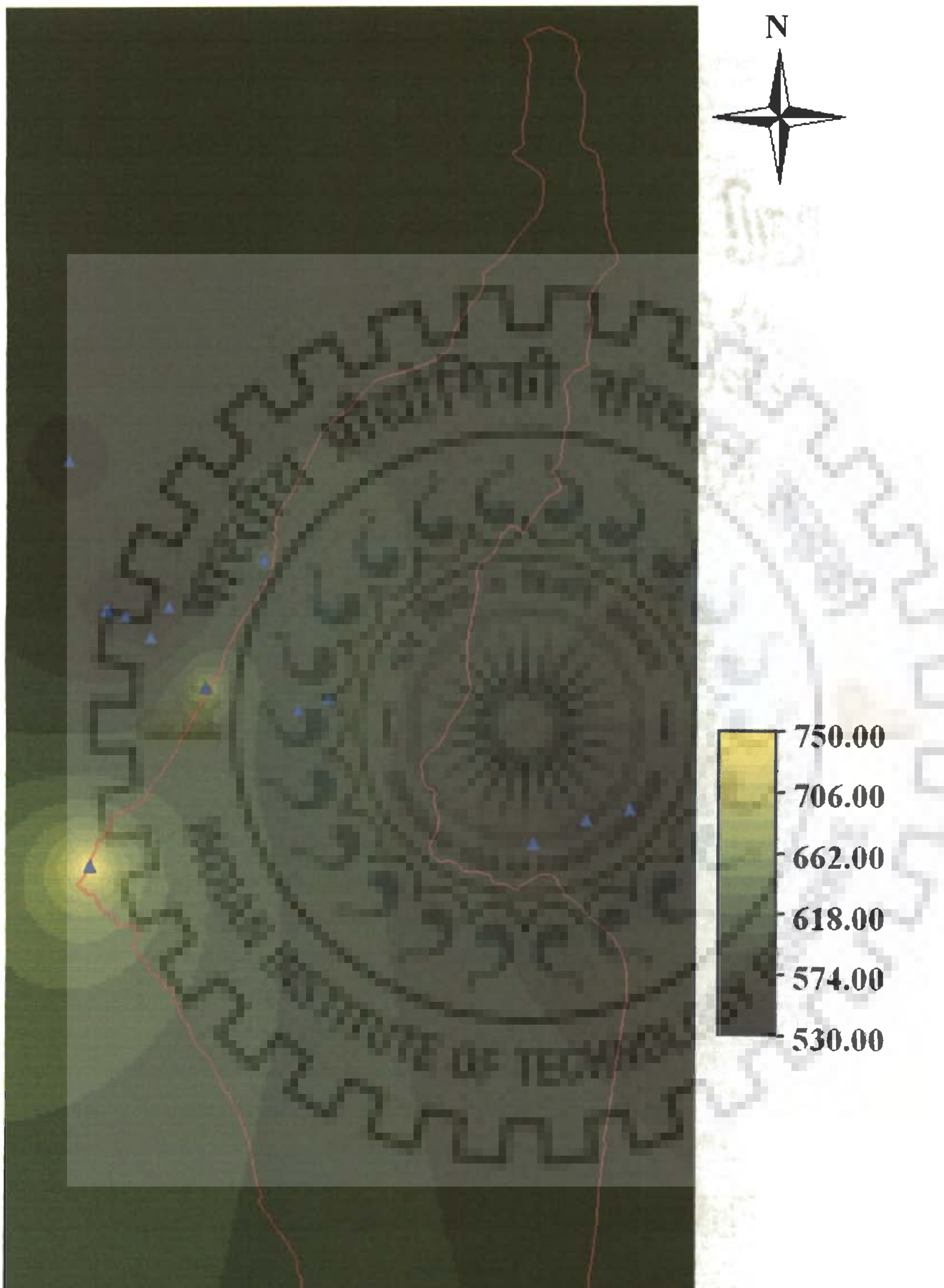


Fig. 5.6: Water table elevation (m AMSL) contour map (Pre-monsoon 2006)

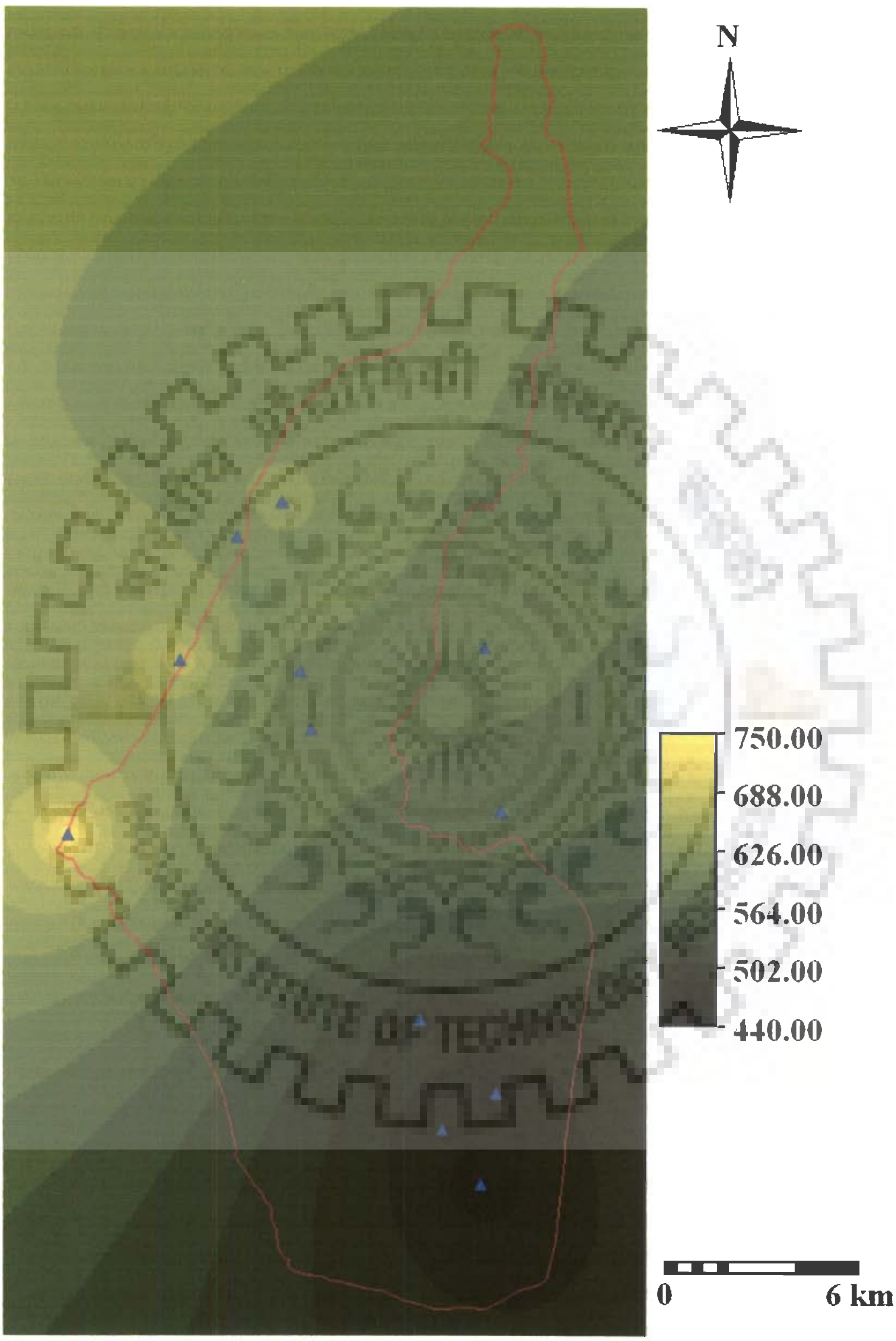


Fig. 5.7: Water table elevation (m AMSL) contour map (Post-monsoon 2006)

5.7 GROUNDWATER ESTIMATION: METHODOLOGY AND COMPUTATIONS

The groundwater assessment in the Suswa Watershed has been carried out by employing the approach of Groundwater Resource Estimation Committee (GEC-1997) (CGWB, 1997). The steps in this calculation are discussed in the following paragraphs of this section whereas computational procedure is shown in Tables 5.6 to 5.8.

5.7.1 Annual Gross Groundwater Draft

The unit groundwater draft per well for different types of wells has been estimated based on the values of unit draft worked out by using the discharge rates of wells and the number of days the wells are in actual use (CGWB, 1995) during monsoon and non-monsoon seasons. The details of computations of unit gross groundwater draft are given in Annexure 5.4, whereas the calculated unit groundwater draft values during monsoon and non-monsoon season are summarized in Table 5.5. The gross groundwater draft has been computed by multiplying the number of structures present in the command and non-command areas by the corresponding unit groundwater draft values from Table 5.5. The current annual gross groundwater drafts are 3874.68 ha-m and 300.32 ha-m in non-command and command areas respectively (Table 5.6).

Table 5.5: Unit groundwater draft during monsoon and non-monsoon season

Area	Type of structure	Groundwater draft (ha-m)	
		Monsoon	Non-monsoon
Command area	State tubewell	5.00	15.00
	Domestic private tubewell	2.20	4.60
	Industrial private tubewell	4.50	8.50
	Dug well	0.24	0.80
	Bore well with pump set	0.48	1.84
Non-command area	State tubewell	8.00	24.00
	Domestic private tubewell	3.30	6.90
	Industrial private tubewell	4.50	8.50
	Dug well	0.24	0.80
	Bore well with pump set	0.48	1.84

Table 5.6: Gross groundwater draft and recharge from 'other sources'

Sr. No.	Parameter	Value/ Description	
4.1	(a) Total area (ha)	29160.00	
	(b) Hilly area (ha) [slope > 20 %]	4480.00	
4.2	Groundwater recharge area (ha) [= 4.1(a)–4.1(b)]	24680.00	
4.3	Command area (ha)	1996.00	
4.4	Non-command area (ha)	22684.00	
Gross groundwater draft in command area in ha-m (No of structures are given in bracket)		Monsoon (A)	Non-monsoon (B)
4.5	State tubewells (10 Nos)	50.00	150.00
4.6	Private tubewells (3-domestic + 2-industrial) and dug wells (5 Nos)	16.80	34.80
4.7	Pump sets (21 Nos)	10.08	38.64
4.8	Gross groundwater draft, D_G [= 4.5+4.6+4.7]	76.88	223.44
4.9	Current annual gross groundwater draft for all uses [= 4.8(A)+4.8(B)]	300.32	
Gross groundwater draft in non-command area in ha-m (No of structures are given in bracket)		Monsoon (A)	Non-monsoon (B)
4.10	State tubewells (90 Nos)	720.00	2160.00
4.11	Private tubewells (27-domestic + 18-industrial) and dug wells (45 Nos)	180.90	375.30
4.12	Pump sets (189 Nos)	90.72	347.76
4.13	Gross groundwater draft, D_G [= 4.10+4.11+4.12]	991.62	2883.06
4.14	Current annual gross groundwater draft for all uses [= 4.13(A)+4.13(B)]	3874.68	
Recharge from 'other sources' in command area in ha-m		Monsoon (A)	Non-monsoon (B)
4.15	Recharge from canals (from Annexure 5.5)	21.89	43.78
4.16	Recharge from surface water irrigation	228.87	419.60
4.17	Recharge from groundwater irrigation	12.50	37.50
4.18	Recharge from 'other sources' [4.15+4.16+4.17]	263.26	500.88
4.19	Annual Recharge from 'other sources' in command area [= 4.18(A)+4.18(B)]	764.14	
Recharge from 'other sources' in non-command area in ha-m			
4.20	Recharge from groundwater irrigation	180.00	540.00
4.21	Annual Recharge from 'other sources' in non-command area [= 4.20(A)+4.20(B)]	720.00	

5.7.2 Annual Recharge from 'Other Sources'

The sources of groundwater recharge other than rainfall (i.e. 'other sources') in the Suswa Watershed are: (a) canals, (b) return flow from surface water irrigation, and (c) return flow from groundwater irrigation.

The recharge from these sources in command area has been computed separately during monsoon and non-monsoon season and the annual recharge from 'other sources' in command area have been arrived at by adding these values for monsoon and non-monsoon season. Likewise, annual recharge from 'other sources' in non-command area have been computed by adding the recharge from groundwater irrigation during monsoon and non-monsoon season (Table 5.6).

(a) Canals:

For computing the wetted area of canal segments, the required data of length of canal segments, design discharge of flow and base width pertaining to canals in the Suswa Watershed have been collected from Irrigation Division, Dehradun. In this calculation (tabulated in Annexure 5.5), the values of design depth have been arrived at by considering all canals as lined and rectangular in cross section. Operating days of the canals have been considered as 30 days and 60 days during monsoon and non-monsoon seasons respectively (CGWB, 1995). As per GEC-1997 norms, the canal seepage factor values of 4.0, 3.5 and 3.0 ha-m per day per Mm^2 of wetted area have been assigned to main-, branch- and minor-canal segments respectively. The recharge from canals is arrived at by multiplication of assigned seepage factors, number of canal operation days and corresponding wetted areas. This is found to be 21.89 ha-m and 43.78 ha-m during monsoon and non-monsoon season respectively (Annexure 5.5 and Table 5.6).

(b) Return flow from surface water irrigation:

Recharge due to return flow from surface water irrigation is computed only for the command area by using the design discharge data of canal segments. The total design discharge of all the canal outlets has been found to be 35.32 ha-m/day (4.09 m^3/s). As per norms, it is assumed that the actual average discharge from the canal is 0.6 times the total design discharge, thus giving the actual discharge value of 21.192 ha-m/day (35.32 × 0.6). This value multiplied by number of canal running days gave the water released from canal outlet which has been found to be 635.76 ha-m and 1271.52 ha-m during monsoon and non-monsoon seasons respectively. The return flow factors for computing recharge due to return flow from surface water irrigation in command area have been taken as 0.36 and 0.33 (using 0.4 for paddy and 0.3 for non-paddy areas) for monsoon and non-monsoon seasons respectively (CGWB, 1995). Thus, recharge from surface water irrigation in command area (Table 5.6) is worked out as 228.87 ha-m in monsoon season and as 419.60 ha-m in non-monsoon season.

(c) Return flow from groundwater irrigation:

Recharge due to return flow from groundwater irrigation is computed for the command area and the non-command area during monsoon and non-monsoon seasons by using the similar approach, as applied above for computing recharge from surface water irrigation. Amount of water applied by groundwater irrigation during a given season was considered equal to the gross groundwater draft for irrigation during that season (GEC-1997). In the command area, it was 50 ha-m during monsoon season and 150 ha-m during non-monsoon season, whereas in the non-command area it was 720 ha-m during monsoon season and 2160 ha-m during non-monsoon season. Return flow factor of 0.25 have been adopted equal for paddy and non-paddy areas for computing the recharge from water applied by groundwater irrigation in the command and non-command areas both during monsoon and non-monsoon seasons (CGWB, 1997). Multiplication of return flow factor and corresponding amounts of water applied by groundwater irrigation gave the required values of recharge due to return flow from groundwater irrigation (Table 5.6).

Taking account of above caculations, the annual recharge from 'other sources' in command area have been of the order of 764.14 ha-m and that in non-command area have been found to be 720.00 ha-m (Table 5.6).

5.7.3 Rainfall Recharge by WTF Method

The water table fluctuation (WTF) method, also known as groundwater balance method, has been employed for computing the recharge for the monsoon season only in both the command and non-command areas. The product of water table fluctuation (rise) during monsoon season (h), the specific yield (S_y), and the corresponding command and non-command areas (A) gives the change in the groundwater storage during monsoon season (ΔS). The rainfall recharge is then found by adding the gross groundwater draft to

ΔS and deducting the recharge from 'other sources' from the ΔS, for the command and non-command areas. Accordingly, the values of 'normal monsoon season rainfall' (NMR) of 1264.5 mm and average annual monsoon season rainfall for the year 2005-06 of 1739.4 mm have been employed for computing the normalized rainfall recharge during monsoon season (Table 5.7).

Table 5.7: Rainfall recharge assessment by WTF and RIF method

Sr. No.	Description	Command (A)	Non-command (B)
5.1	Average decline in groundwater level during dry season (m) [from Table 5.2]	6.21	
5.2	Average water table rise in monsoon season, h (m) [from Table 5.2]	4.96	
5.3	Specific yield, S_y (as a fraction) [from pumping test data]	0.12	
5.4	Rainfall infiltration factor (as a fraction) [from GEC-1997 norms]	0.22	
5.5	Change in groundwater storage during monsoon season (ha-m) ($\Delta S = h \times S_y \times A$) [= 5.2 × 5.3 × 4.3 or 4.4]	1188.02	13501.52
5.6	Rainfall recharge by WTF method during monsoon season (ha-m) [5.6 (A) = 5.5 (A) + 4.8 (A) – 4.18 (A)] [5.6 (B) = 5.5 (B) + 4.13 (A) – 4.20 (A)]	1001.64	14313.14
5.7	Normal rainfall recharge by WTF method during monsoon season (ha-m) [5.7(A) = 5.6 (A) × 2.13 (A)/2.13 (D)] [5.7(B) = 5.6 (B) × 2.13 (A)/2.13 (D)]	728.17	10405.29
5.8	Normal rainfall recharge by RIF method in monsoon season (ha-m) [5.8 (A) = 4.3 × 5.4 × 2.13 (A)/1000] [5.8 (B) = 4.4 × 5.4 × 2.13 (A)/1000]	555.27	6310.46
5.9	Normal rainfall recharge by RIF method in non-monsoon season (ha-m) [5.9 (A) = 4.3 × 5.4 × 2.13 (B)/1000] [5.9 (B) = 4.4 × 5.4 × 2.13 (B)/1000]	177.27	2014.66

5.7.4 Specific Yield Values

Specific yield (S_y) of 1.04 % calculated for the study area by using groundwater balance equation for dry season is found to be too low and falls much out of the ranges given in the literature (Todd, 1980; CGWB, 1997). Accordingly, geologically more logical value (of 12 %) calculated from interpretation of pumping test data for Dehradun area has been used for calculation of groundwater recharge during monsoon season (CGWB, 1995).

5.7.5 Rainfall Recharge by RIF Method

The rainfall recharge during monsoon and non-monsoon seasons of year 2005-06 has been estimated by employing the rainfall infiltration factor (RIF) method in both command and non-command areas. Rainfall recharge in the command and non-command areas by this method is the product of the corresponding areas, RIF and the normal rainfall in monsoon and non-monsoon season (Table 5.7). The value of RIF of 0.22 as recommended by GEC-1997 for sandy aquifers of Ganges alluvium has been adopted in the present study.

5.7.6 Annual Rainfall Recharge

The WTF method may yield rainfall recharge estimates which are either unreasonably high or low. This is taken care of by: (a) computing a term called the percentage difference (PD) which is the difference between the rainfall recharge by the WTF method and that by the RIF method expressed as a percentage of the latter, and (b) finally assigning a value for the rainfall recharge during monsoon season in the command and non-command areas on the basis of a set of criteria which depends on the computed value of PD.

The values of PD for monsoon season of year 2005-06 in command and non-command areas has been calculated as 31.14 % and 64.88 % respectively. As these values are more than 20 %, the rainfall recharge during monsoon season is taken as 1.2 times the normal rainfall recharge obtained by RIF method as per GEC-1997 norms. Rainfall recharge during non-monsoon season is taken as equal to the normal rainfall recharge obtained by employing the RIF method. Finally, the annual groundwater recharge from rainfall is the sum of the recharge values obtained for monsoon and non-monsoon seasons (Table 5.8).

Table 5.8: Computations for stage of groundwater development

Sr. No.	Description	Command (A)	Non-command (B)
6.1	PD between rainfall recharge estimated for monsoon season by WTF method & RIF method (%) [6.1 (A) = {5.7 (A) – 5.8 (A)}/ 5.8 (A)] [6.1 (B) = {5.7 (B) – 5.8 (B)}/ 5.8 (B)]	31.14 (> 20 %)	64.88 (> 20 %)
6.2	Recharge from rainfall during monsoon season (ha-m) [Factor 1.2 × 5.8 (A)] [Factor 1.2 × 5.8 (B)]	666.32	7572.55
6.3	Recharge from rainfall during non-monsoon season (ha-m) [6.3 (A) = 5.9 (A)] [6.3 (B) = 5.9 (B)]	177.27	2014.66
6.4	Annual groundwater recharge from rainfall (ha-m) [6.4 (A) = 6.2 (A) + 6.3 (A)] [6.4 (B) = 6.2 (B) + 6.3 (B)]	843.59	9587.21
6.5	Net annual groundwater availability (ha-m) [6.5 (A) = 6.4 (A) + 4.19] [6.5 (B) = 6.4 (B) + 4.21]	1607.73	10307.21
6.6	Stage of groundwater development (%) [6.6 (A) = (4.9/6.5 (A)} × 100] [6.6 (B) = (4.14/6.5 (B)} × 100]	18.68	37.59
6.7	Categorization for future groundwater development	SAFE	SAFE

5.7.7 Stage of Groundwater Development

The stage of groundwater development in a given area is defined as a ratio of the current annual gross groundwater draft for all uses to the net annual groundwater availability in that area. Net annual groundwater availability has been arrived at by summing up the annual groundwater recharge from rainfall and the annual recharge from 'other sources', which is of the order of 11914.94 ha-m (or 119.15 million-m^3) for the Suswa Watershed. The stage of groundwater development in the Suswa Watershed has thus been found as 18.68 % in command area and 37.59 % in non-command area, whereas overall stage for the whole Suswa Watershed (for command- and non-command area) is of the order of 35.04 %.

As discussed in section 5.5, the long-term groundwater levels in the Suswa Watershed are declining at a considerable rate of about 0.3 to 0.6 m per year during pre-monsoon and post-monsoon periods respectively. The declining trend of groundwater levels and the overall estimated groundwater development stage of 35 % put the Suswa Watershed in 'Safe' category. Accordingly, further groundwater development can be allowed as the present groundwater development is said to be sustainable. However, further groundwater development may not be considered sustainable in the study area in the light of the declining trend of groundwater levels. Yet, some workers like Kalf and Woolley (2005) question role of water level fluctuations in deciding the sustainability of groundwater resources of a basin.

5.8 CONCLUDING REMARKS

The estimated overall groundwater development stage of about 35 % shows that there is a possibility for future development of groundwater resources in the Suswa Watershed as and when required. However, during further development of groundwater, there is urgent need to watch the long-term declining trend of groundwater levels in both pre-monsoon and post-monsoon periods. Indiscriminate groundwater development may lead to profound adverse effects like over-exploitation associated with increase in the pumping cost and land subsidence etc. due to excessive lowering of groundwater levels making future groundwater development unsustainable. Still, these conclusions have to be considered with a sense of skepticism in light of strong views expressed by Kalf and Woolley (2005) that "water levels alone are ambiguous and cannot be relied upon to determine whether a system yield is sustainable or not." Thus, it appears that though the present method of groundwater budgeting followed in India considers long-term trend of water level fluctuation in a basin as an important component of groundwater sustainability, the approach itself seems to be quite viable as it is based on the safe yield concept derived from a mass balance principle. As such, these estimations should afford a fair degree of confidence to the decision makers and stake holders about the extent of groundwater availability even with the contrary behaviour of water levels.

Notwithstanding the above comments, it is significant to highlight the impact of recharge which is essential in arresting the declining trend of groundwater levels in the Suswa Watershed. Accordingly, it is imperative to take up large scale construction of water conservation structures in the hilly terrain of the study area and in line with some metro cities in the country, rooftop rain water harvesting schemes may also be made mandatory in the Dehradun city for the sustainable development and management of groundwater resources.

Chapter 6

ASSESSMENT OF WATER QUALITY

6.1 GENERAL

The role of regular monitoring of water quality is widely recognized, as water without quality aspects is of little significance in terms of usage. It is accepted by all users that water should be considered safe for consumption only if its quality is regularly monitored and considered acceptable by health officials. In a number of studies worldwide, poor water quality has been analyzed as one of the chief reasons for unsustainability of water resources. The physical, chemical, biological and hygienic properties of groundwater determine its usefulness for various purposes viz. agricultural, domestic and industrial use (Matthess, 1982). The physical and chemical characteristics of groundwater in a watershed can vary considerably from place to place because of natural factors and the anthropogenic influences to which the area has been subjected. Therefore, an overall approach for assessment of sustainability of water quality within a watershed needs to be developed.

This chapter deals with the analysis of water quality in the study area. The findings from the interpretation of the data from chemical analysis of water samples are presented. The objective of this study is to check the quality of water resources in the Suswa Watershed for its usefulness in domestic use considering the procedures, standards and criteria laid down by various workers and national regulatory agencies like Bureau of Indian Standards (BIS).

6.2 GROUNDWATER SAMPLING PROGRAMME

While deep production wells require sampling every year to every few years (because changes in water quality for such wells would be gradual), the shallower wells, particularly domestic wells with smaller pumping rates, need to be sampled more frequently because they are increasingly prone to short-term variations in groundwater quality and contamination (Harter, 2003). In this study, a total of 36 groundwater samples across the Suswa Watershed have been collected during the field visits in 2005 and 2006. During the field campaign carried out in post-monsoon- 2005, groundwater was sampled from 8 hydrograph stations. In pre-monsoon- 2006, the groundwater was tested from 13 hydrograph stations whereas 15 hydrograph stations were sampled in the post-monsoon- 2006. Further, one surface water sample from the Suswa river was also collected during post-monsoon- 2006. The locations of the monitored hydrograph stations in and around the watershed are shown in Fig. 5.1 and their location details (latitude, longitude and GPS altitude) are given in Annexure 5.1. The groundwater samples have been collected either from hand pumps/ dug wells (which draw water from the shallow unconfined aquifer) or production tubewells (which draw water from the deep confined aquifer) as per their availability in the study area. About 58 % of groundwater samples have been collected from the shallow unconfined aquifer and remaining 42 % from the deep (> 30 m depth) semi-confined/ leaky aquifer (Table 6.1).

Table 6.1: Details of groundwater samples

Period and year	Groundwater sample taken from		Total samples
	Hand pump/ dug well	Tubewell	
Post-monsoon- 2005	5	3	8
Pre-monsoon- 2006	7	6	13
Post-monsoon- 2006	9	6	15
Total samples (% of total)	21 (58.3)	15 (41.7)	36 (100)

Hem (1985) has presented guidelines for sampling and preservation of water samples. Prior to the commencement of sampling, the field sampling equipment were cleaned and calibrated as per his recommendations. Field sampling equipment included water level indicator, water quality measuring kit (including hand-held probes for measuring water temperature, electrical conductivity (EC) and pH), sampling bottles and storage containers for storing sampling bottles. Prior to the collection of the groundwater sample, the well (or hand pump) was purged to remove the stagnant water to ensure that the water sample is representative of the aquifer formation being sampled. As a thumb rule, a minimum of three to five well volumes of water were purged as recommended by Harter (2003). The groundwater samples were collected in the sampling bottles immediately after purging and labeled. All sample bottles were filled completely, capped and put into containers and transported to the laboratory. Proper preservation was done to ensure that the water quality of the sample did not change between the time of its collection (in the field) and the time of its analysis in the laboratory.

6.3 WATER QUALITY ANALYSIS

Considerable efforts have been put into the development of standard analytical procedures for estimation of various constituents in natural water. In the present study, the procedures followed for water quality analysis were in accordance with the 'Standard Methods for Examination of Water and Waste Water' (APHA, 1995) as summarized in Annexure 6.4. The analysis was carried out in the laboratories of Department of Hydrology and Institute Instrumentation Center, Indian Institute of Technology Roorkee, Roorkee (some related photographs are shown in Annexure 3.1). Further, the values of water quality parameters have been compared with the relevant Indian drinking water quality standards (BIS: 10500, 1991), as the water is reportedly being used for drinking by sizeable population in the study area. Table 6.2 shows the criteria for the concentrations of various physico-chemical parameters and heavy metals as laid down in India for drinking (BIS: 10500, 1991). However, these standards do not include the criteria for sodium, potassium, phosphate and nickel. Therefore, the water quality standards used internationally are employed for these parameters (WHO, 1971 and 1998; CHASDWR, 2001) (Table 6.3). The different physico-chemical parameters along with selected heavy metals and nutrients analyzed in the water samples are listed along with a summary of their ranges in Table 6.3.

Analytical results of the physico-chemical constituents (along with ion balancing) in groundwater samples are given in Annexure 6.1 to Annexure 6.3 whereas the results of analysis for the heavy metals are given in Table 6.6 (A) to Table 6.6 (C). The variation in physico-chemical parameters has been shown by bar diagrams in Fig. 6.1 (A-1) to (G-1) during pre-monsoon- 2006 and Fig. 6.1 (A-2) to (G-2) during post-monsoon- 2006. The circular diagrams given in Fig. 6.2 to Fig. 6.4 present the synoptic view of groundwater constituents at various locations in the study area. The percent 'ion balance error' ('e' in %) of these water samples has been computed as under:

$$e = \frac{\sum(Cations) - \sum(Anions)}{\sum(Cations) + \sum(Anions)} \times 100 \qquad (6.1)$$

Table 6.2: Indian standards for drinking water quality (BIS: 10500, 1991)

Sl. No.	Substance or characteristics	Desirable limit	Permissible limit in the absence of alternate source	Undesirable effects outside the desirable limit
1	pH value, Range	6.5-8.5	No relaxation	Beyond this range the water will affect the mucous membrane and/or water supply
2	Total hardness (as $CaCO_3$) (mg/L), Maximum	300	600	Encrustation in water supply structure and adverse effects on domestic use
3	Total alkalinity (as $HCO_3 + CO_3$) (mg/L), Maximum	200	600	Alkalinity is not detrimental to humans (IDPH, 2010)
4	Calcium (as Ca) (mg/L), Maximum	75	200	Encrustation in water supply structure and adverse effects on domestic use
5	Magnesium (as Mg) (mg/L), Maximum	30	100	Encrustation in water supply structure and adverse effects on domestic use
6	Copper (as Cu) (mg/L), Maximum	0.05	1.5	Beyond this limit astringent taste, discoloration and corrosion at pipes, fittings and untensils caused
7	Iron (as Fe) (mg/L), Maximum	0.3	1.0	Beyond this limit taste/ appearance are affected, has adverse effect on domestic uses and water supply structures, and promote iron bacteria
8	Manganese (as Mn) (mg/L), Maximum	0.1	0.3	Beyond this limit taste/ appearance are affected, has adverse effect on domestic uses and water supply structures
9	Chloride (as Cl) (mg/L), Maximum	250	1000	Beyond this limit taste, corrosion and palatability are affected
10	Sulfate (as SO_4) (mg/L), Maximum	200	400	Beyond this causes gastro intenstinal irritation when magnesium or sodium is also present
11	Nitrate (as NO_3) (mg/L), Maximum	45	No relaxation	Beyond this methemoglobinemia takes place
12	Cadmium (as Cd) (mg/L), Maximum	0.01	No relaxation	Beyond this the water becomes toxic
13	Zinc (as Zn) (mg/L), Maximum	5	15	Beyond this limit it can cause astringent taste and an opalescence in waters
14	Chromium (as Cr) (mg/L), Maximum	0.05	No relaxation	May be carcinogenic above this limit

Table 6.3: Statistical summary of groundwater quality data

Characteristics	Minimum	Maximum	Median	Mean	Standard deviation	**BIS standard**
Physical properties						
pH	5.9	8.3	7.6	7.5	0.5	**6.5-8.5**
Temperature, (°C)	19.6	25.4	23.3	23.2	1.3	-
Electrical conductivity (μmhos/cm)	100.0	700.0	200.0	282.1	186.7	-
Total dissolved solids (mg/L)	267.0	638.0	416.5	415.4	75.8	**500**
Total hardness (mg/L)	112.0	534.0	247.0	263.5	89.1	**300**
Major ions (mg/L)						
Calcium (Ca^{2+})	22.4	72.0	59.2	56.9	12.7	**75**
Magnesium (Mg^{2+})	14.1	89.4	37.1	38.5	16.7	**30**
Sodium (Na^+)	1.5	12.5	6.7	6.0	2.9	**200#**
Potassium (K^+)	1.4	10.3	2.7	4.1	3.0	-
Total alkalinity ($HCO_3^- + CO_3^{2-}$)	24	336	179	175	90	**200**
Sulfate (SO_4^{2-})	73	335	198	186	72	**200**
Chloride (Cl^-)	2	31	12	13	9	**250**
Nutrients (mg/L)						
Nitrate (NO_3^-)	0.05	57.20	11.72	16.27	14.75	**45**
Phosphate (PO_4^{3-})	0.03	5.83	1.40	1.75	1.44	**5$**
Heavy Metals (μg/L)						
Zinc (Zn)	ND	2638	67	422	712	**5000**
Manganese (Mn)	ND	70	ND	7	17	**100**
Iron (Fe)	ND	1580	ND	65	299	**300**
Nickel (Ni)	ND	226	54	71	73	**20***
Copper (Cu)	ND	45	ND	2	9	**50**
Cadmium (Cd)	ND	45	6	12	14	**10**
Chromium (Cr)	ND	199	11	37	58	**50**

ND = Not detected; $WHO (1971); *WHO (1998); #CHASDWR (2001)

where, 'cations' means concentration of each cation and 'anions' means concentration of each anion, both in milli-equivalents per litre (meq/L). For the values of each parameter to be acceptable in interpretation, Hem (1985) suggested that the value of 'e' for each analysis should be less than 10 %.

In the present study, the values of 'e' for all samples (except for the samples of post-monsoon- 2005) are within the acceptable limit of 10 %, thus showing the acceptability of physico-chemical analysis for samples of pre-monsoon and post-monsoon-2006.

The physico-chemical analysis of the groundwater samples mainly includes cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), anions (Cl^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}), and nutrients (NO_3^-, PO_4^{3-}) besides the physical attributes like total dissolved solids (TDS), EC and pH. The groundwater samples collected during post-monsoon period of 2005 (Annexure 6.1) have not been considered for interpretation of water quality as the values of 'ion balance error (e)' for all these samples are quite high (most values are close to 20 %).

A consolidated statistical summary (range, mean, median and standard deviation values) of the measured water quality parameters is presented in Table 6.3. It is seen that some constituents (like EC, TDS, total hardness, total alkalinity, calcium, magnesium, sulfate, nitrate, and heavy metals like zinc, iron, nickel and chromium) exhibit high standard deviation reflecting a high degree of variation from the corresponding mean values. Table 6.4 shows the number of samples violating the Indian drinking water quality standards (viz. BIS: 10500, 1991). An explanation of the observed characteristics is given in the following sections.

6.4 PHYSICAL PROPERTIES

6.4.1 Electrical Conductivity and pH

The specific conductance or electrical conductivity of fresh groundwater usually ranges between 30 and 2000 μmhos/cm (Matthess, 1982). The EC values for the groundwater samples of the study area have been found to range between 100 and 700 μmhos/cm, the maximum being at Shewala Khurd and a very high variation from the mean value as revealed by the high standard deviation (of about 187 μmhos/cm).

The hydrogen ion concentration (pH) indicates acidity or alkalinity of the water. The median pH value has been observed to be 7.6 with the minimum value of 5.9 (at Kuawala) and maximum being 8.3 (at Raipur). Low and high pH cause corrosion in water supply lines and household plumbing fixtures. It is observed that the pH values are within the desirable range of the Indian standards at all stations except the one at Kuawala (Fig. 6.1 (A-1) and (A-2)). In almost all the samples, the value of pH is more than 7 indicating the alkaline nature of groundwater. The water temperature values for all the samples are constant at around 23.2 °C.

Table 6.4: Violation of drinking water quality standards in groundwater samples (total samples considered: 28)

Characteristics	No of samples	% of samples
pH	1	3.6
Total dissolved solids (mg/L)	3	10.7
Total hardness (mg/L)	7	25.0
Calcium (Ca^{2+})	0	0.0
Magnesium (Mg^{2+})	16	57.1
Total alkalinity ($HCO_3^- + CO_3^{2-}$)	10	35.7
Sulfate (SO_4^{2-})	13	46.4
Chloride (Cl^-)	0	0.0
Nitrate (NO_3^-)	1	3.6
Phosphate (PO_4^{3-})	1	3.6
Zinc (Zn)	0	0.0
Manganese (Mn)	0	0.0
Iron (Fe)	1	3.6
Nickel (Ni)	17	60.7
Copper (Cu)	0	0.0
Cadmium (Cd)	12	42.9
Chromium (Cr)	7	25.0

6.4.2 Total Dissolved Solids

Total dissolved solids (TDS) include both organic and inorganic material dissolved in a sample of water (Bates and Jackson, 1984) and are commonly used as a general indicator of water salinity or quality. Water with a high dissolved solids concentration can produce scaly deposits and cause staining, wear or corrosion of pipes and fittings. Excessively large concentrations of dissolved solids are objectionable in drinking water because of possible physiological effects, unpalatable mineral taste and higher cost due to corrosion or necessity of additional treatment (US EPA, 1986). The median concentration of TDS has been observed to be 416 mg/L with a range of 267-638 mg/L. Out of all the samples, only three samples showed values higher than the Indian standard of 500 mg/L at Shewala Khurd (both pre- and post-monsoon samples of 2006) and Arkediya Grant (pre-monsoon- 2006) (Fig. 6.1 (B-1) and (B-2)). At Shewala Khurd, the sample was collected from a dug well having very shallow water level (< 4 m) and hence, it may be affected by probable contaminants derived from direct entry of surface water into it. Besides, marginally high TDS may not warrant rejection of the groundwater merely on the basis of this single parameter and as per Indian standards for drinking water, TDS values upto extended limit of 2000 mg/L in groundwater may be recommended in the absence of an alternate source (BIS: 10500, 1991).

6.4.3 Total Hardness

Among the physico-chemical parameters, hardness seems to be a significant factor for acceptance of groundwater for drinking. Use of hard water in drinking may cause problem of indigestion to users besides formation of encrustations in the water supply pipes. However, as laid down in BIS standards, in the absence of an alternate source, the limit (of 300 mg/L) may be extended upto 600 mg/L (BIS: 10500, 1991). The total hardness in the groundwater of the study area varies between 112 and 534 mg/L with a high deviation from the mean value, as reflected by standard deviation of 89 mg/L. The maximum concentration of Ca^{2+} observed in the study area is 72 mg/L (at Madhowala), which is within the desirable limit of 75 mg/L (Table 6.3). The standard (of 30 mg/L) for Mg^{2+} has been violated in case of 16 samples (Table 6.4) (Fig. 6.1 (C-1) and (C-2)). However, as laid down in BIS standards, in the absence of an alternate source, the desirable limit for Mg^{2+} concentration (of 30 mg/L) may be extended upto 100 mg/L (BIS: 10500, 1991). Thus, the high total hardness values in the study area reflect the combined result of high concentrations of Ca^{2+} and Mg^{2+} (Fig. 6.2 to 6.4).

Softness (or hardness) of water based on the values of total hardness (as $CaCO_3$) is assessed on a set of criteria as given in Table 6.5. From the mean (247 mg/L) and median (about 264 mg/L) of hardness values, the groundwater in the study area can be categorized as 'hard' (Table 6.3). Also a look at Table 6.4 reveals that a total of 25 % groundwater samples exhibit total hardness more than 300 mg/L, thus categorizing the groundwater in 'very hard' category. However, the margin by which the hardness exceeds the BIS limit is not very large (barring localities like Shewala Khurd, Kaonli, Yamuna Colony, etc.) in terms of the guidelines of the regulatory agencies. Further, its adverse effects can be considered marginal as the population of the study area has almost adjusted to these ranges of hardness in drinking water, though reports indicate some difficulty of users regarding indigestion by consuming such hard waters.

Table 6.5: Classification of water based on its total hardness (Source: Todd, 1980)

Water class	Total hardness (as $CaCO_3$), mg/L
Soft	0 - 75
Moderately soft	75 - 150
Hard	150 - 300
Very hard	> 300

6.5 MAJOR IONS

The analysis indicates that Ca^{2+} and Mg^{2+} (discussed in section 6.4.3) are the dominant cations while SO_4^{2-}, HCO_3^- and CO_3^{2-} are the dominant anions, reflecting the chemical maturity of the groundwater with the rock matrix in the study area. The groundwater displays the diverse range of quality and chemistry of the prominent ions reflecting the mineral composition of geological material contacted by the groundwater in the study area. The results indicate a moderate to high variation in the concentration of major ions. Strong violation of Indian standards has been exhibited by Mg^{2+}, SO_4^{2-} and total alkalinity ($HCO_3^- + CO_3^{2-}$). It is worth mentioning that about 57 %, 46 % and 36 % of groundwater samples have been violating the Indian drinking water standards for Mg^{2+}, SO_4^{2-} and total alkalinity respectively (Table 6.4).

6.5.1 Sodium and Potassium

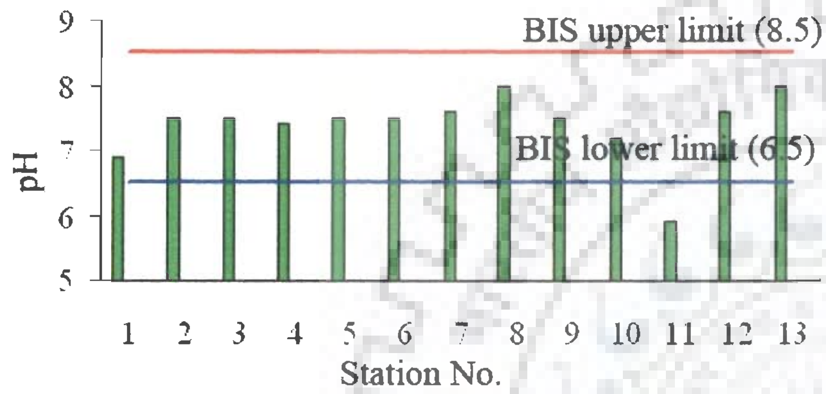
Hem (1970) reported that K^+ is more abundant than Na^+ in sedimentary formations. The maximum permissible values for Na^+ and K^+ have not been listed in the Indian standards (BIS: 10500, 1991). But as reported by Matthess (1982), the Na^+ content of groundwater in humid climates is mostly of the order of 1 to 20 mg/L and the maximum permissible limit for drinking water in Canada (CHASDWR, 2001) is 200 mg/L. The range of Na^+ concentration in the present study area is 1.5-12.5 mg/L whereas that of K^+ is 1.4-10.3 mg/L. The median concentration values of Na^+ and K^+ are 6.7 and 2.7 mg/L respectively (Table 6.3), thus showing the concentration of Na^+ within the ranges given by Matthess (1982) and CHASDWR (2001).

6.5.2 Total Alkalinity

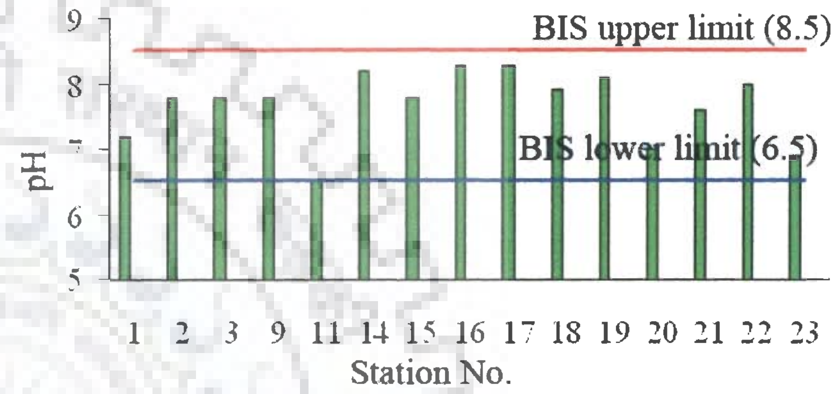
The desirable limit of total alkalinity is 200 mg/L as per Indian standards. It is observed from the Table 6.4 that the concentration of total alkalinity is higher than the Indian standard at ten localities (Fig. 6.1 (D-2)). The range of alkalinity is 24-336 mg/L with a quite high variation in values from the mean value of 175 mg/L (Table 6.3). However, high concentration of alkalinity in drinking water is not known to cause any direct noticeable adverse effects on the human health (IDPH, 2010). Moreover, the maximum permissible limit can be extended to 600 mg/L in the absence of alternate drinking water source (BIS: 10500, 1991).

6.5.3 Sulfate

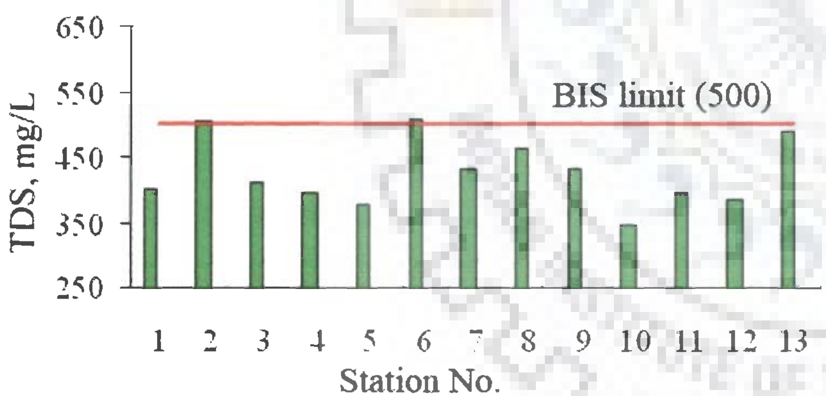
Sulfate is a sensitive physico-chemical parameter in groundwater used for drinking purposes. The maximum desirable limit as per Indian standards is 200 mg/L. If the concentration is higher beyond the desirable limits, it may cause the gastrointestinal problems in users especially when Mg^{2+} and Na^+ are also present in water. It is observed that the concentration of sulfate has the range of 73-335 mg/L and median concentration observed is 198 mg/L (Table 6.3). The BIS limit of sulfate concentration in groundwater is violated in about 46 % of samples considered (Table 6.4) (Fig. 6.2 to 6.4). It is noteworthy that the samples taken in predominantly agricultural areas (station numbers 1 to 9 and 11 to 13 in Fig. 5.1) are found to violate the Indian standard (Fig. 6.1 (E-1) and (E-2)). However, the maximum permissible limit can be extended to 400 mg/L in the absence of alternate drinking water source.



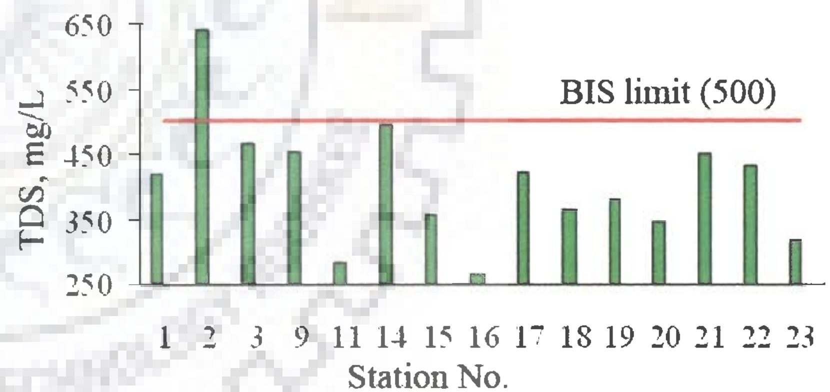
(A-1): pH (Pre-monsoon)



(A-2): pH (Post-monsoon)

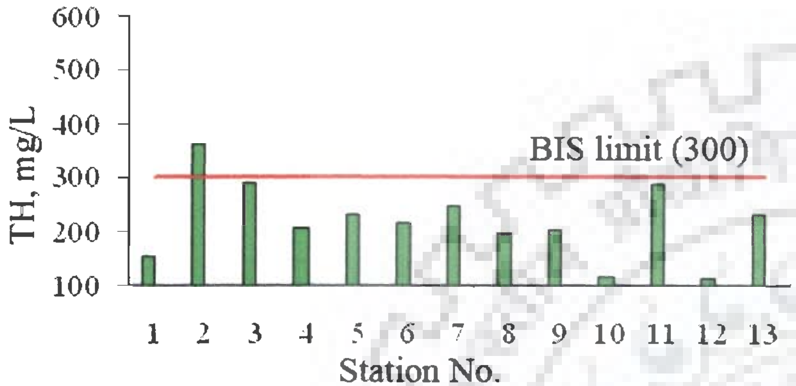


(B-1): Total Dissolved Solids (Pre-monsoon)

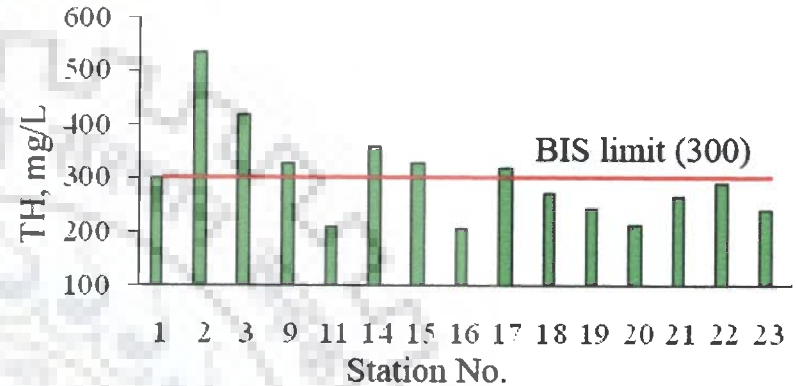


(B-2): Total Dissolved Solids (Post-monsoon)

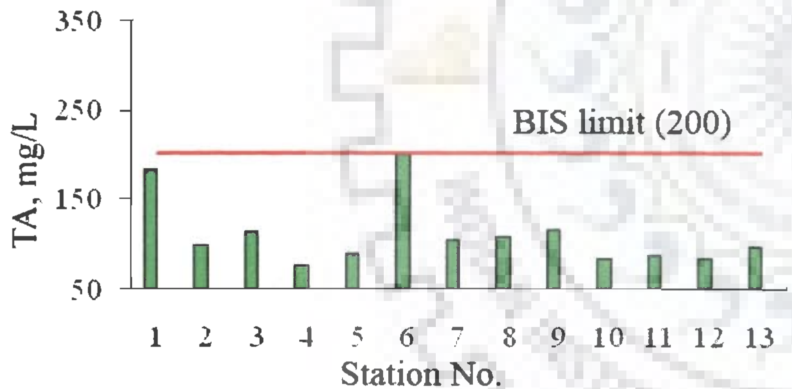
Fig. 6.1: Bar diagrams showing variation of physico-chemical parameters in groundwater (Year 2006) (Continued)



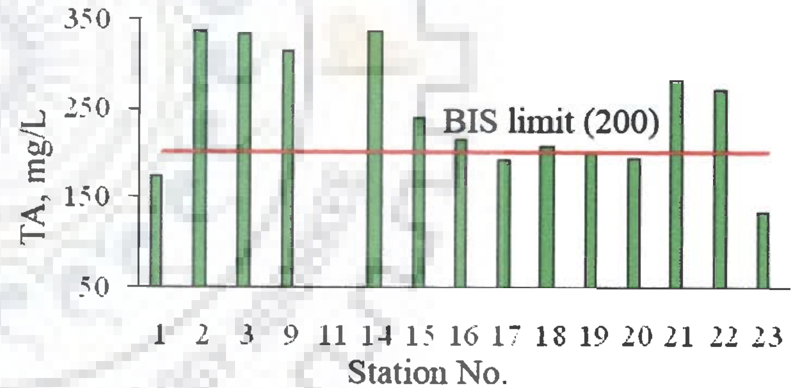
(C-1): Total Hardness (Pre-monsoon)



(C-2): Total Hardness (Post-monsoon)

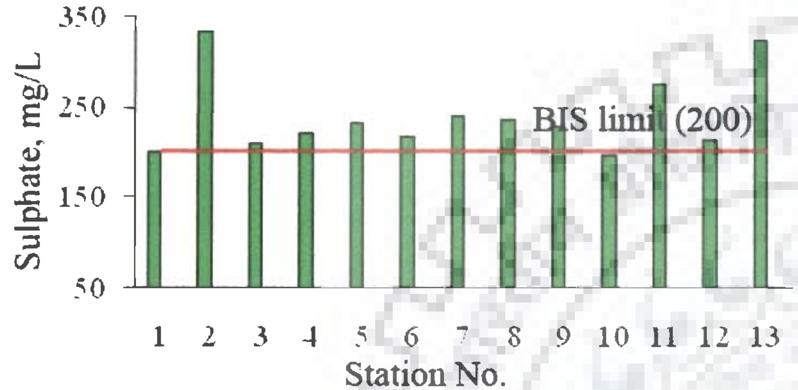


(D-1): Total Alkalinity (Pre-monsoon)

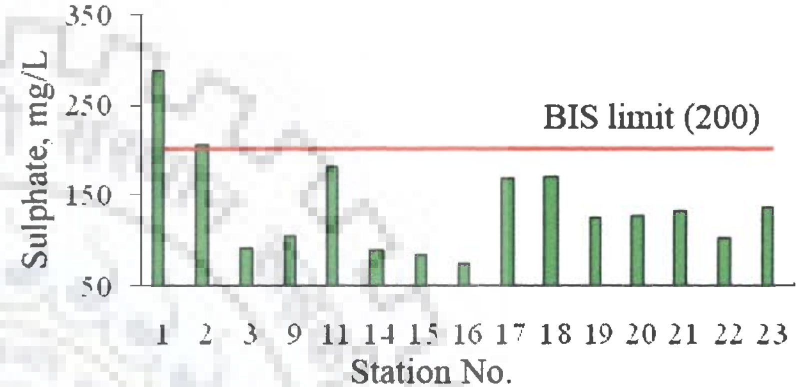


(D-2): Total Alkalinity (Post-monsoon)

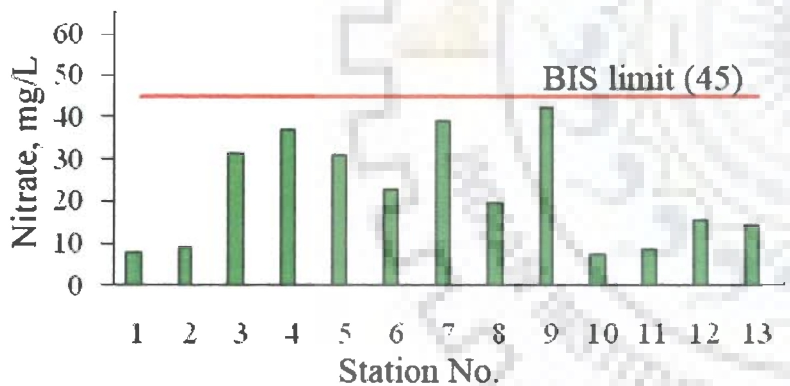
Fig. 6.1: Bar diagrams showing variation of physico-chemical parameters in groundwater (Year 2006) (Continued)



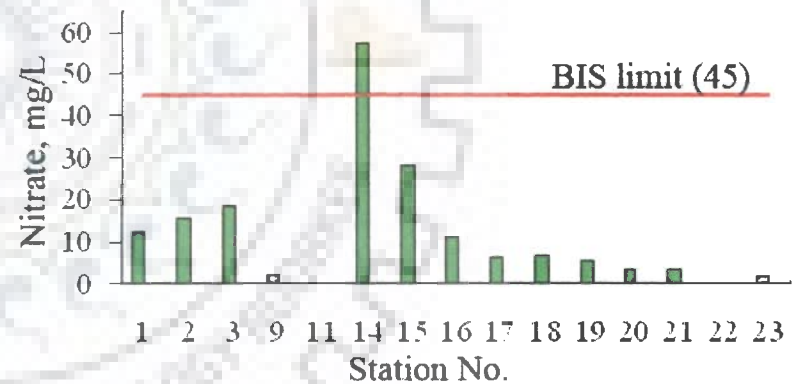
(E-1): Sulfate (Pre-monsoon)



(E-2): Sulfate (Post-monsoon)

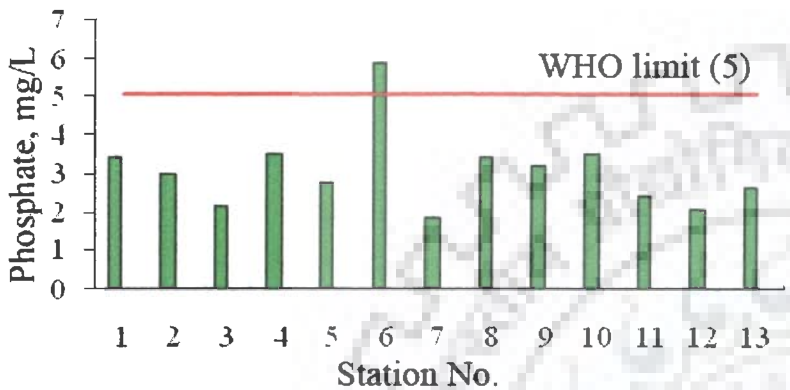


(F-1): Nitrate (Pre-monsoon)

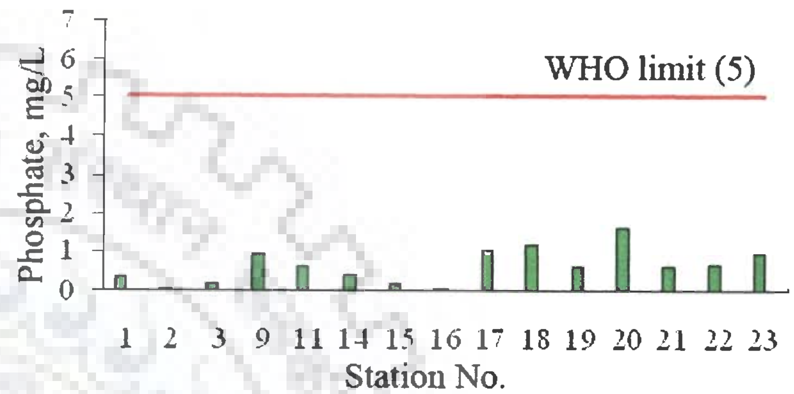


(F-2): Nitrate (Post-monsoon)

Fig. 6.1: Bar diagrams showing variation of physico-chemical parameters in groundwater (Year 2006) (Continued)



(G-1): Phosphate (Pre-monsoon)



(G-2): Phosphate (Post-monsoon)

Fig. 6.1: Bar diagrams showing variation of physico-chemical parameters in groundwater (Year 2006)

6.5.4 Chloride

The desirable limit of chloride is 250 mg/L and may cause bad taste and may affect palatability among the users if taken in higher concentration. The range of chloride is found as 2-31 mg/L in the groundwater which is in the acceptable range as per Indian standard (Table 6.3).

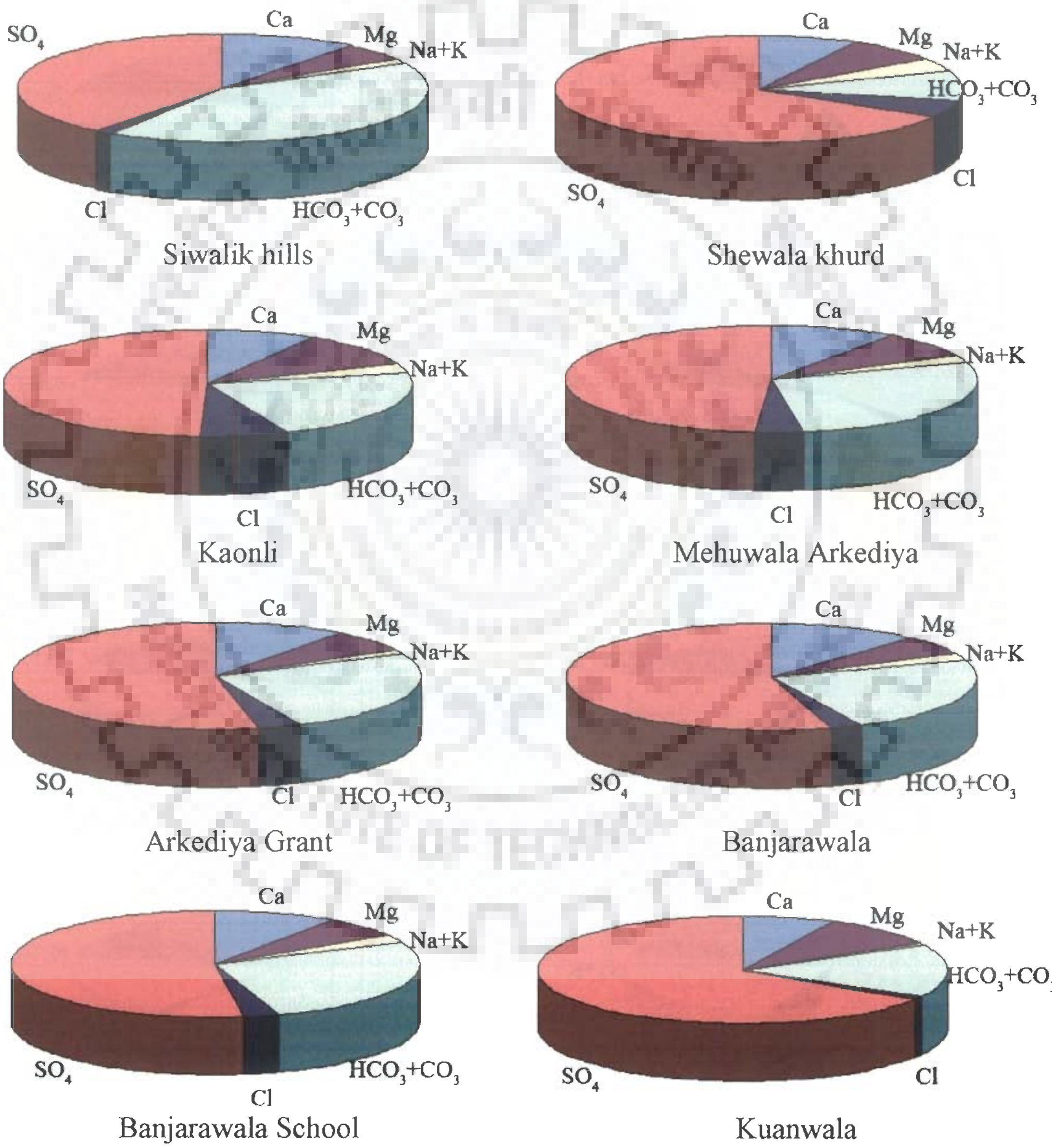


Fig. 6.2: Circular diagrams representing analysis of groundwater for different locations in the Suswa Watershed (Post-monsoon- 2005)

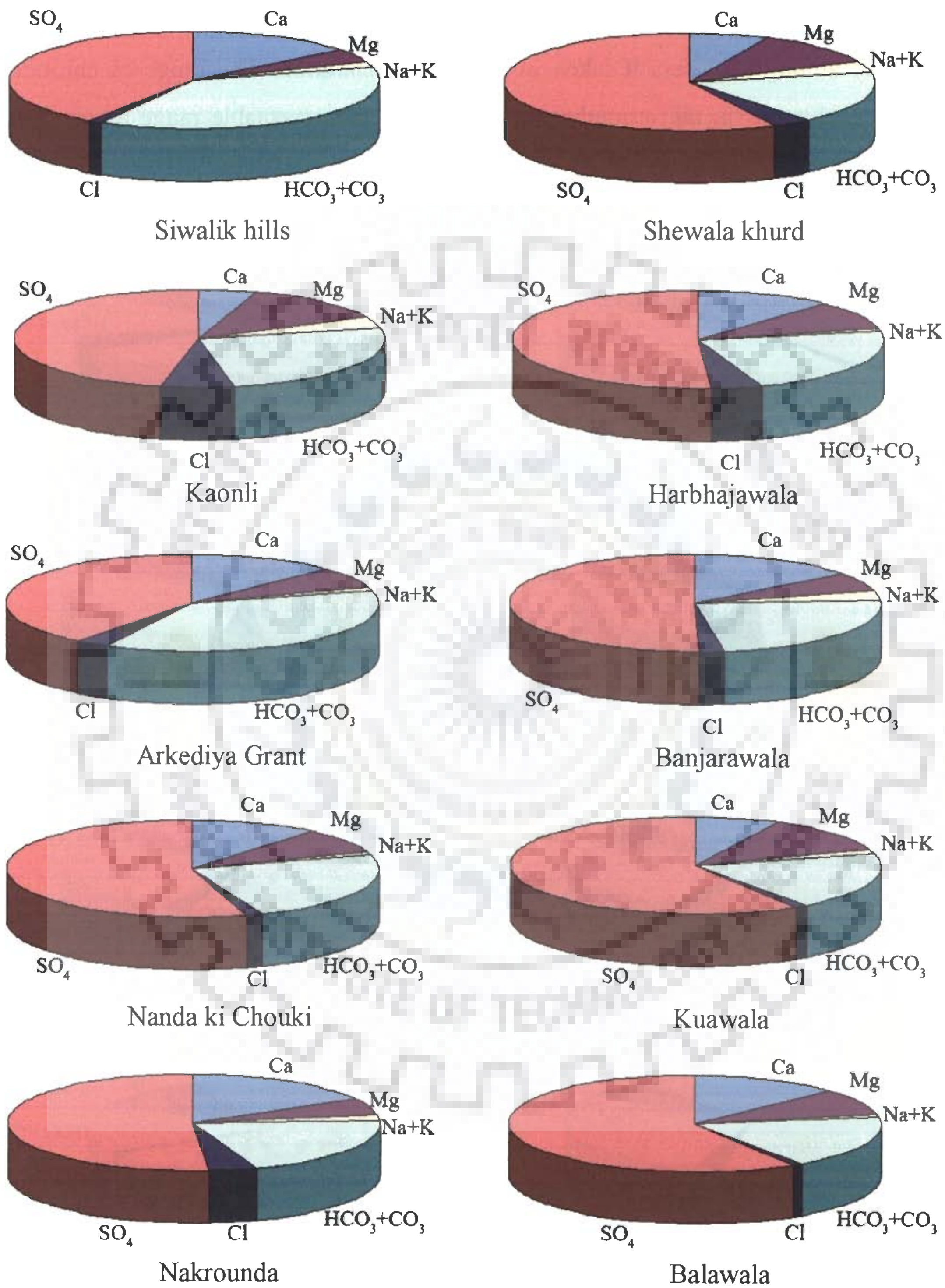


Fig. 6.3: Circular diagrams representing analysis of groundwater for different locations in the Suswa Watershed (Pre-monsoon- 2006)

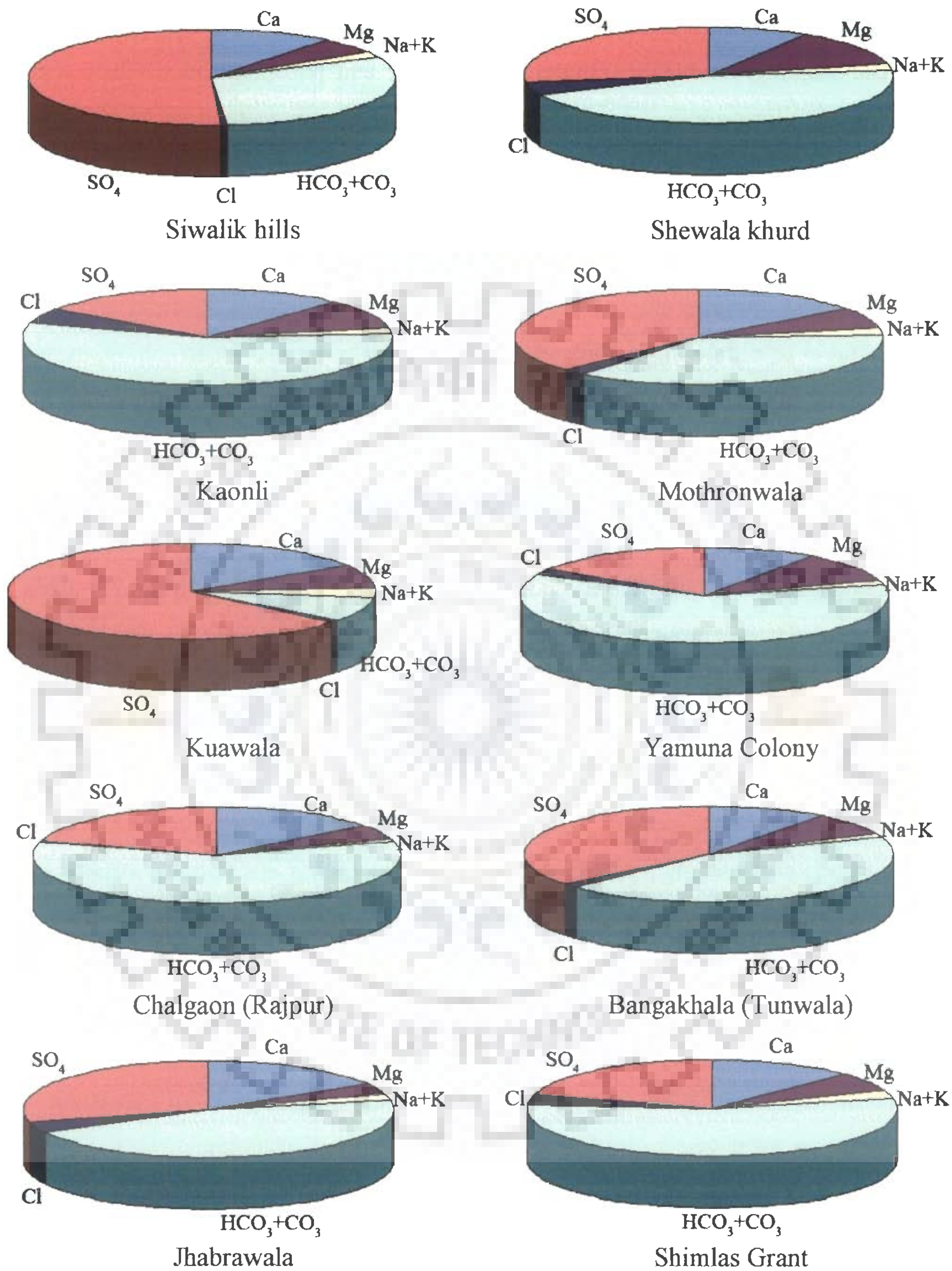


Fig. 6.4: Circular diagrams representing analysis of groundwater for different locations in the Suswa Watershed (Post-monsoon- 2006)

6.6 NUTRIENTS

The major groundwater pollutants are nitrate and phosphate ions which may be derived from fertilizer applications in agricultural fields. In some situations, these may also be derived by contamination from sewage.

6.6.1 Nitrate

Nitrate in groundwater represents a widely distributed pollution concern; it is perhaps the most omnipresent of all the groundwater contaminants. Natural and human-induced sources of nitrate in groundwater are a result of water use for irrigation, excessive applications of commercial fertilizers or manures, and waste disposal practices associated with land application of sludge or wastewater effluents, municipal or industrial landfills, and septic tank systems (Keeney, 1989 and Canter, 1987). As per Indian standards, the maximum desirable limit of nitrate is 45 mg/L. The range of nitrate observed in the groundwater of the study area is 0.05-57.2 mg/L with the median concentration of about 12 mg/L (Table 6.3). All groundwater samples in the study area indicate that the nitrate concentration is within the desirable limits at all locations (except in Yamuna Colony) (Fig. 6.1 (F-1) and (F-2)).

6.6.2 Phosphate

Phosphate occurs in water in several forms including elemental phosphorus and dissolved orthophosphorus. In its elemental form, it may be toxic to aquatic organisms and may bio-accumulate in much the same manner as mercury (US EPA, 1986). Phosphorus is the nutrient most frequently cited as limiting algal growth in surface water. It is a common element that is needed in fairly small amounts compared with other nutrients. The solubility of rocks containing phosphorus is also low. However, once dissolved, it is quickly taken up by living organisms or adsorbed on iron and aluminum hydroxides and oxides. Therefore, the amount of phosphorus available for plant growth at any given time being usually low, contributions from human activities greatly affect phosphorus in water bodies. Manmade sources of phosphate include human sewage, runoff from agricultural crops, sewage from animal feedlots, pulp and paper industry, vegetable and fruit processing, chemical and fertilizer manufacturing, and detergents (Anonymous, 2010).

The tolerance limit for phosphate has not been laid down in the Indian drinking water standards (BIS: 10500, 1991) but WHO (1971) has given a maximum limit of around 5 mg/L. Phosphate concentration in the groundwater of study area is within the desirable limit given by WHO (1971) except at Arkediya Grant (5.83 mg/L) (Table 6.3). It is noteworthy that the higher concentrations have been observed at places characterized by agriculture land use like Arkediya Grant, Banjarawala, Mehuwala Mafi, etc. (Fig. 6.1 (G-1) and (G-2)).

6.7 HYDROCHEMICAL CHARACTER OF GROUNDWATER

Trilinear diagrams are commonly employed to represent hydrochemical character of groundwater flow systems (Piper, 1944). The Piper diagram allows for both the anion as well as the cation compositions to be represented on a single graph. The Piper diagram consists of three distinct fields viz. two triangular fields and a diamond shaped field. In the diagram, the ion concentrations are plotted as percentages with each point representing a chemical analysis. The overall characteristic of water is represented in the diamond shaped field by projecting the position of the plots in the triangular fields (Fig. 6.5). Different types of groundwater can be distinguished by their position in certain sub-areas of the diamond shaped field of the diagram as given below:

Area 1	:	alkaline earths exceed alkalies
Area 2	:	alkalies exceed alkaline earths
Area 3	:	weak acids exceeds strong acids
Area 4	:	strong acids exceeds weak acids
Area 5	:	carbonate hardness exceeds 50 % i.e. chemical properties of the water are dominated by alkali earths and weak acids
Area 6	:	non-carbonate hardness exceeds 50 %
Area 7	:	non-carbonate alkalies exceeds 50 % i.e. chemical properties of the water are dominated by alkalies and strong acids
Area 8	:	carbonate alkalies exceeds 50 %
Area 9	:	no one cation-anion pair exceeds 50 %

The Piper diagrams for the pre-monsoon and post-monsoon- 2006 are given in Figures 6.6 and 6.7 respectively for the groundwater samples in the study area. It is seen from these figures that all the groundwater samples of pre-monsoon period have dominant 'secondary salinity' (falling in area 6) indicating thereby that non-carbonate hardness exceeds 50 % in groundwater (Fig. 6.6). However, during post-monsoon period, the character of groundwater is modified. In post-monsoon period, 10 out of 15 groundwater samples fall in area 5 of the diamond shaped field of the Piper diagram indicating that the carbonate hardness exceeds 50 % and the chemical properties of the groundwater are dominated by alkali earths and weak acids (Fig. 6.7). The remaining five groundwater samples (falling in area 6) indicate the character shown by the groundwater during pre-monsoon period. Finally, from the Piper diagrams it is inferred that during pre-monsoon-2006, the groundwater is of Mg-SO_4 type whereas during post-monsoon- 2006 it becomes Ca-HCO_3 type. One of the reasons for the change in the hydrochemical character of groundwater in post-monsoon season can be the dilution effect associated with rainfall recharge.

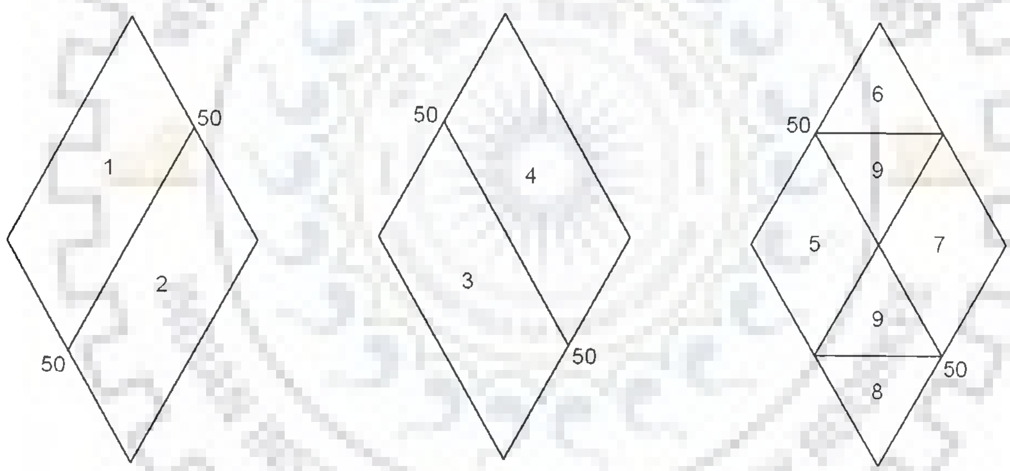


Fig. 6.5: Subdivisions of the diamond shaped field in Piper diagram (after Piper, 1944)

6.8 HEAVY METALS

The most significant and natural source of heavy metals is weathering of rocks, as a result of which the released metals find their way into the groundwater. The anthropogenic influence is exerted through various domestic, industrial and agricultural activities.

The instruments used for analysis of heavy metals in the groundwater samples of the study area were Atomic Absorption Spectrophotometer (AAS) and Inductively Coupled Plasma (ICP) available at Institute Instrumentation Center of IIT Roorkee, Roorkee (India). The concentrations of selected heavy metals (viz. Zn, Mn, Fe, Ni, Cu, Cd, and Cr) in groundwater samples during 2005-06 are given in Tables 6.6 (A) to 6.6 (C).

In the present study, analysis of groundwater samples has revealed presence of a few heavy metals viz. Zn, Mn, Fe, Ni, Cu, Cd, and Cr. However, majority of these metals have generally not violated the Indian drinking water standards (except for cadmium, nickel and chromium). The variation of heavy metals at different locations in the study area is shown by bar diagrams in Fig. 6.8 whereas their description is given in the following paragraphs:

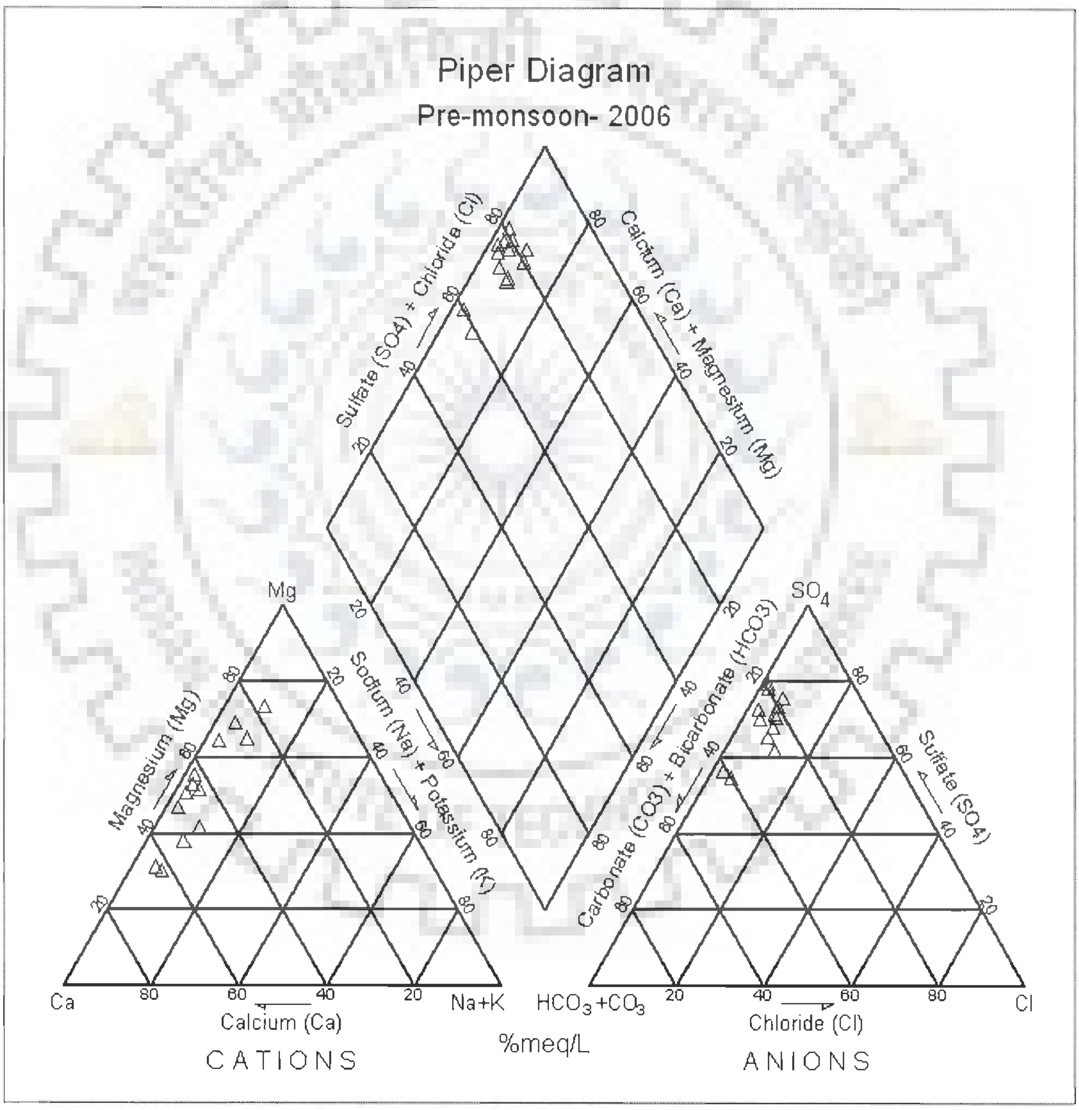


Fig. 6.6: Piper diagram for pre-monsoon- 2006

6.8.1 Cadmium

Cadmium is highly toxic to human and animals (Friberg et al., 1974). Its higher concentration is more toxic for human health and causes disorder of kidney and lungs. In the present study, about 43 % (12 out of 28) of the groundwater samples have been found to violate the maximum desirable limit for Cd concentration of 0.01 mg/L (Fig. 6.8 (A-1) and (A-2)). The median concentration of Cd is 0.006 mg/L and the maximum concentration is 0.045 mg/L at Siwalik hills.

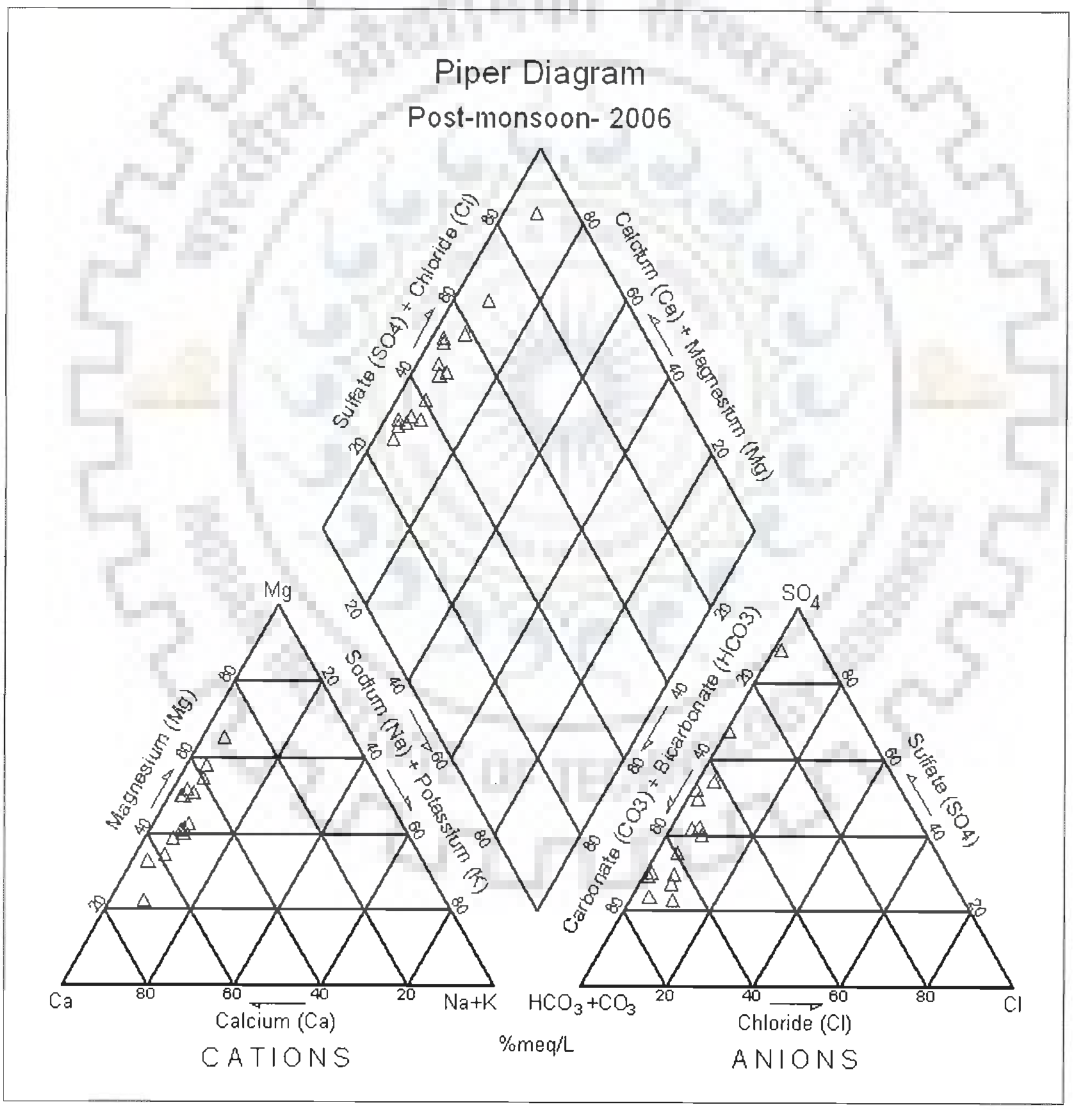


Fig. 6.7: Piper diagram for post-monsoon- 2006

It should be noted that the possible source of Cd in the groundwater may be the soil in the study area. The pathways and migration of Cd could be governed by indiscriminate land dumping of untreated effluents or solid waste of various industries scattered in the study area, especially in the northern part of the study area including Dehradun city. This may be justified by the fact (as mentioned earlier in section 3.2) that the Municipal sewage and domestic waste effluent of entire Dehradun city carried by Bindal Rao is further carried through the Suswa river (Bartarya, 1995) to the southern part of the study area and the localities in the southern part at which higher concentration of Cd was observed are located in the vicinity of Suswa river (station numbers 19 to 23 in Fig. 5.1). Also, the other places in the northern part of the study area at which high concentration of Cd (Table 6.6(C)) has been observed (like Yamuna Colony, Hathibarkala, Shewala Khurd, Rajpur, and Bangakhala) are located in the Dehradun city, reflecting the manifestation of increasing industrial activities in the urban area, whereas at the other localities dominated by agriculture, presence of Cd has not been detected (Table 6.6(A) and (B)).

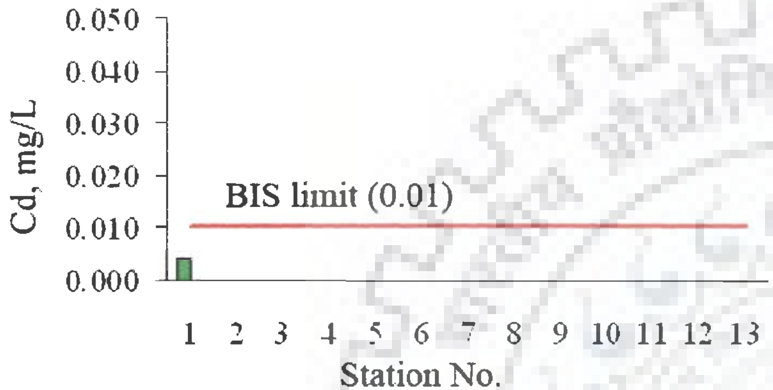
Table 6.6 (A): Data of heavy metals analysis of groundwater samples (Post-monsoon 2005)

Stn. No.	Name of hydrograph station	Zn, mg/L	Mn, mg/L	Fe, mg/L	Ni, mg/L	Cu, mg/L	Cd, mg/L	Cr, mg/L
1	Siwalik hills	0.062	ND	ND	ND	ND	ND	0.039
2	Shewala Khurd	0.067	0.044	ND	ND	ND	ND	0.092
3	Kaonli	0.138	ND	ND	ND	ND	ND	0.070
5	Mehuwala Arkediya	0.059	0.045	ND	ND	ND	ND	0.114
6	Arkediya Grant	0.061	ND	ND	0.037	ND	ND	0.135
8	Banjarawala	0.046	ND	ND	ND	ND	ND	0.117
9	Banjarawala School	0.032	0.046	ND	ND	ND	ND	0.071
11	Kuawala	0.107	0.076	ND	ND	ND	ND	0.045
	BIS: 10500	**5.0**	**0.1**	**0.3**	**0.02***	**0.05**	**0.01**	**0.05**

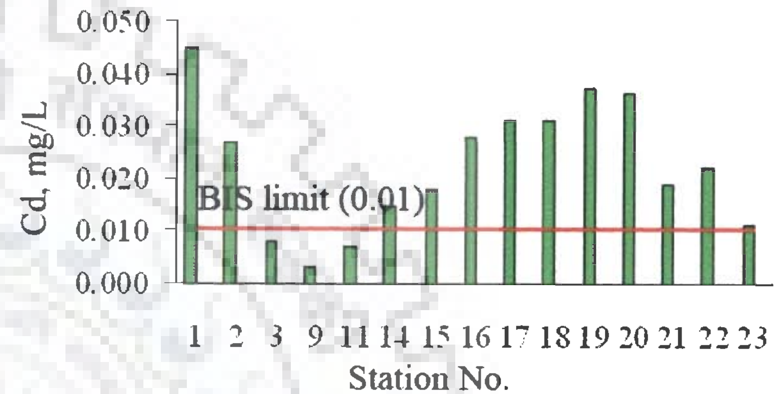
ND = Not detected; * Permissible limit given by WHO (1998)

6.8.2 Zinc

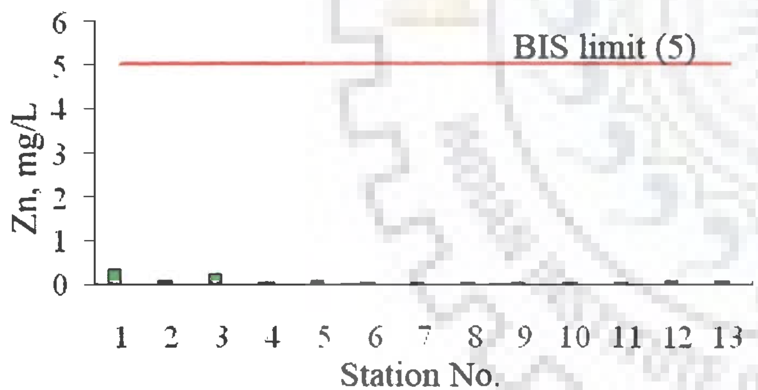
Zinc is essential for plant and animal metabolism. In the groundwater of study area, it is within the desirable limit (5 mg/L) of BIS: 10500 (1991) (Fig. 6.8 (B-1) and (B-2)).



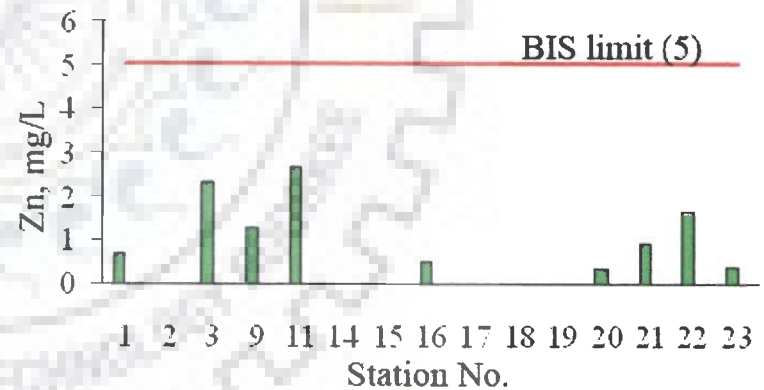
(A-1): Cadmium (Pre-monsoon)



(A-2): Cadmium (Post-monsoon)

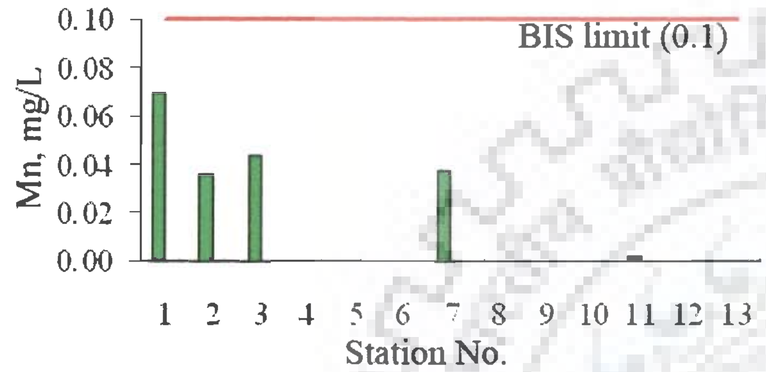


(B-1): Zinc (Pre-monsoon)

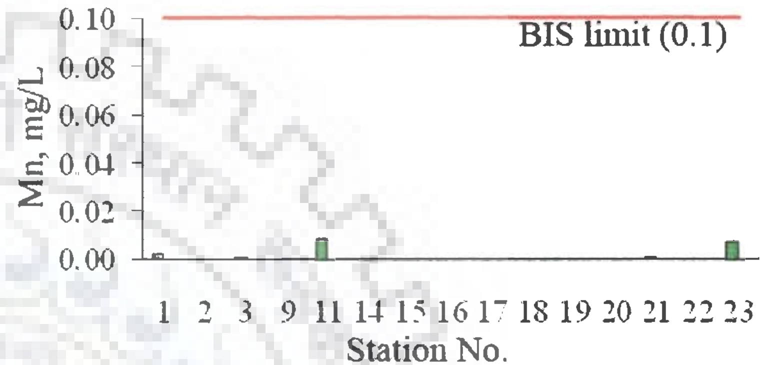


(B-2): Zinc (Post-monsoon)

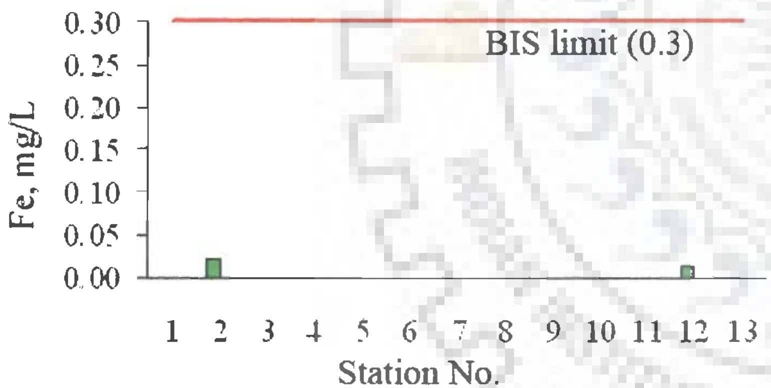
Fig. 6.8: Bar diagrams showing variation of heavy metal concentration in groundwater (Year 2006) (Continued)



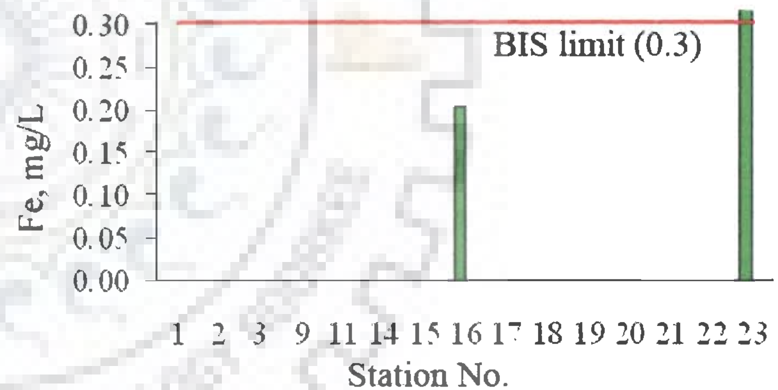
(C-1): Manganese (Pre-monsoon)



(C-2): Manganese (Post-monsoon)



(D-1): Iron (Pre-monsoon)



(D-2): Iron (Post-monsoon)

Fig. 6.8: Bar diagrams showing variation of heavy metal concentration in groundwater (Year 2006) (Continued)

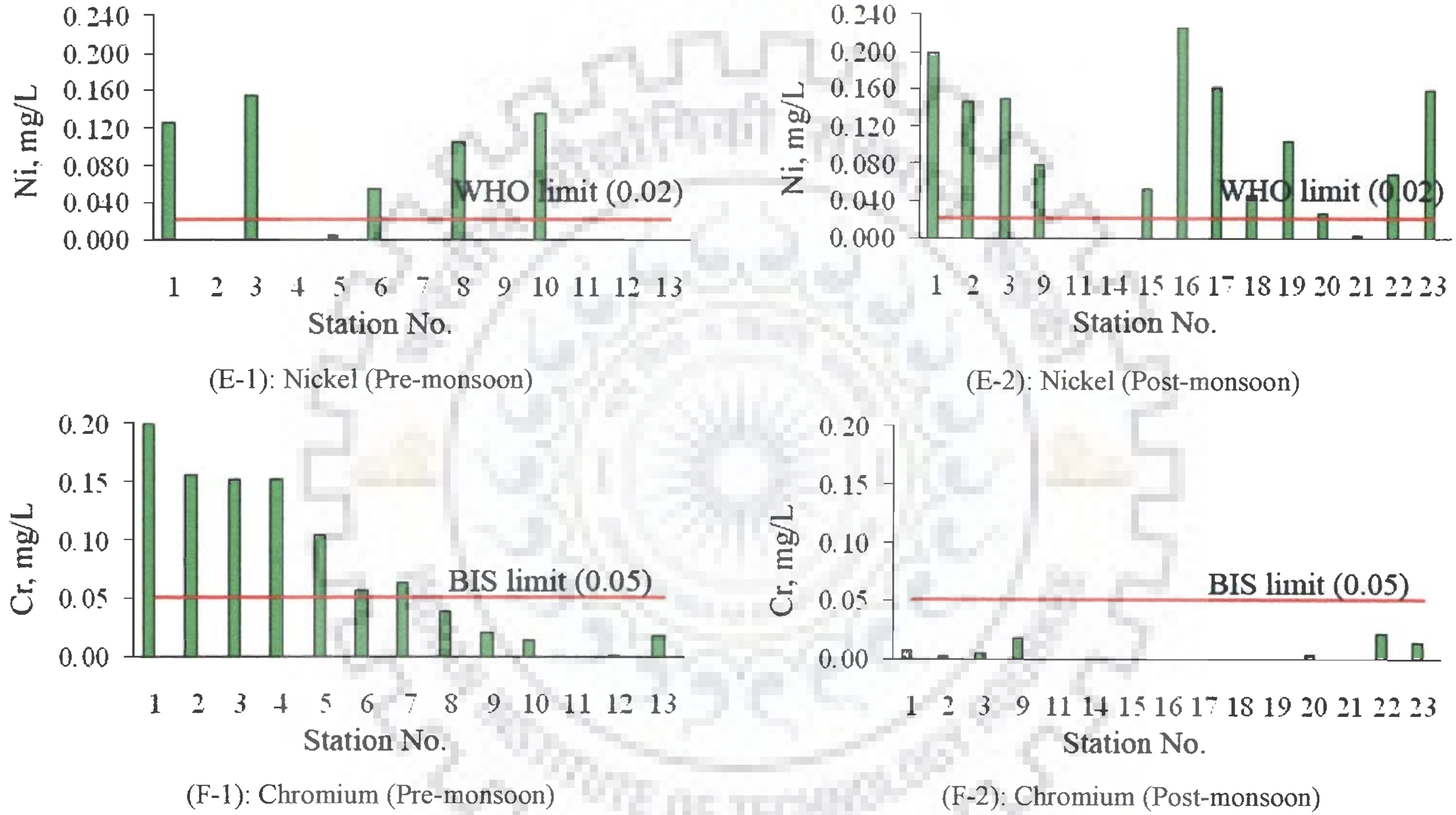


Fig. 6.8: Bar diagrams showing variation of heavy metal concentration in groundwater (Year 2006)

6.8.3 Manganese

Manganese is a naturally occurring element that can be found ubiquitously in the air, soil and water. However, human activities are also responsible for much of the Mn concentration in groundwater of some areas (US EPA, 2004). High concentration of Mn can cause the change in taste/ appearance and has the adverse effect on domestic uses and the water supply infrastructure. The maximum Mn concentration in the groundwater of study area is 0.07 mg/L at Siwalik hills. The concentration of Mn in the study area has been found within the desirable limits of Indian drinking water standard of 0.1 mg/L (Fig. 6.8 (C-1) and (C-2)).

Table 6.6 (B): Data of heavy metals analysis of groundwater samples (Pre-monsoon 2006)

Stn. No.	Name of hydrograph station	Zn, mg/L	Mn, mg/L	Fe, mg/L	Ni, mg/L	Cu, mg/L	Cd, mg/L	Cr, mg/L
1	Siwalik hills	0.310	0.070	ND	0.125	0.045	0.004	0.199
2	Shewala Khurd	0.083	0.036	0.020	ND	ND	ND	0.155
3	Kaonli	0.258	0.044	ND	0.154	ND	ND	0.152
4	Mehuwala Mafi	0.051	ND	ND	ND	ND	ND	0.152
5	Mehuwala Arkediya	0.075	ND	ND	0.005	ND	ND	0.104
6	Arkediya Grant	0.035	ND	ND	0.054	ND	ND	0.057
7	Harbhajwala	0.033	0.037	ND	ND	ND	ND	0.062
8	Banjarawala	0.030	ND	ND	0.105	ND	ND	0.038
9	Banjarawala School	0.050	ND	ND	ND	ND	ND	0.020
10	Nanda ki Chouki	0.044	ND	ND	0.135	ND	ND	0.014
11	Kuawala	0.051	0.002	ND	ND	ND	ND	ND
12	Nakrounda	0.070	ND	0.015	ND	ND	ND	0.002
13	Balawala	0.063	ND	ND	ND	ND	ND	0.017
	BIS: 10500	**5**	**0.1**	**0.3**	**0.02***	**0.05**	**0.01**	**0.05**

ND = Not detected; * Permissible limit given by WHO (1998)

6.8.4 Iron

Iron is essential in human nutrition, but it becomes highly toxic when the concentration increases (Fairbanks and Bentler, 1971). Its concentration in all but one groundwater sample (at Mothronwala) has been found within the desirable limits of Indian drinking water standard (Table 6.6 (C) and Fig. 6.8 (D-2)).

6.8.5 Nickel

Nickel is released into the atmosphere from burning fossil fuels, mining and refining operations and burning of municipal wastes. It is also found in soil treated with sewage sludge. Nickel is one of the most common metals occurring in surface water. Small nickel particles in the air settle to the ground or are taken out of the air in rain. Acidic conditions render nickel more mobile in soil and may lead to seepage into groundwater.

A small amount of nickel is essential to animals and probably to humans also, although a lack of nickel has not been found to affect the health of humans. Generally and unknowingly, humans consume a daily average of 0.2 mg of nickel from air, drinking water and eating food which is usually disposed off in the feces and the urine quickly. The most common adverse health effect of high levels of nickel in humans is an allergic reaction. Dust or fumes containing very high levels of nickel can be carcinogenic to humans that may also have the potential for causing reproductive damage. (www.heavymetalstest.com and www.e-b-i.net).

The maximum permissible value for nickel has not been listed in the Indian standards (BIS: 10500, 1991). Therefore, the maximum permissible value of 0.02 mg/L given by WHO (1998) is used in the present study. Although, nickel has been found to be in higher concentration as compared to the WHO (1998) drinking water standard in about 61 % (17 out of 28) groundwater samples (Fig. 6.8 (E-1) and (E-2)), in view of the reasons discussed in above paragraph, the groundwater is considered safe for drinking as the population of the study area has almost adjusted to these concentrations of nickel in shallow drinking water, whereas deep groundwater is free from this metal.

6.8.6 Copper

The higher concentration of copper in drinking water may cause astringent taste in water, discoloration and corrosion of water supply pipe fittings etc. Its concentration has not been detected in the groundwater samples collected in the study area except at the

Siwalik hills well hydrograph where the concentration of Cu was of the order of 0.045 mg/L, within the desirable limit of 0.05 mg/L.

Table 6.6 (C): Data of heavy metals analysis of groundwater samples (Post-monsoon 2006)

Stn. No.	Name of hydrograph station	Zn, mg/L	Mn, mg/L	Fe, mg/L	Ni, mg/L	Cu, mg/L	Cd, mg/L	Cr, mg/L
1	Siwalik hills	0.681	0.002	ND	0.200	ND	0.045	0.008
2	Shewala Khurd	ND	ND	ND	0.145	ND	0.027	0.003
3	Kaonli	2.318	0.001	ND	0.149	ND	0.008	0.005
9	Banjarawala School	1.271	ND	ND	0.078	ND	0.003	0.017
11	Kuawala	2.638	0.008	ND	ND	ND	0.007	ND
14	Yamuna Colony	ND	ND	ND	ND	ND	0.015	ND
15	SOI (Hathibarkala)	ND	ND	ND	0.053	ND	0.018	ND
16	Chalgaon (Rajpur)	0.482	ND	0.204	0.226	ND	0.028	ND
17	Raipur	ND	ND	ND	0.162	ND	0.031	ND
18	Bangakhala (Tunwala)	ND	ND	ND	0.045	ND	0.031	ND
19	Bullawala	ND	ND	ND	0.105	ND	0.037	ND
20	Jhabrawala	0.316	ND	ND	0.027	ND	0.036	0.004
21	Madhowala	0.931	0.001	ND	0.004	ND	0.019	ND
22	Shimlas Grant	1.655	ND	ND	0.069	ND	0.022	0.022
23	Mothronwala	0.368	0.007	1.580	0.159	ND	0.011	0.014
	BIS: 10500	**5**	**0.1**	**0.3**	**0.02***	**0.05**	**0.01**	**0.05**

ND = Not detected; * Permissible limit given by WHO (1998)

6.8.7 Chromium

The high concentration of Cr may cause carcinogenic effects amongst the users. The median concentration of Cr was of the order of 0.011 mg/L and the maximum value of 0.199 mg/L has been observed at Siwalik hills. The Cr concentration in 25 % (7 out of 28) of groundwater samples has been found to violet the BIS desirable limit of 0.05 mg/L (Fig. 6.8 (F-1)).

To summarize, groundwater quality vis-à-vis concentration of heavy metals is not alarming with the exception of high concentration of cadmium, nickel and chromium at some places. The high concentration of heavy metals observed in the groundwater samples may highlight the impact of anthropogenic activities resulting in transformation in natural soil properties and ultimately, groundwater quality through leaching or infiltration of contaminants (Kolpin, 1997; Burkart and Kolpin, 1993). It is noteworthy that, the highest concentration of heavy metals has been observed for groundwater samples taken from shallow wells (hand pump), thus indicating that the deeper aquifers (> 30 m depth) are not affected by their presence and hence, the probable sources of contamination of shallow groundwater could be due to surface anthropogenic activities.

6.9 SURFACE WATER QUALITY

Only one surface water sample from the Suswa river was collected during the post-monsoon period of 2006 (on 22.11.2006) at a place towards upstream side of and about 16 km from the outlet point of the Suswa Watershed. This sampling point is at about a kilometre distance towards the downstream side of Ramgarh (Fig. 3.2). The water sample has been analyzed in the laboratory and the results obtained are discussed below by comparing with the Indian drinking water standards viz. BIS: 10500 (1991).

6.9.1 Physical Properties

The physical properties for the Suswa river water sample are given in Table 6.7. The observed pH value of 8.5 is within the desirable range of the Indian standards and shows the alkaline nature of water. The value of EC has been found as 712 μmhos/cm. The concentration of TDS of 465 mg/L is within the permissible BIS limits. The total hardness has higher value than the BIS standard of 300 mg/L, and thus, the river water can be termed as 'very hard'.

Table 6.7: Physical properties of the Suswa river water sample

Characteristics	pH	Temperature, (°C)	Electrical conductivity (μmhos/cm)	Total dissolved solids (mg/L)	Total hardness (mg/L)
Suswa river water sample	8.5	23.7	712	465	368
BIS standard	6.5-8.5	-	-	500	300

6.9.2 Major Ions and Nutrients

The concentrations of major ions and nutrients in the Suswa river water sample are given in Table 6.8 (also shown in a circular diagram; Fig. 6.9), wherein ion balancing can be seen from the almost equal sums of the major cations and anions. In the present study, the concentrations of calcium, sulfate, chloride and nitrate are within the desirable limits of BIS standards, whereas sodium is within the permissible limit given by CHASDWR (2001). The magnesium and bicarbonate exhibits higher values than those desired by the BIS, which are responsible for higher value of the total hardness. Phosphate concentration is quite high as compared to the desirable limit of 5 mg/L given by WHO (1971), which can be attributed to manmade sources like human sewage, runoff from agricultural crops, sewage from animal feedlots, and detergents.

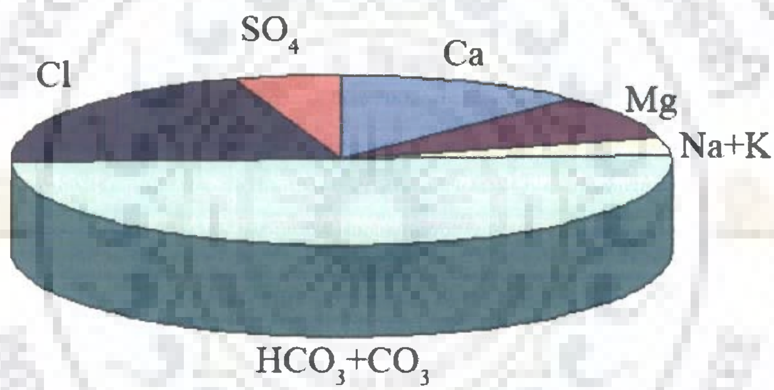


Fig. 6.9: Circular diagram representing analysis of the Suswa river water sample

6.9.3 Heavy Metals

The concentrations of heavy metals in the Suswa river water sample are given in Table 6.9. It is noteworthy that the concentrations of all heavy metals except Cd and Ni (viz. Zn, Mn, Fe, Cu and Cr) are within the desirable limits of BIS standards (BIS: 10500, 1991).

As per U.S.S.L. (1960) classification, the river water is classified into C_2S_1 class i.e. medium salinity and low sodium water based on EC (of 0.712 mmhos/cm) and low sodium adsorption ratio (SAR of 0.258). Accordingly, the water can be used for irrigating the crops that can tolerate the moderate salinity like paddy, sugarcane, maize, sorghum, onion, potato, wheat, etc. Also, from residual sodium carbonate value of –2.652 meq/L (which is less than 1.25 meq/L as per U.S.S.L., 1960 classification), the river water can be considered 'safe' for irrigation purpose.

Table 6.8: Major ions and nutrients in the Suswa river water sample

Cations	BIS standard, mg/L	Concentration		Anions	BIS standard, mg/L	Concentration	
		mg/L	meq/L			mg/L	meq/L
Ca^{2+}	**75**	69.600	3.473	HCO_3^-	**200**	286.00	4.687
Mg^{2+}	**30**	47.100	3.866	SO_4^{2-}	**200**	114.00	2.373
Na^+	**200#**	11.367	0.494	Cl^-	**250**	28.99	0.818
K^+	-	6.930	0.177	NO_3^-	**45**	3.334	0.054
-	-	-	-	PO_4^{3-}	**5***	16.480	-
Total	-	-	8.010	Total	-	-	7.932

* Permissible limit given by WHO (1971); # CHASDWR (2001)

Table 6.9: Heavy metals (µg/L) in the Suswa river water sample

Metal	BIS standard	Concentration	Metal	BIS standard	Concentration
Zn	**5000**	23	Cu	**50**	ND
Mn	**100**	ND	Cd	**10**	11
Fe	**300**	ND	Cr	**50**	24
Ni	**20***	195	-	-	-

ND = Not detected; * Permissible limit given by WHO (1998)

To summarize, although, it will not be prudent to draw any concrete conclusion based on analysis of the only one surface water sample, it is seen that, despite the Bindal Rao discharging waste effluent of Dehradun city into the Suswa river, its water quality is within the BIS limits for drinking purpose (barring high concentration of phosphate) at the sampling point located at one kilometre distance towards downstream side of Ramgarh village (Fig. 3.2). Also, the water quality parameters in the water sample are similar to those in the groundwater samples. It is necessary to analyze more samples collected towards upstream of Ramgarh to check the presence of effects of waste effluent disposal and its spatial variation in the river water.

6.10 TEMPORAL VARIATION IN GROUNDWATER QUALITY

The comparison of groundwater quality parameters during pre-monsoon and post-monsoon periods of 2006 is discussed in the following paragraph for groundwater samples collected at five locations viz. Siwalik hills, Shewala Khurd, Kaonli, Banjarawala School and Kuawala. Remaining locations have only been monitored either during pre-monsoon or post-monsoon period of 2006.

A perusal of Table 6.6 and Annexure 6.1 to Annexure 6.3 indicates the presence of the dilution effect associated with the rainfall recharge as indicated by the lower concentration values of physico-chemical ions and heavy metals during post-monsoon period when compared with the values during pre-monsoon period. At Siwalik hills, higher values have been recorded for majority of the groundwater parameters (TDS, total hardness, Mg, Na, K, SO_4 and NO_3) during post-monsoon period in comparison with those during pre-monsoon period. At Shewala Khurd, the values of total hardness, Ca, Mg, total alkalinity, Cl and NO_3 are also higher during post-monsoon period than those during pre-monsoon period. Likewise, during post-monsoon- 2006, high values of TDS, total hardness, Ca, Mg, Na, K and total alkalinity are observed at Kaonli. At Kuawala, higher concentrations of Ca, Na and K are observed during post-monsoon period than during pre-monsoon period. Amongst the heavy metals, zinc and cadmium concentration in groundwater samples during post-monsoon was found higher at all the five locations than during pre-monsoon period. It appears difficult to assign specific reasons for such higher anomalous ionic concentrations during post-monsoon period when compared to pre-monsoon period. One of the reasons for such a phenomenon can be increased rock-water interaction in the saturated media. However, this aspect may require further study.

6.11 CONCLUDING REMARKS

The overall groundwater quality in the study area is suitable for drinking purpose as per standards of BIS, WHO, etc. Although, the groundwater of shallow aquifers is not fit for drinking at few places, it is found to be within the 'permissible' limits of Indian standards and can thus be allowed for drinking in the absence of alternate drinking water sources. The ionic character of groundwater evaluated using a Piper diagram shows the presence of $Mg\text{-}SO_4$ and $Ca\text{-}HCO_3$ type of water during pre-monsoon and post-monsoon periods respectively. The Piper diagram also indicated the presence of non-carbonate hardness during pre-monsoon period whereas carbonate hardness during post-monsoon period in the groundwater of the study area probably due to the dilution caused by rainfall recharge.

Groundwater quality in the study area is generally acceptable with the exception of high concentration of cadmium and nickel at few places probably as a result of the increased anthropogenic activities in the urban areas of Dehradun city, and due to the direct disposal of municipal waste effluents into the Suswa river. It is noteworthy that the deeper aquifers (> 30 m depth) seem to be free from such heavy metals.

The lone sample of Suswa river water indicated good water quality despite disposal of waste effluent into it. Although, river water is reportedly not being used for drinking purpose in the study area, to have a clear picture of spatial variation of river water quality, more samples need to be collected and further supplemented by bacteriological analysis.

Chapter 7

EVALUATION OF SYNOPTIC GROUNDWATER QUALITY

7.1 GENERAL

Quality of water can play a vital role in determining type of its use for various purposes. As is well known, while water quantity can be assessed by a single parameter (e.g. volume or rate of flow during a given time period), the water quality is often described in terms of concentration of several constituents ranging from twenty and odd to hundreds. Thus, comparison of water quality in terms of a large list of constituents is rather complicated. For example, a water sample containing six components in 5 % higher than desirable (hence objectionable) levels; pH, hardness, chloride, sulphate, iron and sodium may not be as bad for drinking as another water sample with just one constituent e.g. mercury at 5 % higher than desirable level. To simplify such problems, water quality indices (WQIs) may be used which aim at assigning a single synoptic value to the water quality by integrating the concentrations of several constituents.

This chapter deals with generation of a synoptic formulation of groundwater quality characterization by employing a groundwater quality index, which can be used for assessment of sustainability vis-à-vis water quality in the next chapter. On the basis of the hydrogeological as well as the groundwater quality scenario in the present study area, the basic framework of the Index of Aquifer Water Quality (IAWQ) proposed by Melloul and Collin (1998) has been considered suitable in order to get an overall status of the groundwater quality. The necessary weights of water quality parameters used in this index have been estimated by using the Analytical Hierarchy Process (AHP). A brief background of Analytical Hierarchy Process (AHP) is also presented.

7.2 INDEX OF AQUIFER WATER QUALITY (IAWQ)

Melloul and Collin (1998) developed IAWQ for assessing the groundwater quality of Israel's Sharon region by using the chloride and nitrate concentration. Based on the high values of IAWQ, they delineated areas where land use is affecting groundwater quality. In this approach, for relating groundwater quality data to global norms, each value of a parameter, P_i (field data value of parameter i), is related to its desired standard value P_{id} (Indian drinking water standards in the present study). Each relative value, X_i, can be estimated as:

$$X_i = P_i / P_{id} \tag{7.1}$$

To express X_i as a corresponding index rating value related to groundwater quality, Y_i has been assigned to each X_i value as follows:

- For good water quality, with X_i equal to 0.1, the corresponding index rating value would be around 1;
- For acceptable water quality, with X_i equal to 1 (the raw value of the parameter P_i equal to its standard desired value), the corresponding index rating value would be 5; and
- For unacceptable groundwater quality, with X_i equal to or higher than 3.5 (the initial value of the parameter P_i equal to or higher than 3.5 times its standard desired value), the corresponding index value would be 10.

Operational hydrological experience indicates that $Y_1 = 1$ for $X_1 = 0.1$; $Y_2 = 5$ for $X_2 = 1$ and $Y_3 = 10$ for $X_3 = 3.5$ (usually values of Y_i range between 1 and 10). For any parameter i, an adjusted parabolic function of rates $Y_i = f(X_i)$ can be determined from 2nd order polynomial as in equation (7.2) (Melloul and Collin, 1998):

$$Y_i = -0.712\, X_i^2 + 5.228\, X_i + 0.484 \tag{7.2}$$

From this equation the corresponding rating Y_i can be estimated for any value of X_i. However, in order to avoid negative values of Y_i (which may result in negative indices), maximum values of X_i has to be restricted to 3.5. Thus, after this transformation of the field data, the IAWQ index formula (equation 7.3) involves only Y-values, representing input data for the development of IAWQ index formula to numerically assess any groundwater quality situation which is as under:

$$IAWQ = C/n\left[\sum_{i=1}^{n}(W_{ri}.Y_{ri})\right] \tag{7.3}$$

where,

C = a constant, used to ensure desired range of numbers (taken as 10);

i, n = number of chemical parameters involved (i = 1, …, n), which is incorporated in the denominator to average the data;

W_{ri} = the relative value of W_i / W_{max};

W_i = a weight for any given parameter;

W_{max} = the maximum possible weight (taken as 5);

Y_{ri} = the value of Y_i / Y_{max};

Y_i = the rating value for the i^{th} chemical parameter [obtained from equation (7.2)];

Y_{max} = the maximum possible rating for any parameter (taken as 10).

A weight (W_i) is a numerical value given to a parameter to characterize its relative anticipated pollutant impact; lower numerical values define lower pollution potential, while higher values define heightened pollution potential. A W_i value would be larger if a given parameter were toxic or hazardous to groundwater quality. The values of W_{max} and Y_{max} are incorporated into equation (7.3), to represent W and Y values as related to a reference level in order to assess the relative level of salinization and pollution, and also to ensure that the ultimate IAWQ value remains within a scale of 1–10. IAWQ values can thus be more readily compared from one site to the other, while providing a means of determining the relative influence of additional parameters upon groundwater quality.

7.3 GROUNDWATER QUALITY INDEX (GWQI)

Development of groundwater quality index (GWQI) in the Suswa Watershed through inclusion of few modifications in the original work of Melloul and Collin (1998) has been explained in the following paragraphs:

- The range of water quality parameters considered in the original index was extended from two (chloride and nitrate in original work) to include major ions and heavy metals like TDS, total alkalinity (TA), Mg, SO_4, total hardness (TH), Cd, Cr and Ni. From the point of regional significance, only those parameters were included which reflected violation of the drinking water quality standards of BIS: 10500 (1991) and WHO (1998) in more than 10 % of the total samples collected in the study area (Fig. 7.1).

- Out of eight parameters shown in Fig. 7.1, total hardness (TH) is considered more significant than magnesium to include in the GWQI due to the fact that TH is a result of high concentrations of magnesium and calcium in the study area (as discussed in section 6.4.3). Accordingly, the seven chemical parameters finally selected for estimating GWQI were Cd, Ni, Cr, TH, SO_4, TDS and total alkalinity (Table 7.1).
- Weights (W_i) were assigned to these seven parameters as per their analytical hierarchy in the human health (effecting) significance by using the Analytical Hierarchy Process (AHP) but not in a subjective manner as attempted in the original work of Melloul and Collin (1998) who used weights of 1 and 2 for chloride and nitrate respectively.

Table 7.1: Percent of samples exceeding the drinking water quality standards

Sl. No.	Parameter	Percent of samples exceeding the BIS standards	BIS standards (mg/L)
1	Cadmium	42.9	0.01
2	Nickel	60.7	0.02*
3	Chromium	25.0	0.05
4	Total hardness (TH)	25.0	300
5	Sulfate	46.4	200
6	Total dissolved solids (TDS)	10.7	500
7	Total alkalinity (TA)	35.7	200

*drinking water quality standard of WHO (1998)

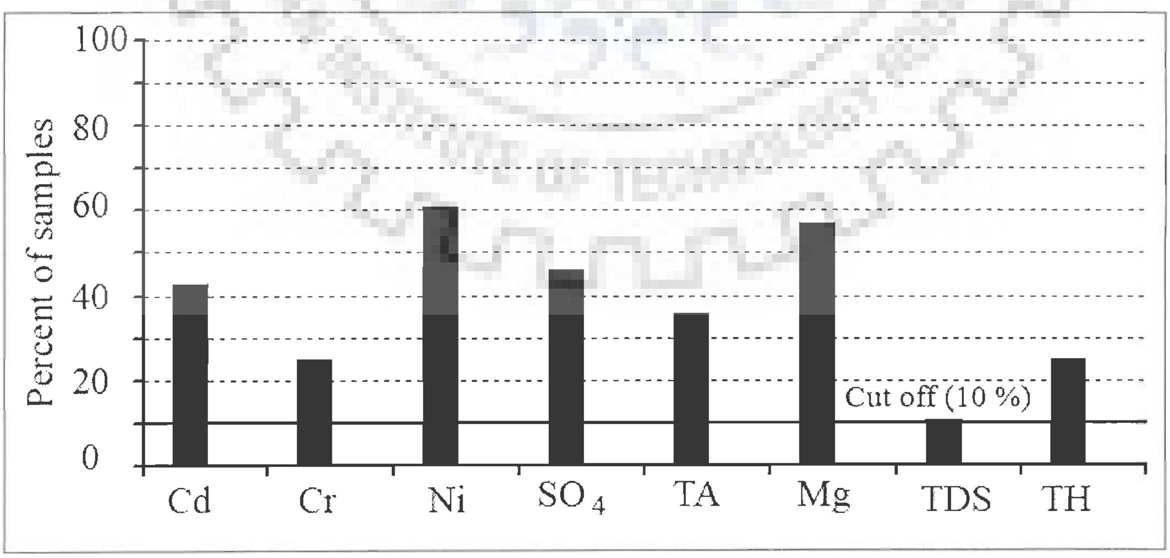


Fig. 7.1: Percent of samples exceeding drinking water quality standards

7.4 THE ANALYTICAL HIERARCHY PROCESS (AHP)

The Analytical Hierarchy Process (AHP) has been used for estimating the weights (W_i) of selected water quality parameters in the GWQI computations. The details of AHP are given below.

7.4.1 The AHP Theory

The Analytical Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) approach introduced by Saaty (1977 and 1994) which offers assistance in solving the MCDM problems of many engineering fields including groundwater pollution potential assessment.

The structure of the typical decision problem considered in this study consists of a number, say N, of alternatives and decision criteria. Each alternative can be evaluated in terms of the decision criteria and the relative weight (significance or priority) of each criterion can be estimated as well. Let the values a_{ij} (i = 1,2,3...N, and j = 1,2,3....N) denote the performance values of the i-th alternative (i.e. A_i) in terms of the j-th criterion (i.e. C_j). Also, the values W_j denote the weight of the criterion C_j. Then, the core of the typical MCDM problem can be represented by the following decision matrix $A = (a_{ij})$ with the constraints that $a_{ij} = 1/a_{ji}$, for $i \neq j$, and $a_{ii} = 1$ for all i. Such a matrix is said to be reciprocal matrix.

	Criteria (C_j) and weights (W_j)				
	C_1	C_2	C_3	...	C_N
Alternatives	W_1	W_2	W_3	...	W_N
A_1	a_{11}	a_{12}	a_{13}	...	a_{1N}
A_2	a_{21}	a_{22}	a_{23}	...	a_{2N}
A_3	a_{31}	a_{32}	a_{33}	...	a_{3N}
...	...	...	...	...	...
A_N	a_{N1}	a_{N2}	a_{N3}		a_{NN}

Given the above decision matrix, the decision problem considered in this study is "how to determine which the best alternative is". A slightly different problem is to determine "the relative significance of the N alternatives when they are examined in terms of the N decision criteria combined". It is this issue of multiple dimensions, which makes the typical MCDM problem to be a complex one and the AHP offers assistance in solving these types of problems.

In AHP, pair-wise comparisons are used to determine the relative importance of each alternative in terms of each criterion. In this approach, the decision-maker has to express his opinion about the value of one single pair-wise comparison at a time. Each comparison is a linguistic phrase, for example "A is more important than B" or "A is of the same importance as B", or "A is a little more important than B" and so on. Pairwise comparisons are quantified by using the common scale given by Saaty (1980) (Table 7.2). Thus, the relative importance is implied in the pairwise comparison matrix. These pairwise comparisons are carried out for all factors to be considered, usually not more than seven, and the matrix is completed.

For matrices involving human judgement, perfect consistency rarely occurs in practice. In the AHP, the pairwise comparisons in judgment matrix are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 0.1. A consistency ratio of zero means the judgements are perfectly consistent (Saaty, 1980).

Table 7.2: Scale of relative importance (Source: Saaty, 1980)

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other
5	Much more important	Experience and judgement strongly favour one over the other
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important.	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values between the two adjacent judgement	When compromise is needed
Reciprocals of above nonzero numbers		If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal values when compared with i

7.4.2 The AHP Calculations

There are several methods for calculating the eigenvector. 'Multiplying together the entries in each row of the judgement matrix and then taking the n^{th} root of that product' known as geometric mean principle, gives a very good approximation to the correct answer. By application of this principle, the eigenvalues for each row are estimated as follows:

$$E_i = (a_{11} \times a_{12} \times a_{13} \times \ldots \times a_{1N})^{(1/N)} \qquad (7.4)$$

where,

E_i = eigenvalue for the row i

N = number of elements in the row i

The priority vector (P_v) can be determined by normalizing each eigenvalue (dividing by their sum) as follows:

$$P_{vi} = \frac{E_i}{\sum_{N}^{i=1} E_i} \qquad (7.5)$$

The next step is to calculate λ_{max} so as to lead to the consistency index (CI) and then to the consistency ratio (CR). First, the CI needs to be estimated. This is done by adding the products of values in a row of the judgement matrix and the individual values in the priority vector column, obtaining the values of a new vector called product vector (PV). Then divide the product vector by the priority vector to get the λ_{max} vector. The mean of all individual values in λ_{max} vector gives the required estimate for the λ_{max}, which is used in equation (7.6) to get the CI. If any of the estimates for λ_{max} turns out to be less than n, there has been an error in the calculation, which is a useful sanity check.

$$CI = (\lambda_{max} - n)/(n - 1) \qquad (7.6)$$

The final step is to calculate the consistency ratio for the set of judgements using the standard values of the Random Consistency Index (RCI) (Table 7.3) given by Saaty (1980) as follows:

CR = CI/ RCI (7.7)

Table 7.3: RCI values for different values of n (Source: Saaty, 1980)

No. of rows (n)	1	2	3	4	5	6	7	8
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41
No. of rows (n)	9	10	11	12	13	14	15	
RCI	1.45	1.49	1.51	1.48	1.56	1.57	1.59	

7.5 CALCULATION OF THE GWQI PARAMETER WEIGHTS

The seven water quality parameters selected for computing the GWQI index were classified in five groups on the basis of the human health significance of these parameters (Table 7.4). The first group was considered relatively the most important, whereas the last group, the least important on the basis of available reports and references. As per the relative importance scheme of the AHP, the criteria of these parameters were transferred as input values for the AHP matrix (Table 7.5). The eigenvalues (E_i) (column 8 of the Table 7.5) were normalized to obtain the priority (pollution impact) vector (P_v). The values in the product vector (PV) were computed by adding the products of values of a row in the judgement matrix and values in the priority vector (P_v). The value of λ_{max} was computed as discussed in above section 7.4.2. The value of CI as per equation (7.6) was 0.077 and the consistency ratio (CR) was calculated as 0.058. As indicated earlier, the value of CR is extremely small (much smaller than 0.10), and hence the pairwise comparisons may be considered fairly consistent. The highest priority vector was given a weight of five (due to the need of rescaling as per the 0-5 scale of GWQI) and weights of the other chemical parameters were deduced accordingly (Table 7.6). The final weights (W_i) to be used in GWQI estimation are given in Table 7.6.

Table 7.4: Classification of water quality parameters based on human health significance

Group	Parameter	Water quality criteria
I	Cadmium (Cd)	• Biologically, cadmium is a non-essential, non-beneficial element recognized to be of high toxic potential. • It is deposited and accumulated in various body tissues and is found in varying concentrations throughout all areas where man lives. • It is toxic to man when ingested or inhaled. It is stored largely in the kidneys and liver and is excreted at an extremely slow rate (Train, 1979).
	Nickel (Ni)	• Very high levels of nickel can be carcinogenic to humans that may also have the potential for causing reproductive damage. • The most common adverse health effect of high levels of nickel in humans is an allergic reaction (www.e-b-i.net).
II	Chromium (Cr)	• Human studies have clearly established that inhaled chromium is a human carcinogen, resulting in an increased risk of lung cancer. • The uptake of too much chromium can cause health effects like skin rashes, shortness of breath, coughing, etc. • Chromium-3, a nutritionally essential element in humans, is often added to vitamins as a dietary supplement and would be a concern in drinking water only at very high levels of contamination, unlike chromium-6 and chromium-0, which are more toxic and pose potential health risks to people. • Some people who use water containing chromium (total) well in excess of the maximum contaminant level over many years could experience allergic dermatitis (US EPA, 2004).
III	Total hardness (TH)	• Use of hard water in drinking may cause problem of indigestion to users besides formation of encrustations in the water supply pipes. • Soft water is not, however, suggested for those with heart or circulatory problems, or others who may be on a low sodium diet. • There does not appear to be any convincing evidence that water hardness causes adverse health effects in humans (WHO, 1996).
	Sulfate (SO_4)	• Sulfate may cause the gastrointestinal problems in users especially when magnesium and sodium are also present in water. • Diarrhea may be associated with the ingestion of water containing high levels of sulfate. • The laxative effects are experienced by people change abruptly from drinking water with low sulfate concentrations to drinking water with high sulfate concentrations (US EPA, 2004).
IV	Total dissolved solids (TDS)	• Excess dissolved solids are objectionable in drinking water because of possible physiological effects, unpalatable mineral tastes (US EPA, 1986). • The physiological effects directly related to dissolved solids include laxative effects principally from sodium sulfate and magnesium sulfate and the adverse effects of sodium on certain patients afflicted with cardiac disease and women with toxemia associated with pregnancy (Train, 1979).
V	Total alkalinity (TA)	• There are no direct effects on the human health (IDPH, 2010).

Table 7.5: Analytical Hierarchy Process judgement matrix

	1 **Cd**	2 **Ni**	3 **Cr**	4 **TH**	5 **SO_4**	6 **TDS**	7 **TA**	8 **Eigenvalue (E_i)**	9 **Priority vector (P_v)**	10 **Product vector (PV)**	11 **λ_{max} vector**
Cd	1	1	5	7	7	8	9	4.042	0.345	2.624	7.598
Ni	1	1	5	7	7	8	9	4.042	0.345	2.624	7.598
Cr	0.2	0.2	1	5	5	7	9	1.807	0.154	1.220	7.903
TH	0.14	0.14	0.20	1	1	2	3	0.589	0.050	0.361	7.178
SO_4	0.14	0.14	0.20	1.00	1	2	3	0.589	0.050	0.361	7.178
TDS	0.13	0.13	0.14	0.50	0.50	1	2	0.379	0.032	0.235	7.268
TA	0.11	0.11	0.11	0.33	0.33	0.50	1	0.258	0.022	0.166	7.514
							Sum =	11.706	1.000	λ_{max} =	**7.462**

Table 7.6: Weights of parameters in GWQI

Sl. No.	Parameter	Priority vector (P_v)	Weight (W_i)	Relative values of W_i/ W_{max} (W_{ri})
1	Cadmium	0.345	5.00	1.000
2	Nickel	0.345	5.00	1.000
3	Chromium	0.154	2.24	0.448
4	Total hardness	0.050	0.73	0.146
5	Sulfate	0.050	0.73	0.146
6	TDS	0.032	0.47	0.094
7	Total alkalinity	0.022	0.32	0.064

7.6 ESTIMATION OF GWQI IN THE SUSWA WATERSHED

The computational procedure employed for GWQI estimation in the Suswa Watershed is given in the following steps:

1. The field data of the seven water quality parameters (P_i) have been taken from Chapter 6. The estimated relative ratios (X_i values) for selected seven parameters [viz. Cd, Ni, Cr, total hardness (TH), SO_4, TDS and total alkalinity (TA)] computed by using equation (7.1) as regards to their corresponding drinking water quality standards are given in Table 7.7. As mentioned earlier (section 7.2), the values of X_i equal to or higher than 3.5 were replaced with 3.5 to avoid unreasonably extreme values of final index.
2. The Y_i and Y_{ri} values have been arrived at by using equation (7.2) with Y_{max} = 10. The estimated Y_i and Y_{ri} values are shown in Table 7.8.

Table 7.7: Estimated relative ratios (X_i) for seven groundwater parameters

Stn. No.	Station/ location	X_{Cd}	X_{Ni}	X_{Cr}	X_{TH}	X_{SO4}	X_{TDS}	X_{TA}
Pre-monsoon- 2006:								
1	Siwalik hills	0.40	6.25*	3.98*	0.51	1.00	0.80	0.92
2	Shewala Khurd	0.00	0.00	3.10	1.21	1.68	1.01	0.50
3	Kaonli	0.00	7.70*	3.04	0.97	1.05	0.83	0.57
4	Mehuwala Mafi	0.00	0.00	3.04	0.68	1.11	0.79	0.38
5	Mehuwala Arkediya	0.00	0.25	2.08	0.77	1.15	0.75	0.45
6	Arkediya Grant	0.00	2.70	1.14	0.71	1.08	1.02	1.01
7	Harbhajwala	0.00	0.00	1.24	0.83	1.20	0.86	0.53
8	Banjarawala	0.00	5.25*	0.76	0.67	1.17	0.93	0.55
9	Banjarawala School	0.00	0.00	0.40	0.67	1.13	0.86	0.58
10	Nanda ki Chouki	0.00	6.75*	0.28	0.39	0.98	0.69	0.42
11	Kuawala	0.00	0.00	0.00	0.95	1.38	0.79	0.44
12	Nakrounda	0.00	0.00	0.04	0.37	1.07	0.77	0.42
13	Balawala	0.00	0.00	0.34	0.77	1.62	0.98	0.49
Post-monsoon- 2006:								
1	Siwalik hills	4.50*	10.00*	0.16	1.00	1.45	0.84	0.87
2	Shewala Khurd	2.70	7.25*	0.06	1.78	1.03	1.28	1.68
3	Kaonli	0.80	7.45*	0.10	1.40	0.46	0.93	1.67
9	Banjarawala School	0.30	3.90*	0.34	1.09	0.53	0.91	1.57
11	Kuawala	0.70	0.00	0.00	0.69	0.91	0.57	0.12
14	Yamuna Colony	1.50	0.00	0.00	1.20	0.45	0.99	1.68
15	SOI (Hathibarkala)	1.80	2.65	0.00	1.09	0.42	0.71	1.20
16	Chalgaon (Rajpur)	2.80	11.30*	0.00	0.69	0.36	0.53	1.08
17	Raipur	3.10	8.10*	0.00	1.07	0.84	0.85	0.96
18	Bangakhala (Tunwala)	3.10	2.25	0.00	0.90	0.85	0.73	1.04
19	Bullawala	3.70*	5.25*	0.00	0.82	0.63	0.76	1.00
20	Jhabrawala	3.60*	1.35	0.08	0.71	0.63	0.69	0.97
21	Madhowala	1.90	0.20	0.00	0.88	0.66	0.90	1.41
22	Shimlas Grant	2.20	3.45	0.44	0.97	0.51	0.86	1.36
23	Mothronwala	1.10	7.95*	0.28	0.81	0.69	0.64	0.67

* These X_i values have been replaced with an assigned value (of 3.5) actually utilized in the computation of Y_i and final GWQI values.

Table 7.8: Estimated Y_i and Y_{ri} values for seven groundwater parameters

Stn. No.	Station/ location	Rating values of parameters (Yi) (by using equation 7.3)							Relative value of Y_i/ Y_{max} (Yri)						
		Y_{Cd}	Y_{Ni}	Y_{Cr}	Y_{TH}	Y_{SO4}	Y_{TDS}	Y_{TA}	Y_{r-Cd}	Y_{r-Ni}	Y_{r-Cr}	Y_{r-TH}	Y_{r-SO4}	Y_{r-TDS}	Y_{r-TA}
Pre-monsoon- 2006:															
1	Siwalik hills	2.46	10.06	10.06	2.95	4.99	4.21	4.69	0.25	1.01	1.01	0.30	0.50	0.42	0.47
2	Shewala Khurd	0.48	0.48	9.85	5.78	7.24	5.04	2.92	0.05	0.05	0.98	0.58	0.72	0.50	0.29
3	Kaonli	0.48	10.06	9.80	4.87	5.19	4.32	3.23	0.05	1.01	0.98	0.49	0.52	0.43	0.32
4	Mehuwala Mafi	0.48	0.48	9.80	3.71	5.39	4.16	2.37	0.05	0.05	0.98	0.37	0.54	0.42	0.24
5	Mehuwala Arkediya	0.48	1.75	8.28	4.07	5.57	4.01	2.67	0.05	0.17	0.83	0.41	0.56	0.40	0.27
6	Arkediya Grant	0.48	9.41	5.52	3.85	5.32	5.06	5.03	0.05	0.94	0.55	0.39	0.53	0.51	0.50
7	Harbhajwala	0.48	0.48	5.87	4.32	5.71	4.47	3.05	0.05	0.05	0.59	0.43	0.57	0.45	0.31
8	Banjarawala	0.48	10.06	4.05	3.65	5.64	4.73	3.14	0.05	1.01	0.40	0.37	0.56	0.47	0.31
9	Banjarawala School	0.48	0.48	2.46	3.68	5.50	4.45	3.28	0.05	0.05	0.25	0.37	0.55	0.45	0.33
10	Nanda ki Chouki	0.48	10.06	1.89	2.43	4.92	3.76	2.55	0.05	1.01	0.19	0.24	0.49	0.38	0.26
11	Kuawala	0.48	0.48	0.48	4.82	6.34	4.18	2.65	0.05	0.05	0.05	0.48	0.63	0.42	0.26
12	Nakrounda	0.48	0.48	0.69	2.34	5.25	4.09	2.55	0.05	0.05	0.07	0.23	0.53	0.41	0.26
13	Balawala	0.48	0.48	2.18	4.07	7.09	4.91	2.87	0.05	0.05	0.22	0.41	0.71	0.49	0.29
Post-monsoon- 2006:															
1	Siwalik hills	10.06	10.06	1.30	5.01	6.56	4.37	4.49	1.01	1.01	0.13	0.50	0.66	0.44	0.45
2	Shewala Khurd	9.41	10.06	0.80	7.53	5.11	6.00	7.26	0.94	1.01	0.08	0.75	0.51	0.60	0.73
3	Kaonli	4.21	10.06	1.00	6.41	2.72	4.74	7.23	0.42	1.01	0.10	0.64	0.27	0.47	0.72
9	Banjarawala School	1.99	10.06	2.18	5.35	3.04	4.64	6.94	0.20	1.01	0.22	0.53	0.30	0.46	0.69
11	Kuawala	3.79	0.48	0.48	3.77	4.66	3.22	1.10	0.38	0.05	0.05	0.38	0.47	0.32	0.11
14	Yamuna Colony	6.72	0.48	0.48	5.73	2.68	4.96	7.26	0.67	0.05	0.05	0.57	0.27	0.50	0.73
15	SOI (Hathibarkala)	7.59	9.34	0.48	5.32	2.56	3.85	5.73	0.76	0.93	0.05	0.53	0.26	0.39	0.57
16	Chalgaon (Rajpur)	9.54	10.06	0.48	3.74	2.29	3.07	5.30	0.95	1.01	0.05	0.37	0.23	0.31	0.53
17	Raipur	9.85	10.06	0.48	5.25	4.37	4.40	4.85	0.98	1.01	0.05	0.53	0.44	0.44	0.48
18	Bangakhala (Tunwala)	9.85	8.64	0.48	4.61	4.42	3.92	5.15	0.98	0.86	0.05	0.46	0.44	0.39	0.52
19	Bullawala	10.06	10.06	0.48	4.29	3.48	4.05	5.00	1.01	1.01	0.05	0.43	0.35	0.40	0.50
20	Jhabrawala	10.06	6.24	0.90	3.82	3.51	3.77	4.89	1.01	0.62	0.09	0.38	0.35	0.38	0.49
21	Madhowala	7.85	1.50	0.48	4.53	3.64	4.60	6.44	0.78	0.15	0.05	0.45	0.36	0.46	0.64
22	Shimlas Grant	8.54	10.05	2.65	4.87	2.98	4.47	6.28	0.85	1.00	0.26	0.49	0.30	0.45	0.63
23	Mothronwala	5.37	10.06	1.89	4.24	3.73	3.52	3.67	0.54	1.01	0.19	0.42	0.37	0.35	0.37

Table 7.9: Groundwater quality index (GWQI) for the Suswa Watershed

Stn. No.	Station/ location	GWQI
Pre-monsoon- 2006:		
1	Siwalik hills	2.70
2	Shewala Khurd	1.13
3	Kaonli	2.43
4	Mehuwala Mafi	1.03
5	Mehuwala Arkediya	1.13
6	Arkediya Grant	2.07
7	Harbhajwala	0.81
8	Banjarawala	2.05
9	Banjarawala School	0.58
10	Nanda ki Chouki	1.85
11	Kuawala	0.48
12	Nakrounda	0.42
13	Balawala	0.60
Post-monsoon- 2006:		
1	Siwalik hills	3.30
2	Shewala Khurd	3.24
3	Kaonli	2.42
9	Banjarawala School	2.16
11	Kuawala	0.87
14	Yamuna Colony	1.37
15	SOI (Hathibarkala)	2.72
16	Chalgaon (Rajpur)	3.05
17	Raipur	3.18
18	Bangakhala (Tunwala)	2.96
19	Bullawala	3.17
20	Jhabrawala	2.63
21	Madhowala	1.66
22	Shimlas Grant	3.11
23	Mothronwala	2.57

3. The weights for the selected parameters (W_i) and the estimated W_{ri} values are given in Table 7.6.
4. Finally, the GWQI has been computed by employing equation (7.3) for selected seven parameters. The final GWQI values for sampled locations in the Suswa Watershed are given in Table 7.9.

7.7 VARIATION IN GWQI

The comparison of GWQI values during pre-monsoon and post-monsoon periods of 2006 at five locations (viz. Siwalik hills, Shewala Khurd, Kaonli, Banjarawala School and Kuawala) indicates that the GWQI values are higher during post-monsoon period than those during pre-monsoon period at these five locations. This anomaly can be attributed to the higher concentration values observed during post-monsoon period for majority of the parameters considered in the computation of GWQI as compared to those during pre-monsoon period.

In Table 7.7, for majority of the locations, the relative concentration (X_i) values of individual parameters are less than (or approaching to) the one showing 'acceptable' groundwater quality as per criteria given (in section 7.2) by Melloul and Collin (1998). At few locations, quite high values (more than 3.5) of X_i have been exhibited by some parameters like cadmium ($X_{i\text{-}Cd}$) at Siwalik hills, Bullawala and Jhabrawala; nickel ($X_{i\text{-}Ni}$) at Siwalik hills, Kaonli, Banjarawala, Nanda ki Chouki, Chalgaon, Bullawala and Mothronwala; chromium at Siwalik hills, showing 'unacceptable' groundwater quality.

Method of incorporating the synoptic groundwater quality index in assessment of sustainability is given in Chapter 8.

Chapter 8

ASSESSMENT OF SUSTAINABILITY

8.1 GENERAL

A holistic approach for assessment of sustainability of water resources in a watershed can bring out viable alternatives for water management in the right perspective. Accordingly, the paramount requirement in such a scenario is to formulate a rational approach for assessing the sustainability of water resources at watershed level especially in the context of their quantity and quality. Keeping this in mind, an attempt has been made in this study to identify key sustainability indicators that are viable to apply on long-term basis in a watershed. Such factors should be capable of withstanding the test of time for water quantity and quality monitoring through periodic assessment, eventually culminating in identification of set of indicators which will provide the ways and means of long-term sustainable water resources development and management.

This chapter deals with the identification and application of such indicators in assessing the sustainability of water resources in the Suswa Watershed. Based on the literature review (given in Chapter 2), suitable parameters have been identified for assessing the sustainability of water resources in the study area. These include annual deforestation rate (a land use indicator), water barrier index and integrated water stress score (the water quantity indicators). The synoptic evaluation of groundwater quality presented in the preceding chapter has been used for assessing the sustainability vis-à-vis water quality in the study area.

8.2 IDENTIFICATION OF SUSTAINABILITY INDICATORS

Sustainability indicators are the ideal means by which progress towards sustainable development can be measured. However, majority of the indicators throughout the world have been aimed at state-of-the-environment reporting, with relatively few aimed at developing sectoral indicators (Wamsley et al., 2001) and water sector is not an exception to this fact. As there is a large number of such indicators developed for varying needs throughout the world, it is necessary to adopt the most appropriate ones. It is also observed from the review of literature that each situation requires a particular method of assessment and no given set of indicators can be applied uniformly and universally in all areas. Accordingly, such indicators must be developed and tested over the time to fit country-specific or area-specific conditions, priorities and capabilities (UN, 2001).

8.2.1 Sustainability Indicators

From the guidelines published by UN (2001), the sustainability indicators have been identified as per their relevance to the present study and are given in Table 8.1.

Table 8.1: Sustainability indicators identified for the Suswa Watershed

Sl. No.	Sustainability indicators	Sub-theme	Theme
1	Forest area as a percent of land area	Forests	Land
2	Annual withdrawal of groundwater and surface water as a percent of total available water	Water quantity	Fresh water
3	Biological oxygen demand (BOD) in water bodies	Water quality	
4	Concentration of fecal coliforms in freshwater		

The first indicator viz. 'forest area as a percent of land area' has been included in the present study in the context of relevant land use-land cover. Another indicator viz. 'annual withdrawal of groundwater and surface water as a percent of total available water' measures total water abstractions divided by total renewable (available) water resources. This indicator is identical to the 'stage of groundwater development' (defined as a ratio of the current annual gross groundwater draft to the net annual groundwater availability) as discussed in Chapter 5.

It is well known that most open surface water bodies are prone to contamination by bio-organic and bio-chemical waste(s) requiring complete oxidation. Hence, it is necessary to incorporate a suitable biological oxygen demand (BOD) parameter in evaluation of sustainability. However, in the present study this parameter (and hence the third indicator in the Table 8.1 viz. 'BOD in water bodies') has been ignored as there is no significant surface water body in the present study area and surface water is reportedly not being used for the drinking purposes.

In the fourth indicator viz. 'concentration of fecal coliforms in freshwater' the term 'fecal coliforms' encompasses mainly *Escherichia coli* or thermotolerant coliforms. These coliforms are often present in surface water. Established standard methods available through the American Public Health Association (APHA) and guidelines for drinking water quality by World Health Organization (WHO) may be used for incorporating this parameter in consideration for sustainability assessment. But the bacteriological analysis carried out earlier (Sahu, 2009) has indicated that the coliforms are generally absent in the groundwater of the study area. Though this finding may not represent whole of the study area and is restricted to a few localities in Dehradun city, this factor has not been considered in the present study, due to paucity of data points.

8.2.2 Sustainability Indicators from Narula et al. (2001)

Narula et al. (2001) identified and evaluated three sustainability indicators for analyzing the water sustainability status of the Yamuna basin (having area of 346000 km^2) viz. water barrier index (WBI), integrated water stress score (IWSS) and use to resource ratio (URR). The first two indicators viz. WBI and IWSS have been used in the present study.

The third indicator viz. URR is based on the common notion that a region which withdraws a large fraction of its renewable resources is likely to face water shortages. According to Raskin et al. (1996) a use to resource ratio above 25 % could introduce potential shortages either due to decreased supply or increased demand. This is indicative of water stress. Instead of defining firm cutoff points, it is simply recognized that, as the use to resource ratio increases, regions will experience greater water stress and scarcity. This indicator is similar to the one suggested by UN (2001) on 'annual withdrawal of groundwater and surface water'.

8.3 SUSTAINABILITY ASSESSMENT IN THE SUSWA WATERSHED

The application of the identified sustainability indicators for assessment of sustainability of water resources in the Suswa Watershed is discussed below.

8.3.1 Forest Area as a Percent of Land Area

Deforestation rate (DR) is the compound annual rate of deforestation in the area of study in percent (between year P to year N):

$$DR(\%) = 100 \times \left(1 - \left(\frac{Forest\ area_{year\ N}}{Forest\ area_{year\ P}} \right)^{\frac{1}{N-P}} \right) \quad (8.1)$$

The annual deforestation rate (DR) in the Suswa Watershed is worked out for the periods from year 1972 to 1990 and from 1990 to 2000 by using equation 8.1 as 0.135 % and 0.888 % respectively. Although, the figures of deforestation rates are minimal, the one in the recent period of 10 years (from 1990 to 2000) is faster than that in the earlier period of 18 years (from 1972 to 1990).

8.3.2 Water Barrier Index (WBI)

This indicator is based on annual per capita availability of renewable water (m^3 per capita per year) as given in Table 8.2. The water barrier concept is the most widely cited measure of water sufficiency for large regions and river basins. It has been used in a number of sustainability evaluation studies (Falkenmark and Widstrand, 1992; Gleick, 1993, 1997; Engleman and LeRoy, 1993). This approach has the advantage of providing a simple view for the basin, thereby stating the category to which it pertains. Notwithstanding the constraint of the size of the study area, this factor has been considered for the Suswa Watershed.

Table 8.2: Water barrier index demarcations (Source: Falkenmark and Widstrand, 1992)

Index (m^3 per capita per year)	Category/condition
> 1700	No stress
1000 - 1700	Stress
500 - 1000	Scarcity
< 500	Absolute scarcity

For the Suswa Watershed, the WBI computations have been made by taking annual runoff volume computed in an earlier chapter (section 4.3.5.2) as the surface water availability. The minimum and average annual surface water availability has been estimated as 63.19 million-m^3 and 122.68 million-m^3 respectively. Yet, the minimum figure of surface water availability (63.19 million-m^3) has been combined with the net quantity of groundwater available (11,914.94 × 10^4 m^3) (Table 5.8, section 5.7.6) to arrive at the total minimum water availability in the Suswa Watershed. Thus, the minimum annual water availability is of the order of 18,23,39,400 m^3. The population for 2005 in the Suswa Watershed (projected from the population of 2001 census) has been worked out as 7,10,938. Finally, the minimum WBI in 2005 is of the order of 256.48 m^3 per capita per year putting the Suswa Watershed in 'absolute scarcity' category.

8.3.3 Integrated Water Stress Score (IWSS)

This indicator, developed for analyzing the sustainability of water resources, is an outcome of the evaluation of eight parameters, population density, irrigation intensity, number of industrial facilities, groundwater development, water table fluctuation (decline or rise), groundwater quality, surface water quality, and surface water flow. The values for each of these parameters have been divided into three subgroups in conformity with the approach given by Narula et al. (2001) for Yamuna river basin: acceptable, average, and undesirable. Each sub-group has been assigned a score (referred as a point by Narula et al., 2001), e.g. acceptable is given a score of 1, average has a score of 2, and undesirable has a score of 3. As an example, a high rate of water table decline (more than 0.5 m/ year) falls in the 'undesirable' category and groundwater level decline rate of 0.1 m/ year or less and absence of waterlogging falls in the 'acceptable' category. Based on the summation of scores for each of the parameters, the scores are allotted in the form of integrated water stress and then converted into relative percentage by dividing the watershed score with 24 (8-parameters × 3-sub-groups).

Watersheds with a percentage stress score of more than 60 are classified as 'highly stressed'. In such areas further water development should be restricted or should only take place if it does not pose a further threat to water depletion and deterioration. 'Moderately stressed' watersheds are classified as having percentage stress scores ranging from 40 to 60. In these watersheds, development could be allowed to a certain extent. Watersheds with percentage scores less than 40 were classified as 'low stress' areas with scope for further water use and development. Tables 8.3 and 8.4 give the minimum and maximum possible integrated water stress scores for the present study area.

Table 8.3: Computations of minimum possible IWSS in the Suswa Watershed

Sl. No.	Eight parameters	Three sub-groups (scores allotted)		
		Acceptable (1)	Average (2)	Undesirable (3)
1	Population density	1	-	-
2	Irrigation intensity	1	-	-
3	No. of industrial facilities	1	-	-
4	Groundwater development	1	-	-
5	Water table decline/ rise	-	-	3
6	Groundwater quality	1	-	-
7	Surface water quality	1	-	-
8	Surface water flow	1	-	-
	Sum of scores	7	0	3
	Grand sum of scores	10 (7 + 0 + 3)		
	IWSS	41.67 [(10 × 100) / 24]		

Table 8.4: Computations of maximum possible IWSS in the Suswa Watershed

Sl. No.	Eight parameters	Three sub-groups (scores allotted)		
		Acceptable (1)	Average (2)	Undesirable (3)
1	Population density	-	-	3
2	Irrigation intensity	-	2	-
3	No. of industrial facilities	-	-	3
4	Groundwater development	1	-	-
5	Water table decline/ rise	-	-	3
6	Groundwater quality	1	-	-
7	Surface water quality	1	-	-
8	Surface water flow	1	-	-
	Sum of scores	4	2	9
	Grand sum of scores	15 (4 + 2 + 9)		
	IWSS	62.50 [(15 × 100) / 24]		

In this study, the lowest possible stress score (Table 8.3) has been of the order of 41.67 % when only one parameter (e.g. water table decline rate) is considered in 'undesirable' category and other seven parameters are considered as 'acceptable'. Based on the IWSS classification system, the Suswa Watershed can be classified as 'moderately stressed'. On the other hand, the Suswa Watershed can be classified as 'highly stressed' (with a stress score of 62.50 %) by considering only three parameters (e.g. water table decline rate, population density and number of industrial facilities) in 'undesirable' category; one parameter like irrigation intensity in 'average' category and the remaining four parameters in 'acceptable' category (Table 8.4). Thus, it is inferred that keeping in view the fast urbanization and increasing demands of population, the Suswa Watershed can either be classified as 'moderately stressed' or 'highly stressed', confirming the outcome inferred from the WBI approach.

8.3.4 Groundwater Quality Index (GWQI)

The variation of GWQI in the Suswa Watershed during pre-monsoon and post-monsoon periods of 2006 discussed in the preceding chapter (section 7.7) is shown in Fig. 8.1 and 8.2. The maps exhibit a range of GWQI values from 0.42 to 2.70 during the pre-monsoon period and from 0.87 to 3.30 during the post-monsoon period. The areas with lower GWQI values indicate the best region (lowest pollution affected) and the areas with higher values indicate the worst region (maximum pollution affected).

From the GWQI maps, it can be seen that the overall groundwater quality is poor near the western boundary of the Suswa Watershed (especially near Siwalik hills hydrograph station) during pre-monsoon as well as post-monsoon periods. Thus, the groundwater quality is substantially deteriorated at few localities like Siwalik hills hydrograph station, Shewala khurd, Shimlas Grant, Bullawala, Raipur and Chalgaon (Fig. 8.2). Barring these areas, the remaining region in the Suswa Watershed indicates availability of good quality groundwater, much within the drinking water limits. Hydrogeologically, the groundwater movement direction in the Suswa Watershed (section 5.6) is also from the west to south-east direction.

Deterioration in groundwater quality at few locations apparently reflects the progress of urban, industrial and agricultural activities in the study area. Mapping of GWQI values can lead to development of a prioritized inventory of those chemical parameters required to properly identify the effects of specific sources of pollution upon groundwater quality. The temporal estimation of GWQI can highlight ongoing increases or decreases in the concentration of particular chemical parameter or combinations of parameters in groundwater for a region (Melloul and Collin, 1998). GWQI can thus prove as a tool to delineate areas where special attention may be required with regard to specific types of land usage. As such, this tool can contribute to meaningful sustainable groundwater management decisions as regards the water resources and land use planning.

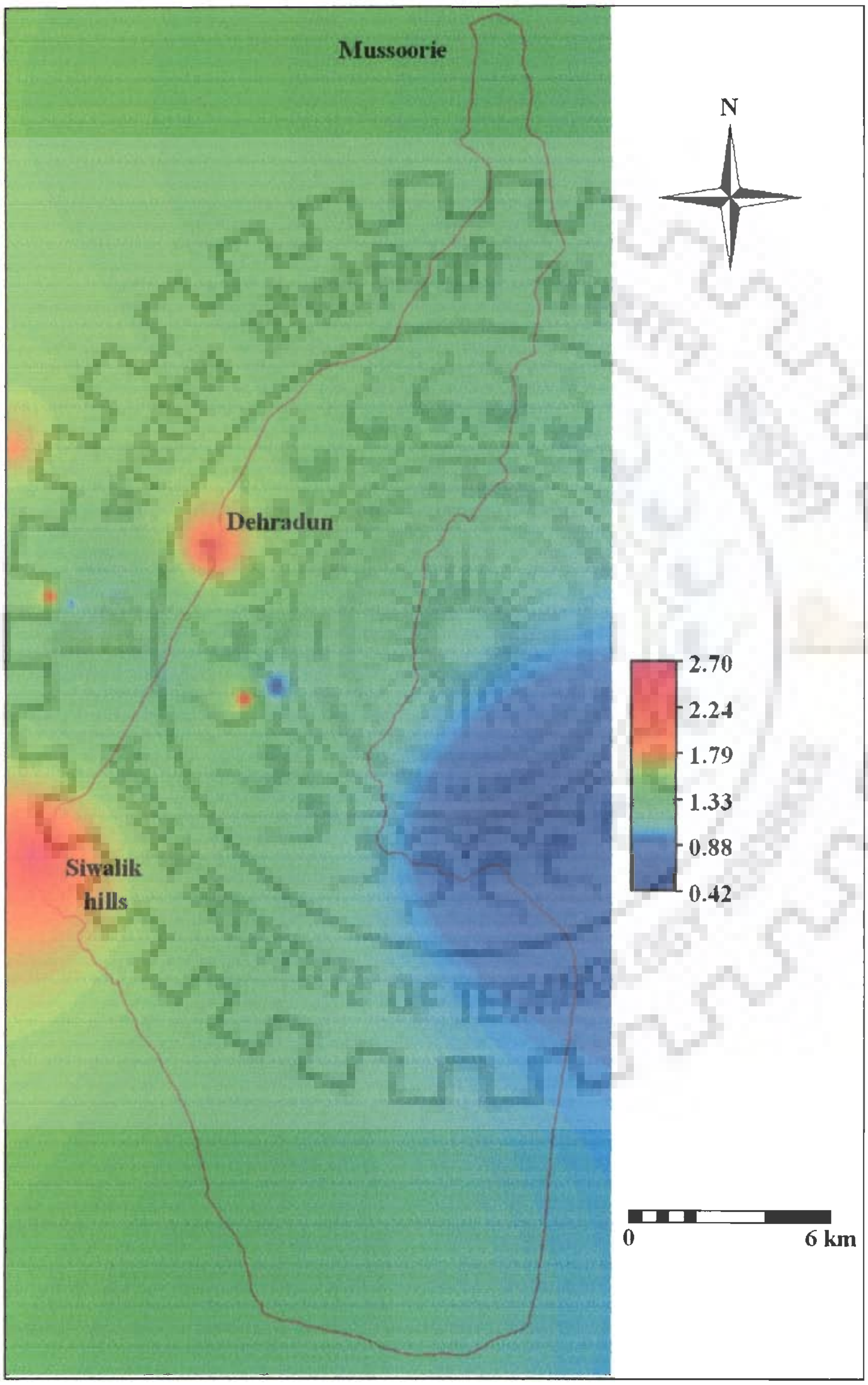


Fig.8.1: Groundwater quality index (GWQI) map (Pre-monsoon-2006)

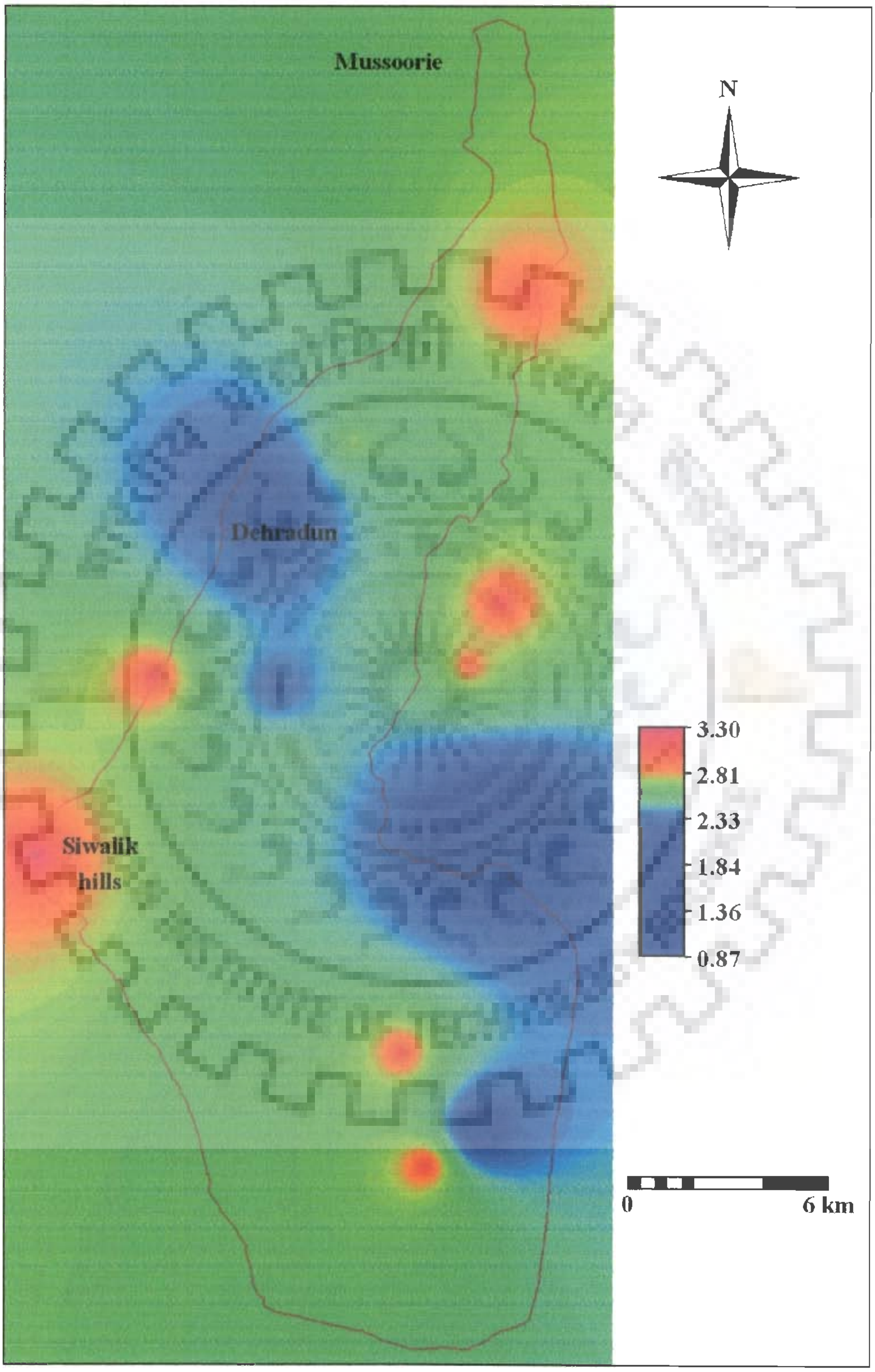


Fig.8.2: Groundwater quality index (GWQI) map (Post-monsoon-2006)

8.4 INTEGRATION OF SUSTAINABILITY INDICATORS

The results of the various indicators need to be organized and presented in a format that allows easy communication and unbiased interpretation. A template table has been developed to capture indicator outcomes and the interpretation of trends (Table 8.5). After computing the indicators, the template table allows to summarize the overall water sustainability condition of the Watershed. This procedure also affords an opportunity to incorporate the local knowledge of the users about the water management system and, if necessary, highlight local pressures that individually pose a significant stress on water sustainability. The proposed template has been used to summarize the results presented in section 8.3, which schematically compares the interpretation of the indicator results. Difficulties associated with data acquisition notwithstanding, the indicators discussed above appear to have the capacity for application at watershed scale, helping to identify the priority issues that may require particular focus.

Table 8.5: Interpretation and comparison of indicator results

Sl. No.	Criteria (sustainability indicators)	Condition	Trend
1	DR	±	↓
2	WBI	– –	↓
3	IWSS	– –	↓
4	GWQI	±	↔

Condition: ++ very good, + good, ± reasonable, – poor, – – very poor.
Trend: ↑ improving, ↔ stable, ↓ degrading.

8.5 CONCLUDING REMARKS

It has been observed that, the deforestation rate in the recent period of 10 years (from 1990 to 2000) is more rapid than that in the earlier period of 18 years (from 1972 to 1990), although it is not alarming in both the periods. The WBI computations have put the Suswa Watershed in 'absolute scarcity' category whereas as per 'IWSS' approach, the watershed can be classified as 'moderately stressed' to 'highly stressed'. Thus, to improve the sustainability of water quantity in the Suswa Watershed, considerable efforts are needed which may call for significant policy changes vis-à-vis water resources development and management. Further, even maintaining the present level of sustainability also needs some efforts from users, stake holders and decision makers.

Considering the chemical parameters involved in the groundwater quality assessment, GWQI values range between 0.42 and 3.30. Mapping of GWQI indicates that, barring few locations, the groundwater of the study area is fit for drinking.

Based on the assessment of sustainability indicators related to water resources, this study explores an optimal approach to ensure the sustainability of water resources development. This study concludes that the regular assessment of sustainability indicators can play a valuable role in ensuring the sustainable development and management of water resources in the Suswa Watershed.

Chapter 9

SUMMARY AND CONCLUSIONS

The present study was undertaken with the aim of assessing the sustainable water resources development in the intermontane watershed of Suswa river in Doon Valley, North India with due consideration to its quantity and quality aspects. The Suswa Watershed is located in the eastern part of the Doon Valley, Dehradun District, Uttarakhand, India. It includes the city of Dehradun to the west and hills of Mussoorie to the north whereas Siwalik range forms the southern boundary of the study area. The watershed belongs to the Song river system which is a tributary of the Ganga river. The area, covering about 292 km^2, is situated approximately between 77° 57' and 78° 10' East longitudes and 30° 08' and 30° 27' North latitudes and is included in the Survey of India topographical sheets Nos. 53J/3, 53J/4, 53F/15 and 53F/16. The land altitude varies from 420 to 2000 m AMSL. The average annual rainfall varies from 1600 to 2200 mm, most of which falls in the monsoon (June to August) months. Its land use mainly is characterized by forest and agriculture besides urban area of Dehradun city. Main crops grown in the area are paddy, wheat, maize and sugarcane.

As per 1991 census, total population of Dehradun city is 2,70,000 and that as per the 2001 census is 4,47,808, thus giving a quite high decadal growth rate of about 66 %, as compared to that of about 25 % in the overall Dehradun District. Although, it is difficult to give the precise population figures of the Suswa Watershed, the figures for Dehradun city indicate the magnitude of stress posed by the population in the area.

An extensive review of existing literature on sustainability indicators vis-à-vis water resources development along with its quantity and quality assessment has led to identification of viable sustainability indicators applicable on watershed basis. For evaluating such indicators, it is necessary to estimate various input parameters like rate and extent of land use-land cover changes with respect to deforestation and urbanization, availability of water resources along with groundwater quality.

In this context, systematic studies have been conducted in the present work to assess the relevant parameters in the Suswa Watershed by using available standard methodologies e.g. analysis of land use-land cover (LULC) changes by using remote sensing imageries in GIS environment, assessment of surface water availability by using the commonly used NRCS-CN method, groundwater resources assessment by using a mass balance based groundwater budgeting methodology, and synoptic groundwater quality assessment by using the standard methods in the light of current drinking water standards of various national agencies like Bureau of Indian Standards (BIS). The salient findings of each of these studies relevant to the Suswa Watershed are as given under.

9.1 ASSESSMENT OF SURFACE WATER RESOURCES

The satellite imageries obtained from the Global Land Cover Facility Data Center of Maryland University, USA have been used for determining the LULC of the study area. The widely used GIS software package viz. ERDAS IMAGINE 8.6 have been used for carrying out LULC classification. Runoff potential of the Suswa Watershed has been arrived at by using the widely practiced NRCS-CN method while annual storm runoff coefficient (ASRC) have been computed by taking ratio of annual runoff to annual rainfall.

- The analysis of LULC changes carried out for the years of 1972, 1990 and 2000 indicates that the rate of urbanization has increased drastically in the recent decade, especially in Dehradun city whereas forest and agricultural land use have decreased.
- The estimated surface water resources availability of about 63 million-m^3 indicates that there is adequate scope for the development of surface water resources by tapping surplus surface runoff by constructing water storage structures.
- The estimated ASRC shows that the annual runoff is around 22 % of the annual rainfall in the area.

9.2 ASSESSMENT OF GROUNDWATER RESOURCES

Estimation of groundwater resources of the study area has been done separately for command (1996 ha) and non-command areas (22684 ha) for hydrological year 2005-06. The necessary field data for the purpose was generated from a number of well hydrograph stations distributed over the watershed for pre-monsoon and post-monsoon periods of 2005-06. Other relevant data was generated from the norms recommended by the CGWB committee on groundwater resources estimation. Rainfall recharge in the watershed computed by using water table fluctuation (WTF) and rainfall infiltration factor (RIF) methods is about 11133 ha-m and 6866 ha-m respectively, which shows a large deviation in recharge estimates from above-mentioned two approaches. The final figures considered in groundwater estimates were, however, those worked out from RIF method (with a RIF of 0.22 from the existing CGWB norms).

- The annual groundwater recharge in the study area is worked out as 11915 ha-m whereas the total draft from all the shallow and deep production wells is of the order of 4175 ha-m.
- The general trend of depth to groundwater table recorded in the well hydrograph stations is declining (0.3 to 0.6 m per year) within Dehradun city and hence during further development of groundwater, there is an urgent need to watch the long-term trend of groundwater levels.
- The range of depth to water table during pre-monsoon and post-monsoon periods of 2005-06 was from 10 m to above 50 m bgl and from 5 m to 22 m bgl respectively. The groundwater in the area flows in the south-east direction.
- The stage of groundwater development in command and non-command areas has been worked out in the order of 19 % and 38 % respectively, which places the Suswa watershed under 'Safe' category. However, this finding is in contrast to the reports of over-exploitation of groundwater in the municipal area of Dehradun city. Further, it appears that the declining trend of groundwater levels in the wells of the study area may not, indeed, reflect the over-exploitation of groundwater, as suggested by some other researchers (Kalf and Woolley, 2005).

9.3 ASSESSMENT OF WATER QUALITY

Chemical analyses of 37 groundwater samples (including one river water sample) have been carried out for determination of physico-chemical parameters (TDS, EC, pH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, CO_3^{2-}, and SO_4^{2-}), nutrients (NO_3^{-} and PO_4^{3}) and heavy metals (Zn, Mn, Fe, Ni, Cu, Cd, and Cr) with the objective of assessing the water quality for drinking purpose.

A synoptic evaluation of groundwater quality was carried out by employing a groundwater quality index (GWQI). The necessary weights of water quality parameters used in GWQI have been estimated by using an analytical hierarchy process. The cutoff GWQI for groundwater fit for drinking purposes computed on the basis of seven identified critical water quality parameters (e.g. cadmium, nickel, chromium, total hardness, sulfate, total dissolved solids and total alkalinity) is 2.0, with higher values than this limit indicating undesirable groundwater quality.

- The major ionic composition of groundwater evaluated using a trilinear diagram shows the presence of dominating non-carbonate hardness during pre-monsoon period whereas it has dominant carbonate hardness after the rainy season.
- The overall groundwater quality in the study area has been found to be suitable for drinking purpose as per the standards of Bureau of Indian Standards (BIS). Yet, the quality of groundwater from shallow aquifers is marginally poor with respect to some critical parameters at few places especially towards south-west due to high concentration of heavy metals like nickel, cadmium, chromium, sulfate and $CaCO_3$ hardness it is generally found within the 'desirable' limits of Indian regulatory agencies, and can thus be allowed for drinking.
- The groundwater quality monitoring network is not adequately representative due to paucity of sampling points especially for deep tubewells.
- The lone Suswa river water sample indicated good water quality; however, river water is not being used for drinking purpose in the study area.

9.4 ASSESSMENT OF SUSTAINABILITY

The indicators identified for application in Suswa watershed to assess the sustainability of water resources are deforestation rate, water barrier index (WBI) and integrated water stress score (IWSS) and a synoptic groundwater quality index.

- The deforestation rate in the recent decade (from 1990 to 2000) is more rapid than that in the earlier period of 18 years (from 1972 to 1990), although it is not alarming in both the periods.
- The WBI computations have placed the Suswa Watershed in 'absolute scarcity' category whereas as per 'IWSS' approach, the watershed can be categorized as 'moderately stressed' to 'highly stressed'. In this context, reduction in stress on the water resources and increase in per capita water availability is greatly needed to improve the sustainability of water resources in the study area.
- Considering the seven relevant chemical parameters in the groundwater quality assessment, GWQI values range between 0.42 and 3.30 with the range for good quality water being below 2.0. Mapping of GWQI indicates that, barring few locations (like Siwalik hills hydrograph station, Shewala khurd, Shimlas Grant, Bullawala and Raipur), the groundwater of the study area is fit for drinking.

It has been inferred from the analysis of sustainability indicators that groundwater resources development in the Suswa Watershed in general, and Dehradun city in particular, is tending to become unsustainable.

9.5 LIMITATIONS OF THE STUDY

The following limitations have been observed in this study:

- Surface runoff estimation could not be validated against a measured discharge in the Suswa river due to unavailability of such data.
- Bacteriological analysis of water samples could not be carried out in the present study which is necessary for checking possible contamination of water from sewage

effluents. However, in another recent study, the groundwater of Dehradun city has been found to be free from bacteriological contamination (Sahu, 2009).

- The present study has not able to incorporate the socio-economical aspects into the assessment of sustainability of water resources development in the study area, which is a multi-disciplinary issue.
- As many hydrograph stations in the area are production tubewells used for drinking (and irrigation) purpose, the pumping sets on them cannot be kept switched off for a long duration in order to measure static groundwater levels. The drawdown due to continuous pumping might have led to misleading observations of groundwater levels in the present study.
- Due to uncertainty in the interconnection of shallow (unconfined) and deep (confined) aquifers, there is a possibility of substantial error in the assessment of groundwater resources for deeper aquifers.

9.6 RECOMMENDATIONS

Specific recommendations based on the present study are given as under:

- Available surface water resources (63 million-m^3) should be tapped for artificial recharge to arrest the declining trend of groundwater table (0.3 to 0.6 m/ year).
- Proper inventory of groundwater withdrawal structures and construction of deep piezometers in Dehradun city should be given priority.
- Values of sustainability indicators need to be estimated periodically.

9.7 RESREACH CONTRIBUTION

This study is an attempt to include the aspect of sustainability assessment into the field of water resources management through computation of sustainability indicators. In this context, identification of appropriate sustainability indicators and their evaluation for the specific areas is an important research contribution in this study, especially in the light of the fact that the application of sustainability indicators in water resources management decisions still is in its infancy.

9.8 SCOPE FOR FUTURE RESEARCH WORK

In spite of present research endeavors, there exists a scope for future research as under.

- Detailed land use-land cover mapping should be carried out by using higher resolution remote sensing data in order to increase the accuracy of assessment of available water resources.
- Groundwater resources estimation needs to be validated against the estimates of groundwater recharge from other techniques (like tritium injection studies) so that stage of groundwater development in an area can be ascertained more realistically.
- If necessary, some additional indicators of sustainability need to be identified on watershed basis to enable sound decision making.

The present study has helped in arriving at a holistic assessment of sustainable water resources in the study area on the basis of a given set of indicators, and can be replicated in other watersheds of the country characterized by similar hydrogeological framework.

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ANNEXURE 3.1

PHOTOGRAPHS: MONITORING AND ANALYSIS

(Continued...)

1- Groundwater sampling

2- Surface water sampling

3- On-field groundwater quality analysis

4- On-field surface water quality analysis

5- Measurement of depth to groundwater

6- Laboratory analysis in progress (at IIC)

7- Laboratory analysis in progress

8- Laboratory analysis in progress

9- The Suswa river having dry bed

10- Land uses of agriculture and forest

<u>ANNEXURE 4.1</u>

VALUES OF 'C' FOR USE IN RATIONAL METHOD

(after Singh et al., 1990)

Vegetative cover and slope	Soil texture		
	Sandy loam	Clay and silt loam	Stiff clay
i. Cultivated land			
0–5 %	0.30	0.50	0.60
5–10 %	0.40	0.60	0.70
10–3 %	0.52	0.72	0.82
ii. Pasture land			
0–5 %	0.10	0.30	0.40
5–10 %	0.16	0.36	0.55
10–30 %	0.22	0.42	0.60
iii. Forest land			
0–5 %	0.10	0.30	0.40
5–10 %	0.25	0.35	0.50
10–30 %	0.30	0.50	0.60

ANNEXURE 5.1

LOCATION DETAILS OF HYDROGRAPH STATIONS

Stn. No.	Name of hydrograph station	Dug well (DW) / tubewell (TW) / hand pump (HP)	Latitude (° N)	Longitude (° E)	Altitude (m AMSL)
1	Siwalik Hills	HP and DW	30° 14' 13.8"	77° 57' 38.5"	756
2	Shewala Khurd	DW	30° 17' 06.9"	77° 59' 41.7"	701
3	Kaonli	HP and DW	30° 19' 09.0"	78° 00' 42.6"	630
5	Mehuwala Arkediya	TW	30° 17' 52.1"	77° 58 40.1"	591
4	Mehuwala Mafi	TW	30° 18' 22.4"	77° 58' 59.9"	588
6	Arkediya Grant	TW	30° 18' 18.3"	77° 57' 49.9"	587
7	Harbhajawala	TW	30° 18' 12.5"	77° 58' 10.3"	587
8	Banjarawala	TW	30° 16' 47.8"	78° 01' 24.0"	598
9	Banjarawala School	HP and DW	30° 16' 59.8"	78° 01' 57.4"	602
10	Nanda ki Chouki	HP and DW	30° 20' 38.1"	77° 57' 03.3"	575
11	Kuawala	HP and DW	30° 14' 46.8"	78° 05' 48.6"	596
12	Nakrounda	HP and TW	30° 15' 11.1"	78° 06' 46.4"	583
13	Balawala	TW	30° 15' 23.1"	78° 07' 34.7"	580
14	Yamuna Colony	TW	30° 19' 43.5"	78° 01' 32.9"	662
15	SOI (Hathibarkala)	TW	30° 20' 53.5"	78° 03' 14.7"	703
16	Chalgaon (Rajpur)	TW	30° 23' 16.0"	78° 06' 15.3"	912
17	Raipur	TW	30° 18' 25.6"	78° 05' 59.0"	642
18	Bangakhala (Tunwala)	TW	30° 17' 24.7"	78° 05' 26.9"	620
19	Bullawala	TW and DW	30° 09' 27.6"	78° 04' 53.9"	467
20	Jhabrawala	DW	30° 08' 34.9"	78° 05' 37.1"	447
21	Madhowala	HP and DW	30° 10' 04.2"	78° 05' 52.0"	457
22	Shimlas Grant	HP and DW	30° 11' 15.8"	78° 04' 24.2"	489
23	Mothronwala	HP and DW	30° 15' 59.7"	78° 02' 11.3"	596

ANNEXURE 5.2

DEPTH TO WATER TABLE (m bgl) MEASURED FOR 2005-06

Stn. No.	Name of hydrograph station	2005		2006	
		Pre-monsoon (19th May)	Post-monsoon (22nd and 23rd October)	Pre-monsoon (10th May)	Post-monsoon (22nd November)
1	Siwalik Hills	9.5	8.78	9.57	7.26
2	Shewala Khurd	5.5	1.96	8.5	3.5
3	Kaonli	15.27	11.64	15.5	13.94
5	Mehuwala Arkediya	-	20.7	31.4	-
4	Mehuwala Mafi	-	27.4	33.85	-
6	Arkediya Grant	-	23.0	26.0	-
7	Harbhajawala	-	21.04	18.2	-
8	Banjarawala	-	8.0	11.0	-
9	Banjarawala School	-	5.0	9.6	8.0
10	Nanda ki Chouki	14.83	8.3	14.7	-
11	Kuawala	15.64	3.68	17.34	7.1
12	Nakrounda	-	7.34	> 50.0**	-
13	Balawala	-	17.2	> 50.0**	-
14	Yamuna Colony	-	-	-	22.0
15	SOI (Hathibarkala)	-	-	-	NA*
16	Chalgaon (Rajpur)	-	-	-	NA*
17	Raipur	-	-	-	NA*
18	Bangakhala (Tunwala)	-	-	-	20.5
19	Bullawala	-	-	-	4.9
20	Jhabrawala	-	-	-	10.2
21	Madhowala	-	-	-	12.2
22	Shimlas Grant	-	-	-	12.0
23	Mothronwala	-	-	-	11.2

* The tubewells are closed from top and no annular space for entering the tape of water level recorder. Therefore, only groundwater samples have been collected.

** Water level recorder has maximum capacity of measuring depth to groundwater level of 50 m bgl.

ANNEXURE 5.3

TREND ANALYSIS: SAMPLE CALCULATION

Trend analysis of pre-monsoon depth to water table for Harbhajawala:

Sr. No.	Ground water year	Year, X_i	Depth to water table for pre-monsoon (m bgl), Y_i	X_i^2	$X_i \times Y_i$
1	1995	1	22.9	1	22.87
2	1996	2	22.9	4	43.29
3	1997	3	21.6	9	73.17
4	1998	4	24.4	16	107.46
5	1999	5	26.9	25	130.00
6	2000	6	26.0	36	146.34
7	2001	7	24.4	49	172.87
8	2002	8	24.7	64	207.32
9	2003	9	25.9	81	233.23
10	2004	10	25.9	100	259.15
		$S_1 = 55$	$S_2 = 245.55$	$S_3 = 385$	$S_4 = 1395.70$

Number of pairs of data considered (N) = 10

Trend of depth to water table below ground level during pre-monsoon (Z) in cm/ year is given by,

$$Z = \frac{(N \times S_4) - (S_1 \times S_2)}{\left[(N \times S_3) - S_1^2\right]} \times 100$$

Z = 54.76 cm/ year (Falling)

In the above computations, water table trend is taken as:

(i) Rising if ‘Z’ is less than -5 cm per year,

(ii) Falling if ‘Z’ is greater than 5 cm per year, and

(iii) Neither rise nor fall if ‘Z’ is between -5 to +5 cm per year.

ANNEXURE 5.4

CALCULATION OF THE UNIT GROSS GROUNDWATER DRAFT FOR DIFFERENT TYPES OF WELLS IN THE SUSWA WATERSHED

Sr. No.	Type of well	Draft per well per day (m^3/day)	Number of days the wells are operated during		Gross groundwater draft per well during (ha-m)		
			Monsoon	Non-monsoon	Monsoon	Non-monsoon	Annual
For Command Area:							
1	State tubewell	1000	50	150	5.00	15.00	20.00
2	Private tubewell for domestic use	200	110	230	2.20	4.60	6.80
	Private tubewell for industrial use	500	90	170	4.50	8.50	13.00
3	Dug well	40	60	200	0.24	0.80	1.04
4	Hand pump	80	60	230	0.48	1.84	2.32
For Non-command Area:							
1	State tube well	1600	50	150	8.00	24.00	32.00
2	Private tubewell for domestic use	300	110	230	3.30	6.90	10.20
	Private tubewell for industrial use	500	90	170	4.50	8.50	13.00
3	Dug well	40	60	200	0.24	0.80	1.04
4	Hand pump	80	60	230	0.48	1.84	2.32

ANNEXURE 5.5

CALCULATION OF WETTED AREA FOR CANAL SEGMENTS IN COMMAND AREA OF THE SUSWA WATERSHED

Sr. No.	Name of canal segment	Culturable (cultivable) command area (ha)	Length of canal segment, L (m)	Design discharge, Q (m^3/s)	Base width, b (m)	Design depth, d $= \frac{Q}{V^* \times b}$ (m)	Wetted perimeter, P = b+2d (m)	Wetted area, W $=P \times L/10^6$ (Mm^2)
1	Badripur branch	187	5900	0.90	2.10	0.71	3.52	0.021
2	Rajpur canal	214	8100	1.26	1.10	1.91	4.92	0.040
3	Kargi minor	374	6070	0.41	1.00	0.68	2.36	0.014
4	Dharampur branch	180	9000	0.72	1.00	1.20	3.40	0.031
5	Shimlas Grant canal	280	13700	0.63	1.28	0.82	2.92	0.040
6	Bullawala canal	401	9650	0.75	1.85	0.68	3.21	0.031
7	Banjarawala canal	184	4800	0.45	1.10	0.68	2.46	0.012
8	Majra minor	176	2600	0.33	1.00	0.55	2.10	0.005
	Total	1996		5.45#				

* V = Velocity of flow in canal segments (assumed = 0.6 m/s). # Total design discharge of all canal outlets is assumed to be 75 % of the total design discharge of all canal segments, i.e. 5.45 × 0.75 = 4.09 m^3/s.

CALCULATION OF RECHARGE FROM CANAL SEGMENTS IN COMMAND AREA OF THE SUSWA WATERSHED

Sr. No.	Name of canal segment	Wetted area, W (Mm^2)	Assigned canal seepage factor (ha-m/day-Mm^2)	No of days the canal segment was in operation during monsoon	No of days the canal segment was in operation during non-monsoon	Recharge from canal segment during monsoon (ha-m)	Recharge from canal segment during non-monsoon (ha-m)
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (3)×(4)×(5)	(8) = (3)×(4)×(6)
1	Badripur branch	0.021	3.5	30	60	2.19	4.37
2	Rajpur canal	0.040	4.0	30	60	4.78	9.56
3	Kargi minor	0.014	3.0	30	60	1.29	2.59
4	Dharampur branch	0.031	3.5	30	60	3.21	6.43
5	Shimlas Grant canal	0.040	4.0	30	60	4.80	9.60
6	Bullawala canal	0.031	4.0	30	60	3.71	7.41
7	Banjarawala canal	0.012	4.0	30	60	1.42	2.84
8	Majra minor	0.005	3.0	30	60	0.49	0.98
					Total	21.89	43.78

ANNEXURE 6.1

DATA OF PHYSICO-CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES (POST-MONSOON- 2005)

Stn. No.	Name of hydrograph station	Temp, °C	pH	EC, µmhos/cm	TDS, mg/L	Total Hardness, mg/L	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Total Alkalinity, mg/L	Cl, mg/L	SO_4, mg/L	NO_3, mg/L	PO_4, mg/L	Sum of cations, meq/L	Sum of anions, meq/L	**e, %
1	Siwalik hills	21.3	7.1	400	364	158	47.2	21.9	5.2	2.2	180	7	171	5.2	2.62	4.44	6.79	-20.95
2	Shewala Khurd	23.5	7.6	900	743	412	64.0	61.2	30.2	1.3	74	44	539	13.7	2.46	9.58	13.91	-18.44
3	Kaonli	24.2	7.4	600	542	204	38.4	46.2	0.2	12.1	98	31	221	58.8	2.23	6.04	8.04	-14.21
5	Mehuwala Arkediya	24.5	7.6	500	430	224	49.6	39.1	3.4	5.9	138	18	242	40.2	2.23	5.99	8.45	-16.98
6	Arkediya Grant	24.5	7.5	400	393	180	46.4	27.7	2.1	4.1	108	15	232	34.7	2.46	4.79	7.58	-22.59
8	Banjarawala	24.7	7.6	400	342	190	52.8	26.2	3.2	5.2	102	10	242	41.4	2.23	5.06	7.67	-20.44
9	Banjarawala School	24.1	7.6	500	412	196	43.2	28.2	4.2	7.2	120	12	236	51.3	1.91	4.84	8.04	-24.85
11	Kuawala	23.0	6.2	200	133	218	34.4	45.7	2.2	0.4	76	5	316	22.4	1.45	5.58	8.33	-19.73
BIS: 10500		-	6.5-8.5	-	**500**	**300**	**75**	**30**	**200#**	-	**200**	**250**	**200**	**45**	**5***	-	-	-

** e = Ion balance error (computed by using equation 6.1); * Permissible limit given by WHO (1971); # CHASDWR (2001)

ANNEXURE 6.2

DATA OF PHYSICO-CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES (PRE-MONSOON- 2006)

Stn. No.	Name of hydrograph station	Temp, °C	pH	EC, μmhos/cm	TDS, mg/L	Total Hardness, mg/L	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Total Alkalinity, mg/L	Cl, mg/L	SO_4, mg/L	NO_3, mg/L	PO_4, mg/L	Sum of cations, meq/L	Sum of anions, meq/L	**e, %
1	Siwalik hills	22.4	6.9	400	400	152	70.5	21	8.0	3.0	184	6	200	7.6	3.40	5.67	7.46	-13.6
2	Shewala Khurd	22.9	7.5	700	505	364	41.2	64	12.5	8.2	100	22	335	9.0	3.01	8.07	9.38	-7.5
3	Kaonli	24.7	7.5	600	413	290	22.4	57	7.8	9.5	114	29	210	31.4	2.15	6.39	7.56	-8.4
4	Mehuwala Mafi	24.2	7.4	500	394	204	54.7	29	7.9	9.5	76	15	221	37.0	3.48	5.71	6.87	-9.2
5	Mehuwala Arkediya	24.4	7.5	400	376	230	39.4	48	2.1	4.2	89	17	231	31.0	2.78	6.14	7.24	-8.2
6	Arkediya Grant	24.4	7.5	500	508	214	67.9	39	1.5	5.1	202	16	217	22.6	5.83	6.82	8.64	-11.8
7	Harbhajwala	24.4	7.6	500	432	248	54.9	44	1.8	2.1	106	21	239	39.1	1.84	6.47	7.94	-10.2
8	Banjarawala	24.4	8.0	400	465	200	66.8	29	6.8	9.4	110	10	235	19.5	3.40	6.27	7.29	-7.5
9	Banjarawala School	23.3	7.5	500	430	202	54.9	40	6.1	3.2	116	21	227	42.5	3.17	6.36	7.90	-10.8
10	Nanda ki Chouki	25.4	7.2	200	346	118	39.6	29	2.2	1.7	84	5	196	7.2	3.48	4.49	5.71	-12.0
11	Kuawala	22.3	5.9	100	396	286	34.0	55	6.1	1.8	88	5	276	8.7	2.38	6.52	7.46	-6.7
12	Nakrounda	24.8	7.6	400	385	112	69.6	21	1.7	8.5	84	17	214	15.4	2.07	5.52	6.55	-8.5
13	Balawala	23.8	8.0	400	488	230	70.4	47	3.2	2.1	98	4	324	14.3	2.62	7.61	8.70	-6.7
	BIS: 10500	-	6.5-8.5	-	**500**	**300**	**75**	**30**	**200#**	**-**	**200**	**250**	**200**	**45**	**5***	-	-	-

** e = Ion balance error (computed by using equation 6.1); * Permissible limit given by WHO (1971); # CHASDWR (2001)

ANNEXURE 6.3

DATA OF PHYSICO-CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES (POST-MONSOON- 2006)

Stn. No.	Name of hydrograph station	Temp, °C	pH	EC, μmhos/cm	TDS, mg/L	Total Hardness, mg/L	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Total Alkalinity, mg/L	Cl, mg/L	SO_4, mg/L	NO_3, mg/L	PO_4, mg/L	Sum of cations, meq/L	Sum of anions, meq/L	**e, %
1	Siwalik hills	20.5	7.2	200	420	271	61	29	9.2	4.0	174	2	290	12.2	0.35	5.91	9.14	-21.4
2	Shewala Khurd	22.6	7.8	400	638	534	66	89	7.0	10.3	336	31	206	15.2	0.03	11.23	10.91	1.5
3	Kaonli	23.6	7.8	300	466	420	70	59	10.1	2.1	334	29	91	18.4	0.19	8.88	8.49	2.2
9	Banjarawala School	21.8	7.8	100	453	328	61	43	5.6	5.6	314	21	105	2.0	0.97	6.94	7.96	-6.9
11	Kuawala	19.6	6.5	100	284	208	46	23	6.6	2.7	24	3	182	0.0	0.58	4.51	4.27	2.7
14	Yamuna Colony	22.8	8.2	100	495	360	56	53	6.9	1.7	336	11	89	57.2	0.43	7.53	8.60	-6.6
15	SOI (Hathibarkala)	22.8	7.8	200	357	326	63	41	4.3	1.6	240	3	84	28.1	0.19	6.74	6.23	3.9
16	Chalgaon (Rajpur)	23.2	8.3	100	267	206	54	17	2.9	1.4	216	2	73	11.2	0.03	4.27	5.29	-10.6
17	Raipur	22.9	8.3	200	423	320	62	40	3.2	2.0	192	2	168	5.8	1.05	6.58	6.79	-1.6
18	Bangakhala (Tunwala)	23.5	7.9	100	365	270	50	35	3.7	1.5	208	6	170	6.3	1.21	5.59	7.23	-12.8
19	Bullawala	22.4	8.1	100	380	246	58	25	7.1	1.8	200	11	125	5.2	0.58	5.27	6.28	-8.7
20	Jhabrawala	23.2	7.0	100	347	235	71	14	8.5	1.6	194	14	127	3.4	1.60	5.11	6.27	-10.1
21	Madhowala	23.5	7.6	100	449	288	72	26	8.0	2.6	282	13	133	3.2	0.58	6.16	7.80	-11.7
22	Shimlas Grant	24.1	8.0	100	432	290	62	33	9.8	3.8	272	17	102	0.1	0.66	6.32	7.07	-5.7
23	Mothronwala	23.0	6.9	100	318	242	54	26	7.1	2.4	134	7	137	1.9	0.97	5.20	5.28	-0.7
	BIS: 10500	-	6.5-8.5	-	**500**	**300**	**75**	**30**	**200[#]**	-	**200**	**250**	**200**	**45**	**5***	-	-	-

** e = Ion balance error (computed by using equation 6.1); * Permissible limit given by WHO (1971); # CHASDWR (2001)

ANNEXURE 6.4

METHODS OF ANALYSIS FOR WATER QUALITY PARAMETERS

Sl. No.	Parameters	Methods Used
	Physical properties	
1	pH*	Method 4500 H+ 'pH Value'
2	Electrical conductivity (EC)*	Method 2510 B, 'Electrical Conductivity'
3	Total dissolved solids (TDS)	Method 2540 C, 'Total dissolved solids dried at 103°C -105°C'
4	Total hardness	Method 2340 C, 'EDTA Titrimetric Method'
	Major ions	
5	Calcium (Ca^{2+})	Method 3500-Ca B, 'EDTA Titrimetric Method'
6	Magnesium (Mg^{2+})	Method 3500-Mg B, 'Calculation Method'
7	Sodium (Na^{+})	Method 3500-Na B, 'Flame Photometric Method'
8	Potassium (K^{+})	Method 3500-K B, 'Flame Photometric Method'
9	Total alkalinity (HCO_3^{-} + CO_3^{2-})	Method 2320 B, 'Methyl Orange Titrimetric Method'
10	Sulfate (SO_4^{2-})	Method 4500-SO_4 F, 'Nephelometric Method'
11	Chloride (Cl^{-})	Method 4500-Cl B, 'Argentometric Method'
	Nutrients	
12	Nitrate (NO_3^{-})	Method 4500-NO_3 D, 'Nitrate Electrode Method'
13	Phosphate (PO_4^{3-})	Method 4500 B, 'Ascorbic Acid Method'
	Heavy metals	
14	Zn, Mn, Fe, Ni, Cu, Cd, and Cr	Method 3030 E, 'Acid Digestion and Analysis by Flame Atomic Absorption Spectrometry'

* Measured at the site
(Source: APHA, 1995)

PUBLICATIONS FROM THE THESIS

1. **Yadav, S.R.**, Sahu, B., Singhal, D.C., Singh, R. and Kumar, S. (2009). Assessment of groundwater resources in Suswa watershed– comparison with Dehradun city. Proceedings of the National Symposium on 'Climate Change and Water Resources in India', Indian Association of Hydrologists, National Institute of Hydrology, Roorkee- 247667 (November, 18-19, 2009).
2. **Yadav, S.R.** and Singhal, D.C. (2010). Evaluation of sustainable groundwater resources in an intermontane watershed of sub-Himalayan region, north India. Proceedings of the CGWB Workshop on Groundwater Resources Estimation, Ministry of Water Resources, Government of India, New Delhi (February, 23-24. 2010).