IMPACT OF URBANIZATION ON GROUNDWATER IN LUCKNOW AREA, INDIA

Ph.D. THESIS

by

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INDIAN INSTITUTE OF TECHNOLOGYROORKEE
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A THESIS

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the thesis entitled "**IMPACT OF URBANIZATION ON GROUNDWATER IN LUCKNOW AREA, INDIA**" in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from December, 2009 to March, 2015 under the supervision of Dr. G. J. Chakrapani, Professor, Department of Earth Sciences, Indian Institute of Technology Roorkee and Dr. S. K. Srivastav, Scientist SG & Head, Geoinformatics Department, Indian Institute of Remote Sensing, Dehradun.

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.

(ANJALI SINGH)

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

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Supervisor

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Date: March , 2015

ABSTRACT

Urbanization often leads to an increase in groundwater demand due to expansion in urban areas and accompanied land use changes. Studies based on satellite gravity observations indicated that Northern India lost about 109 km^3 of groundwater between 2002 and 2008 leading to a decline in water table to the extent of 0.33 meters per annum. The focus of the present study was to assess the effect of urbanization on groundwater in terms of groundwater vulnerability to pollution and groundwater resources, using satellite observations, Geographical Information System (GIS) and ground-based investigations. Lucknow City, the capital of Uttar Pradesh, of North India was taken as the study area. Recently available methods for assessment of groundwater vulnerability to pollution were reviewed and a new (modified) method suitable for an urbanized environment was developed. The results were validated by comparing with the observed groundwater quality characteristics. The groundwater depletion trends were estimated using data obtained from Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS).

The study area, situated in Ganga-Gomti interfluve, witnessed an unprecedented growth in water demand during the last few decades. The groundwater samples of the study area collected during pre-monsoon (May, 2011) and post-monsoon (November, 2011) seasons representing the shallow and deeper aquifers were analyzed for various physico-chemical parameters, such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), major anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, F^-) and trace elements (As, Hg, Fe, Cr, Zn, Pb, Mn). The groundwater quality in the study area did not indicate much variation between pre-monsoon and post-monsoon seasons. Nitrate (NO_3^-) concentration is found to be beyond desirable limit in ~70% groundwater samples indicating to inputs from sewer systems. Amongst the trace elements, acceptable limits of mercury (Hg) and iron (Fe) are violated in many samples.

The groundwater vulnerability assessment was carried out using DRASTIC (D=Depth to water table, R=Recharge, A=Aquifer media, S=Soil media, T=Topography, I=Impact of vadose zone, C=Hydraulic conductivity) method. A new (modified) DRASTIC model, called DRASTICA, was developed by inclusion of a new parameter 'impact of anthropogenic activities' (A). The comparison of DRASTIC and DRASTICA model based groundwater vulnerability/risk maps with the observed groundwater quality indicated that the DRASTICA model performs better than the traditional DRASTIC model in urbanized environment. Sensitivity analysis indicated that anthropogenic impact (A) and depth to water table (D) largely influenced the groundwater vulnerability/ risk to pollution, thereby signifying that anthropogenic influence needs to be appropriately addressed.

Grace is unique in its ability to monitor changes in land water storage at all levels- from the top of the plant canopy to the base of the deepest aquifer and allow us to directly monitor regional changes in stored water. The seasonal and yearly hydrologic signals acquired by GRACE and simulated soil moisture from GLDAS were studied in the entire State of Uttar Pradesh with an emphasis on the Lucknow district for assessing the mass change due to groundwater withdrawal from aquifers. Time series analysis of terrestrial water storage (TWS) obtained from GRACE, soil moisture from GLDAS, and rainfall data indicated volumetric groundwater storage loss of about 0.37 km^3 in Lucknow District. The results compared very well with the observed water table trend.

The study presented a novel approach to holistically understand and assess the effect of urbanization on groundwater by integrating the multi-source datasets and validating the results with ground observations. The results will help water resource managers and urban authorities in taking up appropriate remedial measures to protect groundwater reserves from further deterioration both in terms of quality and quantity. Proper sewerage system; artificial recharge of groundwater, especially through roof water harvesting structures, in the high and very high vulnerable/ risk zones and high-exploitation zones; conjunctive use of surface and groundwater resources in shallow water table areas are some of the suggested measures.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AAS	Atomic Absorption Spectrophotometer
AVI	Aquifer Vulnerability Index
BCM	Billion Cubic Meter
BIS	Bureau of Indian Standards
CAI	Chloro Alkaline Index
CGWB	Central Ground Water Board
CR	Corrosivity Ratio
CSR	University of Texas Center for Space Research
DEM	Digital Elevation Model
DI	DRASTIC Index
DMSP	Defence Meteorological Satellite Program
DRASTICA	Depth to water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, hydraulic Conductivity, Anthropogenic impact
DRASTIC-LU	Depth to water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, hydraulic Conductivity, Land Use
GALDIT	Groundwater occurrence, Aquifer hydraulic conductivity, Depth to water level, Distance from the shore, Impact of existing status of sea water intrusion and Thickness of mapped aquifer
GFZ	Geo-Forschungs Zentrum Potsdam
GIS	Geographic Information System
GLDAS	Global Land Data Assimilation System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GWS	Ground Water Storage

ICP-MS	Induced Coupled Plasma-Mass Spectrophotometer
IIRS	Indian Institute of Remote Sensing
IITR	Indian Institute of Technology, Roorkee
JPL	Jet Propulsion Laboratory
LULC	land-use/ land-cover
MDI	Modified DRASTIC index
MH	Magnesium Hazard
MLD	Mega Liter per Day
NASA	National Aeronautics and Space Administration
NCR	National Capital Territory
NRC	National Research Council
OLS	Operational Line-scan System
PI	Permeability Index
RSAC	Remote Sensing Application Center
RSC	Residual Sodium Carbonate
SAR	Sodium Adsorption Ratio
SM	Soil Moisture
SOI	Survey of India
SWE	Snow Water Equivalent
TDS	Total Dissolved Solids
TW	Tube Well
TWS	Total Water Storage
UPRSAC	Uttar Pradesh Remote Sensing Application Center
USEPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator
WGS	World Geodetic System

WHO	World Health Organisation

SYMBOLS

%Na	Sodium Percent
µg/l	Microgram per liter
µm	Micrometer
µS/cm	Micro Siemen per centimeter
A_r	Aquifer Media Rating
A_r	Anthropogenic Impact Rating
A_s	Arsenic
A_w	Anthropogenic Impact Weight
$Ca\text{-}Mg\text{-}HCO_3$	Calcium-Magnesium-Bicarbonate
C_r	Hydraulic Conductivity Rating
C_w	Hydraulic Conductivity Weight
D_r	Depth To Water Table Rating
D_w	Depth To Water Table Weight
E.C.	Electrical Conductivity
IC	Ion Chromatograph
I_r	Impact Of Vadose Zone Rating
I_w	Impact Of Vadose Zone Weight
KCL	Potassium Chloride
km/hr	Kilometer Per Hour
km^2	Square Kilometer
lpcd	Liter/Day/Capita
lpm	Liters Per Minute
L_r	Rating of Land Use Parameter
L_w	Weight of Land Use Parameter
mbgl	Meters Below Ground Level

meq/l	Milli Equivalent Per Liter
mg/L	Milligram Per Liter
$MgCl_2$	Magnesium Chloride
mmol/l	Milli Mol Per Liter
mol/l	Mol Per Liter
NO_3^{2}-	Nitrate
ppb	Parts Per Billion
ppm	Parts Per Million
P_r	Rating of Respective Parameter
P_w	Weight of Respective Parameter
R_r	Net Recharge Rating
R_w	Net Recharge Weight
S	Sensitivity Measure
S_r	Soil Media Rating
S_w	Soil Media Weight
T_d	Depositional Terraces
T_e	Erosional Terraces
T_r	Topography Rating
T_w	Topography Weight
V	Final Vulnerability Index
V'	Perturbed Vulnerability Index (Vulnerability Index Calculated Using Lower Number Of Parameters)
W_{pi}	Effective Weight (%)

CHAPTER 1

INTRODUCTION

1.1 Introduction

India is the largest groundwater consumer country in the world, with estimated annual extractions exceeding 230 km^3. Approximately 60% of irrigated agriculture, 85% of drinking water, and 50% of industrial and urban water requirements are reliant on groundwater. During last few decades, due to the speedily increasing population and growing economic activities, high intensity of urban expansion or urbanization has been observed in Indian cities. The per capita water availability in India has declined from 5176 m^3 in 1951 to 1820 m^3 as on 1st March 2001 and 1703.6 m^3 on 1st March 2005 (Central Water Commission, 2005), as the resource is limited but the progressive growth rate of shareholders increased many folds from 51.47% to 331.52% in the year 1951 and 2005 respectively (ENVIS Center on Population and Environment). Thus growing population has put immense pressure on the water resources and distribution. New urban expansions as well as irrigation and agricultural activities in adjoining rural areas stressed the hydrological cycle and thus water supplies are getting gradually chaotic in the city. The present study dealt with certain aspects of urban hydrogeology in and around Lucknow region.

Groundwater is a major contributor towards the water requirements of agriculture, industrial and domestic sectors. Agriculture has substantial contribution towards the infrastructure of any country’s economy. Water along with climate, geology and certain hydrological conditions are potential parameters essentially required to meet the demands of ever growing agriculture and industry. Urbanization is putting immense pressure on our groundwater resources to cater to the demands of users. As a result, our groundwater resources are also getting depleted day by day. Groundwater gets polluted by anthropogenic and other activities (such as land disposal of wastes and sewage, leaching of fertilizers and pesticides). The study of increasing concentrations of nitrate, bacteria and pesticides in groundwater have encouraged research on sub-surface fate of contaminants. Prevention of groundwater contamination is more easy and cheaper than its remediation. For the protection of our groundwater resources, the areas which are liable to contamination by anthropogenic activities need to be delineated, which can be best achieved through assessment of groundwater vulnerability. The areas where groundwater resources are depleting should also be mapped which can be studied by remote sensing studies of GRACE/GLDAS data.

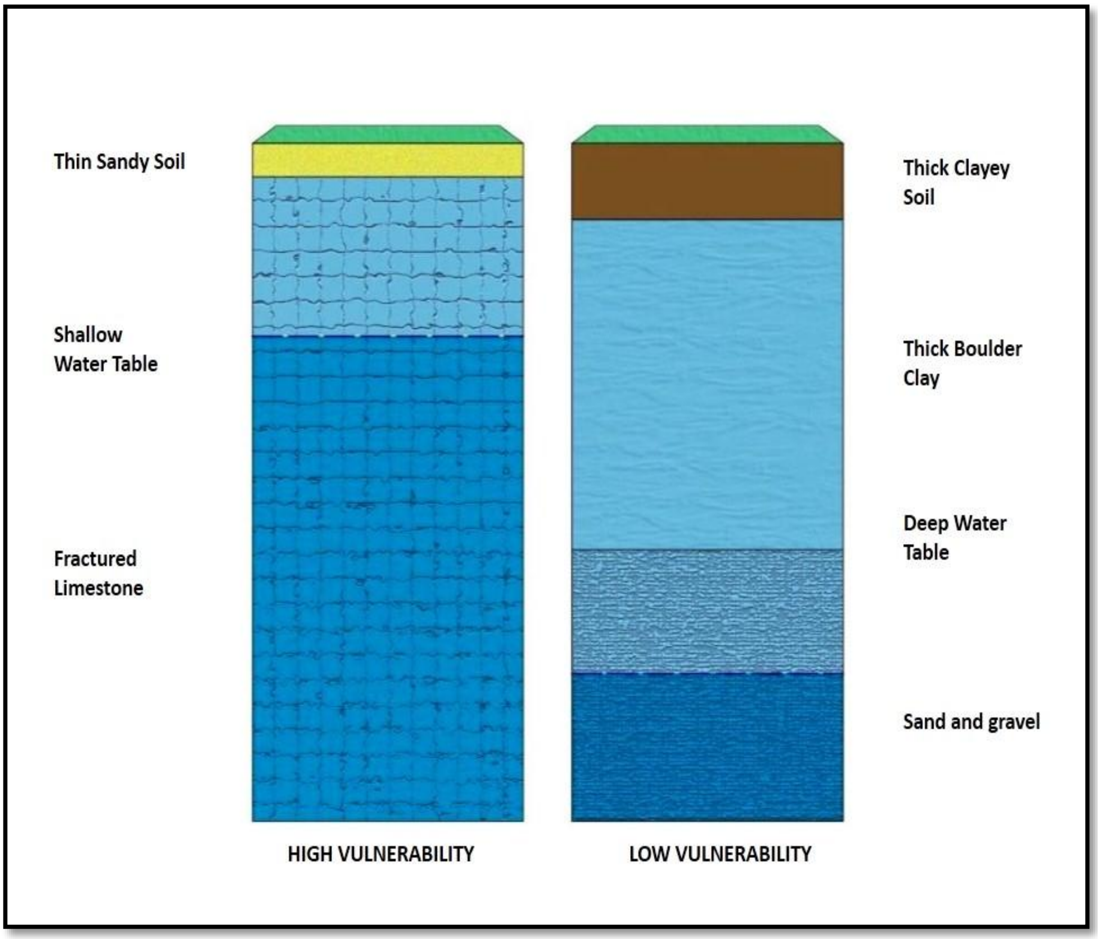
1.2 Groundwater Resources in India

In the past three decades, several attempts have been made by the Government and other organizations in order to utilize all available water resources of the country. In spite of having perennial resources of water availability, a major portion of the country is beset with a highly uneven distribution of both surface and groundwater resources. Groundwater is recharged by rainfall during seasonal monsoon. In Indian sub-continent, average annual rainfall varies with time and space. Maximum rainfall of approximately 250 cm occurs along the Western Ghats and the NE Himalaya, while a minimum in semi-arid to arid condition is exhibited in the western part of the country. Population in India expanded to more than 1.25 billion at the present phase of the 21st century. Such a fast growth exponentially puts high demands on development and basic such as, like frequent supply of drinking and municipal water, power generation to enhance the economical wealth and ecological maintenance. During 1999 to 2009, total utilization of water in India shot up from 573 km^3 to 813 km^3. If the trend continues by the year 2025, projected demand of water is estimated to amount to 1095 km^3 which may cause severe scarcity of water in next 10-20 years (Singhal and Gupta, 2010).

In India, groundwater plays a vital role in maintaining the distribution of water for irrigation and municipal use in both urban and rural regions. Groundwater resource contributes more than 85% of the water demand for domestic purposes in rural areas. Urban water requirement for municipal use and water for irrigation purpose have been met by groundwater with an equal share of 50% each. As mentioned earlier, groundwater is annually replenished by rainfall during the monsoon season which is a function of time and intensity of the monsoonal activity. Groundwater resources which have been recharged annually are known as ‘Annual Replenishable Groundwater Resources’. The Annual Replenishable Groundwater Resources for the India is estimated to be about 431 Billion Cubic Meters (BCM) of which, monsoonal recharge contribute about 57% (i.e. 246 BCM) to the annual replenished groundwater resources. In nut shell, it has been estimated that the total input of rainfall contributes about 68% to Annual Replenished Groundwater Resources in India. The remaining 32% have been contributed by other sources, such as canal seepage, recharge from tanks, ponds, and water conservations structures. The ‘Annual Groundwater Draft’ for the entire country proposed during 2008-09 suggested that the groundwater resources have been predominantly consumed by the agricultural sector. About 91% (221 BCM) of the total annual groundwater draft is mostly for irrigation purposes and only 9% (22 BCM) is left for domestic and industrial use (CGWB, 2009).

1.3 Groundwater Vulnerability

Groundwater vulnerability is proneness of groundwater resources to contamination by various natural and anthropogenic activities.



(Source: UK groundwater forum http://www.ukhydrogeologist.co.uk/)

Figure 1.1 Representation of Groundwater Vulnerability Degree

The groundwater vulnerability (Figure 1.1) is higher where, thinner soils, substrata and shallow water table occurs and vulnerability is lower where thicker soils and substrata as well as deeper water table occurs. These factors such as thickness of soils and substrata and depth to water table play a key role in transporting contaminants to the aquifer. Because the shallowest depth to groundwater zone is characteristically the most prone to contamination, vulnerability assessments are typically concerned with the vulnerability of the uppermost aquifer in a multi-tier aquifer system of any area or with the water table in an unconfined aquifer system.

1.4 Why the Need to Assess Groundwater Vulnerability?

The goal of groundwater vulnerability assessment is to provide a policymaking tool on the basis of best obtainable data and good logical conclusion. The National Research Council (1993) recognized four goals accomplished by assessment of groundwater vulnerability:

- To enable and develop policy analysis at local and regional level.
- To offer program management.
- To advise land use decisions.
- To give general education and awareness of hydrological resources of any region.

Urbanization corresponds to change in land use patterns, which results in an increased demand for water to their daily needs. Considering the fact that surface water is more prone to contamination than groundwater, the demand for groundwater increases. In alluvial regions groundwater is generally lavish and the urban areas are often located there. Such areas are generally more vulnerable to pollution due to more anthropogenic activities and several other factors such as urban sewage, agricultural pesticides, and industrial wastes. Because of these issues, the present study was aimed to review groundwater vulnerability studies in the Ganga-Gomati interfluve area of northern India. The study area is an alluvial plain of Ganga-Gomati interfluve i.e., Lucknow district. The main goal of the study was to recognize the potential for groundwater contamination in the area for the protection of groundwater resources and to provide useful suggestions to policy makers, land use planners and water users.

1.5 Why the Need to Assess Groundwater Depletion?

In Northern India, groundwater extraction in response to the increasing demand for water has recently been surpassed groundwater replenishment, triggering a continuously declining water table (Tiwari et al., 2009). Currently many government organizations are monitoring groundwater resources across India. Their instrumentation errors, maintenance, project costs, spatial and temporal gaps point fingers to low-frequency and unreliable data. Satellite based observational techniques allow us to directly monitor regional variations in stored water leading to more precise estimation of groundwater resources (Rodell et al., 2009).

1.6 Objectives

The major objective of the present study was to understand the impacts of urbanization on groundwater of Lucknow area.

The Lucknow district, Ganga-Gomati interfluve area of northern India, was selected for the present study. The overall purpose of the present study was to assess the groundwater vulnerable zones by developing a suitable model for the alluvial aquifers of Ganga-Gomati interfluve area. The model will be validated by comparing the output of the model with the water quality characteristics of the region and assessment of groundwater depletion trend using GRACE/GLDAS data.

1.7 Approaches

The approaches to achieve the above mentioned objectives comprised of the following:

- Field investigation of groundwater quality in the study area.
- Laboratory analysis of groundwater samples for physical and chemical parameters.
- Preparation of the aquifer vulnerability map of the study area by applying the available approaches.
- Development of more appropriate method for assessment of groundwater vulnerability of an urbanized environment.
- Evaluation of groundwater vulnerability maps and validation using the groundwater quality data.
- Evaluation of depleting groundwater resources of the study area using GRACE/GLDAS data.
- Validation of GRACE/GLDAS derived results with observational wells data of Central Ground Water Board.

1.8 Organization of the Thesis

The thesis was synthesized and organized into the following chapter wise distribution:

Chapter 1	Recognized the purpose and motivation for conducting present research. It established objectives and highlights the approach for the thesis.
Chapter 2	Summarized the literature review of groundwater quality, vulnerability analysis and trend of groundwater depletion.

Chapter 3	Provided basic details of the study area viz. its location, climate, geologic and hydro-geologic features.
Chapter 4	Described the methodology adopted to achieve the objectives of the present study.
Chapter 5	Described the groundwater quality, hydrogeochemical facies and suitability of groundwater for domestic, irrigation and industrial purposes.
Chapter 6	Explained the preparation of aquifer vulnerability map and development of a new method for assessment of groundwater vulnerability and its validation with the groundwater quality data. This chapter dealt with the estimation of groundwater depletion trend by using GRACE/GLDAS data.
Chapter 7	Presented the summary, conclusions and recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

Urbanization leads to the deterioration of groundwater quality and also to the depletion of groundwater resources. Groundwater vulnerability maps are defined as a guide for the location of future developmental projects in any area, in order to minimize its impacts on the quality of the surroundings groundwater resources. Groundwater vulnerability assessment requires understanding concepts such as the basic concept of vulnerability and its assessment, quality of groundwater, its evaluation and interpretation of hydrogeological environment. For estimation of groundwater depletion trends, seasonal and hydrologic signals obtained by NASA Gravity Recovery and Climate Experiment (GRACE) satellites and simulated soil moisture variations from Global Land Data Assimilation Systems (GLDAS) were used for the present study area. This chapter is aimed at a review of literature available on the above concepts.

2.1 Groundwater Quality

The quality of water changes as it moves through the hydrologic cycle, according to the differences in the environment through which it passes. These changes may be either natural or anthropogenic. Assessment of groundwater quality is essential so as to initiate any further action. The status of vulnerability is related to the degree of the change in groundwater quality. List of groundwater quality related research carried out worldwide is given in Table 2.1. The outcomes of the sampling water wells may also be used to validate the vulnerability assessment. A literature review of the environmental research carried out in Lucknow monitoring area is presented in Table 2.2. Review of groundwater quality related research carried out in other districts of India and their findings are given as follows:

Singh et al., 2006 studied water quality parameters of surface water and groundwater samples collected from dug wells, bore wells and hand pumps at different sites of Unnao area in the alluvium plain. It was concluded that groundwater contamination with F, Pb, and Cr in shallow depth aquifers of Unnao area indicates natural and anthropogenic influences.

Table 2.1 List of Selected Groundwater Studies carried out Worldwide in Major Cities

Authors and Year	Area/Country	Objective of the study
Jeong H. C., 2000	Taejon, Korea	Effect of land use and urbanization on hydrochemistry and contamination of groundwater
Dowling et al., 2003	Bangladesh and West Bengal	Groundwater geochemistry
Maila et al., 2004	Gaza Strip	Groundwater nitrate contamination
Singh et al., 2005	Unnao, India	Groundwater quality
Singh et al., 2006	Panki, Kanpur, India	Distribution of nitrogen in groundwater aquifers
Nickson et al., 2007	India	Arsenic distribution in groundwater
Rafique et al., 2008	Thar desert, Pakistan	Fluoride contamination in groundwater
Guo et al., 2008	Inner Mangolia, China	Groundwater geochemistry
Raju et al., 2009	Varanasi, India	Groundwater quality
Kumar et al., 2010	Ghazipur, India	Arsenic contamination in groundwater
Marghade et al., 2011	Nagpur, India	Geochemical characterization of groundwater
Singh et al., 2011	Punjab, India	Geochemical assessment of groundwater quality
Petitia, 2011	Central Italy	Interaction between deep and shallow groundwater systems

Kumar et al., 2011	Delhi, India	Identification of aquifer recharge zones by isotopic tracers
Jalali M, 2011	Toyserkan, Western Iran	Nitrate pollution in groundwater
Suyash and Panwar, 2011	Ankaleshwar, Gujarat	Heavy metals in groundwater
Brehme et al., 2011	Turkey	Hydrochemical characterization of ground and surface water
Andrade and Stigter, 2011	Central Portugal	Hydrochemical controls on shallow alluvial aquifers under agricultural land

Table. 2.2 List of Environmental Studies of Lucknow Monitoring Area

Year	Journal/Publication	Authors	Environmental Components	Type of study
1996	Shiva Offset Press, Dehradun	Prasad and Singh	Drain water	Algal indicators
1997	Geological Survey of India, Special Publication	Chandra et al.	River water	Heavy metal(Arsenic)
2001	Environmental Monitoring and Assessment	Rai and Sinha	Pond water	Heavy metals
2004	Geological Survey of India, Special Publication	Mathur et al.	River water	Heavy metal(Cadmium)
2004	Atmospheric Research	Khare et al.	Rain water	Physicochemical parameters

2004	Bulletin of Environmental Contamination and Toxicology	Malik et al.	River water	Polycyclic aromatic hydrocarbons
2005a	Analytica Chimica Acta	Singh et al.	River water	Water quality assessment
2005b	Analytica Chimica Acta	Singh et al.	River water	Heavy metals
2005c	Journal of Hydrology	Singh et al.	River water	Heavy metals
2005d	Bulletin of Water, Air and Soil Pollution	Singh et al.	River water	Organochlorine pesticides
2005e	Environmental Contamination and Toxicology	Singh et al.	Drain water	Waste water analysis
2005f	Analytica Chimica Acta	Singh et al.	River water	Heavy metals
2005g	Environmental Monitoring and Assessment	Gaur et al.	River water	Heavy metals
2005	Science of the Total Environment	Chandra et al.	Leachates	Heavy metals
2007	Environmental Monitoring and Assessment	Singh et al.	Rain water	Major ions and cations
2008	Environmental Monitoring and Assessment	Lohani et al.	River water	Heavy metals
2009	Journal of Wetlands Ecology	Bhat et al.	Pond water	Water quality
2009	Environmental Monitoring and Assessment	Malik et al.	River water	Organochlorine pesticides

Sankararamakrishnan et al., 2008 studied nitrate and fluoride contamination in the shallow and unconfined groundwater aquifers of Kanpur area. Results of the study revealed that the aquifers of Bithore zone were highly contaminated with the nitrate derived from both point and non-point sources. Fluoride concentration in most of the samples were within maximum permissible limit of 1.5 mg/l (BIS, 2012).

Singh et al., 2009 analyzed groundwater quality of Bareilly at 10 different sites. The results indicated that parameters responsible for groundwater quality variations were mainly related to trace metals. In addition, Raju et al., 2010 studied hydro-geochemical parameters for groundwater samples of the Varanasi area to evaluate the major ion chemistry, weathering and solute acquisition processes controlling water composition, and water quality suitability for domestic and irrigation purpose. Mudaim et al., 2011 studied the groundwater sources from various locations of Lucknow city to assess the urban drinking water quality during pre-monsoon season. The study were mainly concerned with estimation of heavy metals and organo-chlorine pesticides. Heavy metals Cd, Co, and Cr were not detectable in any of the samples except Al, Fe, Ni, and V. Thus these studies reveal that drinking water is mainly contaminated due to anthropogenic activities and improper disposal of solid wastes.

2.2 Groundwater Vulnerability

2.2.1 Definition

Groundwater vulnerability is defined as the likelihood of groundwater vulnerability for contamination at the ground surface to reach the source aquifer. Degree of vulnerability depends upon the available protecting shield of natural sources such as depth to water table, recharge, aquifer media, topography, and land surface activities. Degree of vulnerability will be high if the available protecting shield of natural sources is low, and will be low, if the available protecting shield of natural sources is high.

Some authors have been used the term ‘sensitivity’ instead of using the term ‘vulnerability’ (Pettyjohn et al., 1991). Different terminologies are explained in Table 2.3.

Table 2.3 Glossary of Terms Related to Vulnerability

Author/s & Year	Terms	Explanation
Albinet and Margat, 1970	Aquifer vulnerability	The possibility of percolation and diffusion of contaminants from the ground surface into natural water table reservoir, under natural conditions.
Vrba and Zoporozec, 1994	Vulnerability	An intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts.
Bachmat and Collin, 1987	Groundwater Vulnerability	The sensitivity of groundwater quality to anthropogenic activities which may prove detrimental to the present and/or intended usage or value of the resource.
Foster, 1987	Groundwater pollution risk	The interaction between (a) the natural vulnerability of the aquifer, and (b) the pollution loading that is, or, will be applied on the subsurface environment as a result of human activity.
U.S. General Accounting Office, 1991	Total Vulnerability	A function of these hydrogeologic factors as well as the pesticides use factors that influence the site's susceptibility.
U.S. General Accounting Office, 1991	Total Risk	This approach is even broader, for it incorporates the size of the population at risk from potential pesticides contamination that is, the number of people who obtain their drinking water from groundwater in the area.
Pettyjohn et al., 1991	Aquifer Sensitivity	Aquifer sensitivity is related to the potential for contamination, i.e. aquifer that has a high degree of vulnerability and are in areas of high pollution density, are considered to be the most sensitive.
National Research Council, 1993	Groundwater Vulnerability to Contamination	The tendency of likelihood for contamination to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer.

2.2.2 Assessment of Groundwater Vulnerability

All groundwater resources are vulnerable to contamination. There is a possibility of contamination occurring in coming days and measurable surrogate information must be gathered. (National Research Council, 1993). The National Research Council, 1993 proposed the following divisions for groundwater vulnerability assessment:

2.2.2.1 Overlay and Index Methods

Overlay and Index methods are basically based upon the combination of various physiographic attributes such as depth to water table, soil, aquifer media, geology, topography etc. of any region by giving a rating and weight to each attribute. Each attribute has its own probable values, representing the measure of which that particular parameter or attribute the probability of protecting the groundwater from contamination. A shallow water table is considered to be more vulnerable than a deeper one.

The simplest overlay methods recognize zones where different attributes denoting expression of vulnerability have the same inference, e.g. sandy soil and shallow depth to water table reveal similar degree of vulnerability. More refined systems assign numerical scores based on several attributes. The overlay index methods include variables such as depth to water table, net recharge rate of groundwater, soil media, aquifer media and topography etc. The shorter distance of groundwater movement will decrease the efficiency of soil and underlying vadose zone to act as a filter. Depth to water table also affects the contaminants by influencing the time they have to interact with groundwater. The unsaturated zone or vadose zone affects the potential for vertical transport of contaminants to groundwater, while aquifer properties affect the potential for lateral transport. The National Research Council (NRC, 1993) described seven overlay and index methods as given in Table 2.4. Out of these seven reported methods, DRASTIC is the most popular method for delineating groundwater vulnerable zones.

2.2.2.2 Process-Based Simulation Models

There are various process-based simulation models such as PRZM, GLEAMS and LEACHM available for groundwater vulnerability assessment. These models can predict the flow of water in porous media, fate and movement of contaminants from known sources and behavior of chemical

Table 2.4 Selected Methods Used in United States to Evaluate Groundwater Vulnerability to Contamination (Source: NRC, 1993)

Method	Reference	Map Scale	Reference Location	Intrinsic or Specific
Overlay and Index Methods				
Kansas Leachability Index	Kissel et al., 1982	Small	Soil	Intrinsic
DRASTIC	Aller et al., 1985,1987	Variable	Groundwater	Intrinsic
California Hotspost	Cohen et al., 1986	Large	Water Table	Intrinsic and Specific
Washington Map Overlay Vulnerability	Sacha et al., 1987	Small	Groundwater	Intrinsic and Specific
SEEPAGE	Moore 1988	Variable	Groundwater	Intrinsic
Iowa Groundwater Vulnerability	Hoyer and Hallberg 1991	Small	Groundwater	Intrinsic
EPA/UIC	Pettyjohn et al., 1991	Small	Groundwater	Intrinsic
Process-Based Simulation Models				
PESTANS	Enfield et al., 1982	Large	Soil	Specific
BAM	Jury et al., 1983	Large	Soil	Specific

MOUSE	Steenhuis et al., 1987	Large	Groundwater	Specific
PRZM	Carsel et al., 1984	Large	Soil	Specific
RF/AF	Rao et al., 1985	Variable	Soil	Specific
GLEAMS	Leonardo et al., 1987	Large	Soil	Specific
CMLS	Nofziger and Hornsby 1986	Large	Soil	Specific
RITZ/VIP	McLean et al., 1988	Large	Soil	Specific
LEACHM	Wagenet and Hutson 1987	Large	Large	Specific
RUSTIC	Dean et al., 1989	Large	Groundwater	Specific and Intrinsic
Statistical Methods				
Discriminant Analysis	Teso et al., 1988	Small	Groundwater	Specific
Regression Analysis	Chen and Druliner 1988	Small	Groundwater	Specific

constituents carried by water with significant precision in any localized area by applying fundamental principles.

2.2.2.3 Statistical Methods

Statistical methods include data on actual pollutant distribution. These methods offer depiction of pollutant potential for any specific geographic area, from which the data has been trained. These methods are frequently used for validation of other methods.

2.2.3 DRASTIC Method

2.2.3.1 Definition of DRASTIC Method

The DRASTIC method is the most extensively used method for delineating aquifer vulnerable zones in USA, Canada and in some other countries. This method has been developed by National Well Association and U.S. Environmental Protection Agency, 1987.

This method has been developed for the evaluation of potential for groundwater contamination in any area on the hydrological setting of that particular area (Aller et. al., 1985; 1987a, b). DRASTIC is an empirical method for assessing groundwater vulnerability.

The acronym DRASTIC stands for Depth to water table, net Recharge rate, Aquifer media, Soil media, Topography, Impact of vadose zone media and hydraulic Conductivity of the aquifer. Each of these seven parameters are assigned scores of 0 – 10, with a score of 0 meaning low possibility for pollution and a score of 10 meaning high possibility for pollution. Each of these seven parameters are also weighted according to their relative importance to the pollution potential for aquifers. A visual interpretation of DRASTIC parameters can be understood through Figure 2.1. The description of these measurable parameters are given below:

- **Depth to water table** denotes the depth of the water table from the ground surface. The distance plays a significant role in governing the vulnerability of any area. Locations with deeper water table are less prone to pollution than the areas with shallow water table.
- **Net Recharge** estimates the amount of water that percolates to the saturated zone. The greater the recharge, the higher the probability of contamination to groundwater.

- **Aquifer media** defines the material of the aquifer. It controls the mobility of the pollutant to pass through it.

- **Soil media** is the uppermost portion of the unsaturated zone. Soil with silts and clays have longer retention time for holding water. As a result, it will increase the travel time of the pollutant through the source region.

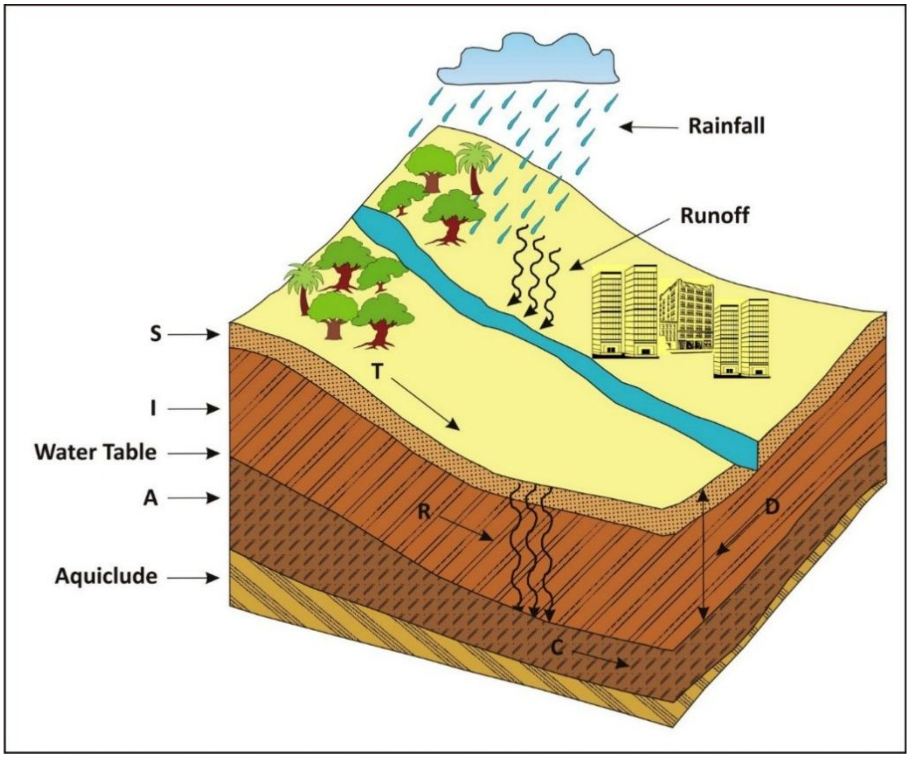


Figure 2.1 Visual Explanation of Parameters of DRASTIC Approach

(Modified after: Aller et al., 1987)

- **Topography** is the slope and variability of the land surface. Areas with steep slope fail to retain water for long periods of time as compared to areas with low slope. Flat areas have a larger amount of water retaining capacity and a higher amount of infiltration. These areas are more vulnerable to groundwater contamination.

- **Impact of vadose zone** is the unsaturated zone above the water table. The constituent material of the vadose zone determines the travel time of pollutants through it.

- **Hydraulic conductivity** of the soil media governs the volume of water percolating to the groundwater.

DRASTIC index for any given area can be calculated by multiplying weight of each parameter to its point rating and summing the total. The higher the DRASTIC Index value, the greater the susceptibility to groundwater contamination. Each parameter of the DRASTIC index like Depth to water, Net recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic conductivity is classified into ranges. Each parameter has an influence on pollution potential. The assigned rating for each parameter ranges from 1 – 10. Some parameters have assigned typical rating while others have assigned variable rating. Weights are allotted to each parameter according to their relative importance. The most important parameter has an assigned weight of 5 while the least significant parameter has been assigned a weight of 1.

After assigning all parameters a rating, each rating of seven parameters is multiplied by the assigned weight and the addition of the resultant numbers, DRASTIC Index (D_I) can be obtained by using following equation 2.1:

$$\text{DRASTIC Index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \tag{2.1}$$

Where, D, R, A, S, T, I and C are the seven parameters.

$_r$ and $_w$ are the ratings and weights assigned to each parameter respectively.

Throughout the world many researchers have extensively used DRASTIC approach (*cf.* Northeast Ohio Environmental Data exchange Network, 1989; Evans and Myers, 1990; Rundquist et al., 1991; Brown et al., 1994; Atkinson and Thomlinson, 1994; Lobo-Ferreira and Oliveira, 1997; Snyder et al., 1998; Stension and Strachotta, 1999; Medina, 2001; Piscopo, 2001; Lilly et al., 2001; Al-Zabet, 2002; Babiker et al., 2005; Panagopoulos et al., 2006; Voudouris et al., 2010; Hasiniaina et al., 2010; Khodaponah et al., 2011).

2.2.3.2 Modification of DRASTIC and other Similar Approaches

Several researchers have applied DRASTIC method after making some modifications. Many researchers have adopted other methods similar to DRASTIC to assess the groundwater vulnerability to pollution. Table 2.5 and Table 2.6 illustrates these modifications and similar methods respectively.

Table 2.5 Reported Modifications in the DRASTIC Method

Authors & Year	Area/Country	Method	Modification
Secunda et al., 1998	Sharon region in Israel	DRASTIC	Applied DRASTIC method by adding land use parameters.
Melloul and Collin, 1998	Sharon region in Isarael	DRASTIC	Developed an index of aquifer water quality and used this index to test the validation of the DRASTIC map.
NAWQA, 1999	Eastern Snake River Plain, Idaho	DRASTIC	Three of the seven DRASTIC factors i.e. depth of water, net recharge (land use) and soil media were used. The final vulnerability map was correlated with NO_2-N and NO_3-N concentration.
Navulur, 1994 and Engel 2003	Indiana, U.S.A.	DRASTIC and SEEPAGE	Validated the accuracy of these approaches by comparing the vulnerability maps with existing well water quality data sampled across the state.
Leal and Castilo, 2003	Turbio river valley, Mexico	DRASTIC and AVI	Modified the range of depth to water parameter by using a scale 5 times the original rating because the groundwater depth in their study are varied from 40 to 140 m.

Al-Adamat et al., 2003	Azraq basin, Jordan	DRASTIC	Omitted the hydraulic conductivity parameter and used other six parameters of DRASTIC model. Also developed DRASTIC risk assessment introducing the land use factor into DRASTIC index
Wei, 2003	Fraser Valley, Southwestern British Columbia	DRASTIC AVI	Studied correlation between DRASTIC and AVI (Aquifer Vulnerability Index) method with nitrate occurrence.
Babiker et al., 2005	Kakamigahara Heights, Gifu Prefecture, Central Japan	DRASTIC	Applied groundwater vulnerability assessment using DRASTIC method and also performed sensitivity analysis to know which layer is more important in vulnerability assessment.
Panagopoulos et al., 2006	Peloponnesus, Greece	DRASTIC	DRASTIC method includes a hydrochemical data set and the recording of the anthropogenic loadings into the groundwater based on the distribution of land use and the contaminant loading that each land use introduces into the natural environment.
Chakraborty et al., 2007	Malda District, West Bengal, India	DRASTIC	Used DRASTIC method.

Kabera et al., 2008	Shanxi, China	DRASTIC	Applied DRASTIC model with sensitivity analysis.
Rahman, 2008	Aligarh, India	DRASTIC	DRASTIC model and validation with nitrate values.
Khan et al., 2010	Indo Gangetic Plain, India	DRASTIC	Used TDS values for estimation of vulnerability to contamination.
Prasad et al., 2010	Hyderabad, India	DRASTIC	Applied DRASTIC method in hard rock granitic aquifer.
Alwathaf et al., 2011	Sana's Basin, Yemen	DRASTIC	Applied DRASTIC model and validated with nitrate values.
Javadi, 2011	Northern Iran, Caspian Sea	DRASTIC	Modification of DRASTIC Model to Map Groundwater Vulnerability to Pollution Using Nitrate Measurements in Agricultural Areas.
Farzad et al., 2012	Izeh Plain, Iran	DRASTIC	Groundwater intrinsic vulnerability and risk mapping with sensitivity analysis.
Murali et al., 2013	Tamilnadu, India	DRASTIC	Assessment of groundwater vulnerability in Coimbatore South Taluk, Tamilnadu, India.

Table 2.6 Methods Similar to DRASTIC Approach

Authors & Year	Method	Brief Explanation
Le Grand (1964)	-	Developed an empirical point count system to evaluate the pollution potential of unconfined and unconsolidated alluvium aquifers.
Schmidt (1987)	-	Developed a new approach which considered the overlaying and rating the five resources maps: type of bedrock, soil characteristics, depth to bedrock, depth to water table and surficial deposits.
Foster and Hirata (1988)	GOD	Developed the method to assess the pollution risk. This method considered three factors: groundwater occurrence (i.e. whether the aquifer is unconfined, semi-confined or confined), overall lithology (aquifer) class in terms of degree of consolidation and lithological character and depth to water table.
Moore (1988)	SEEPAGE	The SEEPAGE model considered factors such as Soil slope, soil depth, depth to water table, vadose zone, aquifer material and attenuation potential which further considered factors like texture of surface soil and subsoil, pH of surface layer, organic content of the surface soils, soil drainage class and soil permeability.
Halliday and Wolfe (1991)	-	Used GIS for assessing groundwater pollution potential from nitrogen fertilizers.
Van Stempvoort et al., (1992)	AVI	Included only the vertical hydraulic conductivity and the thickness of the layers of the vadose zone.

Ray and O’dell (1993)	DIVERSITY	The method is based on an assessment of three aquifer characteristics viz. recharge potential, flow velocity and flow direction.
Tickell (1994)	-	Developed an indicator for assessment of salinity hazard. The indicator includes groundwater salinity, vegetation type, aquifer, laterite and median annual rainfall.
Hiscock et al., (1995)	-	Produced a series of groundwater vulnerability maps to provide a framework for decision making. This approach defined vulnerability as a function
Rine et al., (1998)	-	Developed a new methodology to evaluate and map the contamination.
Bekesi and Mc Conchie (1999 and 2000b)	-	Provided a vulnerability assessment procedure scientifically based on four factors i.e. the soil, the unsaturated zone, rainfall recharge and aquifer medium
Magiera and Wolff (2001)	-	Developed an assessment method programmed within GIS framework.
Daly et al., (2002)	OCKP	Developed an approach for intrinsic and specific vulnerability assessment with the aim to introduce some consistency into the European approach. In this approach, three factors were considered when assessing the intrinsic vulnerability of the whole karst aquifer (Precipitation factor, Flow Concentration, Factor and Overlying Layers Factor).
Collin and Melluol, (2003)	-	Demonstrated the use of GIS to identify areas vulnerable to groundwater pollution by combining information on the quantity and quality of the water leaving the root zone with data from Environment Agency’s Groundwater Vulnerability Maps (GVMs) on soil, drift material and aquifer properties.

2.2.4 Groundwater Vulnerability Assessment in India

Although many researchers worked on DRASTIC model on a global level, literature on groundwater vulnerability assessment in India is relatively limited. Jayakumar, 1996 used DRASTIC method to assess groundwater vulnerability in south India. Mishra and Richaria, 1996 applied DRASTIC method in and nearby Rewa city. Nataraju et al., 2000 used same approach in Bangalore North Taluk. Dey and Bhowmick, 2002 used DRASTIC and AVI (Aquifer Vulnerability Index) to assess the groundwater vulnerability protection policy in Ghaziabad. Chachadi et al., 2002 developed a new methodology GALDIT (Groundwater occurrence, Aquifer hydraulic conductivity, Depth to water level, Distance from the shore, Impact of existing status of sea water intrusion and Thickness of mapped aquifer) to estimate the vulnerability. Thrirumalaivasan et al., 2003 developed a software package AHP-DRASTIC to develop ratings and weights of parameters of modified DRASTIC model. Singhal et al., 2003 applied DRASTIC approach to assess pollution potential of alluvial aquifer in Roorkee. Chakraborty et al., 2007 applied modified DRASTIC to evaluate the aquifer vulnerability of English Bazar Block of Malda District, West Bengal. Rahman, 2008 has identified the groundwater vulnerable zones in shallow aquifer of Aligarh and its surrounding areas. Umar et al., 2009 generated an aquifer vulnerability potential map of an alluvial aquifer in parts of Central Ganga Plain, Western Uttar Pradesh using DRASTIC approach. Khan et al., 2010 adopted DRASTIC methodology to demarcate the zones based on their vulnerability to contamination. Srinivasamoorthy et al., 2010 studied Metur Taluk, Salem District of Tamil Nadu to develop DRASTIC vulnerability index in GIS environment. Prasad et al., 2010 used DRASTIC model to map groundwater vulnerable zones in the hard rock aquifer of granitic terrain of Southern India. Alam et al., 2012 applied modified DRASTIC-LU for evaluating groundwater vulnerability in parts of Central Ganga plain. Murli and Elangovan, 2013 assessed groundwater vulnerability in Coimbator South Taluk, Tamilnadu using DRASTIC approach.

2.3 GRACE: Effect of Urbanization on Groundwater Resources

2.3.1 GRACE Overview

The datasets used in this study were gathered from the GRACE (gravity recovery and climate experiment) twin satellites, launched on 17th March, 2002 as a collaboration between NASA

(USA) and the German Space Agency, named as Gravity Recovery and Climate Experiment (GRACE) twin satellites and from GLDAS.

2.3.2 Working Principle of GRACE satellite

These are the twin satellites named “Tom” And “Jerry” one followed by another in the same orbit, as the satellite rotates along the Earth. When they pass over a gravity anomaly, such an area of higher gravity, the trailing satellite is pulled towards the lead satellite. The microwave ranging system on GRACE detects these changes in the distance between the satellites. The Accelerometer of each satellite located at the centre of mass, locate non-gravitational accelerations like atmosphere drag. GPS receivers determine the exact position of the satellite (Rodell et al., 2006).

2.3.3 GRACE Studies Worldwide

Groundwater, in particular, is difficult to monitor over large spatial scales. The ability to produce global estimates at reasonably high frequency (monthly or better) using GLDAS with GRACE constitutes a significant step forward in our ability to understand and, ultimately, to manage variability in this invaluable hydrologic resource (Rodell et al., 2006). The analysis of groundwater depletion over northern India using GRACE data has been explored by both Tiwari et al., 2009 and Rodell et al., 2009. Both groups have observed that large-scale unsustainable groundwater extraction is taking place (Rodell et al., 2009; Tiwari et al., 2009). Tiwari et al., 2009 carried out research with satellite gravity observations on the dwindling ground water resources in Northern India. They used global gravity field solution at a scale of a few hundred kilometers to remove atmospheric and oceanic contributions and subtracted monthly water storage from global gravity field solutions for estimation of predicted land surface models. They also applied GLDAS model from NOAH, CLM and simultaneously fit a trend and seasonal terms at each grid point. The trend shows most prominent feature as a large negative trend over northern India. Rodell et al., 2009 estimated the groundwater depletion rate under topic “Satellite- based estimates of groundwater depletion in India”. They used (GRACE) Gravity Recovery and Climate Experiment satellite data for the estimation of terrestrial water storage. This study concluded that groundwater was being depleted at a mean rate of 4 ± 1.0 cm/year, which was the equivalent height of water (17.7 ± 4.5 km^3/year) over northwest India (states- Rajasthan, Punjab, Haryana, Uttar Pradesh and northern part of Madhya Pradesh) including NCR. They took difference between TWS anomalies (observed by GRACE) and changes in water storage (determined by GLDAS). They used equation 2.2 to estimate changes in groundwater storage.

$$\Delta\text{Groundwater} = \Delta\text{TWS}(\text{GRACE}) - \Delta\text{SM}\ (\text{GLDAS}) + \Delta\text{SWE}(\text{GLDAS}) \qquad (2.2)$$

Where;

ΔTWS= Terrestrial Water Storage

ΔSM= Soil Moisture and

ΔSWE=Snow Water Equivalent

Gleeson et al., 2012 generated a groundwater stress map or footprint of the Upper Ganges aquifer and concluded that large-scale groundwater extraction was taking place in the region. Many workers have incorporated only first order effects such as net depletion rates, and have not incorporated second-order effects such as the variability of the groundwater storage. Variability of groundwater storage is interpreted as supply irregularity which must be accounted for in water security assessments and met with adequate water storage and governance mechanisms (Reig et al., 2013). Chinnasamy et al., 2013 estimated improved groundwater supply in Gujarat using remote sensing data and also validated results with direct measurement data of Central Ground Water Board.

CHAPTER 3

STUDY AREA

This chapter briefly portrays the base level attributes such as regional setting, climate, sub-surface geology and hydrogeological characteristics of study area.

3.1 General Description

3.1.1 Location

The study area is located on both banks of the Gomti River and is situated between $26^{0}30^{,}$ to $27^{0}10$’ N latitudes and $80^{0}30^{,}$ to $81^{0}13$’E longitudes (Figure 3.1). Lucknow district is spread over an area of about 2500 sq. km. and forms a part of central Ganga plains, with the Lucknow city forming part of Sai-Gomti basin. The drainage of the district is controlled by river Gomti and Sai. Its altitude varies from 103 to 130 meters above mean sea level. The Gomti River divides Lucknow urban center into two halves: the Cis-Gomti and Trans-Gomti Area. It is surrounded by Sitapur, Raibareily, Barabanki, Hardoi and Unnao districts.

3.1.2 Climate

The climate of Lucknow district is classified as sub-tropical type with four marked seasons namely, summer (March-May) followed by monsoon (June-September), post-monsoon (October-November) and winter (December-February). The maximum temperature reaches up to 40^{0}C to 45^{0}C during month of May and minimum temperature remains 5^{0}C during January. The relative humidity averages 25% in morning and 68% in evening. The normal annual potential evapotranspiration of the district is 1519 mm. During winter the average wind speed varies between 4 and 7.5 km/hr while during summer it varies between 9.9 and 11.7km/hr.

3.1.3 Rainfall

The normal rainfall of Lucknow district is approximately 966.24 mm. Maximum rainfall occurs during the monsoon period (about 88% of total annual rainfall). July is the wettest month having normal rainfall of about 290 mm followed by August with normal rainfall of about 288 mm (CGWB, 2009).

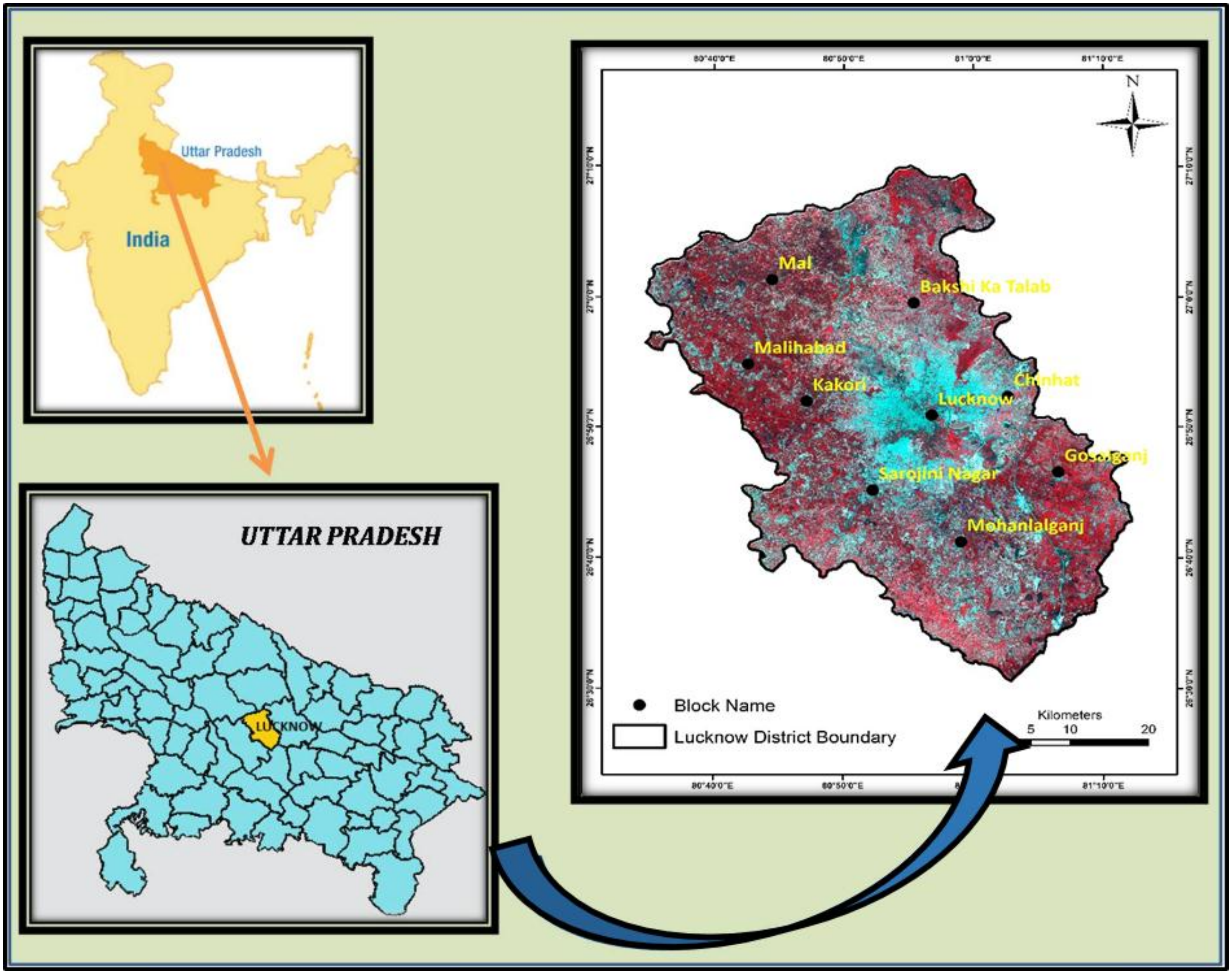


Figure 3.1 Location Map of Lucknow District

3.2 Geology

Lucknow district is completely covered by alluvial deposits of Quaternary age and forms a part of Central Ganga plain (Figure 3.2). The litho-stratigraphical sequence of Lucknow district is as given below:

3.2.1 Lucknow Older Alluvium

It is composed of multi sequence of sand, silt and clay. These oxidized sediments have kankar nodules in varying proportions. The sands of upper and middle horizons are usually fine to medium grained. The sand of lower horizon is coarser than upper and middle horizon.

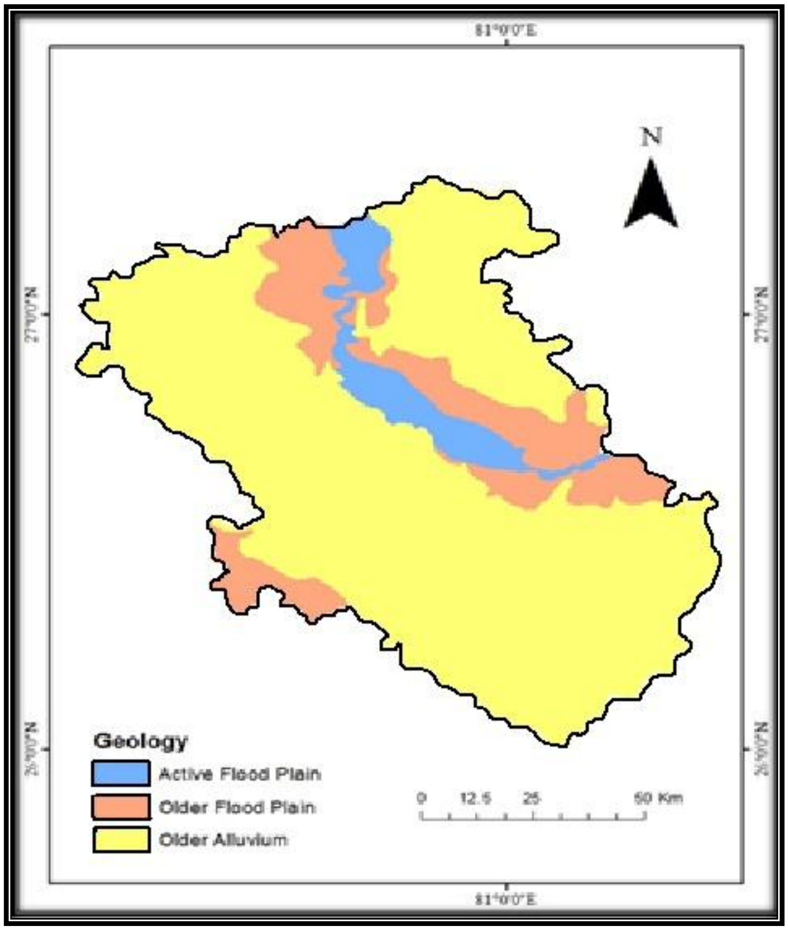


Figure 3.2 Geological Map of Lucknow District

3.2.2 Newer Alluvium

Newer alluvium occupies the depositional active channel of Gomti River. These sediments are without kankar and non-oxidized. Newer alluvium has been further divided into Gomti Terrace Alluvium and Gomti Active Channel Alluvium. Gomti Terrace Alluvium is composed of non-oxidized grey micaceous sand, silts and clays while Gomti Active Channel Alluvium is principally grey micaceous sands and silts occupying various point bars and channel bars.

3.3 Geomorphology

Lucknow forms a part of central Ganga Alluvial plain with flat alluvial plain topography which is characterized by low relief along with entrenched river valleys (Figure 3.3). The maximum and minimum elevations of the area are about 130 m and 103 m above mean sea level. The area is divisible into three major geomorphic units:

3.3.1 Lucknow Older Alluvial Plain

It is characterized by flat upland plain with coarse drainage and a thick soil profile. This geomorphic unit represents palaeo channels, relicts of pre-existing drainage system, and many small and big Tals. It is also characterized by a number of sandy mounds.

3.3.2 Gomti Older Alluvial Plain

Older Alluvial plain is represented by two types of terraces, Erosional and Depositional Terraces. Erosional terraces (T_e) and Depositional terraces (T_d) are found at higher level and at lower depressions respectively. These both terraces are well developed on both sides of the Gomti River. Sai River is also characterized by erosional terraces.

3.3.3 Gomti Active Flood Plain

Various landforms like point bars, channel bars and lateral bars are represented by in active flood plains. These quaternary sediments are further divided into older and younger alluvium. The older alluvium is made up of grey to brown colored silt clay and sand of middle to late Pleistocene age. The older alluvium is overlain by newer alluvium and comprise of grey silt, clay and coarse grained micaceous sand of Holocene age. Newer alluvium is also sub-divided into terrace and channel alluvium.

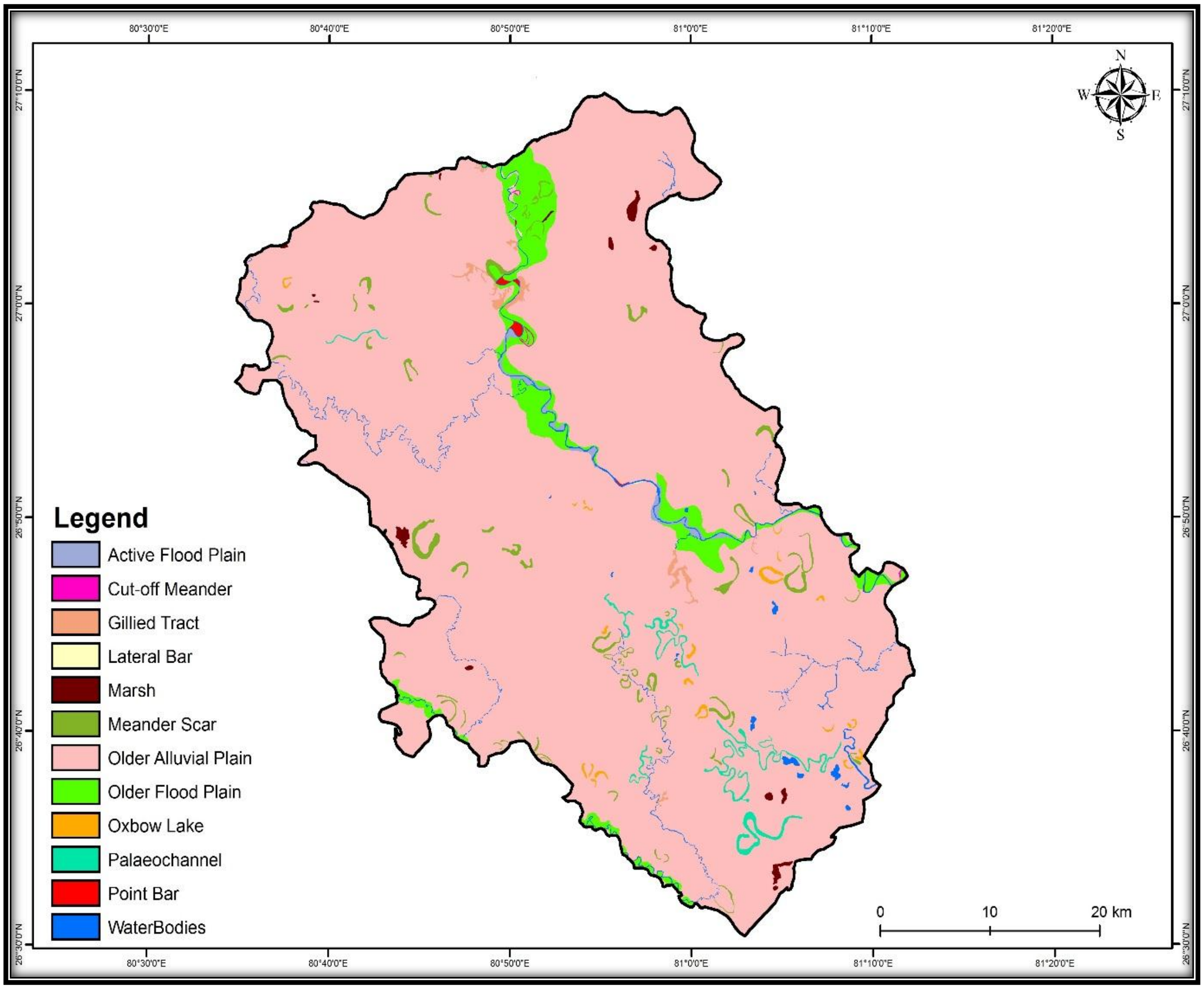


Figure 3.3 Geomorphological Map of Lucknow District

3.4 Soil Types

Soils of the area show variation in composition, texture and appearance. There are three types of soils in the district: Sandy Loam, Silty Loam and Loam. The major part of the area is covered by sandy loam.

3.5 Hydrogeology

Lucknow area is composed of unconsolidated alluvial sediments. The alluvial deposits of the area are made up of interlayered 1-2m thick fine sand and silty mud deposits patches of calcrete horizons. As per the hydrogeology, the river is directly connected to the first aquifer group. Lower aquifers are leaky confined aquifers and may receive vertical recharge from river (Foster et al., 2010). Based on the lithological logs, electrical logs and fence diagram (Figure 3.4), it has been observed that a five tier aquifer system exist in the area. Different characteristics of the five tier aquifer system is given in Table 3.1.

Table 3.1 Details of Aquifer System in Lucknow District

Aquifer Group	Depth Range(mbgl)	Characteristics
First Aquifer Group	0 - 150	Fine to medium grained sand with intercalation of clays. Tube-wells constructed in this aquifer group yields 1000 to 1500 liters per minute (lpm) at draw down up to 10 meters.
Second Aquifer Group	160 - 240	The aquifer material of this group is silty resulting poor discharge of 500 lpm at high draw down more than 20m.
Third Aquifer Group	260 - 370	Highly intercalated with clays and sand which is fine to very fine grained in texture. Tubewells in this aquifer group are capable of yielding discharge of 1200 to 1500 lpm at high draw down about 30m.
Fourth Aquifer Group	380 - 480	Silty sand, hard and compact sand stone chips. Discharge up to 1500 lpm can be obtained at very high draw down up to 33 m. though the piezometric head rest between 10 to 13 mbgl.
Fifth Aquifer Group	483 - 680	Very fine sand and silty in nature. The yield up to 2000 lpm can be obtained by cumulative tapping of aquifer group down to depth of 480 meters.

mbgl – meters below ground level; lpm – liters per minute (Source: CGWB)

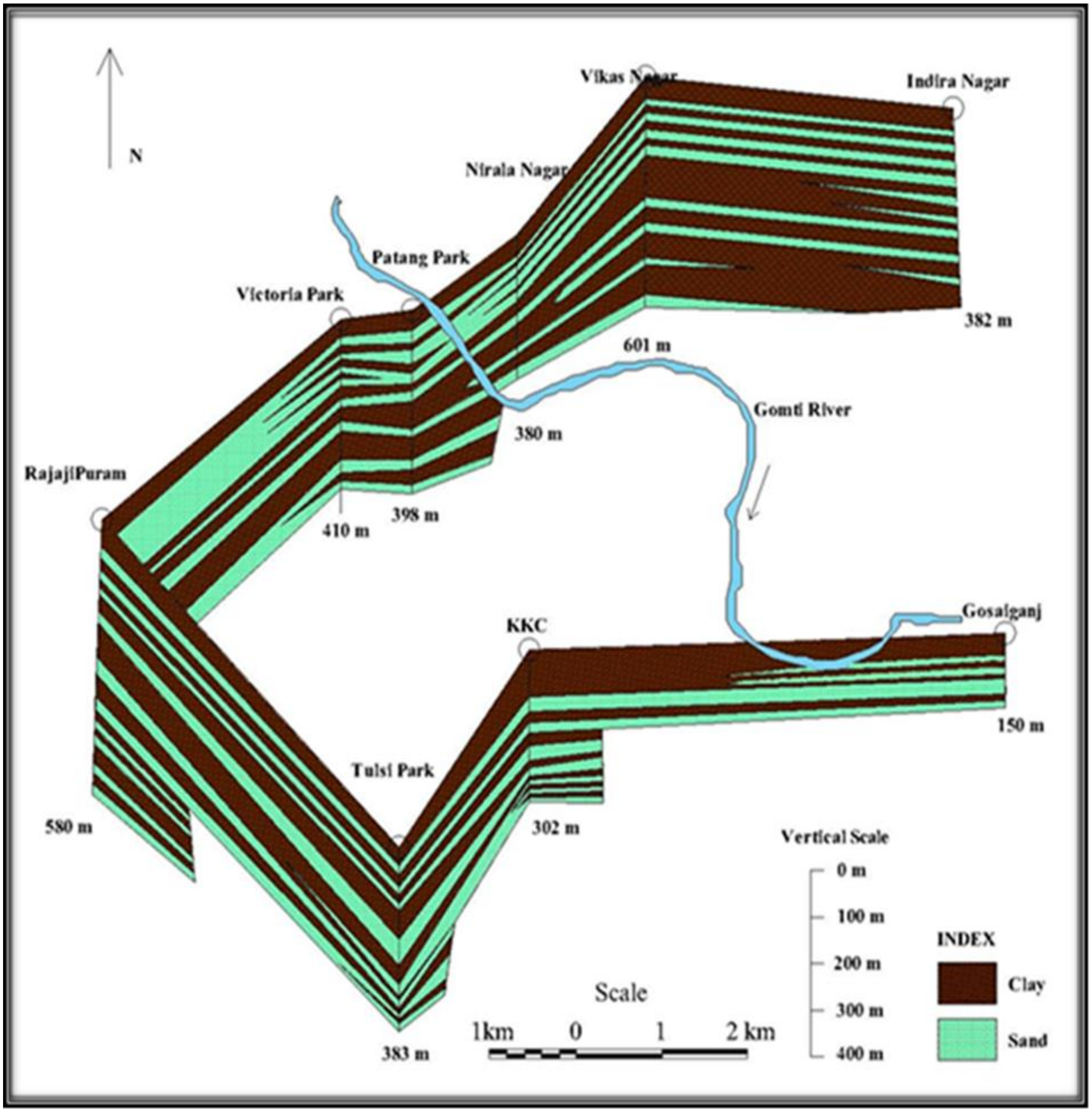


Figure 3.4 Fence Diagram of Lucknow District (Prepared from data of CGWB, 2009)

3.6 Water-Level Scenario in Lucknow City

In this study, the groundwater level data for the period of 2003-2011 was procured from the Central Ground Water Board, Lucknow. The pre and post monsoon groundwater level graph from different locations in Lucknow city have been shown in Figure 3.5.

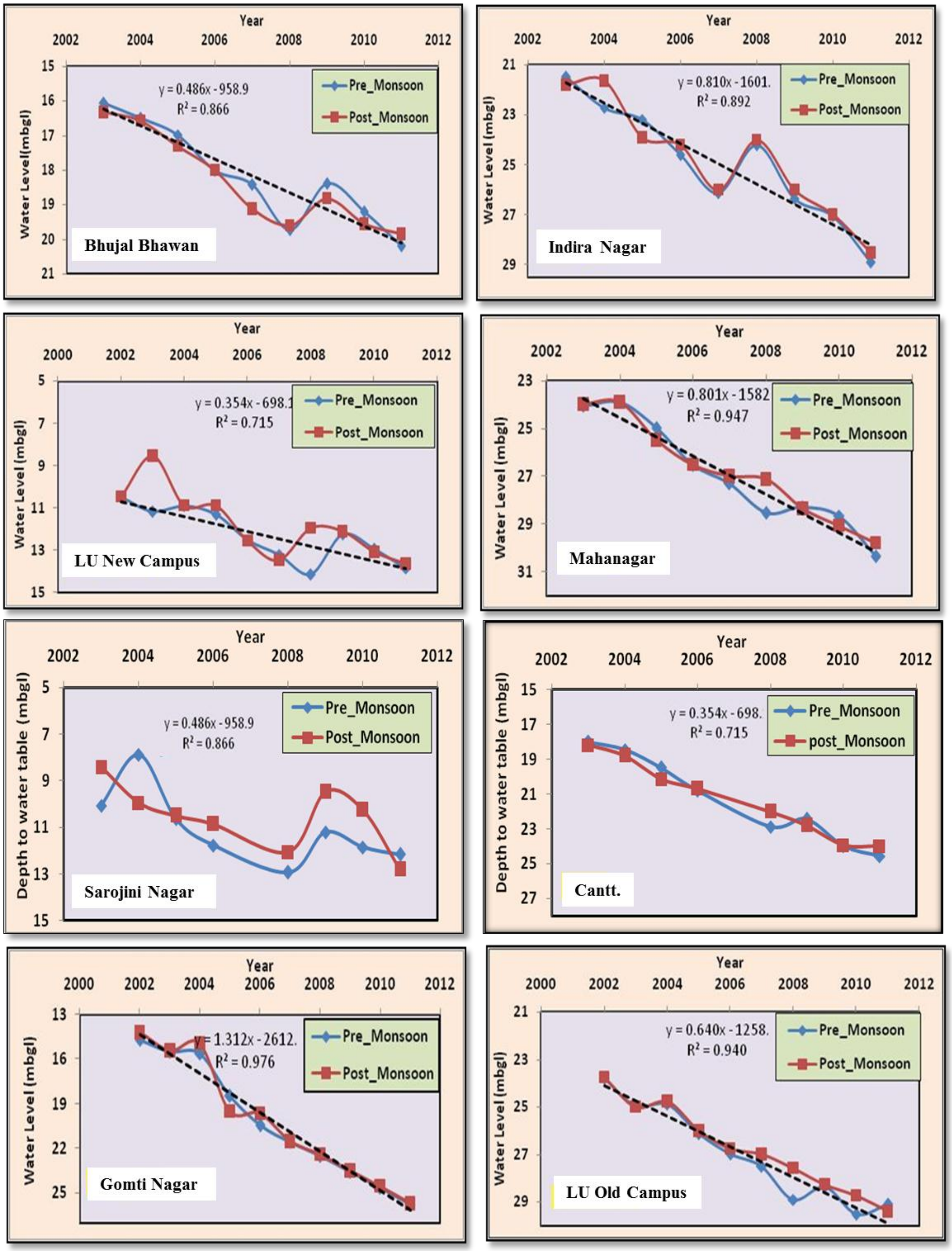


Figure 3.5 Long-Term Water Level Trend of Pre-Monsoon and Post-Monsoon Seasons at Different Observation Wells in Lucknow City (2002 to 2012)

3.6.1 Pre-monsoon Water Level Trend

On the basis of water level data of piezometers from 2000 to 2011 of Cis-Gomti area, it was observed that groundwater levels were declining. In the Northern part of the city, deep water levels were observed at Gulistan colony (33.8 mbgl) and Rajajipuram (30.2 mbgl).

Rising water level trends were also observed in the central part (south of Gomti river), i.e., at Arya Nagar and Aminabad where the groundwater extraction was low. The water level was declining at a very fast rate due to the very high extraction of groundwater at Lucknow city.

It was observed that all piezometrers in Trans-Gomti area show a declining trend. The minimum fall was observed at Sarojini Nagar.

3.6.2 Post-monsoon Water Level Trend

The groundwater levels in the post-monsoon season also showed a declining trend in Trans-Gomti. The minimum fall was observed at Sarojini Nagar and maximum at Gulistan Colony.

On the basis of the last ten years, groundwater level in Lucknow city showed an average rate of decline of 0.8 and 1.0 m/year in Cis-Gomti and Trans-Gomti respectively. The future prediction of trend analysis results showed that by 2020 the groundwater level will decline by another 6.2 m in Trans-Gomti area and 2.12 m in Cis-Gomti area. The Trans-Gomti area will face maximum groundwater level decline.

3.6.3 Status of Water Supply and Demand

As per WHO norm of 250 liter/day/capita (lpcd), the total requirement of Lucknow city was about 849.75 MLD. Thus there was a deficit of about 370 MLD in water supply in the year 2011. Considering the water requirement of 150 lpcd, the total requirement of the city was 509.85 MLD in the year 2011. Currently, Lucknow city is receiving 480 MLD of water supply, leaving behind a gap of 29.85 MLD.

3.7 Land Use and Land Cover Distribution

The environmental quality of any area depends on the land use and land cover distribution pattern. The change in land use is highly associated with groundwater quality (Dasgupta et al., 2001).The expansion of Lucknow city's spatial limit has led to a surmounting pressure on both natural and built drainage systems (Verma et al., 2013).

Like most of the urban scenarios in the world, increasing population and urban sprawl in the city, stressed the city's water resources (Dutta et al., 2010). The land use represented few classes in the city including agricultural land, wetlands, wastelands, water bodies and built up land. With an exponential increase in population, the land use and land cover classes such as agricultural land, Wetlands, Wastelands, Forest area, Water bodies have merged into built up land over the last few years.

Table 3.2 Land Use Change in Lucknow city in the Last 25 years (1980-2005)

Categories of Land Transformation	**Area**	
	km^2	**Percent**
Agriculture to build up land	76.73	62.98
Plantation to build up land	1.69	1,.4
Wetland to build up land	1.45	1.19
Wasteland to build up land	1.17	0.96
Rural to Urban area	2.93	2.42
Forest area to build up land	0.39	0.32
Water body to build up land	0.74	0.61
Land under transformation	36.52	30.12
Total	**121.26**	**100.00**

(Source: Lucknow Master Plan, 2010)

The land use and land cover change over the last 25 years (1985-2005) of the city is shown in Table 3.2. The change in land use and land cover distribution of Lucknow district from 1985 to 2010 can be seen through the land use and land cover map of Lucknow district of 1985 (Figure 3.6) and 2010 (Figure 3.7). It is clear from the land use and land cover map of Lucknow district that the urban area of year 2010 increased greatly when compared to the urban area of year 1985.

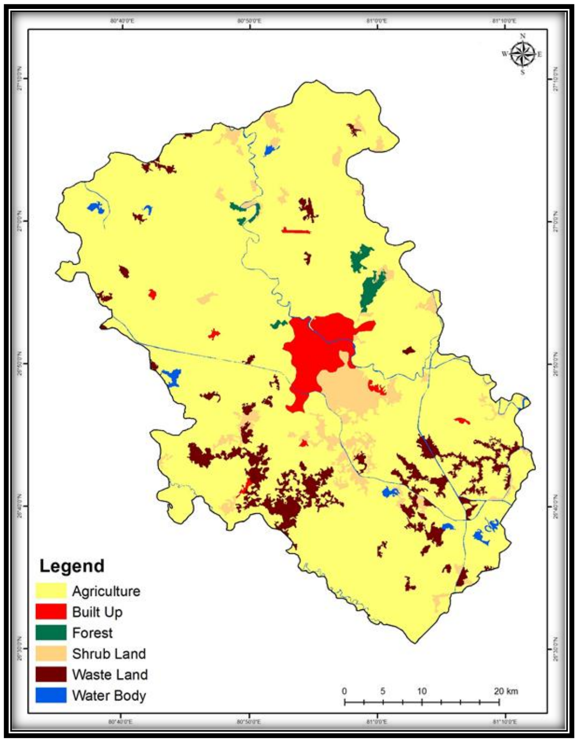


Figure 3.6 Land Use and Land Cover Map of Lucknow district-1985

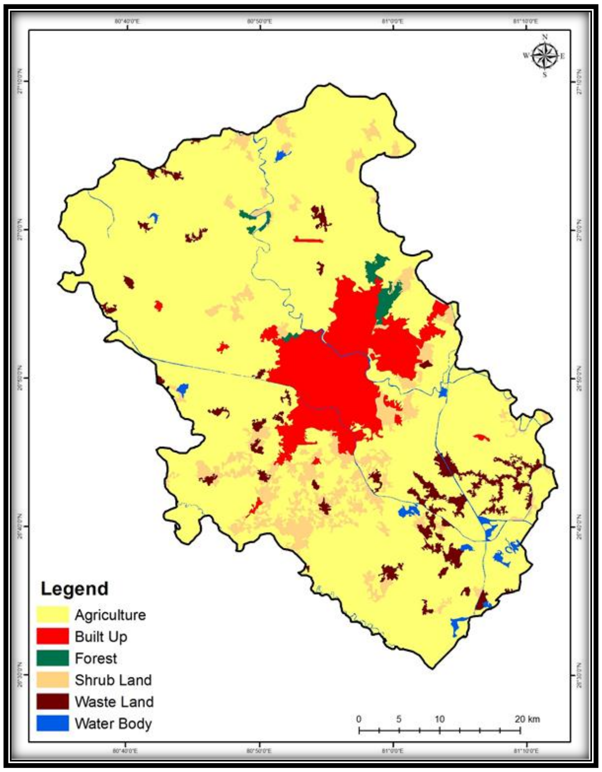


Figure 3.7 Land Use and Land Cover Map of Lucknow District-2010

CHAPTER 4

DATA COLLECTION AND METHODOLOGY

This chapter is compiled to provide an overview of data collection and methodology adopted in order to determine the groundwater quality characteristics, groundwater vulnerable zones and depletion of groundwater resources using GRACE/GLDAS data to adjudge the groundwater scenario in study area.

4.1 Sampling Plan

The methodology of the sampling plan is as shown in Figure 4.1. A total of 84 groundwater samples were collected during pre-monsoon (May, 2011), and post-monsoon (November, 2011) seasons from the Lucknow urban area (Figure 4.2), of which 54 samples were collected from hand pumps (shallow aquifers) and 30 samples from Tube wells (deeper aquifers). Figure 4.3 shows some field photographs of sampling. For a representative sample of groundwater, the hand pumps and tube wells were continuously pumped prior to the sampling. Two sets of samples were collected at each sampling location. The water samples were collected and stored in pre-cleaned, polyethylene bottles of one liter, which were carefully rinsed three times before use. One set of samples were collected as natural, another set of samples were acidified with ultrapure acid for analysis of major and trace constituents respectively. The samples were analyzed to understand the chemical variations of water compositions. The details of sampling sites which is same for pre-monsoon and post-monsoon season, are presented in following Table 4.1.

Table 4.1 Locations of the Collected Groundwater Samples

S.No.	Sample location	Latitude	Longitude	Type of Sample
1	L.U.Old Campus	26^0 51' 10.9"	$80^0$56' 4.3"	Hand Pump
2	Aliganj	26^0 54' 1.8"	$80^0$56' 14.3"	Hand Pump
3	Indira Nagar	26^0 52' 11.1"	$80^0$58' 8.4"	Hand Pump
4	Mahanagar	26^0 52' 13.6"	$80^0$57' 8.6"	Hand Pump

5	Sarojini Nagar	26^{0} 45' 3.4"	80^{0}52' 12.5"	Hand Pump
6	Kaiserbagh	26^{0} 51' 3.6"	80^{0}55' 14.3"	Hand Pump
7	Nishatganj	26^{0} 51' 14.4"	80^{0}57' 5.4"	Hand Pump
8	Charbagh	26^{0} 49' 11.2"	80^{0}55' 5.6"	Hand Pump
9	Gomti Nagar	26^{0} 51' 13.6"	80^{0}0' 4.4"	Hand Pump
10	Krishna Nagar	26^{0} 47' 13.2"	80^{0}53' 4.7"	Hand Pump
11	Hazratganj	26^{0} 50' 14.0"	80^{0}56' 12.2"	Hand Pump
12	Aminabad	26^{0} 50' 12.9"	80^{0}56' 11.3"	Hand Pump
13	Alambagh	26^{0} 48' 13.5"	80^{0}54' 3.3"	Hand Pump
14	Cantt.	26^{0} 49' 12.8"	80^{0}58' 0.9"	Hand Pump
15	Jankipuram	26^{0} 54' 11.9"	80^{0}56' 11.3"	Hand Pump
16	Rsac	26^{0} 54' 14.6"	80^{0}57' 11.1"	Hand Pump
17	Khadra	26^{0} 52' 11.1"	80^{0}55' 3.8"	Hand Pump
18	Triveni Nagar	26^{0} 52' 15.3"	80^{0}55' 3.8"	Hand Pump
19	Mawaiyya	26^{0} 49' 15.4"	80^{0}54' 3.3"	Hand Pump
20	Aishbagh	26^{0} 50' 2.8"	80^{0}54' 7.3"	Hand Pump
21	Rajajipuram	26^{0} 50' 4.5"	80^{0}53' 7.7"	Hand Pump
22	Bada Imambara	26^{0} 52' 4.3"	80^{0}54' 13.6"	Hand Pump
23	Transport Nagar	26^{0} 46' 11.1"	80^{0}53' 4.7"	Hand Pump
24	Bara Birwa	26^{0} 47' 15.9"	80^{0}53' 10.8"	Hand Pump
25	Ambedkar Maidan	26^{0} 48' 2.2"	80^{0}55' 6.5"	Hand Pump

26	PGI	26^{0} 44' 14.3'	80^{0}52' 12.5"	Hand Pump
27	Naka	26^{0} 50' 3.8"	80^{0}55' 4.4"	Hand Pump
28	L.U.Old Campus	26^{0} 51' 13.5"	80^{0}57' 6.2"	Tube-well
29	Aliganj	26^{0} 53' 9.3"	80^{0}57' 6.2"	Tube-well
30	Indira Nagar	26^{0} 50' 3.8"	80^{0}55' 4.4"	Tube-well
31	Mahanagar	26^{0} 52' 11.7"	80^{0}57' 5.1"	Tube-well
32	Sarojini Nagar	26^{0} 44' 14.7"	80^{0}51' 7.9"	Tube-well
33	Kaiserbagh	26^{0} 51' 4.2"	80^{0}55' 13.2"	Tube-well
34	Nishatganj	26^{0} 52' 4.8"	80^{0}57' 7.6"	Tube-well
35	Charbagh	26^{0} 49' 6.1"	80^{0}55' 6.2"	Tube-well
36	Gomti Nagar	26^{0} 51' 1.3"	80^{0}58' 15.2"	Tube-well
37	Krishna Nagar	26^{0} 47' 13.4"	80^{0}53' 4.7"	Tube-well
38	Hazratganj	26^{0} 50' 16.4"	80^{0}56' 12.1"	Tube-well
39	Aminabad	26^{0} 50' 13.8"	80^{0}55' 10.8"	Tube-well
40	Alambagh	26^{0} 50' 3.8"	80^{0}54' 4.3"	Tube-well
41	Cantt.	26^{0} 49' 5.6"	80^{0}56' 15.9"	Tube-well
42	Lalbagh	26^{0} 50' 13.7"	80^{0}56' 5.7"	Tube-well

4.2 Analytical Procedure

All samples were carefully analyzed for various parameters using standard analytical methods. Throughout the analysis double distilled (Ultrapure) water was used. All analytical containers were acid cleaned and rinsed carefully several times. Alkalinity was analyzed using the Metrohm Autotitrator with 0.01N HCL as the titrant following the inflection point titration method.

Subsequently, all samples were filtered using 0.45μm cellulose nitrate membrane filters and analyzed for major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) and major anions (F^-, Cl^-, $NO_3{}^2$- and $SO_4{}^2$-) by Ion Chromatograph (Metrohm 792 Basic) with a precision of ±2%. The system was calibrated using multi-element cation and anion standards. The accuracy of the measurement was checked by measuring freshly prepared standards of known concentrations made from analytical grade reagents before the analysis and regularly between the sample analyses. The accuracy of the chemical analysis was verified by calculating ion-balancing, which was observed to be within an acceptable limit of ±5%.

The trace element concentrations were determined by ICP-MS (Perkin Elmer-SCIEX ICP-MS-ELAN DRC-e). The determination of different trace elements was done using their respective calibration curves of different standard solutions. The details of various instrument used for the various analysis are presented in Table 4.2.

Table 4.2 Parameter and their Techniques and Instruments Used

Parameter	Technique/Instrument used
pH	pH meter
Electrical Conductivity	Electrical Conductivity Meter
Total Dissolved Solids	Electrical Conductivity Meter
Alkalinity (HCO_3^-)	Autotitrator (Metrohm 877 Titrino Plus)
Major Cations (Na+, K+, $Ca^{2+,}$ $Mg^{2+)}$	Ion Exchange Chromatography (Metrohm Ion Chromatograph)
Major Anions (F-, Cl^-, NO_3^{2-}, SO_4^{2-})	Ion Exchange Chromatography (Metrohm Ion Chromatograph)
Trace Elements (As, Cr, Fe, Mg, Hg, K, Mn, V, Zn)	Inductively Coupled Plasma Mass Spectrophotometer (ICP-MS)

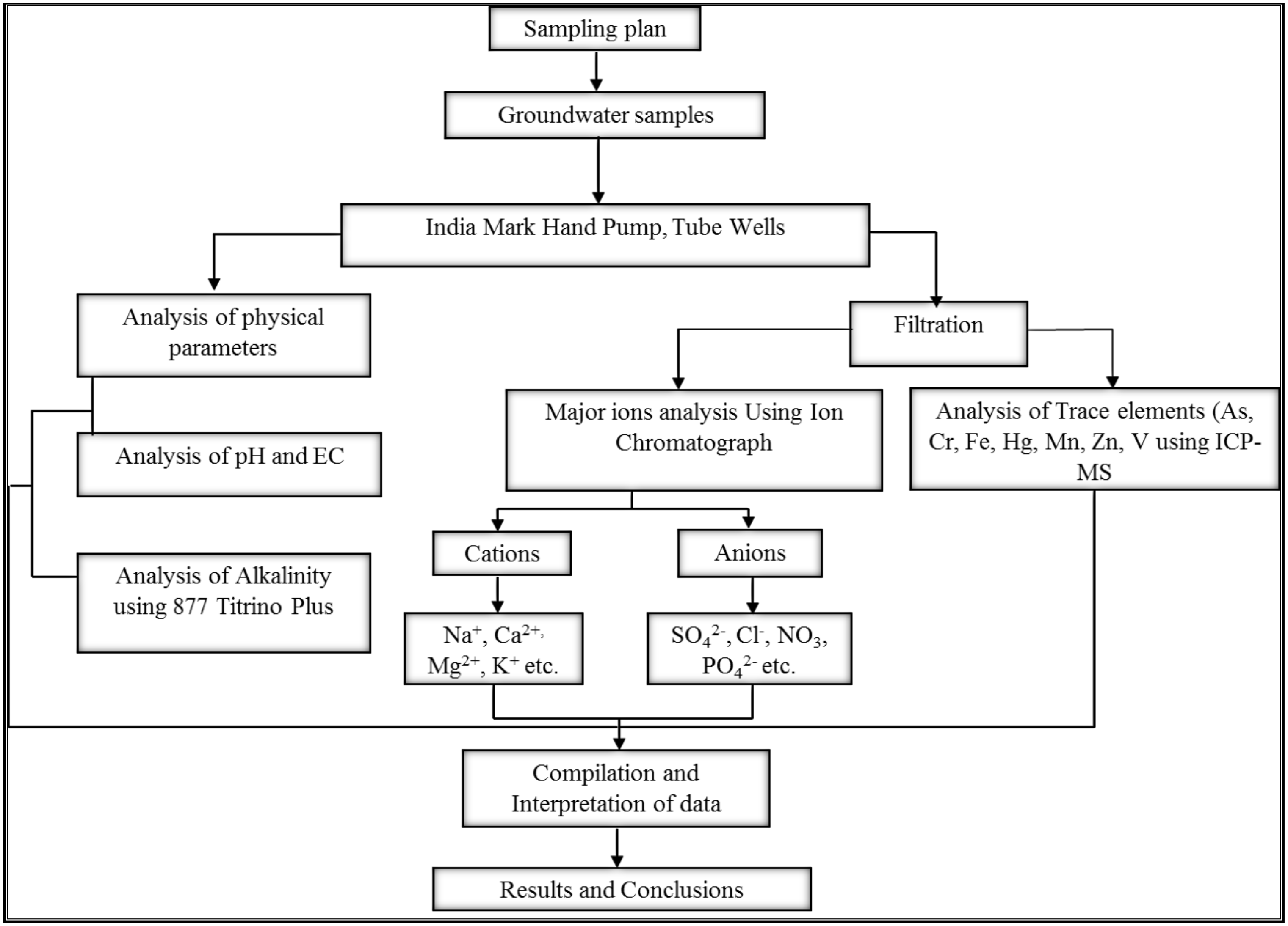


Figure 4.1 Flowchart Representing the Methodology of the Groundwater Sampling Plan and Analytical Procedure

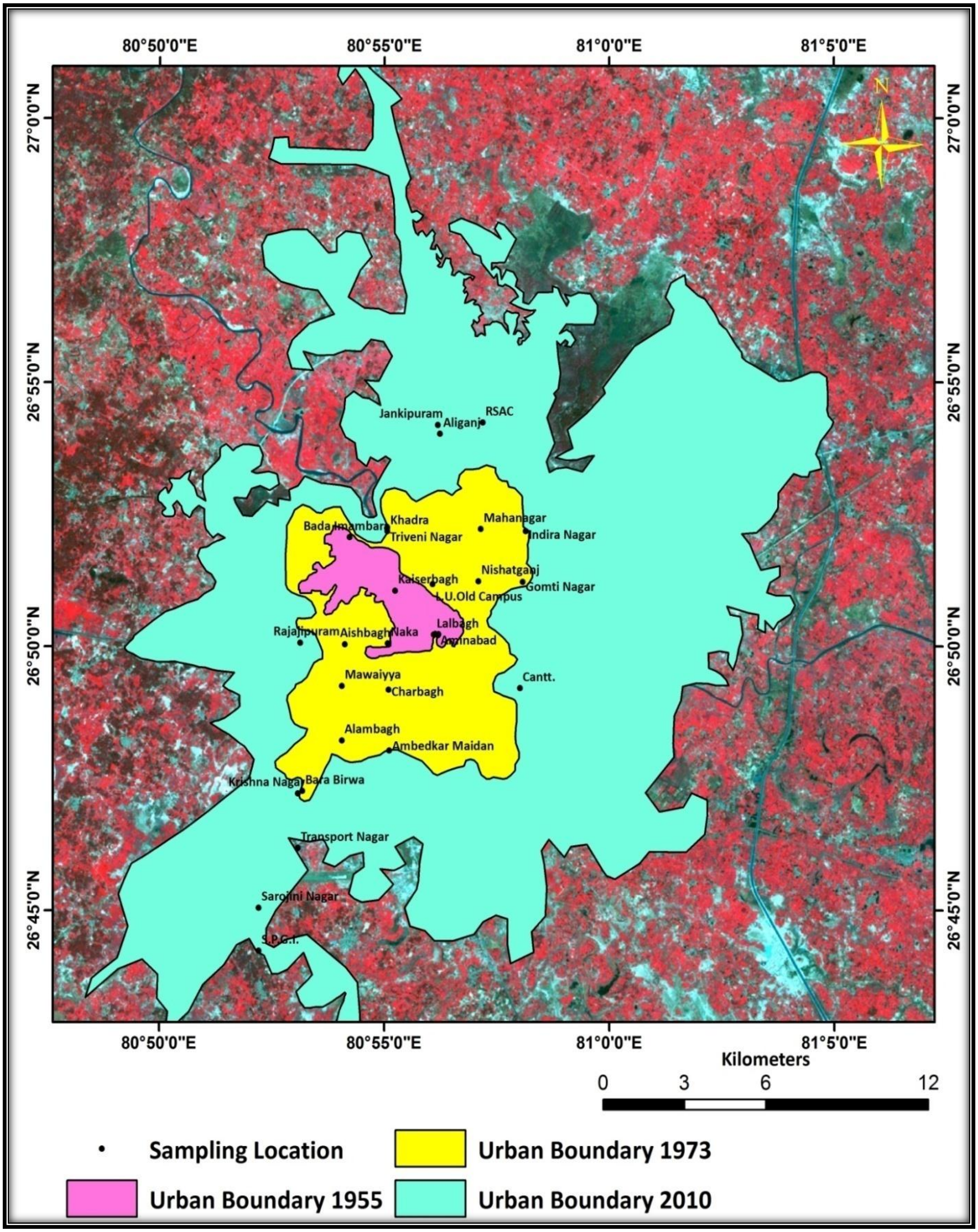


Figure 4.2 Map Showing Pre-Monsoon and Post-Monsoon Sampling Locations of Groundwater Samples

Figure 4.3 Field Photographs of Sampling Locations: (a) HP Alambagh, (b) HP Aishbagh, (c) HP Rajajipuram, (d) HP Sarojini Nagar (e) HP Cantt. (f) TW Indira Nagar. (HP-Hand-pump, TW-Tube-well)

4.2.1 Analytical Procedure of Various Parameters and Instruments Used

The various physical parameters in water samples such as pH, Electrical conductivity, and alkalinity were analyzed using different instruments.

4.2.2 Determination of pH

The pH is a measure of acidity or basicity of water samples. Water with a pH less than 7 is acidic, and with a pH greater than 7 is alkaline in nature. The pH values were obtained by using HACH instrument.

4.2.3 Determination of Electrical Conductivity (EC)

Electrical conductivity is the measure of the capacity of water to conduct electric current. It also estimates the concentration of total dissolved solids in water. The EC values were also obtained by using HACH instrument. The instrument was calibrated by using the buffers of pH 4, 7 and 9.2 before measuring the pH and electrical conductivity. After calibration, the analysis was started, but the instrument was calibrated after every five measurements so as to minimize error in the results.

4.2.4 Determination of Alkalinity

By using auto titrator 877 Titrino plus, the concentration of carbonates and bicarbonates was determined. The auto titrator uses 0.3 mol KCL and 0.01N HCL solutions and a magnetic stirrer dipped in the water sample for the titration to get the concentration of carbonate and bicarbonates. The standard end point pH for the bicarbonate and carbonate was set 4.6 and 8.3 respectively. Following calculations were used to get the bicarbonate and carbonate concentrations:

Concentration of Carbonates = (Normality*EP1*60)*1000/Sample Size (ppm)

Concentration of Bicarbonates = (Normality*EP2*61)*1000/Sample Size (ppm)

Where;

Sample size was the weight of water sample taken in the 25 ml beaker. The collected water samples did not have any carbonate, so the carbonate concentration was zero.

4.2.5 Determination of Cations and Anions

The major cations and anions in the water samples were determined using Ion Chromatography by Metrohm 792 Basic Ion Chromatograph.

Ion Chromatography is a type of liquid chromatography which is based upon the ion-exchange process. This chromatography uses ion-exchange resins to separate ions according to their interaction with the resins. Ion Chromatographs are capable of measuring major cations such as lithium, sodium, ammonium, potassium, calcium and magnesium along with major anions such as fluoride, chloride, nitrate, nitrite and sulfate in parts per billion (ppb). The greatest advantage of this equipment is for anions analysis, as there is no other quick method available.

4.2.5.1 Anion Analysis

- For making of Eluent, 3.2 mmol/l Na_2CO_3 + 1 mmol/l of $NaHCO_3$ was taken in a flask and the solution is made to 1 liter.

- For making of Suppressor, 5.6 ml of H_2SO_4 is taken and mixed in 1 litre of double distilled water.

- For standard preparation, the following six solution were made:

  For Fluoride, 0.0221 g of NaF was used.

  For Chloride, 0.0165 g of NaCl was used.

  For nitrite, 0.0153 g of $NaNO_2$ was used.

  For nitrate, 0.014 g of $NaNO_3$ was used.

  For Phosphate, 0.0144 g of KH_2PO_4 was used.

  For sulphate, 0.0149 g of Na_2SO_4 was used. Each of these solutions was made separately into 100 ml of double distilled water.

4.2.5.2 Cation Analysis

- For making of Eluent, 0.075 mmol/l Pyridine 2, 6 dicarboxylic acid + 4 mmol/l tartaric acid was taken and made it to 1 liter.
- Suppressor is not needed for cation analysis.
- For standard preparation, the following six solutions were made:

  For lithium, 0.101 g of $LiNO_3$ was used.

  For Sodium, 0.038 g of $NaNO_3$ was used.

  For Ammonium, 0.038 g of NH_4Cl was used.

  For Potassium, 0.026 g of KNO_3 was used.

  For Calcium, 0.043 g of $CaCl_2$ was used.

  For Magnesium, 0.086 g of $MgCl_2$ was used. Each of these solutions was made separately into 100 ml of double distilled water.

Each of the cations and anions standard were made separately by mixing the above mentioned different standards. Both for cations and anions 1 ppm, 2.5 ppm and 5 ppm standard was used and the calibration was done for the analysis. The linear calibration curves was obtained. After calibration, the sample was injected and analyzed by ion chromatography technique.

4.2.5.3 Detection of Ions

The Chromatogram is a record of electrical conductivity versus time as the analyte (sample to be analyzed) passes via ion chromatograph. Chromatogram has several peaks corresponding to different times in which the different components of analyte emerge from the column. At the end, based on the peak areas, the calculation of concentration of major cations and anions was done.

4.2.6 Determination of Trace Elements

The analysis of trace elements was done using an Inductively Coupled Plasma Mass Spectrophotometer (ICP-MS). The analysis was done in the Indian Instrumentation Centre, Indian Institute of Technology, Roorkee. This instrument offers many advantages in deriving major and trace elements. ICP-MS derives most of the elements in parts per trillion (ppt) range. The high temperature of the plasma ion source breaks the molecules of the sample. As a result, the ICP-MS detects only elemental ions. This is much more compatible technique for elemental analysis than others like Atomic Absorption Spectrophotometer (AAS) and Inductively Coupled Plasma-Optical Emission Spectrophotometer.

4.2.7 Data Analysis and Interpretation

Data analysis and its interpretation is essential to providing information about the source, magnitude and harshness of groundwater related problems of any area. The results of various chemical analyses of groundwater gave useful information for further analysis and its interpretation. Geochemical studies frequently involve synthesis and interpretation of a mass of analytical data. The data interpretation played a key role in the classification of water of different geochemical characteristics and also gives the reason on which the chemical characteristics of water depend. Due to these aspects, analytical data were represented by different types of diagram such as Piper Diagram, Chadha's Diagram and Stiff Diagram.

- Piper, 1953 has improved the form of tri-linear diagram which was first coined by Hill. Piper diagram, Figure 4.4(a) is used extensively for hydro-geochemical facies interpretation**.** It is an effective tool in segregating analysis data with respect to the source of the dissolved constituents in groundwater, modifications in the character of water as it passes through an area and related geochemical problems. Piper diagram has a central diamond shaped field and two triangular (one for cations and another for anions) fields. In cation triangular field, the concentration of cations ($Na^{+}+K^{+}$, Ca^{2+} and Mg^{2+}), and in anion triangular field the concentration of anions (Cl^{-}, SO_4^{2-} and $HCO_3^{-}+CO_3^{2-}$), is plotted as percentages in meq/l. The total concentration of both ions are considered 100%. After that, the two data points of both cations and anions are combined into a diamond shaped field that represents overall chemical characteristics of water (either groundwater of surface water) sample.

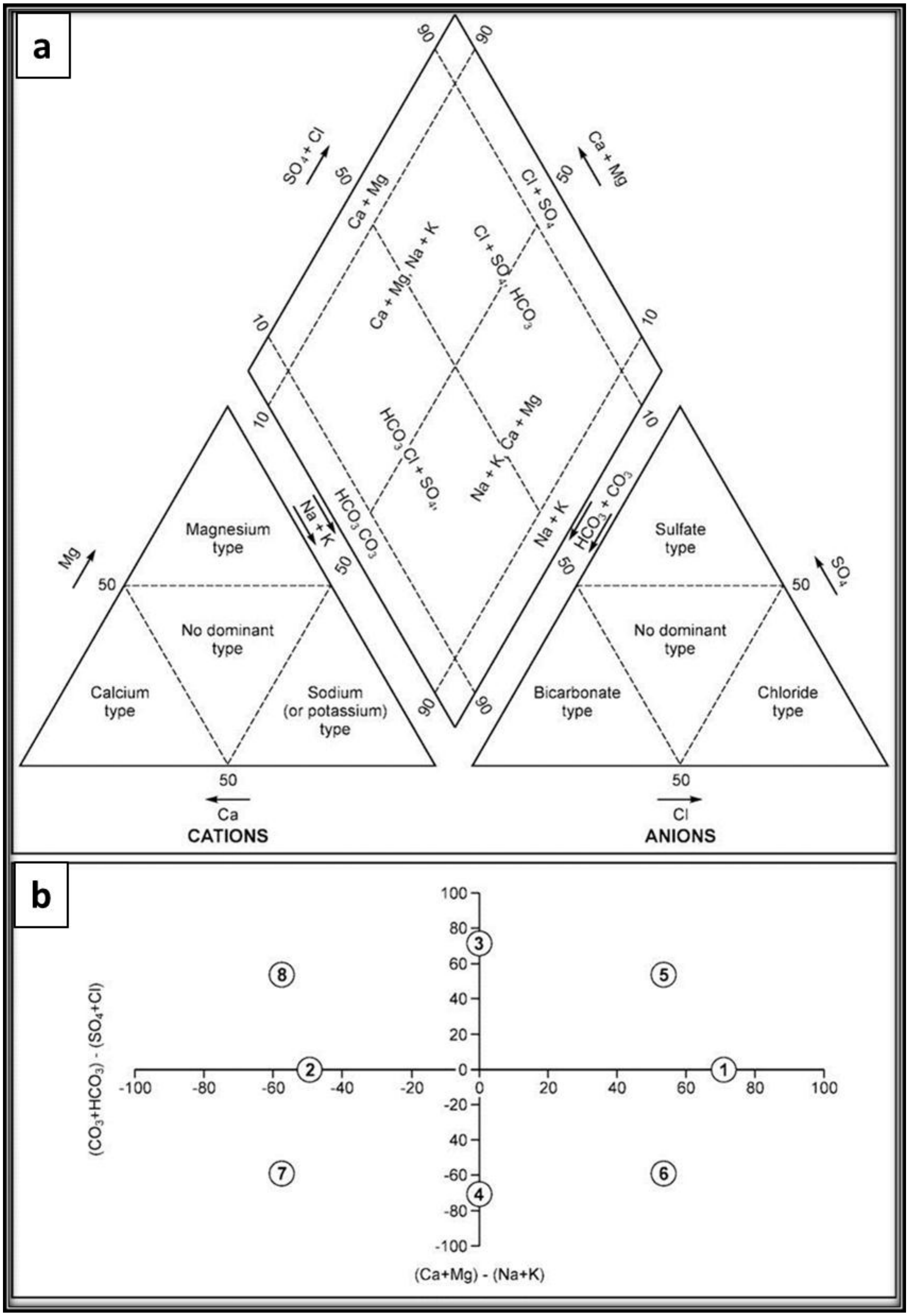


Figure 4.4(a) Piper Diagram Used for Representation of Hydrochemical Facies. (b) Modified Chadha's Diagram (In order to define the primary character of water, the rectangular field is divided into eight sub-fields, each of which represents a water type)

- Chadha, 1999 represents a modified form of the Piper trilinear and expanded Durov diagram. In this diagram, as represented in Figure 4.4 (b), the percentage reacting values which is the difference in mill-equivalent percentage between alkaline earths (Ca^{2+} + Mg^{2+}) and alkali metals (Na^{+} + K^{+}), is plotted on the X axis and the difference in mill equivalent percentage between weak acidic anions (CO_3^{-} + HCO_3^{-}) and strong acidic anions (Cl^{-} + $SO_4^{2\ -)}$ is plotted on the Y axis. The differences in mill equivalent percentages in alkaline earths and alkali metals, and between weak acidic anions and strong acidic anions, would plot in the four possible sub-fields of the proposed diagram. The square and rectangular field describes the overall character of the water. The description of characteristic sub-fields (1 to 8) of Chadha's diagram is given further:

- Sub-Field 1: Alkaline earth exceeds alkalies.
- Sub-Field 2: Alkalies exceeds alkaline earths.
- Sub-Field 3: Weak acids exceeds strong acids.
- Sub-Field 4: strong acids exceeds weak acids.
- Sub-Field 5: Alkaline earths and weak acidic anions exceed both alkali metals and strong acidic anions, respectively. Such water has temporary hardness. The positions of data points in the diagram represent Ca-Mg-HCO_3 type, Ca-Mg-dominant HCO_3 type or HCO_3 dominant Ca-Mg type waters.

- Sub-Field 6: Alkaline earths exceed alkali metals and strong acidic anions exceed weak acidic anions. Such water has permanent hardness and does not deposit residual sodium carbon- ate in irrigation use. The positions of data points in the diagram represents Ca-Mg-Cl type, Ca-Mg dominant Cl type or Cl dominant Ca-Mg type waters.

- Sub-Field 7: Alkali metals exceed alkaline earths and strong acidic anions exceed weak acidic anions. Such water generally creates salinity problems both in irrigation and drinking uses. The positions of data points in the diagram represent Na-Cl type, Na_2SO_4 type, Na dominant Cl type, or Cl dominant Na type waters.

- Sub-Field 8: Alkali metals exceed alkaline earths and weak acidic anions exceed strong acidic anions. Such waters deposit residual sodium carbonate in irrigation use and cause foaming problems. The positions of data points in the diagram represent Na-HCO_3 type, Na dominant Cl type or HCO_3 dominant Na type waters. Finally, the interpreted information will help to fulfill the objective to study groundwater quality and interpret spatial variations in order to identify the problem.

Many hydrochemical parameters (Table 4.3) affect the suitability of water for irrigation and industrial purpose. Electrical Conductivity (EC), Sodium Percent (%Na), Salinity and alkalinity hazards, Sodium Adsorption Ratio (SAR), Permeability Index (PI), Magnesium Hazard (MH), Corrosivity Ratio (CR) and Chloro-Alkaline Index (CAI) are the important hydrochemical parameters which were used to determine the suitability of water for irrigation and industrial purposes.

Table 4.3 Various Indices Useful in Assessment of Water for Irrigation and Industrial Purpose

Parameters	Determination	Water Quality Classes	Reference
Sodium Percent (%Na)	Na $=\frac{(Na+K)100}{Ca+Mg+Na+K}$	Excellent (<20) Good (20-40) Permissible (40-60) Doubtful (60-80) Unsuitable (80)	Wilcox, 1955
Sodium Adsorption Ratio (SAR)	SAR $= \frac{Na}{\sqrt{Ca}+Mg/2}$	Excellent (<10) Good (18) Doubtful (18-26) Unsuitable (26)	Richard, 1954
Permeability Index (PI)	PI $= \frac{Na+\sqrt{HCO3}*100}{Ca+Mg+Na}$	Suitable (Class 1)>75% Suitable (Class 2)= 75% Unsuitable(Class3)=25%	Doneen, 1964
Magnesium Hazard (MH)	MH $= \frac{Mg*100}{Ca+Mg}$	Unsuitable (>50)	Szabolcs and Darab, 1964
Corrosivity Ratio (CR)	CR$= \frac{(Cl/35.5) + 2(SO_4/96)}{2\{(CO_3+HCO_3)/100\}}$	Safe Zone (<1)	Sankar, 1995; Aravindam et

		Unsafe Zone (>1)	al., 2004
Residual Sodium Carbonate (RSC)	RSC=$(HCO_3^{-}+CO_3^{2-})-(Ca^{2+}+Mg^{2+})$	Low (0-1.25) Medium (1.25-2.5) High (>2.5)	USEPA, 1999
Chloroalkaline Index(CA1, CA2)	CA1= $Cl-\frac{(Na+K)}{Cl}$ CA2=$Cl-\frac{(Na+K)}{SO_4+CO_3+HCO_3+NO_3}$	Geochemical evolution of water	Schoeller, 1977

4.3 Assessment of Groundwater Vulnerability

Groundwater vulnerability depends upon the depth to water table, net recharge, aquifer media, soil type, topography (Slope), vadose zone, hydraulic conductivity and anthropogenic activities of any area. To delineate the groundwater vulnerable zones of the study area, conventional DRASTIC and modified DRASTIC or DRASTICA modelling was adopted.

This section describes the procedures for generating thematic maps which depict the above discussed parameters.

4.3.1 Preparation of Input Datasets for Groundwater Vulnerability Assessment

The details of data types and their sources for preparing the input parameter maps (layers) of the DRASTIC and DRASTICA model are provided in Table 4.4. The preparation of input datasets and implementation of DRASTIC and DRASTICA model was carried out in ArcGIS (version 9.3) software. The overall framework of the processing scheme followed in the study is shown in Figure 4.5.

4.3.1.1 Depth to Water Table

Depth to water table data of the past ten years (2002-2012) was collected from Central Ground Water Board (CGWB), Lucknow. The data were stored in MS-Excel. For each observation points of pre-monsoon and post monsoon seasons, mean values for depth to water table were calculated. The depth to water table data was imported into ArcGIS and converted into shape file.

Table 4.4 Description of Data Used in Conventional DRASTIC and DRASTICA Model

Output layer	Data type	Source	Format
Depth to water table (D)	Water level data	CGWB, Lucknow	Vector (Point data)
Net Recharge (R)	Recharge data	CGWB, Lucknow	Vector (Polygon data)
Aquifer media (A)	Borehole data	CGWB, Lucknow	-do-
Soil media (S)	Soil map	UPRSAC, Nagpur	Vector (Polygon data)
Topography (T)	Digital Elevation Model (DEM)	ASTERGDEM http://gdem.ersdac.jspacesystems.or.jp/	Raster
Impact of vadose zone (I)	Borehole data	CGWB, Lucknow	Vector (Point data)
Hydraulic Conductivity (C)	Transmissivity Data	CGWB, Lucknow	-do-
Anthropogenic impact (A)	LULC & Urbanization index map	Landsat 4/5 TM, IIRS, Dehradun	Vector (Polygon data)

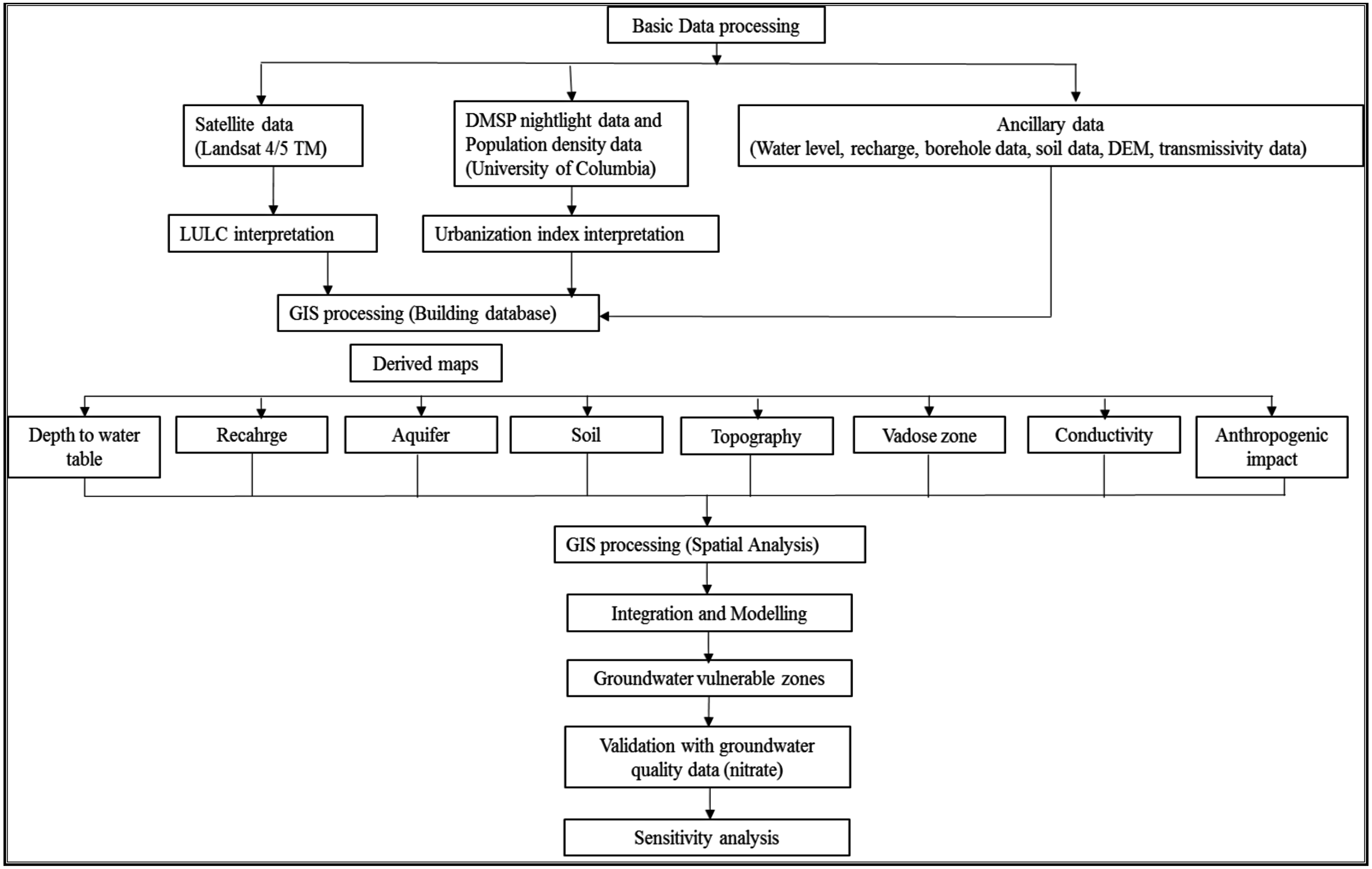


Figure 4.5 Flowchart Representing Innovative DRASTICA Methodology for Groundwater Vulnerability Assessment

The observation points were converted into UTM/WGS86 coordinate system for interpolation. The interpolation for point data was done using Kriging interpolation method.

4.3.1.2 Net Recharge

For the creation of net recharge layer, block-wise recharge data was collected from Central Ground Water Board. The data were first stored in MS-Excel and then converted to Shape file using ArcGIS software.

4.3.1.3 Aquifer Media, Impact of Vadose Zone, Hydraulic Conductivity

Based upon the borehole data of CGWB, a shape file of the aquifer media layer and the impact of vadose zone layer was created in ArcGIS. Hydraulic conductivity was estimated from transmissivity data of CGWB.

Hydraulic conductivity = Transmissivity/total tapped thickness of aquifer

The shape file of hydraulic conductivity was generated in ArcGIS. The interpolation of all three parameters i.e. aquifer media, impact of vadose zone and hydraulic conductivity was done using Kriging method.

4.3.1.4 Soil Map

Soil map was collected from Remote Sensing Application Center (RSAC), Lucknow. The soil map was geo-referenced and brought to same coordinate system of other maps. It was then prepared using reference map obtained from RSAC.

4.3.1.5 Topography (Slope)

The slope map (in percent) was generated using ASTER DEM of the study area. The percent slope map of the study area was reclassified.

4.3.1.6 Anthropogenic Impact

The anthropogenic impact map was generated using land use land cover map and urbanization index map of Lucknow district.

- **Land Use**

Land use map was generated using LANDSAT 4/5 TM data from the year 2011 and SOI toposheets of the Lucknow district. Land use map was generated using supervised classification technique in Erdas imagine software.

- **Urbanization Index Dataset**

Urbanization index map was prepared using Defence Meteorological Satellite Program (DMSP) Operational Line-scan System (OLS) night light dataset and University of Columbia's World Gridded Population Density dataset from 2000 to 2010. The illuminations tend to differ because the datasets were from three different sensors. In order to avoid these differences, all the datasets was calibrated using the Elvidge coefficients (Palanichamy, 2014). The temporal granularity of the dataset was one year. The Elvidge coefficients was applied for calibration of the DMSP Night lights data. The Maximum Night lights value of 63 was obtained. This value was common for large metropolitan cites.

The GPWv3 dataset is available for the years of 2000, 2005 and 2010. Population density growth followed a second order non-linear curve. For every pixel, a second order non-linear regression was fitted and the value for every year in between was predicted. The dataset was resampled to the spatial resolution of DMSP OLS data. Since population density is a ratio of population to area, the resampled data for every pixel was same as the parent pixel.

To create the Urbanization Index dataset, the population density grid data and the night lights data was used. The following formula 4.1 was used for calculating the Urbanization Index (U.I) (Palanichamy, 2014)

$$\text{U.I.} = \frac{\text{Population Density} * \text{Night lights value in the pixel}}{\text{Maximum night light value in the image}} \tag{4.1}$$

To create the Urbanization Index Anomaly dataset, the UI values was averaged for every pixel between the time period of 2004 and 2009. The anomaly was calculated by subtracting the averaged UI value from the actual UI value.

The land use land cover map was modified by using urbanization index map. On the basis of urbanization index map, the built up class of land use and land cover map of Lucknow district was further sub-divided into four classes: built up with high density, built up with medium density, built up with low density and built up with very low density.

Each parameter in the model has a fixed weight according to the relative influence of the parameter in transporting contaminants to the groundwater. The parameter ratings are variable, which permit the user to calibrate the model to suit a given region (Rahman, 2007). The parameters Depth to water table, net recharge, soil media, topography, hydraulic conductivity and anthropogenic impact were assigned one value per range. But parameters aquifer media and impact of vadose zone were assigned a “typical” ratings. After generating all the maps, according to the above discussed methods, all the maps were reclassified according to the assigned ratings as discussed in chapter 6. Ratings and weights of each parameter were assigned as given in Table 6.1 and Table 6.2 which vary from 1 to 10, with higher values describing greater pollution potential. Weights were assigned for various hydrological settings, which range from 1 to 5, with higher weights representing greater pollution potential (Table 6.1 and Table 6.2). These eight set of data layers were digitized and were converted to raster data sets.

4.3.2 Generation of DRASTIC and DRASTICA Risk Map

The DRASTIC and DRASTICA Index was computed as the weighted sum overlay of the seven and eight layers respectively by using the following equation:

$$\text{DRASTIC Index} = \mathrm{D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w} \qquad (4.2)$$

Where $_r$ and $_w$ are the ratings and weights assigned to each parameter respectively.

D=Depth to water table, R=Net recharge, A=Aquifer media, S=Soil media, T=Topography,

I= Impact of vadose zone, C = Hydraulic conductivity

$$\text{DRASTICA Index} = \text{DRASTIC Index} + \mathrm{A_r A_w} \qquad (4.3)$$

Where $_r$ and $_w$ are the ratings and weights assigned to parameter

Where A = Anthropogenic impact

4.3.3 Validation of DRASTIC and DRASTICA Risk Map

The water quality parameter, nitrate was used to validate both the DRASTIC and DRASTICA methods.

4.4 Effect of Urbanization on Groundwater Resources using GRACE/GLDAS Data

The data used in the present study was collected from the GRACE (Gravity Recovery and Climate Experiment), launched on 17th March, 2002 as a joint collaboration of NASA and the German Space Agency and from GLDAS. The Gravity Recovery and Climate Experiment (GRACE) is the first satellite remote sensing mission directly applicable for regional groundwater mapping (Rodell et al., 2006).On the basis of Earth's global gravity field, Grace Mission provide data of approximately changes in terrestrial water storage.

4.4.1 Primary and Secondary Data Used for Estimation of Change in Groundwater Storage

To estimate change in groundwater storage various kinds of primary and secondary datasets were used as presented in Table 4.5. Processed monthly results of GRACE data are released by the CSR, GFZ and JPL and can be accessed online (http://gracetellus.jpl.nasa.gov/data/) (Landerer and Swenson, 2012). Processed monthly results of GLDAS, released by NASA Goddard Space Flight Center, were downloaded from Mirador (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings).

4.4.2 Methodology for Estimation of Change in Groundwater Storage

The methodology proposed for estimation of change in groundwater storage is presented in Figure 4.6. From 2003 to 2012, the trend of groundwater depletion in Uttar Pradesh was studied at a regional scale using monthly grid terrestrial water storage data (from JPL RL05 product of GRACE Mission), soil moisture data and precipitation data (from GLDAS). To estimate the change in groundwater storage, all datasets of same resolution were used (Chinnasamy et al. 2013). The results were plotted and compared. Pre-monsoon, monsoon and post-monsoon maps were prepared. The results have also been validated using groundwater level data of Central Ground Water Board

Table 4.5 Description of Primary and Secondary Sources of Datasets

Dataset	Units	Spatial Resolution	Observation Period	Source
Terrestrial Water Storage				
JPL RL05Land data product	EWT- cm	1^{o}	Jan 2003-Dec 2012	GRACE- Tellus
Soil Moisture				
GLDAS-2.0 NOAH Model	Kg/m^{2} (mm)	1^{o}	Jan 2003-Dec 2012	GIOVANNI-GLDAS
Precipitation				
GLDAS-1 CLM Model	centimeters	1^{o}	Jan 2003-Dec 2012	GIOVANNI-GLDAS
In Situ Well data				
Water level data	Meters	Point	May, Nov (2005-2011)	CGWB

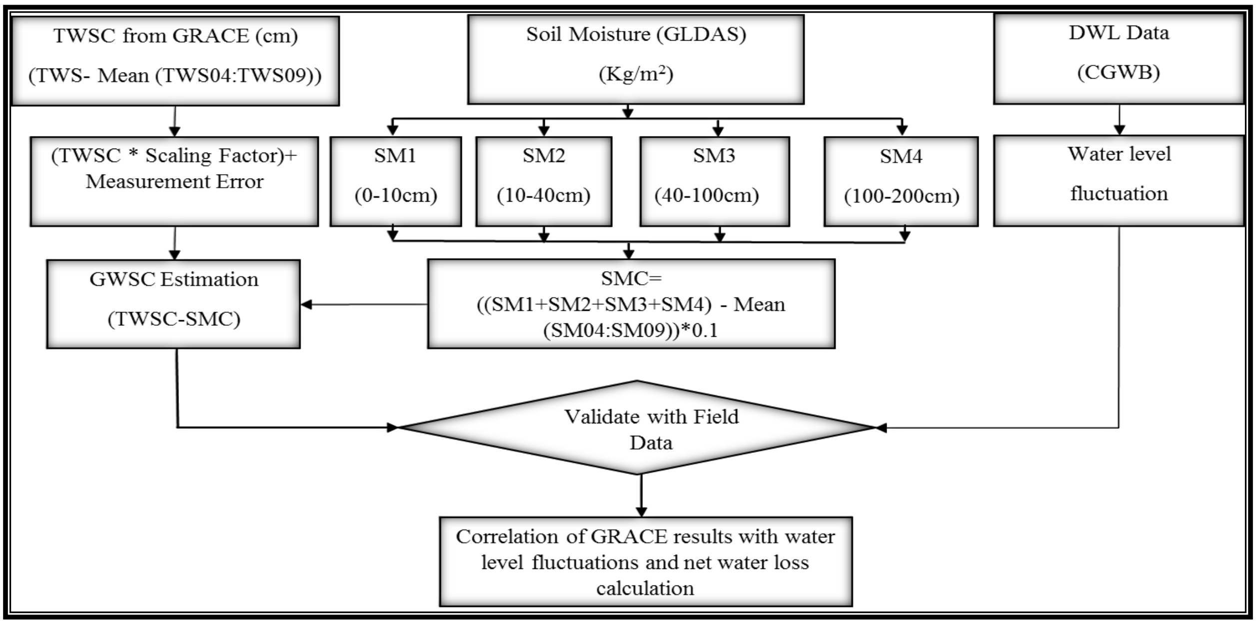


Figure 4.6 Flowchart Showing Methodology for Estimation of Change in Groundwater Storage

CHAPTER 5

ASSESSMENT OF GROUNDWATER QUALITY

5.1 Groundwater Quality

The term water quality encompasses the physical, chemical and biological characteristics of water. It gives the suitability of water for various purposes. Water quality measurement at different times gives the information about the changes (i.e. influxes and out fluxes) in the water system. A total of 84 groundwater samples were collected, of which 54 were from hand pumps and 30 from tube-wells during pre-monsoon (May, 2011) and post-monsoon (November, 2011) seasons. On the basis of definite standards, the quality of water determines its appropriateness for various purposes**.** Drinking water quality was evaluated with Bureau of Indian Standards (BIS, 2012).The results of chemical analysis of ground water samples were evaluated for drinking, domestic and irrigation uses. This chapter presents a detailed scenario of physical and chemical parameters and seasonal variations of groundwater samples. The results of chemical analysis data of 84 groundwater samples of pre-monsoon and post-monsoon season are compiled in Appendix I. All of these physical parameters, dissolved major constituents and trace constituents are illustrated in individual sub-headings and discussed separately in this chapter as follows:

5.2 Physical Parameters

This section deals with the important physical parameters of water quality which serve as controlling variables that strongly influence the behavior of elements and constituents present in groundwater. They can change the hydrochemical nature of ions present in the water by their different chemical processes.

5.2.1 pH

pH of water depicts its acidity or alkalinity or it is the measure of how acidic or alkaline the water is. Its value varies with time and place. The pH also influences the degree of ionization, volatility and toxicity to aquatic life of certain dissolved substances. The pH of natural unpolluted groundwater is generally between 6.0 and 8.5 (Weiner, 2000).

The pH value varied from 7.9 to 8.9 in the groundwater samples collected from hand pumps (n=27), 7.9 to 8.9 in the groundwater samples collected from tube-wells of pre-monsoon season and from 7.1 to 7.6 in the groundwater samples collected from hand pumps (n=27), 7.0 to 8.2 in the groundwater samples collected from tube-wells of post-monsoon season. The distribution accounted for 77% of the total groundwater samples of pre-monsoon season were within permissible limit while 23% of samples were above permissible limit. The samples of post-monsoon season were well within permissible limit. On an average, pH values showed slight alkaline nature. Higher values were found in hand pumps than in tube wells.

5.2.2 Electrical Conductivity (EC)

Electrical conductivity of water is the measure of the capability of water to carry an electric current. The ability depends upon the presence of total ion concentrations and temperature. Its unit is µS/cm.

The electrical conductivity varied from 521 to 1399 µS/cm in the samples collected from hand pumps (n=27) and from 482 to 1345µS/cm in the samples collected from tube-wells (n=15) of pre-monsoon season and from 495 to 1374 µS/cm in the samples collected from hand pumps (n=27) and from 682 to 1303 µS/cm in the samples collected from tube-wells (n=15) of post-monsoon season in the study area. The EC of the 41% samples were mid-range (250-750 µS/cm) and 59% of the samples were upper range (750-2250 µS/cm).

5.2.3 Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) comprises all inorganic and organic substances present in a liquid (in molecular, ionized, colloidal or suspended form). Its concentration in groundwater ranges from 20 ppm (in high rainfall areas) to 100,000 ppm (in some desert areas).

The TDS values in the samples varied from 308 to 895 mg/l during pre-monsoon season and from 316 to 879 mg/l during post-monsoon season. This indicated that the mineralization was low in the area. Only bicarbonate alkalinity was present in the study area.

5.2.4 Hardness

The concentration of calcium and magnesium with their carbonates, sulphates and chlorides constitute the hardness of water.

The hardness of water depends upon the concentration of above mentioned elements. The total hardness value of the groundwater samples for the pre-monsoon season varied from 153 to 575 mg/l during pre-monsoon season and 144 to 545 mg/l during post-monsoon.

5.2.5 Alkalinity

Alkalinity is a measure of the buffering capacity of water or the capacity of bases to neutralize acids. The alkalinity value varied from 316 to 570 mg/l for the pre-monsoon and from 300 to 560 mg/l for the post-monsoon season. The alkalinity value of all ground water samples crossed the desirable limit (200 mg/l) but were well within permissible limit (600 mg/l) as per World Health Organisation (WHO), 1993.

5.3 Major Ions

5.3.1 Sodium (Na^+)

Sodium is an essential element for all animal life and some plant species. Higher concentrations of sodium in groundwater are generally due to erosion of salt deposits, road salt, sodium-bearing rock minerals like feldspars, halites, clays, industrial effluents and agricultural chemicals (Srivastava, 2012). The WHO, 1993 limit for sodium in drinking water is 200 mg/l. Sodium concentration varied from 14.3 to 205.4 mg/l (pre-monsoon) and from 13.89 to 201.80 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), sodium concentration varied from 44.4 to 200.5 mg/l (pre-monsoon) and from 42.52 to 190.5 mg/l (post-monsoon).

5.3.2 Calcium (Ca^{2+})

Calcium ions are those cations that derived from dissolution of minerals like amphiboles, feldspars, gypsum, calcite, dolomite, aragonite and clay minerals. It is essentially non-toxic and contributes to the total hardness of water. It plays a key role in global climate through partial buffering of carbon di-oxide (CO_2) in the atmosphere by calcium carbonate ($CaCO_3$) precipitation and dissolution in oceans (Srivastava, 2012). Calcium concentration varied from 22 to 124.8 mg/l (pre-monsoon) and from 20.23 to 119.50 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), calcium concentration varied from 20.8 to 121.2 mg/l (pre-monsoon) and from 18.5 to 102.03 mg/l (post-monsoon).

According to the BIS, 2012 calcium values in all the ground water samples were well within permissible limits but 23% samples of pre-monsoon season and 26% of post-monsoon season exceeded the desirable limit of 75 mg/l.

5.3.3 Magnesium (Mg^{2+})

Magnesium is a common constituent of water. Along with calcium, it is the main contributor of water hardness. The main sources of magnesium are natural like iron-magnesium (Fe-Mg) minerals in igneous rocks and magnesium carbonate in sedimentary rocks. Other sources are fertilizers, wastewater treatment plants, and chemical industries (Srivastava, 2012).

Magnesium concentration varied from 28.8 to 91.5 mg/l (pre-monsoon) and from 25.84 to 86.60 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), magnesium concentration varied from 23.3 to 68.3 mg/l (pre-monsoon) and from 22.19 to 65.50 mg/l (post-monsoon). According to BIS, 2012 magnesium values in all the ground water samples were well within permissible limit, but all the samples exceeded the desirable limit of 30 mg/l in both pre and post-monsoon seasons.

5.3.4 Potassium (K^+)

Potassium is the seventh most abundant element and makes up about 1.5% of the Earth’s crust. Feldspars, feldspathoids, micas, clays and fertilizers are the main sources of potassium. Potassium ion is present in all living cells and it is essential for all. These ions are found in low concentrations in natural water as these are resistant to weathering (Srivastava, 2012).

Potassium concentration varied from 3.8 to 18.2 mg/l (pre-monsoon) and from 3.8 to 16.20 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), potassium concentration varied from 7.4 to 15.9 mg/l (pre-monsoon) and from 6.5 to 14.30 mg/l (post-monsoon).

5.3.5 Sulphate (SO_4^{2-})

Sulphate is readily soluble in water and is an oxidized form of sulphur. The sources of sulphates are sulphide ores, gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$). The oxidation of sulphur bearing organic materials can contribute sulphates to water (Srivastava, 2012).

Sulphate concentration varied from 6.6 to 140.9 mg/l (pre-monsoon) and from 5.94 to 138.20 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), sulphate concentration varied from 12.6 to 152.3 mg/l (pre-monsoon) and from 11.75 to 149.29 mg/l (post-monsoon).

5.3.6 Chloride (Cl^-)

Chloride is extremely mobile and widely distributed in nature. It is the most abundant anion in the human body and is essential for normal electrolyte balance of body fluids (Srivastava, 2012).

Chloride concentration varied from 1.5 to 183.7 mg/l (pre-monsoon) and from 1.20 to 180.17 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), chloride concentration varied from 15.7 to 180.6 mg/l (pre-monsoon) and from 10.42 to 175.30 mg/l (post-monsoon).

5.3.7 Fluoride (F^-)

Fluoride has the highest electronegativity and is the most reactive among all known elements. Fluoride ions are essential for bones and teeth of human beings. Although, small concentrations are essential, higher concentrations of fluoride causes fluorosis, dental, skeletal and gastrointestinal fluorosis (Srivastava, 2012).

Fluoride concentration varied from 0.2 to 1.3 mg/l (pre-monsoon) and from 0.18 to 1.20 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), fluoride concentration varied from 0.3 to 1.3 mg/l (pre-monsoon) and from 0.26 to 1.23 mg/l (post-monsoon).

5.3.8 Nitrate (NO_3^-)

Nitrate contamination in groundwater is a major problem. Nitrate concentration varied from 9.3 to 173.8 mg/l (pre-monsoon) and from 7.44 to 170.5 mg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=27). In the groundwater samples collected from tube-wells (n=15), nitrate concentration varied from 20.5 to 151 mg/l (pre-monsoon) and from 15.04 to 124.34 mg/l (post-monsoon).

About 71% of the ground water samples of pre-monsoon season and 69% of the post-monsoon season were beyond the desirable limit and showed high concentrations of nitrate. The increased concentration of nitrate in ground water samples reflected the anthropogenic influence on ground water of the urban area. High nitrate concentration can involve the conversion of organic carbon into nitrate during the percolation of domestic sewage water directly from open sewer drainage sources (Raju et al., 2010).

The main cause of nitrogen alterations was associated with domestic sewage (e.g., cesspools and/or septic tanks). The bulk ratio of nitrogen, in the form of Urea, was present in waste water of septic tanks which can be hydrolyzed under anaerobic conditions, and as a result, ammonium anion can be produced (Wilhelm et al., 1994).

5.4 Dissolved Trace Constituents

Total 38 groundwater samples (of which 18 samples of pre-monsoon season and 18 samples of post-monsoon season) were analyzed for trace constituents. The analytical results of distribution of dissolved trace constituents in pre-monsoon and post-monsoon groundwater samples are presented in Appendix II.

5.4.1 Arsenic (As)

Arsenic concentration varied from 0 to 0.06 µg/l (pre-monsoon) and from 0 to 0.04 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, arsenic concentration varied from 0.02 to 0.06 µg/l (pre-monsoon) and from 0.01 to 0.04 µg/l (post-monsoon).

5.4.2 Mercury (Hg)

Mercury concentration varied from 0.03 to 0.1 µg/l (pre-monsoon) and from 0.03 to 0.19 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, mercury concentration varied from 0.02 to 0.07 µg/l (pre-monsoon) and from 0.03 to 0.97 µg/l (post-monsoon).

5.4.3 Chromium (Cr)

Chromium concentration varied from 0.02 to 0.08 µg/l (pre-monsoon) and from 0.02 to 0.06 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, chromium concentration varied from 0.02 to 0.09 µg/l (pre-monsoon) and from 0.02 to 0.04 µg/l (post-monsoon).

5.4.4 Iron (Fe)

Iron concentration varied from 6.1 to 21.97 µg/l (pre-monsoon) and from 2.53 to 19.97 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, iron concentration varied from 6.2 to 17.93 µg/l (pre-monsoon) and from 6.83 to 16.36 µg/l (post-monsoon).

5.4.5 Manganese (Mn)

Manganese concentration varied from 0.07 to 0.27µg/l (pre-monsoon) and from 0.02 to 0.25 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, manganese concentration varied from 0 to 0.23 µg/l (pre-monsoon) and from 0.01 to 0.17 µg/l (post-monsoon).

5.4.6 Zinc (Zn)

Zinc concentration varied from 0.05 to 2.03 µg/l (pre-monsoon) and from 0.12 to 2.28 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, zinc concentration varied from 0.03 to 0.46 µg/l (pre-monsoon) and from 0.05 to 0.34 µg/l (post-monsoon).

5.4.7 Vanadium (V)

Vanadium concentration varied from 0.03 to 0.34 µg/l (pre-monsoon) and from 0.03 to 0.30 µg/l (post-monsoon) in the groundwater samples collected from hand-pump (n=9). In the groundwater samples collected from tube-wells, vanadium concentration varied from 0.07 to 0.3 µg/l (pre-monsoon) and from 0.06 to 0.24 µg/l (post-monsoon).

5.5 Hydro-geochemical Facies

The term hydro-geochemical facies reflects the chemical processes that are occurring between the ground water and subsurface rock units. These facies are the function of lithology, solution kinetics and flow pattern of the aquifer and the following diagrams express the underground reactions which are occurring between groundwater and surrounding minerals in an aquifer. These reactions are believed to be the principal processes accountable for the chemical evolution of groundwater.

Different facies diagrams such as Piper diagram, Chadha's diagram were used in the present study. These diagrams express similarity and dissimilarity in the chemistry of water based on major cations and anions (Jain et al., 2010)

5.5.1 Hill-Piper Diagram

It is evident from the Piper Diagram as represented in Figure 5.1(a) and (b) that the majority of the samples of hand-pumps and tube-wells of both the seasons were fall under subarea (5) of the diamond-shaped field which show hardness exceeding 50%, represented Ca-Mg-HCO_3 hydrochemical facies and was the region of water of temporary hardness. Such waters were generally considered hard.

5.5.2 Chadha's Diagram

The Chadha's diagram as represented in Figure 5.2 (a) and (b) was plotted by using chemical analysis data for all the samples of both the seasons. It is clear from the diagram that the majority of pre and post-monsoon groundwater samples were fall under sub-field (5) of Chadha's diagram which showed that the alkaline earths and weak acidic anions exceed both alkali metals and strong acidic anions, respectively. Such water has temporary hardness and represents Ca-Mg-HCO_3 type. Few samples fall under the sub-field of alkali metals exceed alkaline earths and weak acidic anions exceed strong acidic anions. Such waters deposit, residual sodium carbonate in irrigation use and cause foaming problem.

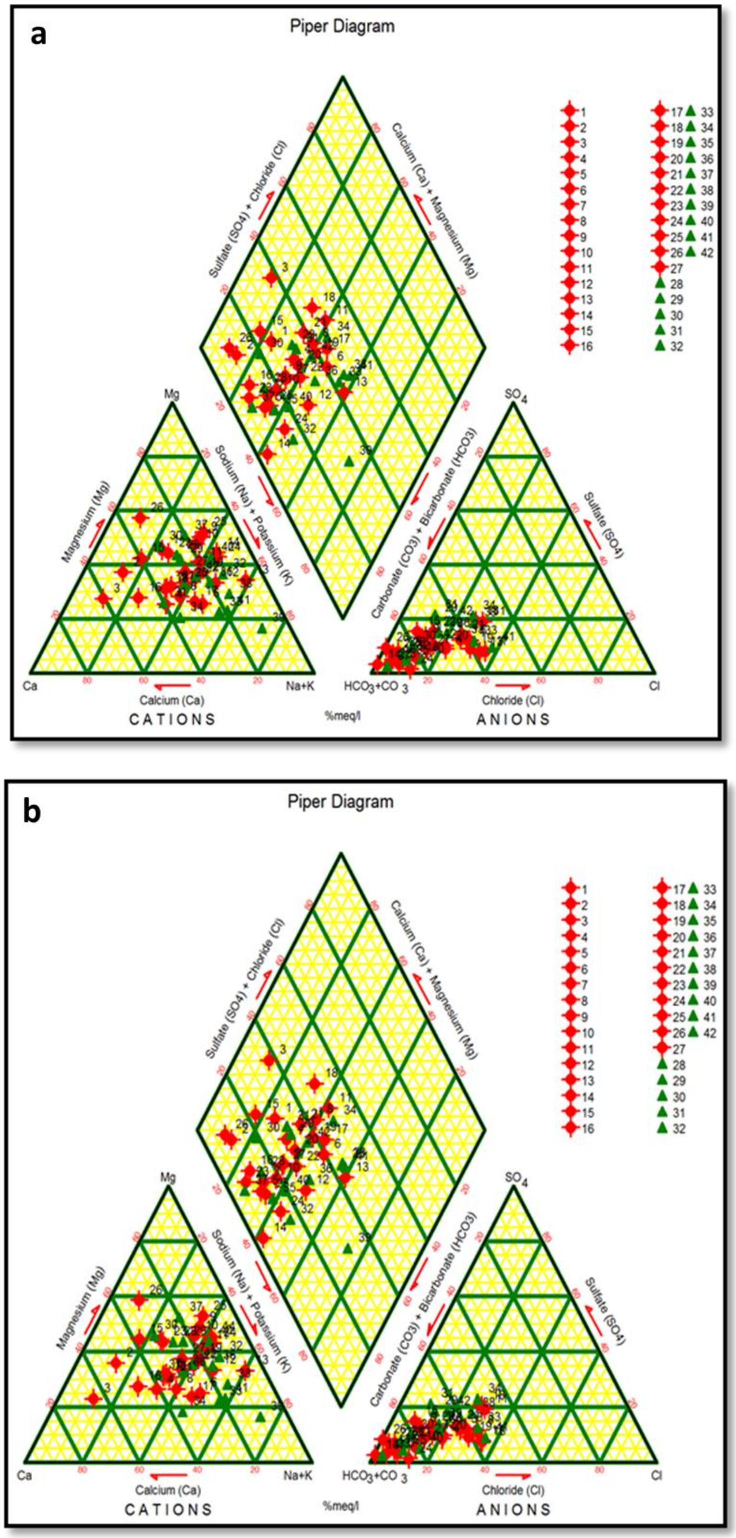


Figure 5.1(a) Pre-Monsoon and (b) Post-Monsoon Piper Trilinear Diagram of Hand Pumps and Tube-Wells Showing Chemical Characters of Samples [sample no. 1-27 = Hand Pump, and sample no. 28-42 = Tube Wells]

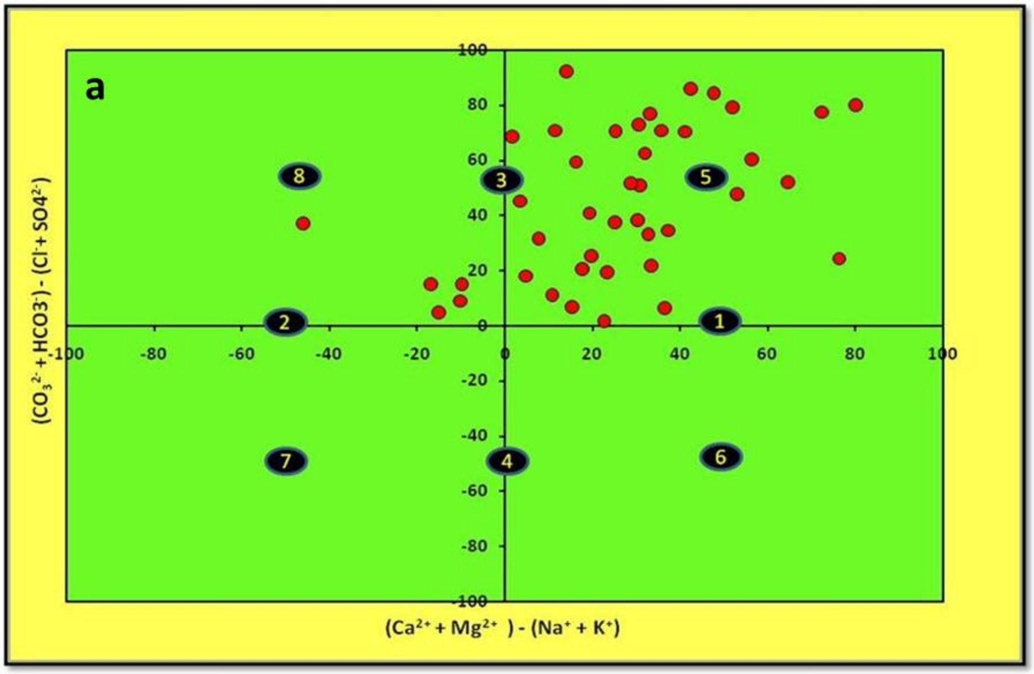


Figure 5.2(a) Chadha's Diagram of Pre-Monsoon Groundwater Samples Showing Chemical Character of Groundwater

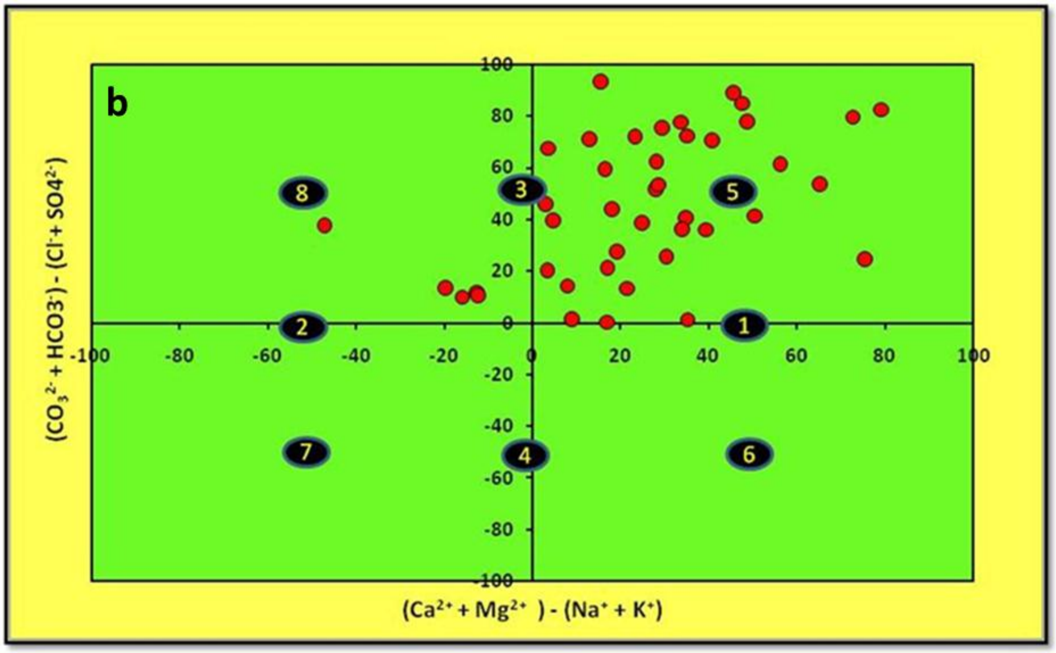


Figure 5.2(b) Chadha's Diagram of Post-Monsoon Groundwater Samples Showing Chemical Character of Groundwater

5.6 Geochemical Evolution of Groundwater

Geochemical evolution of groundwater was evaluated by computing the Chloro-Alkaline Index.

5.6.1 Chloro-Alkaline Index (CAI)

The study of chloro-alkaline index helps in the understanding of the chemical reactions in which ion exchange between the aquifer environment and groundwater occurs during periods of movement and residence (Raju et al., 2010).

The CAI values of the study area range from -66.2 to 0.4 and -0.6 to 0.1 for pre-monsoon and post-monsoon season respectively. Positive CAI value was observed at only one location at Indira Nagar area suggested that magnesium and calcium in rock were exchanged with sodium and potassium from water following direct exchange (chloro-alkaline equilibrium), whereas negative CAI values were observed in all remaining samples suggested that sodium and potassium in rock were exchanged with magnesium and calcium from water following reverse exchange (chloro-alkaline disequilibrium).

5.7 Assessment of Groundwater for Different Purposes

The data obtained by chemical analyses were evaluated in terms of suitability for irrigation and industrial purposes as presented in Appendix III.

5.7.1 Irrigation Use

5.7.1.1 Magnesium Hazard (MH)

Szabolcks and Darab, 1964 proposed magnesium hazard to determine the suitability of water for irrigation and it is calculated by following equation 5.1

$$\text{Magnesium Hazard} = \mathrm{Mg}^{2+} / \left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right) \times 100 (\mathrm{meq/l}) \qquad 5.1$$

Magnesium Hazard values greater than 50 are considered dangerous and unsafe for irrigation uses. The calculated magnesium hazard values for the study area range from 31.5 to 83.3 for pre-monsoon and from 26.5 to 83.4 for post-monsoon season. The results indicated that about 70% of the pre-monsoon and post-monsoon ground water samples exceeded the desirable limit of magnesium.

5.7.1.2 Residual Sodium Carbonate (RSC)

To determine the dangerous effect of CO_3^{2-} and HCO_3^- on the quality of groundwater for agricultural purpose, RSC was calculated (Ramesh et al., 2011). The RSC values were obtained using the following equation 5.2

RSC = $(\mathrm{HCO_3} + \mathrm{CO_3^{2-}}) - (\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})$ milli equivalent per liter (meq/l) 5.2

RSC values are considered unsuitable if it is more than 2.5 and are suitable if it is < 2.5 (USEPA, 1999). The chances of precipitation are more when calcium and magnesium are less than the sum of carbonates. Residual Sodium Carbonate is zero when the carbonates are less than alkaline earths. The results of RSC values and class of water are presented in Table 5.6.

Table 5.6. Residual Sodium Carbonate (RSC) Values and Class of Water

RSC Values	Water Class	Pre-monsoon Wells	Post-monsoon Wells
<1.25	Safe	31	29
1.25-2.5	Moderate	8	11
>2.5	Unsuitable	3	2

The RSC in the study area values range from -4.0 to 4.5 for pre-monsoon and from -4.2 to 4.2 for post-monsoon season. High RSC value in groundwater samples results in an increase in the adsorption of sodium in soil (Raju et al. 2010).

5.7.1.3 Permeability Index (PI)

Doneen, 1964 has classified the water for irrigation use based upon the permeability index. Permeability index indicates the suitability of water for irrigation purpose. Irrigation water with high salt concentration affects the permeability of soil, which is influenced by cations (sodium, calcium, magnesium) and anions (chloride and bicarbonate) of the soil (Raju et al., 2010). The formula (equation 5.3) used for calculating PI and classification of water based on its PI values is as given further:

$PI = (Na^{+}+\sqrt{HCO3^{-}})*100/ (Ca^{2+}+Mg^{2+}+Na^{+})$ (meq/l) 5.3

Table 5.7 Permeability Index (PI) Values and Class of Water

PI Values	Water Class	Pre-monsoon Wells	Post-monsoon Wells
>75%	I (Good)	4	5
25%-75%	II (Good)	38	37
<25%	III (Unsuitable)	None	None

PI values (Table 5.7) for the study area range from 33.1% to 97% for the pre-monsoon and from 34.9% to 97.7% for the post-monsoon season. All samples of both pre-monsoon and post-monsoon season were under Class I and II which were acceptable for irrigation purposes.

5.7.2 Industrial Use

5.7.2.1 Corrosivity Ratio (CR)

Corrosivity Ratio (CR) indicates the proneness of ground water to corrosion. Corrosivity ratio is defined as a ratio of alkaline earths to saline salts in ground water (Raju et al., 2010). It was calculated by following equation 5.4

$CR = (Cl/35.5) + 2(SO_4/96)/2\{(CO_3+HCO_3)/100\}$ (meq/l) 5.4

CR is used to assess the eroding influence of ground water on metallic pipes. If CR of groundwater samples was less than 1, samples were considered to be in a safe zone. For the present study area, the CR of the ground water samples range from 0 to 0.8 for pre-monsoon and post-monsoon season. All the pre-monsoon and post-monsoon samples had CR less than 1. Thus the samples were in safe zone.

5.8 Summary

The groundwater of the study area was neutral to slightly alkaline in nature. Chemical analysis of shallow and deep groundwater samples of Lucknow urban area of pre-monsoon and post-monsoon seasons show that generally the ionic concentrations were found well within permissible limit except

NO_3^- which was found in higher concentrations. Groundwater quality in the study area did not show much variation between pre-monsoon and post-monsoon period. Groundwater samples were found to be suitable for drinking purpose. Nitrate contamination was very high in the urban area which reflected the effect of urbanization on groundwater quality of urban area of the study area. From the point of drinking water quality, dissolved major (except nitrate) and trace constituents/elements (except iron, chromium and mercury) were present within the permissible limits as prescribed by the Bureau of Indian Standards, 2012. Among the trace constituents, acceptable limits of mercury and iron were violated in various samples. Magnesium hazard was present in the study area as 70% of the groundwater samples of both seasons exceed the magnesium ratio of 50. The RSC values of the study area indicated that 74% of the samples were in the safe zone and 19% are in the moderate category while 7% were unsuitable for irrigation. Permeability index showed that all the samples were suitable for irrigation purpose. For industrial purpose, groundwater was considered to be safe as CR was less than 1.

CHAPTER 6

GROUNDWATER VULNERABILITY ASSESSMENT

This chapter presents the assessment of groundwater vulnerability and generation of vulnerability maps by incorporating multiple data sets. A modification of the DRASTIC method (Modified DRASTIC or DRASTICA) was integrated in this chapter and results of validation of both DRASTIC and modified DRASTIC or DRASTICA methods against the groundwater quality analysis were considered. This chapter deals with estimation of depletion trends of groundwater resources using remote sensing GRACE/GLDAS data.

6.1 Assessment and Mapping of Aquifer Vulnerability

The DRASTIC method was developed for generating pollution potential maps of the entire U.S.A. by an identical non-subjective method to relate pollution vulnerability over different areas. For this purpose, weight classes and ratings were considered as constants that could not be changed, otherwise comparison between different areas would not be possible.

The DRASTIC parameters were entered into ArcGIS software as vector map layers. According to the ratings and weights as given by Aller et al. (1987b), the ratings and weights were assigned to the parameters of DRASTIC model. The details of processing in respect of all parameters were presented in the following section.

6.1.1 Depth to Water Table

The water table is the expression of the surface where all the pore spaces are filled with water below the ground level (Aller et al., 1987b). The distance between the surface and the water table plays a significant role in governing the vulnerability of any area to pollution. If the covering materials are same, the areas with shallow water table are more prone to contamination than the areas with deeper water table. Generally, shallow water table does not give enough contact time for contaminated infiltrating waters to interact with aquifer material for their associated attenuation processes. The depth to water table map for the study area was prepared by averaging pre-monsoon and post-monsoon water level data of the year 2011 from CGWB. The depth to water table map was divided into six classes according to DRASTIC rating as shown in Table 6.1.

Table 6.1 Classes and Ratings for DRASTIC Parameters (Source: Aller et al., 1987)

Parameter	Range	Rating	Typical Ratings	Relative Weights
Depth to water table(m)				5
	1.5-4.5	9	-	
	4.5-9.1	7	-	
	9.1-15.2	5	-	
	15.2-22.9	3	-	
	22.9-30.5	2	-	
	>30.5	1	-	
Net Recharge(mm)				4
	177.8-254.0	8	-	
	>254.0	9	-	
Aquifer Media				3
	Sand and Gravel	4-9	8	
Soil Media				2
	Sandy Loam	6	-	
	Loam	5	-	
	Silty Loam	4	-	1
Topography				
	0-2	10	-	
	2-6	9	-	
Impact of Vadose zone				5
	Sand and Gravel	6-9	8	
Hydraulic Conductivity				3
	>10.0	10		

The final depth to water table map was generated as shown in Figure 6.1. The final depth to water table map represents six rating classes (1, 2, 3, 5, 7 and 9). The shallowest water level (less than 2 metres) was observed at Gosainganj block while the deepest water table of about 33.94 mbgl was observed at Gulistan colony of Lucknow urban area of the district. Depth to water table of 5-10 metres and 10-20 metres was observed at northern, southern part (viz. part of Bakshi-ka-Talab, Chinhat, Mohanlalganj) and western part (Mal, Malihabad, part of Bakshi-ka-Talab, Kakori, Sarojini Nagar, part of Chinhat block) of the district. The shallowest depth to water table has a maximum rating of 9 and the deepest depth to water table has a minimum rating of 1 while the rest of the area (shallower to deeper depth to water table) has a rating of 2, 3, 5 and 7. According to the DRASTIC method, the depth to water table was assigned a weight of “5”.

6.1.2 Net Recharge

Precipitation is the principal source of groundwater, which infiltrates through the surface and finally percolates to the water table. Irrigation also contributes to the groundwater recharge. The amount of water that percolates to per unit area of the soil is known as Recharge. Thus recharge plays a very important role in transporting the contaminants to the groundwater. An area with high groundwater recharge is at high risk because of the availability of the permeable pathway from the surface to the subsurface water table (Hussain, 2004). The normal rainfall of Lucknow district is about 960 mm. The maximum rainfall occurs during the monsoon period, i.e. June to September, having normal value of about 850 mm, which is about 88% of the annual rainfall. The block wise groundwater recharge data values were obtained from CGWB.

The net recharge varied from about 178 mm to 270 mm in the area. According to the DRASTIC method, the net recharge parameter was assigned a weight of “4”. As per the DRASTIC ratings (Table 6.1) of net recharge layer, the reclassification of recharge layer was done. The net recharge map, Figure 6.2 represents only two rating classes of 8 and 9. High net recharge was observed in the entire district except Mal block. Mal block has relatively less recharge with a rating of 8.

6.1.3 Aquifer Media

Aquifer media represents the consolidated and unconsolidated material of the aquifer, such as sand and gravel or limestone (Hussain, 2004). According to the DRASTIC method, aquifer media parameter was assigned a weight “3”.

An aquifer media map was prepared using lithology data of CGWB. The borehole data of the study area indicates that the aquifers in the study area are essentially sandy in nature, having a rating between 4 and 9 and typical rating of 8 according to Table 6.1. The whole study area is made up of alluvium. The aquifer media map (Figure 6.3) was assigned only one typical rating of 8.

6.1.4 Soil Media

The uppermost part of the unsaturated zone consists of soil. The soil of any area plays a key role in controlling the amount of recharge, which percolates into the water table. The thickness of soil also determines the movement of contaminants to the water table (Hussain, 2004).According to the DRASTIC method this parameter was assigned a weight of “2”. There are three types of soils in the district; Sandy Loam, Silty Loam and Loam. The DRASTIC ratings were assigned based upon the types of the soil present in the district and by reclassification of these assigned ratings (Table 6.1), soil map was prepared. The soil map (Figure 6.4) represents three ratings 4, 5 and 6. The maximum rating of 6 was assigned to sandy loam soils while the minimum rating of 4 was assigned to the silty loam soils. The maximum part of the district is occupied by loam soils and was assigned a rating of 5.

6.1.5 Topography

Topography of any area defines the slope and slope variability of the land surface. Topography determines whether the pollutant will runoff or remain on the surface of that area to infiltrate (Hussain, 2004). The topography parameter was given a weight of “1”.

The study area is relatively flat area with very small slope. This type of topography allows the contaminant to get more percolation time to reach the water table from ground surface. According to the DRASTIC ratings only two ratings 10 (0-2% slope) and 9 (2-6% slope) were assigned to the study area. The reclassification of the slope map was done according to the DRASTIC ratings (Table 6.1). The topography map (Figure 6.5) represents that more than 90% area of the district corresponds to high rating of 10 which represents the slope percentage less than 2.

6.1.6 Impact of Vadose Zone

The unsaturated zone above water table and below ground surface is known as vadose zone (Hussain, 2004). The type of vadose zone material decides its rating value. According to DRASTIC method this parameter was assigned a weight of 5. The lithology of the area includes a vadose zone composed of sand, silt and clay. This type of material was assigned ratings between 4 to 8 and a typical rating of 6 according to Table 6.1. Though the percentage value of sand, silt and clay differ place to place, the available ratings according to DRASTIC method can only offer unique value for vadose zone in the alluvial areas. Therefore, the impact of vadose zone map (Figure 6.6) represents only one typical rating of 6.

6.1.7 Hydraulic Conductivity

The ease with which a fluid can flow through pore spaces of the aquifer material is known as the hydraulic conductivity of the aquifer. Hydraulic conductivity governs the rate at which groundwater would flow under any hydraulic gradient therefore controlling the contaminant flow (Hussain, 2004). According to the DRASTIC method, this parameter was assigned a weight of 3.

The hydraulic conductivity of the study area was collected from CGWB. The hydraulic conductivity map (Figure 6.7) represents only one rating (10) according to DRASTIC method (Table 6.1).

6.2 Consolidation and Computation of DRASTIC Index and Development of DRASTIC Risk Map

The DRASTIC model was computed according to the processes mentioned above. The final DRASTIC risk map is presented in Figure 6.8. The DRASTIC risk map showed three vulnerable classes i.e. Low, medium and high vulnerable classes on the basis of DRASTIC Index. The city area shows low vulnerability (120-139) and higher vulnerability is (160-189) shown by Gosaiganj and Sarojini Nagar block while the remainder falls under moderate vulnerable (140-159) zone. This indicates a collective influence of all the seven parameters.

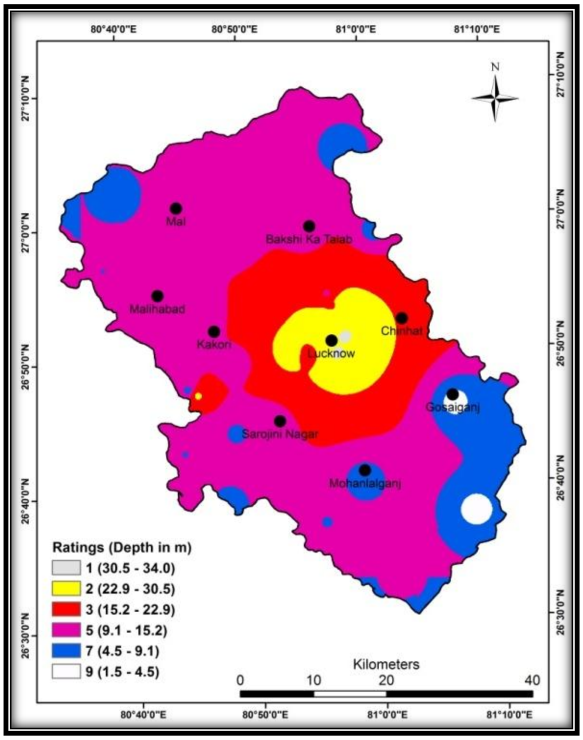


Figure 6.1 Depth to Groundwater Rating Map

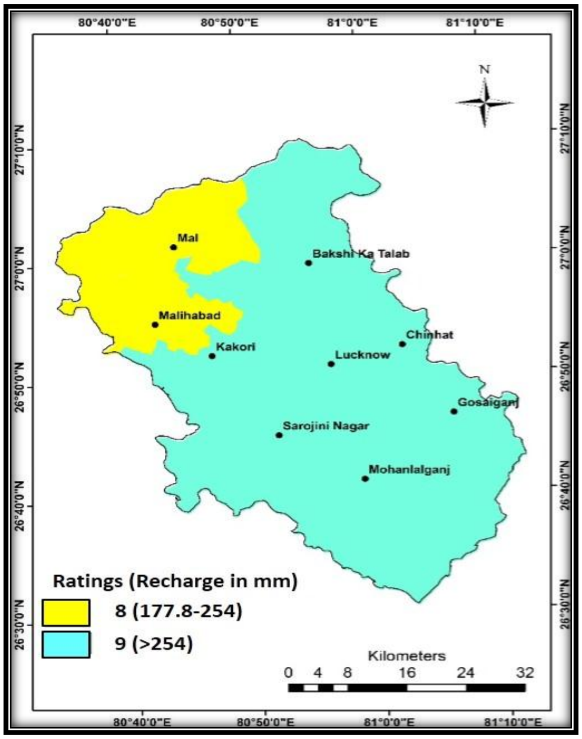


Figure 6.2 Net Recharge Rating Map

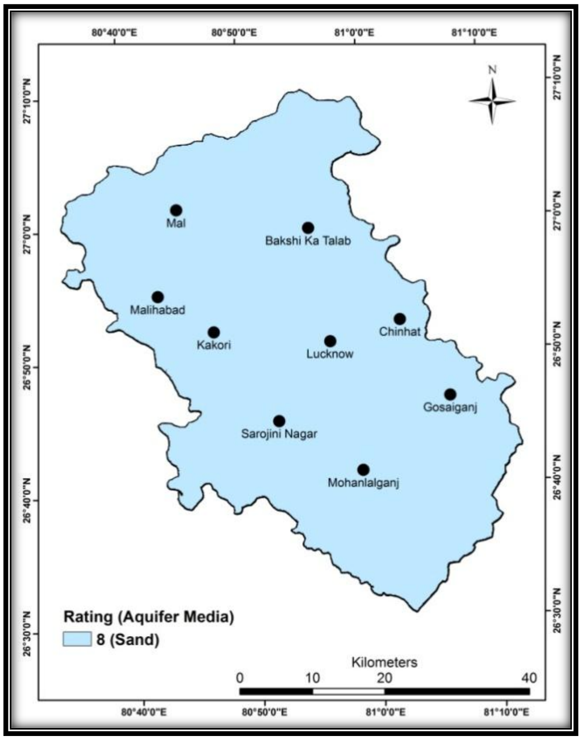


Figure 6.3 Aquifer Media Rating Map

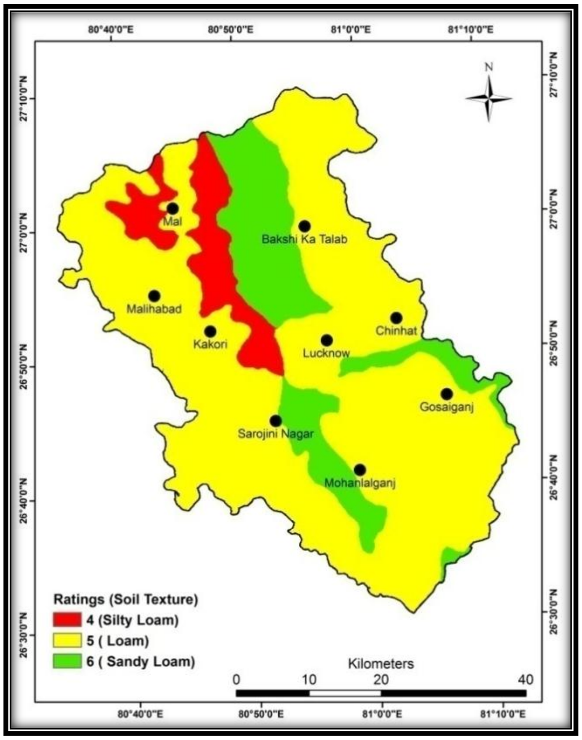


Figure 6.4 Soil Media Rating Map

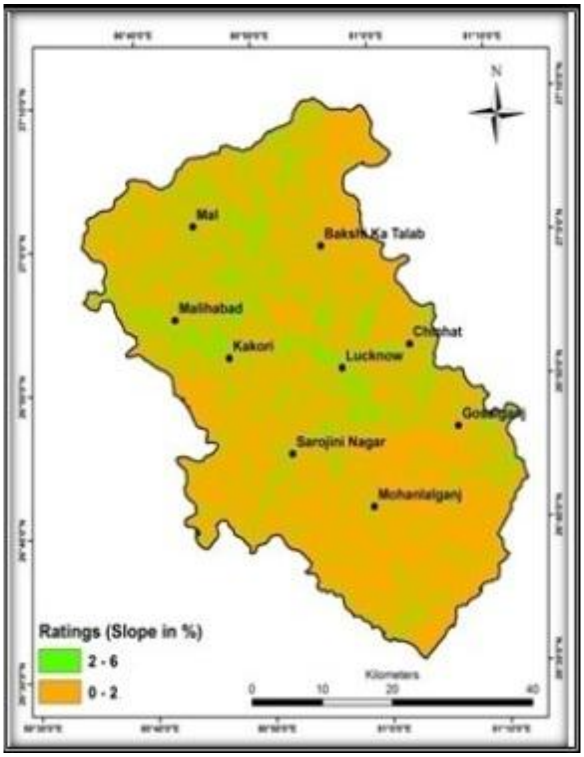


Figure 6.5 Slope Rating Map

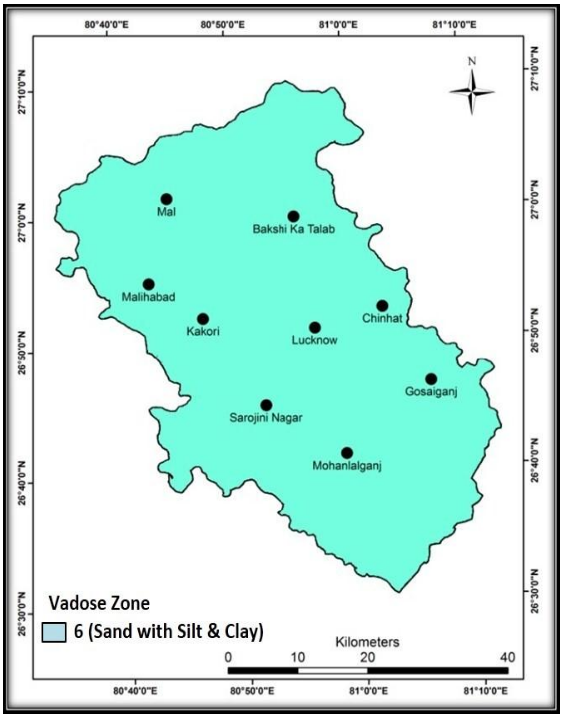


Figure 6.6 Impact of Vadose Zone Rating Map

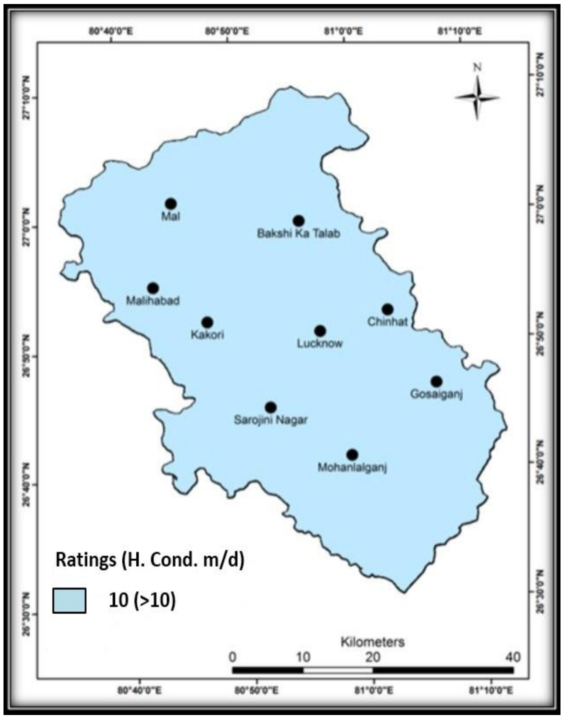


Figure 6.7 Hydraulic Conductivity Rating Map

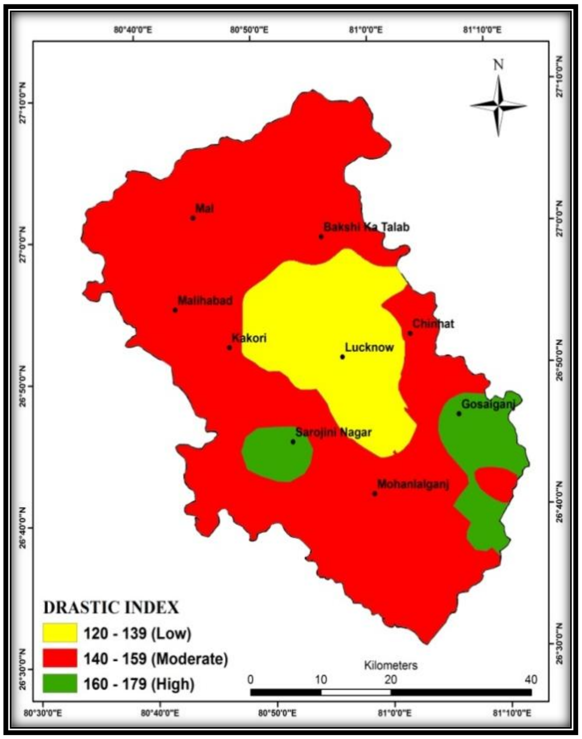


Figure 6.8 DRASTIC Risk Map

6.3 Limitations of DRASTIC Model and Modifications

The DRASTIC model although widely used to evaluate groundwater vulnerability, cannot be applied in an urbanized environment straightaway, as it does not consider the anthropogenic influence as a part of the model parameters. For the present study, it was proposed that a modified DRASTIC model - DRASTICA - be used to overcome this limitation, where 'A' refers to a new parameter called 'impact of anthropogenic activities.' The study also demonstrated an innovative methodology to characterize the anthropogenic influence (A) by using the satellite observations of nightlights from human settlements and land-use/ land-cover (LULC) surrounding the urbanized area as proxy.

6.4 Preparation of Anthropogenic Impact Map

Anthropogenic activities or urbanization influences the groundwater vulnerability of any area. So for assessment of groundwater vulnerability of the present area, one more layer of anthropogenic impact was added to the conventional DRASTIC model. Preparation of anthropogenic impact layer was done by integrating the land use land cover map and urbanization index map (developed from DMSP night light data and University of Columbia’s World Gridded Population Density dataset) of Lucknow district.

6.4.1 Land Use

Type of land use pattern and anthropogenic actions have a noteworthy influence on the groundwater vulnerability for most of the area. Therefore, a land use parameter was applied when generating the DRASTICA index map for the study area. A land use map was prepared using LANDSAT 4/5 TM data of year 2011 and toposheets of the Lucknow district. Land use map was classified into six classes, i.e. built up land, agriculture, forest, shrub land, waste land and water body. As a result of land use pattern such as urban, commercial, agricultural and industrial, the intensity of pollution potential also varies. Land use parameters can significantly affect hydrogeological parameters. The properties of hydrological parameters can be changed by agricultural pesticide, urban wastes such as industrial wastes, septic system and dumping station. Land use classification of study area (Figure 6.9) showed that a major portion of the area was used for agriculture. The second major part of the area represents urban pavements and associated non-agricultural land. Furthermore, the remaining portions of the area was categorized as forest land, water body, shrub land and wasteland. In groundwater system, nitrate distribution is principally dependent upon the soil dynamics; recharge rate, groundwater movement and on-ground nitrogen loading (Shirazi et al., 2011). The occurrence of nitrate in groundwater system indicated the probability of pollution via agricultural and anthropogenic activities. Land use classification of study area designated that groundwater quality of the study area was significantly influenced by the agricultural and urban actions.

6.4.2 Urbanization Index Dataset

For the generation of urbanization index map (Figure 6.10), Defence Meteorological Satellite Program (DMSP) Operational Line-scan System (OLS) night light dataset and University of Columbia’s World Gridded Population Density dataset were used. Further refinement of Land use land cover map was done using Urbanization Index map of the study area. On the basis of urbanization index map, the built up class of land use and land cover map of the study area was further sub-divided into four classes including built up with high density, built up with medium density, built up with low density and built up with very low density. Fresh anthropogenic map (Figure 6.11) was prepared according to the ratings given in Table 6.2. According to the weight of this parameter, anthropogenic impact map was multiplied by the weight of 5.

After incorporating all these refinements, a new layer labeled Anthropogenic Impact layer was generated and added as the eighth parameter in the DRASTIC model. New modified DRASTIC model named DRASTICA was developed for the present study area.

6.5 Development of Modified-DRASTIC or DRASTICA Risk Map

The performed study assesses the groundwater vulnerability based on the anthropogenic activities merged with the DRASTIC map. The modified risk map (Figure 6.12) was produced by the additional parameter of anthropogenic impact, integrating into the conventional DRASTIC method. This arrangement was termed DRASTICA method. In the modified risk map, anthropogenic and urbanization effects were mainly focused on the groundwater vulnerability. Based on the assumptions of land use classes (Secunda et al., 1998; Al-Adamat et al., 2003; Saidi et al., 2010 and Shirazi et al., 2013) anthropogenic impact map was rated and weighted to develop the risk map.

The anthropogenic impact map was transformed into raster grid and multiplied by the weight of the parameter (A_w=5). To generate a spatial correlation between anthropogenic impact and DRASTIC risk map, the anthropogenic impact map was superimposed over the DRASTIC index map. By the addition of final resultant grid coverage with DRASTIC Index (DI), the DRASTICA Index was calculated using the following equation (6.1) (Shirazi et al., 2013):

$$\text{DRASTICA Index} = DI + A_r A_w \tag{6.1}$$

where, $_r$ and $_w$ represent the rate and weight of the anthropogenic impact parameter. The risk map indicates the parts of the study area, and types of anthropogenic activities which are more liable for the groundwater vulnerability.

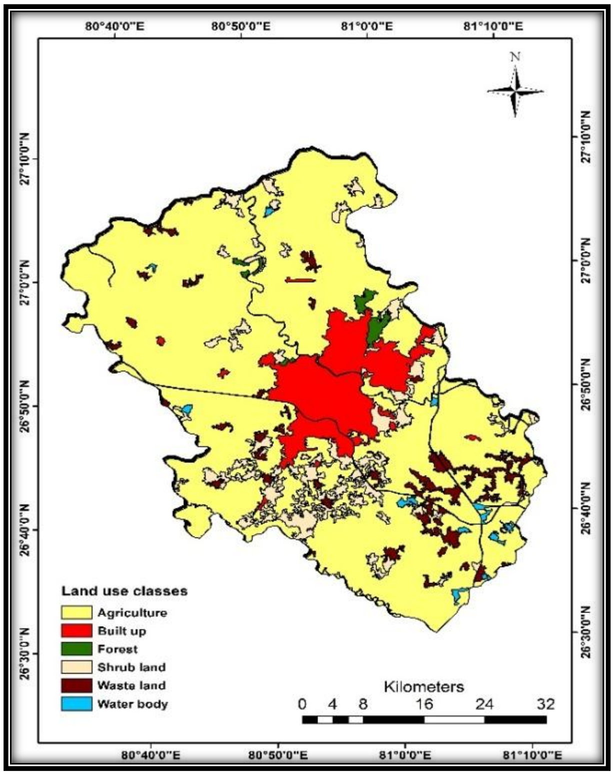


Figure 6.9 Land Use and Land Cover Map of Lucknow District

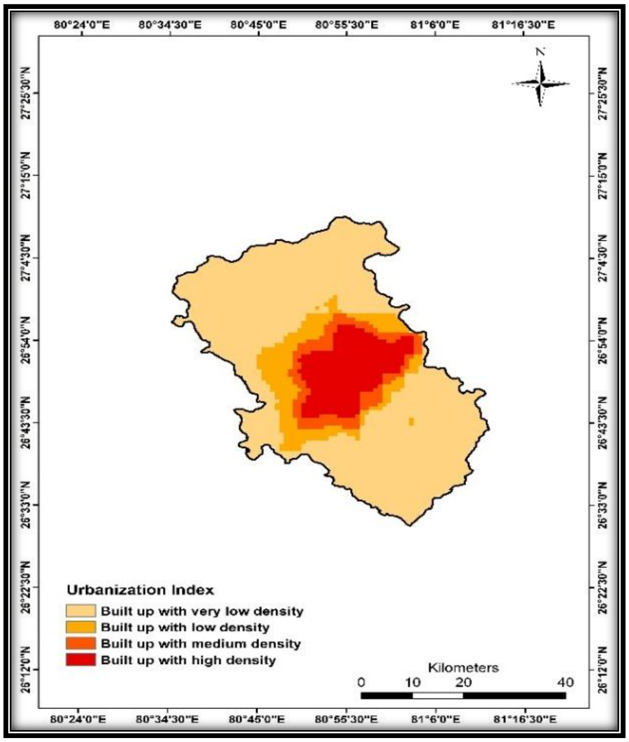


Figure 6.10 Urbanization Index Map (Modified from Palanichamy, 2014)

Table 6.2 Land Use Classes and their Assigned Ratings and Weights

Land Use	Ratings	Weight
Built up with high density	9	5
Built up with medium density	8	5
Built up with low density	7	5
Built up with very low density	5	5
Agriculture	5	5
Forest	2	5
Water body	1	5
Shrub land	2	5
Waste land	1	5

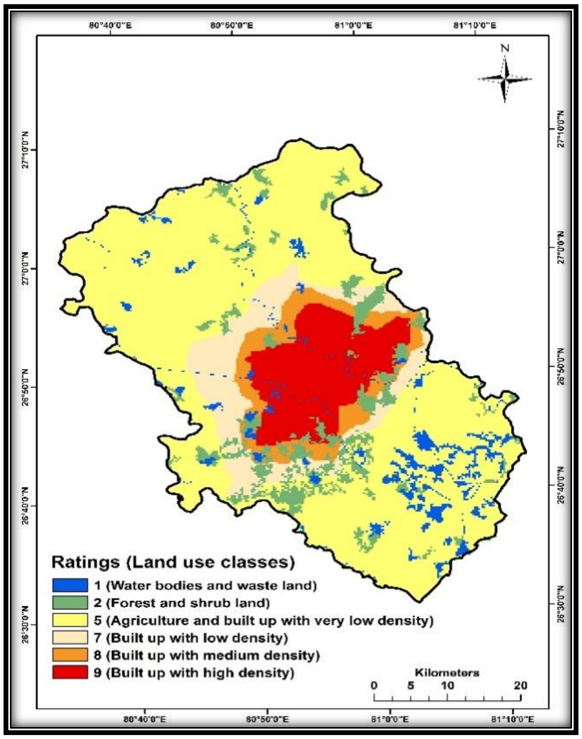


Figure 6.11 Anthropogenic Impact Rating Map

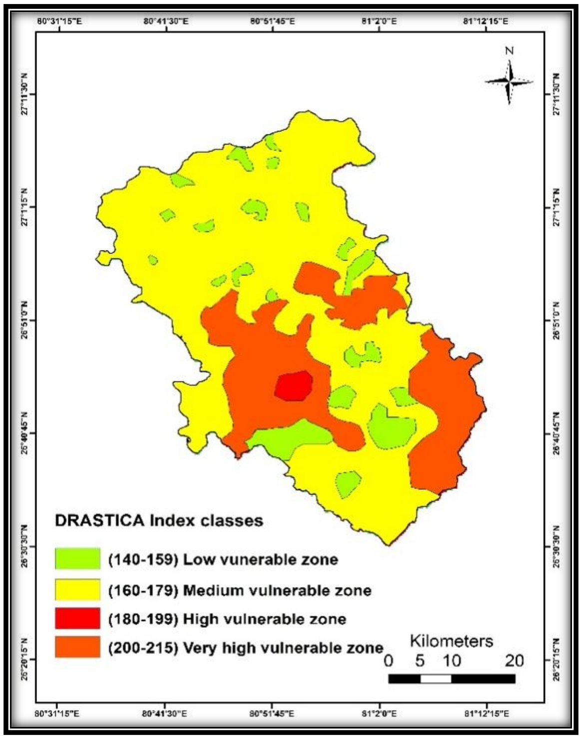


Figure 6.12 DRASTICA Risk Map

Table 6.3 Comparison between Conventional DRASTIC and DRASTICA Risk Maps

Class	Index Ranges	DRASTIC			DRASTICA		
		N. Pixel	Area	Area %	N. Pixel	Area	Area %
1	140 - 159	72929	729.29	30.21	3197	31.97	8.29
2	160 - 179	166203	1662.03	68.85	25617	256.17	66.64
3	180 - 199	2264	22.64	0.93	9462	94.62	24.51
4	200 and above	0	0.00	0.00	275	2.75	0.71

The risk map (Figure 6.12) was categorized into four classes; low (140-159), moderate (160-179), high (180-199) and very high (>200 or 200-215) vulnerability which was presented in Figure 8. The findings of the analysis revealed that 0.71% of the area falls in the very high vulnerable zone, 24.51 % in the high vulnerable zone, 66.64% in the medium vulnerable zone and 8.29% in the low vulnerable zone. The DRASTICA index map designated that high vulnerable area is increased more than about 20 % as compared to DRASTIC index map (Table 6.3), which resulted from agricultural and urban activities. In the conventional DRASTIC map there were only three classes while the DRASTICA map represented four classes.

6.6 Results and Discussions

The conventional DRASTIC risk map represented three classes (low, medium and high vulnerability) while DRASTICA risk map represented four classes (low, medium, high and very high vulnerability) of vulnerability. The modified risk map represented a better scenario of vulnerability as compared to conventional risk map in view of its validation with the field observations of groundwater quality. The nitrate contamination was very high in urban areas due to anthropogenic activities. Depth to water table, anthropogenic impact and hydraulic conductivity were more effective parameters in comparison to net recharge, aquifer media, soil media and topography.

The groundwater vulnerability potential map can be used as a guide or effective preliminary tool for the planning, policy, and operational levels of the decision-making process concerning groundwater management and protection. The Gosaiganj block, Sarojini Nagar block and urban areas of study area were characterized by a high vulnerable zone due to shallow water level and high anthropogenic impact. The major portion of the study area fall in a moderate vulnerable zone due to agricultural activities. The areas around water bodies, forest land, shrub land and waste land fall in a low vulnerability. The urban areas show high vulnerability to pollution. Groundwater samples of urban areas also show high nitrate contamination.

6.7 Validation of Methods

To validate both the conventional DRASTIC and DRASTICA methods, the water quality parameter, nitrate was used. In natural conditions, nitrate is not present in groundwater. It is introduced in groundwater by anthropogenic sources and fertilizers (Shirazi et al., 2013). Therefore, its occurrence in groundwater system indicates groundwater pollution, in which pollutants are transported by infiltrating water from the surface into the groundwater system. Nitrate concentration values were used to develop the correlations with the values of conventional DRASTIC Index (DI) and Modified DRASTIC Index (MDI). Correlation is a method for scrutinizing the connection between two measurable and continuous variables. Pearson's correlation method (Pearson, 1900) was used to establish the correlations between the parameters. In the present study, the highest nitrate concentration values were correlated with the highest MDI values as given in Table 6.4:

Table 6.4 Correlation Coefficient and Significance

Parts of the formula	General formula of Pearson	Correlation coefficient, r	Correlated parameters	Pearson's critical value of 'r' at 1 % probability level
$\frac{\Sigma(DI-\overline{DI})(NO_3-\overline{NO_3})}{\sqrt{[\Sigma(DI-\overline{DI})^2\Sigma(NO_3-\overline{NO_3})^2]}}$	$r_{xy}=\frac{\sum(X-\overline{X})(Y-\overline{Y})}{\sqrt{\Sigma(X-\overline{X})^2\Sigma(Y-\overline{Y})^2}}$	0.67	Nitrate and DI	0.3563
$\frac{\Sigma(MDI-\overline{MDI})(NO_3-\overline{NO_3})}{\sqrt{[\Sigma(MDI-\overline{MDI})^2\Sigma(NO_3-\overline{NO_3})^2]}}$		0.88	Nitrate and MDI	

The correlation coefficients were found 0.67 and 0.82 between DI and nitrate concentration, and MDI and nitrate concentration values, respectively (Table 6.4). The comparison between correlation coefficients and the Pearson’s critical value of ‘r’ at 1% probability level illustrated that a strong correlation existed between the above-mentioned parameters, which ensure the validity of the methods.

6.8 Sensitivity Analysis

One of the major advantages of the DRASTIC model is the implementation of assessment using a high number of input data layers (Evans and Myers, 1990) which is believed to limit the impacts of errors or uncertainties of the individual parameters on the final output (Rosen, 1994). However, some researchers (e.g. Barber et al., 1993; Merchant, 1994), believe that a better accuracy of the DRASTIC result can be obtained by using a lower number of input parameters.

Sensitivity analysis was carried out in the present study to evaluate the accuracy of the vulnerability maps prepared using DRASTICA model. Two sensitivity tests were performed; the map removal sensitivity analysis (Lodwick et al., 1990) and the single parameter sensitivity analysis (Napolitano and Fabbri, 1996).

6.8.1 Map Removal Sensitivity Analysis

The map removal sensitivity test identifies the sensitivity of the DRASTICA index map by removing one or more layers at a time by using following equation (6.2):

$$S= [(V/N-V'/n) /V]*100 \tag{6.2}$$

where,

S= sensitivity measure;

V=unperturbed vulnerability index (actual index obtained by using all seven parameters);

V'=perturbed vulnerability index (vulnerability index calculated using a lower number of parameters); and

N and n= no. of data layers used to compute V and V'

The sensitivity analysis of the DRASTICA model based output was carried out using the method, map removal method and single parameter sensitivity analysis methods. The outcomes of the map removal sensitivity analysis method by eliminating one or more DRASTICA parameter layers at a time are shown in Tables 6.5 (a) and (b). The sensitivity measure was computed for each grid cell by using the raster math tool of ArcGIS according to equation (6.2). The analysis indicated that the removal of depth to water table and anthropogenic impact parameters resulted in high variation of the vulnerability index due to the high weight assigned to this layer. The removal of soil media and topography layers were relatively less sensitive to the vulnerability index after depth to water table because these two parameters had lower weights and lower variation in their ratings. The aquifer media layer was the least sensitive among all the eight DRASTIC parameters used as its removal results is (0.37%).

6.8.2 Single Parameter Sensitivity Analysis

The single parameter sensitivity test was performed to check the influence of the eight DRASTIC parameters on the vulnerability index. This test was carried out by comparing "effective" and assigned "theoretical" weight of each parameter of each sub-area. The "effective" weight W_{pi} (%) of each sub-area was calculated by using equation (6.3):

$$W_{pi} = (P_r P_w/V)*100 \tag{6.3}$$

where,

W_{pi}=Effective weight (%)

P_r = Rating of respective parameter;

P_w = Weight of respective parameter; and

V = final vulnerability index.

Although the map removal sensitivity analysis evaluated the importance of the eight parameters in deriving the DRASTICA vulnerability index, the single parameter sensitivity analysis compares the "theoretical" weight of a parameter with its "effective" weight (equation 6.3). There was a deviation in the effective weights of the DRASTICA parameters from "theoretical" weights (Table 6.6). In the vulnerability assessment, depth to water table, anthropogenic impact and hydraulic conductivity were the most important parameters as their effective weight (24.4%, 22.5% and 16.3%) exceeded the theoretical weight (21.7%, 19 .8% and 13% respectively) assigned by DRASTICA. The effective weight (6.65%) of topography also exceeded its "theoretical" weight (4.3%).

Table 6.5(a) Statistics of the Map Removal Sensitivity Analysis after Removing Parameter

Parameter Removed	Variation Index (%)			
	Mean	Min	Max	SD
D	1.75	1.08	2.41	0.21
R	0.63	0.2	2.13	0.34
A	0.37	0	0.81	0.13
S	1.22	0.81	1.52	0.12
T	1.27	1.06	1.50	0.07
I	1.06	0.5	1.61	0.17
C	0.8	0	1.59	0.30
A	2.25	1.9	2.25	0.25

Table 6.5(b) Statistics of the Map Removal Sensitivity Analysis after Using Parameter

Parameter Used	Variation Index (%)			
	Mean	Min	Max	SD
D,R,S,T,I,C,A	0.33	0	0.82	0.14
D,S,T,I,C,A	0.85	0	2.5	0.47
D,S,T,I,A	0.63	0	2.9	0.51
D,S,T,A	1.63	0	3.63	0.66
D,T,A	1.3	0	3.97	0.62
D,A	10.13	6.52	14.52	1.28
A	8.95	5.54	12.36	1.1

Table 6.6 Results of Single Parameter Based Analysis

Parameter	Theoretical Wt.	Theoretical Wt. (%)	Effective Wt. (%)			
			Mean	Min	Max	SD
D	5	21.7	24.43	20.8	28.80	1.28
R	4	17.4	15.81	3.6	27.11	4.06
A	3	13.0	9.54	4.7	17.39	1.99
S	2	8.7	6.9	5.16	9.37	0.75
T	1	4.3	6.65	5.23	7.94	0.41
I	5	21.7	20.37	17.34	24	1.05
C	3	13	16.29	13.87	19.2	0.85
A	5	20.5	22.29	19.15	25.53	1.20

The remaining parameters net recharge, aquifer media, soil media and impact of vadose zone represent low “effective” weights as compared to their “theoretical” weights. Thus more detailed and accurate information was required about net recharge, hydraulic conductivity and topography for assessment of groundwater vulnerability.

6.9 Effect of Urbanization on Groundwater Resources using GRACE/GLDAS Data

Urbanization affects the quality as well as quantity of ground water. Increasing population is putting an immense pressure on groundwater by over extraction of groundwater to cater to their demands. Therefore, monitoring of change in groundwater storage was done by using following datasets:

6.9.1 Grace-Derived Terrestrial Water Storage

From 2003-2012, monthly solutions for terrestrial water storage (TWS) and soil moisture (SM) data for the entire state of Uttar Pradesh were accessed from GRACE and GLDAS databases. To minimize the north – south stripping errors, a destripping filter was applied to the GRACE data by the CSR (Wahr et al., 1998). To spatially smoothen the data, a Gaussian filter was also applied to GRACE and GLDAS data. (Swenson and Wahr, 2006). By subtracting the time mean TWS from

January 2004 to December 2009, the GRACE data were further normalized as per methods described in website http://grace.jpl.nasa.gov.

6.9.2 GLDAS-Derived Soil Moisture

By using Global Land Data Assimilation System datasets, surface soil moisture was estimated for each layer (0-10, 10-40, 40-100 and 100-200 cm). To obtain the total soil moisture data, all four layers were summed up. Two potential sources of mass variability that were neglected in the present study included surface water, plant biomass and snow water equivalent. The latter has not been important as study area has no snow cover (Chinnasamy et al., 2013). GLDAS gathers grids of total soil moisture every 3 h. The collected grids were averaged and a time averaged grid from January 2004 to December 2009 was subtracted from all the individual grids to normalize the data.

6.9.3 Groundwater Level Fluctuation from Monitoring Well Networks

Yearly groundwater level fluctuation data was used to compare observed (Central Ground Water Board) and estimated (GRACE/GLDAS/NOAH) groundwater fluctuation from 2005 to 2011. Groundwater data from study area with high groundwater depletion rates, was compared to GRACE/GLDAS observed groundwater storage trends across Lucknow.

6.9.4 Estimation of Change in Groundwater Storage

Monthly results of GRACE data were processed and released by the CSR (University of Texas Center for Space Research), GFZ (Geo-Forschungs Zentrum Potsdam) and the JPL (Jet Propulsion Laboratory) and can be accessed online (http://gracetellus.jpl.nasa.gov/data) (Chinnasamy et al. 2013). Processed monthly results of GLDAS was released by the NASA Goddard Space Flight Center, were downloaded online from Mirador. GRACE and GLDAS data of similar spatial and temporal resolution was carefully downloaded to enable groundwater thickness estimation using total water storage (GRACE) and soil moisture (GLDAS) data. By using GRACE-derived terrestrial water storage and GLDAS derived soil moisture, equivalent water thickness or groundwater storage were calculated as per equation (6.4) (Rodell et al., 2007)

$$\mathrm{GWS} = \mathrm{TWS} - \mathrm{SM} \tag{6.4}$$

Where,

TWS= terrestrial water storage

SM= soil moisture

GWS= groundwater storage

Subsequently, the calculated Pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November) changes in groundwater storage from 2003 to 2012 were interpolated in Arc GIS using Kernel smoothening interpolation and masked for the entire state of Uttar Pradesh. Pre-monsoon, monsoon and post-monsoon change in groundwater storage maps were generated to visualize the status of groundwater storage trend. The time-series analysis representing the trend of terrestrial water storage anomaly, soil moisture anomaly, rainfall anomaly and groundwater storage anomaly has also been done from 2003 to 2012 for the study area.

6.10 Results and Discussions

Figure 6.13(a) and (b) indicated the seasonal (pre-monsoon, monsoon and post-monsoon) normalized equivalent groundwater thickness, as per equation (6.4) after removing soil moisture and surface water components, over the entire state of Uttar Pradesh. Variations in map color represent changes in water mass in terms of total net groundwater storage. Time-series analysis was done for study area (Lucknow district) only. Time-series analysis (Figure 6.14) of GRACE/GLDAS data demonstrated that rainfall, total water storage, soil moisture did not show much variations while groundwater storage trend show a declining trend from 2003 to 2012. This suggests that the area was either using the groundwater immensely for the irrigation or the decline was due to urban development.

Thus anthropogenic activities were the main reason for the groundwater depletion in study area. The mean groundwater depletion rate of the study area was -1.46±0.74 cm/yr. The average volumetric groundwater storage loss was also calculated for the study area which was 0.37 km^3.

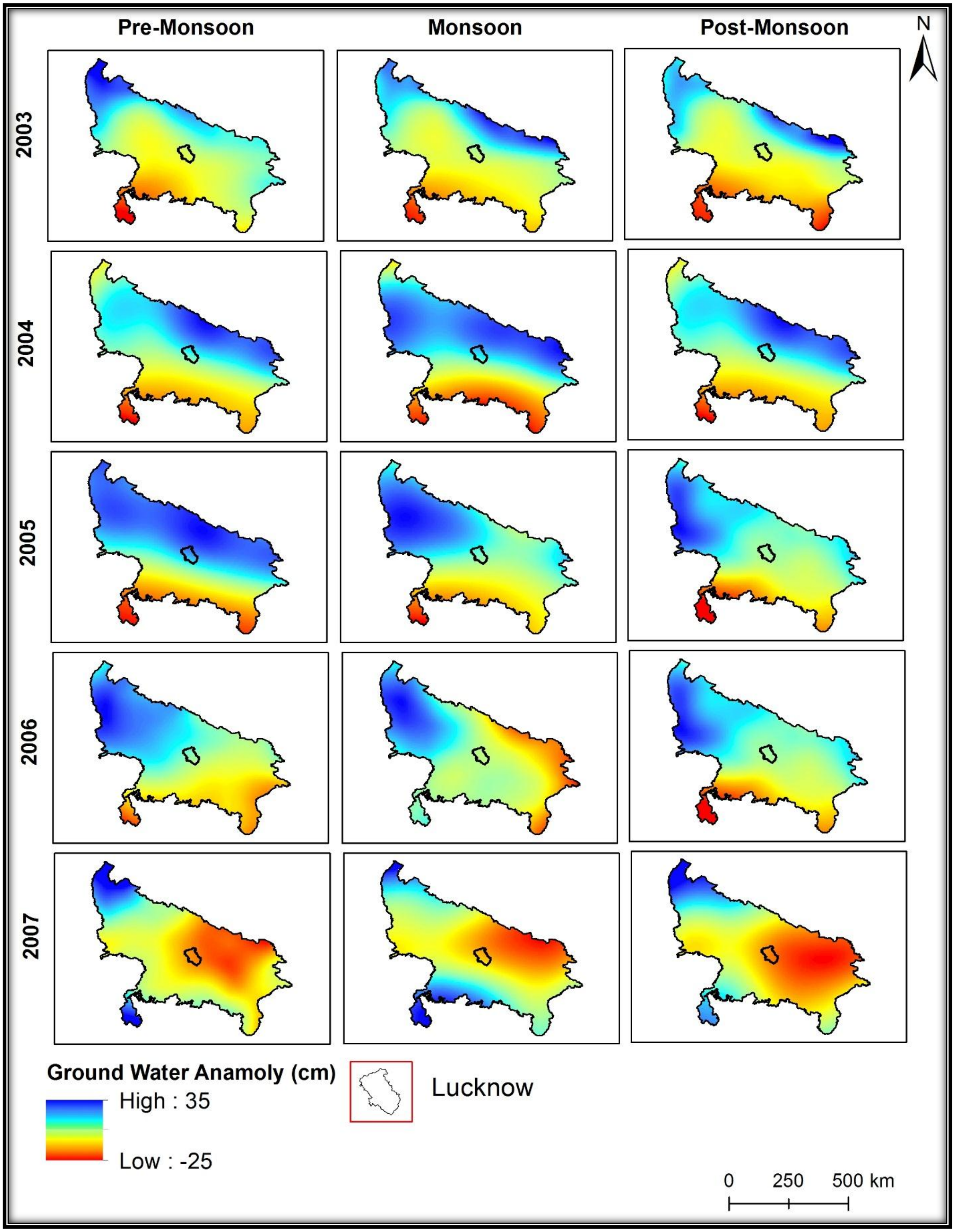


Figure 6.13(a) Yearly GRACE/GLDAS Gravity Solution for Total Groundwater Storage from 2003 to 2007 in Uttar Pradesh, India

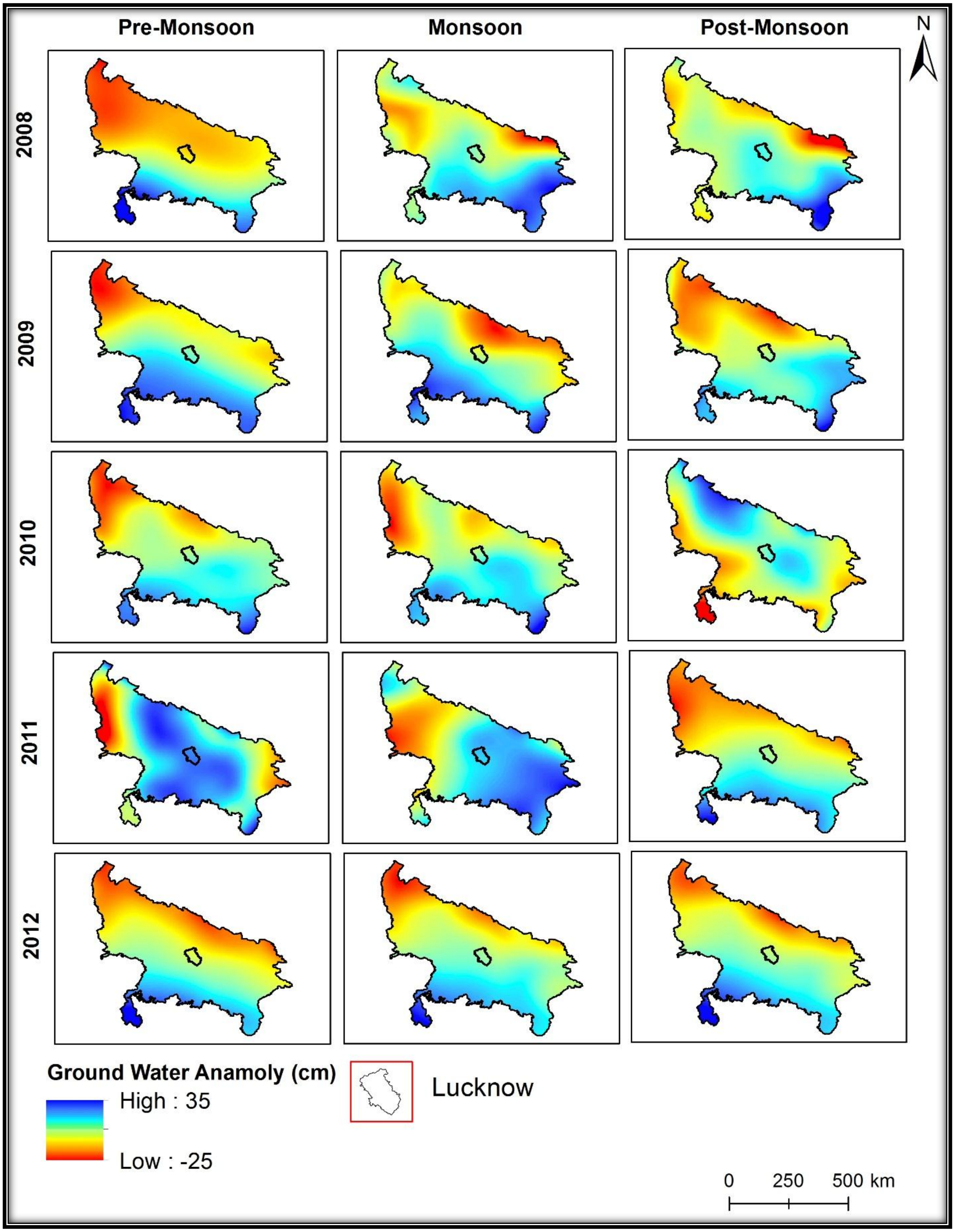


Fig 6.13(b) Yearly GRACE/GLDAS Gravity Solution for Total Groundwater Storage from 2008 to 2012 in Uttar Pradesh, India

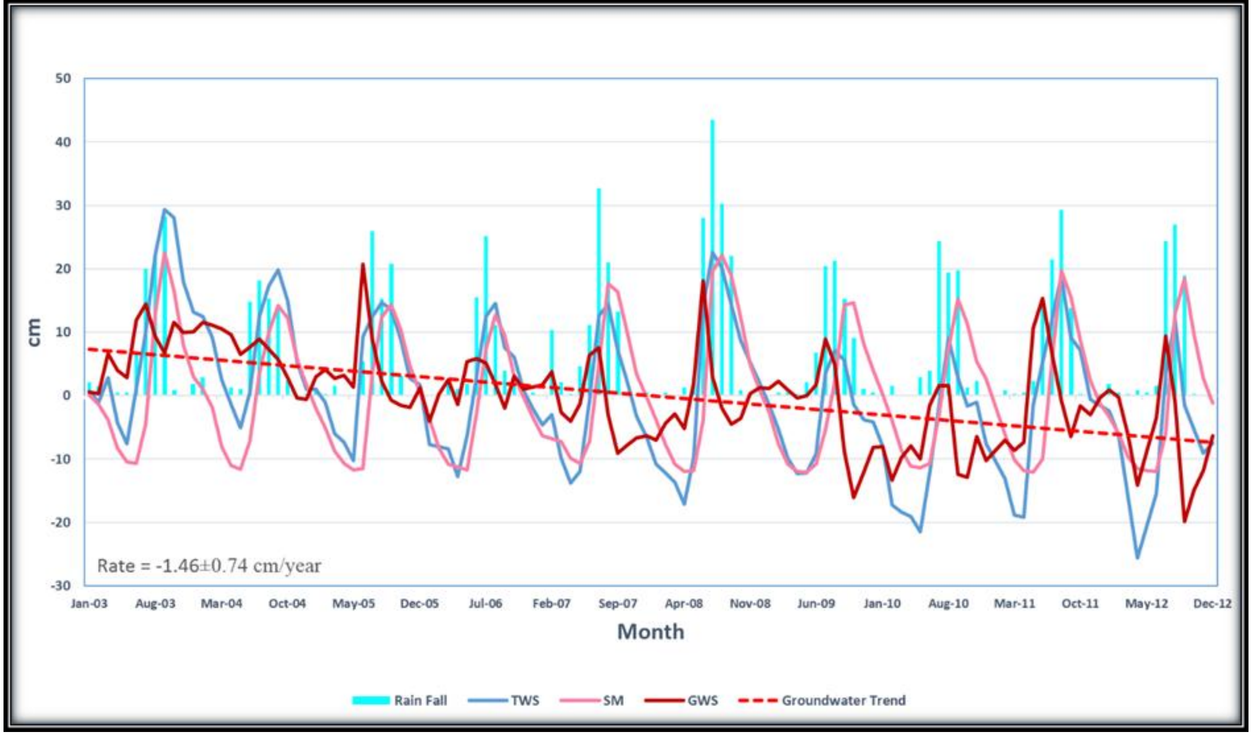


Figure 6.14 Time Series of Water Storage Anomalies in Study Area from 2003-2012

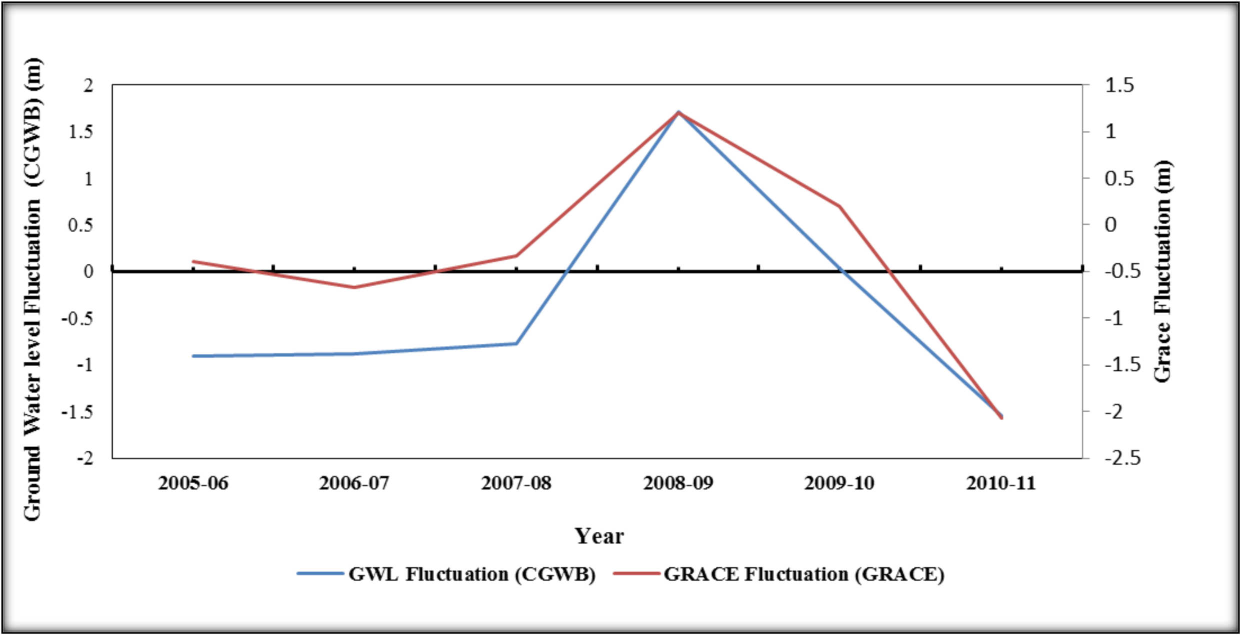


Figure 6.15(a) Comparison between Pre-Monsoon GRACE/GLDAS Derived Groundwater Fluctuation and Observed Groundwater Level Fluctuation at Lucknow District in Uttar Pradesh from 2005 to 2011

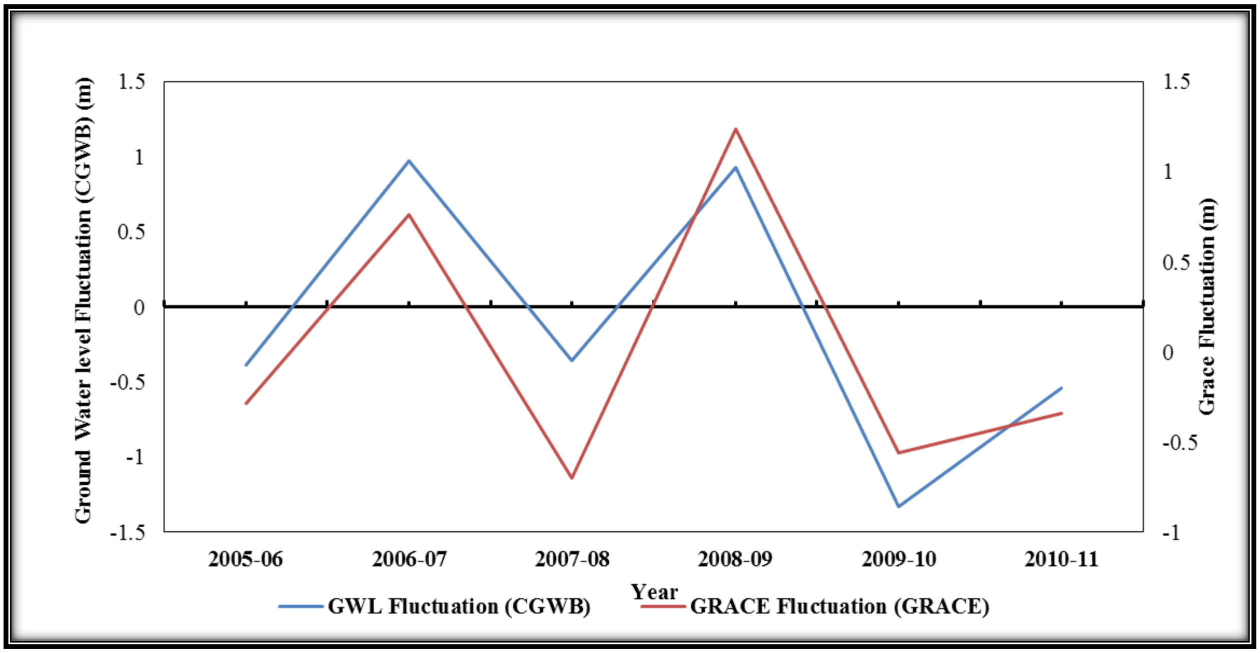


Figure 6.15(b) Comparison between Post-Monsoon GRACE/GLDAS Derived Groundwater Fluctuation and Observed Groundwater Level Fluctuation at Lucknow District in Uttar Pradesh from 2005 to 2011

6.11 Validation of Results

The validation of the GRACE/GLDAS derived results was done only for the study area (Lucknow). Figure 6.15(a) and (b) reveal that the GRACE/GLDAS-derived groundwater storage fluctuation estimated closely tracked the trend observed in the groundwater monitoring wells. A positive trend indicated a favorable comparison between GRACE/GLDAS data and observed well data. A subsequent regression analysis between GRACE/GLDAS-derived groundwater storage fluctuation and observed groundwater level fluctuation, yielded a coefficient of determination (r^2) value of 0.89 for pre-monsoon and 0.77 for post-monsoon season. Therefore, GRACE/GLDAS can be a cost-effective alternative method to estimate groundwater depletion rates.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Systematic studies were carried out in the present research work to develop a suitable method for the assessment of groundwater vulnerability to pollution of the alluvial aquifers of the Ganga-Gomti interfluve area. The method was developed by using a multipurpose database in GIS environment, and by validating the generated vulnerability method by comparing the findings with the observed water quality characteristics of the region. Evaluation of depleting groundwater resources of the Uttar Pradesh was carried out using GRACE/GLDAS data. The validation of trend in groundwater storage was done with water level data of CGWB.

Chemical analysis of shallow and deep groundwater samples of Lucknow urban area of pre-monsoon and post-monsoon seasons showed that ionic concentrations were found well within permissible limit except nitrate (NO_3^-) which showed higher concentration. Groundwater quality of the study area did not show much variation between pre-monsoon and post-monsoon period. Groundwater samples were found suitable for drinking purpose. Nitrate contamination was high in the urban area. This contamination was most likely due to the lack of proper sewage system and use of fertilizers in the area.

Concentration of trace elements such as iron (Fe), and mercury (Hg) were in an alarming state with respect to the use of groundwater for drinking purposes as compared to BIS, 2012. Arsenic (As) concentration varied from 0.02 to 0.06 ppm and 4 samples showed higher concentration than the permissible limit of 0.05 ppm. The concentration of iron (Fe) and mercury (Hg) varied from 2.53 to 21.97 mg/l and from 0.02 to 0.97 mg/l respectively which exceeded the permissible limit. In the study area, mercury contamination occurred due to disposal of tube-lights, incineration of wastes which showed the anthropogenic impact.

The assessment of groundwater vulnerability was studied using two approaches: conventional DRASTIC method and a modified DRASTIC or DRASTICA method. For conventional DRASTIC modelling of groundwater vulnerability in the study area, all of the seven DRASTIC parameters were evaluated in ArcGIS environment. The ratings percentages were subsequently added to get the total cell rating. The DRASTIC index in the study area varied from 140 to199. The Gosaiganj block and Sarojini Nagar block showed higher vulnerability

The outcomes of the conventional DRASTIC model did not represent the real scenario of groundwater vulnerability as nitrate contamination was very high in urban areas of the district while original DRASTIC results represented the urban area as low vulnerable zone. The DRASTIC model although widely used to evaluate the groundwater vulnerability, cannot be applied in an urbanized environment straightaway as it does not consider the anthropogenic influence as a part of the model parameters. The parameter named ‘anthropogenic influence’ by using the satellite observations of nightlights from human settlements and land-use/land-cover (LULC) surrounding the urbanized area as proxy was not integrated in the DRASTIC model till now. A new modified DRASTIC model – DRASTICA model was applied to overcome this limitation, where ‘A’ refers to a new parameter called ‘impact of anthropogenic activities.’

The DRASTICA risk map indicated that about 0.71% area fall under very high vulnerable zone, 24.51% area under high vulnerable zone, 66.64% area under moderately vulnerable zone and 8.29% area under low vulnerable zone. The results were validated using nitrate concentration in groundwater. It was shown that the proposed DRASTICA model performs better than traditional DRASTIC model in any urbanized environment. Sensitivity analysis indicated that anthropogenic impact (A) and depth to water table (D) largely influenced the groundwater vulnerability to pollution, thereby signifying that anthropogenic influence has to be addressed precisely in such studies. The DRASTICA model proposed in this study will help in better categorization of groundwater vulnerable zones to pollution where anthropogenic contaminations are high, particularly in and around urban centers of Indo-Gangetic Plains like Kanpur, Unnao, Varanasi, Mathura, Agra, Aligarh and Allahabad etc.

The assessment of groundwater quantity was done using GRACE/GLDAS data. For this purpose terrestrial water storage (GRACE) and soil moisture data (GLDAS) were used. To visualize the seasonal changes in groundwater storage of Uttar Pradesh from 2003 to 2012, pre-monsoon, monsoon and post-monsoon maps were generated which represented the overall decreasing trend from 2003 to 2012. Time series analysis of Lucknow district indicated declining trend of groundwater while other parameters like soil moisture, rainfall, terrestrial water storage were not showing continuously declining trend with respect to groundwater. This indicated that groundwater extraction was faster than recharge. The mean groundwater depletion rate was -1.46±0.74 cm/yr. The average volumetric groundwater storage loss was also calculated for the Lucknow district which was 0.37 km^3.

GRACE derived groundwater fluctuation was validated with groundwater fluctuation estimated from the water level data of Central Ground Water Board for Lucknow area only for pre-monsoon and post-monsoon season. The results were favorably validated. A positive correlation was found between GRACE derived results and observed water level data of Central Ground Water Board.

Grace derived results showed that remote sensing is an effective tool to compliment and interpolate observed regional groundwater well data and improve groundwater storage estimations. The present study shows that GRACE/GLDAS data is relatively cost-effective, high-frequency, and regional scale groundwater assessment tool.

Limitations of the Study

- The boreholes and piezometers yielding lithology were not found to be as evenly distributed across the study area. The even distribution of lithological information would have helped in better deciphering of the lithological layers. In the alluvial areas, variation in lithological characters are large. The uncertainty introduced due to unevenly distributed data, would have resulted in uncertainty in the computation of DRASTIC and DRASTICA Indices.
- Hydraulic conductivity of the aquifer is an important parameter of DRASTIC model. The movement or accumulation of pollutant in the aquifer depends upon the hydraulic conductivity of the aquifer. The variation in hydraulic conductivity of the unconfined aquifer would have provide better insight into the DRASTIC and DRASTICA indices variability within the study area and its validation with the observed water quality.
- Data of pollution loading from different land use types were not available. DRASTIC index gives the relative intrinsic vulnerability of the media. The method is more suited for the uniform pollution loading. But in the urban areas, the pollution loading vary considerably from low pollution to high pollution loading areas. The groundwater pollution is more in the areas where pollution loading is high rather than the areas where the pollution loading is low, although the DRASTIC index may give opposite vulnerability.
- Historical water level data for the same well and for the same time period for the validation of GRACE derived results was not available. More data will give more positive result for the validation.

Scope for Future Work

Without understanding of the hydrogeological condition and groundwater balance, groundwater vulnerability cannot be estimated, it would be advisable to extend the present study by increasing number of monitoring wells. Additional wells to meet the water demand may preferably be located in shallow water table areas since such areas are at higher risk for contamination, and also in those areas where the temporal trend in water table is steady over the time. Further, the well spacing should be based on 'safe distance' criteria which can be estimated based on aquifer parameters. As the present study concluded that groundwater is declining at a rapid rate, this may result in land subsidence like phenomenon. Hence, it would also be advisable to carry out land subsidence related studies in the study area. The land subsidence caused by aquifer layer compression caused due to ground water withdrawal has been observed using DInSAR technique in many parts of the world like Segura River, SE Spain (Tomás et al., 2005), Antelope Valley, Mojave Desert, California (Galloway et al., 1998), Las Vegas, Nevada, USA (Amelung et al., 1999), New Jersey, USA (Sun, Grandstaff, and Shagam, 1999), including NCT Delhi, India (Sharma et al. 2014), Kolkata city, India (Chatterjee et al., 2006). Amongst various geodetic techniques to measure land subsidence, Differential Interferometry Synthetic Aperture Radar (DInSAR) is a very important remote sensing tool used for estimation of temporal and spatial surface motions due to subsidence (Berardino et al. 2002). One of the main advantages of DInSAR is its high spatial coverage in urban areas.

This may help in the better understanding of the groundwater resources and in disaster monitoring and management.

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Appendix I

Physico-chemical Parameters and Major Ion Composition of the Pre-Monsoon Groundwater Samples

Sample location	**Latitude**	**Longitude**	**PH**	**E.C. (μS/cm)**	**Concentration (mol/l)**								
					Na	**K**	**Ca**	**Mg**	**Cl**	**SO_4**	**HCO_3**	**F**	**NO_3**
HP-L.U.OLD CAMPUS	26^0 51' 10.9"	80^{0}56' 4.3"	8.35	872	2.6	0.1	3.5	5.3	1.4	1.5	8.0	0.0	0.8
HP-ALIGANJ	26^0 54' 1.8"	80^{0}56' 14.3"	8.18	521	1.0	0.1	3.8	3.0	0.3	0.5	6.6	0.0	0.9
HP-INDIRA NAGAR	26^0 52' 11.1"	80^{0}58' 8.4"	8.44	650	1.0	0.2	6.1	2.8	2.1	1.0	5.2	0.0	1.9
HP-MAHANAGAR	26^0 52' 13.6"	80^{0}57' 8.6"	8.62	747	3.8	0.1	4.5	2.9	2.2	0.9	6.9	0.0	1.9
HP-SAROJINI NAGAR	26^0 45' 3.4"	80^{0}52' 12.5"	8.17	482	2.3	0.2	2.5	2.4	0.6	0.2	6.2	0.0	0.3
HP-KAISERBAGH	26^0 51' 3.6"	80^{0}55' 14.3"	8.46	897	5.8	0.3	3.4	3.4	3.1	1.3	6.4	0.1	2.3
HP-NISHATGANJ	26^0 51' 14.4"	80^{0}57' 5.4"	8.06	568	2.4	0.2	2.9	2.6	0.6	0.4	5.8	0.0	1.4
HP-CHARBAGH	26^0 49' 11.2"	80^{0}55' 5.6"	8.16	956	4.9	0.3	4.5	3.9	3.6	1.5	7.5	0.1	0.9
HP-GOMTI NAGAR	26^0 51' 13.6"	80^{0}0' 4.4"	8.84	827	3.5	0.2	1.6	5.5	1.2	1.3	7.4	0.0	0.9
HP-KRISHNA NAGAR	26^0 47' 13.2"	80^{0}53' 4.7"	8.24	882	4.0	0.3	2.2	6.0	1.5	0.7	9.3	0.1	0.6
HP-HAZRATGANJ	26^0 50' 14.0"	80^{0}56' 12.2"	8.2	1239	6.8	0.3	3.7	7.6	4.6	2.9	7.8	0.0	2.8
HP-AMINABAD	26^0 50' 12.9"	80^{0}56' 11.3"	8.24	842	4.6	0.5	1.9	3.5	1.6	1.0	6.9	0.1	0.8
HP-ALAMBAGH	26^0 48' 13.5"	80^{0}54' 3.3"	7.91	1345	8.9	0.4	1.1	5.5	5.2	1.2	8.7	0.0	1.3
HP-CANTT.	26^0 49' 12.8"	80^{0}58' 0.9"	8.85	758	3.6	0.4	1.1	4.2	0.1	0.3	9.0	0.0	0.3
HP-JANKIPURAM	26^0 54' 11.9"	80^{0}56' 11.3"	8.23	619	1.5	0.2	3.7	4.0	0.7	1.3	6.2	0.0	0.9
HP-RSAC	26^0 54' 14.6"	80^{0}57' 11.1"	8.22	671	2.2	0.1	4.5	2.7	0.5	0.5	7.8	0.0	0.3
HP-KHADRA	26^0 52' 11.1"	80^{0}55' 3.8"	8.61	1147	6.0	0.3	4.0	3.8	4.7	1.0	7.2	0.0	1.3
HP-TRIVENI NAGAR	26^0 52' 15.3"	80^{0}55' 3.8"	8.47	1184	5.0	0.4	6.2	5.3	4.0	2.8	7.6	0.0	2.3
HP-MAWAIYYA	26^0 49' 15.4"	80^{0}54' 3.3"	8.35	1066	5.3	0.3	2.9	5.1	3.7	1.1	7.2	0.0	1.1
HP-AISHBAGH	26^0 50' 2.8"	80^{0}54' 7.3"	8.36	983	4.8	0.3	3.9	4.6	2.4	1.2	7.9	0.1	1.3
HP-RAJAJIPURAM	26^0 50' 4.5"	80^{0}53' 7.7"	8.32	1163	4.4	0.3	4.9	4.6	3.2	1.8	7.8	0.0	0.6

HP-BADA IMAMBARA	26^0 52' 4.3"	$80^0$54' 13.6"	8.8	812	4.1	0.2	2.6	3.8	1.5	1.6	7.2	0.1	0.8
HP-TRANSPORT NAGAR	26^0 46' 11.1"	$80^0$53' 4.7"	8.8	716	2.2	0.2	2.7	4.1	0.4	0.3	8.0	0.0	0.2
HP-BARA BIRWA	26^0 47' 15.9"	$80^0$53' 10.8"	8.19	789	3.5	0.4	1.1	3.8	1.2	0.1	7.6	0.1	0.2
HP-AMBEDKAR MAIDAN	26^0 48' 2.2"	$80^0$55' 6.5"	8.25	692	3.2	0.3	1.3	5.2	0.5	0.7	7.4	0.0	0.5
HP-PGI	26^0 44' 14.3'	$80^0$52' 12.5"	8.16	536	0.6	0.2	2.8	5.0	0.0	0.7	7.1	0.0	0.3
HP-NAKA	26^0 50' 3.8"	$80^0$55' 4.4"	8.5	706	2.8	0.3	2.3	3.3	1.2	0.7	6.0	0.0	0.8
TW-L.U.OLD CAMPUS	26^0 51' 13.5"	$80^0$57' 6.2"	8.74	732	2.9	0.2	2.8	4.7	0.7	0.7	8.3	0.0	1.0
TW-ALIGANJ	26^0 53' 9.3"	$80^0$57' 6.2"	8.28	810	3.6	0.4	3.3	5.3	1.4	2.4	7.9	0.0	0.8
TW-INDIRA NAGAR	26^0 50' 3.8"	$80^0$55' 4.4"	8.2	718	1.9	0.2	3.1	4.7	0.8	0.9	6.9	0.0	1.6
TW-MAHANAGAR	26^0 52' 11.7"	$80^0$57' 5.1"	8.51	968	4.0	0.3	5.0	3.3	1.4	2.5	7.7	0.0	1.1
TW-SAROJINI NAGAR	26^0 44' 14.7"	$80^0$51' 7.9"	8.34	686	3.5	0.2	1.0	2.8	0.7	0.5	6.0	0.0	0.5
TW-KAISERBAGH	26^0 51' 4.2"	$80^0$55' 13.2"	8.35	1328	6.8	0.4	2.9	3.0	3.4	1.3	6.3	0.0	2.4
TW-NISHATGANJ	26^0 52' 4.8"	$80^0$57' 7.6"	8.41	1399	6.6	0.3	6.1	3.4	3.8	3.2	8.0	0.0	1.5
TW-CHARBAGH	26^0 49' 6.1"	$80^0$55' 6.2"	8.29	811	3.5	0.2	2.9	3.3	0.9	0.4	7.7	0.0	1.1
TW-GOMTI NAGAR	26^0 51' 1.3"	$80^0$58' 15.2"	8.43	672	4.3	0.2	1.9	3.3	1.7	1.3	5.8	0.1	0.7
TW-KRISHNA NAGAR	26^0 47' 13.4"	$80^0$53' 4.7"	8.2	733	3.0	0.2	2.2	5.7	0.4	0.3	9.3	0.0	0.3
TW-HAZRATGANJ	26^0 50' 16.4"	$80^0$56' 12.1"	8.2	1170	8.7	0.4	2.5	4.9	3.9	2.7	7.9	0.0	1.9
TW-AMINABAD	26^0 50' 13.8"	$80^0$55' 10.8"	8.42	917	8.2	0.2	1.2	1.9	1.9	1.7	7.6	0.1	0.8
TW-ALAMBAGH	26^0 50' 3.8"	$80^0$54' 4.3"	8	901	4.5	0.2	1.7	4.9	1.6	0.5	8.1	0.0	1.2
TW-CANTT.	26^0 49' 5.6"	$80^0$56' 15.9"	8.71	975	7.9	0.3	2.7	3.4	5.2	1.3	7.1	0.1	0.3
TW-LALBAGH	26^0 50' 13.7"	$80^0$56' 5.7"	8.62	1100	5.6	0.4	3.5	5.3	2.5	2.7	8.8	0.0	1.2

*HP=Hand-Pump, TW=Tube-Well, E.C. =Electrical Conductivity

Physico-chemical Parameters and Major Ion Composition of the Post-monsoon Groundwater Samples

Sample location	Latitude	Longitude	PH	E.C. (μS/cm)	Concentration (mol/l)								
					Na	K	Ca	Mg	Cl	SO_4	HCO_3	F	NO_3
HP-L.U.OLD CAMPUS	26^0 51' 10.9"	$80^0$56' 4.3"	7.6	844	2.56	0.22	3.42	5.02	1.4	1.5	7.80	0.03	0.75
HP-ALIGANJ	26^0 54' 1.8"	$80^0$56' 14.3"	7.5	523	0.90	0.11	3.74	2.70	0.3	0.5	6.23	0.02	0.79
HP-INDIRA NAGAR	26^0 52' 11.1"	$80^0$58' 8.4"	7.6	644	0.95	0.19	5.98	2.15	2.1	1.0	4.92	0.03	1.86
HP-MAHANAGAR	26^0 52' 13.6"	$80^0$57' 8.6"	7.6	738	3.43	0.10	4.42	2.89	2.2	0.9	6.73	0.02	1.91
HP-SAROJINI NAGAR	26^0 45' 3.4"	$80^0$52' 12.5"	7.5	495	2.18	0.18	2.46	2.30	0.6	0.2	6.15	0.03	0.20
HP-KAISERBAGH	26^0 51' 3.6"	$80^0$55' 14.3"	7.4	900	5.77	0.27	3.30	3.18	3.1	1.3	6.32	0.04	2.18
HP-NISHATGANJ	26^0 51' 14.4"	$80^0$57' 5.4"	7.5	564	2.41	0.15	2.82	2.52	0.6	0.4	5.74	0.02	1.29
HP-CHARBAGH	26^0 49' 11.2"	$80^0$55' 5.6"	7.3	961	4.85	0.27	4.41	3.49	3.6	1.5	7.31	0.05	0.85
HP-GOMTI NAGAR	26^0 51' 13.6"	$80^0$0' 4.4"	7.3	786	3.44	0.22	1.51	5.03	1.2	1.3	7.30	0.02	0.85
HP-KRISHNA NAGAR	26^0 47' 13.2"	$80^0$53' 4.7"	7.2	892	3.83	0.24	2.03	5.23	1.5	0.7	9.02	0.05	0.54
HP-HAZRATGANJ	26^0 50' 14.0"	$80^0$56' 12.2"	7.4	1350	6.73	0.32	2.71	7.22	4.6	2.9	7.51	0.03	2.75
HP-AMINABAD	26^0 50' 12.9"	$80^0$56' 11.3"	7.3	832	4.45	0.42	1.79	3.38	1.6	1.0	6.81	0.05	0.74
HP-ALAMBAGH	26^0 48' 13.5"	$80^0$54' 3.3"	7.1	1374	8.77	0.28	1.01	5.07	5.2	1.2	8.21	0.02	1.27
HP-CANTT.	26^0 49' 12.8"	$80^0$58' 0.9"	7.6	751	3.47	0.34	1.09	4.13	0.1	0.3	8.93	0.05	0.30
HP-JANKIPURAM	26^0 54' 11.9"	$80^0$56' 11.3"	7.3	640	1.32	0.16	3.19	3.82	0.7	1.3	6.07	0.01	0.87
HP-RSAC	26^0 54' 14.6"	$80^0$57' 11.1"	7.2	616	2.15	0.17	4.25	2.52	0.5	0.5	7.80	0.04	0.21
HP-KHADRA	26^0 52' 11.1"	$80^0$55' 3.8"	7.6	1183	5.62	0.30	3.85	3.10	4.7	1.0	6.95	0.03	1.21
HP-TRIVENI NAGAR	26^0 52' 15.3"	$80^0$55' 3.8"	7.3	1255	4.90	0.35	5.87	5.12	4.0	2.8	6.75	0.04	2.23
HP-MAWAIYYA	26^0 49' 15.4"	$80^0$54' 3.3"	7.2	1101	5.09	0.27	2.67	4.91	3.7	1.1	6.95	0.02	1.11
HP-AISHBAGH	26^0 50' 2.8"	$80^0$54' 7.3"	7.3	982	4.72	0.24	3.79	4.48	2.4	1.2	7.80	0.05	1.26
HP-RAJAJIPURAM	26^0 50' 4.5"	$80^0$53' 7.7"	7.1	1129	4.33	0.28	4.52	4.12	3.2	1.8	7.71	0.02	0.53
HP-BADA IMAMBARA	26^0 52' 4.3"	$80^0$54' 13.6"	7.4	736	4.03	0.19	2.43	3.65	1.5	1.6	6.89	0.06	0.75

HP-TRANSPORT NAGAR	26^0 46' 11.1"	$80^0$53' 4.7"	7.5	715	2.10	0.19	2.62	3.85	0.4	0.3	7.71	0.03	0.20
HP-BARA BIRWA	26^0 47' 15.9"	$80^0$53' 10.8"	7.5	810	3.35	0.32	1.09	3.67	1.2	0.1	7.22	0.05	0.12
HP-AMBEDKAR MAIDAN	26^0 48' 2.2"	$80^0$55' 6.5"	7.3	618	3.08	0.25	1.09	5.04	0.5	0.7	7.30	0.03	0.46
HP-PGI	26^0 44' 14.3'	$80^0$52' 12.5"	7.4	525	0.60	0.22	2.43	4.66	0.0	0.7	6.86	0.02	0.25
HP-NAKA	26^0 50' 3.8"	$80^0$55' 4.4"	7.4	671	2.66	0.33	2.21	3.16	1.2	0.7	5.94	0.02	0.78
TW-L.U.OLD CAMPUS	26^0 51' 13.5"	$80^0$57' 6.2"	7.8	730	2.73	0.21	2.64	4.37	0.7	0.7	8.17	0.03	0.82
TW-ALIGANJ	26^0 53' 9.3"	$80^0$57' 6.2"	7.5	847	3.48	0.37	2.67	5.12	1.4	2.4	7.81	0.02	0.74
TW-INDIRA NAGAR	26^0 50' 3.8"	$80^0$55' 4.4"	7.3	706	1.85	0.20	2.99	4.34	0.8	0.9	6.75	0.01	1.30
TW-MAHANAGAR	26^0 52' 11.7"	$80^0$57' 5.1"	7.9	931	3.71	0.25	4.93	4.18	1.4	2.5	7.68	0.06	1.10
TW-SAROJINI NAGAR	26^0 44' 14.7"	$80^0$51' 7.9"	7.6	701	3.19	0.19	0.93	2.71	0.7	0.5	5.38	0.03	0.46
TW-KAISERBAGH	26^0 51' 4.2"	$80^0$55' 13.2"	7.4	1303	6.56	0.32	2.64	2.72	3.4	1.3	5.70	0.03	2.01
TW-NISHATGANJ	26^0 52' 4.8"	$80^0$57' 7.6"	7.3	1101	6.13	0.33	5.10	2.64	3.8	3.2	6.89	0.02	1.43
TW-CHARBAGH	26^0 49' 6.1"	$80^0$55' 6.2"	7.5	803	3.36	0.24	2.70	3.10	0.9	0.4	7.58	0.03	1.05
TW-GOMTI NAGAR	26^0 51' 1.3"	$80^0$58' 15.2"	7.5	682	4.13	0.21	1.57	3.21	1.7	1.3	6.10	0.04	0.68
TW-KRISHNA NAGAR	26^0 47' 13.4"	$80^0$53' 4.7"	7.3	695	2.64	0.17	2.06	5.46	0.4	0.3	9.18	0.03	0.25
TW-HAZRATGANJ	26^0 50' 16.4"	$80^0$56' 12.1"	7.2	1179	8.28	0.36	2.35	4.40	3.9	2.7	7.70	0.04	1.78
TW-AMINABAD	26^0 50' 13.8"	$80^0$55' 10.8"	7.5	936	7.93	0.18	1.08	1.85	1.9	1.7	7.15	0.06	0.73
TW-ALAMBAGH	26^0 50' 3.8"	$80^0$54' 4.3"	7.3	883	4.37	0.20	1.53	4.86	1.6	0.5	8.04	0.02	1.14
TW-CANTT.	26^0 49' 5.6"	$80^0$56' 15.9"	8.2	1055	7.67	0.29	2.57	3.21	5.2	1.3	7.64	0.05	0.24
TW-LALBAGH	26^0 50' 13.7"	$80^0$56' 5.7"	7.6	1179	5.47	0.33	3.39	5.17	2.5	2.7	8.70	0.04	1.14

*HP=Hand-Pump, TW=Tube-Well, E.C. =Electrical Conductivity

Appendix II

Trace Elements Concentration of Pre-Monsoon Groundwater Samples

Location	Type of Sample	Latitude	Longitude	Trace Elements Concentration (µg/l)							
				As	Cr	Fe	Hg	K	Mn	V	Zn
SAROJINI NAGAR	HAND PUMP	26^0 45' 3.4"	$80^0$52' 12.5"	0.01	0.04	9.31	0.08	1.60	0.07	0.03	0.18
SAROJINI NAGAR	TUBE WELL	26^0 44' 14.7"	$80^0$51' 7.9"	0.01	0.04	8.78	0.07	1.95	0.00	0.07	0.03
KAISERBAGH	HAND PUMP	26^0 51' 4.2"	$80^0$55' 13.2"	0.00	0.03	6.10	0.06	2.35	0.07	0.12	0.09
KAISERBAGH	TUBE WELL	26^0 51' 4.2"	$80^0$55' 13.2"	0.06	0.04	17.93	0.06	2.49	0.23	0.30	0.07
HAZRATGANJ	HAND PUMP	26^0 50' 14.0"	$80^0$56' 12.2"	0.03	0.02	14.79	0.05	1.83	0.20	0.22	2.03
HAZRATGANJ	TUBE WELL	26^0 50' 16.4"	$80^0$56' 12.1"	0.02	0.03	15.10	0.03	2.34	0.07	0.25	0.46
KRISHNA NAGAR	HAND PUMP	26^0 47' 13.2"	$80^0$53' 4.7"	0.02	0.02	12.26	0.04	1.64	0.16	0.13	0.09
KRISHNA NAGAR	TUBE WELL	26^0 47' 13.4"	$80^0$53' 4.7"	0.01	0.03	11.01	0.03	1.45	0.12	0.07	0.11
ALIGANJ	HAND PUMP	26^0 54' 1.8"	$80^0$56' 14.3"	0.00	0.02	12.24	0.03	2.10	0.15	0.04	0.19
ALIGANJ	TUBE WELL	26^0 53' 9.3"	$80^0$57' 6.2"	0.02	0.02	17.45	0.02	1.96	0.09	0.11	0.10
ALAMBAGH	HAND PUMP	26^0 48' 13.5"	$80^0$54' 3.3"	0.06	0.08	21.97	0.10	2.49	0.27	0.34	0.08
ALAMBAGH	TUBE WELL	26^0 50' 3.8"	$80^0$54' 4.3"	0.03	0.09	14.57	0.07	1.94	0.03	0.16	0.03
LU OLD CAMPUS	HAND PUMP	26^0 51' 10.9"	$80^0$56' 4.3"	0.01	0.04	10.47	0.06	1.45	0.07	0.14	0.05
LU OLD CAMPUS	TUBE WELL	26^0 51' 13.5"	$80^0$57' 6.2"	0.00	0.02	9.52	0.06	1.41	0.06	0.09	0.08
GOMTI NAGAR	HAND PUMP	26^0 51' 13.6"	$80^0$0' 4.4"	0.01	0.03	9.36	0.06	1.45	0.14	0.08	1.13
GOMTI NAGAR	TUBE WELL	26^0 51' 1.3"	$80^0$58' 15."	0.02	0.02	8.12	0.05	1.08	0.14	0.09	0.19
MAHANAGAR	HAND PUMP	26^0 52' 13.6"	$80^0$57' 8.6"	0.01	0.05	6.37	0.08	1.22	0.10	0.14	0.26
MAHANAGAR	TUBE WELL	26^0 52' 11.7"	$80^0$57' 5.1"	0.01	0.04	6.20	0.05	1.09	0.00	0.13	0.06

Trace Elements Concentration of Post-Monsoon Groundwater Samples

Location	Type of Sample	Latitude	Longitude	Trace Elements Concentration (µg/l)							
				As	**Cr**	**Fe**	**Hg**	**K**	**Mn**	**V**	**Zn**
SAROJINI NAGAR	HAND PUMP	26^{0} 45' 3.4"	80^{0}52' 12.5"	0.00	0.03	9.40	0.09	1.69	0.05	0.03	0.12
SAROJINI NAGAR	TUBE WELL	26^{0} 44' 14.7"	80^{0}51' 7.9"	0.01	0.03	12.56	0.08	2.09	0.01	0.07	0.34
KAISERBAGH	HAND PUMP	26^{0} 51' 4.2"	80^{0}55' 13.2"	0.01	0.03	14.84	0.06	2.20	0.19	0.13	0.92
KAISERBAGH	TUBE WELL	26^{0} 51' 4.2"	80^{0}55' 13.2"	0.04	0.03	15.64	0.05	1.96	0.17	0.24	0.29
HAZRATGANJ	HAND PUMP	26^{0} 50' 14.0"	80^{0}56' 12.2"	0.04	0.03	18.41	0.06	2.81	0.03	0.28	0.57
HAZRATGANJ	TUBE WELL	26^{0} 50' 16.4"	80^{0}56' 12.1"	0.01	0.03	14.17	0.05	2.18	0.03	0.23	0.16
KRISHNA NAGAR	HAND PUMP	26^{0} 47' 13.2"	80^{0}53' 4.7"	0.01	0.02	12.69	0.03	1.64	0.22	0.10	0.19
KRISHNA NAGAR	TUBE WELL	26^{0} 47' 13.4"	80^{0}53' 4.7"	0.01	0.03	11.57	0.03	1.39	0.15	0.06	0.19
ALIGANJ	HAND PUMP	26^{0} 54' 1.8"	80^{0}56' 14.3"	0.01	0.02	11.83	0.03	1.87	0.14	0.05	0.12
ALIGANJ	TUBE WELL	26^{0} 53' 9.3"	80^{0}57' 6.2"	0.01	0.04	14.02	0.10	1.90	0.10	0.14	0.12
ALAMBAGH	HAND PUMP	26^{0} 48' 13.5"	80^{0}54' 3.3"	0.04	0.05	19.97	0.09	2.42	0.25	0.30	0.29
ALAMBAGH	TUBE WELL	26^{0} 50' 3.8"	80^{0}54' 4.3"	0.01	0.02	16.36	0.05	2.11	0.05	0.15	0.06
LU OLD CAMPUS	HAND PUMP	26^{0} 51' 10.9"	80^{0}56' 4.3"	0.01	0.03	12.55	0.19	1.53	0.09	0.14	0.54
LU OLD CAMPUS	TUBE WELL	26^{0} 51' 13.5"	80^{0}57' 6.2"	0.01	0.02	9.43	0.97	1.36	0.03	0.10	0.05
GOMTI NAGAR	HAND PUMP	26^{0} 51' 13.6"	80^{0}0' 4.4"	0.00	0.06	12.07	0.07	1.74	0.19	0.09	2.28
GOMTI NAGAR	TUBE WELL	26^{0} 51' 1.3"	80^{0}58' 15.2"	0.01	0.02	8.92	0.11	1.12	0.14	0.09	0.24
MAHANAGAR	HAND PUMP	26^{0} 52' 13.6"	80^{0}57' 8.6"	0.00	0.03	2.53	0.03	0.29	0.02	0.04	0.22
MAHANAGAR	TUBE WELL	26^{0} 52' 11.7"	80^{0}57' 5.1"	0.01	0.02	6.83	0.09	1.08	0.04	0.10	0.12

Appendix III

Table 5.5 Chemical Indices Derived from Chemical Parameters for Irrigation and Industrial Purpose

Sample location	Irrigation Use										Industrial Use	
	P.I. PRM	P.I. PSM	RSC PRM	RSC PSM	Na% PRM	Na% PSM	SAR PRM	SAR PSM	M.H. PRM	M.H. PSM	C.R. PRM	C.R. PSM
HP-L.U.OLD CAMPUS	47.4	48.7	-0.9	-0.6	23.5	24.8	1.2	1.2	59.9	59.5	0.3	0.3
HP-ALIGANJ	45.5	46.3	-0.2	-0.2	13.9	13.6	0.5	0.5	43.6	42.0	0.1	0.1
HP-INDIRA NAGAR	33.1	34.9	-3.7	-3.2	11.8	12.3	0.5	0.5	31.5	26.5	0.5	0.5
HP-MAHANAGAR	57.5	56.1	-0.5	-0.6	34.8	32.6	2.0	1.8	39.4	39.6	0.4	0.3
HP-SAROJINI NAGAR	66.2	67.2	1.3	1.4	33.4	33.1	1.4	1.4	48.6	48.3	0.1	0.1
HP-KAISERBAGH	66.4	67.7	-0.4	-0.2	47.6	48.3	3.2	3.2	49.5	49.1	0.6	0.5
HP-NISHATGANJ	60.9	62.0	0.3	0.4	32.2	32.4	1.5	1.5	46.9	47.2	0.1	0.1
HP-CHARBAGH	57.6	59.2	-0.9	-0.6	38.4	39.3	2.4	2.4	46.3	44.2	0.5	0.6
HP-GOMTI NAGAR	58.7	61.6	0.3	0.8	34.6	35.9	1.9	1.9	77.4	76.9	0.3	0.3
HP-KRISHNA NAGAR	57.5	61.6	1.1	1.8	34.0	35.9	2.0	2.0	72.9	72.0	0.2	0.2
HP-HAZRATGANJ	53.0	56.9	-3.5	-2.4	38.6	41.5	2.8	3.0	67.6	72.7	0.8	0.8
HP-AMINABAD	72.4	73.4	1.5	1.6	48.3	48.5	2.8	2.8	65.1	65.4	0.3	0.3
HP-ALAMBAGH	76.3	78.4	2.1	2.1	58.4	59.8	4.9	5.0	83.3	83.4	0.6	0.6
HP-CANTT.	74.1	74.3	3.7	3.7	43.0	42.2	2.2	2.1	78.9	79.1	0.0	0.0
HP-JANKIPURAM	43.1	45.4	-1.5	-0.9	17.7	17.4	0.7	0.7	51.9	54.4	0.3	0.2
HP-RSAC	53.1	55.5	0.6	1.0	24.0	25.6	1.2	1.2	37.0	37.3	0.1	0.1
HP-KHADRA	62.7	65.6	-0.7	0.0	44.6	46.0	3.0	3.0	48.3	44.6	0.6	0.6
HP-TRIVENI NAGAR	46.8	47.2	-4.0	-4.2	31.7	32.3	2.1	2.1	46.1	46.6	0.7	0.8

HP-MAWAIYA	59.8	61.0	-0.9	-0.6	41.1	41.5	2.7	2.6	63.5	64.8	0.5	0.5
HP-AISHBAGH	57.3	57.8	-0.6	-0.5	37.5	37.5	2.3	2.3	53.8	54.2	0.4	0.4
HP-RAJAJIPURAM	51.9	54.8	-1.7	-0.9	33.3	34.8	2.0	2.1	48.6	47.7	0.5	0.5
HP-BADA IMAMBARA	64.5	65.8	0.8	0.8	40.3	41.0	2.3	2.3	59.3	60.0	0.3	0.3
HP-TRANSPORT NAGAR	56.3	56.9	1.3	1.2	26.2	26.2	1.2	1.2	60.5	59.5	0.1	0.1
HP-BARA BIRWA	74.5	74.4	2.7	2.5	44.3	43.5	2.3	2.2	77.5	77.0	0.1	0.1
HP-AMBEDKAR MAIDAN	61.0	62.8	0.9	1.2	34.7	35.2	1.8	1.8	80.1	82.3	0.1	0.1
HP-PGI	39.0	41.9	-0.7	-0.2	10.0	10.4	0.3	0.3	64.0	65.8	0.1	0.1
HP-NAKA	62.4	63.5	0.4	0.6	35.6	35.7	1.6	1.6	58.7	58.8	0.3	0.2
TW-L.U.OLD CAMPUS	55.5	57.4	0.8	1.2	29.5	29.6	1.5	1.5	62.4	62.3	0.1	0.1
TW-ALIGANJ	52.2	55.7	-0.7	0.0	31.4	33.0	1.7	1.8	61.9	65.8	0.4	0.4
TW-INDIRA NAGAR	47.3	48.5	-0.8	-0.6	21.8	21.9	1.0	1.0	60.4	59.2	0.2	0.2
TW-MAHANAGAR	54.7	50.6	-0.6	-1.4	33.6	30.3	1.9	1.7	39.8	45.9	0.4	0.4
TW-SAROJINI NAGAR	81.1	80.8	2.1	1.7	49.1	48.2	2.5	2.4	72.8	74.5	0.2	0.2
TW-KAISERBAGH	73.3	75.1	0.4	0.3	54.9	56.2	3.9	4.0	50.8	50.8	0.6	0.6
TW-NISHATGANJ	58.6	63.1	-1.5	-0.9	42.3	45.5	3.0	3.1	36.0	34.1	0.7	0.8
TW-CHARBAGH	64.6	66.8	1.5	1.8	37.4	38.3	2.0	2.0	53.4	53.5	0.1	0.1
TW-GOMTI NAGAR	70.3	74.1	0.6	1.3	46.1	47.6	2.6	2.7	63.0	67.2	0.4	0.4
TW-KRISHNA NAGAR	55.5	55.8	1.4	1.7	28.8	27.2	1.5	1.4	71.8	72.6	0.1	0.0
TW-HAZRATGANJ	71.3	73.6	0.4	1.0	55.1	56.2	4.5	4.5	65.9	65.2	0.7	0.7
TW-AMINABAD	97.0	97.7	4.5	4.2	73.0	73.5	6.6	6.6	62.6	63.2	0.4	0.4
TW-ALAMBAGH	66.4	67.0	1.6	1.7	41.9	41.7	2.5	2.4	74.2	76.1	0.2	0.2
TW-CANTT.	75.6	77.5	1.0	1.9	57.5	57.9	4.6	4.5	55.1	55.5	0.7	0.7
TW-LALBAGH	59.3	60.0	-0.1	0.1	40.1	40.4	2.6	2.6	60.4	60.4	0.5	0.5