Spatial Temporal Analysis of Groundwater Quality: A Case Study of Islamabad

By

Aneeqa Abrar

(2010-NUST-MS-GIS-20)

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Remote Sensing and GIS

Institute of Geographical Information Systems
School of Civil and Environmental Engineering
National University of Sciences & Technology
Islamabad, Pakistan

September, 2014

CERTIFICATE

Certified that the contents and form of thesis entitled **"Spatial – Temporal Analysis of Groundwater: Case Study of Islamabad"** submitted by Ms. Aneeqa Abrar have been found satisfactory for the requirement of the degree.

Supervisor: Dr. Ejaz Hussain

Associate Dean, IGIS

Member: Dr. Imran Hashmi

Professor, IESE

Member: Mr. Ahsan Mehboob

Lecturer, IGIS

Member: Ms. Khunsa Fatima

Lecturer, IGIS

DEDICATION

Dedicated to my Parents

ACADEMIC THESIS: DECLARATION OF AUTHORSHIP

I, Aneeqa Abrar declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Spatial Temporal Analysis of Groundwater Quality: A Case Study of Islamabad

I confirm that:

1. This work was done wholly by me in candidature for an MS research degree at the National University of Sciences and Technology, Islamabad.
2. Wherever I have consulted the published work of others, it has been clearly attributed.
3. Wherever I have quoted from the work of others, the source has been always cited. With the exception of such quotations, this thesis is entirely my own.
4. I have acknowledged all main sources of help.
5. Where the work of thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
6. None of this work has been published before submission. This work is not plagiarized under the HEC plagiarism policy.

Signed: ……………………………

Date: ………………………………

ACKNOWLEDGMENTS

I am thankful to Almighty Allah who enabled me to perceive and pursue my ambitions and special praises and Salams to Hazrat Muhammad (SAW), who is bellwether for whole humanity.

Special appreciation goes to my supervisor Dr. Ejaz Hussain for his supervision and constant support. His invaluable help, constructive comments, and suggestions throughout the thesis work have contributed in the success of this research. I thank the faculty of IGIS for providing me with an academic base, which enabled me to take up this study.

I am extremely grateful to my teacher Dr. Anwar Qadir (Bahria University) for his constant support. I would also like to appreciate the help provided by Sajjad Munir, Adeel Arif, Mirza Muhammad Waqar, and Syed Zubair, during the data collection phase. I would like to thank Mr. Usman Akram, the manager of WWF-P GIS Lab, for his help and guidance in the GIS portion of the project.

I would like to express my appreciation to my whole family, especially my mother, for her constant encouragement to help me reach this stage. Sincere thanks to all my friends, especially Saher Hasnain, Salva Rishi, and Syeda Sara Hayder, for their endless love, care and moral support during my study.

Lastly, I am thankful to my colleagues at LMKR and LMKT, especially my managers, Salman Rashid, and Asim Ghaffar, and my colleagues, Sheeba Sbeen, Aamir Malik, Nosheen Nisar and Yusra Dar for their support and encouragement.

Aneeqa Abrar

CONTENTS

DEDICATION .... **II**

ACKNOWLEDGMENTS .... **III**

FIGURES .... **VII**

TABLES .... **VII**

ABSTRACT .... **IX**

1. INTRODUCTION **1**

1.1 Importance of Groundwater 1

1.2. Groundwater Resources at Risk 3

1.3. Groundwater Contamination Sources 4

1.4. Scope of Thesis 5

1.5. Research Problem 6

1.6. Research Questions 7

1.7. Research Objectives 7

2. LITERATURE REVIEW **8**

2.1. Conceptual Models 8

2.2. Integration of Remote Sensing and GIS for Groundwater Quality Assessment 10

3. MATERIALS AND METHODS **12**

3.1. Study Area 12

3.2. Existing Status of Groundwater 13

3.3. Methodology 17

4. RESULTS 33

4.1. SPATIAL AND TEMPORAL ANALYSIS 33

5. CONCLUSION AND RECOMMENDATIONS 61

5.1. LIMITATIONS 61

5.2. CONCLUSION 61

5.3. RECOMMENDATIONS 63

REFERENCES 64

FIGURES

FIGURE 1.1: DISTRIBUTION OF EARTH'S WATER 2

FIGURE 2.1: EXISTING APPROACHES 9

FIGURE 3.1: STUDY AREA 13

FIGURE 3.2: GROUNDWATER VULNERABILITY ASSESSMENT FLOWCHART 22

FIGURE 3.3: FLOWCHART SHOWING THE LAND USE CLASSIFICATION 22

FIGURE 4.1: ISLAMABAD LAND COVER 2003 (JULY) 34

FIGURE 4.2: ISLAMABAD LAND COVER 2010 (MARCH) 35

FIGURE 4.3: DEPTH TO GROUNDWATER 2003 (MEASURE IN METERS) 37

FIGURE 4.4: DEPTH TO GROUNDWATER 2010 (MEASURE IN METERS) 38

FIGURE 4.5: NET RECHARGE 2003 (MEASURED IN VOLUME PER UNIT TIME) 40

FIGURE 4.6: NET RECHARGE 2010 (MEASURED IN VOLUME PER UNIT TIME) 41

FIGURE 4.7: AQUIFER MEDIA 43

FIGURE 4.8: SOIL MEDIA 45

FIGURE 4.9: TOPOGRAPHY (MEASURED IN PERCENTAGE SLOPE) 47

FIGURE 4.10: IMPACT OF VADOSE ZONE 2003 (MEASURED IN METERS) 49

FIGURE 4.11: IMPACT OF VADOSE ZONE 2010 (MEASURED IN METERS) 50

FIGURE 4.12: SOIL PERMEABILITY 2003 (MEASURED IN CM^2) 53

FIGURE 4.13: SOIL PERMEABILITY 2010 (MEASURED IN CM^2) 54

FIGURE 4.14: GROUNDWATER VULNERABILITY 2003 56

FIGURE 4.15: GROUNDWATER VULNERABILITY 2010 57

FIGURE 4.16: WATER QUALITY INDEX 2003 59

FIGURE 4.17: WATER QUALITY INDEX 2010 60

TABLES

TABLE 2.1.: COMPARISON OF THE EXISTING APPROACHES. 9

TABLE 3.1.: WATER SUPPLY DISTRIBUTION IN ISLAMABAD. 16

TABLE 3.2.: ACQUIRED DATA...16

TABLE 3.3.: WATER QUALITY INDEX MAPPING FLOWCHART. 23

TABLE 3.4. : WEIGHTS ASSIGNED FOR A) TOPOGRAPHY B) SOIL PERMEABILITY
C) RAINFALL. 28

TABLE 3.5.: WEIGHTS ASSIGNED FOR A) DEPTH TO GROUNDWATER
B)SOIL PERMEABILITY. 28

TABLE 3.6.: RATINGS ASSIGNED FOR A) DEPTH TO GROUNDWATER B) NET RECHARGE
C) AQUIFER MEDIA. 31

TABLE 3.7.:RATINGS ASSIGNED FOR A) SOIL MEDIA B) SLOPE
C) IMPACT OF VADOSE ZONE. 31

TABLE 3.8.: RATINGS ASSIGNED FOR SOIL PERMEABILITY..31

TABLE 3.9.: WEIGHTS ASSIGNED FOR GROUNDWATER
VULNERABILITY CALCULATIONS...31

TABLE 3.10.: DEFINING THE VULNERABILITY AREAS. 32

TABLE 3.11.: SELECTION OF PARAMETERS, ASSIGNING OF WEIGHTS (WI),
ASSIGNING OF WHO STANDARDS AND CALCULATING RELATIVE WEIGHT (WI). 32

TABLE 3.12: DEFINING THE WATER QUALITY INDEX 32

TABLE 4.1: COMPARISON OF LAND COVER 36

TABLE 4.2: COMPARISON OF DEPTH TO GROUNDWATER 39

TABLE 4.3: COMPARISON OF NET RECHARGE 42

TABLE 4.4: COMPARISON OF IMPACT OF VADOSE ZONE 51

TABLE 4.5: COMPARISON OF SOIL PERMEABILITY 55

ABSTRACT

Islamabad is a planned city of Pakistan. Over the years, due to economic growth it has been a hub for immigrants. Apart from Rawal and Simly Lakes, most of the city's water supply demand is met by the groundwater resources. However, urbanization and industrialization has brought these groundwater resources under high risks of contamination. This study assesses the groundwater pollution risk in Islamabad. The study demonstrated that GIS technology is an efficient environment for analyses of spatial data. The combined use of DRASTIC model and geographic information system (GIS) was adopted to provide a spatial assessment of groundwater quality. Seven thematic maps of the DRASTIC model were developed in order to assess the vulnerability of groundwater to contamination and these include the depth to water table, recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. The GIS software (ArcGIS) was used to create an integrated vulnerability map of Islamabad to demarcate vulnerable zones. Temporal monitoring of land cover areas were derived from classified land-cover maps. This was done to describe the relative degree of natural protection of the groundwater from contamination due to the physical characteristics of the land and subsurface. Most of the area of Islamabad lies within the moderate vulnerability which means that the increase in vulnerability from 2003 to 2010 has been from 5% to 8.5%. These results indicate that reforms are required by the government to protect this groundwater asset. Perverse policies are the main cause of the waste and inefficiency that drive freshwater pollution and over-consumption. Reforming these policies requires governments to implement far-reaching institutional change and promote technical innovation.

Chapter 1

1. INTRODUCTION

1.1 Importance of Groundwater

Groundwater is essential for every country in the world. It is not only a significant and a valuable renewable resource of freshwater but also in some countries the only source. Groundwater is one of the vital resources to last forever.

Groundwater is less prone to pollution compared to surface water, hence its importance in arid and semi-arid region (Sener & Davraz 2012). Groundwater, existing under the ground, is an essential component of the water cycle.

Only 3% of the total water available in the world is freshwater, rest being salt water (oceans and seas). Except for freshwater trapped in glaciers and icecaps (68.70%), the majority of freshwater resources are in the form of groundwater (30.10%). Only 0.3% of freshwater is surface water in lakes (87%) and rivers (2%) (Margat Jean & Gun Jac van der 2013). Hence, groundwater is the largest reservoir of fresh water (figure 1.1.).

Recently, groundwater has gained importance not only as a source of water supply but also as an environmental factor (Huan et al. 2012). Groundwater is used for drinking, in industry, and in agriculture (Rodriguez, Galiano et al. 2014). Groundwater is also considered as a buffer against droughts as they are the backup reservoirs. Ecological and recreational values of streams and lakes also depend on groundwater discharge, as it sustains flow in perennial streams and rivers.

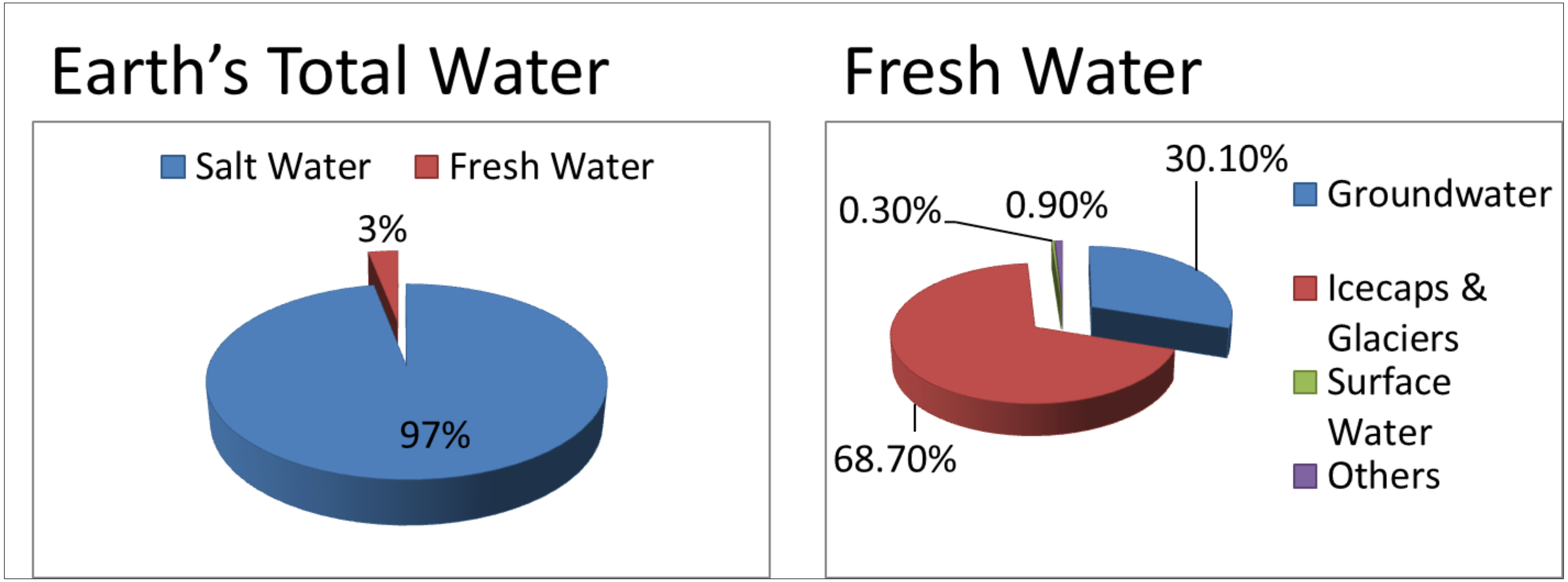

Figure 1.1.: Distribution of earth's water (Margat Jean & Gun Jac van der 2013).

1.2. Groundwater Resources at Risk

Groundwater pollution is defined as "*the detrimental alteration of the naturally occurring physical, thermal, chemical, or biological quality of groundwater*" (Stewart 2009). This means that any alteration in physical, thermal, chemical, or biological properties of water means contamination of water.

Groundwater is an important drinking water source for human consumption, and any alteration in the quality can have serious consequences (Nucleus et al. 2011). Groundwater pollution is an environmental catastrophe which affects the normal activities of society (e.g. washing clothes, drinking water, usage in cars and industries etc.) and does serious harm to the water ecological environment. Once an aquifer is contaminated it becomes increasingly difficult to purify it (Saidi et al. 2009).

Effective management of groundwater resources has become a global issue since the rapid expansion of industrial and agricultural activities, the population increase and climate changes have major effects on groundwater quality and quantity (Rodriguez, Galiano et al. 2014). Great amount of effluents enter the groundwater from industries and homes (Sener & Davraz 2012). Many aquifers worldwide and their related ecosystems have been put at risk due to high extraction rates. The effective management is a concern due to the increase in population, industries, and over-use of chemicals (Saidi et al. 2011).

Drinking contaminated water not only effects people but also the wildlife (Anon 2008), (Howard Perlman 2014)(Amjad et al. 2013) (Akhtar & Tang 2013). Some of the effects of drinking contaminated water are:

- Epidemics of typhoid and cholera occur.
- Toxins in the contaminated groundwater can cause poisoning.

- High nitrates in water effects the infants causing methemo-globinemia or more commonly known as blue-baby syndrome.
- Cancers like bladder, colon, rectal, and esophageal are more likely to occur in people.
- Hepatitis A and E.

1.3. Groundwater Contamination Sources

Groundwater quality is deteriorating due to the adverse effects of an increase in urbanization (Nadun et al. 2010). Groundwater pollution is a major issue as it is prone to contamination from anthropogenic activities (Yin et al. 2012). Groundwater can be affected by human activities like urbanization, farming and industrialization indicating the fragility of these resources (Shirazi et al. 2013).

The groundwater contamination sources are as follows:

1.3.1. Natural

Most of the naturally occurring minerals like iron, manganese, chlorides are dissolvable in water. When these substances dissolve in higher concentration, they can cause threat to human health and wildlife (Anon 2010a).

1.3.2. Septic Systems

Human waste is drained away underground at a slow rate using septic systems. Human waste consists of bacteria, viruses and other contamination which can enter groundwater in case of a faulty septic system (Howard Perlman 2014).

1.3.3. Disposal of Hazardous Materials

Industrial wastes need to be disposed of after treating them properly. They cannot be disposed of into on-site septic systems. If these hazardous chemicals are drained directly, they will eventually seep into the ground and contaminate the water resources (Anon 2010a).

1.3.4. Landfills

Solid wastes are disposed of in the landfills sites. The by-products of decomposition of these wastes are called a leachate. If this untreated leachate enters the soil it can contaminate groundwater severely (Anon 2010a).

1.3.5.Improperly Constructed Wells

Abandoned wells are used as disposal sites for materials such as motor oils. Improperly constructed wells allow seepage of materials to and fro from the subsurface. These wells eventually contaminate aquifers, effecting the quality of groundwater (Mason 2010).

1.3.6. Atmospheric Contaminants

As mentioned before, groundwater is a part of water cycle and contaminants present in any phase (or state) eventually end up as particles in groundwater (Anon, 2010).

1.4. Scope of Thesis

This study focuses on assessing the contamination of water resources and the impacts of various urban developments on the vulnerability of groundwater supplies. The reassessment of the existing and historical field data on various parameters helped to identify limiting factors and to devise a strategic water utilization plan along scientific lines to ensure vulnerability of available water resources.

1.5. Research Problem

Recent urbanization has affected the groundwater quality, as a significant proportion of the land has become impermeable. Furthermore, population growth and progressive migration of people to Islamabad, in hopes of increasing the standard of living, has resulted in a rapid increase in water supply demands. To meet these demands, groundwater is being extracted from tube wells. As a consequence of heavy withdrawal and reduction in recharge, the water table is lowering and aquifers are under stress. Untreated industrial effluents and domestic wastes are disposed of into watercourses flowing through or in the vicinity of large population centers and industrial zones. Hazardous chemicals from construction sites and road salts mix with soil and infiltrate into the groundwater making it unfit for drinking. Due to the non-existence of proper sewerage systems in under developed areas (such as Golra, sector G-12 and other rural areas of the city); the human waste enters the water system especially through recharge areas. Groundwater environments are being seriously polluted due to these activities. Prevention of the pollution of the groundwater resources from anthropogenic sources is a crucial issue since remediation is expensive. For the purposes of this report the problem statement of this study is as follows:

'Characterize the aquifer vulnerability, elucidating the relationship between land use and groundwater quality.'

The main aim of this report is to identify key factors threatening the ground-water sustainability. So that by controlling these factors, effective development and use of ground water can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.

1.6. Research Questions

The research questions taken into account for this study were:

- What is the level of risk posed by contamination of ground water?
- Is water quality currently deteriorating?
- What are the factors affecting water quality?

1.7. Research Objectives

The main objective of the study was to *'identify and assess groundwater quality using GIS and Remote Sensing techniques so as to locate highly vulnerable areas.'* This helps us target areas for greater attention and land use restriction in the future, to prevent further contamination of ground water in Islamabad. The research objectives pursued in order to answer the research questions are:

- Identifying temporal variations in water quality parameters affecting water quality.
- Develop groundwater vulnerability maps for groundwater resources of selected sectors of Islamabad.
- Comparison of actual data with vulnerability maps as validation.

Chapter 2

2. LITERATURE REVIEW

This chapter describes the literature studied for this study. This chapter is divided into sections that cover the vulnerability of groundwater resources to contamination, and approaches to quantify the groundwater vulnerability to contamination.

2.1. Conceptual Models

For preventing and controlling groundwater pollution, groundwater vulnerability assessment is an essential model which evaluates the sensitivity of aquifers to pollution by differentiating the vulnerability extents. Mapping these extents identify the vulnerability of aquifers to contamination (Huan et al. 2012). The following methods have been developed to estimate aquifer vulnerability:

- **Process Based Methods:** uses stimulation models to estimate the contamination levels.
- **Statistical Methods:** uses statistics to associate spatial attributes with the existing pollutants.
- **Overlay and Index Methods:** uses specific indices depending upon factors that control the penetration of pollutants from ground surface to the water table.

Selecting an appropriate method depends upon multiple factors such as the data availability and desired results (figure 2.1.) (Kumar et al. 2013). These approaches have been described in detail in various research studies, Table 1 below summarize these approaches (Liggett & Talwar 2009). The table 2.1 describes the difference between the three approaches for groundwater vulnerability assessment (Mair & El-Kadi 2013).

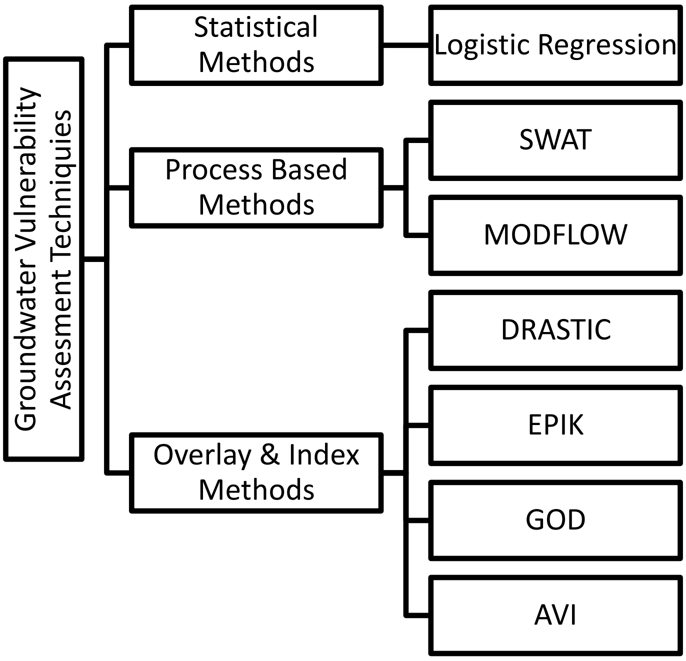

Figure 2.1.: Existing approaches for groundwater vulnerability assessment.

Table 2.1.: Comparison of the existing approaches.

Statistical	Process Based	Overlay and Index
Calculates the probability of contamination by characterizing contamination potential using data from known contamination distribution	Predicts how long a contaminant takes to reach a given depth and the amount of contaminant using mathematically modeling	Intersecting maps of different parameters that affect the groundwater vulnerability
Requires sufficient information about input parameters to build the probability distribution for each parameter	Good hydro-geologic and geochemical database coverage required	Requires basic and preliminary data
Quite complex	Complexity of the models range from simple transport model indices to multi-phase, multi-dimensional modeling	Easy to implement

2.2. Integration of Remote Sensing and GIS for Groundwater Quality Assessment

GIS is a powerful tool used for storing, analyzing, and displaying spatial data. This data can be manipulated using the GIS technology for decision making purposes and assessments of natural resources and environmental issues (Srivastava et al. 2011). GIS techniques are utilized in suitability analysis, groundwater vulnerability assessment, flow modeling, and risk assessments (Jaiswal et al. 2003)(George 2013). Maps are prepared using GIS to identify vulnerable areas and classify aquifer characteristics (Nobre et al. 2007). This is also used to make water quality maps depending on parameters effecting groundwater quality (Renji & R. 2007). Remote Sensing is used for land use and land cover classification because of its spatial and temporal coverage capabilities. The land coverage changes with time due to anthropogenic and environmental conditions which can be detected using satellite imagery (Singh et al. 2011).

The paper 'Spatial-Temporal Groundwater Vulnerability Assessment - A Coupled Remote Sensing and GIS Approach for Historical Land Cover Reconstruction' (Albuquerque et al. 2013) does a spatial-temporal groundwater vulnerability assessment, based on a coupled remote sensing and GIS approach for historical land cover reconstruction. This methodology can be used for spatiotemporal vulnerability assessment in fresh water systems. The trans-boundary watershed of the Águeda River was used as an experimental case study where the DRASTIC and the Susceptibility Index (SI) were used for vulnerability assessment. Land-use was mapped using remote sensing data. The results indicated that in the last 50 years, the highest vulnerability areas for groundwater contamination have been concentrated mainly in the central zone of the watershed where the tertiary aquifer and the largest urban area are located.

In the study by Aminreza Neshat, Biswajeet Pradhan, and Mohsen Dadras, (Neshat et al. 2014) a modified DRASTIC (Depth to groundwater, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity) approach using GIS was applied to evaluate groundwater vulnerability in Kerman plain (Iran). In addition, the Analytic Hierarchy Process (AHP) method was used to evaluate the validity of the criteria and sub criteria of all the parameters of the DRASTIC model, which is proposed as an alternative method. The best result was obtained by using AHP–AHP, followed by DRASTIC–AHP, modified DRASTIC–AHP, and AHP–DRASTIC models. The results suggested that the southern and south east parts of the area required immediate attention for conservation against contamination.

The study by Huan Huan, Jinsheng Wang, and Yanguo Teng used a modified DRASTIC model to assess the groundwater vulnerability to nitrates in Jilin City of northeast China. The model was optimized by rebuilding the index system, adjusting the rating scale of each index, reassigning the index weights and comparing grading methods for groundwater vulnerability to nitrate. The sensitivity analysis indicated that the soil media and groundwater velocity were the most critical factors affecting groundwater vulnerability to nitrate (Huan et al. 2012).

GIS technology has an important part in evaluating the groundwater pollution potential which helps in policy making.

Chapter 3

3. MATERIALS AND METHODS

3.1. Study Area

The capital city of Pakistan, Islamabad, lies in the midst of Margalla Hills and ancient city of Rawalpindi. Islamabad occupies an area of approximately 906 square kilometers (Sheikh et al. 2007).

Geologically, Islamabad lies on Pothohar Plateau (Anon 2010b). Islamabad has been a crossroad between Punjab and Khyber Pakhtunkhwa (Anon 2013b). It is divided into eight zones as follows (Anon 2013a):

- Administrative Zone
- Commercial District
- Diplomatic enclave
- Educational Sector
- Green Areas
- Industrial Sector
- Residential Areas
- Rural Areas

Hydro-geologically, Islamabad lies in the Soan River basin. This area is drained by two main rivers namely Soan and Kurang , three perennial streams namely Gumrah Kas, Tanawala Kas, Bedarwali Kas and Lei Nala and three reservoirs, Rawal, Simili and Khanpur Dams (Sajid et al. 2008).

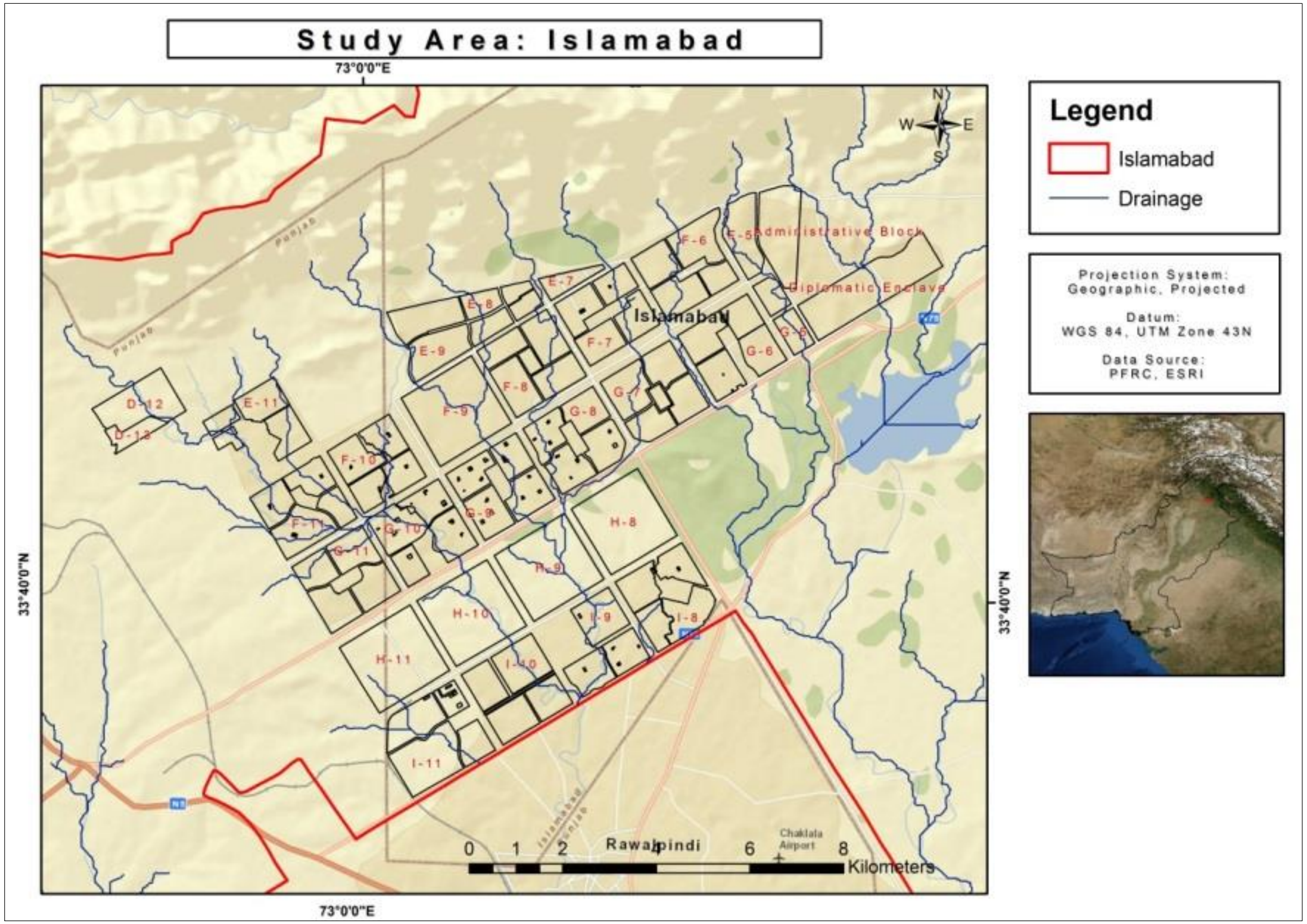

Figure 3.1.: Study area.

3.2. Existing Status of Groundwater

Water in Islamabad is supplied via four main sources, reservoirs, streams, springs and groundwater. The Simli dam covers urban area of Islamabad whereas the Khanpur dam supplies water mainly to the Rawalpindi area. The Rawal lake provides water to the out skirts of Islamabad (Sun-Ok et al. 2001). More than 200 wells installed by the Capital Development Authority (CDA) are used to supply water in Islamabad.

As per the records (table 3.1.), the major water source which produces and supplies water to Islamabad and Rawalpindi is groundwater. This water is extracted from the tube wells, both private and government, and are used mainly for drinking purposes and alongside also for gardening washing etc. The government pumps are controlled by the Capital Development Authority (CDA) and the water is treated accordingly before supply. There are a number of residents who have drilled their own tube wells to overcome the water shortage. These wells are not controlled or treated by neither the government nor the owners.

The streams Shahdara and Korang provide water to the E-5 administrative block and Diplomatic Enclave II. These waters are treated by the conventional method (Coagulation, sedimentation, filtration and disinfection) and monitored on an hourly basis. The water supplied to F-6/2 comes via Saidpur spring after the filtration and chlorination treatment. The spring located in the Noorpur village supplies water to the surrounding areas which includes the Secretariat block, near Bari Imam Village(Sun-Ok et al. 2001).

There have been few studies regarding water resources assessment in the region; such as geohydrology of the Federal Capital Area availability of groundwater in Islamabad carried out a detailed study for hydrogeological survey in Soan Basin. The study was undertaken to explore the groundwater, aquifer characteristic and estimation of groundwater potential(Ashfaq et al. 2007).

After that, no comprehensive assessment or study has been conducted in the region, especially in the Soan basin which is one of the major basins of Pothohar region consisting about 50% of the area.

There have been many media reports claiming about the low water quantity and contamination of water. These claims have been supported by a number of reports and surveys conducted by various organizations, both government and non-government. Studies showing that around 78% of water supplied to the capital as unfit for human consumption have surfaced through various projects and surveys conducted by the Pakistan Council of Research in Water Resources (PCRWR), Pakistan Institute of Nuclear Science and Technology (PINST), Nutrition Division of National Institute of Health (NIH), and Capital Development Authority (CDA) (Ashfaq et al. 2007).

There are a number of sources of contamination that have been identified in the reports and surveys done by various organizations, the most important ones being industrial waste and untreated sewage. Other interesting sources identified in various reports are related to the bacterial contamination of groundwater (Cheema et al. 2008)(Iqbal et al. 2012). Some reports suggest that over extraction of groundwater has exposed the upper aquifer, leading to a higher rate of bacterial contamination. Untreated domestic wastewater flowing in open drains is also contributing towards groundwater bacterial contamination. Geo-chemical analysis of soil has identified the traces of hazardous metals which contributes to the chemical pollution of groundwater(Ali & Qamar 2013)(Ahmad et al. 2010).

Table 3.1.: Water supply distribution in Islamabad.

Name	Sources	Total Capacity (MGD)	Production (MGD)
Simli	Lake	42	26
Khanpur	Lake	17	7
Korang	River	2	1.2
Saidpur	Spring	0.8	0.4
Shahdara	Stream	1.6	0.7
Noorpur	Spring	0.7	0.4
Tubewells	Groundwater	40	30

Table 3.2.: Acquired data.

Data	Source
Islamabad Map	IGIS – NUST
Depth to Groundwater	PCRWR/PINSTECH
Rainfall	Metrological Department
DEM	ASTER
Soil	Soil Survey Of Pakistan
Aquifer Map	WAPDA
Land Use Map	Landsat
Water Quality	PCRWR/PINSTECH

3.3. Methodology

The approach used in this study discusses the impact of anthropogenic activities on groundwater quality by vulnerability assessment. In vulnerability assessment of a system, the identification, quantification and prioritization of the vulnerabilities is done (Güler et al. 2013).

Different parameters and related information such as geology, soil types, depth to groundwater, hydraulic properties, and precipitation are used to measure the vulnerability. These properties and information assess the relative ease of the contaminants for reaching and moving through the groundwater system (Kumar et al. 2013).

3.3.1. Data Acquisition

The first phase of a groundwater study consists of collecting all existing geological and hydrological data on the groundwater basin including information on subsurface geology, water table, precipitation, soils, land use, aquifer characteristics, and groundwater quality. Some data was obtained from existing reports of various departments. Additional work (such as digitizing maps, entering data in spreadsheets, and apply mathematical equations to turn the data into information) was required to process the obtained data. The table 3.2 shows the data acquired from the relevant departments.

Some of the maps cannot be prepared without first making a number of auxiliary maps. A map of the net recharge, for instance, can only be made after topographical, geological, soil, land use and rainfall maps have been made.

The following equations were used to manipulate the auxiliary data to obtain maps required for groundwater vulnerability assessment:

$\boldsymbol{Net\ Recharge} = Slope\% + Rainfall + Soil\ Permeability$ (Gennaro 2001)

$\boldsymbol{Soil\ Permeability} = Soil\ Permeability + Land\ Use$

$\boldsymbol{Impact\ of\ Vadose\ Zone} =$
$Soil\ Permeability + Depth\ to\ Water\ Table$ (Piscopo 2001)

$\boldsymbol{Groundwater\ Vulnerability\ Assessment} = 5 * Depth\ to\ Water\ Table + 4 * Net\ Recharge + 3 * Aquifer\ Media + 2 * Soil\ Media + 1 * Topography + 5 * Impact\ of\ Vadose\ zone + 3 * Soil\ Permeability$ (Aller et al. 1987)

$\boldsymbol{Water\ Quality\ Index} = \sum SIi$ (Sharma & Patel 2010)(P & K 2010)

In the current study, the issue of groundwater vulnerability has been addressed from the perspective of assessment in a GIS environment. Thus the map based on multi criteria analysis is prepared with the help of tools available in Arc GIS 9.3.1.

The tool and software used in this study are as follows:

1. ArcGIS Modules – Arc-Map, Arc Catalogue, Arc-ToolBox
2. ARCGIS Extension – Spatial Analyst
3. ERDAS Imagine 2011
4. ENVI 4.7

3.3.2. DRASTIC Model

In 1987, an EPA funded effort to research and develop a method for evaluating pollution potential anywhere in the United States successfully produced the DRASTIC model. DRASTIC was used to evaluate the relative vulnerability of areas to groundwater contamination by focusing on hydro-geologic factors that influence pollution potential (Aller et al., 1987). Today the DRASTIC method is a standardized system for evaluating groundwater pollution potential.

DRASTIC has frequently been adapted to situations other than those it was designed for. DRASTIC coupled with other factors such as application methods may help delineate areas where aquifer vulnerability is higher and land use suggests a potential source of pollution.

As detailed site-specific analyses are costly and time consuming, regional vulnerability assessment using the DRASTIC method with modifications can be used as an economical tool to identify the zones of concern and as a tool to overcome problems of haphazard, uncontrolled development of land and of undesirable activities having an impact on groundwater quality. DRASTIC was originally developed as an easy-to-use method for aquifer vulnerability assessment, encompassing diverse hydro-geologic settings, based on vulnerability index. The DRASTIC model defines ranges of model parameters, which at times warrants modifications for better addressing of local issues and for refined representation of local hydro-geologic settings. Thus the DRASTIC is flexible.

The DRASTIC method was selected because the study is focused on a region and not on a specific local field. Moreover, it is economical and suits the scarce financial resources in the essence that no detailed data is needed to carry out the work but just the literature-based data that are available in reports and past studies.

This method uses some hydrogeological factors of an area in order to determine the relative groundwater vulnerability to contaminants. DRASTIC is an acronym created of the first letters of features used to create the map. There are 7 included features: Depth to the groundwater (D), Recharge net 590 (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I) and Conductivity of the aquifer (C). These are then weighted and ranked, and then are combined to obtain a final ranking value using a groundwater vulnerability algorithm. There are three significant part: weight, ranges and ratings. The approach used was DRASTIC model. As mentioned earlier, DRASTIC is one of the most widely used groundwater vulnerability mapping methods. Having a good precision and flexibility, DRASTIC model is much used in detailed studies. The DRASTIC technique produces a standardized methodology which provides suitable results for evaluating a region with respect to groundwater protection and monitoring.

Weight values from 1 to 5 are assigned for each parameter used. A benefit of the DRASTIC model is its flexibility to adjust the relative weight of the seven primary parameters for a particular application

Ratings from (generally from 1 to 10) are assigned based on the attribute values of the data used for each of the DRASTIC model parameters. Ratings must be assessed for all attribute data selected for use as inputs for the parameters.

The DRASTIC value, which is calculated for each mapping unit, is produced by multiplying the weight and rating values together for each parameter, and then adding up all the sum values. A higher value equates to a higher likelihood of groundwater contamination; conversely, a lower DI means a lower likelihood of contaminated. The final values are classified into ranges with descriptors indicating low, and high.

The data collected comprises of years 2003 and 2010. The following flowcharts show the methodology used for evaluating groundwater vulnerability and mapping water quality index. The flowcharts below describe the entire methodology in the simplest form.

The flowchart (figure 3.2) shows the data required to create a groundwater vulnerability map. It consists of depth to groundwater table, net recharge, aquifer media, soil media, topography, impact of vadose zone and soil permeability. Most of these maps require further auxiliary data as represented in the flowchart. For instance, net recharge requires slope (which is extracted from DEM), rainfall and soil permeability information. Similarly, impact of vadose zone is calculated using soil permeability and depth to groundwater (Piscopo 2001).

The process for creating a land cover map is described in the flowchart (figure 3.3). The first step was to download the image from the www.glovis.usgs.gov. This site was used because Landsat images are freely available here. The image for 2003 has no major issues but the image for 2010 required preprocessing because it has Scan Line Corrector (SLC). The gap filled analysis was done using ENVI 4.7. The next step was to stack the bands and extract the area of interest from the entire image. The signatures were picked for four different classes – vegetation, soil, urban, and water. The supervised classification was performed to classify the image.

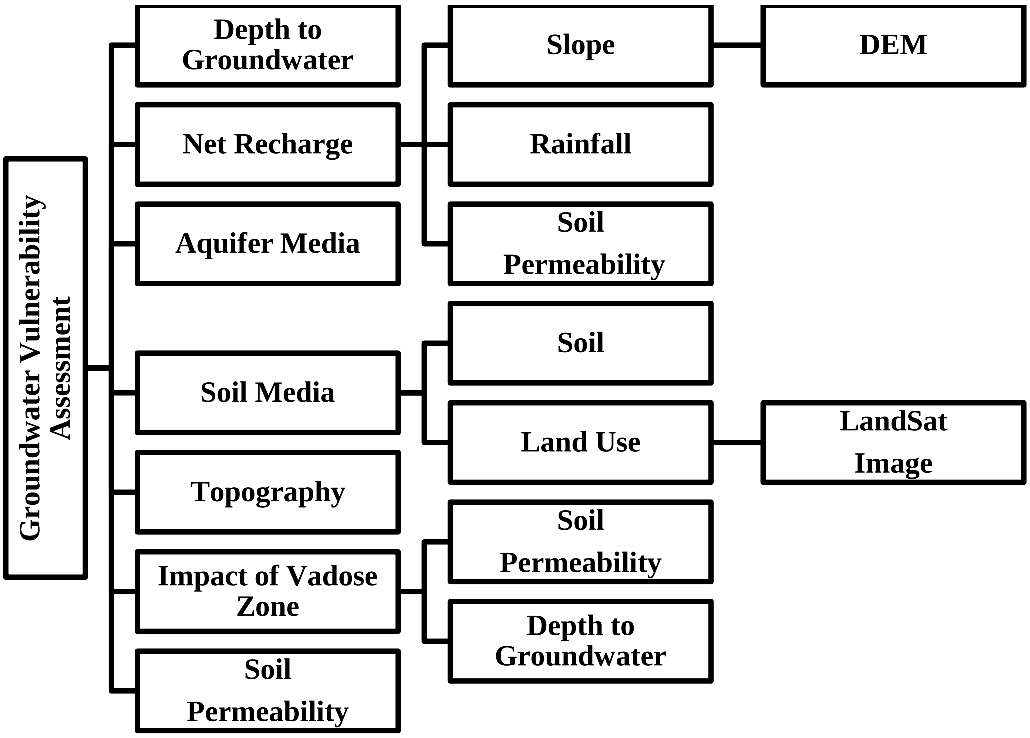

Figure 3.2.: Groundwater vulnerability assessment flowchart.

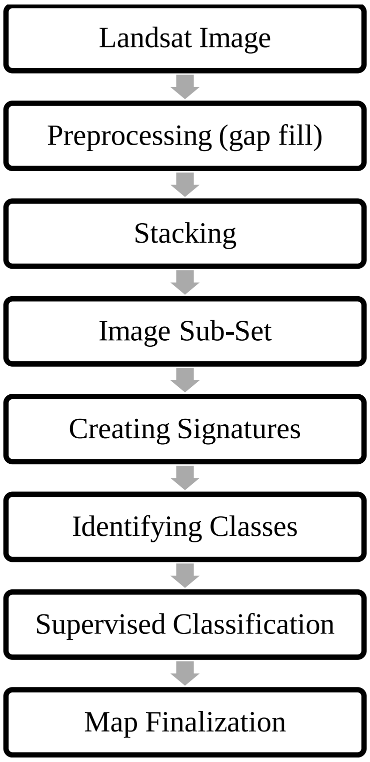

Figure 3.3.: Flowchart showing the land cover classification.

Table 3.3.: Water quality index mapping flowchart.

1. Selection of Parameters
2. Assign Weights (Wi)
3. Calculate Relative Weight (WI = Wi / ∑ Wi)
4. Use WHO Standards (Si)
5. Identify the Concentration (ci)
6. Calculate the Quantity Rating (Qi = Ci /Si * 100)
7. Calculate Sub Index (SI = Wi X Qi)
8. Calculate Water Quality Index (WQI = ∑ SI)
9. Create Map using IDW Interpolation
10. Finalize Map

Water quality index mapping was done as a validation for the groundwater vulnerability assessment results. The flowchart (table 3.3.) shows the process followed for calculating the WQI. These calculations were done in Microsoft (MS) Excel 2010.The maps were then generated in ARCGIS 9.3.1 using these values(Sharma & Patel 2010)(P & K 2010)(Bhoi et al. 2011).

3.3.3. Data Preparation

The second phase of the study was to prepare all the required maps. Some maps had to be digitized and some to be created using interpolated techniques.

A. Land Use Land Cover

Land use and land cover change is a continuous process. The changes of land use and land cover within the watershed changes the hydrological patterns and pose serious challenges for the community(Dams et al. 2007).

The Landsat 7 images were acquired from www.glovis.usgs.gov. The image for year 2003 and year 2010 were downloaded, stacked and a subset of the study area was created. Supervised classification was then performed on those images to identify the changes in the land cover over the course of seven years. Classification of a satellite image can be achieved by supervised or unsupervised procedures. A supervised approach relies on the prior specification of training areas, in which major land cover types are delimited manually as a key for electronically classifying the image. In contrast, no such visual interpretation is involved in an unsupervised method. It uses automated methods to cluster reflectance values in order to derive a required number of land classes and their associated spectral signatures. The land cover classification was done on the basis of reflectance characteristics of the different land use types by using false color composites. This was supplemented by a number of field visits that made it possible to establish the main land use land cover types. The classification of changed area may be performed according to any desired decision rule like maximum likelihood, minimum distance, neural networks, and decision trees and so on. The two major frequently used classification methods are unsupervised and supervised classifications. For this study a supervised classification scheme with maximum likelihood classifier decision rule was used by following three stages, assigning training sites, classification and outputs.

B. Depth to Groundwater

Depth to groundwater is an important factor when determining the groundwater vulnerability analysis. It determines the distance contaminants travel before reaching the groundwater. Deeper the water table, the less vulnerable it is to contamination because the deeper water levels result in longer travel time for contaminants (Gennaro 2001).

The groundwater table data for 2003 was acquired from a published report of Pakistan Council of Research in Water resources (PCRWR) while the data for 2010 was acquired from PINSTECH(Pakistan Institute of Nuclear Science and Technology) (S Munir, A Mashiatullah 2012). The map was generated using the IDW interpolation technique. The IDW method in the ArcGIS Spatial Analyst involves an interactive investigation of the spatial behavior represented by the z-values.

C. Net Recharge

Net Recharge is the amount of water that infiltrates into the ground surface and reaches the water table. The recharge water transports the contaminant to the water table and within the aquifer (Sener & Davraz 2012). Estimating the groundwater recharge was a challenge. As water recharge cannot be measure directly, it was estimated using the following equation:

$$\textbf{Recharge value} = \text{Slope\%} + \text{Rainfall} + \text{Soil Permeability (Gennaro 2001)}$$

These factors are chosen as they are considered to be major contributors in recharge of water table. The maps for slope, rainfall and soil permeability were made using the ArcGIS software. Slope was extracted from the DEM using the slope tool in the Spatial Analyst extension. The rainfall data acquired from the Metrological Department Islamabad was interpolated using IDW (inverse distance weighted) technique. The third and final map for the equation is soil permeability map using the IDW interpolation method. The soil data was acquired from Soil Survey of Pakistan.

Once these factor maps had been generated, they were reclassified and the ratings were applied as shown in the tables 3.4. In the final step of the process the equation needs to be regenerated in ArcGIS. The raster calculator is the tool available in spatial analyst for this purpose.

D. Aquifer Media

An aquifer is a body of permeable rock that contains or transmits groundwater. The aquifer media refers to the lithology of the aquifer. It determines the time available for attenuation processes (sorption, reactivity, dispersion) to occur. The aquifer medium influences the amount of effective surface area of materials with which the contaminant comes in contact within the aquifer(Saidi et al. 2011). The map was digitized from hydrogeological map made by the WAPDA. The digitizing was carried out using the ArcGIS 9.3.1.

E. Soil Media

Soil is perhaps the most important component in the movement of contaminants. The existence of fine textured particles such as silt and clay decreases the relative soil permeability and restricts contamination migration. Soil media is described in terms of its textural classification and ranked in order of pollution potential (Sener & Davraz 2012). The soil map was obtained from Soil Survey of Pakistan and it was digitized using ArcGIS 9.3.1.

F. Topography

Topography is the slope of the study area. The pollutants run off and rate of retention depends on slope variability of the land’s surface. Higher the slope greater is the opportunity for the contaminants to infiltrate resulting in higher groundwater pollution potential (Piscopo 2001). Slope was calculated using the Digital Elevation Model (DEM) with the help of slope tool in the spatial analyst extension.

G. Impact of Vadose Zone

The Vadose zone refers to the unsaturated zone above the water table. The Vadose zone media determines the attenuation characteristics of the material including the typical soil horizon and rock above the water table. It also controls the time available for attenuation as the path length of the contamination is determined by the medium (Aller et al. 1987).

The two factors considered for defining the impact to vadose zone are soil permeability and depth to water table (DTWT). The equation provides a Vadose Zone

Value for a particular area and is relative to the other zone within the context of the study area.

$$\boldsymbol{Impact\ of\ Vadose\ Zone} =$$

$$Soil\ Permeability + Depth\ to\ Water\ Table$$ (Gennaro 2001)

Both the factor maps have been explained in detail in previous sections. These factor maps were reclassified, weights were assigned (table 3.5) and the impact of Vadose Zone map was generated using raster calculator.

H. Soil Permeability

Soil Permeability is the ability of soil to transmit water which in turn controls the rate at which groundwater flows (Aller et al. 1987).

Soil Permeability = *Soil Permeability* + *Land use and Land Cover*

The absence of spatially complete data for hydraulic conductivity had led to using soil permeability map instead. Hydraulic conductivity is controlled by the amount and interconnection of void spaces within the aquifer that may occur as a consequence of inter-granular porosity, fracturing planes. Soil permeability is related to hydraulic conductivity as higher the permeability, higher is the conductivity (Piscopo 2001).

Table 3.4. : Weights assigned for a) topography b) soil Permeability c) rainfall.

a)

Slope (%)	Factors
< 2	5
2-10	4
10 – 20	3
20 – 33	2
> 33	1

b)

K (cm^2)	Factors
Impermeable	0
Very Slow	1
Slow	2
Moderate	4
High	5

c)

Rainfall (mm)	Factors
> 1000 mm	4

T

Table 3.5.: Weights assigned for a) depth to groundwater b)soil permeability.

a)

Range (meters)	Factors
< 88	5
88 – 92	4
92 – 96	3
96 – 100	2
>100	1

b)

K (cm^2)	Factors
Impermeable	0
Very Slow	1
Slow	2
Moderate	4
High	5

I. Vulnerability Map Preparation

Vulnerability is susceptibility to injury or damage from hazards(Liggett & Talwar 2009). All the nine (9) parameter maps were classified and ratings applied as per the tables shown 3.6 to 3.8. The ratings and weights were applied using the reclassify tool in the spatial analyst extension. The values were taken from the literature(Piscopo 2001).

The reclassified raster images were then used to solve the equation using the raster calculator, another important tool found in the spatial analyst extension. The weights assigned (table 3.9) represent the importance of the parameters in groundwater vulnerability assessment.

The DRASTIC method was applied to calculate the groundwater vulnerability. The equation used was as follows:

$$\boldsymbol{Groundwater\ Vulnerability\ Assessment} = 5 * Depth\ to\ Water\ Table + 4 * Net\ Recharge + 3 * Aquifer\ Media + 2 * Soil\ Media + 1 * Topography + 5 * Impact\ of\ Vadose\ zone + 3 * Soil\ Permeability\ \text{(Aller et al. 1987)}$$

Table 3.10 describes the meaning of low and high vulnerability classes. There are an infinite number of classes between the two extremes but we need to concentrate on the extremes, especially the high vulnerability areas, so as to better utilize the process and therefore save more groundwater from contamination (Piscopo 2001).

J. Validation: Groundwater Quality Index Map

The water quality parameters were obtained from the PCRWR's published data. They had conducted a six (6) year groundwater quality monitoring program for the entire country. Hence the data for year 2003 was copied from the published reports and entered into the excel files. For 2010, the data was acquired from PINSTECH (S Munir, A Mashiatullah 2012). These parameters values were used for calculating Water Quality Index (WQI) in the following steps (Sharma & Patel 2010)(P & K 2010):

Step 1: Assigning of weights (wi) to the parameters

Step 2: Calculating the relative weight for each parameter using

$\boldsymbol{Wi} = wi/\sum wi$

Step 3: WHO standard (Si) for each parameter is assigned.

Step 4: Quality rating scale (Qi) is calculated using

$$\boldsymbol{Quality\ rating}\ (\boldsymbol{Qi}) = concentration\ of\ each\ parameter\ (Ci)/Si\ X\ 100$$

Step 5: WQI is determined, where sub index (SI) is calculated for each parameter first.

$$\boldsymbol{SI} = Wi\ X\ qi$$

$$\boldsymbol{WQI} = \sum SIi$$

After the WQI for every well was calculated, the data was displayed in ArcGIS using the Display XY tool. The Water Quality map was generated using the IDW interpolation technique and the data was classified as per the literature (Sharma & Patel 2010)(P & K 2010). This map was classified into two major classes: good quality drinking water and water unfit for drinking described in table 3.12.

Table 3.6.: Ratings assigned for a) depth to groundwater b) net recharge c) aquifer media.

a)

Range (meters)	Ratings
< 88	10
88 - 92	8
92 - 96	6
96 - 100	4
> 100	1

b)

Recharge (volume per unit time)	Ratings
3 – 5	1
5 – 7	3
7 – 9	5
9 - 11	8
11 - 12	10

c)

Lithology	Ratings
Igneous	3
Shale	6
Sand with minor clay	7
Sandstone	8
Gravel	9

Table 3.7.:Ratings assigned for a) soil media b) slope c) impact of vadose zone.

a)

Type	Ratings
Bad Land	0
Silt/Clay Loam	4
Loam	5
Sand	9
Gravel	10

b)

Slope (%)	Ratings
< 2	10
2 -10	8
10 – 20	5
20 - 33	2
> 33	1

c)

Depth (meters)	Ratings
1 – 3	10
3 – 4	8
4 – 6	5
6 - 8	3
8 - 9	1

Table 3.8.: Ratings assigned for soil permeability.

K (cm^2)	Ratings
Impermeable	0
Very Slow	1
Slow	4
Moderate	6
High	10

Table 3.9.: Weights assigned for groundwater vulnerability calculations.

Parameters	Ratings
Depth to Groundwater	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of Vadose Zone	5
Soil Permeability	3

Table 3.10.: Defining the vulnerability areas.

Vulnerability Classes	**Groundwater Assessment Requirements**
Low	A desk study is required to identify the concerns and potential risk to groundwater or the environment, and the need for any further action to be presented in the development application
High	The risk to groundwater is an area in which contamination to groundwater cannot be tolerated and an effective protection design system needs to be demonstrated

Table 3.11.: Selection of parameters, assigning of weights (wi), assigning of WHO standards and calculating relative weight (Wi).

Parameters	**Weights (wi)**	**WHO Standards (Si)**	**Relative Weights (Wi)**
EC	4	500	0.19
pH	4	7.5	0.19
Ca	2	75	0.10
Mg	2	30	0.10
Cl	3	200	0.14
Na	3	200	0.14
K	2	12	0.10
Coliform	5	10	0.24
	Σwi = 21		Σ Wi = 1.00

Table 3.12: Defining the water quality index

Water Quality Classes	**Explanations**
Unfit for Drinking	Water containing hazardous material and is not safe for drinking.
Good Quality	Water quality meets the WHO standards and is safe for drinking.

Chapter 4

4. RESULTS

4.1. Spatial and Temporal Analysis

After the data had been studied, prepared and analyzed on an individual basis, the next step was to compare these maps temporally. The main objective of the study was to observe the changes in groundwater quality over the years with specific reference to land use changes over that time.

A. Land Use - Land Cover

In 2003, the sectors D-12, D13, and E-11 were just raw land under CDA, represented in brown (soil) and green (vegetation). However, in seven years, sector E-11 has been developed, and D-12 and D-13 are being developed, represented by yellow (urban). In 2003, there was no developed area beyond F-11 and G-11 (represented by green), but by 2010, further development into sectors F-12, G-12, G-13, etc. has taken place (represented by yellow). In 2003, H-8, H-9 and H-10 were almost barren lands (brown and green). However, by 2010, much of this area has been urbanized (yellow). In 2003, 18.34% of Islamabad was urbanized. In 2010, 23.88% of the area was covered with buildings, roads and other impermeable surfaces. In seven years, Islamabad lost 5.54% (approximately 50 km^2) land area to urban development. It is a huge loss considering the amount of green area destroyed to make building and roads. Almost 50 km^2 of the area not only became impermeable to water but during the construction, chemicals and other salts infiltrated and contaminated groundwater. The difference in vegetation and soil areas can be accounted for by the seasonal variation. In March, the vegetation is comparatively less than that in July.

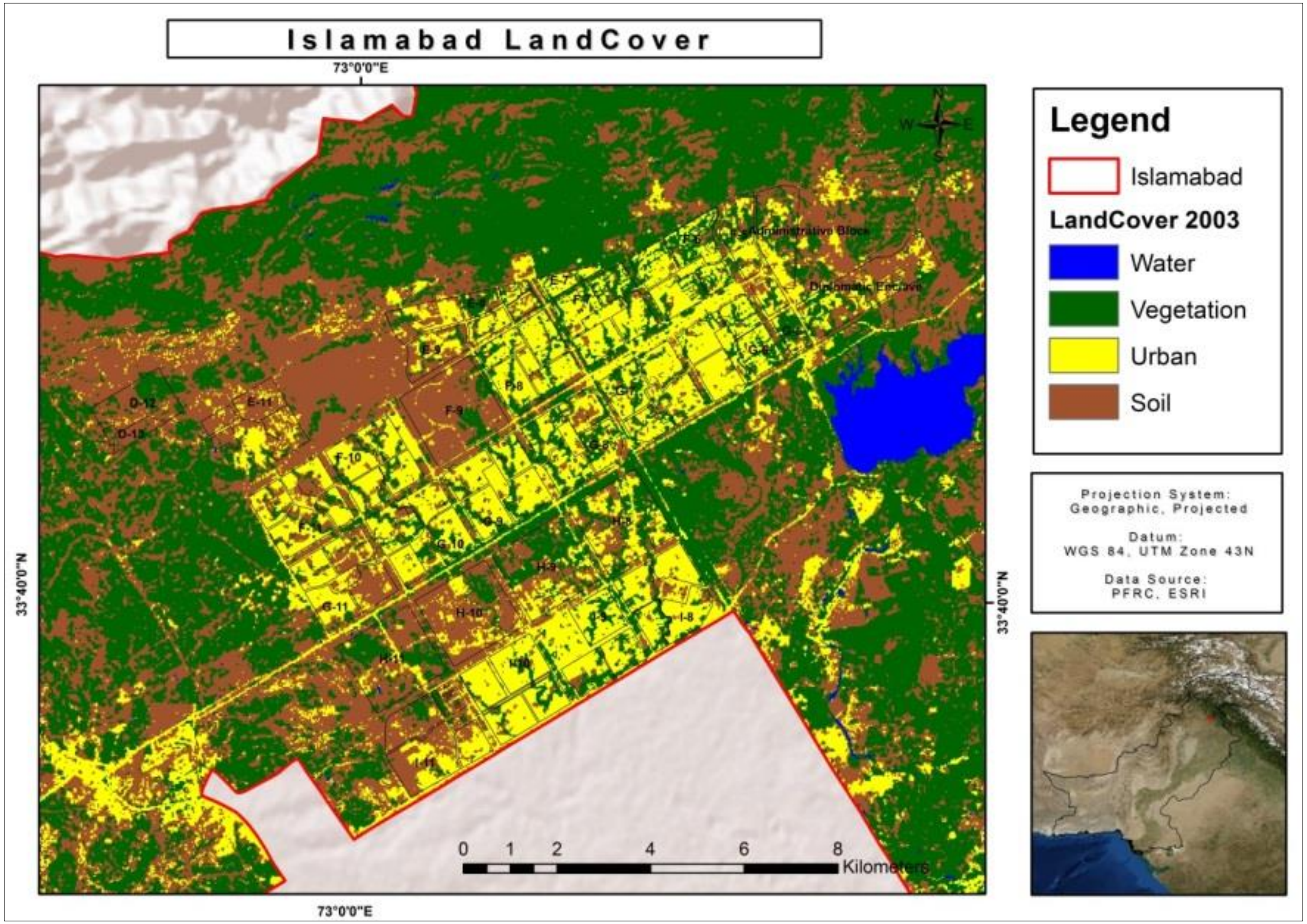

Figure 4.1.: Islamabad land cover 2003 (July).

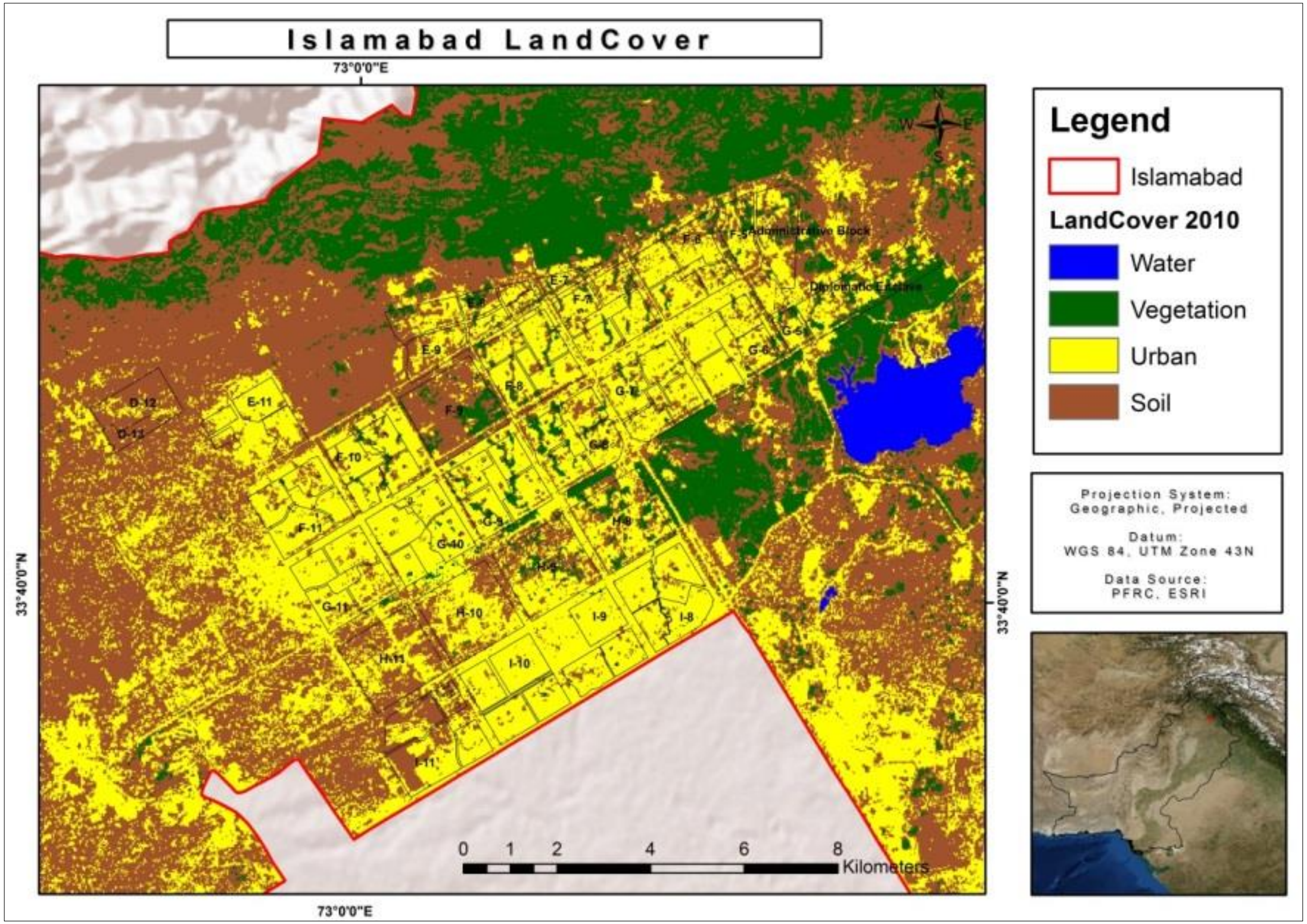

Figure 4.2.: Islamabad land cover 2010 (March).

Table 4.1.: Comparison of land cover.

Classes	2003	2010
Water	1.08%	0.7%
Vegetation	47.91%	12.29%
Urban	18.32%	23.88%
Soil	32.66%	63.13%

B. Depth to Groundwater

In 2003, the water-table had a depth of 88-92 meters in D-12, D13 and E-11 sectors of Islamabad. In 2010 the depth reached 92-96 meters. In 2003, these areas were not developed, however by 2010 these sectors were not only developed but were fully functional. From 2003 to 2010, depth of groundwater table decreased from 92-96 meters to greater than 100 meters in F-11, G-5, G-6, G-11, H-8, H-9, H-10, I-8, I-9, I-10, I- 11. In seven years, these sectors had attracted a lot of population and the trend of personal borings was not only a trend but also the need of time. In 2003, 24.41% of groundwater table had a depth of less than 88 meters. By 2010, only 2.43% area had less than 80 meters of groundwater table. In 2003, only around 1.61% of groundwater table was greater than 100 meters but this area increased to 5.31% by 2010. In 2003, 3.51% of groundwater table was between 96 – 100 meters but by 2010, 33.87% area had reached this level. Overall, the groundwater table has lowered drastically in last seven years. More than 3.7% of groundwater table is lowered to greater than 100 meters while 30.36% of groundwater table is lowered between 96 – 100 meters. Almost 21.98% of shallow groundwater table has been lost due to over population and over urbanization in span of seven years.

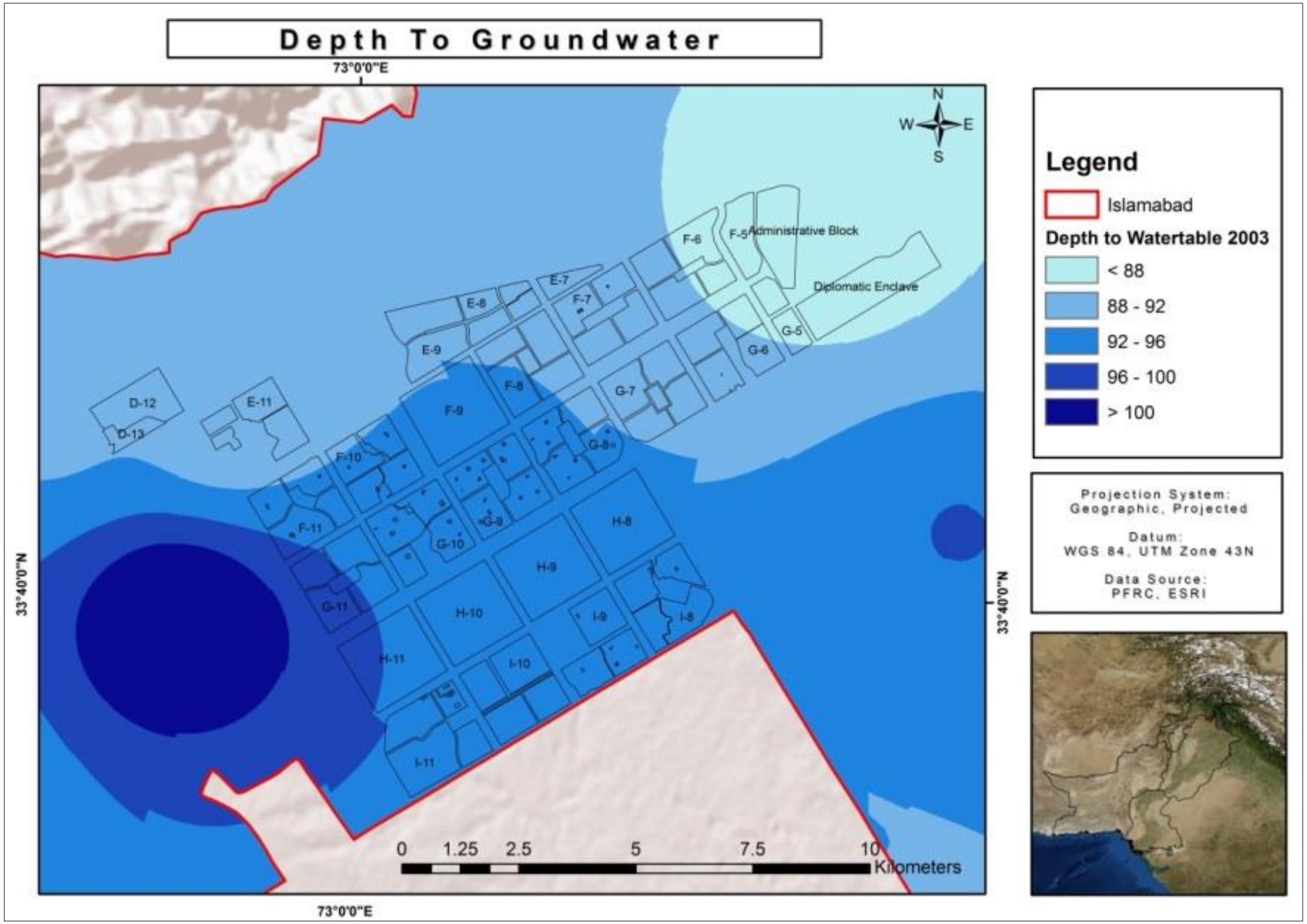

Figure 4.3.: Depth to groundwater 2003 (measure in meters).

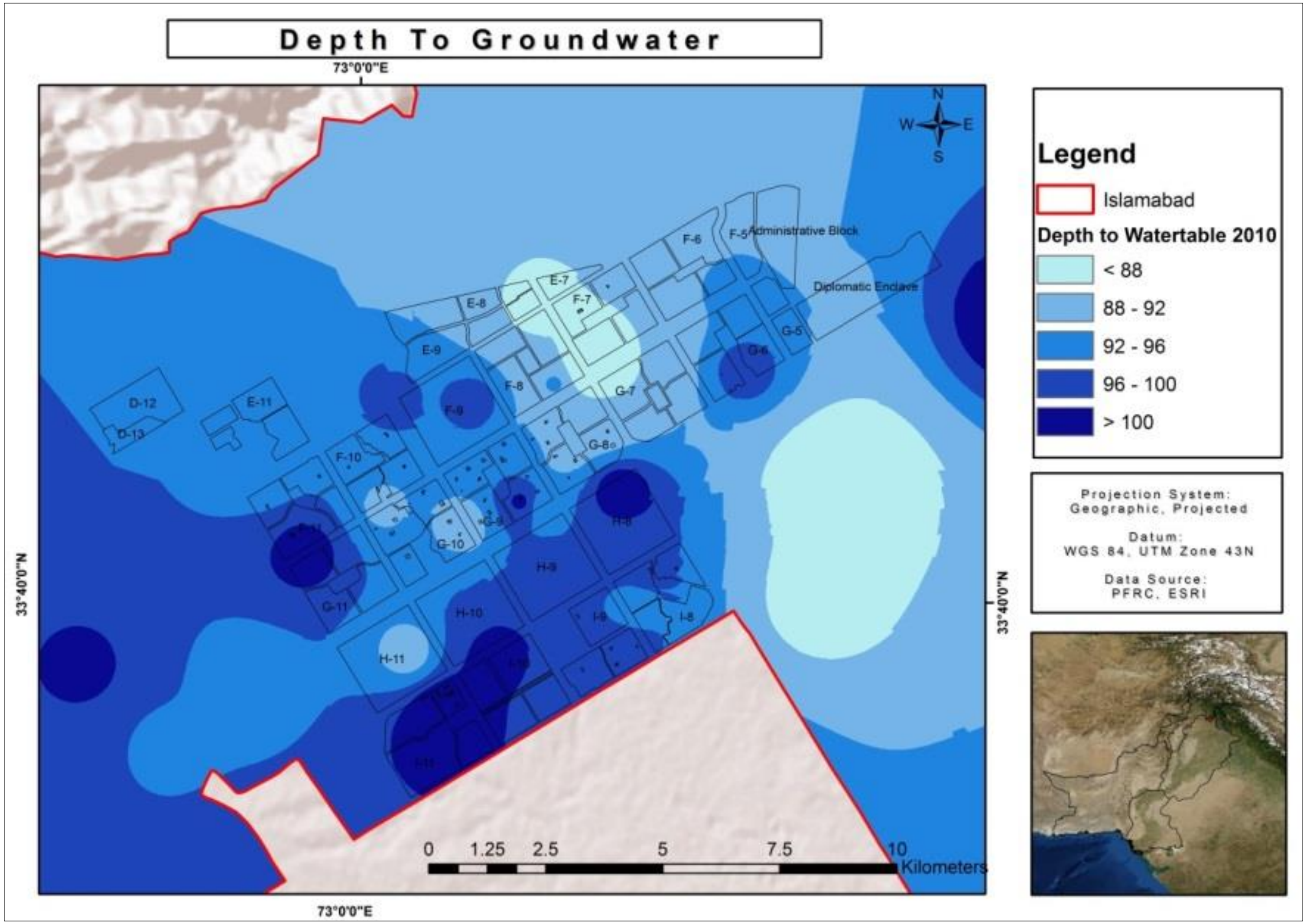

Figure 4.4.: Depth to groundwater 2010 (measure in meters).

Table 4.2.: Comparison of depth to groundwater.

Classes	2003	2010
< 88	24.41%	2.43%
88 - 92	42.63%	13.06%
92 – 96	27.84%	44.53%
96 – 100	3.51%	33.67%
> 100	5.31%	5.31%

C. Net Recharge

The net recharge is defined as the amount of water that penetrates the ground surface and reaches the water table. Net recharge is calculated using rainfall, slope, and soil permeability. Islamabad has an uneven topography, gradually rising in elevation from 500 meters to 600 meters above sea level. On average, annual rainfall in Islamabad is 1143 millimeters. In 2003, it was approximately 1504 millimeters and in 2010 it was around 1171 millimeters. Soil permeability has decreased with time (discussed in the section). The major noticeable change is in area between G-11 and H-11 where the net recharge has decreased from 9-11 to 7-9. Overall, the net recharge has decreased over the years. The noticeable changes are in values 5-7 which decrease from 38.68% to 39.72% and values 11-12 which decrease from 29.63% to 29.7%. These minute changes are because of the changes in soil permeability which can be proven when both maps are observed simultaneously. Net recharge is indirectly related to urbanization over the years. As urbanization increased, the groundwater depth decreased, increasing the impact of the vadose zone. Decrease in soil permeability means less recharge in those areas. Hence all factors complement each other perfectly.

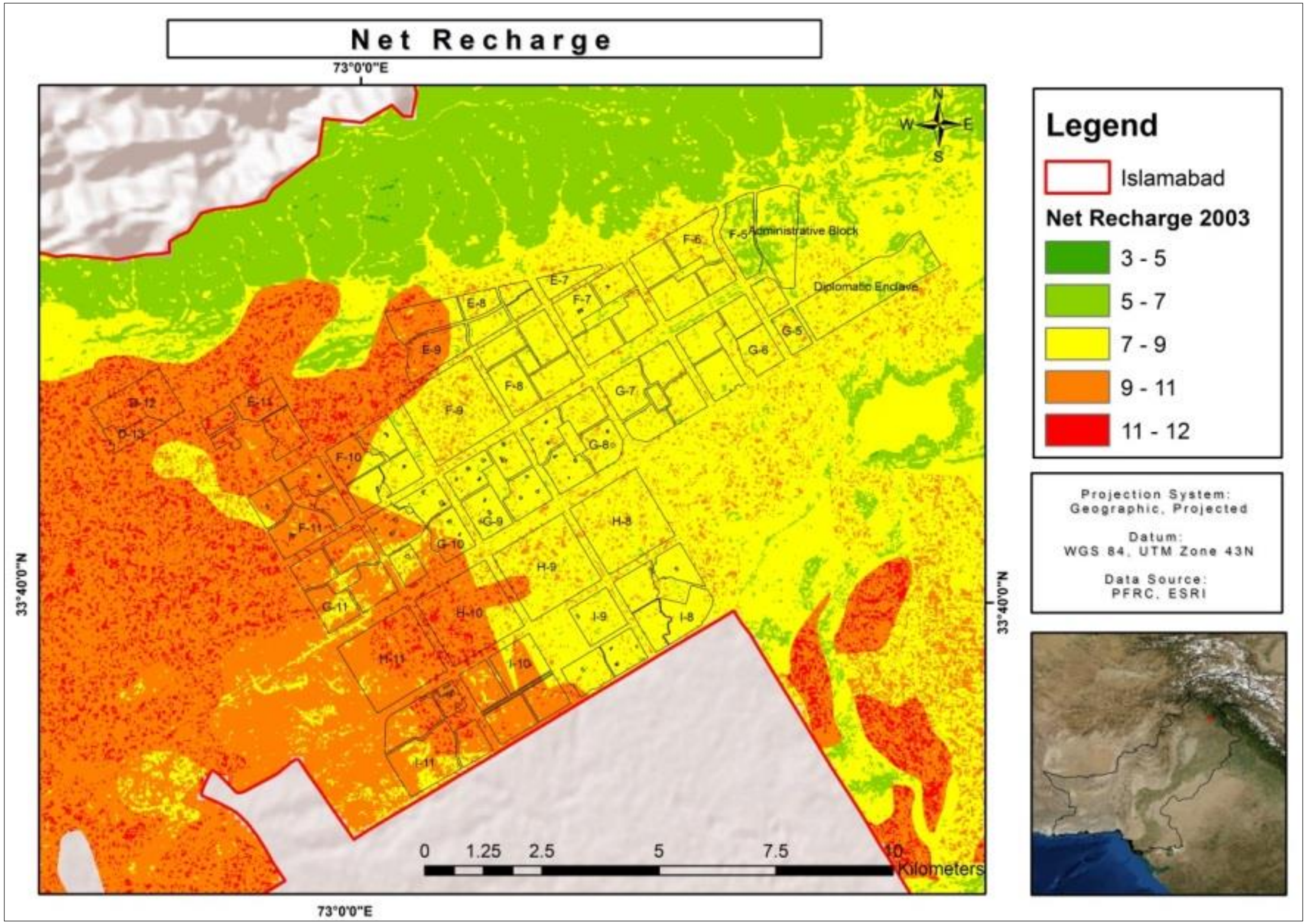

Figure 4.5.: Net recharge 2003 (measured in volume per unit time).

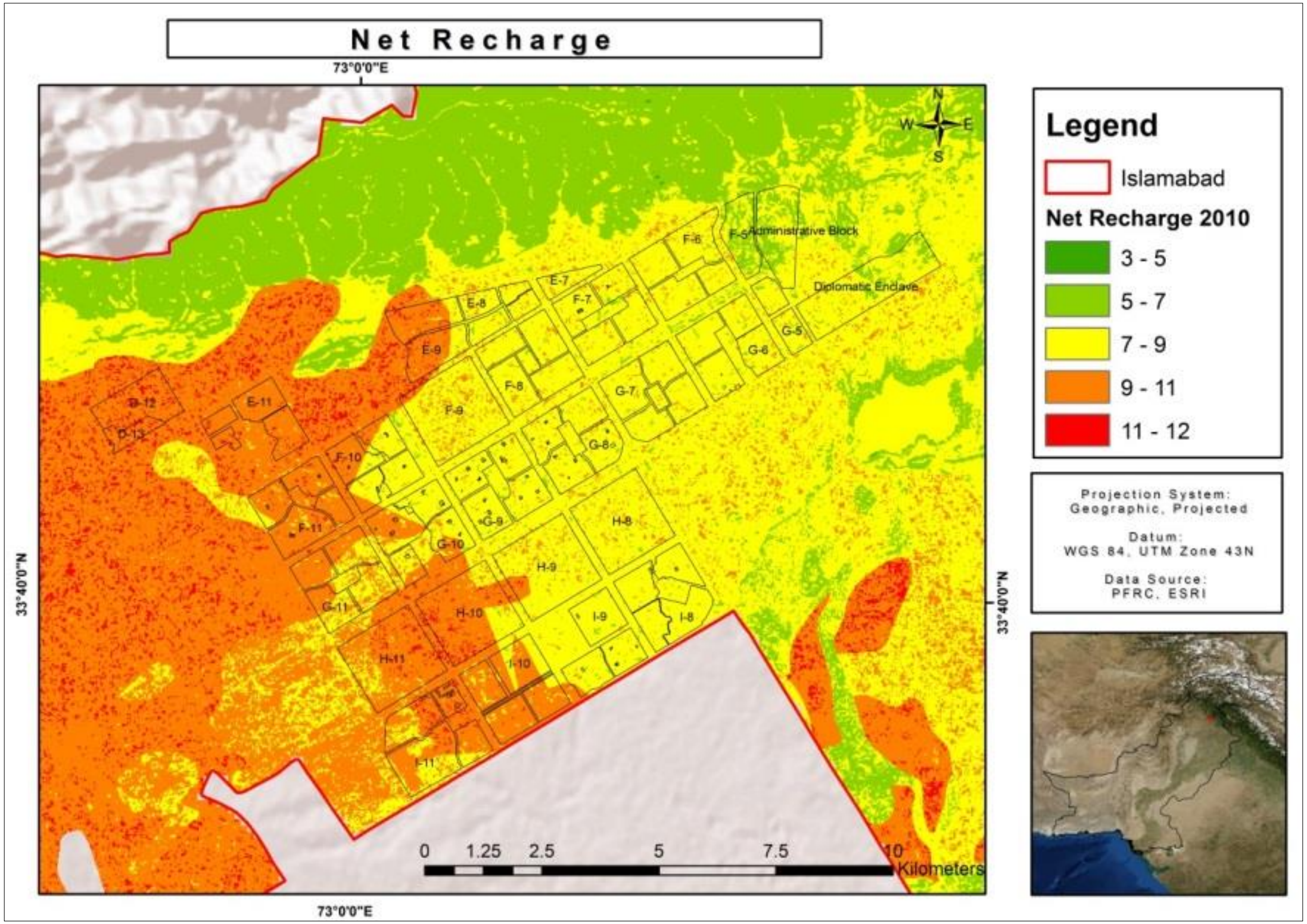

Figure 4.6.: Net recharge 2010 (measured in volume per unit time).

Table 4.3.: Comparison of net recharge.

Classes	2003	2010
3 - 5	0.05%	0.01%
5 - 7	42.63%	29.59%
7 – 9	27.84%	39.72%
9 – 11	3.51%	29.7%
11 - 12	4.48 %	3.98%

D. Aquifer Media

This map has been digitized on a map made in 1985. Since then aquifers have depleted due to lowering of water table, water contamination, development and other related factors. But maps have not been accordingly updated.

All of sectors G-7, G-8, G9, G-20, G-11, H-8, H-9, H-10, H-11, I-8, I-9, and I-10 are situated on the Gravel lithology. Part of F-8, F-9 and most of F-10 and F-11 is also covered by Gravel. However, the other parts of these sectors have an igneous lithology. Sectors D-11, D-12, E-7, E-8, E-9, E11, F-6, and F-7 lie completely over Limestone. Islamabad’s aquifer lithology comprises of Sandstone and Shale (21.81%), Limestone (24.68%), Igneous (4.11%), Sand with minor Clay and Silt (12.91%), Shale (2.5%), and Gravel (33.99%). Limestone and Gravel have high infiltration rate and makes a good ground-water recharge medium and aquifer. Sandstones are favorable as aquifers but require mechanical drilling whereas shale is unfavorable.

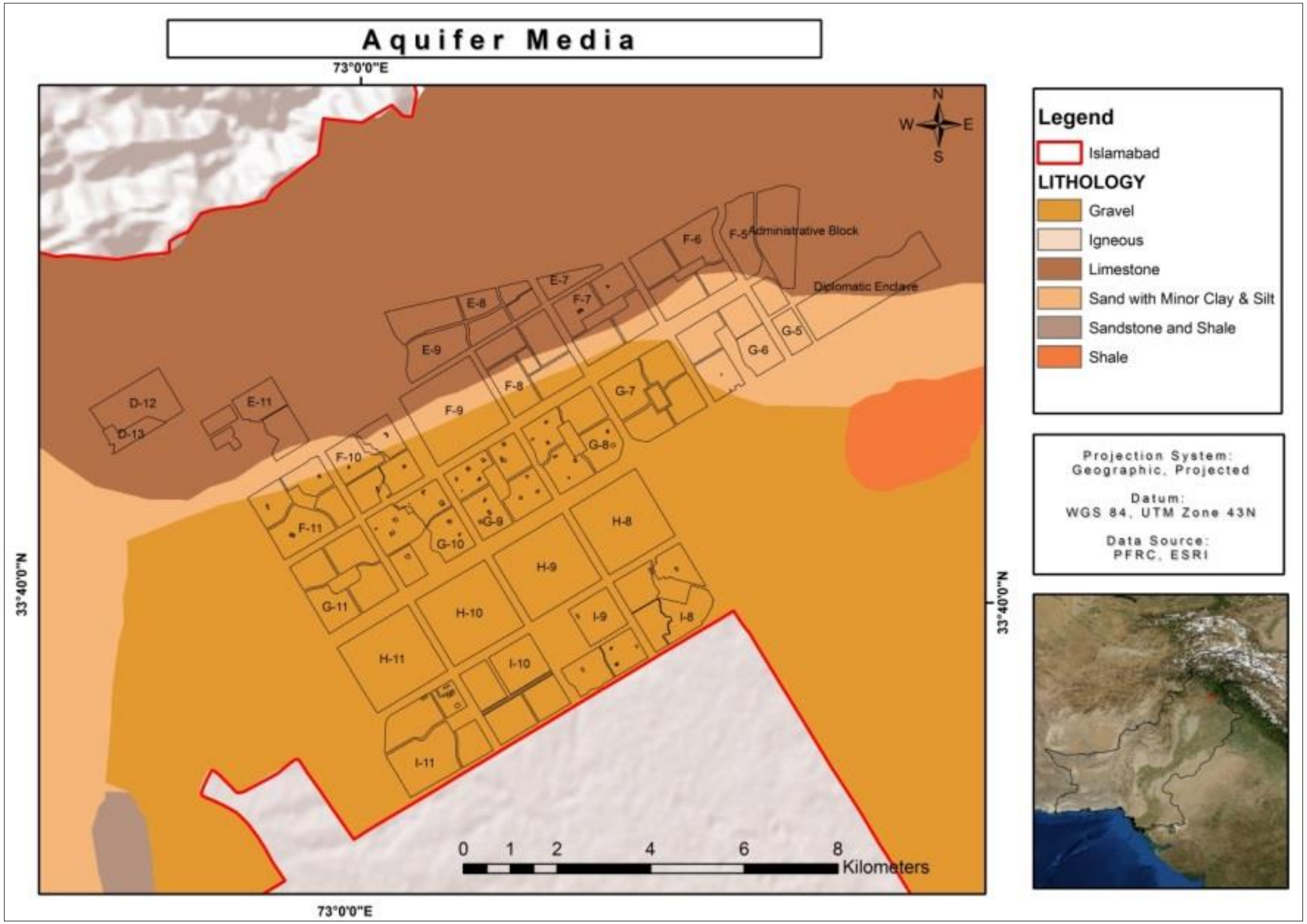

Figure 4.7.: Aquifer media.

E. Soil Media

The soil map was acquired from soil survey of Pakistan. It was combined with land cover map of Islamabad to take into account the impermeable surfaces. Soil media is the upper weathered zone of the earth, which averages a depth of six feet or less from the ground surface. Soil has a significant impact on the amount of recharge that can infiltrate into the ground. Sand has low runoff potential and high infiltration rates, even when thoroughly wetted. Loam has moderate infiltration rate when thoroughly wetted. Sandy/Clay Loam has low infiltration rates when thoroughly wetted. Gravel has high infiltration rate. Bad land refers to impermeable layers. With increase in urbanization, there has been an increase in loam soils.

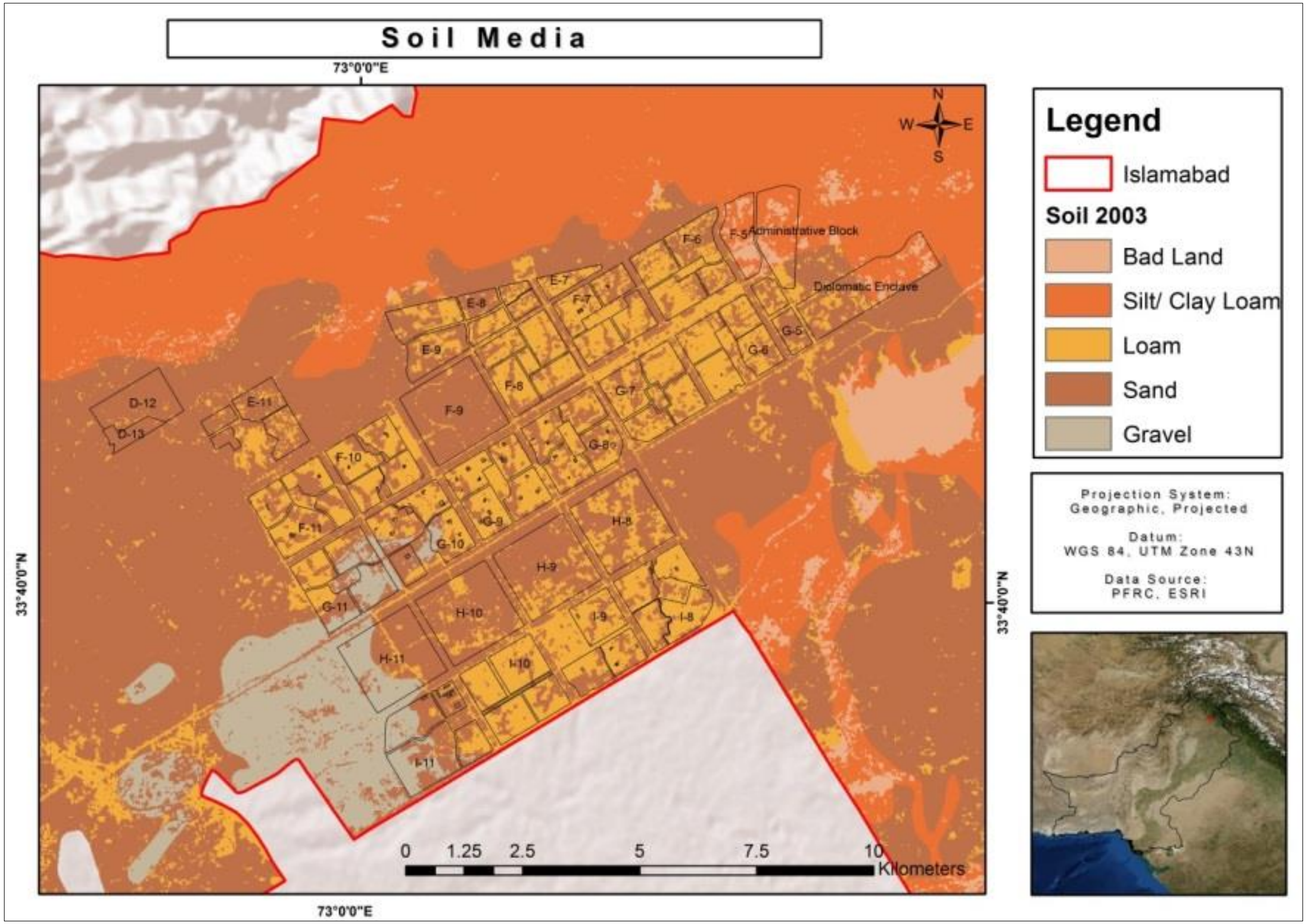

Figure 4.8.: Soil media.

F. Topography

Topography is the slope of the land surface. It is the deciding factor for the fate of the water runoff. Topography of the land surface controls the general direction of groundwater flow, and it impacts groundwater recharge and discharge. A recharge area is where water moves downward from a topographical high area into the zone of saturation. A discharge area is where groundwater moves towards the surface to into spring, lake, wetland, or a stream. Statistically speaking, 63.3% of the land has a slope of 2- 10%, hence allowing plenty of area and time for infiltration. 14.79% of the land has slope less than 2%, again allowing plenty of space for penetration of contamination. 10.96 % has slope of 10 – 20 %, 6.79% has slope between 20 -33%, and 4.14% has slope greater than 33% facilitating water runoff, therefore, no infiltration in these areas.

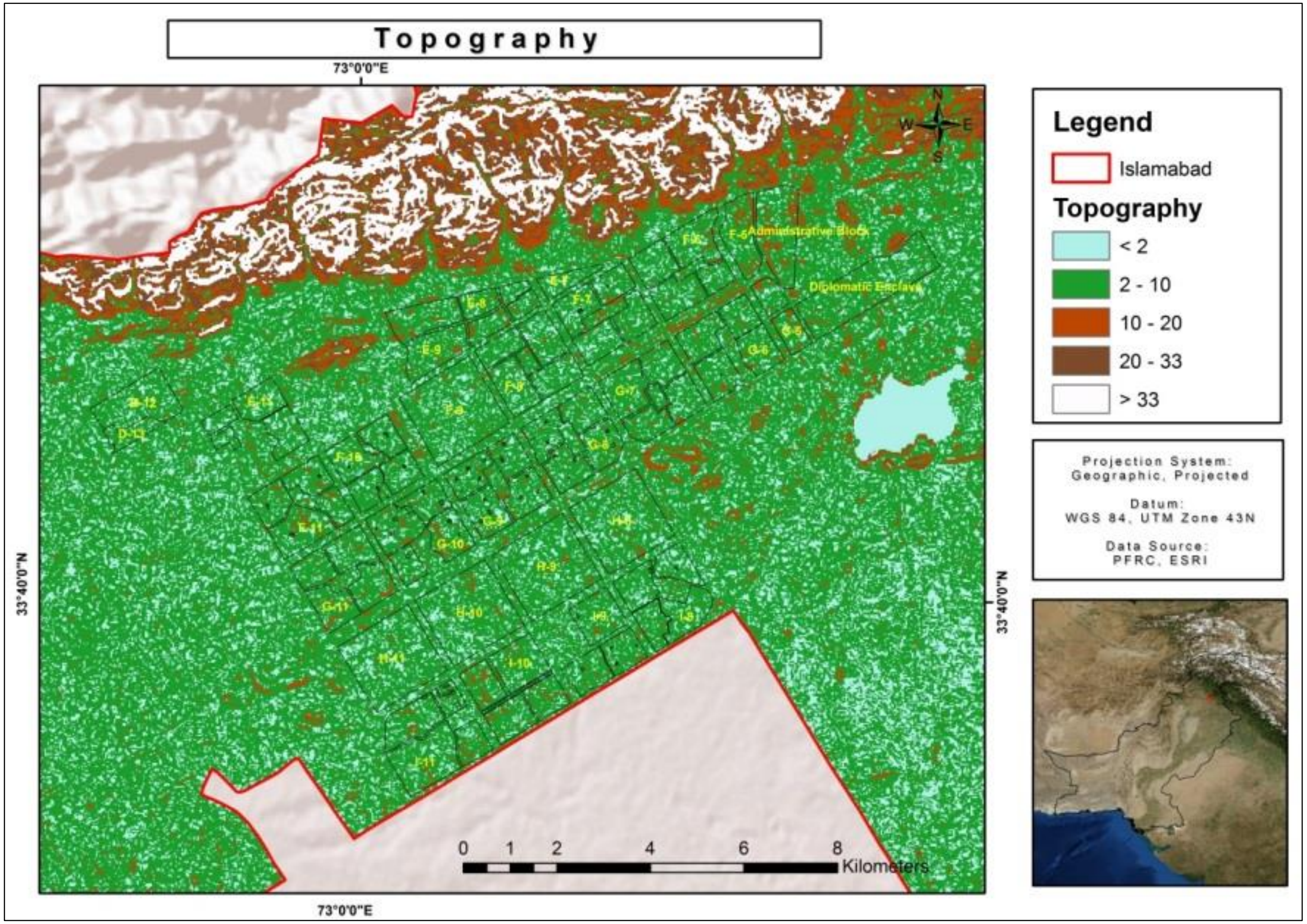

Figure 4.9.: Topography (measured in percentage slope).

G. Impact of Vadose Zone

Impact of Vadose zone is dependent on groundwater depth and soil permeability. The Vadose zone extends from the top of the ground surface to the water table. Vadose zone map was made by combining the soil permeability (discussed in the next section) and depth to groundwater maps. The vadose zone is the unsaturated soil horizon above the water table. The flow rates and chemical reactions in the unsaturated zone control whether, where, and how fast contaminants enter groundwater supplies.

In the diplomatic area of Islamabad, the impact of vadose zone has decreased over the seven years, whereas in other areas it has increased. However, in the rest of Islamabad the impact of vadose zone has increased, following a pattern similar to that of soil permeability map. Statistically, the impact of vadose zone values vary as follows: 1-3: 50.08% in 2003 and 14.91% in 2010, 3-4: 13.14% in 2003 and 31.881% in 2010, 4-6: 23.92% in 2003 and 26.04% in 2010, 6-8: 11.59% in 2003 and 26.68% in 2010, and 8-9: 1.27% in 2003 and 0.5 % in 2010. Decrease in depth to groundwater means increase in vertical distance from ground surface to groundwater table. All three maps: depth to groundwater table, soil permeability and their outcome, impact of vadose zone map complement each other. Hence this change can also be indirectly related with land use over the span of seven years.

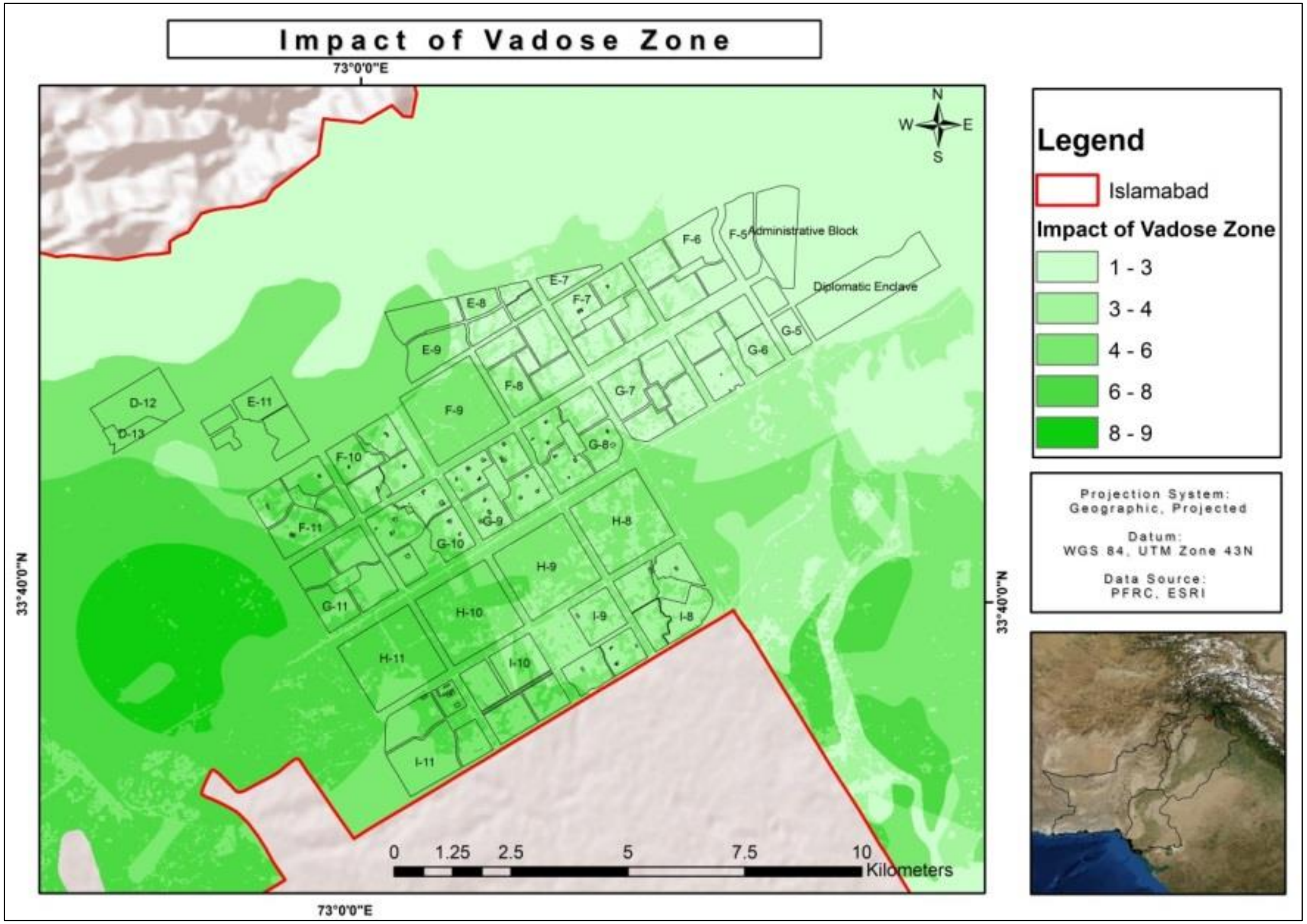

Figure 4.10.: Impact of vadose zone 2003 (measured in meters).

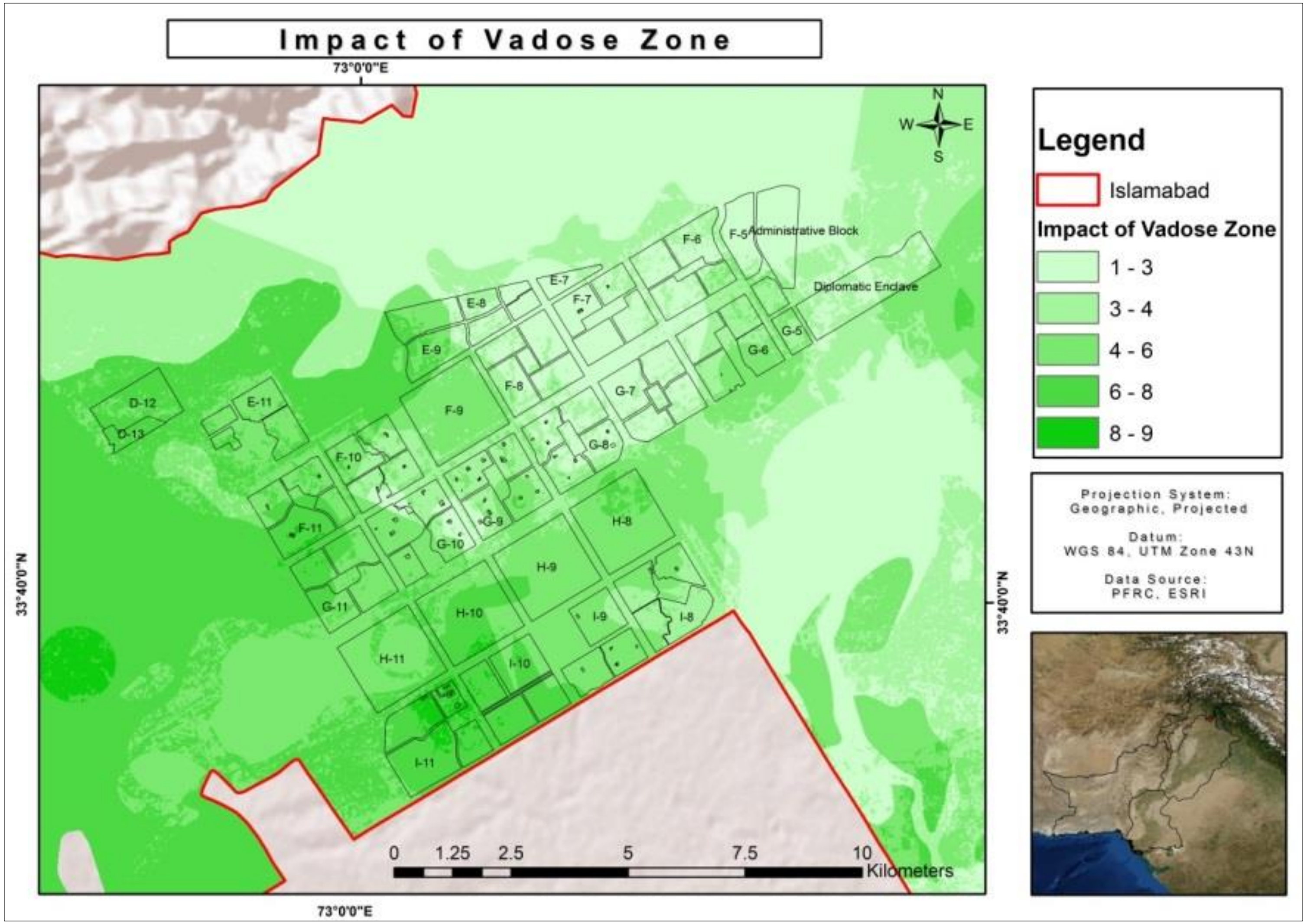

Figure 4.11.: Impact of vadose zone 2010 (measured in meters).

Table 4.4.: Comparison of impact of vadose zone.

Classes	2003	2010
1- 3	50.08%	14.92%
3- 4	13.14%	31.88%
4 – 6	23.92%	26.04%
6 – 8	11.59%	26.68%
8 - 9	1.27%	0.5%

H. Soil Permeability

Soil permeability is the property of the soil to transmit water. High permeability means high pollution potential. This map was made by combining the land use land cover map with soil permeability map obtained from soil survey of Pakistan. In seven years (2003 – 2010) the Diplomatic Area has seen a change in soil permeability from very slow to impermeable. Impermeable layer refers to areas where flow of water is zero. This is due to urban development. Soil permeability in Sector E-11 has changed from high to moderate as indicated by color change (from pink to purple). Area near or beyond sectors F-11, G-11 and H-11 has also experienced the decrease in the permeability from high to moderate or from moderate to slow. In sectors H-9 and H-8 the soil permeability has decreased from slow to very slow. In 2003, 48.79% area had very slow soil permeability whereas this percentage increased to 51.06% by 2010. If statistically studied, the soil permeability has decreased over the span of seven years. In 2003, 9.21% of the area was covered with slow permeable soil, 10.67% has a moderate permeable layer and 22.43% had high permeability. However, by 2010 there percentages dropped to 7.94%, 13.47% and 29.1% respectively. This change can be explained by the increase in development of Islamabad. As previously discussed, the seven years lost 5.54% area of Islamabad to development, hence the loss of soil layer (independent of the permeability). One of the major factors influencing the soil permeability is impurities in water, which means any foreign matter in water has a tendency to plug the flow passage and reduce the effective voids and hence permeability of soil. As a result of this development we saw a major decrease in soil potential. Hence less amount of water infiltrates into the ground contributing to the decrease in depth of groundwater table. The anomaly in this map is loss of impermeable area of the span of seven years from 8.9% to 8.42%; which can be explained by the fact that despite rapid development in the study area the plantation has been encouraged, even around the official buildings and roads.

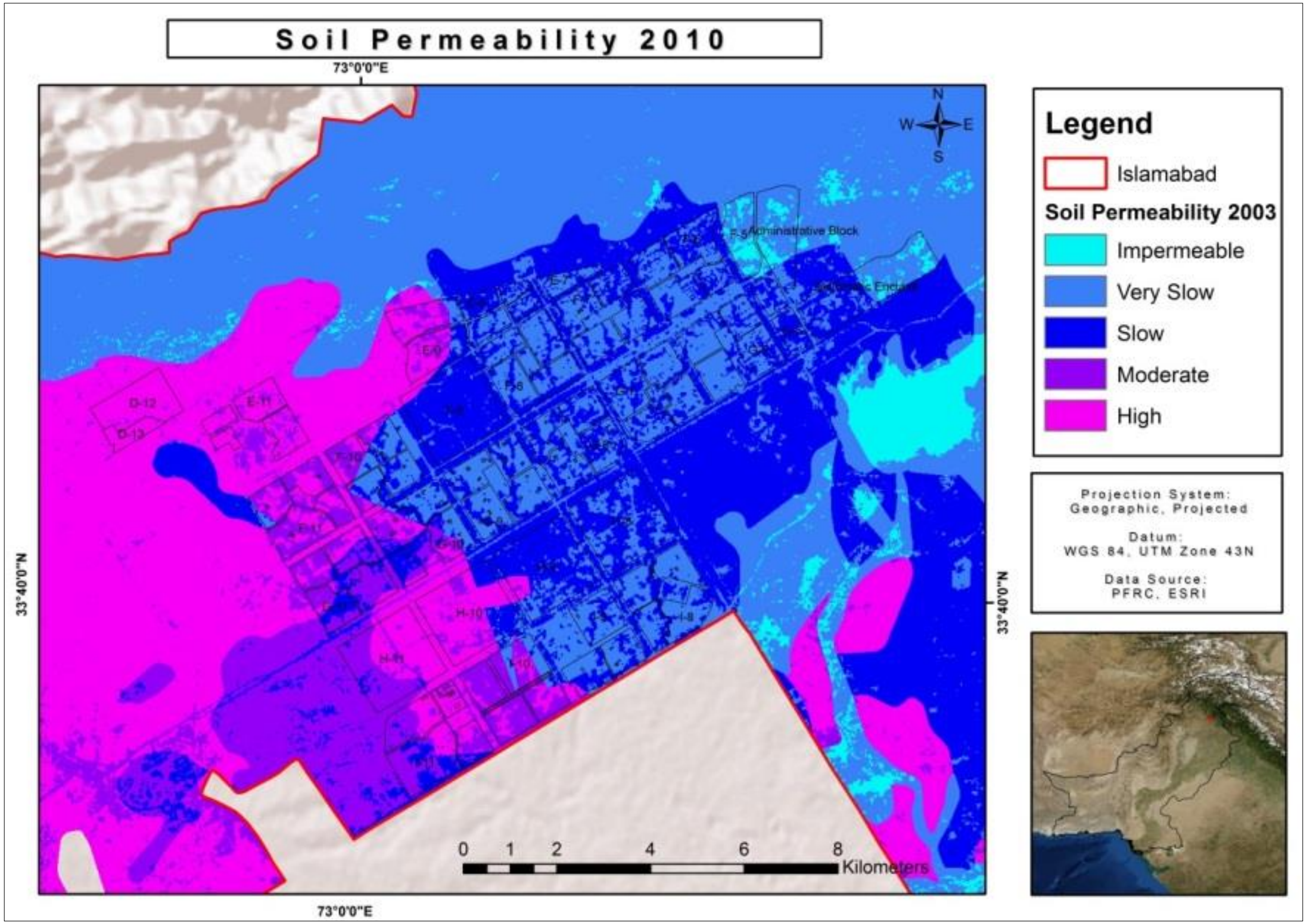

Figure 4.12.: Soil permeability 2003 (measured in cm^2).

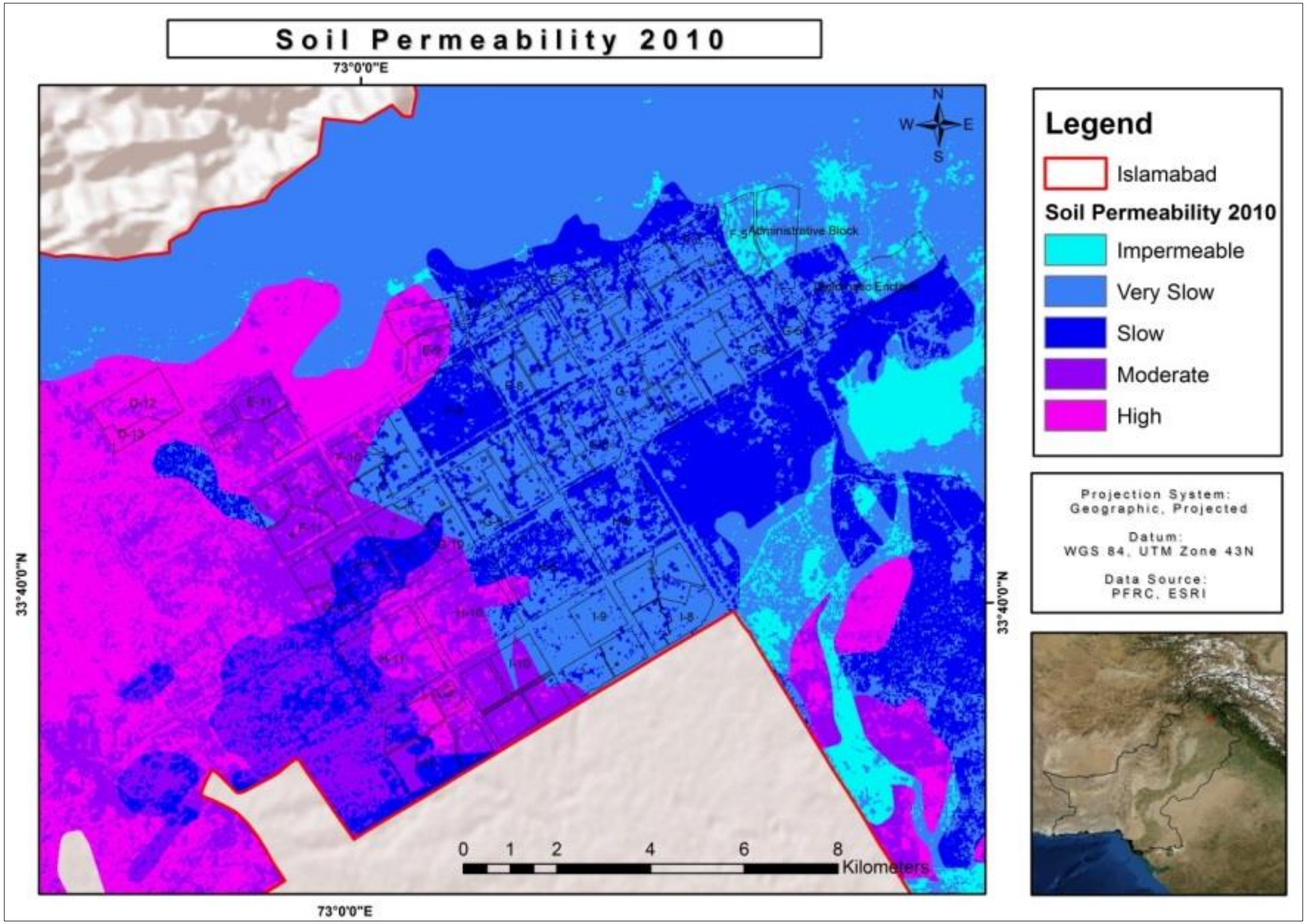

Figure 4.13.: Soil permeability 2010 (measured in cm^2).

Table 4.5.: Comparison of soil permeability.

Classes	2003	2010
Impermeable	8.9%	8.42%
Very Slow	48.79%	51.08%
Slow	9.21%	7.94%
Moderate	10.67%	13.47%
High	22.43%	19.1%

I. Groundwater Vulnerability

Groundwater vulnerability can be defined as natural susceptibility to contamination based on the properties of land and subsurface. Highly vulnerable areas mean more risk and need immediate attention. Moderately vulnerable areas can be saved if proper measures are taken. Low vulnerable areas are which possess the threat but for now are safe. Vulnerability has increased in sectors D-12, D-11, E-11, and E-8 over the span of seven years. A number of factors had a role in this increase. Land Use has increased during this time period. These sectors, which were by 2003 barren land, are now fully developed sectors. Of course, this leads to increase in depth to groundwater table, which lead to increase in vadose zone impact. These sectors can also be considered as rechargeable areas. Hence need immediate attention. Statistically, most of the area lies within the moderate vulnerability which means the increase from 2003 to 2010 has been from 5% to 8.5%. High vulnerability has increased from 1.5% to 4.5% in the span of seven years.

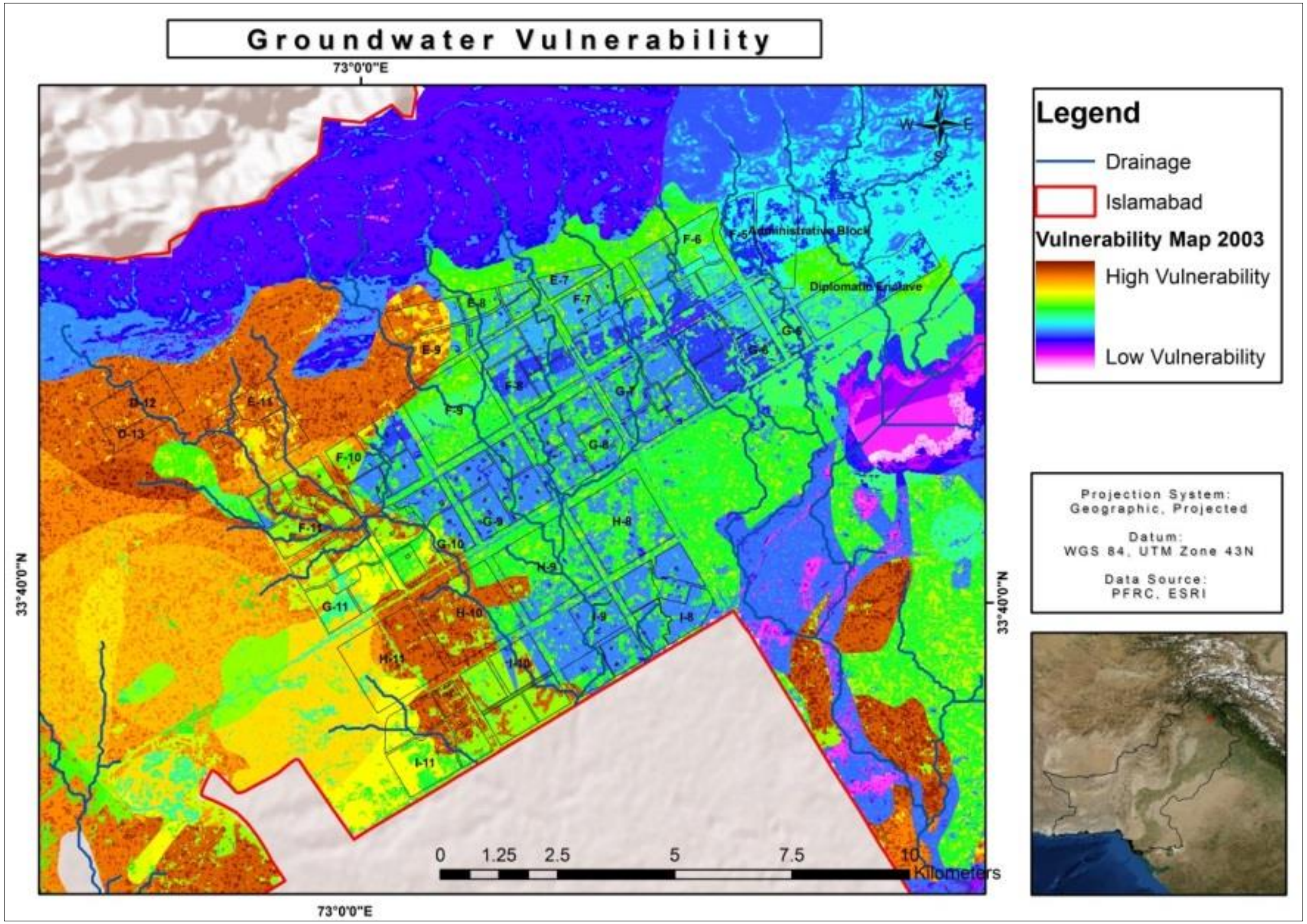

Figure 4.14.: Groundwater vulnerability 2003.

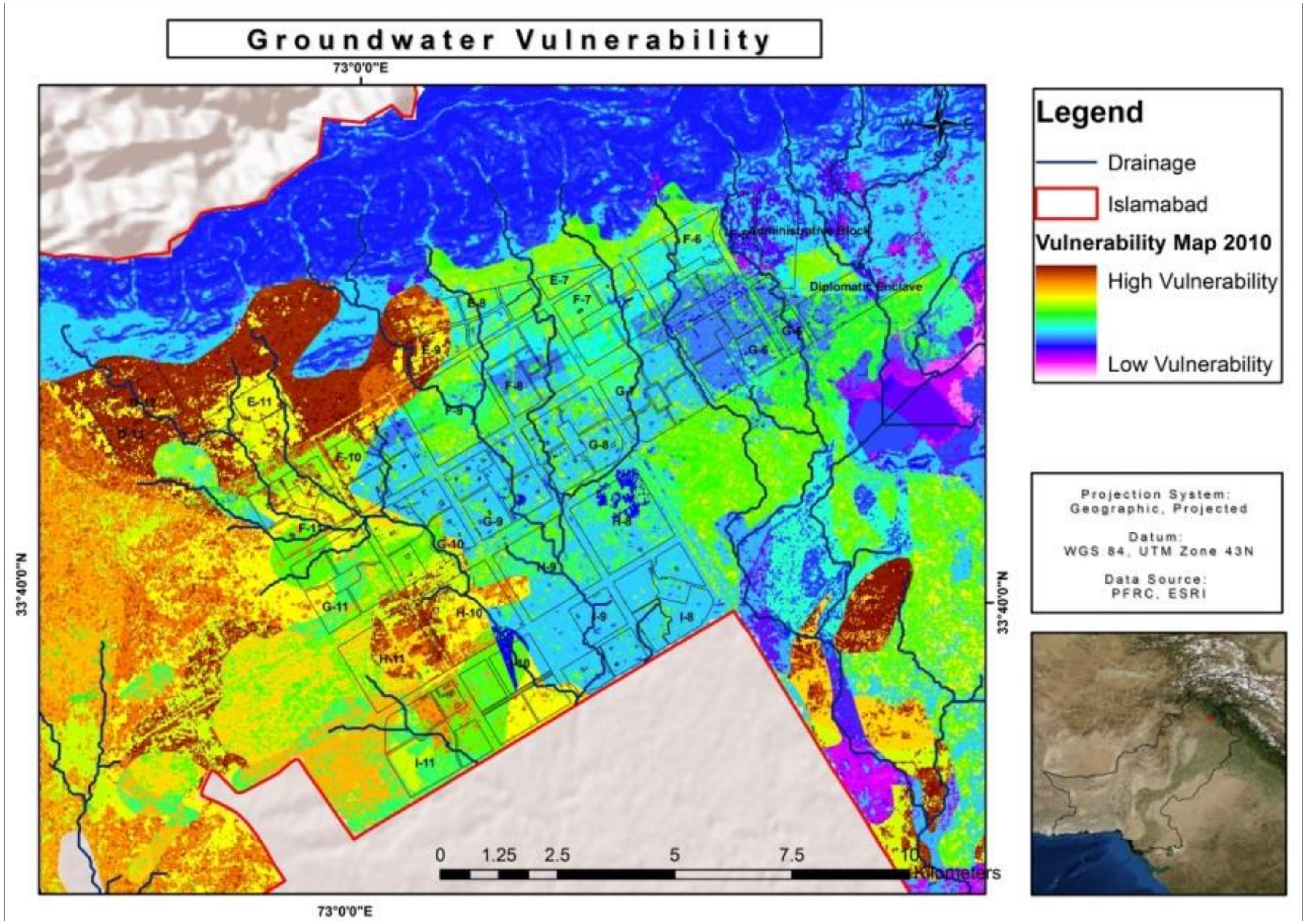

Figure 4.15.: Groundwater vulnerability 2010.

J. Validation: Water Quality Index

The Water Quality Index is a valuable and an effective tool to review the monitoring data in order to apprehend the status of the groundwater quality. In this study Water Quality Index was used as a validation. The pre-existing data of 2003 and 2010 were used to calculate the index value and then a map was generated for both the years. WQI determination has a number of limiting factors, such as extensive man power for data collection and expensive data analysis. Therefore, the methodology used for this study provides an alternative for regular monitoring of groundwater with a few maps and already available data. According to the map made water quality in sectors F-10 and F-11 has improved over the years. Many factors can be considered in this improvement such as the government took initiative and improved the water quality of these areas. As these areas are more commonly known as posh areas of the city, it is likely that the residents themselves have taken great measures to ensure that they get a better quality drinking water. Another factor that needs to be taken into account is that the data was not sufficient for each sector and hence these maps are based on interpolation of the available points. However, the water quality in rest of Islamabad has worsened over the years. Again, a lot of factors contribute to this change. The areas which were once moderately populated are now densely populated, which leads to more usage of water and increased the changes of water contamination. Increase in industrialization in Islamabad has also affected the water quality badly. Above all, government organizations are not actively working towards improving water quality of Islamabad. No regularized monitoring is done and no measures are taken to protect the wells – not even the government wells.

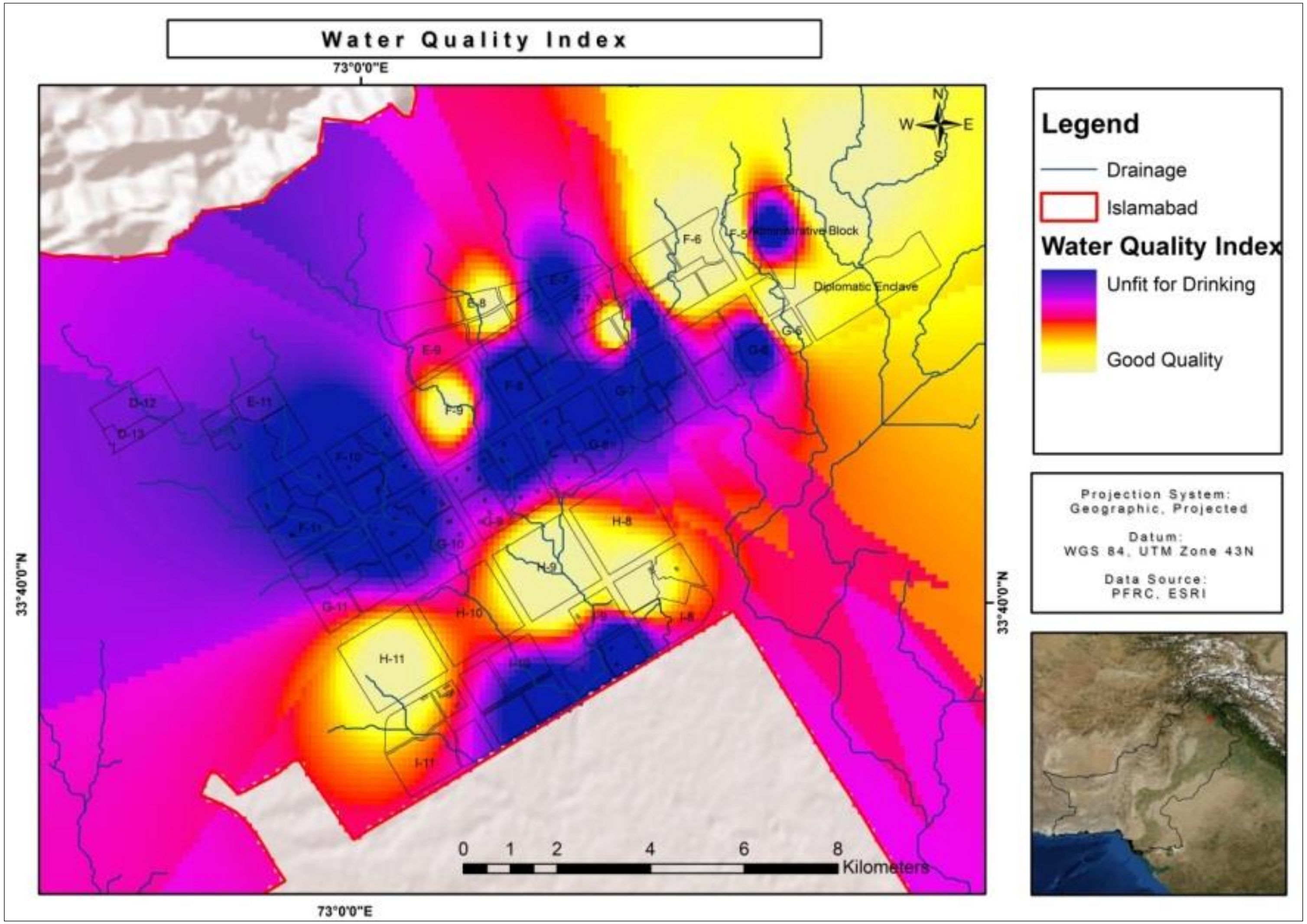

Figure 4.16.: Water quality index 2003.

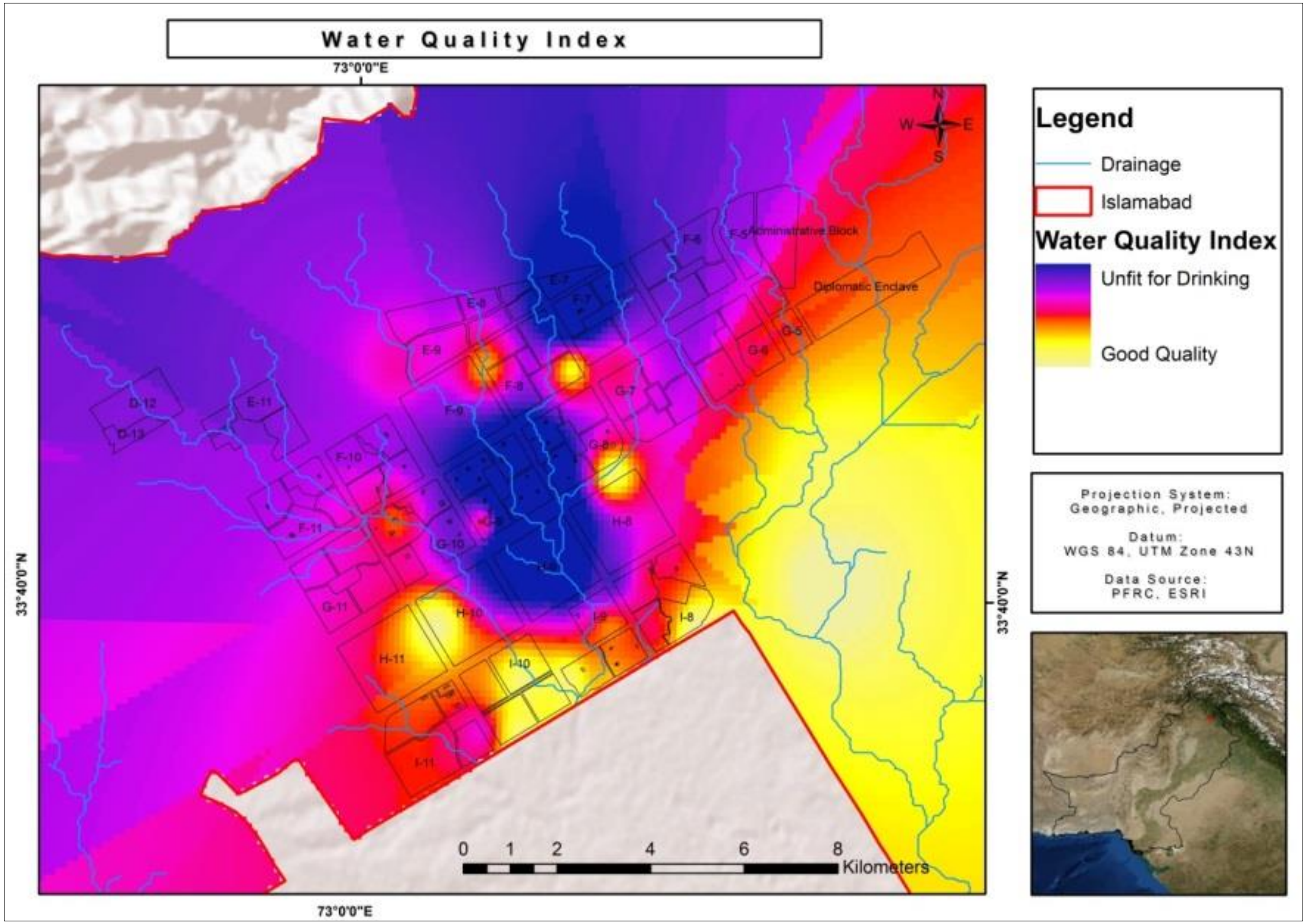

Figure 4.17.: Water quality index 2010.

Chapter 5

5. CONCLUSION AND RECOMMENDATIONS

5.1. Limitations

As such, there are few limitations regarding the methodology and its application that ought to be considered in the future. There was a lack of consistent data availability. The available data was not of the same seasons or the same wells which could explain the diversity in results. A lack of cooperation of government organizations while sharing data for research purposes was another constraint. There is no existence of required data due to lack of surveys conducted. The data available has to be manually entered into the system – no digital data available. Surveys for soil media, soil permeability, aquifer media etc. were done in early 1990's and no recent data is available.

5.2. Conclusion

This study employed a GIS model to determine the vulnerability of groundwater to contamination in Islamabad. This was accomplished using the DRASTIC model. The results reveal that GW in and around in substantial part are under moderate to high pollution vulnerable zone. The study shows that with the help of GIS once the different data layers are prepared and overlaid the water vulnerable zones can easily be identified. The high vulnerability of groundwater contamination makes it absolutely necessary to local authorities for managing groundwater resources, monitoring this problem closely and to act accordingly. The DRASTIC model, used for preparing the pollution potential map, can be used as a screening tool to see whether a particular area is more or less vulnerable to groundwater pollution. The mapping technique used for this analysis is a qualitative method of describing the occurrence and distribution of groundwater pollution.

The objective of this study was to delineate the spatial variation of groundwater quality in the study area indicating that the water quality of the region is generally good, but deterioration has commenced with the onset of urbanization. The remote sensing data used in study is Landsat image of 2003 and 2010 with a spatial resolution of 30 m. Supervised digital classification was applied for preparing land cover.

The study characterizes aquifer vulnerability, elucidating the relationship between land use & groundwater quality. The water quality currently is deteriorating. Seven years lost 5.54% (approximately 50 km2) area of Islamabad to development. Almost 21.98% of shallow groundwater table has been lowered due to over population and over urbanization in span of seven years. Overall, the net recharge has decreased over the years. As the urbanization increased the groundwater depth decreased, increasing the impact of vadose zone. Decrease in soil permeability means less recharge in those areas. Hence all factors complement each other perfectly.

Islamabad's aquifer lithology comprises of Sandstone and Shale (21.81%), Limestone (24.68%), Igneous (4.11%), Sand with minor Clay and Silt (12.91%), Shale (2.5%), and Gravel (33.99%). With increase in urbanization, there has been an increase in loam soils. When comparing the two maps, it shows that quantity of loam has increased about 5.15% in the seven years duration. Spatially, it follows the pattern similar to the urban development. In the diplomatic area of Islamabad, the impact of vadose zone has decreased over the seven years, whereas in other areas it has increased. In seven years (2003 – 2010) the diplomatic area has seen a change in soil permeability from very slow to impermeable. Impermeable layer refers to areas where flow of water is zero. This is due to urban development.

Over the years, groundwater quality of Islamabad has deteriorated considerably. Over the last seven years (2003 – 2010) there has been considerable change in land use. This development has adversely affected the groundwater quality. Residual from construction sites, building of roads, and industries over the time had an irreversible impact on groundwater quality. Other factors include landfills, improper disposal of sewage, and no maintenance of areas not under CDA. Extraction of groundwater has lowered the water table.

Islamabad's groundwater is endangered and in need of protective measures. In the seven years moderate vulnerability of aquifers has increased from 5% to 8.5%, and high vulnerability has increased from 1.5% to 4.5% leading us to conclude that the groundwater quality is degrading.

5.3. Recommendations

Policy or decisions should be made that any future licenses for the installation of fueling stations will be made after considering Groundwater vulnerability in that area. To derive more accurate results, data on regional level was required but no such data repository is currently available. It is recommended that a national database should be developed. CDA should install observation wells in high vulnerability areas as well as careful in planning of urban growth, preservation of green areas, and plant more trees.

Since testing of water quality of wells within large watersheds is not economically feasible, one frequently used monitoring strategy is to develop contamination maps of groundwater, and then prioritize those wells located in the potentially highly contaminated areas for testing of contaminants.

REFERENCES

Ahmad, Z., Kausar, R., & Ahmad, I. (2010). Implications of depletion of groundwater levels in three layered aquifers and its management to optimize the supply demand in the urban settlement near Kahota Industrial Triangle area, Islamabad, Pakistan. *Environmental Monitoring and Assessment*, *166*(1-4), 41–55. doi:10.1007/s10661-009-0983-9

Akhtar, M. M., & Tang, Z. (2013). Identification of Contamination Sources and TDS Concentration in Groundwater of Second Biggest City of Pakistan. *International Journal of Environmental Science and Development*, *4*(3). doi:10.7763/IJESD.2013.V4.367

Albuquerque, M. T. D., Sanz, G., Oliveira, S. F., Martínez-Alegría, R., & Antunes, I. M. H. R. (2013). Spatio-Temporal Groundwater Vulnerability Assessment - A Coupled Remote Sensing and GIS Approach for Historical Land Cover Reconstruction. *Water Resources Management*, *27*(13), 4509–4526. doi:10.1007/s11269-013-0422-0

Ali, M., & Qamar, A. M. (2013). Data analysis, quality indexing and prediction of water quality for the management of rawal watershed in Pakistan. *Eighth International Conference on Digital Information Management (ICDIM 2013)*, 108–113. doi:10.1109/ICDIM.2013.6694009

Aller, L., Hackett, G., & Thornhill, J. (1987). DRASTIC : A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings by. *Robert S. Kerr Environemental Research Laboratory Office of Reseach and Develovpment U.S Environmental Protection Agency*.

Amjad, H., Hashmi, I., Rehman, M. S. U., Ali Awan, M., Ghaffar, S., & Khan, Z. (2013). Cancer and non-cancer risk assessment of trihalomethanes in urban drinking water supplies of Pakistan. *Ecotoxicology and Environmental Safety*, *91*, 25–31. doi:10.1016/j.ecoenv.2013.01.008

Ashfaq, S. A. D., Muhammad, A. D., & Ali, B. (2007). *Assessment of water Resources and Developement of Strategic Water Utilization Plan in Pothwar Region for its Sustainable Management*.

Bhoi, D. K., Dabhi, H. R., Pandya, S. N., & Chauhan, N. B. (2011). Water Quality Index (W.Q.I.) of Pariyej Lake Dist. Kheda - Gujarat. *Current World Environment*, *6*(2), 225–231.

Cheema, W. A., Naseer, A., & Haq, T. (M) R. I. U. (2008). Multifaceted ground water quality and recharge mechanism issues in a mega-city (Rawalpindi , Pakistan), and mitigation strategies. In *Securing Groundwater Quality in Urban and Industrial Environments* (pp. 2–7).

Dams, J., Woldeamlak, S. T., & Batelaan, O. (2007). Forecasting land-use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. *Hydrology and Earth System Sciences Discussions*, *4*(6), 4265–4295. doi:10.5194/hessd-4-4265-2007

Gennaro, P. (2001). *Groundwater vulnerability map explanatory notes*.

George, P. (2013). Investigation of Land-Use Change and Groundwater – Surface Water Interaction in the Kiskatinaw River Watershed , Northeastern British Columbia (Parts of NTS. *Geoscience BC*, 139–148.

Groundwater Contamination. (2008). *Blacksmith Institute*. Retrieved from http://www.worstpolluted.org/projects_reports/display/58

Groundwater Contamination. (2010). *Environment Canada*. Retrieved from https://www.ec.gc.ca/eau-water/default.asp?lang=En&n=6A7FB7B2-1

Güler, C., Kurt, M. A., & Korkut, R. N. (2013). Assessment of groundwater vulnerability to nonpoint source pollution in a Mediterranean coastal zone (Mersin, Turkey) under conflicting land use practices. *Ocean & Coastal Management*, *71*, 141–152. doi:10.1016/j.ocecoaman.2012.10.010

Howard Perlman. (2014). Contaminants Found in Groundwater. *USGS*. Retrieved from http://water.usgs.gov/edu/groundwater-contaminants.html

Huan, H., Wang, J., & Teng, Y. (2012). Assessment and validation of groundwater vulnerability to nitrate based on a modified DRASTIC model: a case study in Jilin City of northeast China. *The Science of the Total Environment*, *440*, 14–23. doi:10.1016/j.scitotenv.2012.08.037

Iqbal, S., Wasim, M., Tufail, M., Arif, M., & Chaudhry, M. M. (2012). Elemental contamination in urban parks of Rawalpindi/Islamabad--a source identification and pollution level assessment study. *Environmental Monitoring and Assessment*, *184*(9), 5497–510. doi:10.1007/s10661-011-2356-4

Islamabad. (n.d.). *Wikipedia*. Retrieved from http://en.wikipedia.org/wiki/Islamabad

Islamabad Facts & Statistics. (2013). *Capital Development Authority*. Retrieved from http://www.cda.gov.pk/about_islamabad/vitalstats.asp

Islamabad History. (2013). *Capital Development Authority*. Retrieved from http://www.cda.gov.pk/about_islamabad/history/#ad-image-0

Jaiswal, R. K., Mukherjee, S., Krishnamurthy, J., & Saxena, R. (2003). Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development--an approach. *International Journal of Remote Sensing*, *24*(5), 993–1008. doi:10.1080/01431160210144543

Kumar, S., Thirumalaivasan, D., & Radhakrishnan, N. (2013). GIS Based Assessment of Groundwater Vulnerability Using Drastic Model. *Arabian Journal for Science and Engineering*, *39*(1), 207–216. doi:10.1007/s13369-013-0843-3

Liggett, J. E., & Talwar, S. (2009). Groundwater Vulnerability Assessments and Integrated Water Resource Management. *Streamline Watershed Management Bulletin*, *13*(1).

Mair, A., & El-Kadi, A. I. (2013). Logistic regression modeling to assess groundwater vulnerability to contamination in Hawaii, USA. *Journal of Contaminant Hydrology*, *153*, 1–23. doi:10.1016/j.jconhyd.2013.07.004

Margat Jean, & Gun Jac van der. (2013). *Groundwater around the World: A Geographic Synopsis* (pp. 5 – 9). CRC Press, 2013.

Mason, W. R. (n.d.). Pollution of Groundwater. *Water Encyclopedia*. Retrieved from http://www.waterencyclopedia.com/Oc-Po/Pollution-of-Groundwater.html

Nadun, S. M. E. M., Maarof, I., Ghazali, R., Samad, A. M., & Adnan, R. (2010). Sustainable Groundwater Potential Zone Using Remote Sensing and GIS. In *International Colloquium on Signal Processing & Its Applications (CSPA) Sustainable* (pp. 104–109).

Neshat, A., Pradhan, B., & Dadras, M. (2014). Groundwater vulnerability assessment using an improved DRASTIC method in GIS. *Resources, Conservation and Recycling*, *86*, 74–86. doi:10.1016/j.resconrec.2014.02.008

Nobre, R. C. M., Rotunno Filho, O. C., Mansur, W. J., Nobre, M. M. M., & Cosenza, C. a N. (2007). Groundwater vulnerability and risk mapping using GIS, modeling and a fuzzy logic tool. *Journal of Contaminant Hydrology*, *94*(3-4), 277–92. doi:10.1016/j.jconhyd.2007.07.008

Nucleus, T., Munir, S., Mashiatullah, A., Mahmood, S., Javed, T., Khan, M. S., & Zafar, M. (2011). Assessment of Groundwater Quality Using Physiochemical and Geochemical Analysis In The Vicinity Of Lei Nala, Islamabad. *The Nucleus*, *2*(2), 149–158.

P, S. L., & K, N. R. (2010). Assessment and Spatial Distribution of Quality of Groundwater in Zone II and III , Greater Visakhapatnam , India Using Water Quality Index (WQI) and GIS. *International Journal of Environmental Sciences*, *1*(2), 198–212.

Piscopo, G. (2001). *Groundwater vulnerability map explanatory notes Lachlan Catchment Groundwater vulnerability map explanatory notes Lachlan Catchment*.

Renji, R., & R., P. K. (2007). Mapping Using GIS : A Study from India ' s Kapgari Watershed. *Environmental Quality Management*, 41–60. doi:10.1002/tqem

Rodriguez, Galiano, V., Mendes, M. P., Garcia, Soldado, M. J., Chica, Olmo, M., & Ribeiro, L. (2014). Predictive modeling of groundwater nitrate pollution using Random Forest and multisource variables related to intrinsic and specific vulnerability: A case study in an agricultural setting (Southern Spain). *The Science of the Total Environment*, *476-477*, 189–206. doi:10.1016/j.scitotenv.2014.01.001

S Munir, A Mashiatullah, S. M. (2012). Using Geochemical Techniques to Study Surface/Groundwater Interaction. In *74th EAGE Conference & Exhibition*.

Saidi, S., Bouri, S., & Ben Dhia, H. (2009). Groundwater vulnerability and risk mapping of the Hajeb-jelma aquifer (Central Tunisia) using a GIS-based DRASTIC model. *Environmental Earth Sciences*, *59*(7), 1579–1588. doi:10.1007/s12665-009-0143-0

Saidi, S., Bouri, S., Ben Dhia, H., & Anselme, B. (2011). Assessment of groundwater risk using intrinsic vulnerability and hazard mapping: Application to Souassi aquifer, Tunisian Sahel. *Agricultural Water Management*, *98*(10), 1671–1682. doi:10.1016/j.agwat.2011.06.005

Sajid, R., Khalid, A., & Abdul, K. Q. (2008). Hydrological Studies and Groundwater Potential of Islamabad Region. In *Third South Asia Geological Congress Lahore* (pp. 1–2).

Sener, E., & Davraz, A. (2012). Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Egirdir Lake basin (Isparta, Turkey). *Hydrogeology Journal*, *21*(3), 701–714. doi:10.1007/s10040-012-0947-y

Sharma, N. D., & Patel, J. N. (2010). Evaluation of Groundwater Quality Index of the Urban Segments of Surat City , India. *International Journal of Geology*, *4*(1), 1–4.

Sheikh, I. M., Pasha, M. K., Williams, V. S., Raza, S. Q., & Khan, K. S. A. (2007). *U.S. Geological Survey Bulletin: Environmental Geology of the Islamabad-Rawalpindi Area, Northern Pakistan*. U.S. Geological Survey. Retrieved from pubs.usgs.gov/bul/2078/B2078_chapter_G.pdf

Shirazi, S. M., Imran, H. M., Akib, S., Yusop, Z., & Harun, Z. B. (2013). Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques. *Environmental Earth Sciences*, *70*(5), 2293–2304. doi:10.1007/s12665-013-2360-9

Singh, C. K., Shashtri, S., Mukherjee, S., Kumari, R., Avatar, R., Singh, A., & Singh, R. P. (2011). Application of GWQI to Assess Effect of Land Use Change on Groundwater Quality in Lower Shiwaliks of Punjab: Remote Sensing and GIS Based Approach. *Water Resources Management*, *25*(7), 1881–1898. doi:10.1007/s11269-011-9779-0

Srivastava, P. K., Gupta, M., & Mukherjee, S. (2011). Mapping spatial distribution of pollutants in groundwater of a tropical area of India using remote sensing and GIS. *Applied Geomatics*, *4*(1), 21–32. doi:10.1007/s12518-011-0072-y

Stewart, R. (2009). Groundwater Contamination. *Environmental Geoscience*. Retrieved from http://oceanworld.tamu.edu/resources/environment-book/groundwatercontamination.html

Sun-Ok, H., Shin-Ho, C., Nasir, N. A. D., & Noor-us, S. (2001). *Drinking Water Quality Monitoring in Islamabad*.

Yin, L., Zhang, E., Wang, X., Wenninger, J., Dong, J., Guo, L., & Huang, J. (2012). A GIS-based DRASTIC model for assessing groundwater vulnerability in the Ordos Plateau, China. *Environmental Earth Sciences*, *69*(1), 171–185. doi:10.1007/s12665-012-1945-z