Groundwater Vulnerability Assessment and Contamination Risk Mapping in Narayanganj Sadar Upazila, Bangladesh Using GIS-based DRASTIC Modeling

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Certificate of Approval

The thesis entitled " Groundwater Vulnerability Assessment and Contamination Risk Mapping in Narayanganj Sadar Upazila, Bangladesh Using GIS-based DRASTIC Modeling" by Shrabonti Zaman, Exam Roll No: 110908, Reg No: 2015-718-817, and MS session: 2020-21, is hereby approved as a creditable study of Geography and Environment carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite for the degree for which it has been submitted.

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Candidate's Declaration

I hereby certify that the work which is being presented in the thesis, titled " Groundwater Vulnerability Assessment and Contamination Risk Mapping in Narayanganj Sadar Upazila, Bangladesh Using GIS-based DRASTIC Modeling" in partial fulfilment of the MS degree and submitted to the Department of Geography and Environment, University of Dhaka is an original piece of research work under the supervision of Nazmoon Nahar Sumiya, Assistant Professor, Department of Geography and Environment. University of Dhaka. The matter embodied in the thesis has not been submitted by me for the award of any other degree by any other University/Institute.

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Abstract

Bangladesh has significant groundwater contamination and associated disasters, with a majority of these incidents concentrated in industrial and urbanized regions. This study aims to evaluate the degree of susceptibility of groundwater contamination, its sources of pollution, and its relationship with land use and land cover patterns in an urbanized periphery region. A research investigation was carried out in the Narayanganj Sadar region of the Dhaka division in Bangladesh. This location was chosen due to its categorization as one of the most extensively industrialized and urbanized regions in the country. The selection was based on a study of the industrial sectors during the past three decades. The completion of this research involved the integration of secondary data obtained from several government entities, along with the utilization of GIS and statistical analytic techniques, alongside with semi-quantitative field data. Five zones of vulnerability were established based on the DRASTIC parameters and their interconnectedness with the patterns of land use and land cover in Narayanganj Sadar. The results of the GIS analysis and drastic index indicate that the zones with the highest levels of vulnerability are located in regions characterized by significant industrial activity. These locations also exhibit characteristics such as a vadose zone, depth to aquifer, and soil and aquifer media that are particularly susceptible to pollution. The aforementioned regions encompass Fatullah, Enayetnagar, the southern sector of Narayanganj City Corporation, as well as a portion of the northern Baktaballi and Alirtek localities. On the other hand, the regions that are least vulnerable to pollution are characterized by a shallower aquifer depth and a less porous vadose medium and aquifer media. The aforementioned regions encompass Kashipur, Gognagar, Baktaballi, and Kutubpur. The obtained results were further verified by two forms of sensitivity analysis: a map removal sensitivity analysis, and a single parameter sensitivity analysis that examines the specific impact of each parameter. The study revealed that each component had a significant impact on the drastic vulnerability index, with certain parameters exhibiting more relevance relative to their given weights (e.g., vadose zone, net recharge, topography, hydraulic conductivity), while others shown lesser importance (e.g., depth to aquifer, soil media, aquifer media). It was also observed that there was a favorable correlation between the change in land development and the rise in built-up area from 2000 to 2022.

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Acronyms

ADB = Asian Development Bank

AHP = Analytic Hierarchy Process

ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer

BADC = Bangladesh Agriculture Development Corporation

BARC = Bangladesh Agricultural Research Council

BBS = Bangladesh Bureau of Statistics

BDS = Bangladesh Standards

BWDB = Bangladesh Water Development Board

COST = Cooperation in Science and Technology

CRU = Climate Research Unit

DI = DRASTIC index

DPHE = Department of Public Health Engineering.

DPSIR = Driver-Pressure-State-Impact-Response

EEA = European environment agency

EPA = Environmental Protection Agency

ESRI = Environmental Systems Research Institute

FAO = Food and Agricultural Organization

GDP = Gross Domestic Product

GIS = Geographical Information System

GSB = Geological Survey of Bangladesh

HCS = Hydrogeological Complex and Settings methods

HFE = Hydrochemical Facies Evolution

IGRAC = International Groundwater Resources Assessment Centre

KR = Kelly’s ratio

LULC = Land use and Land cover

MAR = Magnesium Adsorption Ratio

MDA = Middle Dupi Tila aquifer

NCC = Narayanganj City Corporation

NRC = National Research Council

PCA = Principal Component Analysis

PI = Permeability Index

RMG = Ready Made Garments

RSBC = Residual Sodium Bicarbonate

SAR = Sodium Absorption Ratio

SME = Small and Medium Enterprises

SSP = Soluble Sodium Percentage

TDS = Total Dissolved Solids

TH = Total Hardness

UDA = Upper Dupi Tila Aquifer

UNICEF = United Nations Children's Fund

USEPA = United States Environmental Protection Agency

USGS = United States Geological Survey

WHO = World Health Organization

Chapter 1: Introduction

1.1 Introduction:

The Earth's water resources are facing escalating pressure due to climate change, environmental degradation, and population growth. Presently, a staggering 3.6 billion individuals encounter insufficient availability of water for a minimum of one month annually, with projections indicating that this figure will escalate to over 5 billion by the year 2050 (State of *Global Water Resources 2021*, 2022). Groundwater plays a crucial role in the overall water resource system owing to its inherent usability and widespread availability. Groundwater constitutes approximately 99% of the global supply of liquid freshwater and serves as the most readily accessible reservoir of freshwater on our planet. (Lall et al., 2020). The current trajectory of groundwater utilization suggests that it will maintain its critical significance in ensuring worldwide water security, sustaining agricultural economies, and supporting the livelihoods of individuals (Shahid et al. 2014; Singh et al. 2015).

Groundwater, as a natural resource, holds the distinction of being the most extensively extracted substance globally. Presently, withdrawal rates of groundwater are estimated to fall within the range of 982 cubic kilometers per year. (Brassington, 2014). Of all the nations that extract groundwater, Bangladesh ranks sixth. The escalation of withdrawals to satiate increasing human requirements has precipitated a marked exhaustion of groundwater levels in primary agricultural and demographic hubs. Consequently, this has resulted in a considerable depletion of the aquifer, with reports indicating a decline in groundwater levels of approximately 20–30 meters (Zahid and Ahmed, 2006; Jahan et al., 2010; Sumiya and Khatun, 2016). And even though many of the pollutants found in groundwater are derived from geogenic sources, which arise from the dissolution of naturally occurring mineral deposits beneath the Earth's crust (Basu et al., 2014; Pandey et al., 2016; Subba Rao et al., 2020; He et al., 2020a), most of the severe groundwater contamination issues that are prevalent now have anthropogenic origin. The nations that see the most impact from these global transformations are those undergoing swift economic growth, predominantly situated in the eastern hemisphere (Clement and Meunie, 2010; Hayashi et al., 2013; Lam et al., 2015).

The issue of groundwater depletion and contamination in Bangladesh poses a significant concern, as they detrimentally impact the well-being and sustenance of a substantial population that relies on groundwater for human consumption and agricultural purposes (Sresto et al., 2021; Saha & Rahman, 2020; Sarker et al., 2020; Salman et al., 2018). Geographic variations, which are a result of a combination of natural and anthropogenic factors that have an impact on groundwater quality, are what determine the variability of groundwater contamination in Bangladesh. The urban areas, particularly Dhaka city and its surrounding fringe areas such as Savar, Narayanganj, Tongi, etc., experience groundwater issues due to over extraction and the presence of diverse chemical and microbial pollutants resulting from increased urbanization and industrialization. There has been a substantial annual decrease in groundwater levels observed in the regions adjacent to the Dhaka metropolitan city. (Ahmed, 1994; Alam, 2006). The prolonged residence times of groundwater result in the simultaneous effects of extraction, recharge, and contamination, and it is near impossible to regulate the breakdown of undesired components in groundwater after they have penetrated the subsurface. The chronic contamination of shallow and deep groundwater on a global scale is primarily attributed to the utilization of fertilizers and pesticides in agricultural practices, the employment of solvents and chemicals in manufacturing procedures, the introduction of medicinal goods and pathogens through human waste, the extraction of minerals through mining activities, the generation of energy, and various commercial applications disrupting the pathways of water flow. (Mackay and Cherry, 1989; Pitt et al., 1999.; Saha et al., 2020; Neumann et al., 2010; Tareq et al., 2003). The presence of these contaminants has the potential to impact the physical, chemical, and biological characteristics of groundwater, thereby posing potential hazards to both human well-being and the surrounding ecosystem (Ahmed, 2011; Islam and Mostafa, 2021).

Groundwater vulnerability refers to the extent to which groundwater can be susceptible to being contaminated as a result of human activities. Groundwater vulnerability is subject to variation based on the various factors that influence the transport and reduction of contaminants within the subsurface. This is categorized as either intrinsic or specific vulnerability (Groundwater Protection and Vulnerability - British Geological Survey, n.d.; Frind et al., 2006; Gogu and Dassargues, 2000; Stigter et al., 2006). Among the various techniques employed for the assessment of groundwater resources, The GIS overlay and index method, which is both simple and extensively employed, incorporates various physical factors that are pertinent to potential contamination (Aller, 1985; Almasri, 2008; Gogu and Dassargues, 2000; Vu et al., 2019; Sahu et al., 2022). The DRASTIC method, which stands for depth to aquifer (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C), is widely recognized as the most widely used of the GIS overlay and index methods. This method was first introduced by Aller et al. (1987a).

The human and economic significance of groundwater is unavoidable. The majority of diseases in developing countries are caused by drinking contaminated water. Therefore, groundwater quality analysis and assessment are of utmost importance. However, the lack of accessible, verified hydrological data is a major challenge for monitoring and managing water resources. Narayanganj's groundwater is facing serious threats from pollution due to various anthropogenic activities. Thus, The examination of Narayanganj's groundwater is imperative in comprehending its present condition, patterns, and potential hazards. The examination of Narayanganj's groundwater can yield significant knowledge applicable to comparable urban environments in Bangladesh and other regions, where the depletion and contamination of groundwater resources are pressing concerns. The primary aim of this study was to employ the Geographic Information System (GIS)-based DRASTIC model to delineate and classify areas within an urban fringe region that exhibit susceptibility to groundwater vulnerability. Furthermore, the study sought to classify these areas based on their degree of susceptibility.

1.2 Statement of the Problem

Bangladesh, being an environmentally vulnerable country, experiences a deteriorating groundwater condition primarily attributed to the substantial population pressure it faces. Due to the increasing urban population and heightened levels of exploitation within urban areas, the vulnerability of groundwater contamination is notably pronounced in these regions. To date, groundwater vulnerability assessment studies have substantiated this concept. (NRC 1993; Alam et al., 2012; Singh et al.,_2015; Kumar et al., 2015) Contaminants resulting from anthropogenic activities on terrestrial surfaces infiltrate the subsurface and compromise the integrity of subsurface water reserves. Consequently, there exists a direct correlation between land use and groundwater contamination (Salman et al., 2011; Haque, 2018).

The town of Narayanganj has experienced a notable escalation in groundwater extraction from the shallow Holocene alluvial and deeper Dupi Tila aquifers (Morris et al., 2001). This is in response to the growing needs of urbanization and industrialization. If present trends continue, it will ensue detrimental consequences. Thus, the development of models for sustainable and secure global groundwater is of utmost importance. There are also other reasons, such as a large population that depends on groundwater, recharge mechanisms that are affected by climate and cannot be predicted, transboundary water sources, large amounts of nonpoint pollution from geological sources, inefficient irrigation techniques and human practices, and land use changes that are not planned because of growing urbanization. (Mukherjee et al., 2018**)**. The depletion of water, pollution, and land subsidence that follows may surpass an irreversible threshold due to the exceeding costs of remediation. (1. United Nations WATER. 2018. *Groundwater Overview: Making the Invisible Visible*. The region of Narayanganj Sadar serves as an industrial hub, contributing significantly to the nation's jute commerce, plant processing, and garment industry. The region is commonly referred to as the "Dundee of Bangladesh" because of its significant concentration of jute mills, shipbuilding industry, and textile industry. The port serves as a crucial infrastructure for several cement plants and other industrial enterprises, facilitating the exportation of their goods across the river (Facts.net, 2023). The aforementioned factors have a detrimental impact on the local water resources, leading to a severe decline in water quality. Consequently, the shallow aquifers in the area have grown very noxious and malodorous, rendering them unsuitable for usage which is causing various issues for the inhabitants. Furthermore, there is evidence to suggest that this phenomenon is beginning to have an impact on the underlying deep aquifers. Therefore, it is crucial to evaluate the extent of their susceptibility to pollution.

1.3 Research question

Considering the condition of the groundwater in Bangladesh as well as the expansion of urbanization and industrialization scenarios, this research is focusing on two issues:

1) What are the zones in Narayanganj Sadar that are most susceptible to groundwater pollution and depletion?
2) What are the major contaminants that pollute the groundwater of that region?
3) To what extent do the physicochemical characteristics of the groundwater differ from the established standard?
4) How much is the groundwater condition in Narayanganj Sadar interconnected with the land use of the area?

1.4 Aims and Objectives:

In general, the aim of the research is to identify the zones where the groundwater is most vulnerable and to identify the existing relationship between the level of risk and the human activities occurring in Narayanganj Sadar Upazila.

1. To assess the groundwater level and pollution vulnerability using the DRASTIC method of modeling.
2. To compare and analyze the spatial distribution of pollutants and contamination in the groundwater.
3. To identify the potential sources of groundwater level and pollution vulnerability.

1.5 Study area

As the main focus point of the study is Groundwater vulnerability due to urbanization and industrialization, an area that is heavily impacted by the unabated industrialization and urbanization processes will be apposite for the study.

The Narayanganj Sadar Upazila in Narayanganj District is an optimal spot for that. Narayanganj Sadar is an upazila of Narayanganj District in the Division of Dhaka, Bangladesh. It is the administrative center of the district and the city of Narayanganj. It is also a major industrial and commercial hub, as well as a historical and cultural center. It is surrounded by Demra Thana on the north, Munshiganj Sadar and Tongibari upazilas on the south, Bandar (Narayanganj) and Sonargaon upazilas on the east, and Keraniganj and Sirajdikhan upazilas on the west. Its major watershed rivers are, Shitalakshya , Dhaleswari , Buriganga and Ichamati .

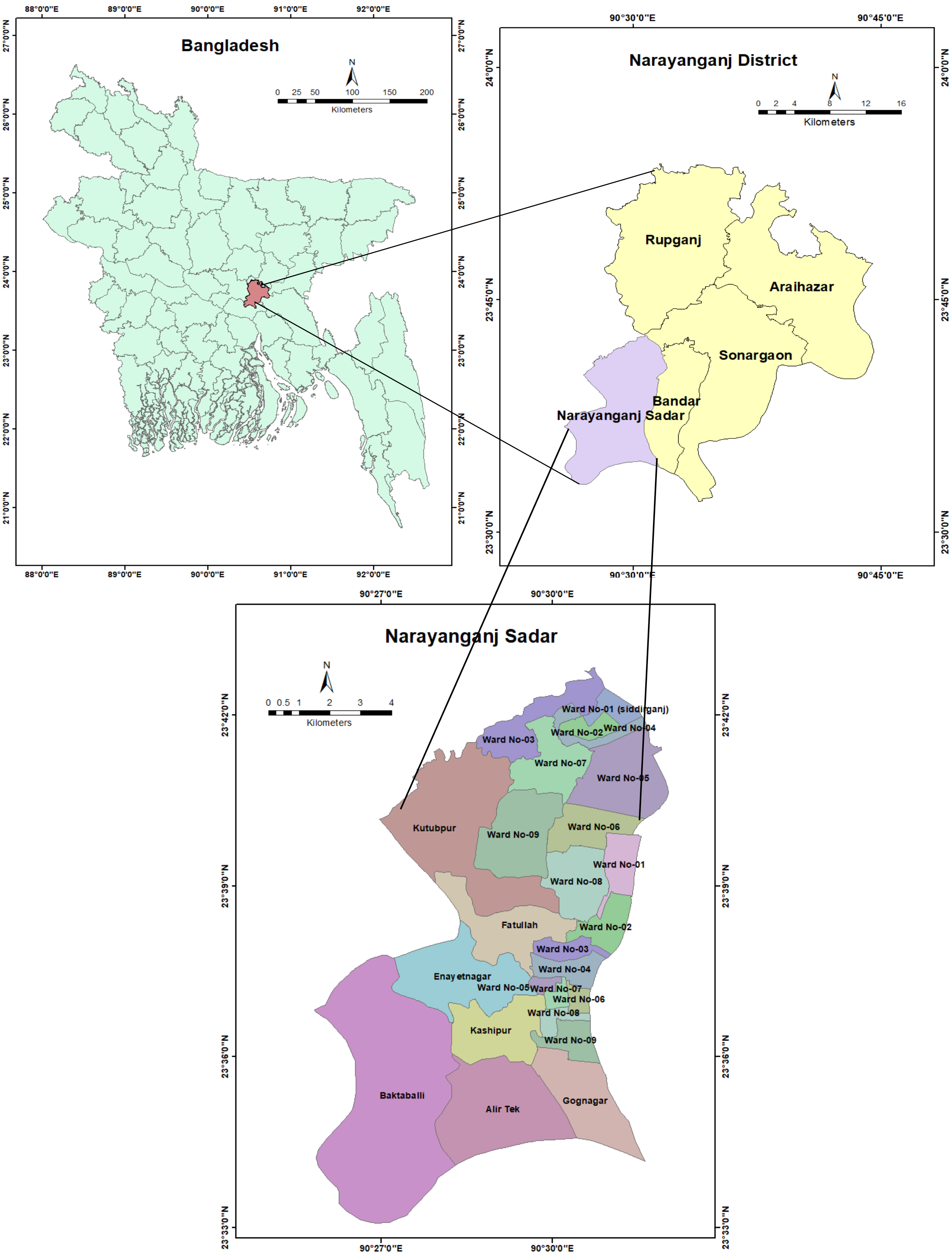


Fig 1.1: Map of the study area (Source: Prepared by author)

Narayanganj Sadar had 1,023,190 households and a population of 3,909,138 as of the 2022 Census of Bangladesh, 40.5% of whom lived in urban areas. More than 2,000 industries on the banks of the river stretching from Kanchpur to Narayanganj are dumping various types of toxic chemicals into the river, causing widespread pollution. Narayanganj has a total of 1,091 industrial units, of which 1,003 are small and medium enterprises (SMEs) and 88 are large enterprises. The major industries in Narayanganj are: Jute and jute goods, Food and beverage, Chemicals and pharmaceuticals, Metal and engineering, and most prominently, Textiles and garments. Narayanganj is a major producer and exporter of textile and garments in Bangladesh. It has about 200 textile mills and 300 garment factories that employ about 200,000 workers. The main products are cotton yarn, fabrics, knitwear, woven garments and accessories. Approximately 200 different types of toxic chemicals and heavy metals are used by several industries located in Narayangnaj town and are producing large volumes of chemical and other waste. The wastes are commonly disposed to nearby channels, lowlands and shallow pits without any treatment (Siddique et al., 2004).

1.6 Organization of the thesis report

Chapter No.	Chapter Name	Chapter Content
Chapter 1	Introduction	This chapter deals with the introduction with conceptual background, describing the study area, mentioning the aim and objective and limitations of the study.
Chapter 2	Literature review	This chapter explains the existing knowledge and research done such global, continental, national, regional and local scenario of groundwater and the relevant research that has been conducted on this topic
Chapter 3	Methodology	The approach, selection procedure of the study area, data collection and analysis techniques and limitations of the study are explained in this chapter.

Chapter 4	Results and Analysis	Vulnerability zone mapping and analyzing different parameters, validating the results and their association with the land use of the study area.
Chapter 5	Discussion and conclusion	The major findings of the research have been summed up and discussed in this chapter to evaluate the goal of the research.

1.7 Limitations of the Study

- Lack of data regarding the depth to shallow aquifer, as the water is polluted, smelly, and unusable, no organization collects comprehensive data of that.
- Insufficient bore log data. One bore log survey per union does not show the full picture of each union’s stratigraphic unit.
- No data regarding net recharge in different government organizations.
- Lack of weather station and rainfall data of Narayanganj Sadar.
- Lack of groundwater chemical analysis information in BWDB, DPHE.
- Lack of accessibility and equipment for grain size analysis and chemical analysis.
- As the study area is only 108 square kilometers, the spatial resolution of remotely sensed data is not of high quality.
- No standard data for hydraulic conductivity of the soil of Bangladesh.
- High cost and low quantity of chemical research laboratories.
- Lack of literature on the study area regarding groundwater and hydrogeological properties.
- Inaccessibility of groundwater from shallow aquifers and lack of depth information of the tube wells from where the water samples were collected for validation.

1.9 Conclusion

Given the escalating environmental vulnerability of our planet, it is essential to promptly undertake measures to ensure effective management of water resources. The multifaceted value of water is frequently overlooked or inadequately addressed in policy and planning endeavors. In order to facilitate change, it is imperative that further extensive research be conducted on the various dimensions of water, particularly groundwater. Despite its invisibility to the naked eye, groundwater takes on a pivotal role in the sustenance of ecosystems, as well as the organisms and the broader natural environment that reside in there. Technology plays a pivotal role in narrowing the divide and enhancing our understanding of the natural world.

Chapter 2: Literature Review

2.1 Introduction

This study examines the inherent vulnerability of groundwater in Narayanganj Sadar, Bangladesh, and its relationship with changes in land use and land cover across time. Moreover, identification of factors which are associated with the geographical extent and intensity of vulnerability under consideration. The research has been carried out at Narayanganj Sadar Upazila. This chapter presents a concise examination of the global state of groundwater, encompassing its condition on a continental, national, regional, and local scale and the types and sources of groundwater contaminants. It also delves into the industrial scenario of Bangladesh and specifically focuses on Narayanganj Sadar. The concept of groundwater vulnerability and its assessment are discussed, along with an overview of existing research on groundwater in Bangladesh, its methodologies, and the potential for further exploration. The chapter further explores the methods employed in vulnerability assessment worldwide. Additionally, the variation of parameters utilized, study area and implementation, are presented in this chapter.

2.2 Global Groundwater Scenario

Groundwater often serves as the sole year-round water supply in numerous areas, particularly in cases where energy and machinery are accessible (Lall et al., 2020). The utilization of groundwater has experienced a notable increase over the past six decades as a result of significant advancements in well drilling and pumping technology (Foster et al., 2013). Currently, groundwater is the main source of 50% of drinkable water, 40% of agricultural irrigation water, and 33% of industrial water consumption (IGRAC, 2018).

It has been observed that the rate of global groundwater depletion has surged twofold compared to the 40-year time frame spanning from 1960 to 2000 (Wada et al., 2010). Additionally, the proportion of non-renewable groundwater extraction on a global scale has risen from 11% during the period of 1960–2000 to 15% in the ensuing decade of 2000–2009 (Döll et al., 2014). Apart from depletion, groundwater faces the risk of contamination resulting from a multitude of anthropogenic activities. The UN World Water Development Report 2021 highlights that groundwater contamination has a significant impact on a minimum of 10% of global aquifers, hence presenting substantial threats to several aspects such as human well-being, food production stability, ecological variety, and resistance to climate change. The rate of groundwater pollution had doubled from 1960 to 2000, resulting in an annual contamination extent of 280 square kilometers. The annual quantity amounts to 280 billion tons, equivalent to a rate of 9000 tons every second. (The World Counts, n.d.)

Country	Population 2010 (in thousands)	groundwater extraction 2010 (km3/yr)	Groundwater extraction for irrigation (%)	Groundwater extraction for domestic use (%)	Groundwater extraction for industry (%)
India	1224614	251	89	9	2
China	1341335	111.95	54	20	26
United States	310384	111.7	71	23	6
Pakistan	173593	64.82	94	6	0
Iran	73974	63.4	87	11	2
Bangladesh	148692	30.21	86	13	1
Mexico	113423	29.45	72	22	6
Saudi Arabia	27448	24.24	92	5	3
Indonesia	239871	14.93	2	93	5
Turkey	72752	13.22	60	32	8
Russia	142985	11.62	3	79	18
Syria	20411	11.29	90	5	5
Japan	126536	10.94	23	29	48
Thailand	69122	10.74	14	60	26
Italy	60551	10.4	67	23	10

Table 2.1: The 15 nations with the largest estimated annual groundwater extractions (2010) (Brassington, 2014)

Contaminant	Sources of groundwater
Antimony	natural weathering processes, industrial activities, municipal waste disposal practices, and the creation of flame retardants, ceramics, glass, batteries, pyrotechnics, and explosives.
Arsenic	Enters the environment through natural processes, industrial operations, pesticides, and the discharge of industrial waste resulting from the smelting of copper, lead, and zinc ore.

Beryllium	Frequently employed within the electrical industry, as well as in equipment and components utilized in the nuclear power and space sectors. Environmental contamination arises as a result of mining activities, processing facilities, and inadequate disposal of waste materials.
Cadmium	Industrial discharge, mining waste, metal plating, water pipes, batteries, paints and pigments, plastic stabilizers, and landfill leachate.
Chloride	May be associated with the presence of sodium in drinking water when present in high concentrations. Often from saltwater intrusion, mineral dissolution, industrial and domestic waste.
Chromium	Enters environment from old mining operations runoff and leaching into groundwater, fossil-fuel combustion, cement-plant emissions, mineral leaching electroplating, leather tanning, textile industries, and chemical plants, and waste incineration.
Copper	Enters the environment from metal plating, industrial and domestic waste, mining, and mineral leaching.
Cyanide	Often used in electroplating, steel processing, plastics, synthetic fabrics, and fertilizer production; also, from improper waste disposal.
Iron	Occurs naturally as a mineral from sediment and rocks or from mining, industrial waste, and corroding metal.
Lead	Enters the environment from industry, mining, plumbing, gasoline, coal, and as a water additive.
Manganese	Occurs naturally as a mineral from sediment and rocks or from mining and industrial waste.
Mercury	Occurs as an inorganic salt and as organic mercury compounds. Enters the environment from industrial waste, mining, pesticides, coal, electrical equipment (batteries, lamps, switches), smelting, and fossil-fuel combustion.

Nickel	Occurs naturally in soils, groundwater, and surface water. Often used in electroplating, stainless steel and alloy products, mining, and refining.
Nitrate (as nitrogen)	Occurs naturally in mineral deposits, soils, seawater, freshwater systems, the atmosphere, and biota. More stable form of combined nitrogen in oxygenated water. Found in the highest levels in groundwater under extensively developed areas. Enters the environment from fertilizer, feedlots, and sewage.
Silver	Ore mining and processing, product fabrication, and disposal. Often used in photography, electric and electronic equipment, sterling and electroplating, alloy, and solder.
Sodium	Derived geologically from leaching of surface and underground deposits of salt and the decomposition of various minerals. Human activities contribute through de-icing and washing products.
Sulfate	Elevated concentrations may result from saltwater intrusion, mineral dissolution, and domestic or industrial waste.
Thallium	Enters the environment from soils; used in electronics, pharmaceuticals manufacturing, glass, and alloys.
Zinc	Industrial waste, metal plating, and plumbing, and is a major component of sludge.

Table 2.2: Inorganic contaminants found in groundwater (Source: Contamination of Groundwater | U.S. Geological Survey, 2018)

2.3 The Notion of Groundwater Vulnerability

This idea was initially introduced in the 1970s in France with the aim of identifying susceptible regions where surface contamination may impinge upon groundwater and facilitating the formulation of management strategies for safeguarding groundwater from surface pollutants (Taghavi et al., 2022). The National Research Council defined this term as "the relative ease with which a contaminant applied on or near the land surface can migrate to the aquifer of inundation," while Hirata and Bertolo defined it as "the property of a groundwater system that depends on the sensitivity of the material in permitting the degradation of the saturated zone by pollutant substances originating from human activities." The concept of groundwater vulnerability is based on the assumption that the physical environment can serve as a protective barrier to some degree, particularly in terms of preventing the entry of contaminants into the subsurface (Baalousha, 2006; Hasiniaina et al., 2010). The consideration of groundwater vulnerability can also be incorporated within the DPSIR model, a system of environmental metrics. The DPSIR model encompasses the analysis of driving forces, pressures, state, impacts, and responses (EEA, 2003; Kristensen, 2004).

Aquifer water is considered safe from infectious contamination as it is a concealed resource that exhibits variations in both quality and quantity dependent upon the hydrological and lithological characteristics of its environment (Islam and Mostafa 2021b). The existence of inorganic pollutants originating from underlying geological formations or anthropogenic sources poses a significant challenge to the restoration of aquifers, thereby exacerbating the deleterious effects of pollution (Yidana and Yidana 2010; Singh et al. 2013; Kumar and Singh 2015).

There are two types of vulnerability:

- **Intrinsic:** The concept of intrinsic vulnerability refers to the extent to which the attributes of a species or ecosystem render it susceptible or resistant to natural or human-induced pressures or calamities (Intrinsic Vulnerability Rating, n.d.). The groundwater intrinsic vulnerability refers to the degree of sensitivity exhibited by aquifer systems in terms of their capacity to receive, disperse, and potentially mitigate the impacts of pollutants, thereby influencing the overall quality of groundwater. The determination of an aquifer's properties is reliant upon its inherent geological, hydrological, and hydrogeological characteristics. (Neukum & Azzam, 2009; Şener, 2021; Lasagna et al., 2018)
- **Specific:** The term "specific vulnerability" was conceptualized as the susceptibility to environmental degradation resulting from the potential influence of particular land uses and contaminants (Vrba and Zaporozec, 1994; Gogu and Dassargues, 2000a; Margane, 2003; Zwahlen, 2004). Given that the aquifers have different reactions to the same pollutant due to their physicochemical characteristics, The term specific vulnerability refers to the susceptibility of groundwater to a pollutant or a set of pollutants. This susceptibility is

influenced by the properties of the pollutant, considering factors such as the timing and magnitude of its effect, as well as the interaction between the various components of intrinsic vulnerability and the contaminant (Doerfliger et al., 1999; Gogu et al., 2000).

2.4 Groundwater Scenario in Bangladesh

The South Asian region encompasses three of the largest river systems globally, namely the Indus, Ganges, and Brahmaputra rivers. These river systems give rise to one of the most productive aquifers, making them significant contributors to global water resources. The region possesses a substantial volume of groundwater resources, estimated to be approximately 380–400 km3/year, representing over 50% of the global annual usage of groundwater (Mukherjee, 2018). In Southeast Asian and Pacific countries, a significant proportion of households, specifically 66% in urban areas and 60% in rural areas, depend on groundwater as their primary source of water for consumption. (Morris et al., 2003; Manasaki et al., 2018).

Groundwater serves as a crucial natural resource for sustaining the livelihoods and ensuring food security of numerous rural people in Bangladesh. It ranks 6th in total groundwater extraction in the world. Groundwater serves as the primary water supply in Bangladesh, fulfilling diverse needs such as irrigation, home consumption, and industrial usage, among other applications. According to available data, a significant proportion of the population, namely 76%, lacks access to a piped water system and instead relies on hand tube wells. Furthermore, a substantial majority of rural individuals, around 95%, rely entirely on untreated groundwater for their home water needs. (ADB 2007b, c; Mojid et al. 2019).

Within this nation, approximately 32 cubic kilometers of underground water are extracted on an annual basis. Of this amount, 90% is allocated for agricultural use, while the remaining 10% is utilized for residential and industrial purposes. This collective usage equates to 4% of global groundwater extraction (BADC, 2013; Hanasaki et al., 2018; Shamsudduha et al., 2019).

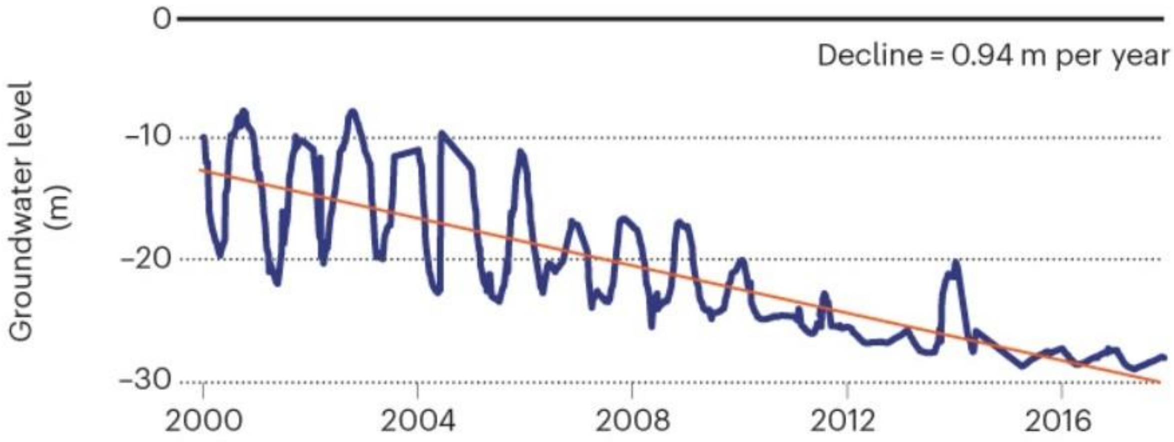


Fig 2.1: Groundwater Storage in Bangladesh from 2000-2020
(Source: Bangladesh Water Development Board)

The availability of groundwater in Bangladesh is governed by several factors, including the subtropical monsoon climate, the capacity of aquifer storage, the rate of consumption, and variations in the volume and distribution of groundwater recharge conditions. In Bangladesh, groundwater is found at a relatively shallow depth, primarily within the floodplains where abundant aquifers are formed by the deposition of sediments carried by rivers. The Pleistocene Dupi Tila sands serve as aquifers in the elevated terraces, specifically in the Barind and Madhupur tracts. The Pliocene Tipam sands function as aquifers in regions characterized by hilly terrain (Zahir, 2006). It occurs in two main aquifer systems: a shallow unconfined or semi-confined aquifer (depth <150 m) and a deep confined aquifer (depth >150 m) (Haque, 2018). The shallow aquifer is recharged by rainfall and surface water infiltration, while the deep aquifer is recharged by lateral flow from adjacent areas or vertical leakage from overlying aquifers. The unconsolidated sediments found in Bangladesh exhibit favorable characteristics for manual drilling, allowing for depths of at least 50 meters or greater to be achieved within a 48-hour timeframe. (DPHE/BGS/MML 1999). There are at least five million hand tube wells (HTW) all over the country. These tube wells are mostly used for drinking and domestic use. In addition, there are shallow tube wells (STW) and deep tube wells (DTW) that are mostly used for irrigation. STW have 5.08-10.16 cm diameter and DTW have 15.24-20.32 cm diameter (Tube well - Banglapedia, n.d.). An estimated volume of 32 cubic kilometers of groundwater is extracted on a yearly basis, with approximately 90% allocated for irrigation purposes and the remaining 10% utilised for domestic and industrial applications collectively. (Shamsudduha et al., 2019).

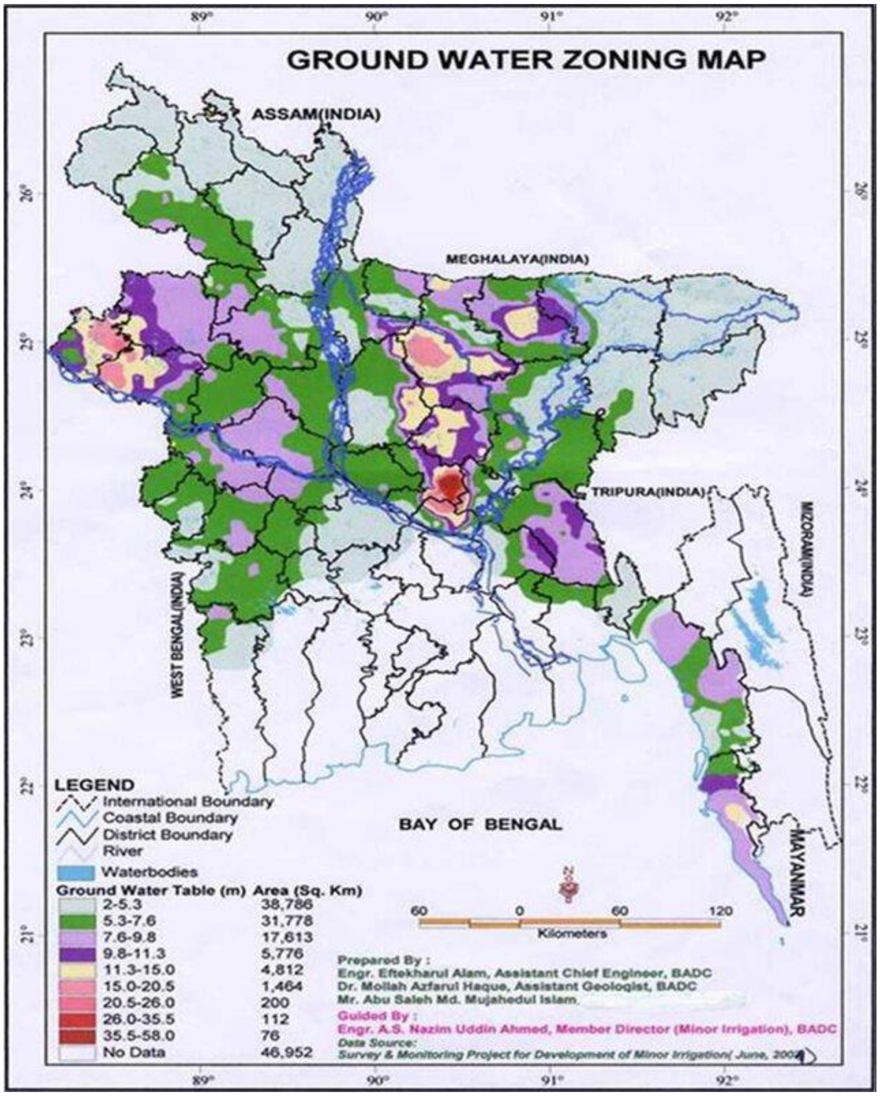


Fig 2.2: Groundwater Zoning Map of Bangladesh (Source: Amin, 2017)

The predominant direction of groundwater flow typically aligns with the topography and river courses, flowing from north to south. The hydraulic gradient exhibits spatial and temporal variability, ranging from 0.0005 to 0.0015, contingent upon the specific geographical location and prevailing season. The hydraulic conductivity of the shallow aquifer varies between 10 and 100 m per day, while the deep aquifer exhibits a hydraulic conductivity ranging from 1 to 10 m per day (Haque, 2018).

Groundwater quality has become a thoughtful concern in Bangladesh, over the last 2/3 decades (UNICEF, 2010). According to a report by the World Health Organization (WHO), a significant number of individuals, approximately 140 million, residing in 50 different countries are exposed to arsenic through groundwater that is contaminated with arsenic at levels exceeding 10 µg/L. The majority of these individuals are located in India and Bangladesh. The current state of affairs in Bangladesh is widely considered to be the most significant instance of environmental arsenic contamination, posing a potential hazard to approximately 50 million individuals (WHO 2018, Bagchi, 2007; Ahmed et al., 2015; Dhar et al., 1997; Smith et al., 2000). The initial assumption regarding the presence of arsenic contamination in tube well water in Bangladesh was limited to the Gangetic delta plain. However, subsequent investigations revealed that the contamination extended to nearly all sedimentary regions of Bangladesh, with the exception of the Hilly and Pleistocene Uplands areas, commonly referred to as Terrace Land. (Ahmed et al., 2015; Islam et al., 2018; Shangkar et al., 2014). The southern coastal region is characterized by elevated levels of groundwater salinity, primarily attributed to factors such as seawater intrusion, irrigation return flows, salt mining, and industrial effluents. The salinity of groundwater has a significant impact on its potability and suitability for both drinking and irrigation applications. The population residing in coastal regions experiencing groundwater salinity levels surpassing the World Health Organization's recommended threshold of 600 mg/L amounts to approximately 20 million individuals. Additionally, The shallow alluvial aquifer zone, where arsenic levels in groundwater are high owing to natural geochemical processes. Arsenic naturally exists in some aquifer sediments as a result of weathering and leaching processes. Arsenic gets mobilized into groundwater in shallow aquifers due to decreasing circumstances. Approximately 35 million individuals are impacted by elevated arsenic levels that surpass the World Health Organization's recommended threshold of 10 g/L (Ahmed, 2011; Haque, 2008; Islam and Mostafa 2021b). Practically, not only the arsenic contamination, the groundwater is highly susceptible to pollution with respect to other heavy metals as well as some anions such as Pb, Cd, Co, Hg, F−, NO3−, NO2−, PO4 3− etc. by lithological or human activities (Seddique et al., 2004). Among the anthropic compounds commonly handled, the most problematic are the chlorinated organic solvents and heavy metals, and in non-sewage areas, nitrate (Hirata et al., 2019). Additionally, elevated concentrations of dissolved iron, manganese, and boron are commonly observed in groundwater across various regions of the country (Ahmed, 2011; Rahman et al., 2020).

2.5 Industrial Scenario in Bangladesh

Bangladesh is currently one of the world's fastest-growing economies, incorporating one of the top five exporters of ready-made Garments (RMG), textiles, and apparel, which account for approximately 20% of total GDP. (Bbs. Statistical Year Book Of Bangladesh 2019). The process of rapid urbanization, industrialization, unanticipated rural housing, and infrastructure development in Bangladesh results in the annual loss of 8000 hectares of farmland. (Khan, 2019). Annually, the textile dyeing sector produces approximately 113.72 metric tons of solid waste and 99.75 million cubic meters of liquid waste. Every year, the tanning industry produces approximately 26,250 metric tons of solid waste and 1.3 million cubic meters of liquid waste. Hospitals and clinics produce a total of 12,271 tons of solid waste. The agricultural sector encompasses various industries, including pesticide production, which is responsible for generating an annual solid waste output of 277 tons and a liquid waste volume of 7.8 million cubic meters. Similarly, fertilizer manufacturing contributes to the generation of 357 tons of solid waste and 10.97 million cubic meters of liquid waste on a yearly basis. The process of oil refining results in the production of approximately 4 metric tons of solid waste and 0.61 million cubic meters of liquid waste annually. (Ruba et al.,2021). Additionally, Fuel storage tanks that are buried underground may corrode or rupture over time, releasing petroleum products or other hazardous substances into the soil and groundwater. These substances can contaminate large volumes of groundwater and pose fire and explosion risks (Contamination of Groundwater | U.S. Geological Survey, 2018). Rubbish tips or landfill areas serve as designated locations for the disposal of solid waste through burial in the ground. The waste materials have the potential to contain various components such as organic matter, plastics, metals, batteries, medical waste, and other substances that have the capability to degrade and subsequently release hazardous substances into the groundwater. These substances can consist of leachate, a liquid that is generated when water permeates through the waste materials and dissolves or suspends different contaminants (Guimarães et al., 2019). Among these, the residual components are infiltrating through the top soil and eventually penetrating groundwater aquifers, resulting in water pollution. Contamination can persist for a long time as groundwater moves slowly and often lacks the natural biological, chemical and physical processes that help cleanse surface water (e.g. sunlight). The existence of diverse contaminants is responsible for the proliferation of numerous diseases on a global scale. At any given moment, approximately 50% of the population residing in developing regions suffers from the presence of one or more of the six primary diseases linked to water supply and sanitation. (Gadgil, 1998).

2.6 Groundwater Research in Bangladesh

Research on Bangladesh's groundwater sources has predominantly focused on hydrogeological and hydrogeochemical aspects, encompassing investigations into groundwater potential, groundwater quality, hydrogeological modeling, and the presence of heavy-metal pollutants. (Zahid, 2003; Khan et al., 2011a, 2011b; Salam and Alam, 2014; Zakir et al., 2006). However, very little has been attempted in the context of vulnerability due to urbanization and industrialization. (Chakraborty et al., 2022; Hasan et al., 2021).

Ahmed et al., (2018) investigated the hydrogeochemical characteristics of groundwater of Sylhet, north-eastern Bangladesh, by collecting 23 shallow, 30 intermediate, and 38 deep wells samples, and analyzing them for temperature, pH, Eh, EC, DO, DOC, Na+, K+, Ca2+, Mg2+, Cl−, SO42−, NO3−, HCO3−, SiO2−, Fe, Mn and As. Additionally, Pearson's correlation matrix, principal component analysis, and cluster analysis were utilized to assess the determining factors. Salman et al. (2018) analyzed a total of 113 groundwater samples collected from shallow aquifers at different locations in Bangladesh to estimate eight standard groundwater quality indices namely, sodium absorption ratio (SAR), soluble sodium percentage (SSP), residual sodium bicarbonate (RSBC), permeability index (PI), total hardness (TH), magnesium adsorption ratio (MAR), Kelly's ratio (KR), and total dissolved solids (TDS). The results showed that the SAR in the groundwater of Bangladesh varies between 1 and 818, SSP between 9 and 99%, RSBC between −13 and 719 meq/L, PI between 21 and 112%, TH between 233 and 19400 meq/L, MAR between 5 and 74%, KR between 0.06 and 135 meq/L, and TDS in the range of 51–15200 mg/L. Das et al., (2021) collected a total of 30 water samples from the deep aquifer, specifically at depths ranging from 550 to 700 feet in December 2016, in order to determine their physio-chemical properties. The paper used various methods such as Piper diagram, Gibbs diagram, correlation matrix, and principal component analysis (PCA) to evaluate the hydro-chemistry of water in the study area. The obtained results were then compared to the drinking water quality standards set by the World Health Organization (WHO), the United States Environmental Protection Agency (USEPA), and the Bangladesh Bureau of Standards (BBS). Additionally, the results were also compared to the irrigation standards established by the Food and Agriculture Organization (FAO). Sarkar et al., (2020) used various physicochemical (pH, Electrical Conductivity, Total Dissolved Solids, Salinity, Total Hardness, Potassium, Sulfate, and Chloride ions) and microbial parameters (Total Coliform, Fecal Coliform, and Total Bacterial Viable Count) to assess the quality of groundwater in the Noakhali region of Bangladesh. Saha et al., (2020) investigated the hydrogeochemical processes regulating the water quality of the Meghna floodplain, the sources and mechanisms of arsenic (As) release, and determined the extent of carcinogenic and non-carcinogenic health risks to adults and children in the Comilla district, central-east Bangladesh, using probabilistic and deterministic approaches. Sarker et al. (2021) evaluated the hydrogeochemical processes in the coastal aquifers of southwest Bangladesh. They used Conventional plots, Ionic delta, HFE-diagram, Stable isotopes, and Geochemical modelling to interpret the hydrogeochemical processes in the multilayer aquifers of the study area and to quantify hydro chemical differences between different aquifers. Rahman et al., (2020) assessed heavy metal pollution in the groundwater of the Meghna Ghat industrial area, Bangladesh, by using a water pollution index approach. Haqueet al. (2018) on the other hand, investigated the susceptibility of groundwater contamination resulting from mining operations in an open-pit coal mine located in Bangladesh.

Several investigations have been undertaken to identify and categorize various regions and basins into zones of vulnerability based on diverse parameters. Fatema et al. (2023) created a precise groundwater potential map for Bangladesh's Jessore district by combining geospatial approach and an analytical hierarchy process. The study incorporated a total of fourteen parameters, specifically lineament density, drainage density, land use and land cover, slope, curvature, topographic position index, topographic wetness index, rainfall, geology, roughness, fractional impervious surface, topsoil texture, soil permeability, and general soil types. Sresto et al. (2021) identified potential groundwater zones in the northwest region of Bangladesh using geospatial technology and the fuzzy analytic hierarchy process. The study conducted by Samsudduha et al. (2019) investigated the potential risks associated with several hazards on the groundwater resources that serve as the primary source of drinking water in Bangladesh. Islam et al. (2017) developed an irrigation water quality index (IWQI) through the utilization of a geostatistical model and multivariate indices in the Gopalganj district, situated in the south-central region of Bangladesh. Haque et al., (2016) studied the groundwater dynamics and balance for the assessment of groundwater abstraction status in the western part of greater Kushtia district, Bangladesh using data from 28 groundwater level monitoring wells, 180 lithologs, and one rainfall station for the period 2001-2007. Kirby et al., (2015) developed monthly water balances for the main regions of Bangladesh to investigate historic trends in water use and availability and possible future trends under changed management to lessen groundwater use by using more surface water for irrigation. Hasanuzzaman et al., (2017) analyzed the groundwater level dynamics with a model named "MAKESENS" and with geographical information systems (GIS) to predict the water table depth and rainfall intensity in Bogra district, the northwest region of Bangladesh. Raihan et al., (2008) investigated different indices for irrigation and drinking uses in Sunamganj district, including sodium absorption ratio, soluble sodium percentage, residual sodium carbonate, electrical conductance, magnesium adsorption ratio, Kelly's ratio, total hardness, permeability index, and residual sodium bi-carbonate. According to the results of geographic information system (GIS) analysis, the groundwater quality in Zone-1 has been classified as belonging to the "excellent" category, indicating a high level of suitability for irrigation purposes. The groundwater quality in Zone-2 was classified as "risky," while in Zone-3 it was categorized as "poor."

2.7 Groundwater Research in Dhaka and Surrounding Fringe Area

Dhaka, the capital city of Bangladesh, heavily depends on groundwater sourced from the Plio-Pleistocene fluvio-deltaic sands of the Dupi Tila Formation, which accounts for approximately 95% of its water supply (Hasan et al.,1999). Multiple studies have been conducted pertaining to the characterization of groundwater quality and identification of pollution sources in the Dupi Tila aquifer (Ahmed 1999; Hasan et al.,1999; Burgess et al. 2011; Karim et al. 2013; Rahman et al., 2013; Bodrud-Doza et al. 2019; Khan et al. 2020; Sharmin et al. 2020). Islam et al., (2022) investigated the correlation between ion chemistry, hydrochemical processes, and groundwater quality, specifically focusing on the Dupi Tila aquifer. Additionally, they assessed the consequences of over-exploitation on this aquifer. Islam et al., (2021) focused on analyzing the long-term evolution of piezometric heads in the Upper Dupi Tila aquifer (UDA) and the Middle Dupi Tila aquifer (MDA). The analysis is based on extensive hydrographs, piezometric maps, and synthetic graphical representations of piezometric trends. Arham et al., (2022) determined the temporal trend change and the correlation between parameters across 18 distinct locations within the Dhaka division over a 40-year time span. Trend analysis of water quality at various sites is conducted using the Man Kendall test, Modified Man Kendall, and Sens Slope methods. In addition, the spatio-temporal variability of 15 groundwater quality parameters (including Ca, Mg, Na, pH, CO2, TDS, K, Cl, CO3, SO4, NO2, Fe, Si, F, and HCO3) is assessed through the process of mapping in a Geographic Information System (GIS). Rabbi et al. (2020) assessed the physical and chemical contamination content and assimilated it with WHO and BDS, where six physicochemical parameters, namely pH, iron, hardness, turbidity, odor, and color were tested. The study conducted by Seddique and Matin (2013) focused on assessing the vulnerability of groundwater in two cities, Narayanganj and Tongi, which have experienced rapid urbanization and high population density. Nevertheless, the researchers deviated from conventional DRASTIC parameters in their investigations on groundwater vulnerability. Instead, they solely focused on the upper clay thickness, water level depth, and land use pattern. Hasan (2019) conducted a study regarding this in the Savar Upazila using the DRASTIC method. And Rahman et al. (2021) used the model to assess groundwater vulnerability in the south-central part of Bangladesh However, the aforementioned study failed to consider the susceptibility of peripheral regions within the jurisdiction of Narayanganj City Corporation that are subject to the impact of industrial operations. Seddique et al. (2004) examined Heavy Metal Pollution in Groundwater in and around Narayanganj Town, Bangladesh and observed that the pollution in the upper aquifer is evident in shallow groundwater due to its increased concentration of dissolved solids, which was more obvious in industrial and densely inhabited regions. Moris et al. (2001) assessed the groundwater vulnerability in Narayanganj Town but only examined minimal parameters for vulnerability mapping, such as thickness of upper clay and depth to water level.

2.8 Methods of Groundwater Vulnerability Assessment

Groundwater vulnerability assessment has been reported in various climatic regions of the world, such as semi-arid regions (Djoudi et al., 2019; Arya et al., 2020; Meng et al., 2020), humid tropical regions (Seabra et al., 2009; Omotola et al., 2020), sub-tropical regions (Singh et al., 2015; Xiaoyu et al., 2018), temperate regions (Luoma et al., 2017; Haidu and Nistor, 2020), arid regions (Ghazavi and Ebrahimi, 2015; Heiß et al., 2020). The assessment has also been reported in various hydrogeological environments, i.e. Karst aquifers (Vías et al., 2010; Nanou and Zagana, 2018), Coastal regions (Kardan Moghaddam et al., 2017; Motevalli et al., 2018), Alluvial aquifers (Alam et al., 2014; Hussain et al., 2017), Hard rock aquifers (Shekhar et al., 2014; Jenifer and Jha, 2018).

There are three groups of groundwater vulnerability assessment methods: first is Index based methods, which are divided into Hydrogeological Complex and Settings methods (HCS) (Albinet et al., 1970); Matrix Systems (Goosseens et al., 1987), approaches based on the combination of two parameters; and Rating Systems (Civita et al., 1995; Foster et al., 1987; Stempvoort et al., 1993). The second category comprises statistical methodologies that evaluate groundwater vulnerability via statistical analysis or regression models (Eckhardt et al., 1995; Masetti et al., 2009; Yen et al., 1996). The third method pertains to simulation-based techniques that utilize simulation methods to predict the processes associated with the transportation of contaminants. Index and overlay methods are based on integrating maps of different physiographic attributes (geology, soil, aquifer media, and water depth) that control the groundwater vulnerability of the region by assigning a numerical score or rating to each attribute.

The DRASTIC technique, created by Aller et al. (1987) for the US Environmental Protection Agency (EPA), is a commonly employed index and overlay approach utilized to systematically assess the risk for groundwater contamination in various hydrogeological environments. Despite its original purpose for mapping applications, the DRASTIC model was not specifically developed for implementation within a Geographic Information System (GIS). Its initial usage involved a manual process of map overlay and computation (Merchant, 1994). He was the first to use GIS for DRASTIC implementation. GIS methods have been efficiently utilized for evaluating groundwater vulnerability owing to their ability to retrieve, store, organize, analyze, and present spatial data with geographic references.

2.9 Justification of The DRASTIC Method

The identification and assessment of risk zones and groundwater vulnerability necessitate comprehensive research employing various methodologies, such as process-based, statistical, and overlay and index methods. (Thirumalaivasan et al., 2003; Robins et al., 2007; Chenini et al., 2015; Mfumu Kihumba et al., 2017; Sakala et al., 2018; Ghouili et al., 2021; Kerzabi et al., 2021). These techniques are applicable to a variety of hydrogeological contexts, regardless of whether or not they contain identified aquifers.

The most commonly used index methods for studying groundwater vulnerability are: DRASTIC ((Fritch et al., 2000; Collin and Melloul, 2003; Machiwal et al. 2018; Wen et al., 2009; Wang et al., 2012; Shiraji et al., 2013; Saha et al., 2014; Shekhar et al., 2014; Ghosh et al., 2015; Ghazavi et al., 2015; Jang et al., 2017; Kura et al., 2015; Ahirwar et al., 2018; Hu et al., 2018; Xiaoyu et al., 2018; Barzegar et al., 2019; Bordbar et al., 2019; Barbulescu et al., 2020; Omotola et al., 2020; Bera et al., 2021; Alamne et al., 2022; Chakraborty et al., 2022; Ilamurugan et al., 2022; Yu et al., 2022); GOD (Foster, 1987; Boulabeiz et al., 2019; Taazzouzte et al., 2020), AVI rating system (Stempvoort et al. 1993), DIVERSITY (Ray & O'dell, 1993); SINTACS (Civita and DeMaio, 1997; Noori et al., 2019; Awawdeh et al., 2020), SIGA (Vrba, 1991); random forest (Lahjouj et al., 2020), PCA technique (Rahmani et al., 2019); Decision tree-based data mining (Yoo et al., 2016); Boosted regression tree (Motevalli et al., 2019); Fuzzy Clustering (Javadi et al., 2020). For the karst aquifer, EPIK (Doerfliger and Zwahlen, 1997; Nekkoub et al., 2020), multilayer FIS (Pathak and Bhandary, 2020), COP and COP + K (Assayed et al., 2022; Andreo et al., 2008; Vías et al., 2006), PaPRIKa (Kavouri et al., 2011), PI, and the Slovene approach (Goldscheider, 2003; Ravbar & Goldscheider, 2007) have been proposed. The choice of model depends on the aquifer type and data availability in that region.

Neshat et al. (2014) applied a modified DRASTIC approach using geographic information system (GIS) to evaluate groundwater vulnerability in Kerman Plain (Iran). The Wilcoxon rank-sum nonparametric statistical test was applied to modify the rates of DRASTIC. In addition, the analytic hierarchy process (AHP) method was employed to evaluate the validity of the criteria and subcriteria of all the parameters of the DRASTIC model, which was proposed as an alternative treatment of the imprecision demands.

Ribeiro et al. (2017) tests the applicability of the susceptibility index assessment method in evaluating the impact of agricultural activities on groundwater quality, using as a case study an aquifer of the Guayas River basin in Ecuador. The index adapts four parameters of the DRASTIC method and incorporates a new land use parameter.

In order to attain a certain level of uniformity in the development of groundwater intrinsic vulnerability maps across Europe, Working Group 1 of the European COST Action 620 on

"Vulnerability mapping for the protection of carbonate (karst) aquifers" put forth a novel approach. A comprehensive methodology was presented that ensures uniformity while accommodating the necessary adaptability for implementation across different continents and in the presence of diverse geological conditions, scales, data availability, time constraints, and resource limitations.

Daly et al. (2002) introduced a methodology that exhibits a higher degree of physical basis compared to the prevailing vulnerability-mapping techniques. The consideration of karstic environments is taken into consideration without necessarily excluding its applicability to other geological conditions. The collection of "core factors" connected to the overlying layers and the concentration of flow are instrumental in the preservation of groundwater from contamination, while simultaneously considering any potential bypass of the overlying layers.

In India, DRASTIC modeling has been applied in several areas of West Bengal (Dwarakeshwar River Basin, Nangasai River Basin, Kolkata Metropolitan, Tamil Nadu (Thoothukudi District, Vellore, South Taluk, Palar River Basin), Ahmedabad District, Gujrat, Mandla, Aligarh, Jharkhand, Dhanbad, and Lucknow and a positive correlation and high level of accuracy have been discovered between the DRASTIC and modified DRASTIC vulnerability maps and actual scenarios (Chakraborty et al., 2022; Nera et al., 2021; Saravanan et al., 2022; Venkatesan et al., 2019; Ghosh et al., 2015; Khakhar et al., 2019; Islam et al., 2022; Prasad et al., 2014; Saw et al., 2023; Rahman. 2008; Singh et al., 2015; Dobhal & Keshari, n.d). Given the similarities in geologic structure and characteristics between Bangladesh and India, it can be inferred that this approach would be opt for conducting vulnerability assessments in Bangladesh.

Chapter 3: Methodology

3.1 Introduction

The primary objective of the methodology section in any report is to enhance the comprehensibility of the study for readers. This chapter focuses on the procedural aspects of conducting the study. This chapter will explain the methodological approach employed in the study, including the selection of the study area, methods of data collection, sources of primary and secondary data, methods of analysis, software and tools implemented for the analysis, methods of sensitivity analysis, methods of model validation and limits of the study.

3.2 Selection of the Study Area

The identification of the study area was conducted through a comprehensive analysis of urbanized regions, taking into account factors such as population density, level of industrialization, and environmental conditions, with a specific focus on water resources. The research focuses on the study area of Narayanganj Sadar Upazila in Bangladesh. The region under consideration is situated within the latitudinal range of 23°33′ to 23°43′ north and the longitudinal range of 90°26′ to 90°33′ east, encompassing a total land area of 113.98 square kilometers (BBS, 2011). According to data from the Bangladesh Bureau of Statistics from 2011, the area has a noticeable concentration of people, with a population density of 8,764 people per square kilometer. Additionally, the area experiences a population growth rate of 1.5% annually. The non-agricultural sectors account for approximately 96% of the overall income earned by individuals (BBS, 2011). Shitalakshya and Dhaleshwari are two well-known rivers that cross the Upazila. The region is currently undergoing a process of rapid urbanization, characterized by a substantial influx of individuals migrating from various parts of the country. This migration is primarily driven by the desire to take advantage of the expanded employment prospects resulting from the ongoing industrial development. As a result of the aforementioned demographic changes, there has been a noticeable increase in the pressure exerted on open and unoccupied areas, as well as water bodies. This has consequently led to periodic transformations in the land use and land cover (LULC) of the study area. The growth of the garments industry, knitwear garments, shipyards, brickfields, global trading, and commercial and built-in land uses has experienced a notable expansion.

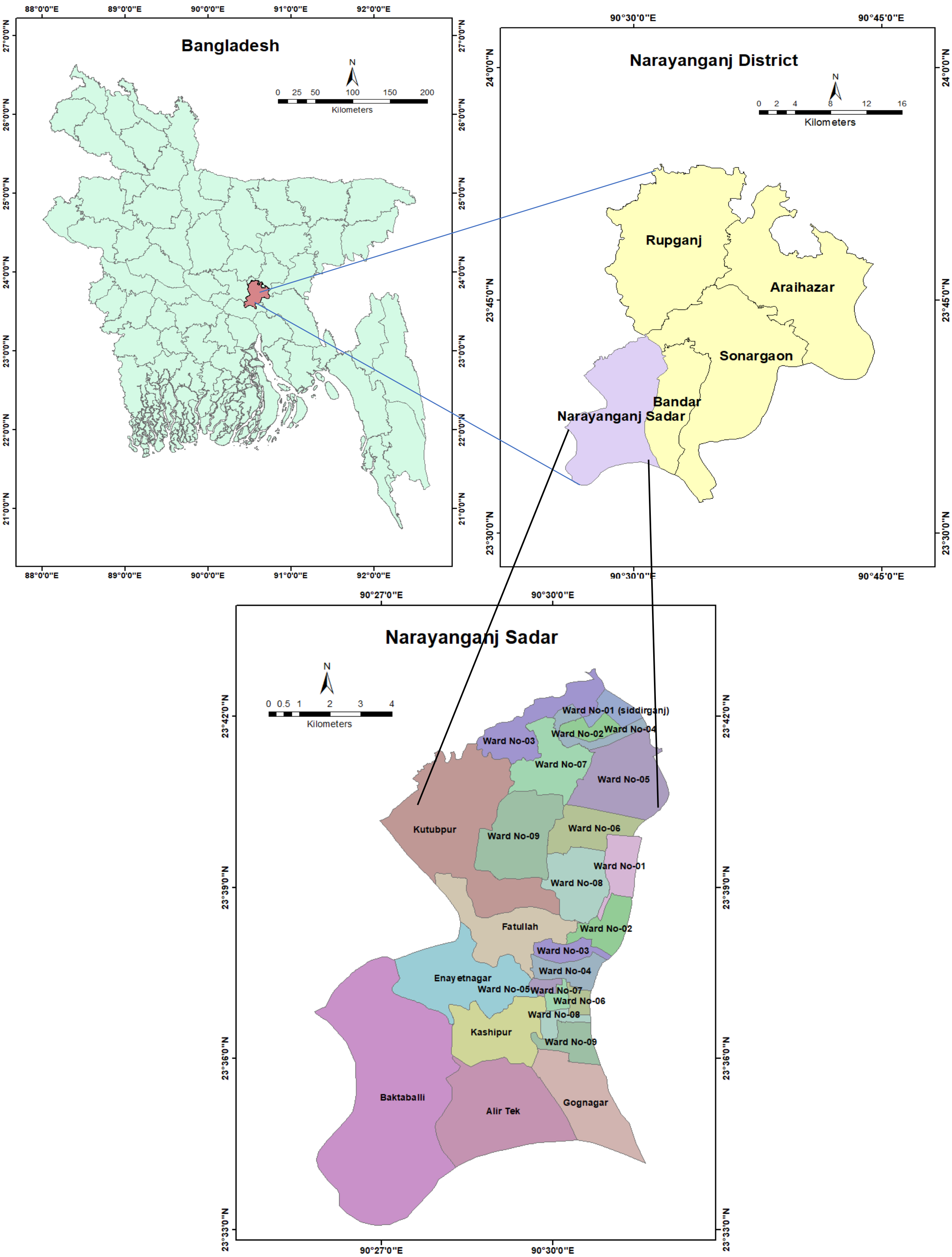


Fig 3.1: Map of the study area (Source: Prepared by author)

This upward trend continues to persist. Due to the aforementioned spatiotemporal alteration, there is an ongoing diminishment in the availability of land for vegetation and agricultural purposes and an increase in the extraction of groundwater, as the surface water of that region is unusable for most purposes. The discharge of industrial wastes and sewage, as well as the utilization of adjacent rivers and inlets for water consumption in public and domestic services such as transportation, sanitation, and water supply, along with the construction of infrastructure by encroaching upon water bodies, are exerting detrimental effects on both the water quality and sources in the region. Therefore, it is imperative to conduct comprehensive research on the groundwater vulnerability of this fringe area.

3.2.1 Physical characteristics of Narayanganj Sadar Upazila

3.2.1.1 Geology

From a geological perspective, it can be observed that the Narayanganj Sadar region is situated at the periphery of the Madhupur Tract, alongside the Holocene floodplain deposits originating from the aquifers (Ahmed, 1950). Geologically, it is a terrace situated at an elevation ranging from one to ten meters above the surrounding floodplains. While the current state of the formation suggests it belongs to the Pleistocene epoch, its initial development could be traced back to the late Miocene period, a time characterized by the rapid sedimentation of the Bengal Basin. In contrast to the Barind Tract, the geographical area under consideration is predominantly contiguous, with the presence of seven minor outliers. The primary geographical divisions within the city encompass the elevated terrain, commonly referred to as the terrace, as well as the lower-lying floodplain. Additionally, the city features various depressions and abandoned channels. The region is characterized by the presence of low-lying swamps and marshes, which constitute significant topographical elements within and in the vicinity of the area. The soils within the region have predominantly formed on Madhupur Clay, which has a low nutrient content and a slightly acidic nature. Their color can be described as either red or brown. The transition from floodplains to the Tract is generally characterized by a pronounced contrast in most locations. However, in certain instances, the floodplain soils overlay the gradually sloping boundaries. The Madhupur Tract exhibits a significant degree of dissection, with narrow or broad valleys that penetrate deeply into the flat terrain. The drainage pattern within this region is distinctly dendritic in nature. The elevated terrain is commonly referred to as Chala, while the lower-lying areas are designated as Baid. During the dry season, the valleys are utilized for the cultivation of Boro rice through the practice of impounding streams to facilitate irrigation.

3.2.1.2 Groundwater

Groundwater serves as a vital resource for domestic and industrial needs inside the urban confines of Narayanganj City. Tube wells are often located at distances ranging from around 50 to 320 meters from disposal sites. It is worth noting that individuals residing in neighboring households frequently use this water, despite the fact that doing so is not advised owing to the significant likelihood of groundwater contamination. The groundwater basin relies exclusively on groundwater supplies, since all other sources of freshwater are severely depleted or rendered nonviable. Surface water withdrawal from the rivers near the Narayanganj river basin region is not a viable alternative due to the significant presence of industrial and domestic contamination resulting from uncontrolled waste disposal practices. The urban water supply of Narayanganj city relies mostly on groundwater. The depletion of groundwater in Narayanganj city has been attributed to excessive extraction and the increasing demand resulting from urbanization. Recent data indicates that the water level in the city has been decreasing at a pace of around 2.5 meters per year.

3.2.1.3 Aquifer and Aquitard Properties

The Basin region exhibits distinctive Quaternary alluvial formations found in the Madhupur tract. This elevated Pleistocene terrace encompasses the floodplains of the Jamuna, Ganges, and Meghna rivers. The Narayanganj Sadar region is characterized by a primary aquifer composed of unconsolidated sediments originating from the Dupi-Tila Formation. These sediments are found beneath the Madhupur clay, which acts as an Aquitard with a thickness of approximately 48 meters. Aquifers exhibit a notable degree of homogeneity with respect to their properties and constituent materials. The shallow aquifers consist of unconsolidated deposits of sand, silt, clay, and gravel, with a thickness ranging from 10 to 150 meters. The replenishment of shallow aquifers occurs through precipitation and the infiltration of rivers, which are subsequently utilized for domestic and agricultural needs through the utilization of shallow tube wells and hand pumps. Shallow aquifers are susceptible to contamination originating from various surface sources, including sewage, industrial effluents, solid waste, and agricultural runoff. The deep aquifers consist of compacted sandstone and limestone formations, with depths ranging from 150 to 600 meters. The deep aquifers receive replenishment through the regional movement of groundwater from the adjacent elevated areas and are utilized for municipal and industrial needs through the extraction of water using deep tube wells. The deep aquifers exhibit a relatively high degree of protection against contamination owing to the existence of substantial clay layers that serve as confining units.

Layers	Average Thickness (meter)	Depth (meter)
Top soil	3	0-3
Aquitard - 1	11	3-14
Upper Dupitila Aquifer 1	23	14-37
Aquitard - 2	21	37-58
Upper Dupitila Aquifer 2	97	58-155
Aquitard- 3	16	155-171
Lower Dupitila Aquifer 1	57	171-228
Aquitard- 4	6	228-244

Table 3.1: Average thickness of the different hydro-geological layers at Narayanganj basin

3.3: Data Source

Most of the data required for the vulnerability mapping was collected from secondary data sources.

Parameters	***Data Type***	***Source***
Depth to Aquifer	Bore Log Data Excel Sheet	Department of Public Health Engineering, Narayanganj City Corporation
Recharge	Composite Map	Climate Research Unit, ASTER digital elevation model, Bangladesh Agricultural Research Council
Aquifer media	Bore Log Data Excel Sheet	Bangladesh water Development Board
Soil media	Topsoil Texture Map	Bangladesh Agricultural Research Council
Topography	Elevation Map	ASTER digital elevation model
Impact of Vadose zone	Bore Log	Bangladesh water Development Board
Hydraulic conductivity	Standardized Hydraulic conductivity Excel	(Domenico and Schwartz 1990).
Anthropogenic influence/ Land use Landcover Change	Land use Landcover Map 2000, 2022	Esri Landcover
Study Area	Administration	Bangladesh Agricultural Research Council

Table 3.2: The parameters and their sources for the study

The measurements of the water level were obtained from the Department of Public Health Engineering (DPHE), specifically from the Research and Development Division, for the year 2022.

In the Narayanganj Sadar Upazila, an annual assessment of aquifer depth is conducted during the monsoon season using a total of seven deep tube wells.

The rainfall data was acquired from The Climate Research Unit's Global Climate Dataset. The slope percentage within the designated research area was determined by utilizing the ASTER digital elevation model. The soil permeability map was acquired from the Bangladesh Agricultural Research Council.

The calculation of aquifer media and vadose zone was conducted utilizing the bore log data obtained from the Groundwater Hydrology Division of the Bangladesh Water Development Board.

Soil Map was acquired as a shapefile with the name topsoil texture from the website of the Bangladesh Agricultural Research Council.

Due to the unavailability of site-specific data for this investigation, the hydraulic conductivity was determined by referencing a database of standardized hydraulic conductivity values for different types of unconsolidated sedimentary materials (Domenico and Schwartz, 1990).

The land use/land cover map for the research region in 2022 was created using Esri Landcover software, with a 10m resolution and Sentinel-2 source images. The 2020 land use/land cover map was generated by acquiring a Landsat 8 image of Narayanganj Sadar from the official website of the United States Geological Survey (USGS).

For the purpose of model validation, a total of 14 groundwater samples were collected from shallow and deep tube wells located at various sites within Narayanganj Sadar. These wells were specifically chosen for their proximity to industrial zones. The gathered samples were considered as the primary data for the study.

3.4: Data Processing and Analysis

The data obtained from several organizations and secondary sources was systematically sorted and analyzed in accordance with the specific requirements of the DRASTIC modeling approach and its associated parameters.

3.4.1: DRASTIC Modeling Parameters

The DRASTIC approach, initially established in 1985, is extensively employed for the assessment of groundwater vulnerability due to its efficacy and intuitive characteristics.

The risk assessment of the Narayanganj Sadar Upazila was conducted using the DRASTIC model inside a Geographic Information System (GIS) framework. The notion being discussed is rooted in the hydrogeological environment, encompassing the significant geological and hydrological elements that influence and regulate the flow of groundwater within a given region (Aller et al., 1987). The DRASTIC model encompasses seven parameters, namely:

- The depth to water refers to the vertical distance between the ground surface and the water table. A greater depth to the water table indicates a reduced likelihood of pollution.
- Net recharge refers to the quantity of water that infiltrates the Earth's surface and reaches the water table. This recharge water serves as a medium for the transportation of contaminants.
- Aquifer media pertains to the qualities of saturated zone materials that govern the processes of pollution attenuation.
- Soil media refers to the highest weathered section of the unsaturated zone, which plays a crucial role in regulating the downward infiltration of recharge.
- The term "topography" pertains to the degree of inclination or steepness of a land surface. Regions characterised by low slopes have a tendency to hold water for extended periods, hence facilitating enhanced penetration of recharged water and an increased likelihood of pollutant migration.
- The vadose zone, which refers to the unsaturated zone material, plays a crucial role in regulating the movement and reduction of contaminated substances into the saturated zone.
- Hydraulic conductivity serves as an indicator of an aquifer formation's capacity to transmit water, with aquifers possessing high conductivity being more susceptible to significant contamination.

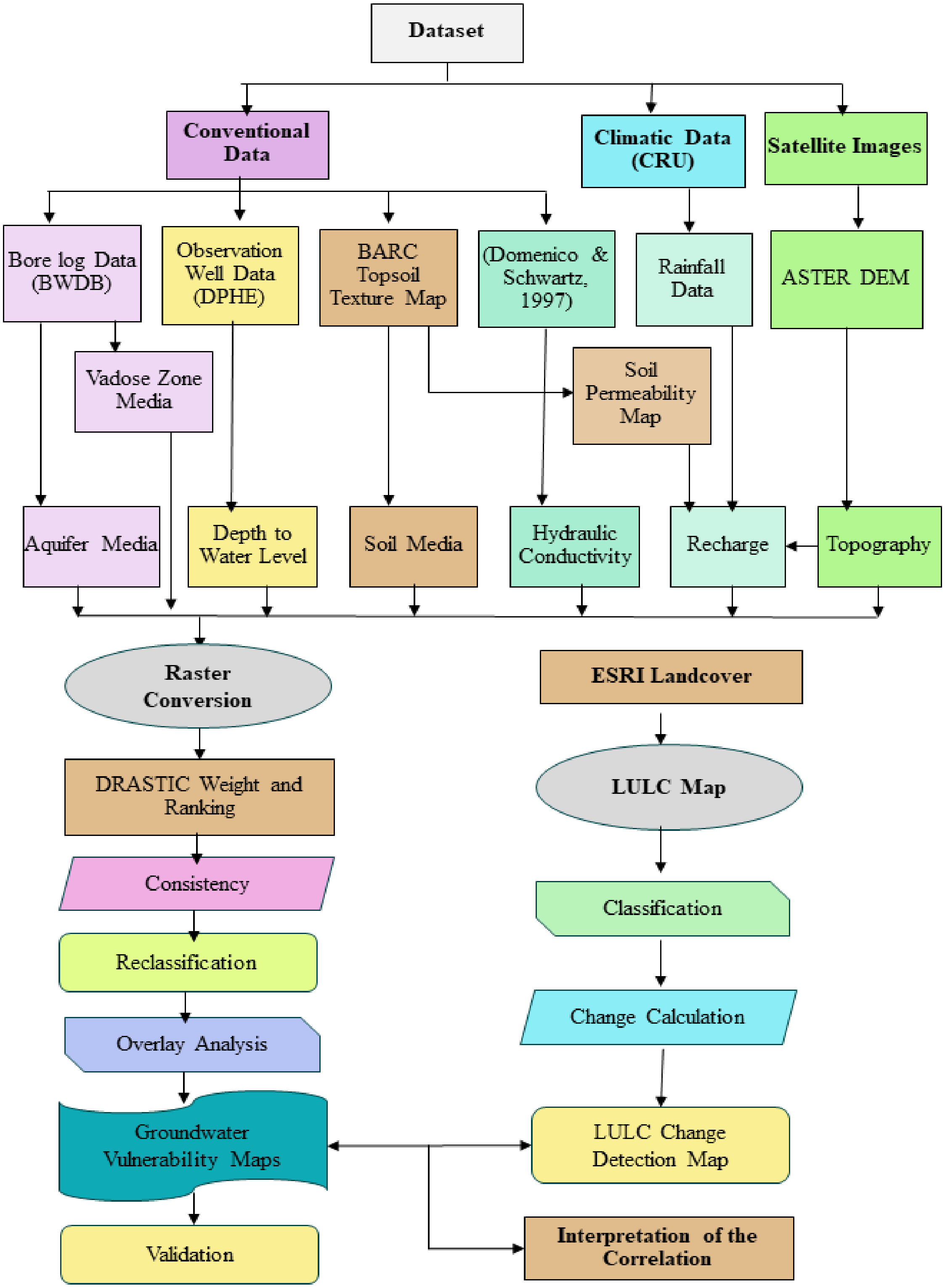


Fig 3.2: Methodological flow chart for groundwater vulnerability mapping. (Source: Prepared by author)

The DRASTIC technique utilises a numerical rating system that spans from 1 to 10 in order to grade each parameter. This assessment is based on functional curves. The rating is subsequently modified by the application of a weighting factor, and the resultant weighted ratings are aggregated to compute the DRASTIC index (DI). The weights of the criteria are determined depending on their individual sensitivity to the pollutant.

The DRASTIC parameters are assigned relative weights ranging from 1 to 5, which are determined based on their susceptibilities to contaminants (Fortin et al., 1997; Babiker et al., 2005). The characteristics of utmost importance are awarded a weight of 5, whilst the parameters of lesser value are allocated a comparatively lower weight. The weights utilised by the United States Environmental Protection Agency (EPA) were determined after a comprehensive study process conducted by professionals, as documented by Barbulescu (2020). The seven DRASTIC criteria are methodically delineated and classified into several ranges or important media kinds, which contribute to the assessment of contamination potential.

The development of the final vulnerability map relies on the application of the DRASTIC index (DI). This index is obtained by the application of a weighted sum overlay technique on seven layers, as described by Knox et al. (1993), and may be represented by the following equation:

The DRASTIC index = $DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$,

where D, R, A, S, T, I, and C represent the seven parameters, r denotes the rating value, and w signifies the weight associated with each parameter (Navulur & Engel, 1998).

After the computation of the DRASTIC Index, it becomes feasible to discern the relative susceptibility of different places to groundwater pollution. There is a positive correlation between the DRASTIC Index and the possibility of groundwater contamination. The seven types of information layers were scanned and subsequently transformed into raster data sets. These raster datasets were then processed using the integrated ArcGIS 10.3 software.

The DRASTIC technique operates under the following assumptions:

1) The introduction of the contamination occurs at the surface of the ground.
2) The pollutant is transported into the groundwater by precipitation.
3) The toxin exhibits the same movability as water.

4) The assessed area encompasses a minimum of 100 acres.

Moreover, the numerical weights and ratings, ascertained through the use of the Delphi approach, possess clear and explicit definitions and have been widely employed on a global scale (Aller et al., 1987; Dang & Nguyen, 2021). The Delphi Method is a methodology that leverages the expertise and empirical knowledge of specialists within a certain field to evaluate and determine the degree of risk involved.

3.4.1.1 Depth to Aquifer (D)

The vertical gauge from the ground surface to the water table is commonly known as the depth to the water table. This refers to the precise extent of travel undertaken by toxins and pollutants before their eventual disintegration in the groundwater. The vertical extent of the aquifer is a critical determinant that significantly impacts the susceptibility of groundwater. Land subsidence, saltwater intrusion, groundwater abstraction, and climate change are just a few of the factors that can affect an aquifer's depth. These factors have the potential to modify both the groundwater levels and the properties of the aquifer over time. The degree to which toxins engage in chemical and biological processes, such as dispersion, oxidation, and sorption (the sequestration of a chemical species by a solid constituent of a soil), resulting in natural devitalization, is contingent upon the length of interaction among the infiltrating water and the solid or semi-solid components within the vadose zone. The likelihood of groundwater pollution decreases as the distance to the water level increases (Ahmed, 2009; Aller et al., 1987). Attenuation plays a significant role in the filtration of contaminants to prevent their infiltration into the soil medium. Therefore, this component has importance in the process of ranking and providing weight to the relevant factors. The depth to water level was collected from DPHE of the year 2022. In the Narayanganj Sadar Upazila, a total of seven deep tube wells are utilized to annually assess the depth of aquifers, specifically during the monsoon season. The depth characteristics were recorded and organized in an Excel spreadsheet, along with the corresponding geographic coordinates for each bore log.

3.4.1.2 Net Recharge (R)

Water originating from precipitation and other anthropogenic sources infiltrates the soil and percolates downward to the groundwater table. While net recharge does contribute to the dilution of contaminants in the aquifer, it also serves as the largest pathway for the transfer of contaminants (Awawdeh et al., 2015). The recharge process is influenced by several factors, including slope, permeability, rainfall, land cover, and the quantity of infiltrating water (Shirazi et al., 2013). The research region mostly relies on precipitation as its main source of recharge. The regions experiencing greater precipitation will exhibit an elevated rate of groundwater replenishment and an increased susceptibility to degradation, given the clear correlation between groundwater replenishment and pollution. (Tilahun and Merkel, 2010; Lathamani et al., 2015; Mondal et al., 2019).

Net Recharge was calculated from rainfall data using the Piscopo formula (2001) because there was a lack of information for net recharge in the research region. It is a widely used method for the assessment of Net recharge for the vulnerability analysis (Saravanan et al., 2020; Awawdeh et al., 2014; Ahirwar & Shukla, 2018)

Recharge value = Slope factor (%) + Rainfall factor (mm) + Soil permeability factor

This equation is utilized to compute a recharge value. The recharge value is subsequently organized into a series of values that are assigned a rating for utilization in the ultimate DRASTIC computation. The rainfall data was obtained from The Climate Research Unit Global Climate Dataset, which is spatially gridded at a resolution of 0.5 degrees by 0.5 degrees. The slope percentage within the research region was calculated using the ASTER digital elevation model. The slope map was transformed into a raster layer with grids, where the pixel values in the grid correspond to the slope ratings. The soil permeability map was obtained from the Bangladesh Agricultural Research Council and afterwards transformed into grid coverage. A rating value was provided to each element based on its capacity to enhance the probable recharge value.

The application of Equation to the designated research region facilitated the computation of recharge ratings, as seen in the following table:

Slope		**Precipitation**		**Permeability**		**Recharge**	
Range (%)	Factor	Range (mm)	Factor	Range	Factor	Range	Factor
<1	5	>1500	5	Moderate to High	4	11-13	10
1-3	4	1450-1500	4			9-11	8
3-5	3	1400-1450	3	Moderate	3	7-9	5
5-10	2			Slow	2	5-7	3
>10	1			Very slow	1		

Table 3.3: The recharge range and ratings for the study area: (a) Slope; (b) Rainfall; (c) Soil permeability; and (d) Recharge value.

3.4.1.3 Aquifer media (A)

Aquifer media pertains to the geological characteristics of formations that function as aquifers. For instance, alluvium predominantly consists of sand and gravel, whereas solid stone aquifers are characterized by corroded zones and subsidiary porosities, such as cracks or joints. There are many types of interactions that occur between the water and the aquifer media, such as dissolution, precipitation, adsorption, ion exchange, oxidation-reduction, and biological processes which influence the hydrochemistry of the aquifer (Thapa et al., 2018). The hydrodynamic characteristics of an aquifer, including its flow rate and behavior, are primarily influenced by its geological composition, also referred to as the media. The media also exerts significant influence over the trajectory and distance traveled by pollutants. The length of time during which the enfeeblement process stays operational within the flow is dependent on many characteristics of the aquifer media, including sorption, reactivity, dispersion, and the functional surface area of the aquifer framework substance. (Aller et al. 1987). Formations characterized by lesser permeability and greater thickness are considered to have a reduced risk of contamination due to their capacity to facilitate higher levels of dissolution and diffusion of pollutants. The ability of pollutants to be impaired is reduced by larger grain size, higher porosity, the existence of fractures, and interconnected aquifer media. This particular aquifer medium allows for the efficient movement of water that is combined with pollutants and the likelihood of contamination is elevated (Anwar et al., 2002; Edet, 2004; Asfaw & Ayalew, 2020; Xiaoyu et al., 2018). Aquifer media was calculated using the bore log data from Bangladesh Water Development Board. They conducted bore log surveys on seven unions of the Narayanganj Sadar Upazila from where the aquifer media data was extracted in comparison with the water level data. Strater 5 software was used in order to visualize the lithostratigraphic units along with a demarcated layer of aquifer media of different locations in the study area.

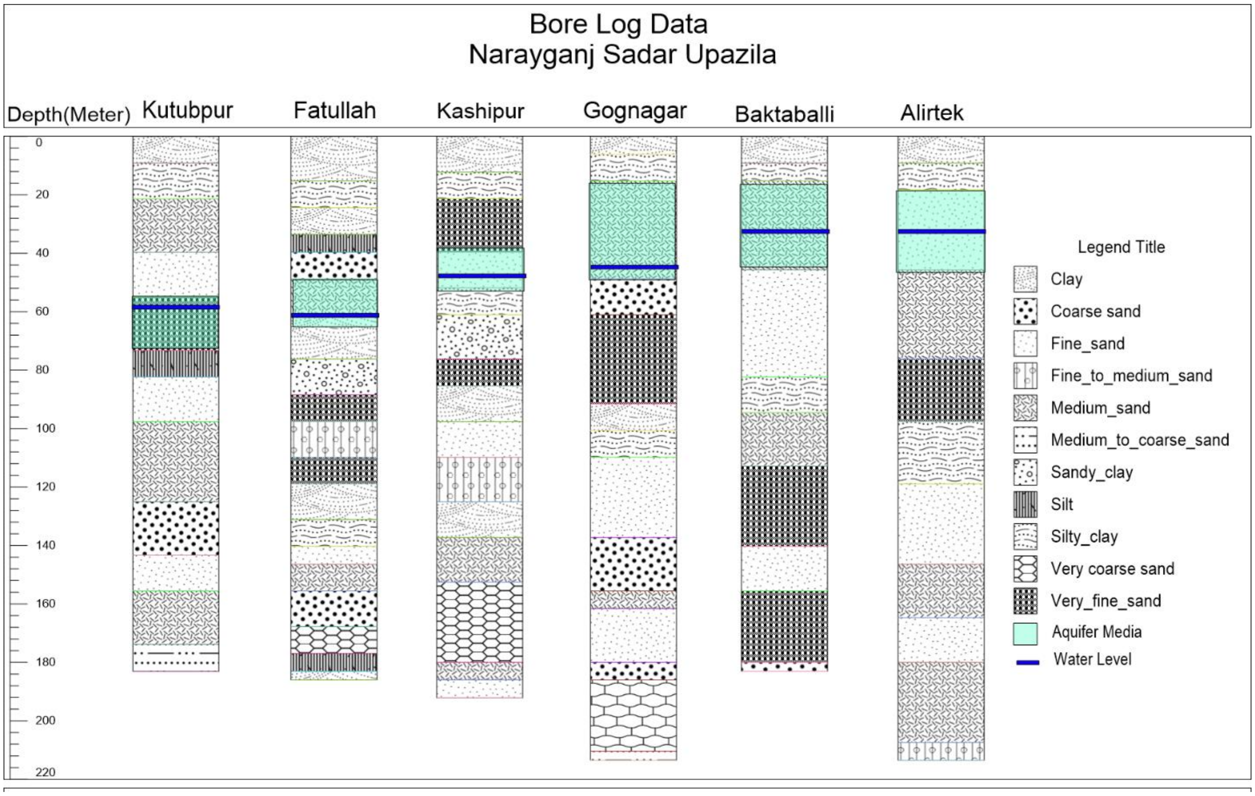


Fig 3.3: Lithology data of the Aquifer Media of Narayanganj Sadar (Data Source: BWDB, Prepared by author)

3.4.1.4 Soil Media (S)

The term "soil media" pertains to the topmost section of the vadose zone, which is distinguished by notable biological activity. Soil is typically regarded as the uppermost layer of the earth's surface that undergoes weathering, with an average thickness of 6 feet or less within a given area (Prasad and Shukla, 2014). The transport and retention of pollutants in the soil layer are influenced by many characteristics of soil, including permeability, porosity, organic matter concentration, which vary across different soil types. The presence of fine-grained soil particles, like as clay and silt, can impede the movement of pollutants when they are combined with recharge water due to their relatively poor permeability. Nevertheless, it should be noted that clayey soils exhibit a higher susceptibility to inorganic pollutants, namely heavy metals, which have the potential to be mobilized by complexation (the reaction between a cation and one or more anions) or ion exchange processes (Shaheen et al., 2023; Chukwuma et al., 2023; Smail & Dişli, 2023). Conversely, soil particles characterized by bigger grain size exhibit a heightened rate of penetration, hence facilitating the entry of pollutants through recharge water and subsequent contamination of the aquifer. Organic matter content influences soil's ability to retain and absorb the pollutants. The primary mechanisms of attenuation in thick soil media, including volatilization, biodegradation, filtration, and sorption, result in a significantly reduced risk of contamination (Singh et al., 2015). The various soil layers support a diverse array of microorganisms that play a crucial role in the biodegradation process of pollutants (Aller, 1985).

3.4.1.5 Topography (T)

Topography is the term used to describe the slope of the ground surface and its variability. The topography and landscape location exert an impact on the hydrological processes governing water movement on and within the soil (Ahada & Suthar, 2018). The slope influences whether contaminated groundwater proceeds downhill as runoff or into the groundwater storage. In regions characterized by little incline, the duration of water runoff is extended, resulting in increased infiltration rates and hence a heightened risk for contamination. In regions characterized by a more pronounced incline, the precipitation or surface runoff exhibits a heightened velocity, resulting in a reduced duration for the process of percolation (Magesh et al., 2010; Waikar and Nilawar, 2014). Another crucial element that helps to forecast water circulation gradient and direction on the site is the slope's form. The phrases planer/linear, convex, and concave are used in the slope description to define the land surface that runs parallel to and along the slope. Determining surface and subsurface drainage patterns may be done using this information (Heger, 2021)

The topographic data was acquired from the digital elevation and slope model (DEM). The slope, expressed as a percentage, was derived by the use of spatial analyst tools inside a Geographic Information System (GIS). The slope was thereafter categorized and evaluated for its suitability in the creation of the topography component map.

3.4.1.6 Impact of Vadose zone (I)

The vadose zone refers to the region of the Earth's subsurface that lies between the terrestrial surface and the upper boundary of the phreatic zone, where the water is maintained at atmospheric pressure. This zone is alternatively referred to as the unsaturated zone due to its inclusion of both air and water within its pores. The vadose zone is of utmost importance in the hydrological cycle due to its crucial function in regulating groundwater recharge and the conveyance of surface contaminants to the aquifer. The vadose zone can act as a source, sink, or barrier for contaminants, depending on the physical, chemical, and biological processes that occur within it (Panda & S, 2019). Some of these processes include:

Advection: The movement of water and dissolved contaminants along the hydraulic gradient.
Dispersion: The spreading of contaminants due to heterogeneity and molecular diffusion.
Sorption: The attachment of contaminants to solid surfaces or organic matter.
Degradation: The transformation or breakdown of contaminants by chemical or biological reactions.
Volatilization: The transfer of contaminants from liquid to gas phase.
Plant uptake: The absorption of water and contaminants by plant roots.

The influence of the vadose zone on groundwater contamination is contingent upon various factors, including the characteristics of the soil and rock, the quantity and nature of pollutants, the vertical and horizontal dimensions of the vadose zone, and the prevailing climatic conditions. The attenuation process of recharge water is controlled by vadose zone media and the rate of permeability. It also regulates the route and journey length of recharge water. If the vadose zone media has more clay and silt, the risks of degradation are lower, but a high sand percentage raises the likelihood of contamination significantly (Asfaw and Ayalew, 2020). If the residence period of recharge water in the vadose zone is longer, the process of attenuation takes longer to transpire.

The impact of vadose zone index was created using lithological data using methods similar to those used for the markers A.

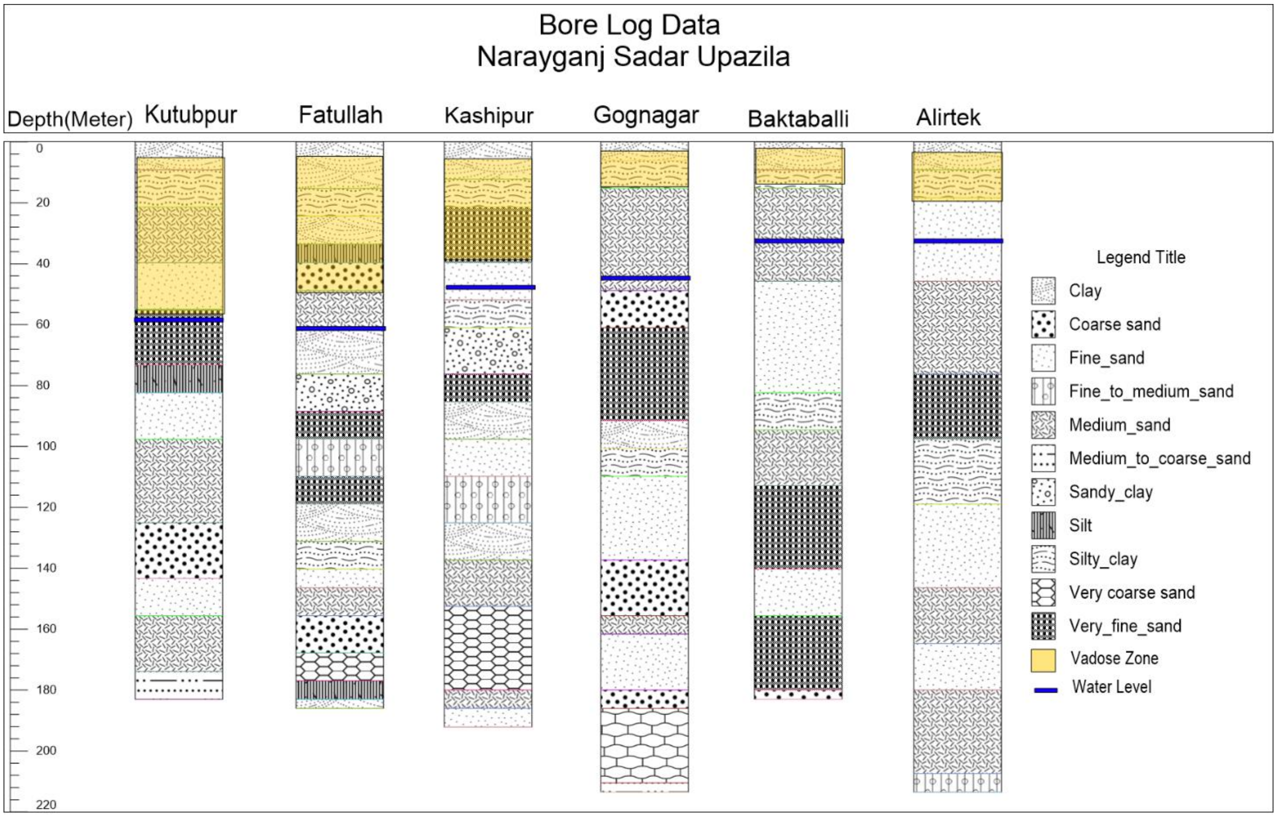


Fig 3.4: Lithology data of the Vadose Zones of Narayanganj Sadar (Data Source: BWDB, Prepared by author)

3.4.1.7 Hydraulic Conductivity (C)

Hydraulic conductivity refers to the capacity of the aquifer medium to facilitate the movement of water in response to a hydraulic gradient (Lobo Ferreira et al., 2005). The porosity, permeability, and tortuosity of the media, as well as the viscosity and density of the water, are some of the variables that affect an aquifer's hydraulic conductivity. The hydraulic conductivity of an aquifer plays a significant role in determining the velocity and discharge of groundwater within it. In a broad context, it may be seen that a decrease in grain size corresponds to a reduction in hydraulic conductivity. Aquifers with high conductivity exhibit heightened susceptibility to contamination, since the presence of pollutants facilitates their facile movement within the aquifer (Bera et al., 2022). The hydraulic conductivity, which is shaped by the viscosity and density of water, can technically be considered a function of water temperature. However, due to the limited range of temperature fluctuations typically observed in groundwater systems, the impact of temperature on hydraulic conductivity is commonly disregarded.

As the site-specific data are unavailable for this study, the hydraulic conductivity was measured from a table of standardized hydraulic conductivity values for various unconsolidated sedimentary materials (Domenico and Schwartz 1990).

3.4.1.8 Mapping of the DRASTIC Parameters and Vulnerability Index

Data on the influence of the vadose zone, the depth to the aquifer, and the aquifer media were collected on analogue sheets and subsequently converted to excel sheets with the appropriate coordinate information. The latitude and longitude information were then linked to the server when those tables were incorporated to the Arcmap software and a point shapefile was created. The values of those particular data points were then subjected to the inverse distance weighted tool. It is an interpolation technique used when there is no previous information of the connection between the points and a decent distribution of observations to estimate values at unmeasured locations based on the values of adjacent measured points. This strategy was acceptable because the data came from particular points within the various unions of the upazila and the correlation was not known. The reclassification tool was used to assign rankings to them. The parameter was classified using the natural break and equal interval approaches. The raster data was transformed into polygon format, and then, the area and area percentage were determined using attribute tables, calculate geometry, and field calculator tools. Once the raster layers representing the seven parameters were generated and assigned their respective ratings, the layers were combined using the weighted sum tool, which incorporated the weights of the distinct parameters. The vulnerability index was developed and classified into five subgroups. The classification was done by Natural Breaks (Jenks) process.

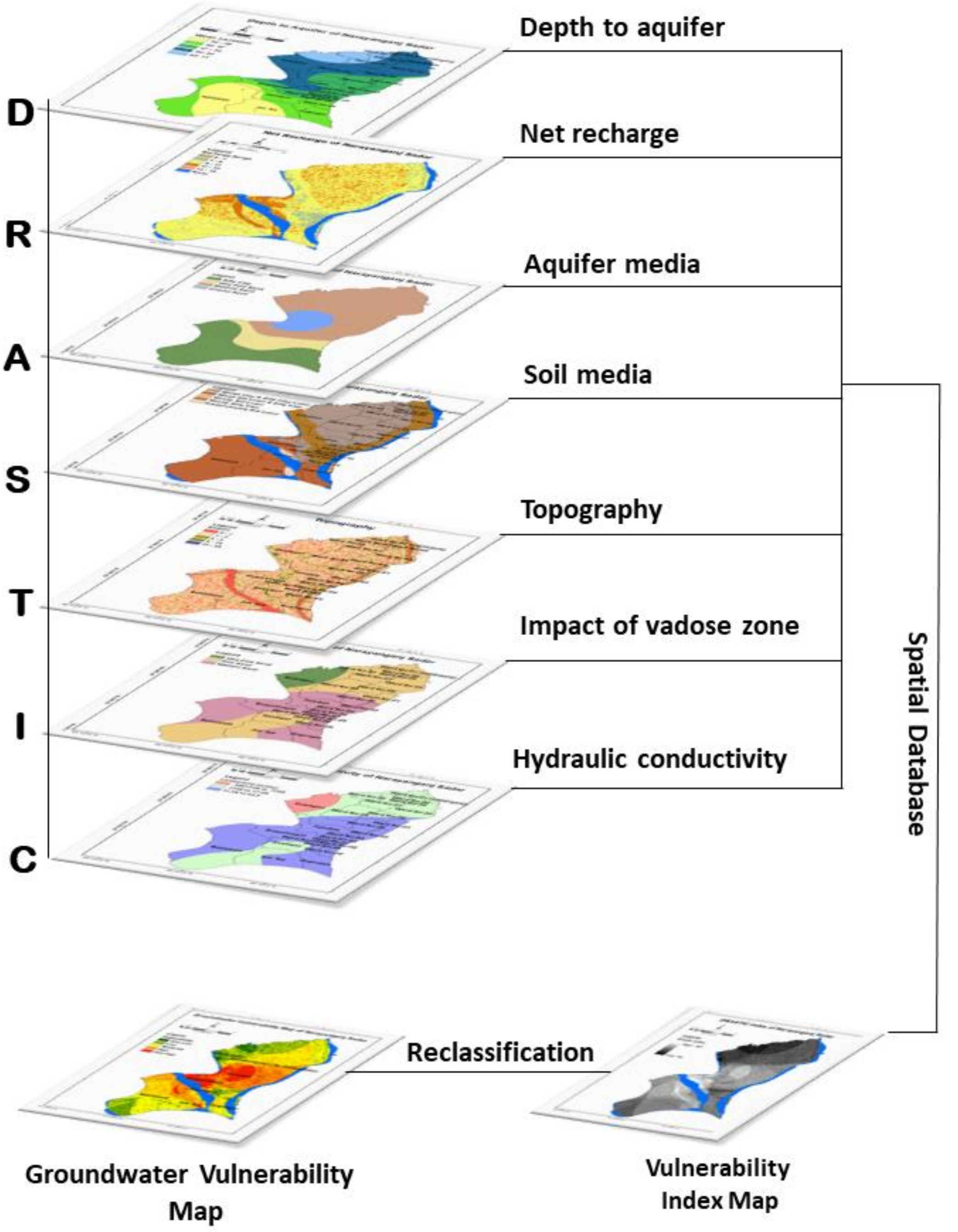


Fig 3.5: Methodology flowchart for DRASTIC method. (Source: Prepared by author)

DRASTIC PARAMETERS	RANGE	RATING	RELATIVE WEIGHT	TOTAL WEIGHT
DEPTH TO AQUIFER	<40	5	5	25
	40-47	4		20
	47-55	3		15
	55-63	2		10
	> 63	1		5
NET RECHARGE	5-7	3	4	12
	7-9	4		I 6
	9-11	6		24
	> 11	8		32
AQUIFER MEDIA	Medium sand	6	3	18
	Fine sand	4		12
	Very fine sand	2		6
SOIL MEDIA	Predominantly Silt Loam	7	2	14
	Mostly Silt Loam	6		12
	Mixed Silt Loam & Silty Clay	5		10
	Mostly Silty Clay	3		6
	Mixed Clay & Silty Clay Loam	1		2
TOPOGRAPHY	< l	10	1	10
	1-3	8		8
	3-5	6		6
	5-10	4		4
	> 10	2		2
IMPACT OF VADOSE ZONE	Coarse sand	10	5	50
	Medium Sand	8		40

	Very fine sand	5		25
	Silty Clay	3		15
HYDRAULIC CONDUCTIVITY	.0001728 to .1728	4	3	12
	.1728 to 17.28	5		15
	17.28 to 43.2	6		18

Table 3.4: Ranges, ratings and relative weights used for the indicators in the DRASTIC model. (Prepared By Author)

3.5 Correlation of The Vulnerability Map With Land use and Landcover (LULC) Change

Land Use/Land Cover (LU/LC) refers to the physical characteristics of the Earth's surface, including flora, infrastructure, and human activities, that are present in a certain geographical area. These features can encompass a wide range of cultural and economic activities, such as agriculture, industry, residential areas, recreational spaces, and mining operations. The dynamics of groundwater are significantly impacted by land use, exploitation, and various other human activities. These activities alter the conditions of groundwater discharge and recharge, leading to changes in the response characteristics of groundwater levels to factors such as precipitation, runoff, and exploitation (Prabhakar & Tiwari, 2015; Yankey et al., 2020). It is important to note that these response characteristics can vary over time and are influenced by the specific hydrogeological conditions in a given area. Land use and land cover (LULC) also have the ability to influence the groundwater recharge process by introducing or mobilizing possible pollutants within the soil and aquifer, hence impacting the overall quality of groundwater recharge. One instance of human agricultural practices is the introduction of fertilizers, insecticides, and animal waste into the environment, which may contain substances such as nitrate, phosphate, and pathogens. Industrial operations have the potential to introduce various chemical compounds, metallic elements, and organic contaminants into the subsurface water reservoirs, hence resulting in the leaching of these substances into the groundwater. Urban activities have the potential to bring many pollutants into the environment, such as sewage, solid wastes, oil, and road salts. These substances can pollute both surface runoff and infiltration processes.

The 2022 land use/land cover map for the research region was generated by Esri Landcover with 10m resolution and Sentinel-2 source imagery. Then the image was clipped to the study area and reclassified by spatial analyst tool. Afterwards, the area and percentage of different classes were calculated. The 2020 land use/ land cover map was prepared by downloading a Landsat 8 picture of Narayanganj Sadar from the United States Geological Survey (USGS) website. The image underwent categorization within the ArcGIS environment via an interactive supervised classification method. The primary land use and land cover (LU/LC) classifications seen within the research region consist of settlement, predominantly including built-up areas. Additionally, there are smaller portions of land categorized as water bodies, bare land, agricultural land, and vegetation cover. The area change between these years was calculated using Intersect of Geoprocessing tools.

3.6 Sensitivity Analysis

The DRASTIC model is distinguished by its utilization of a substantial quantity of parameters (Evan & Myers, 1990), a feature that is thought to mitigate the influence of mistakes and uncertainties associated with each individual parameter on the ultimate outcome (Rosen,1994; Babiker et al.,2005). However, several writers (Barber et al., 1993; Merchant et al., 1987) have argued that a comparable outcome to DRASTIC may be achieved with a reduced set of input. The validation of aquifer vulnerability methodologies is necessary in order to minimize subjectivity and discrepancy in the selection of rating ranges and to enhance the dependability of the results (Ramos-Leal & Rodríguez-Castillo, 2003; Pathak et al., 2009; Barber et al., 1993; Napolitano and Fabbri, 1996).

Sensitivity analysis (SA) quantifies the level of uncertainty or variability in the output outcomes derived from the application of models (Napolitano and Fabbri, 1996; Saltelli et al., 2008). In broader terms, it quantifies the resilience of the model's output when the input variables are modified. Estimating the impact of specific input parameters on the model's output is beneficial for comprehending their effect. This may be achieved by assessing the change in the output map that occurs with each alteration in the input variables. The impact of input parameters on the model output has been investigated by researchers. This impact is determined by several elements, including the quantity of input parameters, the inaccuracy associated with inputs, the weights allocated, and the rankings awarded. Additionally, the nature of the overlay conducted has been considered in these studies (Heuvelink et al., 1989).

3.6.1 Map removal sensitivity analysis

The approach of Map removal sensitivity analysis involves the systematic removal of each theme layer individually, followed by the computation of a variation index (Lodwick et al., 1990). The maps illustrate the spatial distribution of several vulnerability groups within the variation index. The resulting individual maps are depicted in Figure 4.14 to 4.20, accompanied by Table 4.6. These visual representations provide valuable insights into the changes in the vulnerability index when each layer is removed from the evaluation.

The initial stage of the study was the computation of vulnerability values utilizing a set of six maps, as opposed to the original seven maps, by excluding one map from the dataset. The vulnerability index for each sub-area was computed by employing various combinations of six out of the seven criteria, as described by Gogu and Dassargues (2000). In order to ensure comparability, the output values were rescaled using a factor of 7/6. By comparing the new index with the initial one, one may obtain a direct assessment of the impact of the parameter that is absent. Lodwick et al. (1990) provide a sensitivity measure for map removal, which quantifies the level of sensitivity linked to the removal of one or many maps.

$$S = 100 * (| V/N - V'/n |) / (V)$$

In this context, the sensitivity variation index (S) is defined as the ratio of the difference between the unperturbed vulnerability indexes (V) divided by the total parameters of the DRASTIC Index and the perturbed vulnerability indexes (V') divided by the number of parameters (n) used to estimate the new vulnerability index following the removal of a parameter.

3.6.2 Single parameter sensitivity analysis

The utilization of single parameter sensitivity analysis, as described by Napolitano and Fabbri in 1996, is employed to evaluate the impact of specific input parameters on the vulnerability index. The single indicator sensitivity analysis appraises the relationship between the theoretical weights given to each metric during the computation of the DRASTIC model and their corresponding effective weights. The theoretical weight was calculated using the following equation:

$$Tw = 100 * (Xw / \sum Xx)$$

Where Tw refers to the “theoretical” weight of each parameter and Xw is the weight for each parameter. The determination of effective weight is derived by considering the relative importance of a specific indication in relation to the weights assigned to the remaining six indicators during the computation of the vulnerability index (Babiker et al., 2005). The mathematical expression may be represented as follows.

$$Sp = [(Rp * Rw) / V] * 100$$

The sensitivity analysis, denoted as Sp, involves the assessment of the rating (Rp) and weights (Rw) attributed to each parameter and V is the total vulnerability index.

3.7 Model Validation

The validation of the DRASTIC model has significance due to its reliance on subjective judgments and weights of characteristics influencing groundwater sensitivity to pollution, making it a semi-empirical approach. The determination of ratings and weights for parameters is frequently informed by expert opinions, literature studies, or default values, which may not necessarily align with the local conditions or the specific contaminant being considered. Hence, the process of verifying the DRASTIC model can contribute to:

- Evaluate the precision and dependability of the vulnerability assessment, while also identifying any potential inaccuracies or uncertainties inherent in the methodology.
- Assess the correlation or agreement between the theoretical vulnerability score and the real groundwater quality data.
- Offer a more pragmatic and credible foundation for making choices on the protection and management of groundwater resources.

Relying solely on a single chemical parameter for validation is not a valid method to establish the vulnerability of a certain aquifer. This is due to the fact that the concentration of an individual indicator is influenced by its exposure to a specific pollutant (Hamza et al., 2014). In order to validate our findings, we utilized correlation approaches to analyze five groundwater parameters: electrical conductivity (EC), total dissolved solid (TDS), pH, nitrate ($NO3^-$), and chromium (Cr). The five physical and chemical measurements were anticipated to provide insight into the pollution state of the groundwater system.

Several researchers have conducted nitrate concentration tests to adjust the weights assigned to the indices in order to address the issue of subjectivity in the implementation of the DRASTIC technique (Jhariya, 2019; He et al., 2018; Kazakis and Voudouris, 2015; Barzegar et al., 2019). The exacerbation of nitrate contamination in groundwater can be attributed to anthropogenic farming practices, excessive utilization of fertilizers, and liquid waste discharged from septic tanks (Shrestha et al., 2016; Jianmin et al., 2015; Ghahremanzadeh et al., 2017; Mohammad et al., 2018).

Chromium can enter water bodies through leaching from topsoil and rocks, which is the most important natural source of chromium. However, human activities such as electroplating, leather tanning, textile industries, and chemical plants can also release large amounts of chromium in surface waters or groundwater (Agency for Toxic Substances and Disease Registry, 2019). Solid wastes from chromate-processing facilities, when disposed of improperly in landfills, can be sources of contamination for groundwater as well. According to Rahman et al., (2020) Chromium is the second most abundant heavy metal in the industrial area of the Meghna Ghat, Narayanganj City. Narayanganj Sadar is home to a variety of metal businesses engaged in the production of stainless steel, metal alloys, metal joint prosthesis, and other metal-based items. Chromium is utilized as a crucial constituent in several sectors, which have the potential to discharge chromium into the atmosphere, aquatic bodies, and terrestrial environments. Additionally, Narayanganj Sadar has earned a reputation as the "Dundee of Bangladesh" due to its notable concentration of textile mills and enterprises. The aforementioned sectors are responsible for the production of cotton, jute, silk, synthetic textiles, clothing, and several other textile commodities (Narayanganj Sadar Upazila, n.d.). Various businesses utilize chromium for dyeing or finishing procedures, potentially resulting in the release of wastewater containing chromium into rivers or groundwater systems. This is the rationale for the selection of chromium for the validation of the groundwater vulnerability DRASTIC Index. A total of 14 samples were gathered from various locations inside Narayanganj Sadar. These samples were then subjected to examination in the laboratory of the Department of Geography and Environment at the University of Dhaka. The analysis focused on determining the physical characteristics, including pH, electric conductivity, and total dissolved solids. The chemical parameters were assessed inside the confines of the WAFFEN Research Laboratory. Additional data pertaining to the examination of groundwater quality was acquired from both the Bangladesh Water Development Board (BWDB) and the Department of Public Health Engineering (DPHE) for further validation.

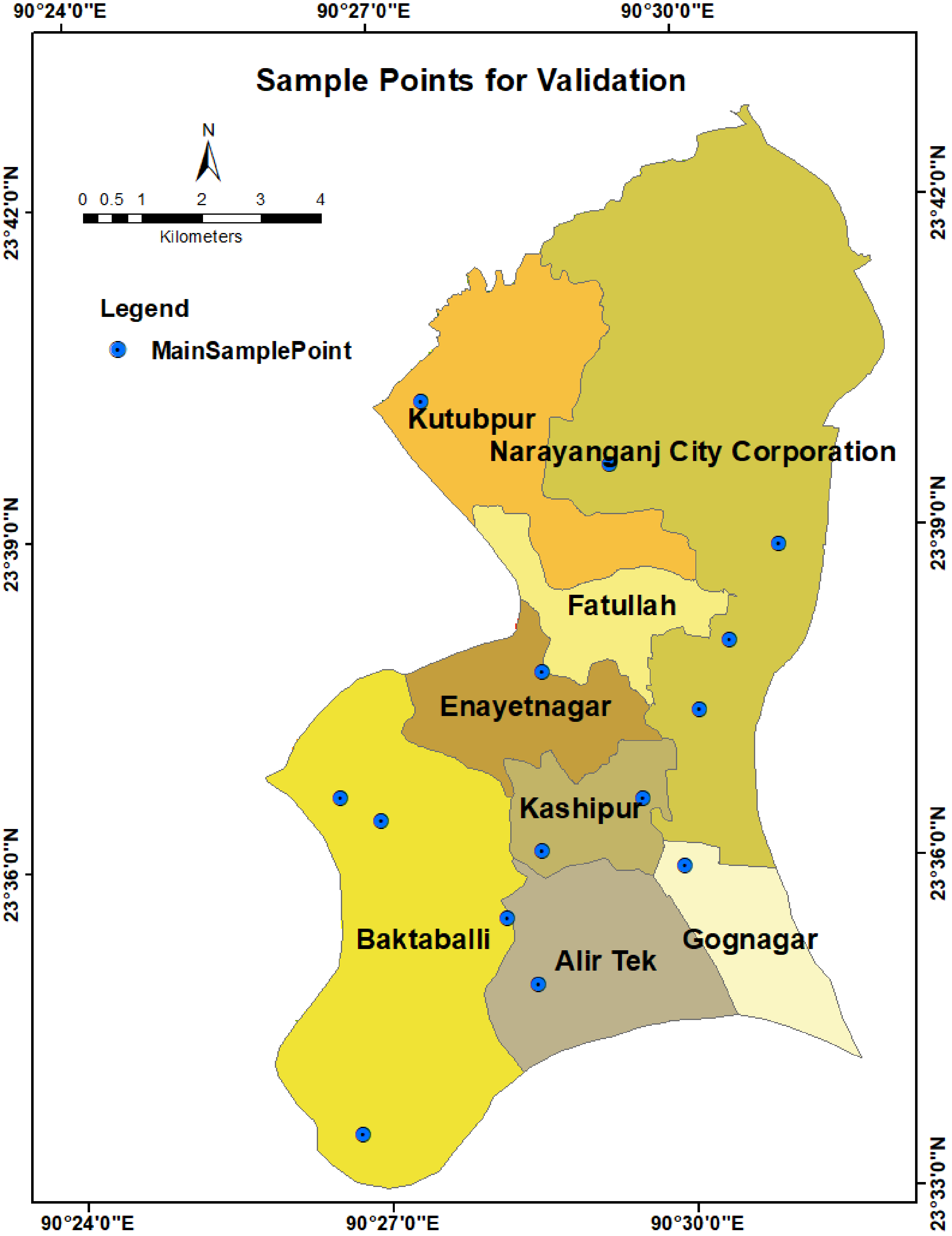


Fig 3.6: Main Sample Points for Groundwater Quality Analysis for Model Validation. (Samples Collected by Author).

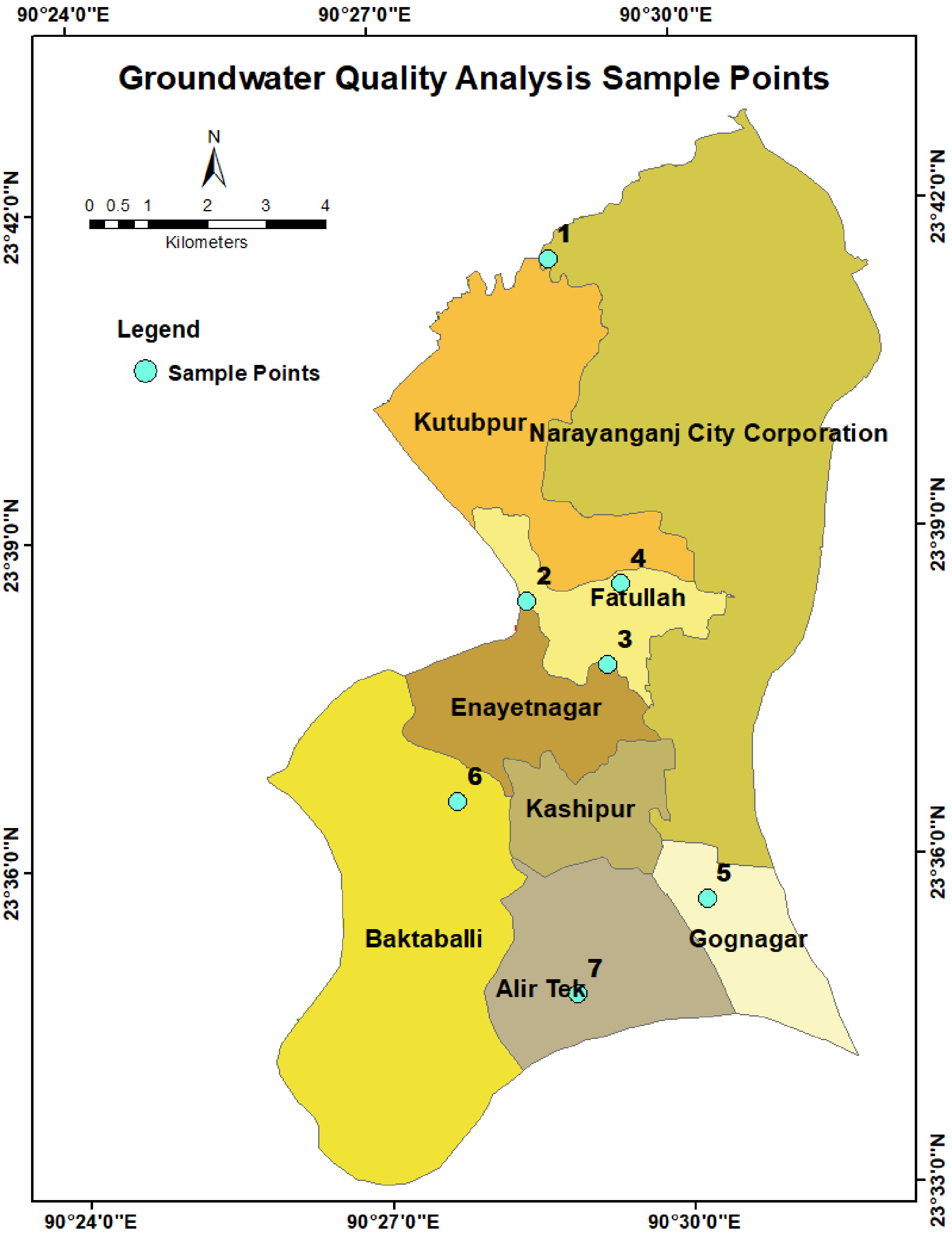


Fig 3.7: Groundwater Quality Analysis Sample Points from BWDB and DPHE the DRASTIC vulnerability map.

Chapter 4: Results and Discussion

4.1 Introduction

As mentioned earlier, the DRASTIC model utilizes seven hydrogeological indicators to evaluate the likelihood of groundwater contamination, namely its sensitivity to contamination. The next sections include a comprehensive examination of the consequences, classification, and geographical patterns of the indicators within the specified study area. Furthermore, an analysis will be conducted to examine the outcomes of the two distinct forms of sensitivity analysis and their corresponding consequences. The correlation between the model validation parameters and the vulnerability index will be monitored and computed.

4.2. Individual indicators

4.2.1. Depth to aquifer (D)

In several rural regions of Narayanganj Sadar, a significant number of shallow tube wells have become inoperable due to the decline in the water table, rendering them inaccessible. Furthermore, the water quality of the majority of shallow tube wells has significantly degraded to the extent that it no longer serves any practical use for the general population. Consequently, a significant number of monitoring wells and public-use wells have been strategically built up to the deeper aquifer. Water for general use is collected from there, additionally for monitoring and analysis. The present investigation reveals that the observed values for the variable D fall between the interval of 32 m to 71 m. The southern regions, including the Baktaballi and Alir Tek unions, have lower values (<40 m), whereas the northwestern portion of the research area (including parts of the Kutubpur union and ward no. 03,07 of the Narayanganj municipal corporation) has greater values (>63). The depth in the remaining portion of the region varies between 40 meters and 63 meters. The variable D has been categorized into five distinct groups. (1) <40 m (2) 40-47 m (3) 47-55 m (4) 55-63 m (5) >63 m, with a majority of values exceeding 63. Furthermore, the first three classes of this variable account for almost equal proportions of the total area, namely 20.14%, 23.33%, and 19.9% respectively. While class 4 encompasses the largest proportion of the whole area, accounting for 28.2%, class 5 is reported in less than 8% of the overall area.

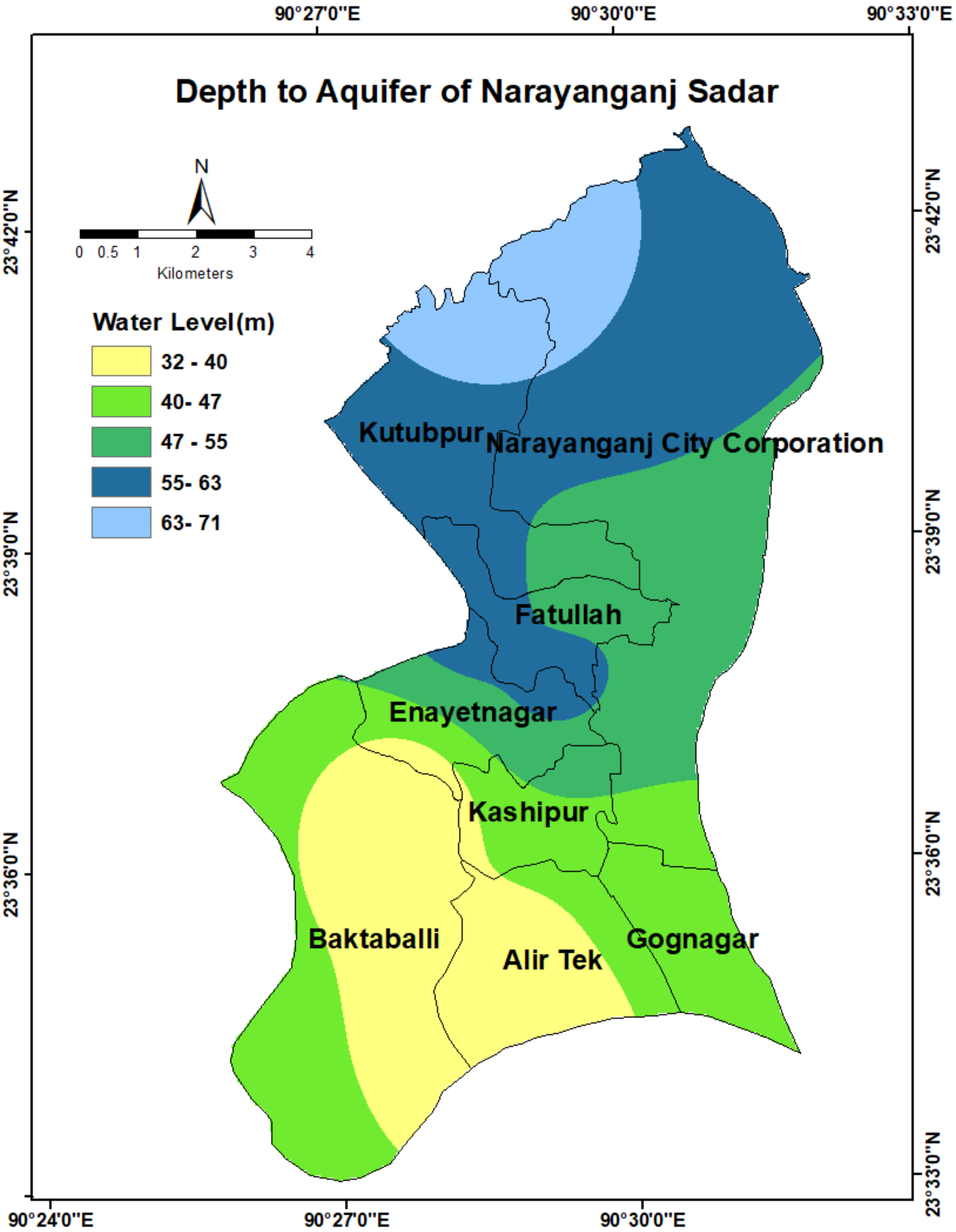


Fig 4.1: Depth to Aquifer of the study Area (Source: Prepared using the data from DPHE)

4.2.2 Net Recharge

Based on Piscopo's methodology, the Narayanganj Sadar region was classified into four discrete categories (5-7; 7-9; 9-11; and greater than 11) according to net recharge. The recharge rate with the highest rating covers an area of 18.044644 square kilometers, or about 19% of the whole research area. The group exhibiting the lowest grade possesses an area measuring 0.306513 square kilometers. The second group, including the range of 9 to 11, has the most extensive spatial coverage, measuring precisely 69.05 square kilometers. The area with a recharge range of 7-9 covers the southern part of Narayanganj City Corporation and the southern part of Kashipur. The recharging range of 9-11 encompasses the majority of Narayanganj City Corporation, Kutubpur, Fatullah, Kashipur, Gognagar, as well as half of Baktaballi, Alirtek, and Eneyetnagar. The remaining portion of Baktaballi, Alirtek, and Eneyetnagar has a comparatively elevated recharge rate because of its increased elevation and enhanced permeability. This phenomenon may possibly be attributed to their close proximity to the river. The recharge rate in the southern portion of Narayanganj City Corporation is comparatively lower than the norm due to less precipitation and reduced permeability.

4.2.3 Aquifer Media

The aquifer media within the research region may be categorized into three distinct groups: very fine sand (8.884873 square kilometers), fine sand (53.27 square kilometers), and medium sand (45.23 square kilometers). Out of all the options considered, it can be observed that fine sand has the most coverage inside the Narayanganj Sadar region. This area encompasses the northern eastern and southern western regions, comprising almost half of Narayanganj City Corporation, Baktaballi, Alirtek, and a significant portion of Kashipur. The classification of "medium" is assigned to it due to its capacity to transport a greater amount of water compared to very fine sand, yet a lesser amount than that of medium sand. The research area comprises Enayetnagar, Fatullah, Gognagar, and part of Baktaballi and Alirtek. These regions are characterized by a medium sand aquifer media, which accounts for approximately 42% of the overall area under investigation. The category of very fine sand, constituting 8% of the area, predominates in Kutubpur in a circular pattern, exhibiting the lowest rating.

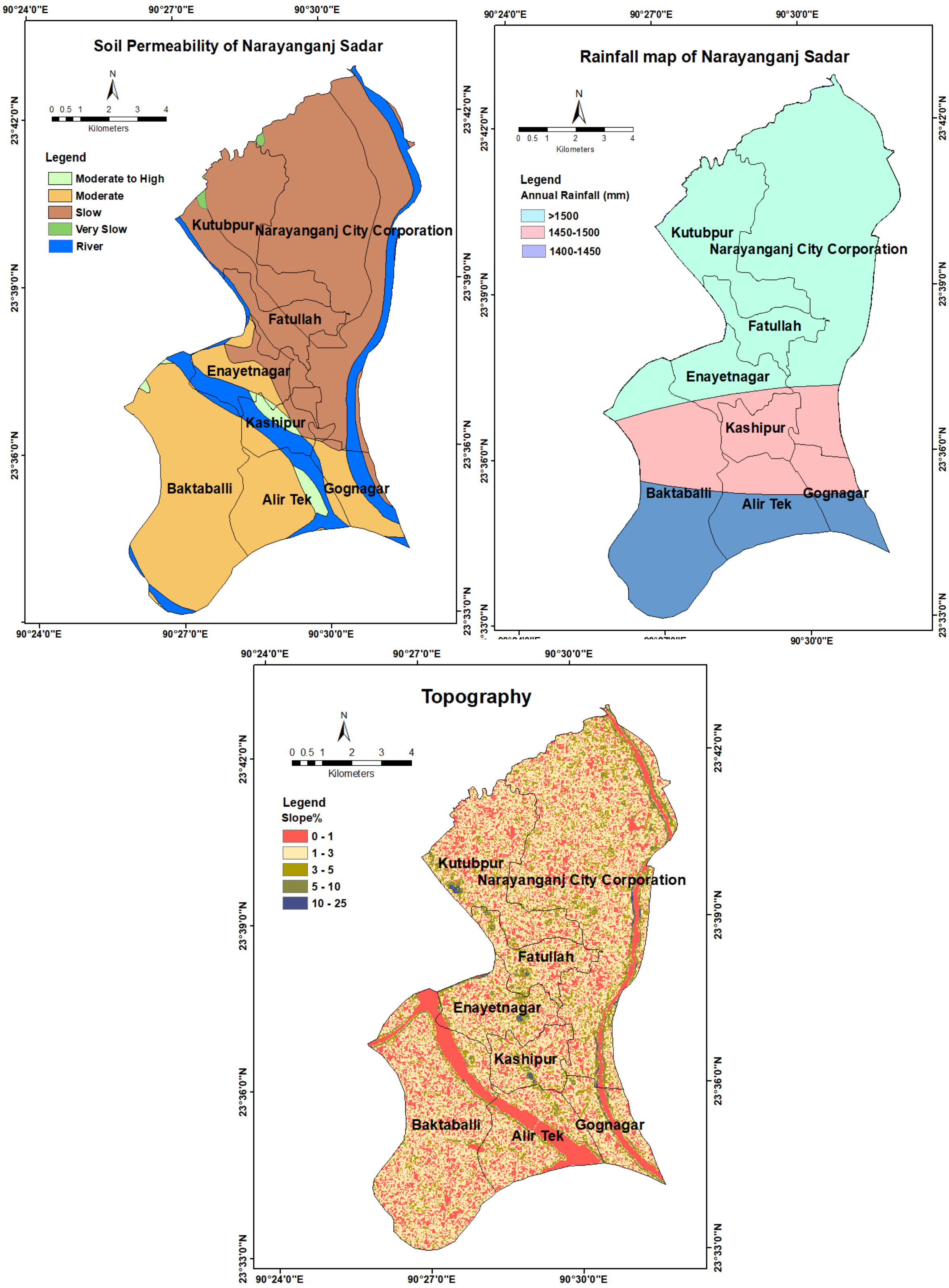


Fig 4.2: Maps used to Calculate net recharge (Soil Permeability, Rainfall and Topography)
(Source: Prepared using the data from BARC, CRU, USGS)

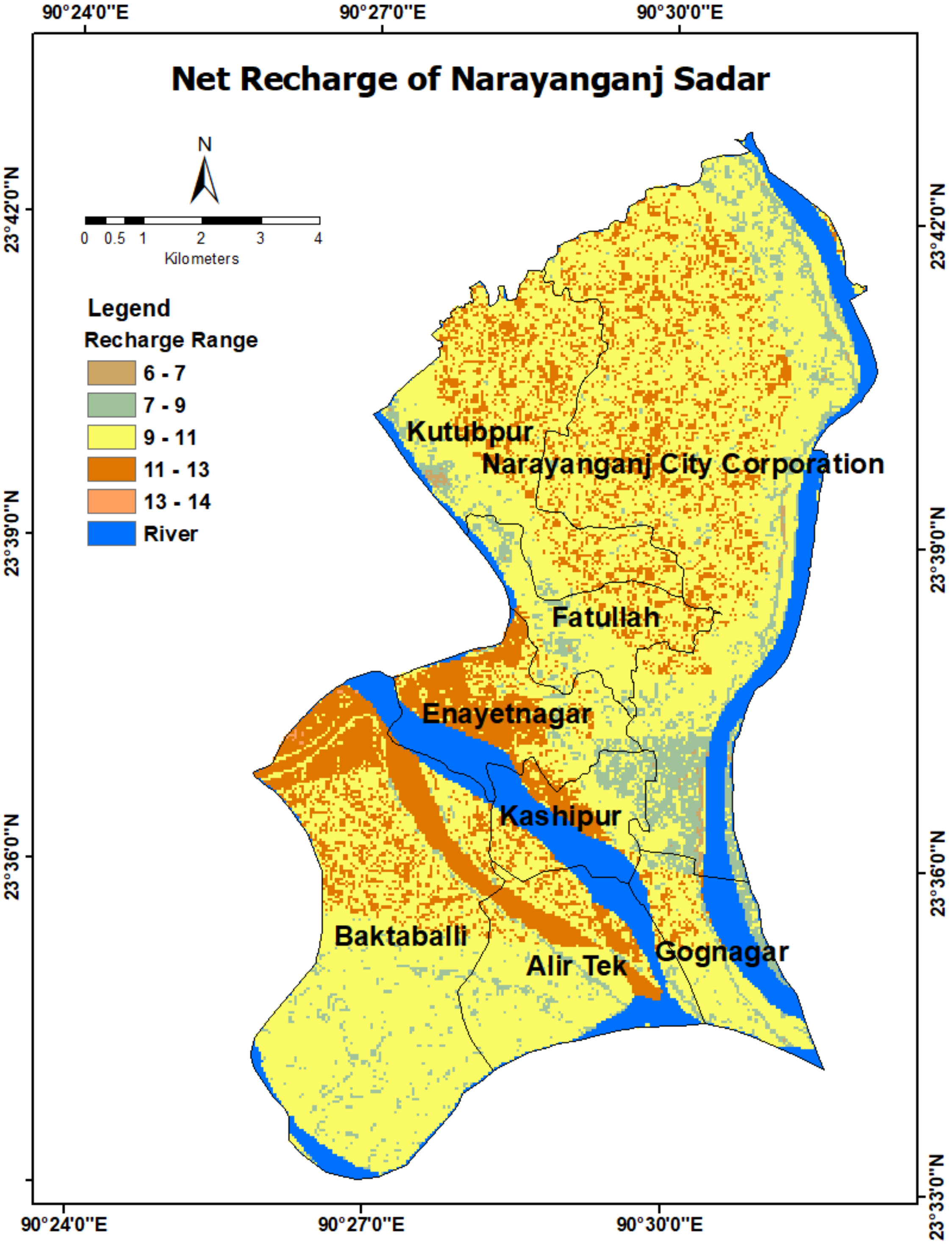


Fig 4.3: Net Recharge of the study Area (Source: Prepared using the data from BARC, CRU, USGS)

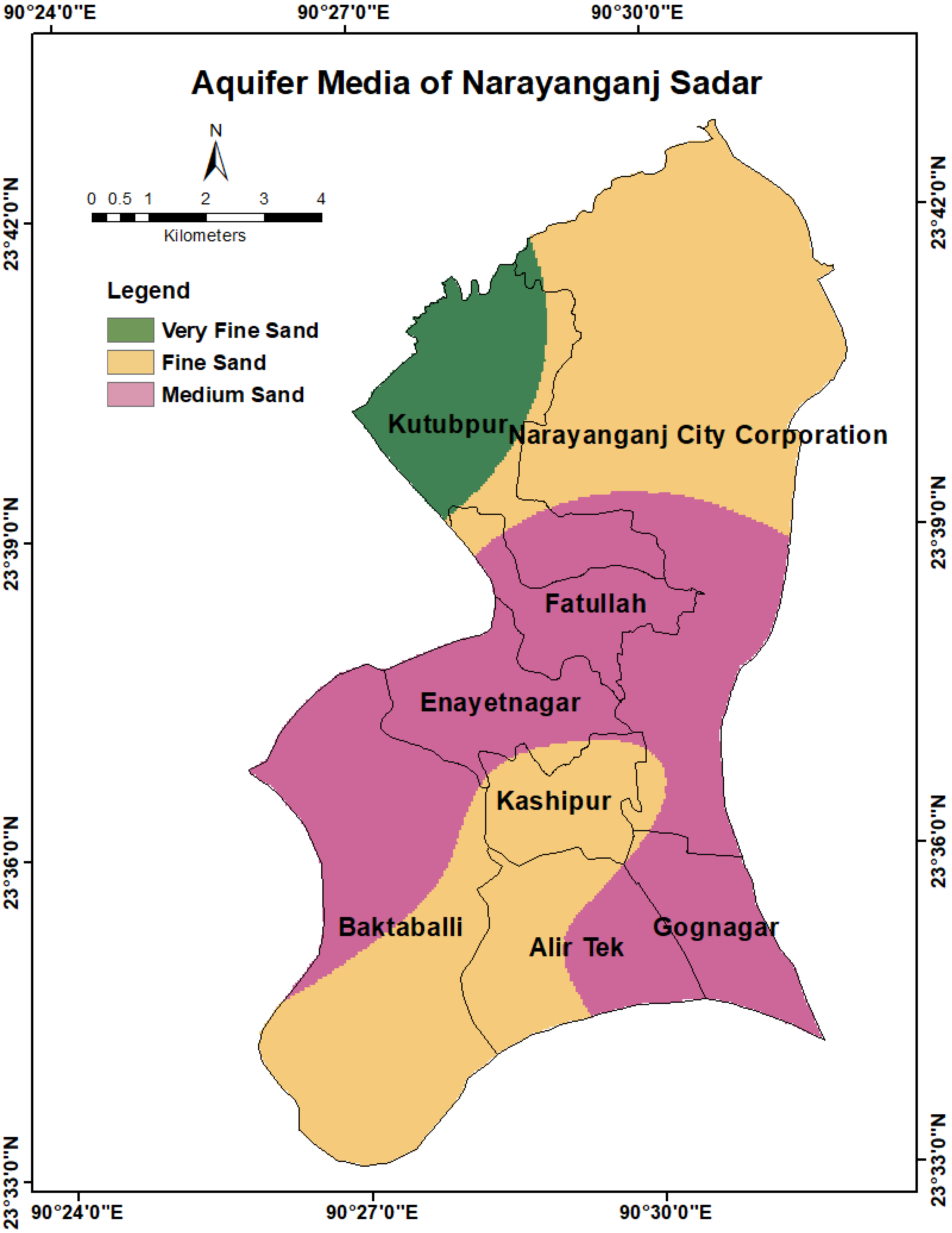


Fig 4.4: Aquifer Media of the study Area (Source: Prepared using the data from BWDB)

4.2.4 Soil Media

Based on the map, it can be observed that the research region is primarily characterized by three primary soil types: mixed silt loam and silty clay, mostly silty clay, and mixed clay and silty clay loam. These three soil types collectively encompass over 90% of the overall study area. The first category encompasses the most extensive geographical region, accounting for 39.78% of the total area. This category is predominantly found in the southern half of the region, specifically in the Baktaballi, Alirtek, Gognagar, and Enayetnagar unions. A significant portion of the research area, encompassing Kutubpur, Fatullah union, and Narayanganj city corporation, is characterized by the presence of mostly silty clay soil. This soil type forms a belt-like configuration along the eastern and western edges of the region, namely in the corners of Narayanganj City Corporation, Kutubpur, and an extensive portion of Fatullah. This silty clay coverage accounts for approximately 21% of the total study area. Predominantly silt loam and mostly silt loam were the other soil types found in the study area which constitute a small fragment (2.4%) of the total study area. mixed clay and silty clay loam had the least rating (1) as it the least permeable and most resistant to the transport of contaminants. And predominantly silt load was assigned the highest rating (7) as it is the most porous and transferable soil media found in the study area.

4.1.5 Topography

The parameter T incorporates the variance of slope and governs the discharge of water following intense precipitation events on the terrestrial surface. In general, the research region has a predominantly level terrain, characterized by slopes ranging from 0° to 25°. The western part of Kutubpur, middle of Enayetnagar and Kashipur has a slope range of 10° to 25° which has the lowest rank as the rainfall faces most interception in this area due to high elevation and slope and reaches the ground level at a delayed rate and in the process gets evaporated or absorbed by the interception material. Most of the study area 63.708734 square kilometers (59.26%) have 1 to 3 degree slope which is one of the lowest slope percent. The region surrounding the river in Gognagar, Baktaballi, Narayanganj City Corporation habe a higher slope of 5-10°. The rest of the area have a relatively low slope percentage ranging from 1° to 3°. The research area is divided into five slope percent groups: (1) less than 1°, (2) 1-3°, (3) 3-5°, (4) 5-10°, and (5) 10°- 25°. These classes account for about 27.67%, 59.26%, 9.86%, 2.73% and 0.29% of the study area, respectively.

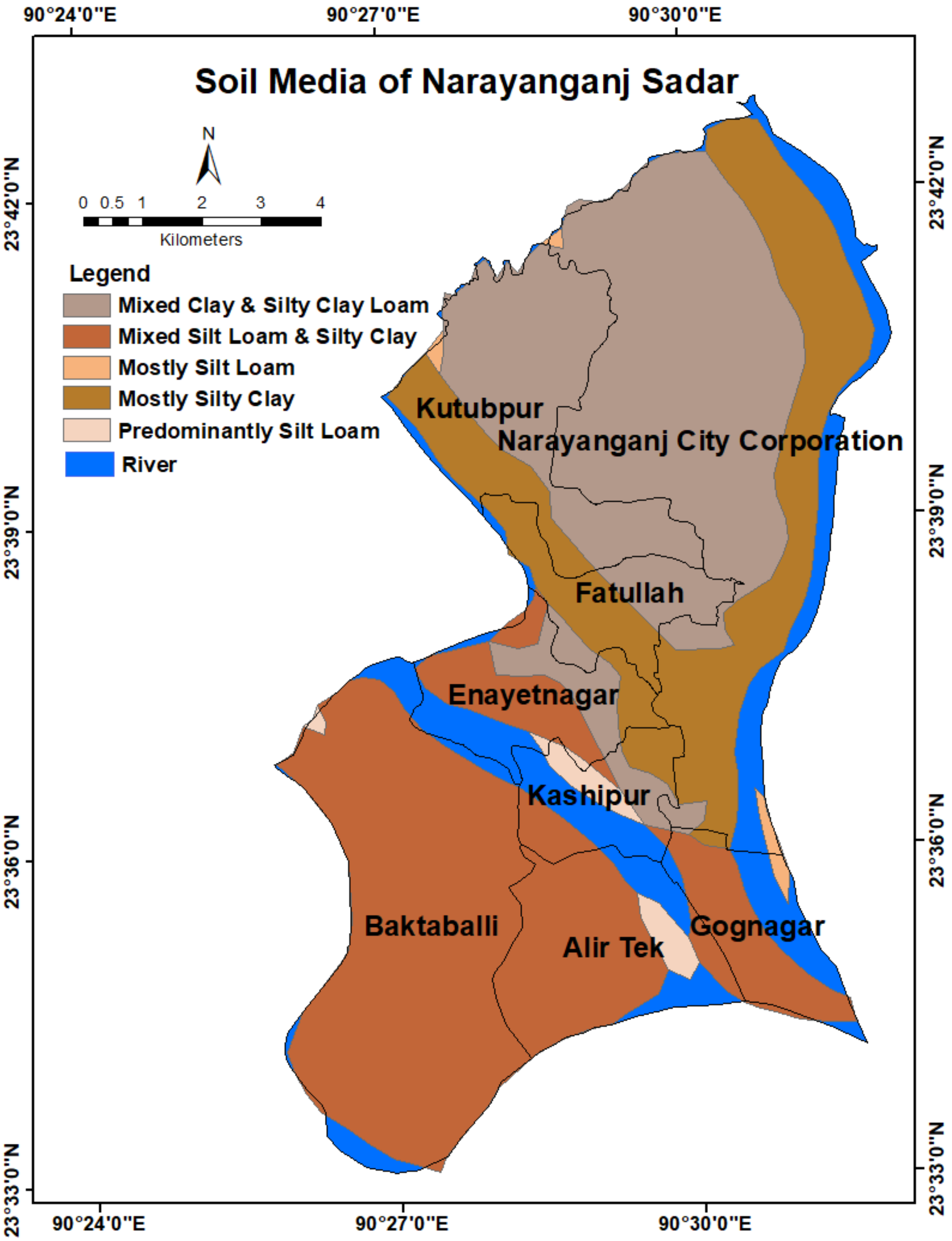


Fig 4.5: Soil Media of the study Area (Source: Prepared using the data from BARC)

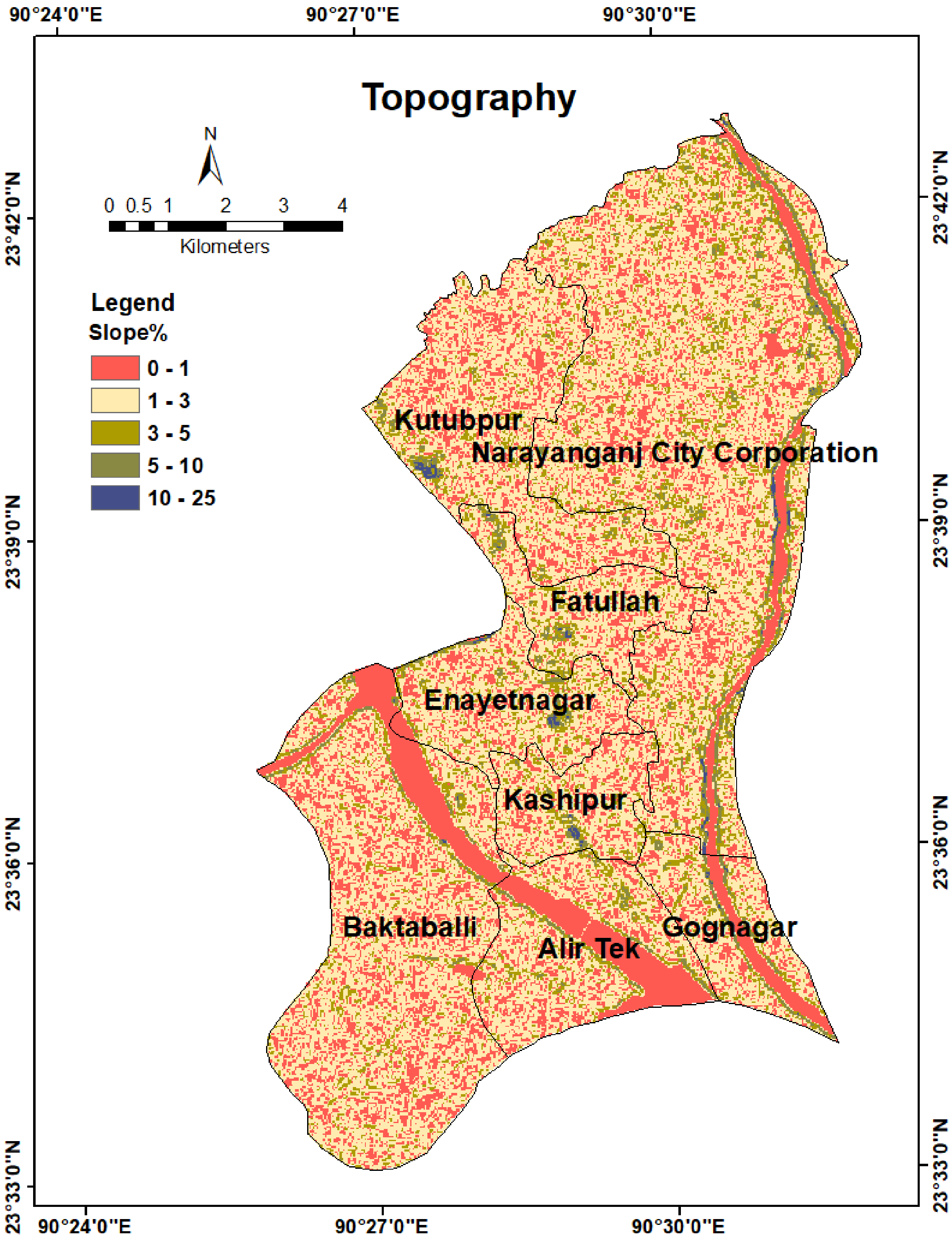


Fig 4.6: Topography of the study Area (Source: Prepared using the data from USGS)

4.1.6 Impact of vadose zone

The study area encompasses four primary soil classifications, namely silty clay, very fine sand, medium sand, and coarse sand. The soil types in question encompass an estimated area of 34.65 square kilometers (32.23%), 12.07 square kilometers (11.23%), 51.76 square kilometers (48.06%), and 9.01 square kilometers (8.39%) of the overall land area, respectively. The vadose zone is characterized by its heterogeneity, which gives rise to significant fluctuation in the transfer of groundwater, leading to varying rates of flow. The mid-western region of the research area, encompassing most of Fatullah and half of Kutubpur and Enayetnagar, has the maximum flow rate as it is composed of coarse sand. The majority of Enayetnagar, Narayanganj City Corporation, and Kutubpur are characterized by a vadose zone consisting of medium sand, which surrounds the area with coarse sand vadose zone. The vadose zone in the southern region of the research area, encompassing Baktaballi, Alirtek, and Gognagar, is characterized by a low level of transmissivity due to the presence of silty clay. As a result, these areas are less susceptible to contamination passing via the vadose zone.

4.1.7 Hydraulic Conductivity

The majority of the studied region (55%) has a hydraulic conductivity range between 17.27 and 43.2 meters per day encompassing the entirety of Gognagar, Fatullah, Enayetnagar, as well as around fifty percent of Baktaballi and Alirtek. The highest rating gets assigned to these locations due to their capacity to transport toxins at the highest rate. The second highest rating has been assigned to the conductivity range of .1728 to 17.28 meters per day, which encompasses 39.6% of the research region. The geographical area situated north of the study area, encompassing Alirtek, Baktaballi, and Kashipur, exhibits a pinball-like form. Additionally, another portion of this region assumes a fan-shaped configuration, spanning through the majority of the northern region up to the Narayanganj City Corporation, as well as the eastern side of Kutubpur. The range of conductivity with the lowest values is from .0001728 to .1728. Additionally, this range encompasses the smallest proportion, accounting for just 6% of all the classes. The research area encompasses a significant portion of Kutubpur, specifically its northeastern region. The aquifer media in Kutubpur consists of fine sand, which is considered to be the least favorable material for groundwater flow. As a result, it has been awarded the lowest rating of 4.

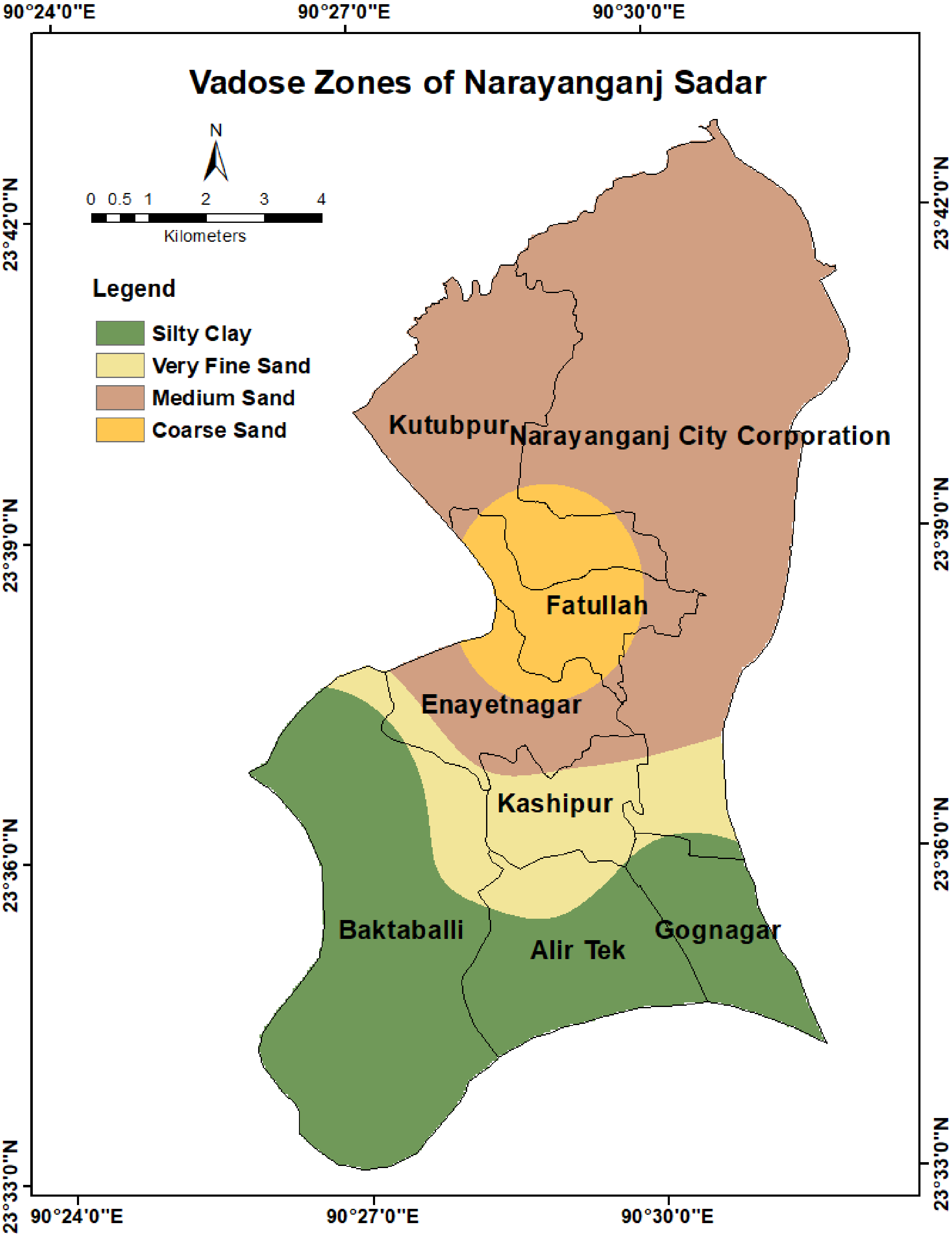


Fig 4.7: Vadose Zones of the study Area (Source: Prepared using the data from BWDB)

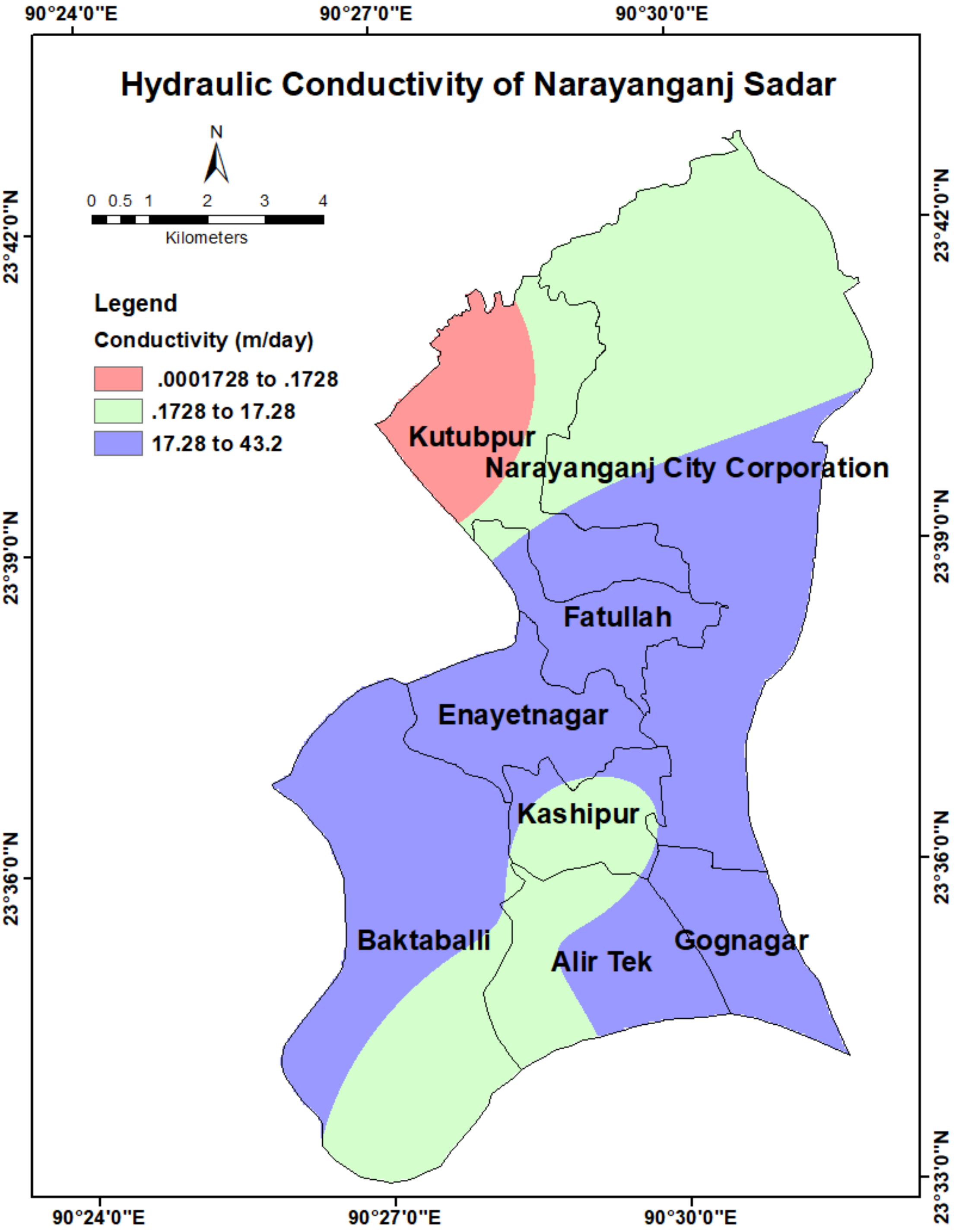


Fig 4.8: Hydraulic Conductivity of the study Area (Source: Domenico and Schwartz 1990)

4.2 DRASTIC Vulnerability Index

DRASTIC Indicators	Range	Rating	Relative weight	Area (Sq km)	Percentage
Depth to aquifer	<40	5	5	21.751487	20.14
	40-47	4		25.204549	23.33
	47-55	3		21.496235	19.9
	55-63	2		30.456376	28.2
	> 63	1		8.476565	7.84
Net recharge	5-7	3	4	0.306513	0.3224
	7-9	4		7.678062	8.0754
	9-11	6		69.055351	72.6287
	> 11	8		18.044644	18.9784
Aquifer media	Medium sand	6	3	45.229519	42.074
	Fine sand	4		53.272126	49.5555
	Very fine sand	2		8.884873	8.265
Soil media	Predominantly Silt Loam	7	2	1.559421	1.6243
	Mostly Silt Loam	6		0.521087	0.545206
	Mixed Silt Loam & Silty Clay	5		38.0274	39.78
	Mostly Silty Clay	3		19.862531	20 .7818
	Mixed Clay & Silty Clay Loam	1		35.9462	37.8381
Topography	< l	10	1	29.749492	27.6739
	1-3	8		63.708734	59.2639
	3-5	6		10.607627	9.8676
	5-10	4		2.938718	2.7337
	> 10	2		0.315688	0.2937

Impact of vadose zone	Coarse sand	10	5	9.01923	8.39
	Medium Sand	8		51.7694	48.046
	Very fine sand	5		12.076963	11.2344
	Silty Clay	3		34.655825	32.238
Hydraulic conductivity	.0001728 to .1728	4	3	6.440269	5.9909
	.1728 to 17.28	5		42.578341	39.6078
	17.28 to 43.2	6		58.36393	54.292

Table 4.1: The seven DRASTIC parameters, ranges, rating, area and percent of total area in Narayanganj Sadar.

According to the model's results, it is determined that within the total land area of 95 square kilometers apart from the rivers, approximately 2.56 square kilometers fall within the Very Low vulnerability zone. This classification is based on a DRASTIC index ranging from 88 to 98. Additionally, an area of approximately 17.72 square kilometers is classified as being in the Low vulnerability zone, which accounts for approximately 18.85% of the entire study area. This zone is characterized by DRASTIC values ranging from 98 to 108. The research area is occupied by regions located in the northwest, southwest, and mid-eastern portions. The southwestern region is situated within the Kutubpur region which is an industrial area. Even though it is industrialized and densely populated the area may be classified as having minimal susceptibility to contamination due to its very low water table. Furthermore, a significant portion of industrial waste is discharged straight into the river, resulting in contamination of surface water rather than groundwater. Granted that some harmful substances infiltrate the groundwater due to the presence of a vadose zone consisting of medium sand; it has medium recharge which reduces the chances of the transportation of toxins. Additionally, the soil type of this region is mixed clay and silty clay loam which has a very low porosity and permeability impeding the movement of contaminants. The region in question has a high susceptibility to water level depletion.

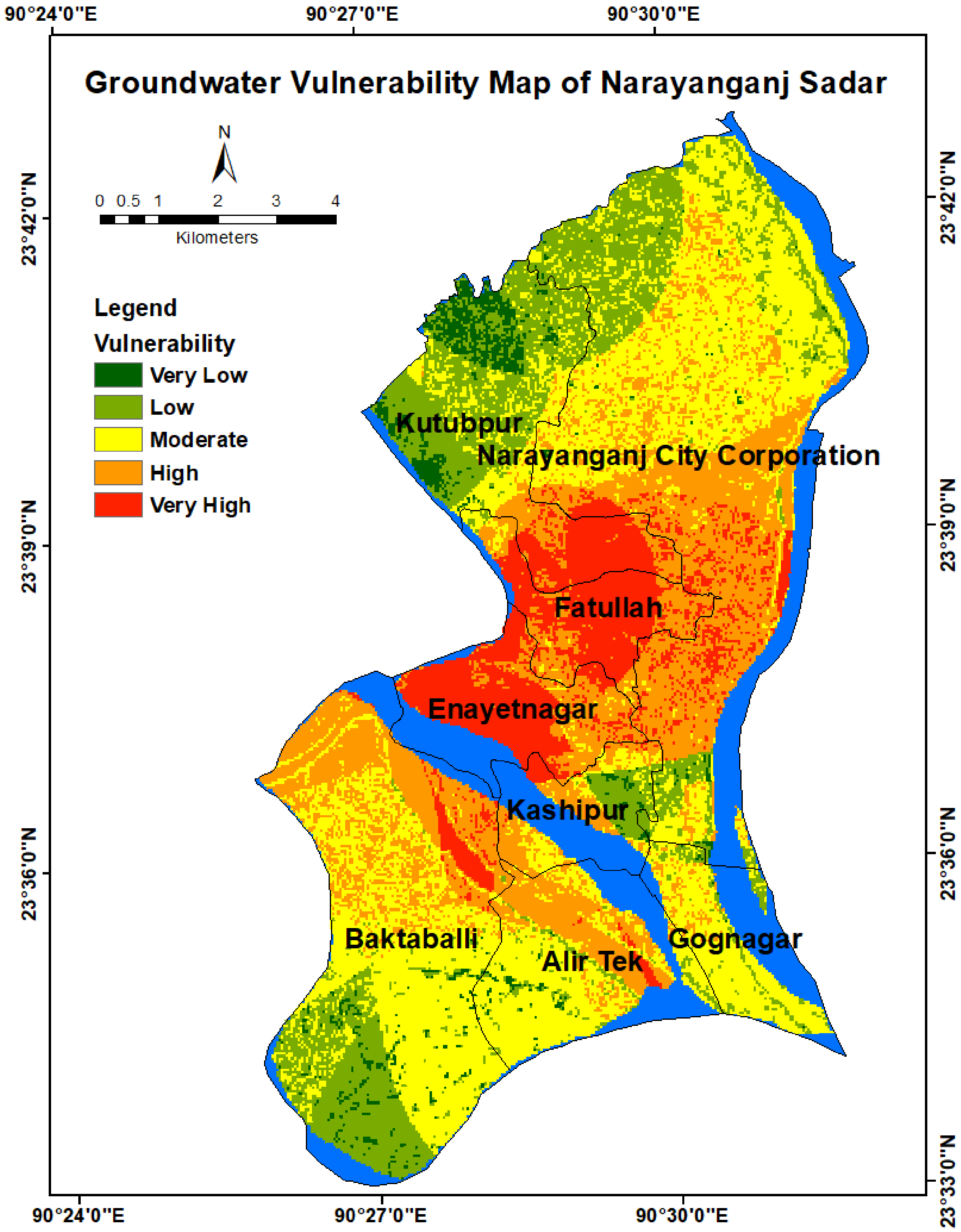


Fig 4.9: Groundwater Vulnerability of the study Area (Source: Prepared by author)

Sl No.	Vulnerability	Index Value	Area (in km2)	Area (in %)
1	Very Low	88-98	2.5659	2.729680851
2	Low	98-108	17.722102	18.8533
3	Moderate	108-118	36.145833	38.45301383
4	High	118-135	25.628713	27.2645883
5	Very High	135-153	11.794681	12.54753298

Table 4.2: Groundwater Vulnerability Zone Classes, Index and Areal Extension of the study area.

However, in terms of susceptibility to contamination, it demonstrates a comparatively lower degree of risk. This is attributed to the delayed arrival of toxins at lower water levels, which results in a reduction in their strength. Similarly, a region measuring around 36.14 square kilometers is situated inside the Medium vulnerability zone as shown in table 4.2, which is distinguished by DRASTIC values ranging from 108 to 135. The vulnerability class in question encompasses the largest proportion of the whole region, accounting for over 40% of the total. The majority of the southern section is encompassed by the areas of Gognagar, Alirtek, and Baktaballi which fall into this category. The majority of the area under consideration is predominantly rural, with distinct sections characterized by the presence of various businesses, including brick fields and garment manufacturing. The category in question also includes the northern section of the Narayanganj city corporation, specifically Shiddhirganj. Within the entirety of the region, an area of 25.62 square kilometers is designated as possessing a high vulnerability, with the DRASTIC index falling within the range of 118 to 135. Furthermore, an area measuring 11.79 square kilometers is classified as being situated inside a zone of exceptionally high vulnerability, as indicated by a DRASTIC score ranging from 135 to 153. Approximately 40% of the entire region is classified as falling under high to very high risk zones. The majority of these locations are mostly concentrated within the central region of the research area, including Fatullah, Enayetnagar, and Chashara, which serve as the urban hub of Narayanganj Sadar. This zoning was produced by a variety of factors. The vadose zone in this region is predominantly composed of coarse sand, which has one of the greatest hydraulic conductivities among all forms of soil. The region under consideration is characterized by a significant concentration of industries, resulting in a notable level of pollution. Additionally, the population residing in the Narayanganj Sadar area is among the largest in the region. Consequently, there is a considerable demand for water extraction, leading to its excessive and unsustainable utilization in this locality. The vicinity next to the river exhibits a substantial net recharge, resulting in the potential dissolution of toxins from waste materials into the abundant water volume. These contaminants can then migrate via the vadose zone and reach the water table. Numerous tube wells have become inoperable, necessitating the installation of submersible pumps by both local inhabitants and industrial entities for the purpose of water acquisition. Moreover, it is worth noting that a significant number of locations classified as high-risk zones lack access to potable water throughout the dry season. Furthermore, in places where shallow tube wells are prevalent, the issue of water scarcity persists even during the rainy season.

4.3 Correlation of The Vulnerability Map With Land use and Landcover (LULC) Change

Land use and land cover (LULC) have the potential to impact the susceptibility of groundwater through modifications to the recharge and discharge processes, as well as the utilization and demand for groundwater resources.

Class	**Area (2000)**	**Area (2010)**	**Area (2022)**
Water Body	9.747939	8.93353	12.80694
Vegetation	26.47501	18.42667	1.077707
Agriculture	42.7738	20.04968	12.36541
Built Up	20.51396	60.58977	79.44119
Bare Land	9.158737	0.665391	3.019044

Table 4.3: Total area of the LULC classes from 2000 to 2022 (in sq km).

Based on the data provided in the table 4.3, it is evident that in the year 2000, the predominant land use was agricultural activities, occupying the biggest land area of 42.77 square kilometers, followed by vegetation with an area of 26.47 square kilometers. The urbanized region ranked third in terms of land area coverage, accounting for 22% of the total area. In 2010, a notable change occurred in land utilization patterns, when the built-up area exhibited the greatest extent of coverage, succeeded by agricultural and vegetation. Significantly, the aquatic environment had the least extent of terrestrial coverage during the course of the three-year period. In the year 2022, there is a significant prevalence of built-up areas in comparison to other land use and land cover categories. This is due to a considerable portion of the different categories undergoing conversion into built-up areas.

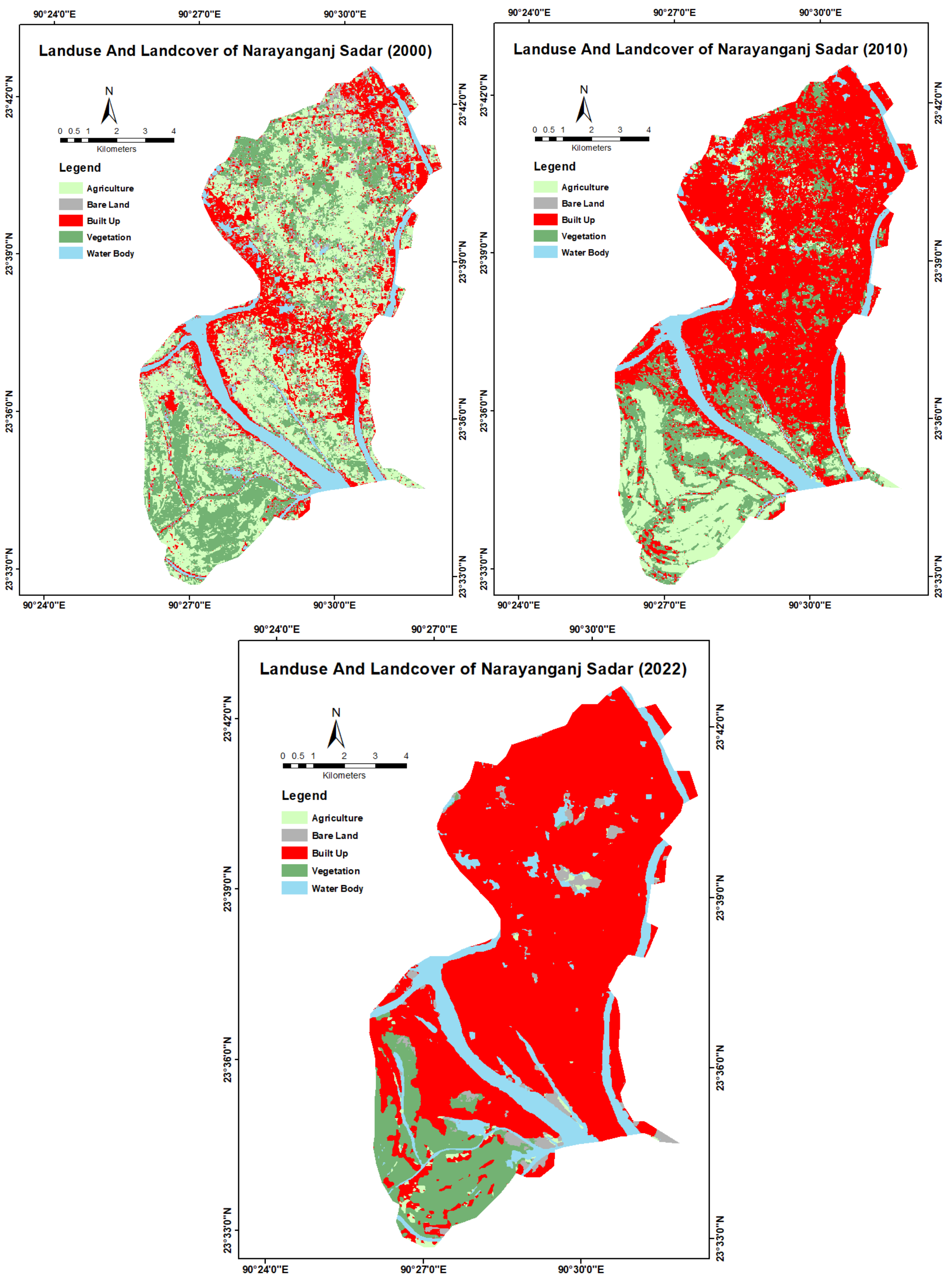


Fig 4.10: Land use Landcover of the study area in the 2000, 2010 and 2022. (Source: Prepared by author)

Subsequently, the alteration and conversion of various land use and land cover (LULC) classes, as well as the determination of the ratio of changed classes, were observed and estimated. The major changes are illustrated in the following maps:

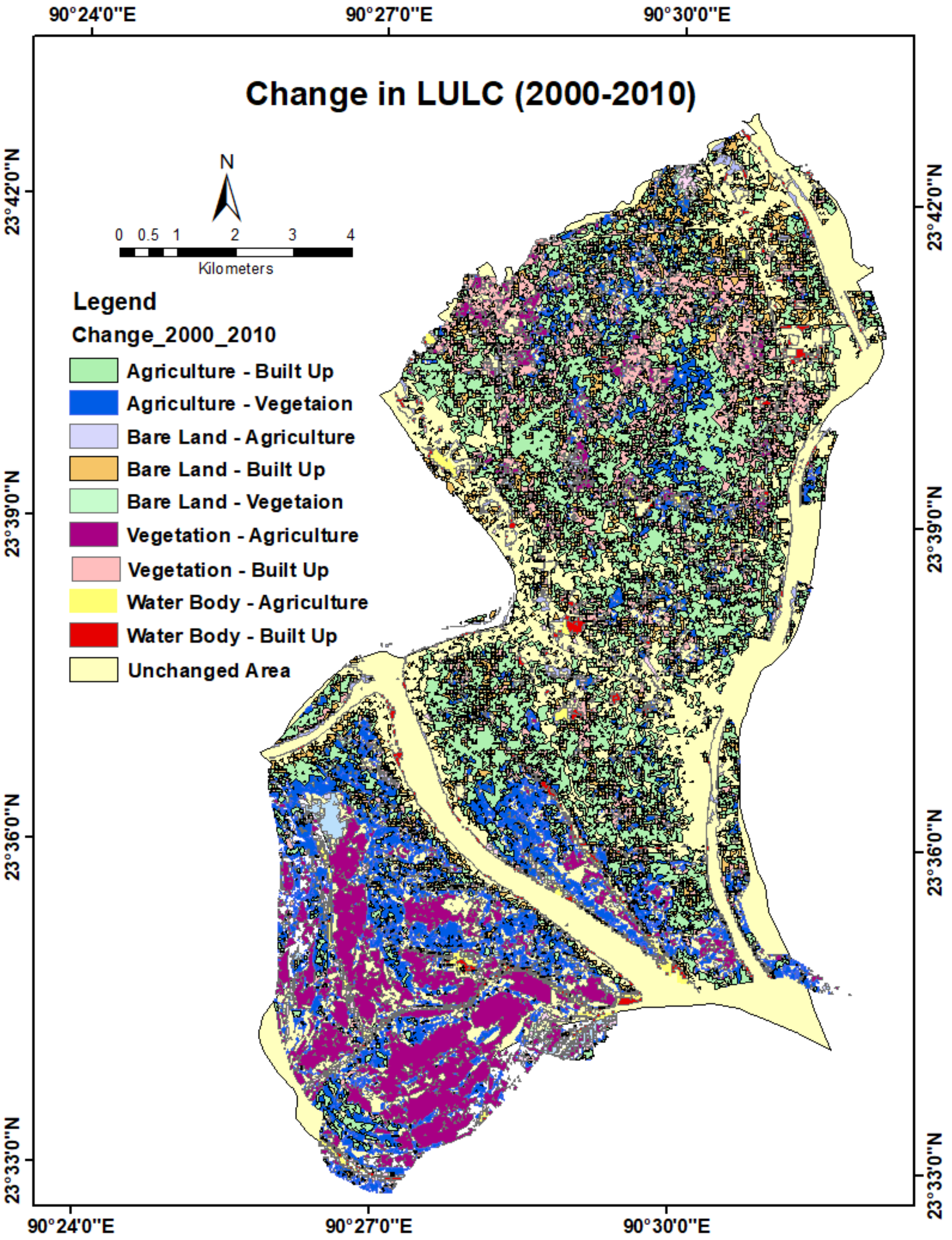


Fig 4.11: Land use Landcover change of the study area (2000-2010). (Source: Prepared by author)

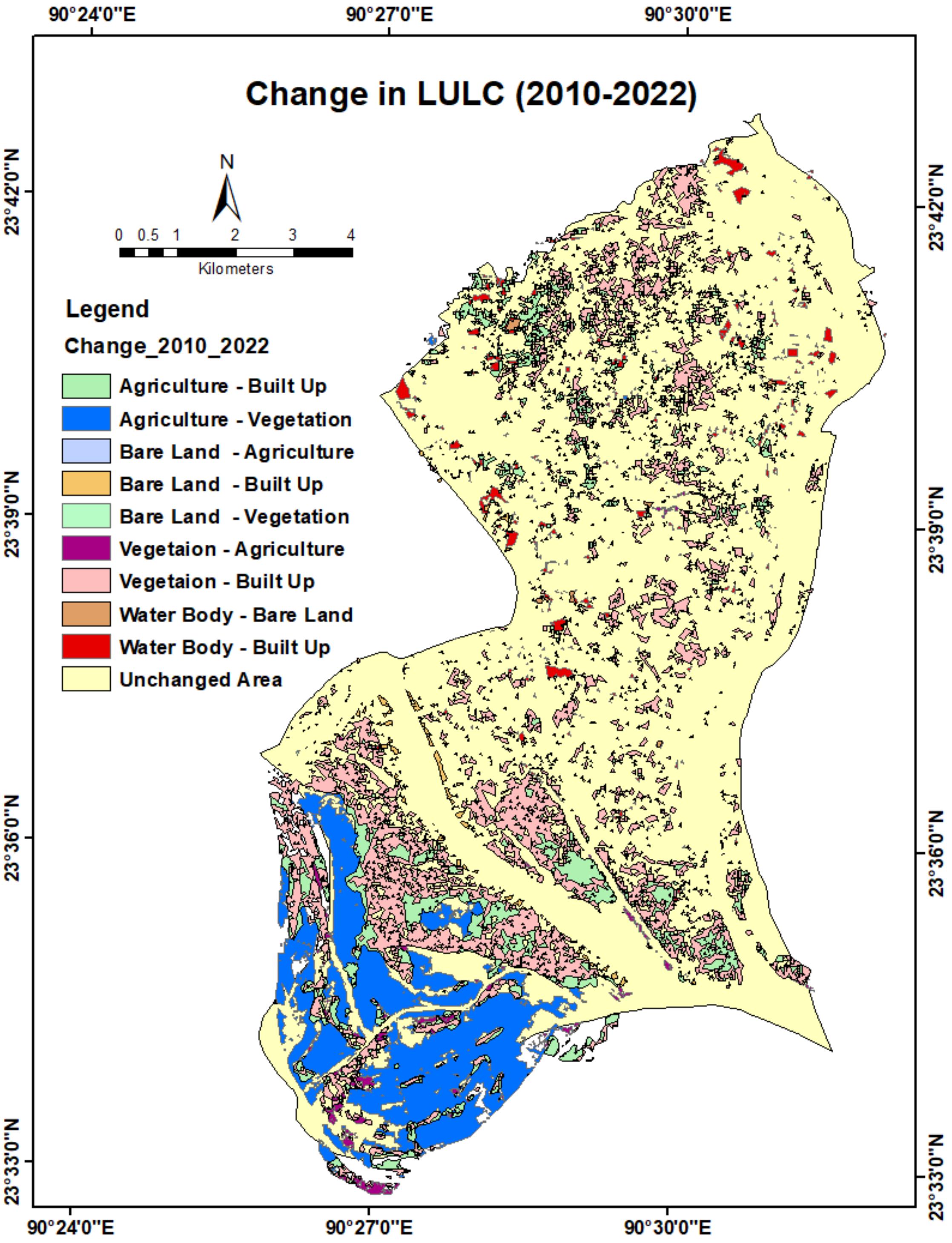


Fig 4.12: Land use Landcover change of the study area (2010-2022). (Source: Prepared by author)

The analysis reveals that the period between 2000 and 2010 had the most significant changes in land use and land cover. The primary transformation was the conversion of agricultural land into built-up area of roughly 25.41 square kilometers. The second most significant alteration was the interchange between agricultural land and vegetation, spanning an area of nearly 22 square kilometers. The various types of land, including water bodies, vegetation, agricultural, and bare ground, have undergone transformations into built-up areas. Between the years 2000 and 2010, the overall growth in built-up area amounted to around 42 square kilometers, representing nearly 40% of the entire study area. The expansion of built-up areas corresponds to a rise in the development of industrial, commercial, and residential infrastructure. These infrastructural developments have a direct impact on the extraction of groundwater and the increased generation of waste from these sectors. Consequently, this poses a serious threat to the environment and the water resources within the designated research area. The pollution is transferred to the soil medium, then infiltrating the water table and subsequently leading to the pollution of groundwater recharge in the studied region. Moreover, the notable expansion of agricultural land in the study area also presents a potential risk to the environmental state of the region. This is primarily due to the limited biodiversity observed in these agricultural regions, as well as the excessive extraction of groundwater and the overutilization of pesticides and manure for agricultural purposes. These practices contribute to soil pollution and hinder the net recharge of the area. The study region has experienced a decline in the overall surface area of the water body due to the construction of industrial and residential infrastructure, which is a response to the growing demand from the population. The adulteration of the surface layer diminishes its capacity to effectively remove pollutants and increases the susceptibility of the soil to pollution, hence impacting the underlying water table. Furthermore, when urban development expands, the land surface becomes increasingly covered with materials that have a lower albedo. This impedes the infiltration of water into the ground, thus leading to a decrease in groundwater recharge.

The observed land use and land cover change between 2010 and 2022 exhibited a relatively low magnitude. Notably, the most substantial change was observed in the conversion from vegetation to built-up areas, spanning an area of 15.16 square kilometers. This outcome aligns with expectations, as it can be attributed to the growing population and their heightened demand for residential, educational, medical, industrial, and commercial infrastructure expansion.

Furthermore, a substantial proportion of the vegetation and water bodies in the research region have been converted into built-up areas. This transformation has resulted in a reduction of ecological balance, making the groundwater more susceptible to vulnerability.

Class	***Total Area Change From 2000-2010***	***Total Area Change From 2010-2022***
Water Body	-0.81441	3.873411
Agriculture	-24.3471	-17.349
Vegetation	-6.42533	-7.68427
Built Up	40.07581	18.85142
Bare Land	-8.49335	2.353653

Table 4.4: Total area change of the LULC classes from 2000 to 2022.

Based on the provided table 4.4, it is evident that there was a decline in the extent of water bodies, agricultural land, vegetation, and bare land between 2000 and 2010. Furthermore, this trend persisted specifically for agricultural land and vegetation from 2010 to 2022. The reduction in agricultural land and vegetation can be attributed to the expansion of built-up areas, which consequently leads to a substantial increase in waste generation and contamination compared to the agricultural and vegetation sectors. Furthermore, it is evident that despite a decrease in the water body area from 2000 to 2010, there was a growth of 3.87 square kilometers seen from 2010 to 2022. The area of undeveloped land saw a decline between 2000 and 2010, followed by a rise of 2.35 square kilometers from 2010 to 2022. This upward trend can be linked to the continued implementation of government and private initiatives, which have resulted in deforestation. The absence of vegetation leads to soil deterioration, resulting in decreased soil porosity and permeability, leading to compaction and reduced capacity for water absorption and transformation into base flow.

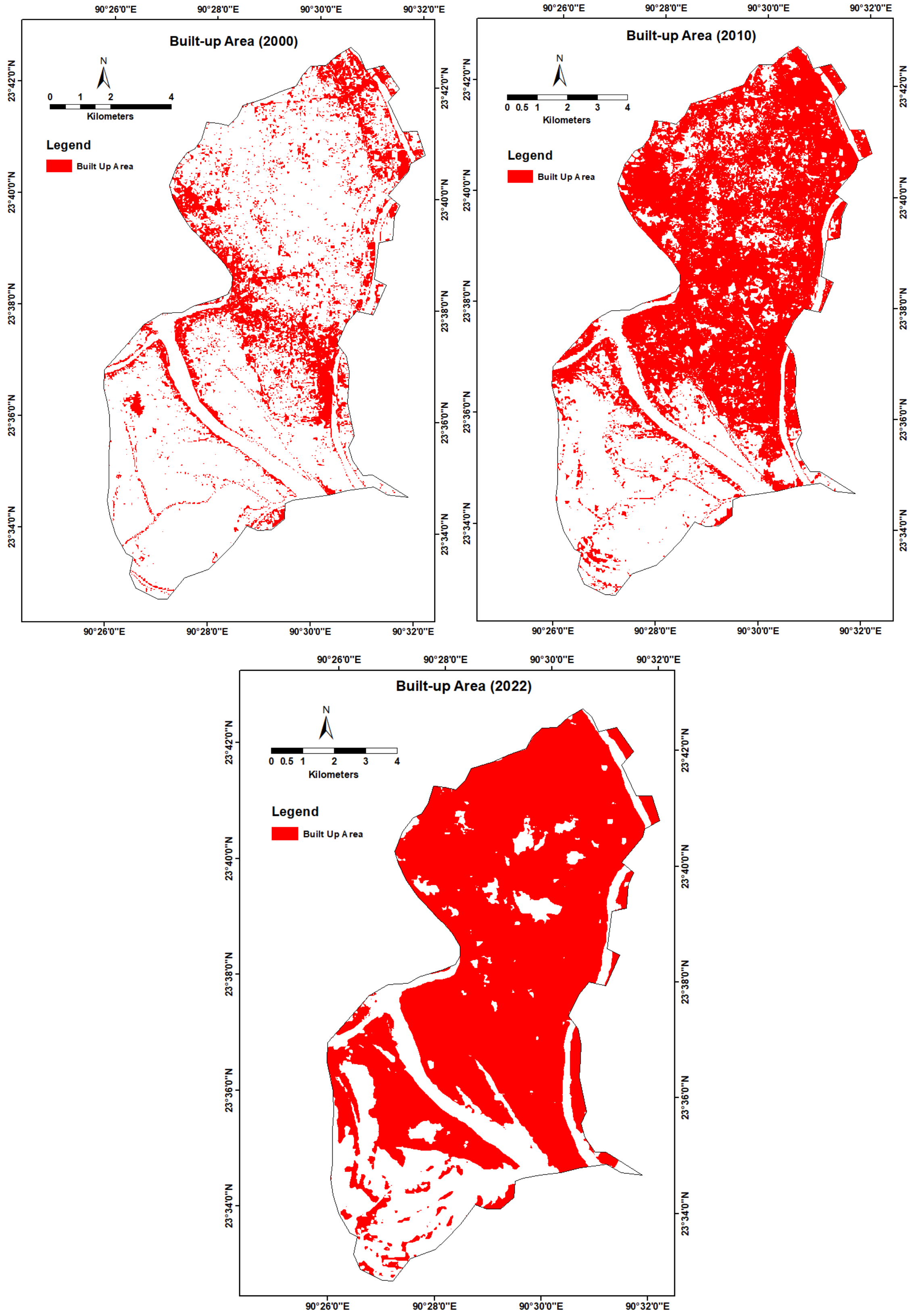


Fig 4.13: Growth of the Built-up Area from 2000 to 2022 (Source: Prepared by author)

The presence of a built-up region has the potential to impact the volume of groundwater recharge through two primary mechanisms: diminishing the capacity for precipitation penetration into the soil and aquifer, and augmenting the processes of runoff and evaporation. This phenomenon has the potential to diminish the quantity of water accessible for the purpose of refilling groundwater reservoirs, thus augmenting the likelihood of groundwater depletion. The urban heat island phenomenon has the potential to elevate temperatures and accelerate evaporation rates inside urbanized regions, thereby leading to a decrease in soil and aquifer moisture levels. Additionally, The presence of a built-up region can have an influence on the quality of groundwater recharge due to its ability to introduce or mobilize pollutants into the soil and aquifer. Urban activities encompass a range of human endeavors, including household, industrial, and commercial pursuits, which can give rise to many forms of trash including organic, inorganic, biological, or radioactive pollution. These waste materials have the potential to pollute the water that flows over the surface and seeps into the ground, ultimately reaching the underground layer of water known as the aquifer. Several types of urban pollutants may be identified, including sewage, solid wastes, oil and grease, metals, pesticides, fertilizers, road salts, detergents, medicines, pathogens, and radionuclides. The presence of these contaminants has the potential to deteriorate the quality of groundwater (R. & G., 2019; Moraru & Hannigan (2018).

Through a comparative analysis of land use change maps and groundwater vulnerability maps, it can be inferred that regions experiencing a decrease in vegetation and agricultural activities are concurrently more susceptible to groundwater pollution. Moreover, the region characterized by high levels of urbanization and industrialization has a greater depletion of groundwater resources. The aforementioned locations encompass the geographical territory of Kutubpur, Fatullah, AlirTek, Enayetnagar, and the central portion of Narayanganj City Corporation. The regions characterized by a greater extent of vegetation, water body and a correspondingly lower level of agricultural operations, result in a reduced likelihood of groundwater pollution. The aforementioned regions encompass a significant portion of Baktaboli, Gognagar, Alirtek, and Kashipur. Therefore, it can be deduced that land use and land cover (LULC) are inherently interconnected with the susceptibility of groundwater in the Narayanganj Sadar Upazila.

4.4 Sensitivity Analysis

Table 4.5 provides a statistical overview of the seven rated parameters of the DRASTIC model. The primary sources of contamination include topography (mean: 8.255), net recharge (mean: 6.226), and impact of vadose zone (mean: 6.217). Secondary sources include depth of groundwater (mean: 5.772) The hydraulic conductivity (mean: 5.483). The aquifer media, the soil media present a minimal danger of aquifer pollution, with values of 4.677 and 3.11 respectively. The coefficients of variation (CV) suggest that the vulnerability score is mostly influenced by the soil type (51.918%), with vadose zone (40.165%) and depth of groundwater (39.392%) in the second and third. The characteristic with the least variability in this research region is the hydraulic conductivity accounting for just 11.088% of the variation in the vulnerability index. Parameters with the most range is topography (2-10), then Depth to aquifer (3-9), Aquifer Media (2-8) and the parameter with the least range is hydraulic conductivity (4-6). This means that the study area is heterogenous in most of these indicators except for soil type, and hydraulic conductivity.

DRASTIC Indicators	Mean	Minimum	Maximum	SD	CV
D	5.77289	3	9	2.2741	39.3927
R	6.22656	3	8	1.0724	17.2247
A	4.67705	2	8	1.24803	26.6841
S	3.11845	1	7	1.83735	51.9186
T	8.25521	2	10	1.44928	17.5559
I	6.21772	3	10	2.4974	40.1658
C	5.48343	4	6	0.60795	11.0888

Table 4.5: Statistical summary of DRASTIC parameters map
(SD- Standard Deviation; CV- coefficient of variation)

4.4.1 Map removal sensitivity analysis

The sensitivity analysis conducted in this study served to check and assess the consistency of the analytical findings, forming the foundation for a thorough examination of the vulnerability maps by employing sensitivity analysis, a more effective interpretation of the vulnerability index may be attained (Raj Pathak et al., 2008). Following maps depicts the DRASTIC Vulnerability to Groundwater without each of the seven indicators and their classification and index ranges. Table 4 depicts the fluctuations in the vulnerability index when a single layer is eliminated from the evaluation.

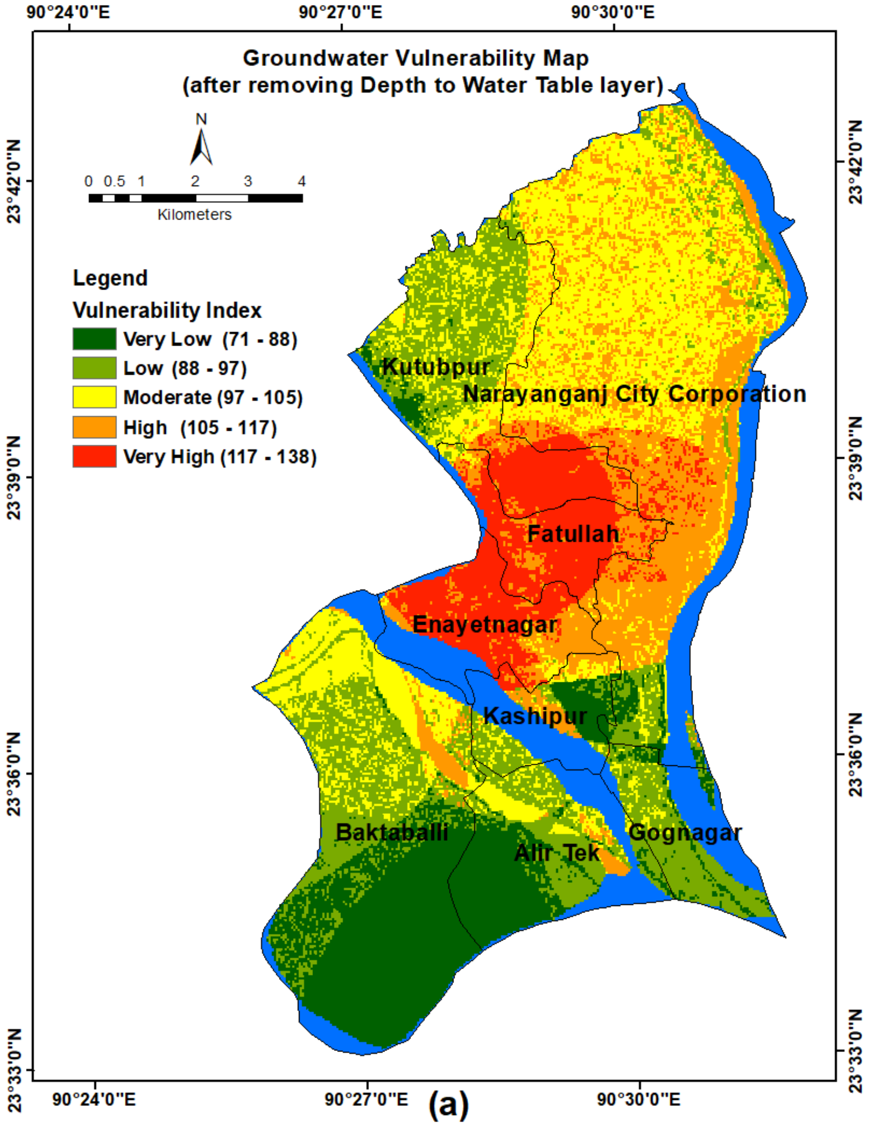


Fig. 4.14: Spatial distribution of vulnerability classes after removing thematic layer: Depth to water table

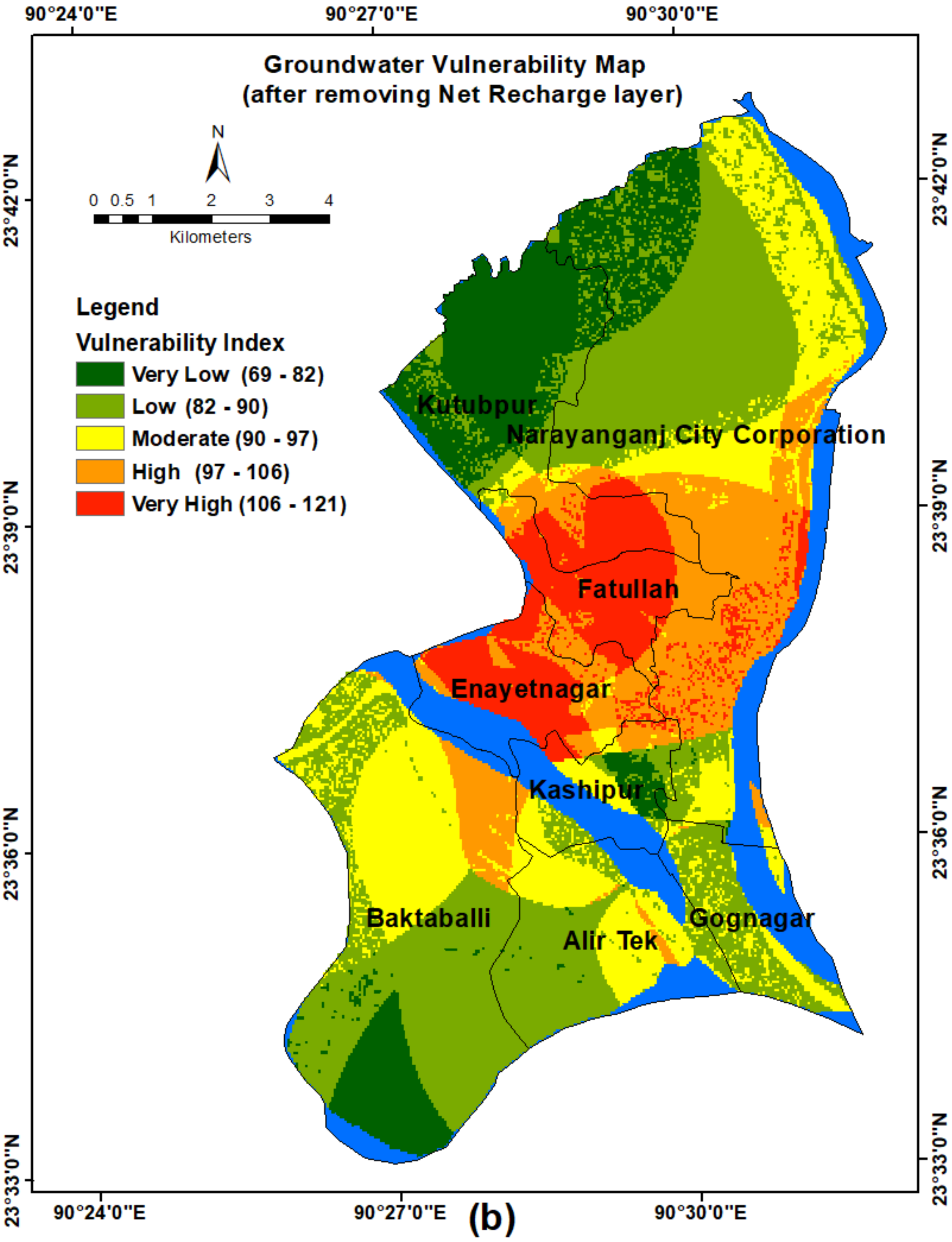


Fig 4.15: Spatial distribution of vulnerability classes after removing thematic layer: Net recharge

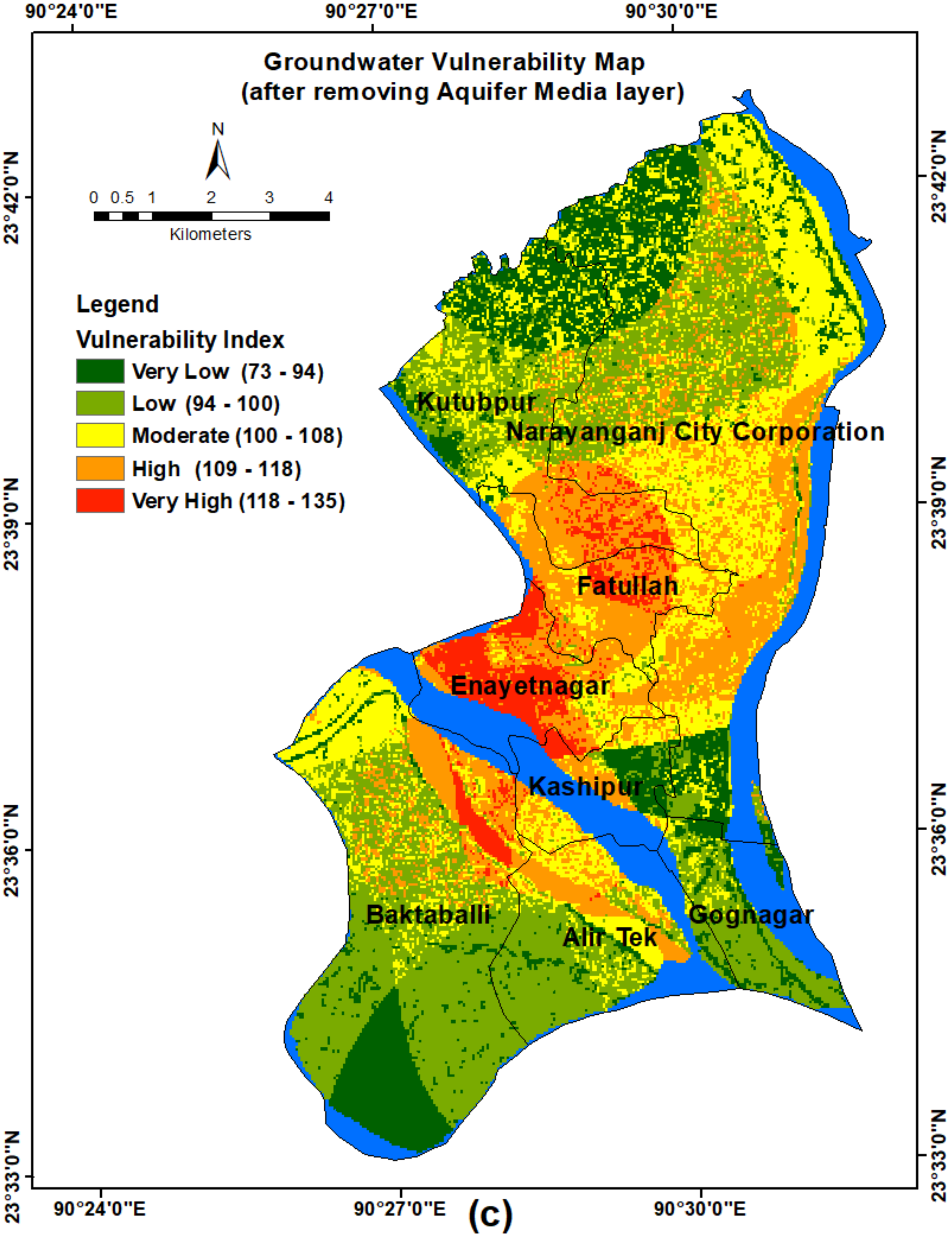


Fig 4.16: Spatial distribution of vulnerability classes after removing thematic layer: Aquifer media (Source: Prepared by author)

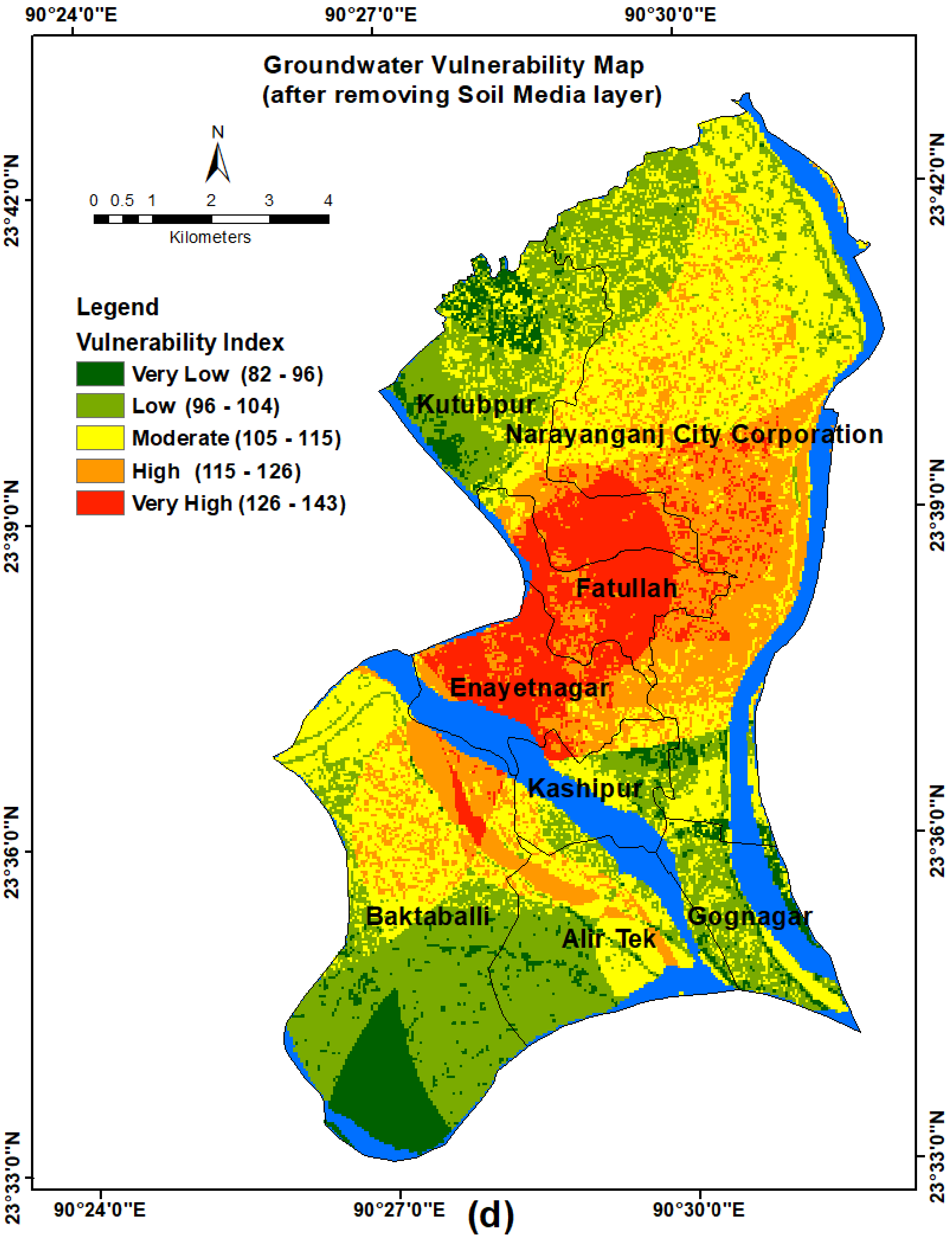


Fig 4.17: Spatial distribution of vulnerability classes after removing thematic layer: Soil media (Source: Prepared by author)

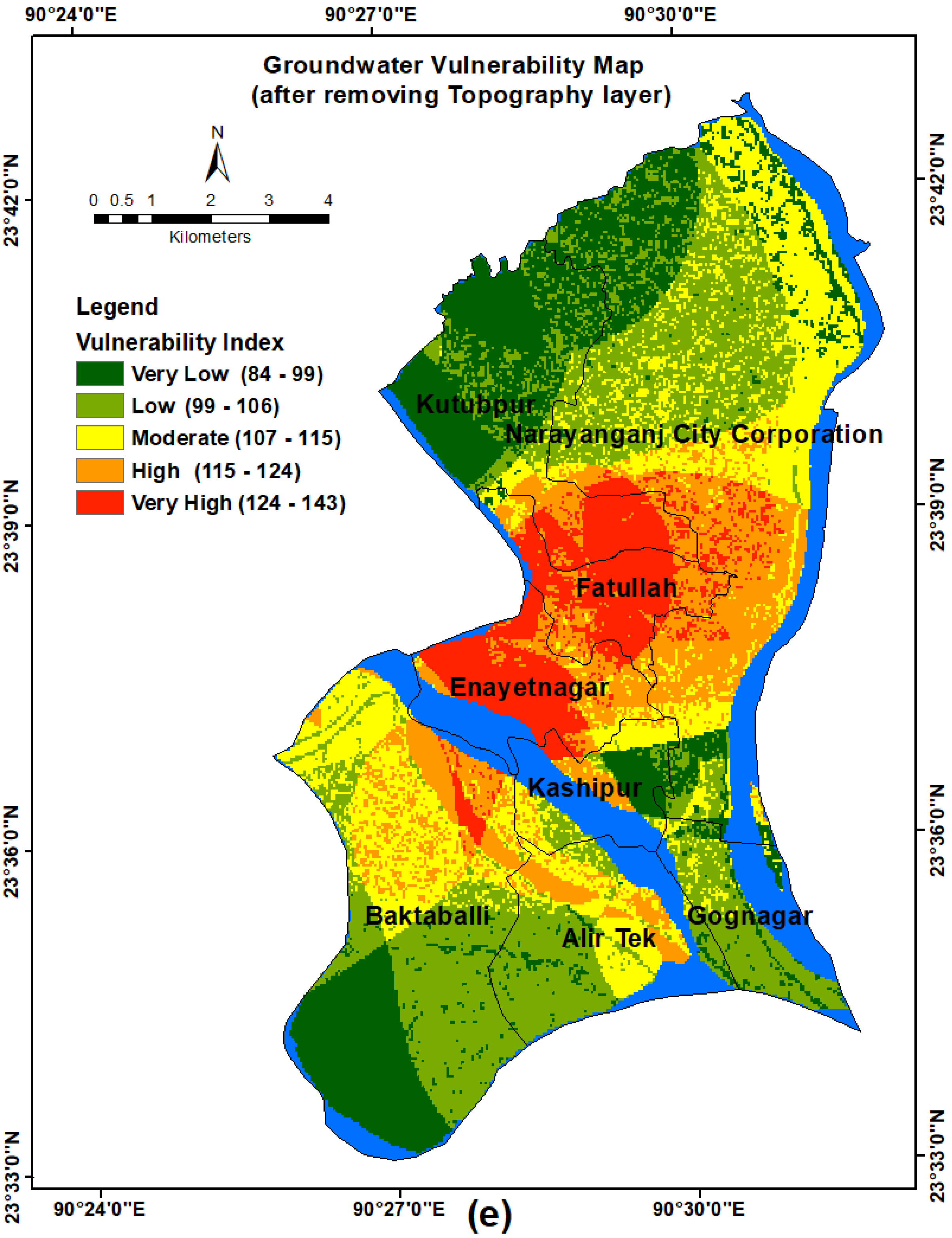
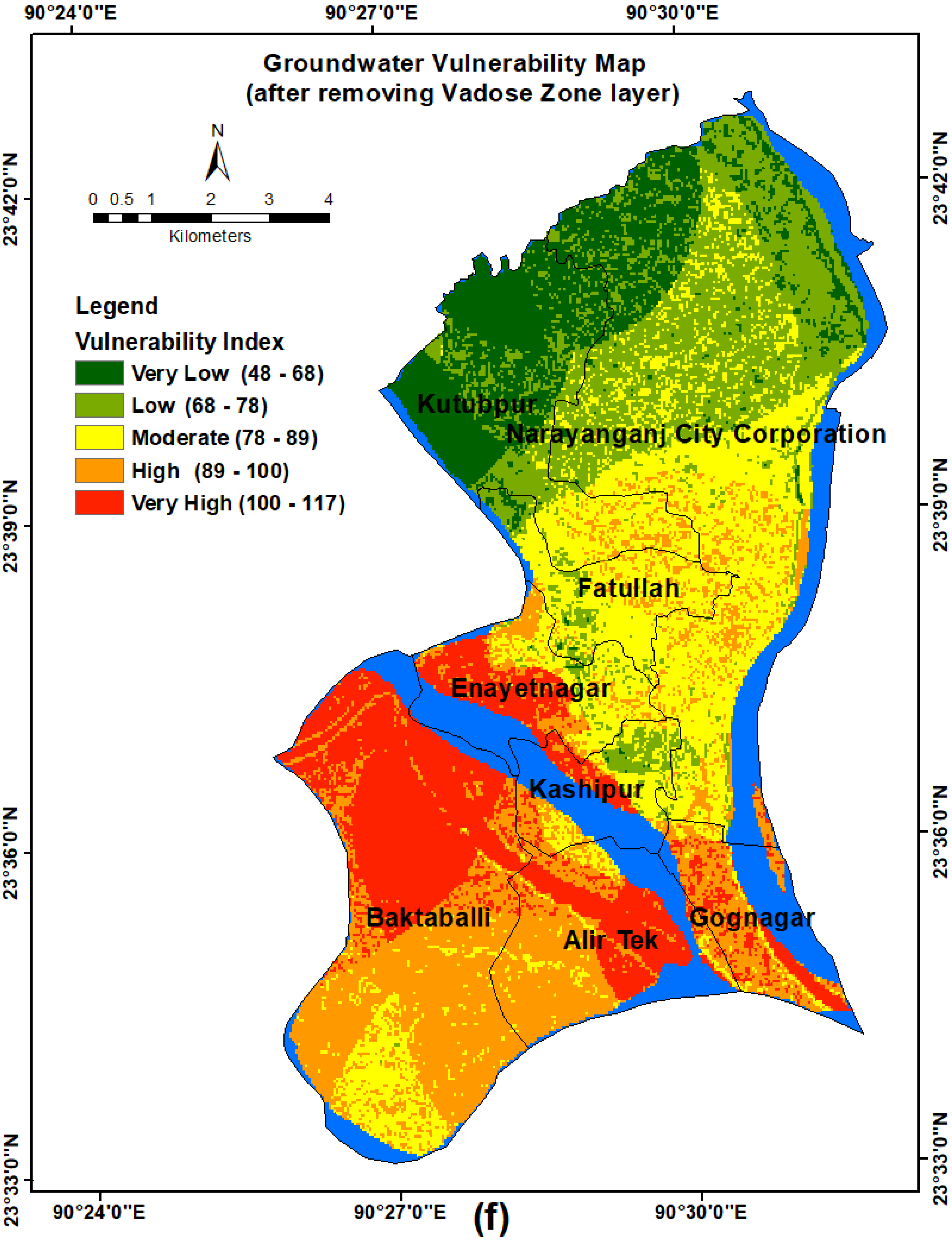


Fig 4.18: Spatial distribution of vulnerability classes after removing thematic layer: Topography.



(f)

Fig 4.19: Spatial distribution of vulnerability classes after removing thematic layer: Vadose zone.

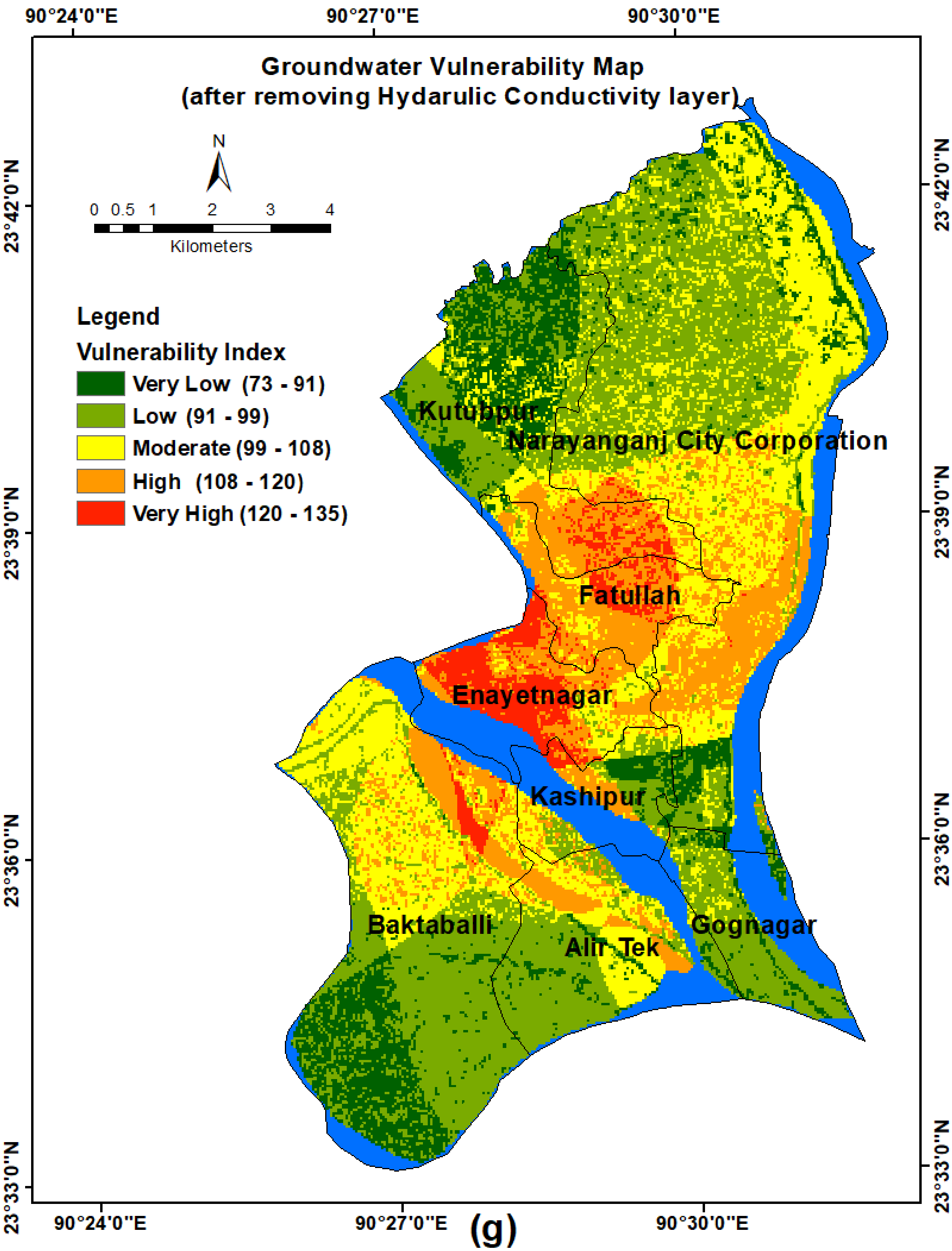


Fig 4.20: Spatial distribution of vulnerability classes after removing thematic layer: Hydraulic conductivity.

INDICATORS REMOVED	VARIATION INDEX (%)			
	Mean	Minimum	Maximum	SD
D	0.1355	1.66	1.92	0.958
R	1.176	0.77	2.69	0.537
A	0.424	0.915	1.56	0.454
S	1.494	1.483	4.064	0.605
T	0.119	0.626	2.142	0.203
I	2.115	0.887	5.194	1.749
C	0.82	0.741	0.915	0.222

Table 4.6: Statistics of Map Removal Sensitivity analysis in the DRASTIC Index.

The findings demonstrated a significant degree of variability in the vulnerability index when the influence of the vadose zone component was eliminated. Consequently, the mean variation index was determined to be 2.115%. This finding indicates that this particular component exhibits more efficacy in the context of vulnerability assessment when employing the DRASTIC index. The removal of this parameter from the overlay process results in a notable reduction in the vulnerability index (5.194%). This phenomenon may be attributed to the significant theoretical weight allocated to this particular element (weight = 5). The soil layer removal had the second greatest variation in the vulnerability index, the vulnerability decreases 4.064% maximum and 1.5% on average. The results of this study align with the findings of Lazar et al., (2012), who demonstrated that factors such as vadose zone, topography and net recharge heavily influence the vulnerability index. Furthermore, the study conducted by SAMAKE et al., (2011) revealed that the vulnerability index was significantly influenced by the vadose zone and hydraulic conductivity parameters. The sensitivity analysis indicated that the vulnerability index demonstrated a moderate sensitivity to the removal of water table depth (1.9%), net recharge (1.36%), and topography (2.142%) parameters. The minimal variance in the menu index was attained by excluding the hydraulic conductivity element, resulting in a decrease of 0.74%, as shown in Table 4.6.

4.4.2 Single parameter sensitivity analysis

The specific assignments of Effective and Theoretical weights to each parameter may be found in the following table.

Effective weight (%)				Theoretical Weight (%)	Theoretical Weight	Parameters
SD	Min.	Max.	Ave.			
5.748	4.310	25.773	13.472	21.74	5	D
3.417	9.677	33.684	21.356	17.4	4	R
2.726	4.918	19.780	11.736	13.04	3	A
3.188	1.379	13.333	5.321	8.7	2	S
1.220	1.428	10.526	7.116	4.3	1	T
10.494	11.363	45.454	26.979	21.74	5	I
1.335	9.836	19.780	14.024	13.04	3	C

Table 4.7: Statistics of Single Parameter Sensitivity Analysis in the DRASTIC Index.

As shown in table 4.7, the mean value of the effective weight of the impact of vadose zone factor is 26.979%. This finding demonstrates that this particular component exhibits more efficacy in the context of vulnerability assessment when employing the DRASTIC index. The mean value of the net recharge parameter's effective weight is 21.356%. This indicates that the statistic in question is the second most influential parameter in assessing aquifer vulnerability, as determined by the DRASTIC index. The soil media has the minimum effective weights, measuring at 5.321%. The weights assigned to depth to aquifer, net recharge, and hydraulic conductivity are also effective in the context of DRASTIC index having mean effective weight of 13.472%, 21.356% and 14.024% respectively. Additionally, their effective weight in relation to the theoretical weights indicated by the DRASTIC index were found to be higher. Depth to aquifer, aquifer media and soil media affective weights are found to be less than their assigned theoretical weight. The sole major discrepancy observed is the difference between the theoretical and effective weight in the depth to aquifer. it has the highest theoretical weight (21.74%), while the average actual weight is 13.472%. This discrepancy arises from the fact that the different classes of depth in the aquifer were assigned lower ratings compared to the standardized ratings as all of these levels represent deep aquifers, which are inherently less susceptible to contamination compared to shallow aquifers.

4.5 Model Validation

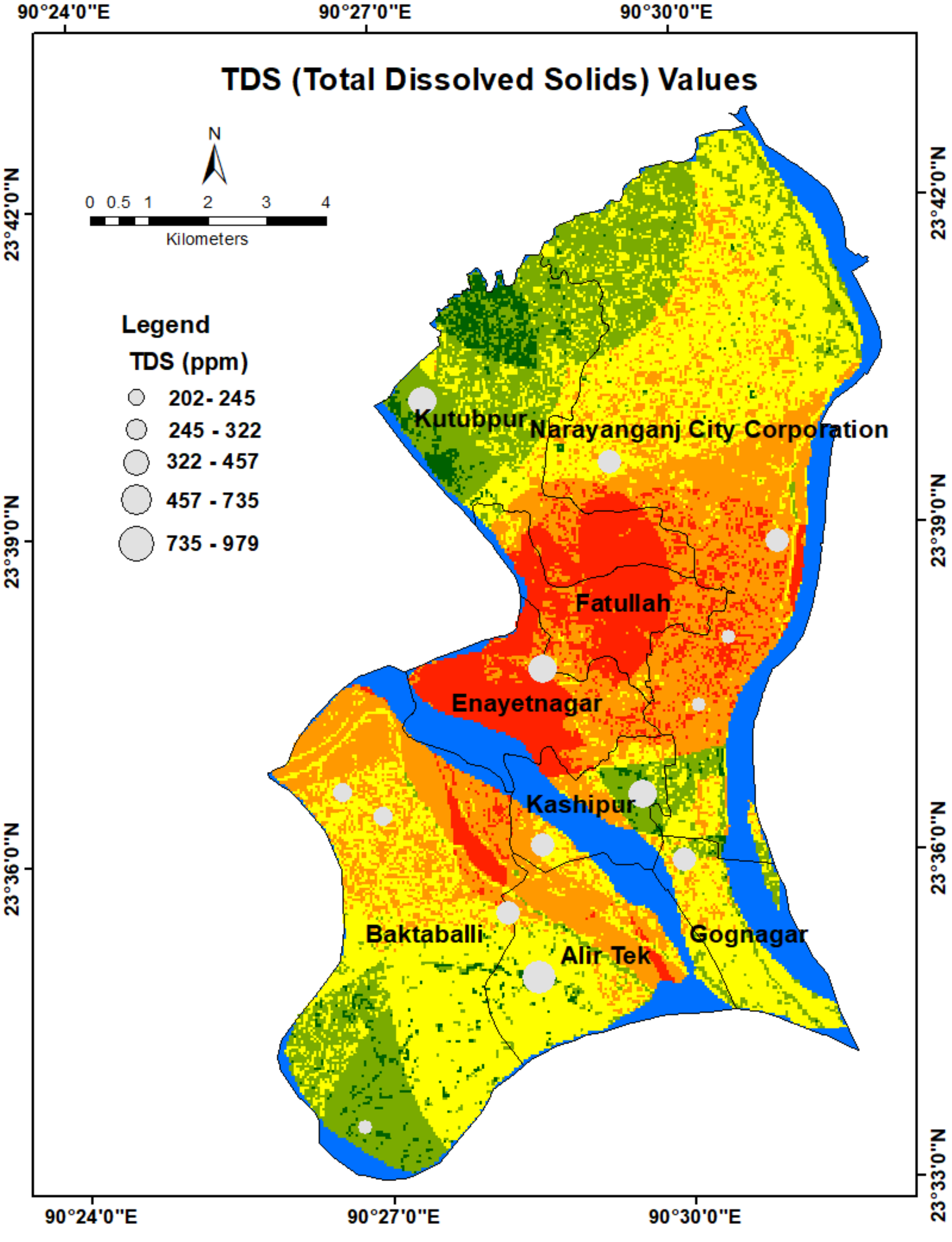


Fig 4.21: Spatial distribution pattern of Total Dissolved Solids concentration in groundwater on the vulnerability map.

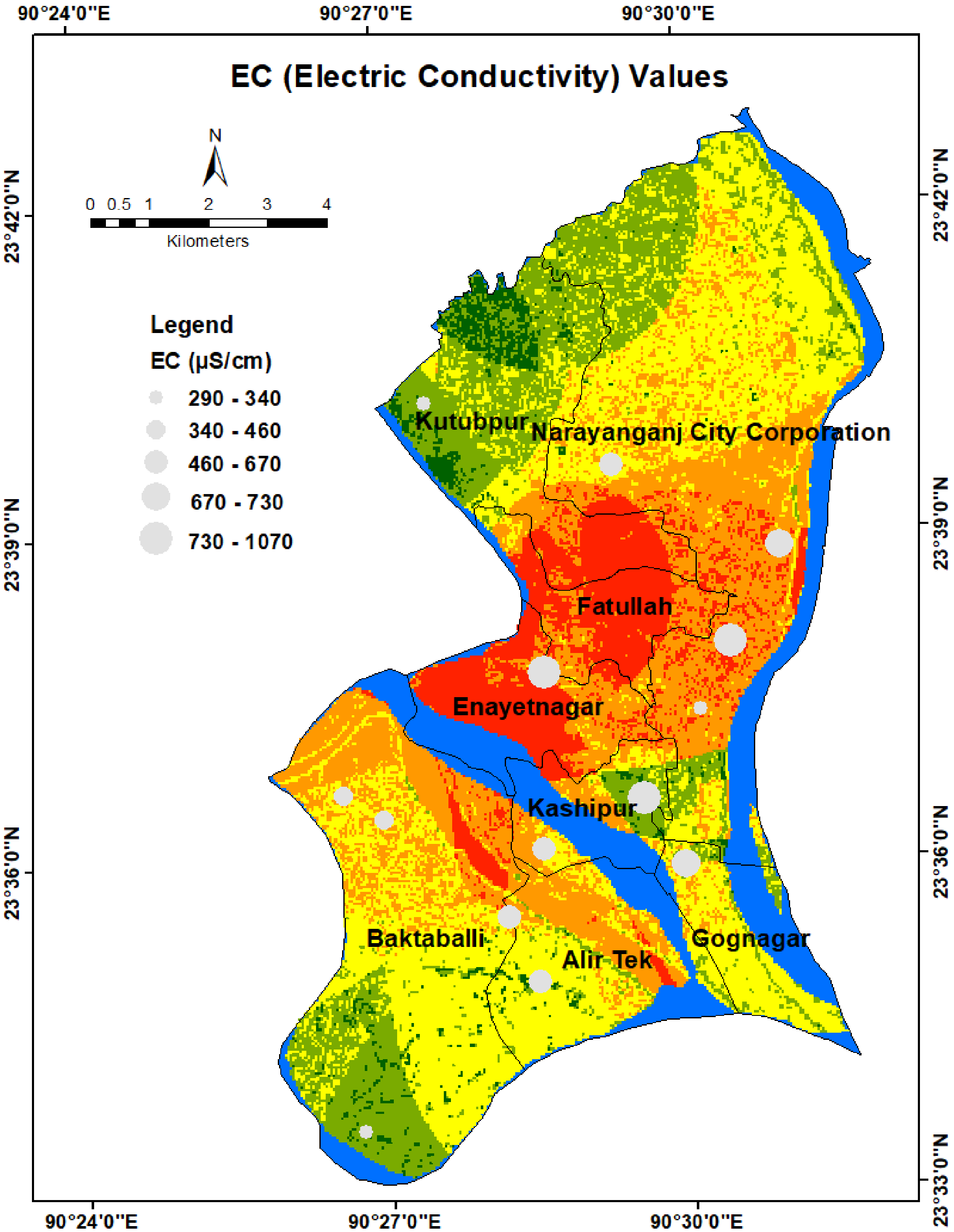


Fig 4.22: Spatial distribution pattern of Electrical Conductivity in groundwater on the vulnerability map.

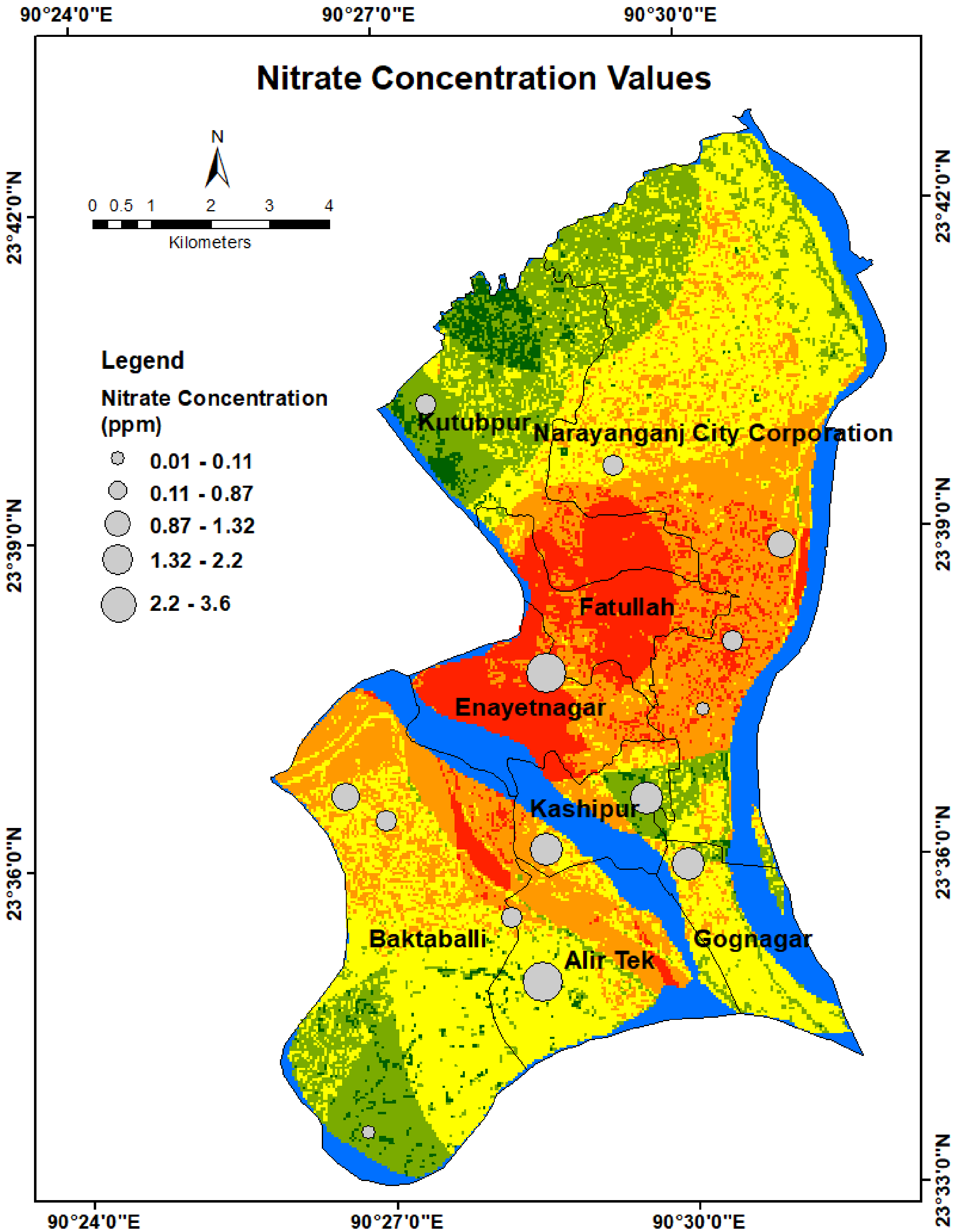


Fig 4.23: Spatial distribution pattern of Nitrate concentration in groundwater on the vulnerability map.

Out of the 14 samples utilized in the validation process, it was seen that 2 samples were classified as belonging to the category of very low vulnerability, while an additional 2 samples were categorized as being within the low vulnerability zone. Moreover, 4 samples were found to be situated within both the medium vulnerability zone and the high vulnerability zone, each. Lastly, 2 samples were identified as being part of the very high vulnerability zone.

The total dissolved solids (TDS) observed in the groundwater samples vary between 202 to 735 ppm. The electrical conductivity (EC) values observed in the groundwater samples vary between 290 and 1070 μS/cm. The analysis demonstrated a significant positive correlation between TDS, EC and DRASTIC vulnerability classes, as seen in Figure 4.22 and 4.23.

This association indicates that low susceptible zones tend to have low electrical conductivity (EC) values (< 500 μS/cm), whereas highly vulnerable zones have higher EC values. The observed upward trajectory of electrical conductivity (EC) levels in groundwater, beyond the threshold of 750 μS/cm, across areas classified as very vulnerable, indicates a potential contamination of groundwater by industrial wastewater. This contamination is likely attributed to the elevated total dissolved solids (TDS) often present in such wastewater. The discovery is further supported by the geographical distribution of EC, which exhibits high values in areas of high sensitivity on the groundwater vulnerability map (4.22 and 4.23).

Although the concentrations of $NO3^-$ in the groundwater samples are generally low (ranging from 0.01 to 3.60 ppm with most values below 1ppm, across the entire study area, the positive correlation and the comparatively higher concentration of nitrate in the high vulnerability zones on the groundwater vulnerability map (Fig. 4.24) provide further support for the validity of the model's results.

The recorded chromium (Cr) concentrations of the samples were all below detection level, thus no validation could be done from this parameter.

In order to enhance the validation of the findings, additional data on groundwater quality were obtained from the Bangladesh Water Development Board (BWDB) and the Department of Public Health Engineering (DPHE). The points were put on the vulnerability model in order to better compare the correlation.

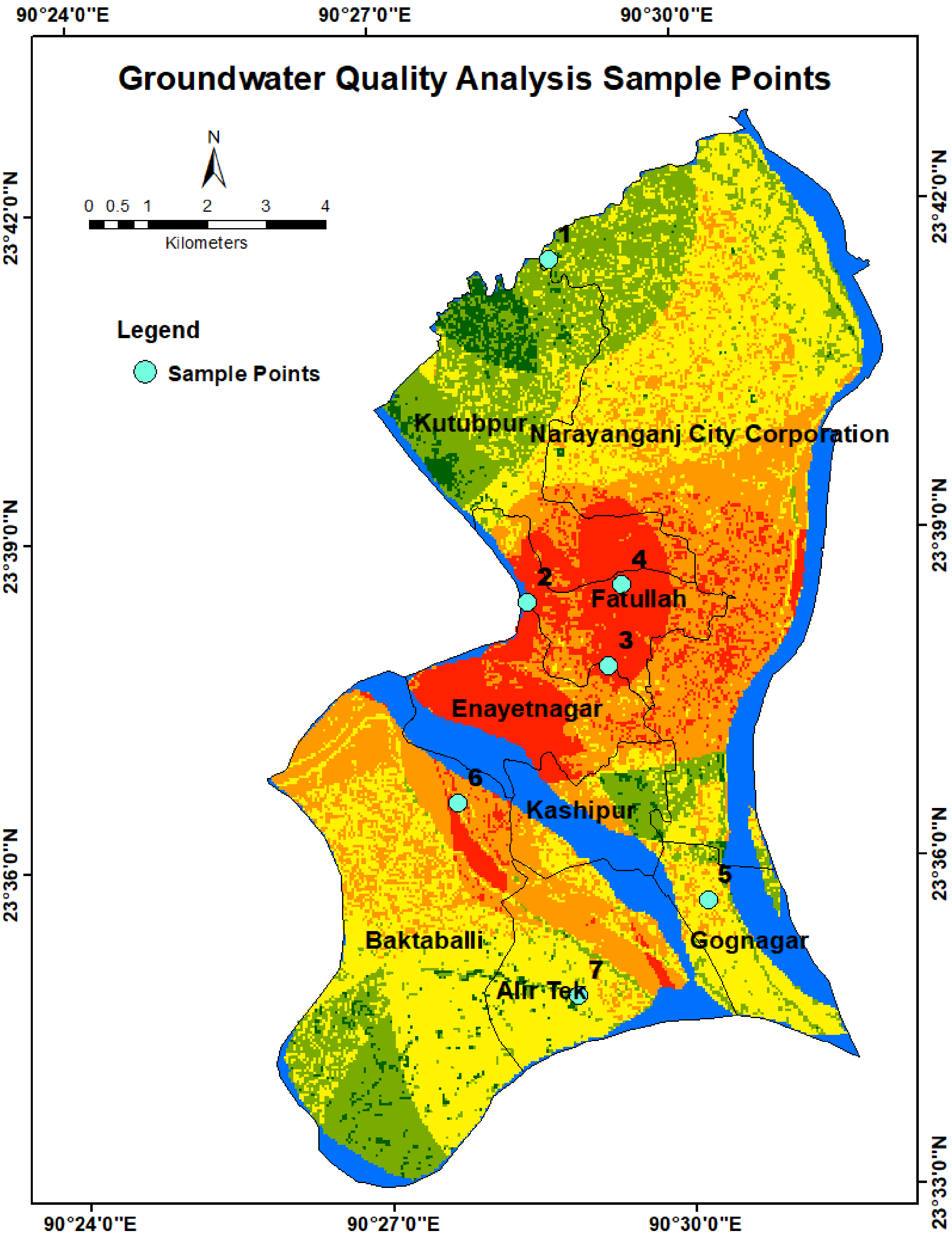


Fig 4.24: Groundwater Quality Analysis Sample Points from BWDB and DPHE on the DRASTIC vulnerability map.

The results of the analysis demonstrated a positive correlation between the vulnerability classes and the groundwater quality parameters. Notably, the high vulnerability zones exhibited a significantly high range of total dissolved solids (TDS) levels (663-697 mg/l), EC (1098-1153 µS/cm), Nitrate (2.1-6.8 mg/l), Sulfate (7.18 mg/l), Chloride (107-127mg/l), Iron (3-8mg/l) and Arsenic (8-11 µg/l) as shown in the table 4.8. Furthermore, the recorded measurements of EC, Nitrate, Sulfate, and heavy metals in the Kutubpur, Gognagar, and Baktaballi regions were found to be consistent with their respective DRASTIC index values, indicating that these areas fell within the low to moderate sensitive zones. It is noteworthy to add that the levels of Chlorine and Iron detected in all of the samples beyond the minimal acceptable threshold established by the World Health Organization (WHO) for drinking water.

Sl. No.	**Location**	**Depth (m)**	**pH**	**EC (µS/cm)**	**TDS (mg/l)**	**NO_3^- (mg/l)**	**SO_4^{2-} (mg/l)**	**Cl^- (mg/l)**	**Fe^{2-} (mg/L)**	**As (µg/l)**
1	Kutubpur	152.00	7.2	460	351	1.02	5	24.7	.3455	7.464
2	Enayetnagar	25.87	7.76	613	290	1.3	3	92.3	0.2298	7.7198
3	Enayetnagar	107.00	8.37	1098	663	2.1	7	107	8.0002	8.2620
4	Fatullah	186.00	8.74	1153	697	6.8	18	127.8	2.8979	11.3712
5	Gognagar	250.00	8.42	537	325	1.9	4	28.4	0.4128	8.0932
6	Baktaballi	190.50	8.4	465	274	1.1	3	21.3	0.8426	9.4380
7	Alirtek	298.00	8.3	647	385	3.8	2.	42.6	2.7894	9.0310

Table 4.8: Groundwater Sample Analysis of Narayanganj Sadar at the wet season of 2020.

(Source: BWDB and DPHE)

Chapter 5: Conclusion and Recommendation

The contamination of groundwater is emerging as a widespread issue that poses a significant risk to the reliability of drinking water on a worldwide scale. Due to its inherent concealment and the delayed detection, remediation of groundwater pollution becomes challenging once the contamination is identified. Hence, the mitigation and management of groundwater contamination are essential in effectively mitigating the degradation of groundwater quality (Elçi, 2017). Monitoring and understanding the coupled human and natural dynamics (e.g., physics, biology, chemistry, sociology and economics) of groundwater systems in response to climate variations and regional human activity are essential for developing appropriate management strategies and predicting social outcomes (Ghosh et al.,2015).

One effective approach for mitigating groundwater contamination involves assessing the susceptibility of aquifers and directing management interventions towards these regions to sustain water quality. This study focused on evaluating the susceptibility of groundwater to contamination in the Narayanganj Sadar region of Bangladesh taking into consideration its physiological and hydrogeological parameters, utilizing the DRASTIC approach. The objective was also to present current information regarding groundwater contamination and its correlation with various physiographic and anthropogenic parameters, thereby facilitating the implementation of appropriate management strategies for the identified high-risk zones. This discovery aligns with the findings of previous research conducted in many regions around the globe (Ckakraborty et al., 2007; Rahman, 2008; Srinivasamoorthy et al., 2011; Nera et al., 2021; Saravanan et al., 2022; Venkatesan et al., 2019; Ghosh et al., 2015; Khakhar et al., 2019; Islam et al., 2022). The findings of the study revealed that a significant proportion, specifically 40%, of the designated study region was categorized as having high or very high vulnerability and approximately 20% of the total study area falls into the low to very low vulnerability zone, which is not a large area. This classification signifies a substantial risk to both the quality of groundwater and the well-being of individuals. The study found a favorable correlation between the DRASTIC index and the land use and landcover change in the study area over the last 22 years. The study also found a favorable correlation between the DRASTIC index and the observed physical and chemical parameters such as pH, TDS, EC, nitrate and chromium content in groundwater samples, providing evidence for the method's validity and dependability. The research further identified the primary contributors of vulnerability, including impact of vadose zone, net recharge topography as analyzed by the map removal sensitivity analysis. The same conclusion was supported by doing a sensitivity analysis on a single parameter, since the resulting weights mostly aligned with the variation index values (impact of vadose zone, net recharge, hydraulic conductivity, topography) and some parameters held less significance than its theoretical value (depth to water, soil media and aquifer media). The analysis presented in this research showcases the efficacy and practicality of the DRASTIC approach in evaluating groundwater vulnerability in Bangladesh and similar developing nations.

Nevertheless, the research encountered several constraints and obstacles, including a paucity of data, regional variability, ambiguity in parameters, and sensitivity of the model. Several factors have the potential to influence the accuracy and precision of the DRASTIC index and its subsequent interpretation. Hence, it is recommended that future research endeavors should aim to gather a larger volume of data, employ maps with higher levels of spatial precision, integrate uncertainty analysis techniques, and conduct comparative evaluations of various methodologies. These measures are expected to enhance the accuracy and effectiveness of groundwater risk assessments.

This study offers significant findings and perspectives that are of great use to policy makers, practitioners, and scholars who are actively engaged in the preservation and administration of groundwater resources.

5.2 Recommendation

Planning for regional land use and groundwater resources should be combined. In order to optimize the quality of human life, a balance between ecological and engineering methods to land-use change need to be maintained. Such planning should include objectives that are responsive to regional and long-term design demands. To give enough rural amenities to urban regions and adequate urban facilities to rural areas, regional plans should be planned in harmony with natural amenities, environmental limits, and water demands.

In order for these remediation measures to be as effective as possible in urban areas, hydrological barriers that protect freshwater resources from pollution must be installed at the same time as greenbelts that not only encourage ground vegetation and soil stability but also minimize the input of potential pollutants. Similar to this, aquifer recharging should occur simultaneously with the abstraction of fresh groundwater in rural regions. This study shows that in order to achieve integrated urban/rural land-use for sustainable groundwater resource planning, integrated hydrological, environmental, and land-use measures are the only ones that can alleviate the current problem of incoherent land-use, water resources, and socio-economic planning.

The comprehensive evaluation of water expenses is frequently overlooked in water management practices, resulting in the adoption of inefficient and unsustainable water utilization strategies. The true cost of water encompasses not just the immediate expenditures associated with water provisioning and wastewater management, but also the secondary expenditures linked to water utilization, including the ramifications of water shortages, pollution, and degradation on the environment, society, and economy (Clere, 2016). One may determine the direct and indirect water usage along the value chain and evaluate the possible hazards and possibilities for water management by utilizing the water footprint in different scales: blue water (surface and groundwater), green water (rainwater stored in soil), and grey water (water required to dilute pollutants). An alternative approach for assessing true cost of water involves the utilization of real cost accounting, a methodology that integrates environmental and social expenses into financial evaluation. The utilization of true cost accounting can facilitate the assessment of the consequences associated with water utilization on several dimensions of capital, including natural capital (e.g., ecosystems, biodiversity, and climate), human capital (e.g., health, education, and well-being), and social capital (e.g., equality, justice, and governance). Through the utilization of real cost accounting, individuals are able to engage in a comprehensive analysis of various water management scenarios, hence facilitating the identification of the most sustainable and financially advantageous alternatives (Getirana et al., 2022).

As for more localized interventions, regular and spatial monitoring and testing of groundwater quality should be conducted. groundwater samples obtained from diverse depths, localities, and seasons need to be evaluate in order to identify quantify the occurrence of different pollutants. It is important to employ dependable and precise tools and methodologies while conducting an examination of groundwater quality. The implementation of a comprehensive database and network infrastructure is proposed to facilitate the exchange and distribution of groundwater quality data. This can result in a more accurate assessment and quantification of the vulnerability and sustainability (Haque, 2018). Additionally, alternate water sources or employ treatment technology for the provision of potable water need to be used. The implementation of water efficiency and conservation methods within the agricultural and industrial sectors need to be advocated. Furthermore, regulations to monitor and regulate the utilization and proper disposal of fertilizers, pesticides, and industrial wastes should be implemented.

One of the drawbacks of the DRASTIC Model is that the classification and assessment of parameters rely on expert opinion. Consequently, this gives rise to ambiguity in the outcomes. In order to address this issue, it is recommended that a research study be conducted to examine the susceptibility of the environment to prevalent contaminants, such as nitrate and pesticides. Additionally, it is advised to calibrate the DRASTIC Model, a widely used tool for assessing groundwater sensitivity. It is advisable to use fuzzy logic and neural network approaches in the vulnerability assessment process, and thereafter compare their outcomes with those obtained from the DRASTIC Model and real data. This may aid to enhancing vulnerability assessment or determining the optimal approach for doing vulnerability assessment.

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