Application of Analytical Hierarchy Process (AHP) in identification and analysis of Groundwater Potential Zones in Delhi, India

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SUBMITTED BY:
Shivani Gupta
(2K21/ENE/10)

RESEARCH SUPERVISOR:
PROF. S. K. SINGH
PROF. A. K. HARITASH

DEPARTMENT OF ENVIRONMENTAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

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DELHI TECHNOLOGICAL UNIVERSITY

(*FORMERLY* DELHI COLLEGE OF ENGINEERING)
MAIN BAWANA ROAD, NEW DELHI -110042

DEPARTMENT OF ENVIRORNMENTAL ENGINEERING

CERTIFICATE

This is to certify that the research work embodied in this dissertation entitled "**Application of Analytical Hierarchy Process (AHP) in identification and analysis of Groundwater Potential Zones in Delhi, India"** has been carried out in the Department of Environmental Engineering, Delhi Technological University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma to any university or institute.

Dr. S.K Singh	**Dr. A.K Haritash**	**Shivani Gupta**
(Research Supervisor)	(Research Supervisor)	(2K21/ENE/10)

Date:
Place:

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Date: **Shivani Gupta**

Place:

ABSTRACT

The utilization of Geographic Information System (GIS) offers a wide range of applications for groundwater assessment, delineation, discovery, and resource management. The aim of the present study is to establish a long-term plan for groundwater consumption by implementing novel approaches that ensure the proper utilization and effective maintenance of critical groundwater resources. In this study, GIS techniques, employing Satty's analytical hierarchy method (AHP), were used to demarcate groundwater potential zones in the National Capital Territory (NCT) of India. Seven spatial and non-spatial thematic layers, including Slope, Geology, Rainfall, Soil, Land use / Land cover, Soil, Lineament, and Drainage Density, were examined in the GIS software, and appropriate weights were assigned to define the Groundwater potential zones. An integrated map for Delhi, India was generated as a result. The groundwater potential areas were categorized into five zones: 1-very poor, 2-poor, 3-moderate, 4-good, and 5-very good. The very poor class covered an area of 12.87 km2, poor class covered 174.24 km2, moderate class covered 695.58 km2, good class covered 592.61 km2, and very good class covered 23.08 km2, respectively. This study helps in effective resource management, water supply planning, agricultural development, environmental protection, and disaster management. By understanding the distribution and availability of groundwater, stakeholders can make informed decisions to ensure sustainable use and protection of this valuable resource.

KEY WORDS: GIS, Ground water potential zones (GWPZs), LULC, Digital elevation model (DEM), Saaty’s Analytical Hierarchy Process (AHP)

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ABBREVIATIONS

AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
ARIMA	Autoregressive Integrated Moving Average
CGWB	Central Ground Water Board
CI	Consistency Index
CR	Consistency Ratio
CRU	Climatic Research Unit
DD	Drainage Density
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geological Information System
GWPZ	Ground Water Potential Zone
IDW	Inverse Distance Weighted
LD	Lineament Density
LULC	Land Use/Land Cover
MCDM	Multi-Criteria Decision Making
RI	Random Index
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WYC	Western Yamuna Canal

CHAPTER - 1

INTRODUCTION

In several dry and semi-arid regions, groundwater meets nearly all human needs. Freshwater is only 3% of the total amount of water on Earth. 30% are readily available to humans as groundwater, which is necessary for drinking, sanitation, habitats, and power production (Noori & Singh, 2021c). 95% or more of the world liquid fresh water supply comes from groundwater reservoirs, which are a plentiful source of freshwater (Goyal et al., 2023). Around 3 billion people worldwide depend on groundwater sources to fullfill their water needs (Singh & Noori, 2022b). In dry and semi-arid regions, groundwater resources are more susceptible to overexploitation, and the declining quality of groundwater resources is also a major problem (Singh & Noori, 2022b). and the pollutants included in the effluent from sectors like iron and steel represent a severe threat to the environment and have a negative impact on receiving water bodies (Garg & Singh, 2022).

A recent study found microplastics in regularly used sea salts and emphasized the problems with human health that go along with it. Tonnes of plastic were dumped in the oceans, and this number is rising daily (Gola et al., 2021). Due to a lack of water treatment facilities, surface water sources in India are much more contaminated than deep well sources (Kumar, 2014). Groundwater recharge is a highly sluggish process because of the complexity involved in its occurrence and recharging, which has further contributed to concerns over its rising quality and quantity (Goyal et al., 2023). Contaminants produced through human activity that seep into underground aquifers also contribute to groundwater pollution. Nitrate, fluoride, hazardous metals, pesticides, medicines, hydrocarbons, and radioactive compounds are the main pollutants found in groundwater (Sarma & Singh, 2023). Additionally, the health of humans is adversely affected by polluted ground water. Once contaminated, it is quite challenging to restore the quality of the ground water. The only method to stop pollutants from contaminating ground water is to prevent them at the source (Dagar et al., 2022). Therefore, sthe evaluation and assessment of groundwater quality and quantity is of importance to academics and managers of water resources (Noori & Singh, 2023). Changes in land cover patterns, population increase, urbanisation, and industrialization all have an impact on groundwater quality (Singh & Noori, 2022b) (Goyal et al., 2023). Frequent water quality monitoring always requires the use of water quality assessment as a monitoring tool (Singh & Noori, 2022b).

The utilization of GIS in groundwater evaluation is crucial as it enables researchers to identify and statistically analyze unique spatial characteristics within groundwater quality data (Noori & Singh, 2023). Leveraging a geographic information system (GIS) for generating spatial distribution maps is a valuable tool that aids in creating interpolated maps for various quality parameters measured at specific point locations. This technique has proven beneficial for researchers in estimating parameter values at unsampled locations (Goyal et al., 2023).

The capacity of numerical modelling approaches to predict the potential effects of water management strategies has led to their enormous popularity in recent years. For the purpose of predicting streamflow, several researchers divided data-driven models into three categories: conventional, Artificial Intelligence based, and hybrid. Traditional time series models are extensively used and simple to apply (Sarma & Singh, 2022).

Groundwater shortages and declining water levels are primarily caused by climate change and excessive extraction from aquifers for various purposes. Additionally, regular drought events hinder groundwater recharge and regulation, leading to a decrease in the groundwater table. Insufficient infiltration due to drying riverbeds further compounds the issue, making it challenging to maintain river health and stage. Furthermore, the impacts of climate change, such as reduced rainfall and increased evapotranspiration, directly affect groundwater recharge mechanisms in many regions (Noori & Singh, 2021b). Some nations, like Kabul Municipality, have begun a small-scale biological wastewater treatment programme and warned that unless immediate and thorough action is taken to prevent groundwater contamination in Kabul, groundwater may become unusable in the upcoming years (Noori & Singh, 2021a).

In Delhi, the primary sources of raw water include the Yamuna River. (S. Singh & Kaushik, 2018) According to a researcher, Delhi's population increased from 1911 to 2015 in millions, placing an ever-increasing strain on the city's water resources as a result of higher living standards and more access to sanitary facilities (Singh & SK, 2015).

The North-West region of Delhi comprises industrial, residential, and agricultural zones. Over the past two decades, significant transformations in land use have occurred within this region. A substantial portion of agricultural land and rural built-up areas have been converted into urban areas. It is crucial to identify the mechanisms of groundwater pollution resulting from the rapid urbanization in this region (Sarma & Singh, 2023). The monsoon season has more noticeable environmental effects, including increased rates of runoff and erosion, leaching of pollutants, overflowing of mining pits, etc. The runoff has a negative impact on agricultural fields and streams directly or indirectly. Groundwater pollution is increased when contaminated water percolates via the vadose zone into aquifers (Haritash et al., 2017).

The study is designed to meet the following objectives:

- Delineation and analysis of different Groundwater potential zones for Delhi, India
- Determine the fluctuations of water level in Groundwater potential zones for a duration of 2011-2020.

CHAPTER - 2

REVIEW OF LITERATURE

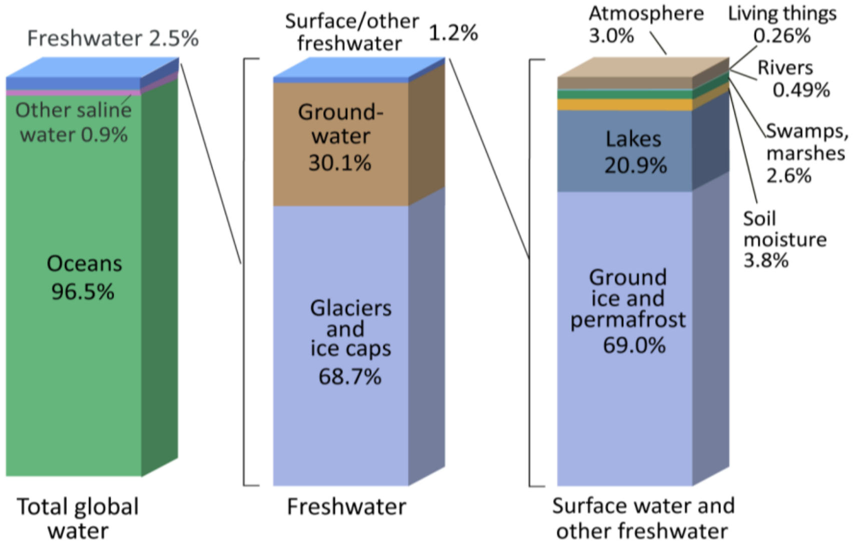
2.1 Background of the study

Groundwater, a vital and invaluable freshwater resource on our planet, plays a crucial role in sustaining all forms of life. Yet, growing consumption demands, coupled with advancements in agriculture and industry, have made it imperative to optimize the utilization of groundwater sources. Groundwater is a finite natural resource, closely tied to the prosperity of every nation (Kumar et al., 2022). Unfortunately, the world's water table has been suffering from a worrisome fall as a result of ongoing groundwater extraction. In addition to surface water contamination, groundwater contamination is rapidly growing in importance as a problem. In the North West Delhi region, numerous studies on groundwater contamination have been carried out to comprehend the causes of contamination and evaluate the associated health hazards (Sarma & Singh, 2023). India leads the world as the largest consumer of groundwater, accounting for 26% of global groundwater extraction. With an estimated 20 million wells and tube wells in operation, India withdraws approximately 251 km^3 of groundwater annually. Notably, a significant portion, around 89%, is utilized for irrigation purposes within the country. (The United Nations World Water Development Report, 2022).

While research projects using proximal and remote sensing to manage water resources were started years ago, there is still little practical knowledge about the availability of groundwater and the best methods of extraction.

2.2 Global water distribution

Water constituting the predominant component on earth. The vast majority, around 96.5 percent, exists as saline water within the oceans. However, water manifests in diverse forms and locations. A bar chart visually depicts the distribution of Earth's water, emphasizing that nearly all of it is saline and resides in the oceans. Among the limited amount of freshwater available, only a relatively small portion is capable of sustaining human, plant, and animal life. The first bar emphasises that freshwater, which is necessary for living things to survive, makes up only 2.5% of the total amount of water on Earth. The breakdown of freshwater is shown in the centre bar, which demonstrates that the vast bulk of it is buried beneath ice and soil. The majority of life's needs are met by surface water, which makes up just over 1.2 percent of all freshwater. The surface freshwater is broken down in further detail in the right bar. The majority is enclosed in ice, and lakes account for about 20.9 percent of the total. Only 0.49 percent of surface freshwater comes from rivers. Despite being few in number, rivers provide an essential source of water for human consumption. (USGS)



Credit: U.S. Geological Survey, Water Science School. https://www.usgs.gov/special-topic/water-science-school
Data source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

Fig 2.1. The spatial distribution of water across the Earth's surface, within its depths, and in the atmosphere (USGS)

2.3 Groundwater distribution in India

The country has many aquifers characterized according to their hydrogeological attributes. Among these, the Alluviums occupy the largest land area, approximately. Another substantial portion, roughly 20% of the country's area.

About 17% of the nation's land is covered by the Basalt aquifer, which predominantly encircles the states of 5 states. Meanwhile, the Sandstone aquifer, which is present in another 5, makes up about 8% of the nation. The limestone aquifer takes up only around 2% of the country's total land area, compared to the shale aquifer's roughly 7% share. (CGWB, Manual of Aquifer Mapping, 2016)

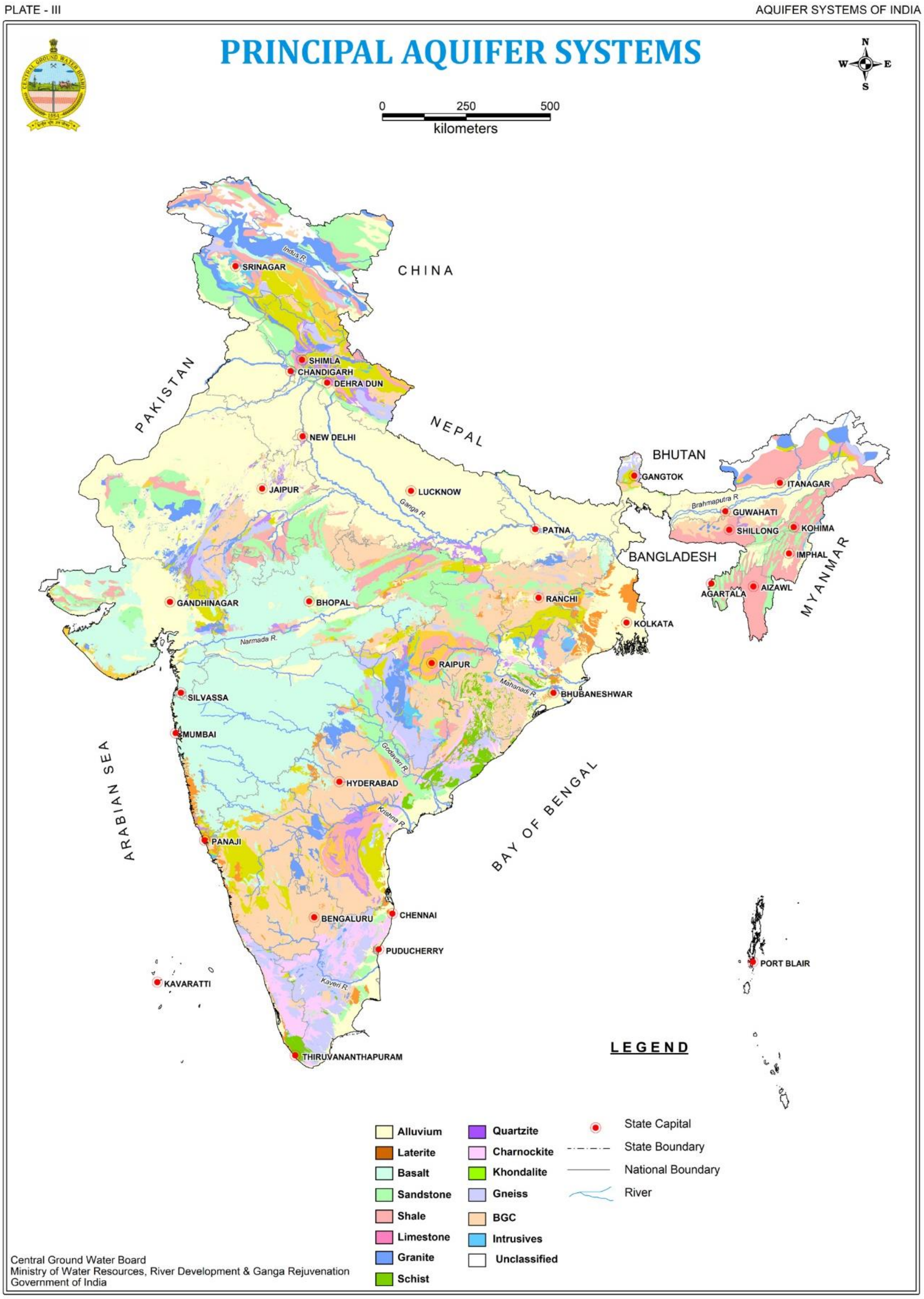
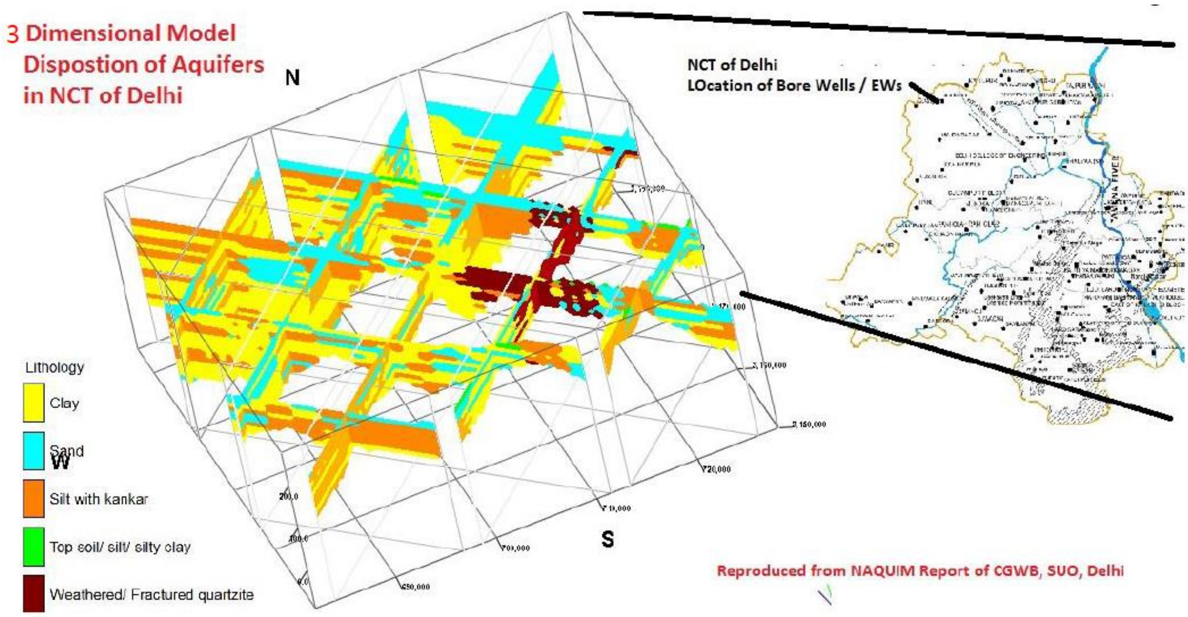


Fig 2.2 Aquifer system of India (Manual of aquifer mapping, CGWB, 2016)

2.4 Ground water distribution in Delhi

The NCT (National Capital Territory) of Delhi has undergone a comprehensive study done by the CGWB as part of the NAQUIM Project. This study aimed to establish a detailed understanding of the regional-scale aquifer geometry in the region. To achieve this, all available data regarding subsurface aquifer configuration, including lithological and geophysical logs from exploratory wells drilled by the CGWB's Ground Water Exploration Programme, as well as interpreted records from various geophysical studies, were integrated. The culmination of these efforts resulted in the creation of an aquifer map for the area. The principal aquifers were delineated by grouping fine, medium, and coarse sand, along with sand containing gravels, as "sand." This integrated approach allowed for a comprehensive understanding of the aquifer system in the NCT, Delhi.)



Reproduced from NAQUIM Report of CGWB, SUO, Delhi

Fig :2.3 Aquifer Disposition in the Delhi: A 3-D Model (CGWB)

Due to the multiple geo-environmental elements that have an impact on groundwater growth deep inside the earth's crust, identifying groundwater is a challenging task. Over time, conventional techniques, like as geophysical inspections, gave solutions for the pursuit of groundwater (Danso & Ma, 2023). Over the years, several studies dating back to the early 1960s have attempted to understand the spatial variability of groundwater occurrence in different terrains. These studies have utilized technologies such as aerial photography and geographic information systems (GIS) to analyze and explain the patterns of groundwater occurrence. More recently, remote sensing from satellites has emerged as a valuable tool for providing rapid and preliminary information about subsurface water conditions. This technology enables the collection of baseline data on groundwater, which aids in identifying the factors that influence its occurrence and movement. These factors include lithology (rock types), geological structures, geomorphology (landforms), soil characteristics, land use and land cover, as well as other relevant attributes of the area. By integrating data obtained through remote sensing and other techniques, researchers and hydrogeologists can gain insights into the factors that control groundwater occurrence potential and its behavior. This information is crucial for effective management and sustainable use of groundwater resources. (Sitender, 2019) It is now possible to establish the baseline data for delineation of groundwater potential zones (GPZs) because to the recently widespread use of satellite photos coupled with conventional maps and the Global Positioning System (GPS) (Nasir et al., 2018). GIS techniques provide quick and affordable management of natural resource surveys. Additionally, remotely sensed data are a crucial tool for finding groundwater. In the past ten years, a lot of attention has been paid to a number of strategies, including the Weighted Overlay Index method, Analytical Hierarchy Process, multi variant decision making, and Trend detection in time-series data. (Sarma & Singh, 2023) Geospatial technology can be used to create groundwater, flood, and drought potential zones as well as groundwater recharge zones, as shown in a study on Kabul (Singh & Noori, 2022a).

The geographical distribution map of water quality characteristics of NCT Delhi was created using a study employing inverse distance weighting (IDW) in QGIS software (Raghav & Singh, 2021). A comprehensive study conducted in Kabul, Afghanistan aimed to examine the spatiotemporal distribution of groundwater, as well as the physicochemical and bacteriological characteristics of groundwater in the region. The study also investigated patterns of groundwater consumption. It focused on understanding the various factors contributing to the annual decline in groundwater levels in Kabul between 2008 and 2016. The study shed light on the causes behind this decrease and provided insights into the changing dynamics of groundwater availability in the area (Noori & Singh, 2021c).

2.5 Different tools for assessing groundwater potential

Various tools and techniques have been employed worldwide to assess groundwater depletion and pollution scenarios. Geostatistical interpolation and index-based methods are often utilized when quantitative information about the groundwater system is insufficient. These methods are commonly employed for preliminary investigations in areas of concern. They assume a homogeneous distribution of parameters within polygons, both temporally and spatially. However, this approach may overlook localized variations in parameters at specific sites. Subjectivity arises when assigning weights and ratings to input layers, introducing a potential source of bias. Consequently, where data availability and software capabilities permit, numerical simulation models offer a more comprehensive and quantitative approach to vulnerability mapping. These models require substantial data, focusing on localized areas and necessitating extensive information for accurate analysis.(Goyal et al., 2021)

Depending on the type, quantity, and quality of the available data, several interpolation techniques, including regular kriging, cokriging, and inverse distance weighted methods, were used to create these pollution plume maps. Over the years, results from various interpolation methods employing various circumstances and amounts of sampling data have been compared. (Goyal et al., 2021) The MIF technique is relatively straightforward and efficient since it is simple to rank and weight the input criteria used to define groundwater potential zones. (Paul et al., 2020) The groundwater level signifies the upper boundary of the saturated zone, and any factors influencing groundwater pressure will result in changes in the groundwater level. Rainfall is a significant factor contributing to the fluctuations in water levels. (Arya et al., 2020) Identification of Groundwater Potential Zones study benefits effective water resource management, sustainable development, placing water supply projects, agricultural planning, environmental conservation, and disaster management. In order to ensure the best and most sustainable use of this essential resource, it offers useful information into the availability of groundwater.

2.6 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), developed by Thomas Saaty (1980), is a powerful decision-making technique designed to assist in complex decision-making scenarios and aid decision-makers in making informed choices. The AHP involves considering a set of parameters for evaluation and a range of potential choices to arrive at the optimal decision. Saaty's approach assigns weights to the parameters by utilizing the principal eigenvector of the pairwise comparison matrix, which captures the relative importance between two variables. The weights for pairwise comparisons are determined using the continuous ranking scale employed in Saaty's AHP methodology. The AHP evaluates a set of appraisal parameters and various alternatives, ultimately identifying the best choice to be made. By breaking down challenging decisions into a series of pairwise comparisons, the AHP simplifies the decision-making process. The AHP is considered analytic as it converts the inputs provided by the decision-maker into numerical values, allowing for a more systematic and quantitative analysis of decision options.(Banerjee et al., 2020)

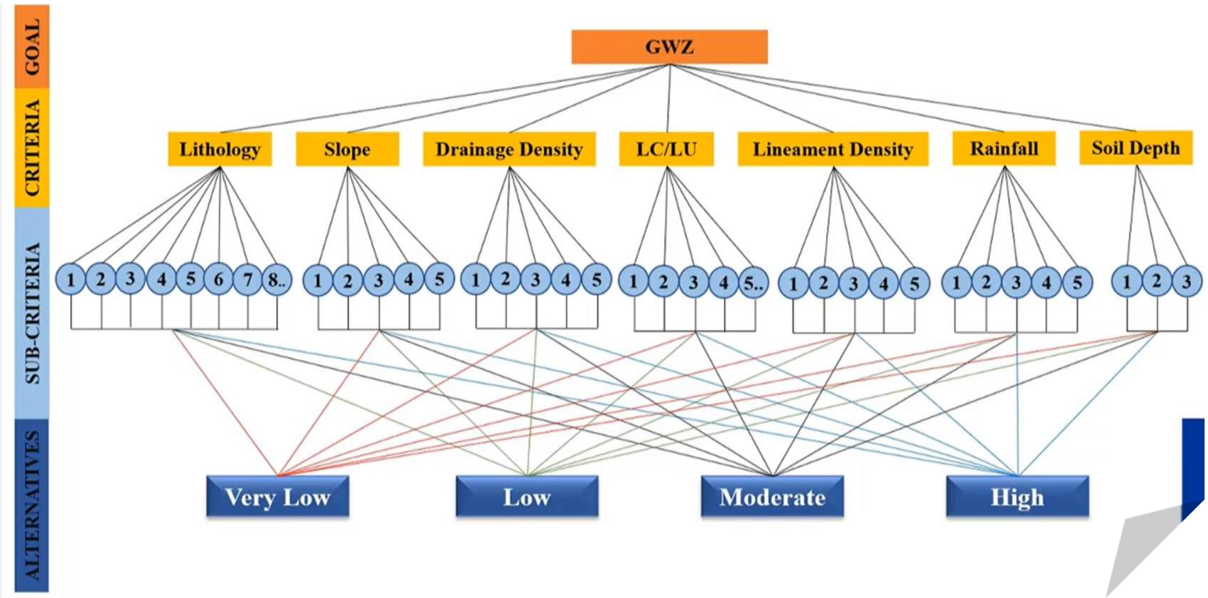


Fig. 2.4: Analytical Hierarchy Process diagram

An analysis of the causes of groundwater pollution and its potential effects on human health is conducted. These studies shed important light on the degree of groundwater contamination in the area and its effects on public health by exploring the sources of contamination and evaluating the associated dangers. (Sarma & Singh, 2023)

Multi-criteria analysis is an emerging technique used for decision-making, and one of the prominent methods within this approach is the Analytical Hierarchy Process. AHP has found application in a wide range of socio-economic decision-making problems. AHP is particularly suitable when the dimensions being evaluated are independent from each other. Saaty (1996) provides a methodology within AHP that involves input judgment and measurement to establish ratio scale priorities for the allocation of influence among different thematic layers. This approach addresses the issue of independence among alternatives or criteria. Additionally, Saaty (1996) proposed the Analytic Network Process (ANP) to handle situations where there are dependencies among alternatives.(T. Kumar et al., 2014)

Due to their capacity to forecast outcomes, mathematical models for groundwater contamination investigations have been extremely popular in recent years. Groundwater aquifer system mathematical models predict water table depths, degrees of contamination, and the effects of suggested water management measures. The most often used models nowadays, thanks to new developments in modelling methodologies, are mathematical ones based on the conservation of mass, momentum, and energy that call for partial differential equation solutions within predetermined boundary or beginning conditions of the aquifer system. These models might range from straightforward one-dimensional solutions to extremely complex three-dimensional structures. (Sarma & Singh, 2021)

2.7 Digital Elevation Model (DEM)

High-altitude regions are generally associated with lower probabilities of groundwater presence, whereas low-altitude areas have a higher likelihood. This is due to the gravitational forces of the Earth, which cause water to flow downhill. (Alikhanov et al., 2021) DEMs provide essential elevation data that is used to create accurate groundwater flow models. These models simulate the movement of groundwater through an aquifer system by incorporating the topographic slope derived from the DEM.

By integrating information on elevation, surface water bodies, and subsurface geological structures, groundwater flow models can predict the direction and velocity of groundwater flow, helping in understanding aquifer behaviour and identifying potential recharge and discharge areas. DEMs help identify areas where groundwater recharge (infiltration of water into an aquifer) and discharge (flow of groundwater to the surface or to other water bodies) occur. By analysing the slope and elevation patterns in a DEM, hydrologists can identify regions with high potential for groundwater recharge, such as areas with gentle slopes and permeable soils. Conversely, areas with low slopes or depressions can indicate potential discharge zones, where groundwater may emerge as springs or contribute to surface water bodies. Due to the multi spectral coverage of a terrain satellite remote sensing offers the chance for improved observation and more systematic analysis of various geomorphic units, landforms and lineaments. (Arkoprovo et al., 2012)

2.8 Drainage Density

Drainage density refers to the proximity of stream channels within a given area. Permeability plays a crucial role in determining drainage density. Rocks with lower permeability impede the infiltration of rainfall, leading to a greater concentration of surface runoff. Consequently, the drainage density tends to be inversely proportional to permeability. (Magesh et al., 2012)

A terrain's drainage map provides information on the porosity of the rocks and the accessibility of groundwater. (Arya et al., 2020). A high drainage density indicates the presence of a dense network of streams and channels, which can facilitate the infiltration of water into the ground. As surface water flows along streams, it can seep into the surrounding soil and recharge the underlying aquifers. Thus, areas with high drainage density often have increased opportunities for groundwater recharge. Drainage density affects the storage and flow of groundwater within an aquifer system. In regions with high drainage density, the interconnected network of streams and channels can serve as conduits for groundwater flow. This can facilitate the movement of groundwater towards discharge areas, such as springs or rivers, and influence the overall behavior of the groundwater system.

2.9 Lineament Density

Lineaments, particularly in hard rock terrains, play a crucial role in the storage and movement of groundwater. As such, lineaments serve as dependable indicators of groundwater storage and movement dynamics in such terrains. (Achu et al., 2020) Lineaments, particularly fractures and faults, can act as preferential pathways for groundwater flow. These linear features often have higher permeability compared to the surrounding rock or soil, allowing groundwater to move more easily along their pathways. Higher lineament density can provide more conduits for groundwater flow, affecting the overall flow patterns and velocities within an aquifer. Lineaments have the potential to facilitate the movement of groundwater, directing it from areas of recharge to areas of discharge. They can also influence the overall direction of groundwater flow. Additionally, lineaments play a significant role in groundwater recharge and discharge processes. Within lineaments, fractures and faults can serve as pathways for surface water to infiltrate into the subsurface, thus contributing to groundwater recharge.

Similarly, lineaments can act as conduits for groundwater to discharge to the surface, such as emerging as springs or seeping into streams or lakes. Higher lineament density can provide more opportunities for both recharge and discharge, affecting the overall water balance of an aquifer system.

2.10 Slope

Slope is an illustrated as keen factor which helps in the identification of ground water potential zones. (Saravanan et al., 2020) If we increase the degree of slope in rapid runoff it increases erosion rate with limited recharge potential (Magesh et al., 2012) Areas characterized by longer percolation times for rainwater and greater opportunities for water to infiltrate into the ground are classified as good groundwater prospects. Conversely, high slope areas experience increased runoff, resulting in shorter residence times for rainwater and reduced infiltration. As a consequence, these high slope areas are considered poor groundwater prospects due to limited opportunities for groundwater recharge. (Jasrotia et al., 2016) Groundwater behaviour is significantly influenced by slope. The slope has an impact on surface water runoff's rate and direction. Surface water flows more swiftly where there are steeper slopes, which limits the time for infiltration and recharge.

As a result, groundwater recharge may be limited in steeply sloping regions compared to areas with gentler slopes. Conversely, areas with gentle slopes allow for slower surface water movement, facilitating greater infiltration and groundwater recharge. Slope influences the direction and velocity of groundwater flow within an aquifer. Groundwater normally flows from higher altitude to lower altitude due to action of gravity. Steeper slopes can generate higher hydraulic gradients, leading to faster groundwater flow rates. The slope gradient can dictate the flow path and affect the travel time of groundwater through an aquifer. In addition, the slope can interact with geological structures, such as fractures or bedding planes, influencing preferential flow pathways. Slope can impact the storage capacity and configuration of an aquifer. In sloping aquifers, the GWT, which represents upper boundary of the saturated zone, tends to follow the contour of the land surface. Steeper slopes may result in a more rapid decline in the water table with distance, indicating a thinner saturated zone. Conversely, gentle slopes may allow for a more extensive saturated zone and increased aquifer storage capacity.

2.11 Soil type:

The presence of groundwater is influenced by various factors, and one crucial variable is soil composition. Specifically, the texture of the soil plays a significant role in controlling the rate of infiltration in a given area. The texture of the soil directly affects how easily water can penetrate into the ground and ultimately impacts groundwater occurrence. (Achu et al., 2020) The entry of water into the ground and subsequent percolation to the water table are significantly influenced by the texture and structure of the soil. Water can enter the subsurface more quickly in soils with a coarse texture, such as sandy soils, since they have bigger pore spaces and typically have higher infiltration rates. Contrarily, fine-textured soils, like clay soils, have smaller pore spaces and lower rates of infiltration, which causes water to travel more slowly. The soil's permeability, which is influenced by its texture and structure, dictates how easily water may pass through it, which has an impact on the rate at which groundwater recharges.

Soil plays a crucial role in storing and releasing water for groundwater recharge. Soils with high water-holding capacity, such as loams or clayey soils, can retain more water within their pore spaces, which is gradually released over time. This stored water can contribute to groundwater recharge during dry periods when precipitation is limited. Soils with low water-holding capacity, such as sandy soils, have limited ability to retain water, resulting in less water available for groundwater recharge. Soil properties affect the storage capacity of aquifer systems. The porosity of the soil, which represents the volume of pore space available for water storage, determines the amount of groundwater that can be stored within the aquifer. Soils with high porosity, such as sandy or gravelly soils, can store more water, contributing to a higher aquifer storage capacity. In contrast, soils with low porosity, such as clayey soils, have limited storage capacity and may have lower groundwater storage potential.

Silt particles have smaller sizes compared to sand or gravel, resulting in smaller pore spaces between particles. A finer texture of soil can reduce the rate at which water infiltrates into the soil. Silt soils tend to have lower permeability, limiting the movement of water through the soil profile. As a result, groundwater recharge rates in areas with high silt content soils may be slower compared to soils with higher sand content.

2.12 Geology

Groundwater quality, presence, and transport are significantly influenced by geological formations. (Anbarasu et al., 2019) Geology plays a crucial role in governing the occurrence, movement, and storage of groundwater. In the case of igneous and metamorphic rocks, lithology emerges as a significant factor influencing groundwater availability. The type of rock directly influences variables such as depth and degree of weathering, porosity, permeability, and the formation of water-bearing discontinuities within the bedrock. Additionally, geologic structure impacts the distribution, characteristics, and productivity of water-bearing zones by providing the framework for weathering and potential stress-relief processes. (Achu et al., 2020) The geology of a particular area plays a vital role in the assessment of groundwater resources, the prediction of groundwater behavior, and the effective management of water supplies. Hydrogeological investigations, geological mapping, and monitoring programs are essential for evaluating the impact of geology on groundwater dynamics, availability, and quality in a given region. Different geological formations can serve as aquifers, which are underground layers of rock, sediment, or soil that hold and transmit water. The properties of the aquifer, such as its porosity, permeability, and storage capacity, are determined by the geology of the area. For example, sedimentary rocks like sandstone or limestone can form highly productive aquifers, while impermeable rocks like shale or granite may act as confining layers or aquitards, limiting groundwater movement.

2.13 Land use and land cover

The area covered by forest regulates continuous water flow and infiltrates water on a regular basis, whereas cultivated land influences slope stability due to saturation of covered soil. (Ghorbani Nejad et al., 2017) Land cover changes can alter the surface water balance, affecting the recharge and discharge of groundwater. When natural land cover, such as forests or grasslands, is converted to impervious surfaces like buildings, roads, or pavement, the infiltration of rainfall decreases. As a result, less water is able to percolate into the ground and recharge the underlying aquifer. Conversely, land use practices that promote infiltration, such as green spaces or agricultural practices that reduce soil compaction, can enhance groundwater recharge. Changes in land use such as deforestation and urbanization can lead to increased runoff and erosion. When vegetation is removed or land is extensively paved, the land's ability to absorb and retain water deteriorates. This increased runoff can result in higher peak flows in rivers and streams, lowering the available water for groundwater recharge. Erosion can also lead to the loss of topsoil, which may impact the quality of infiltrating water and increase sedimentation in aquifers.

Land use changes can affect the availability of space for groundwater storage within aquifers. Urbanization and infrastructure development often involve the excavation and compaction of soils, reducing the porosity and storage capacity of the subsurface. Additionally, land cover changes can impact the vegetation and soil characteristics that contribute to natural recharge processes. Proper land use planning that preserves natural recharge areas and allows for the infiltration of water can help maintain groundwater availability. LULC changes can interact with climate change and exacerbate its impacts on groundwater. Altered land cover such as deforestation or changes in vegetation patterns can affect evapotranspiration rates, altering the overall water balance in an area. Changes in temperature and precipitation patterns associated with climate change can further impact the recharge and availability of groundwater.

2.14 Rainfall

The amount of rainfall has a direct impact on the amount of recharge. (Saravanan et al., 2020) Understanding the link between rainfall and groundwater is essential for effective water resource management. Monitoring rainfall patterns, estimating recharge rates, and assessing the vulnerability of aquifers to changes in precipitation are important steps in sustainable groundwater management. Integrated water resource planning and conservation measures can help optimize the use of groundwater in response to rainfall variations and ensure its long-term availability. Rainfall is a vital source of recharge for groundwater. When rain falls on the land surface, it can percolate down through the unsaturated zone and penetrate into the soil, eventually reaching the water table and replenishing groundwater. The rate and amount of infiltration are affected by variables such as soil type, land cover, slope, and previous moisture conditions. When rain falls on the land surface, it can percolate down through the unsaturated zone and penetrate into the soil, eventually reaching the water table and replenishing groundwater. The rate and amount of infiltration are affected by variables such as soil type, land cover, slope, and previous moisture conditions. Adequate and consistent rainfall is necessary to sustain groundwater resources and maintain water levels in aquifers. Rainfall patterns often exhibit seasonal variability, with wet and dry seasons. During periods of higher rainfall, such as monsoons or rainy seasons, the recharge of groundwater can be more significant. Increased precipitation enhances the infiltration and replenishment of aquifers. Conversely, extended dry periods or droughts can lead to reduced groundwater recharge, depleting water levels in aquifers.

Climate change can alter rainfall patterns, intensify extreme weather events, and impact groundwater resources. Changes in precipitation patterns, including shifts in timing, intensity, and frequency of rainfall, can influence groundwater recharge rates and availability. Increased variability, more frequent droughts, or intense rainfall events associated with climate change can pose challenges to groundwater management and sustainability.

2.15 Ground Water Potential Zones (GWPZS) using AHP

Groundwater zones vary greatly in space and time. Hydrological elements gives a great impact on the availability if ground water. (Alikhanov et al., 2021) Groundwater zones vary greatly in space and time. Hydrological elements such as land use and land cover, soil types, geology and geomorphology, precipitation and evaporation, water bodies, irrigation, and so on are examples of these factors. (Saravanan et al., 2020) The AHP strategy is regarded as an accurate method for identifying prospective groundwater recharge locations. (S. K. Singh & Noori, 2022a) In this system, each variable is ranked from one to five for equal and great importance. The paired comparison is used to examine all of the qualities. (S. K. Singh & Noori, 2022a) Different researchers consider different thematic layer for their analysis as shown in table 2.1. For this study seven different thematic layers are considered i.e Slope, Drainage Density, lineament density, land use and land cover (LULC), soil type, rainfall, geology. For better understanding of the geology of Delhi geomorphology of Delhi is also considered. Table 2.1 shows that generally researchers consider seven to twelve thematic layer for their analysis and they uses the method for analysis is simple weighted overlay, AHP, MCDM all these method are widely used for determining ground water potential zones in their study area.

S.No.	Location	Parameters	Thematic parameters	Reference
1	Gautham Buddh Nagar, Uttar Pradesh, India	6	Drainage Density, LULC, Soil, Slope, Geomorphology, Geology	(Banerjee et al., 2020)
2	Karha river basin, Maharashtra, India	10	Geomorphology, geology, LULC, drainage density, curvature, slope, soil, lineament density, rainfall, topographical wetness index	(Verma & Patel, 2021a)
3	Sonipat district, Haryana, India	7	Landuse and landcover (LULC), geology, water table depth, geomorphology, lineament density, drainage density, slope	(Sheikh & Rina, 2017)
4	Bankura district, West Bengal, India,	6	Geology, lineament, soil, slope, LULC, drainage density	(Mandal et al., 2021)
5	Rihand River Basin, India	9	Lineament density, geomorphology, soil, rainfall, drainage density, relief, landuse and landcover, lithology, slope	(Verma & Patel, 2021b)
6	Komenda-Edina-Eguafo-Abrem, Ghana, China	8	Lineament density, topographic wetness index, drainage density, land use/land cover, slope, normalized difference vegetation index (NDVI), geology, and soil	(Danso & Ma, 2023)
7	Theni district, Tamil Nadu	7	Lithology, slope, land-use, lineament, drainage, soil, and rainfall	(Magesh et al., 2012)
8	Arkavathi sub-watershed, Karnataka	7	Geomorphology, geology, soil, drainage density, lineament density, slope, land use, and rainfall variation	(Saravanan et al., 2021)
9	Perambalur, southern India	7	Geology, soil, drainage density, slope, lineament density, geomorphology, and land use	(Anbarasu et al., 2019)
10	Gundihalla watershed, Chitradurga District, Karnataka	9	Geomorphology, land use, soil, drainage density, lineament density, rainfall, lithology, and slope	(Saravanan et al., 2020)
11	Vattamalaikarai Basin, South India	10	Soil, drainage density, lineament density, geology, slope, LULC, geomorphology, topographic position index, rainfall and groundwater level	(Arya et al., 2020)

12	Birbhum district in eastern India	12	Geology, geomorphology, Land Use and Land Cover fault and drainage density, rainfall, soil type, slope, roughness, topographic wetness index, lineament density, topographic position index and curvature	(Mukherjee & Singh, 2020)
13	Dumka district, Jharkhand, India	8	Lithology, geomorphology, lineament density, slope, soil, rainfall, drainage density, and LULC	(Murmu et al., 2019)
14	Manimala River Basin, Kerala, India	8	lithology, geomorphology, land use/land cover, the density of lineaments and stream network, slope, and soil texture	(Ghorbani Nejad et al., 2017)
15	Atria–Sib river basin, Bangladesh	7	Geomorphology, drainage density, rainfall, lithology, lineament density, slope and land use/ land cover	(Jahan et al., 2019)
16	Durg district, Chhattisgarh	7	geology, slope, land-use, lineament, drainage, soil, and rainfall	(T. Kumar et al., 2014)
17	Deoria watershed, Hazaribagh district, Jharkhand	8	Lithology, geomorphology, soil, lineament density, slope, drainage density, land use and land cover, and groundwater depth	(Kumari & Singh, 2021)
18	Delhi, India	10	Geomorphology, geology, soil, topographic elevation (digital elevation model), land use/land cover, drainage density, lineament density, proximity of surface water bodies, surface temperature and post-monsoon groundwater depth,	(Mallick et al., 2015)
19	Mula River, pune	10	Land Use/Land Cover (LULC), Digital Elevation Model (DEM), hillshade, soil texture, slope, groundwater depth, geomorphology, Normalized Difference Vegetation Index (NDVI), and flow direction and accumulation	(Pande et al., 2021)
20	Ganga Alluvial Plain, Hooghly, India	12	Land use, land cover, soil type, geomorphology, geology, elevation, slope, rainfall, normalized difference vegetation index, drainage density, recharge rate, groundwater depth	(Patra et al., 2018)

Table 2.1 Literature review of identification of the Groundwater Potential Zones using AHP technique.

CHAPTER - 3

MATERIALS AND METHOD

3.1 Study Area

Delhi has a total size of 1483 square kilometres. Its latitude ranges from 28o24'15" to 28o53'00" north and its longitude ranges from 76o50'24" to 77o20'30" east. (Roy et al., 2020) 794 mm of rain falls annually in the Delhi. From the west to the east, the rainfall increases. (CGWB) Delhi is located in the Indian Subcontinent's Northern Plains. Delhi experiences a variety of climates, from humid subtropical to semi-arid, with long, hot summers and chilly winters. (Raghav & Singh, 2021)

The Delhi-NCR region (Fig. 1) is located in the Indo-Gangetic alluvial plain and has a quartzite ridge (trending N.N.E. to S.S.W.), which serves as a groundwater divide between the western and eastern portions and creates the main watershed. (Datta & Tyagi, 2009) The complicated aquifer geology of Delhi is caused by a variety of geological formations, including quartzite `1and alluvium (Sarma & Singh, 2022)

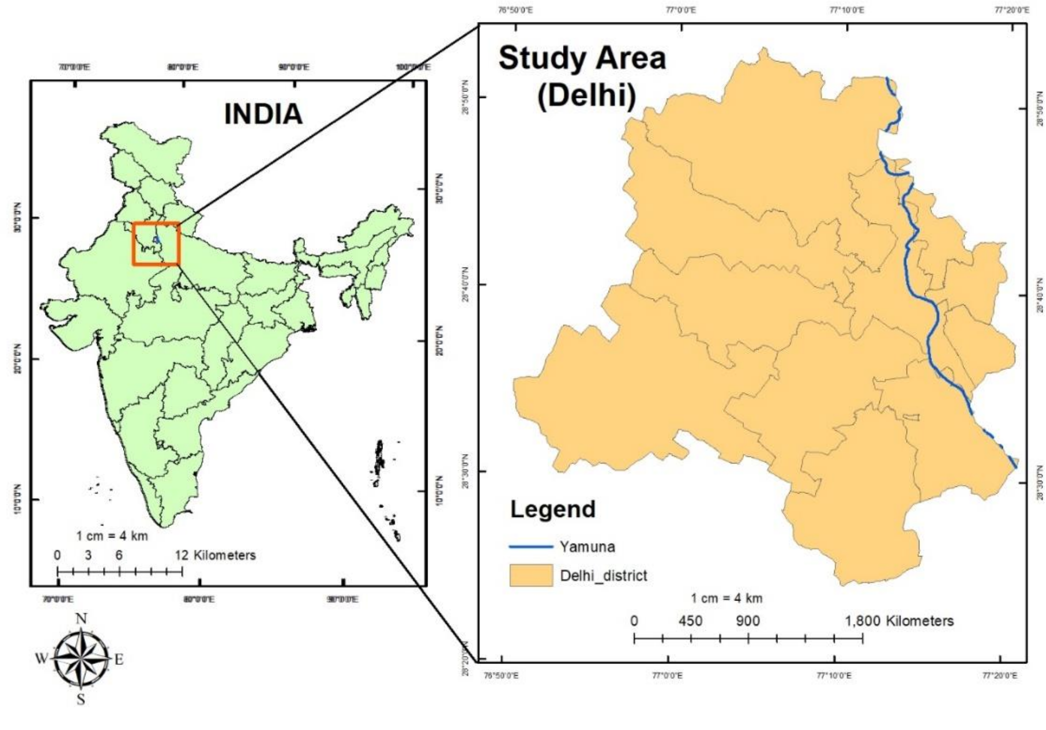


Fig 3.1: Study area

Alluvium deposits from the Middle to Late Pleistocene Age make up the majority of the soil types in the North West District, though in varying amounts.(Sarma & Singh, 2023) Delhi is located on the Yamuna River's banks, which is the Ganges River's biggest tributary. Before entering Delhi at the Wazirabad barrage, the Yamuna's water is comparatively of good quality. The river is extremely contaminated because to the wastewater discharged through various drains between Wazirabad and Okhla barrage.. (Mallick et al., 2015) Over a hundred monitoring stations operated by the CGWB are dispersed across the alluvial and quartzitic region of Delhi. For monitoring sites in the NCT of Delhi, CGWB provided historical data on groundwater levels for the winter (January), pre-monsoon (May), monsoon (August), and post-monsoon (November) seasons.(Sarma & Singh, 2022)

3.2 Data used

Table 3 lists the various data used in the approach for the study.1Slope map, Drainage Density map, and Lineament Density map were created from data consisting of DEM of 30m resolution retrieved from (https://earthexplorer.usgs.gov) is WGS 84, Geo-Tiff format Digital elevation model.

Thematic layer	**Description**	**Source**	**Reference**
Delhi Boundary	Vector data of India Administrative boundaries	Survey of India onlinemaps.surveyofindia.gov.in	(Banerjee et al., 2020), (Verma & Patel, 2021a), (Mandal et al., 2021)
DEM	30m resolution raster data	USGS https://earthexplorer.usgs.gov/	(Verma & Patel, 2021a), (Mandal et al., 2021), (Jahan et al., 2019)
LULC	10m resolution raster data	Esri Landuse 2021 https://livingatlas.arcgis.com/	(Al-Djazouli et al., 2021)
Soil	Re-categorized to raster data in to the 30-m resolution.	FAO GeoNetwork https://www.fao.org/	(Verma & Patel, 2021b), (Alikhanov et al., 2021), (Kumari & Singh, 2021)
Rainfall	The rainfall measurements for 2020	Climatic Research Unit (CRU) https://crudata.uea.ac.uk/	(Alikhanov et al., 2021)
Geology	Downloaded and listed in to the 30-m raster data resolution.	Bhukosh-Geological Survey of India https://bhukosh.gsi.gov.in/	(Verma & Patel, 2021a), (Mandal et al., 2021)
Geomorphology	Downloaded and listed in to the 30-m raster data resolution.	Bhukosh-Geological Survey of India https://bhukosh.gsi.gov.in/	(Verma & Patel, 2021b), (M. Kumar et al., 2022)
Ground water Depth	Minimum, maximum and average ground water level	India-WRIS https://indiawris.gov.in/wris/#/	(Kumari & Singh, 2021)

Table 3.1: Thematic layer used and their Sources

3.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchical Method (AHP) can assist the decision-maker in setting goals that lead to the right option. In order to choose the best course of action, the AHP takes into account a variety of factors and options. By adding the major eigenvector of the pairwise relationship of the square reciprocal matrix between the two variables, Satty's method calculates the weights of the parameters. The continuous ranking scale of Satty's analytical hierarchical method was utilised to allocate weights for pairwise contrast. The AHP assesses a variety of options, including the optimum decision to be made, along with a set of evaluation parameters. It lessens difficulty a variety of pairwise differentiation decisions. Because it transforms decision makers' inputs into figures, the AHP is analytical.

These were the steps that were taken:

• In the beginning, criteria for the analysis of solar potential were chosen.

• Following the pairwise comparison, weight was assigned. (Banerjee et al., 2020):

-

Parameters	**A1**	**A2**	**A3**
A1	a11=1	a12	a13
A2	a21=1/ x12	a22=1	a23
A3	a31=1/ x13	a32=1/ x23	a33=1

Table 3.2: Pairwise Comparison Matrix

- Take into account the 'n' compared items A1, A2, A3,... A which create a comparison matrix A= aij of order n with the restrictions such that aij= 1/aji where i-j and aij =1 where i=j.
- • A 3x3 pairwise comparison matrix. The inclusion of items from A denotes the significance of i in comparison to j.

Intensity Importance	**Linguistic value**
1	A1 and A2 have exactly equal importance
3	A1 is slightly more important than A2
5	A1 is much more important than A2
7	A1 is highly important than A2
9	A1 is exceptionally more important than A2
Where 2,4,6,8 lying between two adjacent judgements	

Table 3.3: Scales for Pairwise Comparison Matrix with AHP described

• If xij=1, then i and j are both equally significant.

• If xij>1, i will be more powerful than j.

- If xij>1, j will be more dominating than i.

Each column's sum in matrix A was determined using the following formula:

$$S_j = \sum x_{ji} (1<j<n)$$

The weights were then calculated from the pairwise comparison of the parameters as the mean of the normalised values of each row.

Consistency index (CI): The formula for CI is ((λmax-n)/(n-1), where n stands for the size of the matrix and (λmax is the average eigenvalue of the matrix. (Al-Djazouli et al., 2021)

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

Random Index (RI): The order of the matrix affects the average random index.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 3.4: Index of Random Consistency (Satty's AHP, 1980)

Consistency ratio (CR): It is characterised as the consistency index to random index ratio. (Al-Djazouli et al., 2021)

$$CR = CI/RI$$

Only if the CR is less than 0.1 will the pairwise comparison matrix pass the consistency test. The formula shown below is used to compute " λmax":

$$AB = \lambda_{max} * B$$

where B is the matrix of criteria weighting.

Saaty asserts that the comparison matrix is flawlessly consistent if λmax = n. The decision maker must review his choices if the consistency ratio is higher than 0.1. A straightforward technique can be used to determine consistency:

For the mapping of groundwater potential zones in Delhi, India, seven factors were used in total. These parameters are crucial for the distribution of groundwater. Groundwater potential zones were mapped using thematic maps created with the aid of remote sensing and GIS techniques for the research region. All of the theme maps in the GIS environment were spatially organised while maintaining the same resolution and projected coordinate system. Each thematic map was classed in a GIS framework using knowledge-based rankings and weights.

The mapping of groundwater potential zones is done using overlay analysis within the GIS software's Spatial Analyst function. Each relationship is given a weight based on how powerful it is. The methods employed is shown in Fig. 3.2.

Consistency ratio (C.R.) = 0.074 < 0.1

Therefore, the current study takes this tactic into account. The representative weights of a given factor in the potential zone are the sum weights from each component.. Factors with higher weight values have a greater impact on groundwater potential zones than those with lower weightage. These parameters, along with weights, are assimilated using weighted overlay in ArcGIS. (Saha et al., 2017)

3.4 Method used: Flow chart

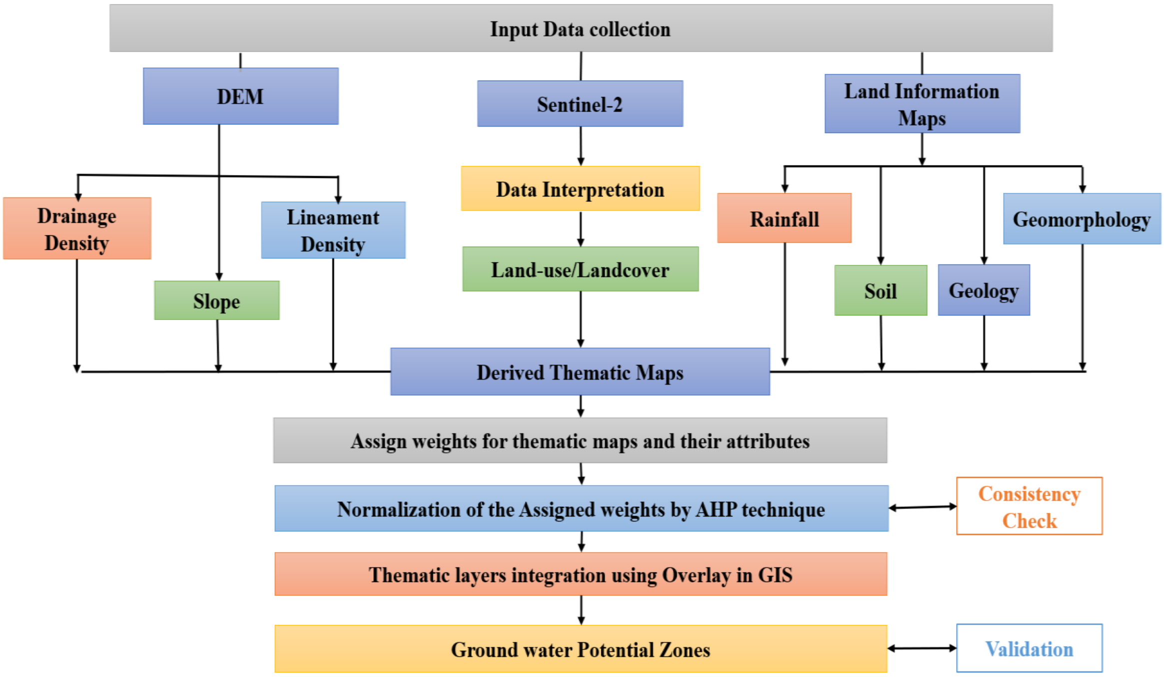


Fig 3.2: Flow chart for ground water potential zone mapping

CHAPTER - 4

RESULTS AND DISCUSSION

4.1 General Observation

Top surface of the saturation zone is known as the ground water table, and it is monitored during water level monitoring. The water level is a representation of the pressure or Piezometric Head at the depth to which limited aquifers are penetrated by wells. With its broad, gently sloping plains dominated by the Yamuna River, low linear ridges, and isolated hillocks, the NCT of Delhi has an established topography. The Yamuna River, the Aravalli Mountain, and the plains between them dominate the physiography of Delhi, which were produced by alluvium deposits from the Recent era.

The Delhi Ridge, sometimes referred to as the SSW-NNE trending Aravalli Ranges, is situated in Delhi's south- central region and extends up to the western bank of the Yamuna River between Okhla in the south and Wazirabad in the north-east. Ecology claims that the Thar desert's physical barrier to the plains, the Aravalli Ridge, slows the wind and dust that originate there. The wooded ridge area of NCT Delhi acts as the city's lungs and contributes to environmental preservation. This natural forest's green belt not only offers the public numerous benefits that are well known, but it also slightly affects temperature.

4.2 Digital Elevation Model (DEM)

DEM is often made using data from remote sensing techniques. It offers a thorough and precise description of the terrain's elevation at diverse geographic areas. In disciplines including geography, geology, cartography, urban planning, and environmental science, DEM data is frequently employed. Aerial photogrammetry, LiDAR (Light Detection and Ranging), satellite photography, and radar interferometry are some of the common methods used to get DEM data. In order to provide a precise and accurate picture of the landscape, these techniques measure the distance between the sensor and the Earth's surface in order to collect elevation information.

Input data used was a USGS DEM model with a 30 m resolution. Study area has maximum elevation of 329 meters and minimum is 171 meters. Most of area is found below elevation 240 meters. Details of elevation are shown in Figure 4.1

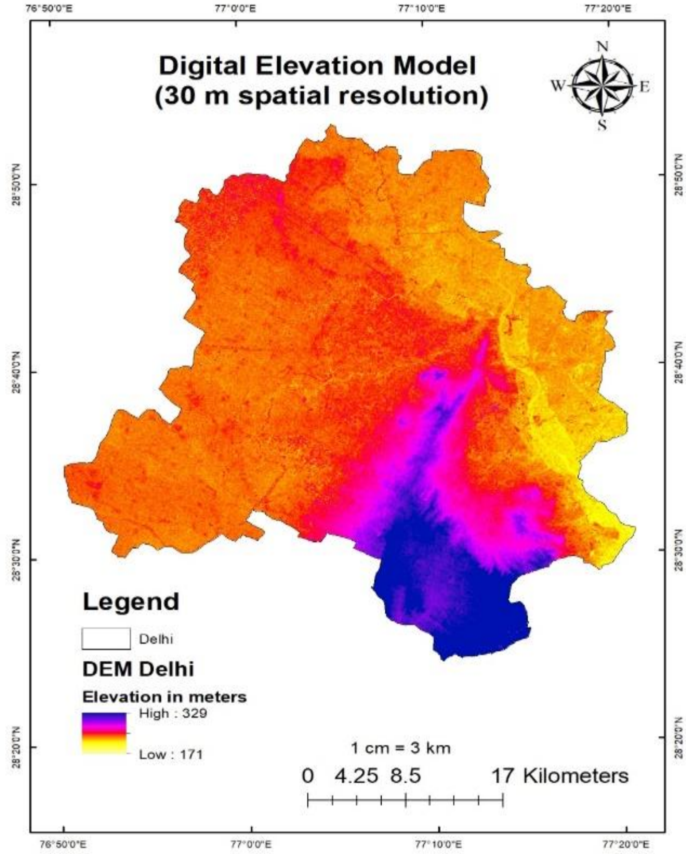


Fig 4.1: Digital Elevation Model (DEM) map of Delhi, India

4.3 Drainage Density

The number of stream lines per square metre is the drainage density. A geomorphological measure called drainage density counts the number of drainage networks or stream channels present in a particular area. It is generally expressed in kilometres per square kilometre (km/km^2) or metres per hectare (m/ha) and it represents total length of all streams per unit area.

Total length of stream channels within a given region is measured, and the size of that region is divided by that total length to determine drainage density. Depending on the scope of the investigation, the region can range in size from small catchments to enormous river basins. A landscape's hydrological system's characteristics can be gleaned from its drainage density. Climate, geology, slope, vegetation cover, and land usage all have an impact on it. From the DEM, the Drainage Density for the current study has been defined. Drainage density is defined using arc hydro tools within a GIS system. As infiltration rises, the greater the drainage density there, the more groundwater is available. Drainage density map of Delhi was divided into five subclasses. 0-0.46 km/km^2, 0.47-0.93 km/km^2, 0.94-1.39 km/km^2, 1.4-1.86 km/km^2, 1.87-2.32 km/km^2 Figure 4.2.

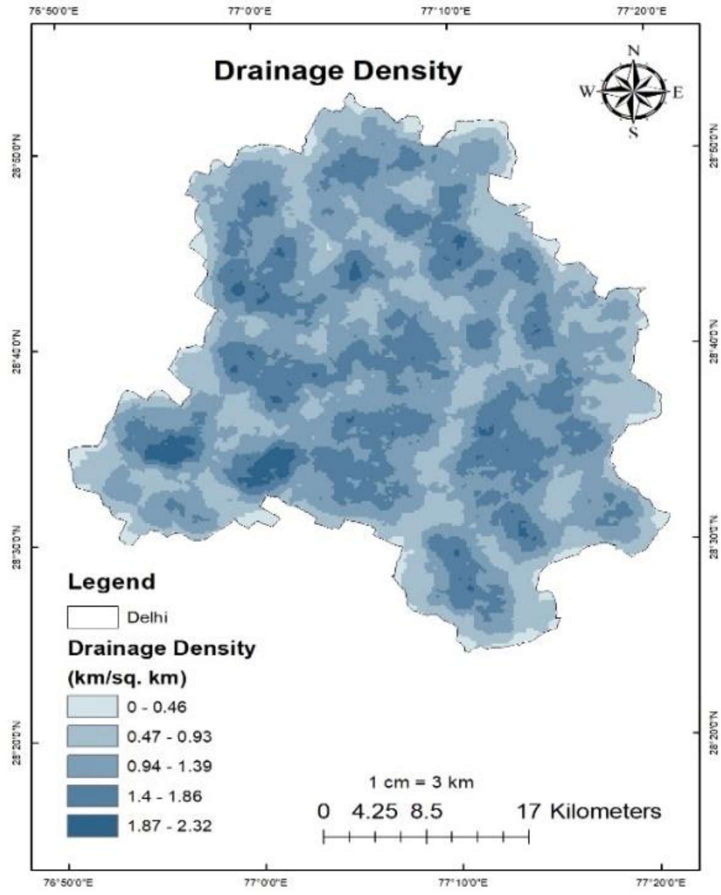


Fig 4.2: Drainage Density map of Delhi, India

4.4 Lineament Density

Lineament density is measurement of the number or frequency of lineaments in a given area. Lineaments are recognised geologic or geomorphic structures on the Earth's surface. They might be dykes, joints, faults, fractures, or other linear features. The density of lineaments is derived by dividing the total length of lineaments in a given area by the area itself. The generated graph shows the length of lineaments per unit area in kilometres per square kilometre (km/km^2) or metres per hectare (m/ha). Linear density analysis is extensively used in geology, remote sensing, and geomorphology to characterise the geographical distribution and significance of linear features.

Lineaments are the external expression of linear or curvilinear characteristics on the earth's surface that are align expressions of an underlying lithological structure such as a fault, fractures, and cleavages, as observed by satellite images. (Verma & Patel, 2021a) Around 75 lineaments from the basin region were mapped in total. In the study area, prominently lineaments were identified, i.e., towards Yamuna. Density of lineaments in Delhi region has been classified into five groups: 0-0.5 km^2/km^2, 0.51-0.99 km^2/km^2, 1–1.49 km^2/km^2, and 1.5–

1.98 km^2/km^2in Fig. 4.3. Groundwater development has a strong potential in three places with extremely high to high lineament density.

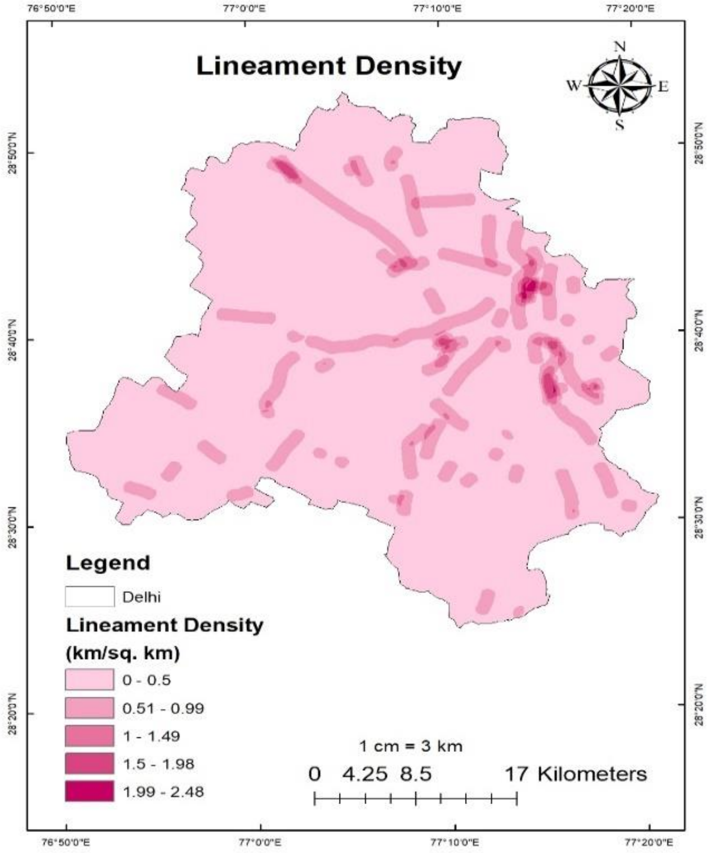


Fig 4.3: Lineament Density of Delhi, India

4.5 Slope

The slope map in Fig. 4.4, which was created using a USGS DEM with a 30m resolution in a GIS environment, will be used to analyse the study area's terrain steepness. The slope tool determines the maximum rate of value change from that cell to its neighbours. Essentially, the steepest downhill fall from the cell is determined by the greatest elevation change across the distance between the cell and its neighbours.

The slope map for the research region is depicted in Figure 4.4. Nearly Level (0-1.9), Strong Sloping (1.91-3.63), Moderate Slope (3.64-6.05), Slight Strong Slope (6.06-10.55), and Strong Slope (10.56-44.08) are the four categories of slope classification in angles. In comparison to a low slope zone, a high slope region produces greater runoff and less infiltration, leading to poorer groundwater contribution. The majority of the study area is located on terrain that is fairly level and gently sloping.

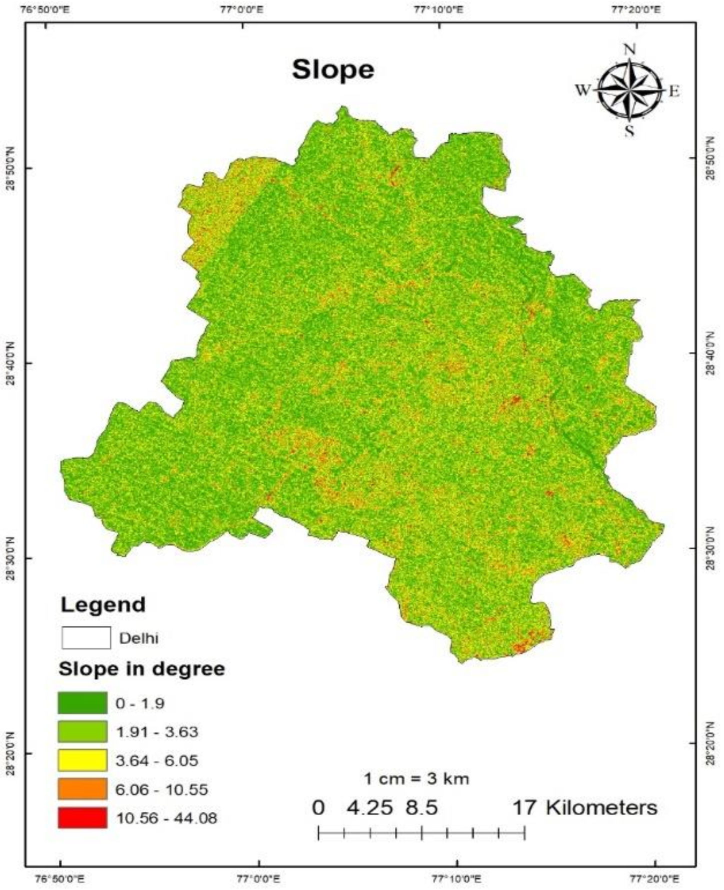


Fig 4.4: Slope map of Delhi, India

4.6 Land use and Land Cover (LULC)

The thematic map of land use and land cover was outlined, assessed, and reclassified using Esri Land use and land cover data. The land use/land cover pattern in Delhi was categorised into seven different categories of Water body/river(1.4%), Vegetation (5.28%), Waterbody/Pond (0.04%), Cropland (30.13%), Settlement (58.14%), Build-Up land (0.28%), Bareland (4.7%) Fig 4.5.

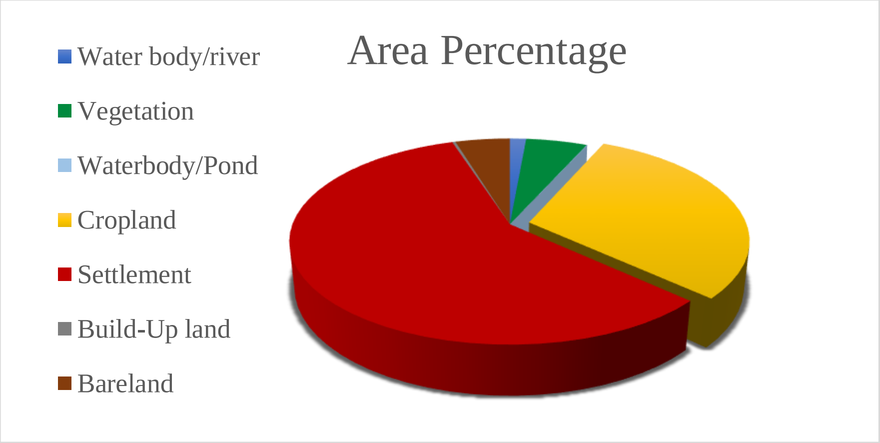


Fig. 4.5 Area allocation among various land use and land cover classes in Delhi, India

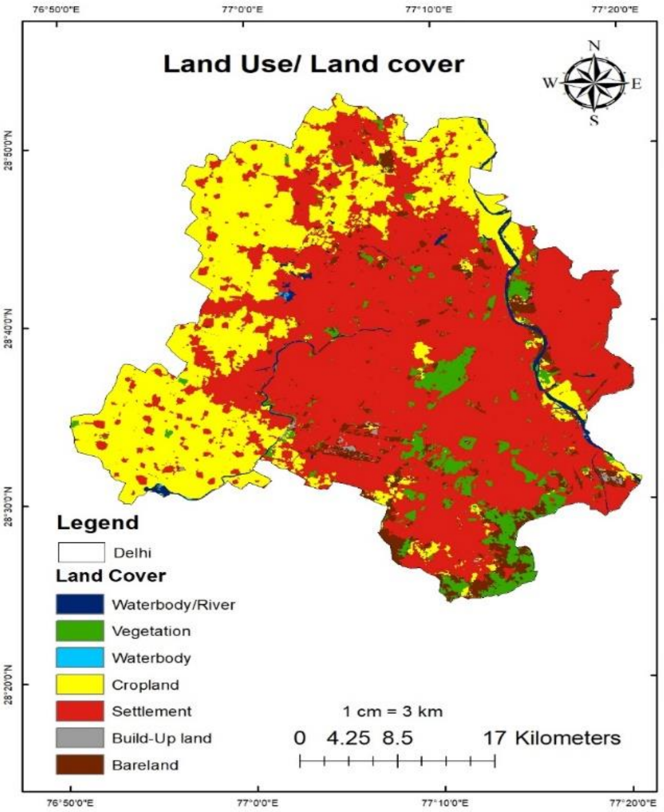


Fig 4.6: Land use (LULC) map of Delhi, India

4.7 Soil

The soil's permeability and capacity to hold water determine the infiltration rate. According to data provided by the FAO in Fig. 4.6, the soil map of Delhi shows loamy soil texture. Soil classification as per FAO code (SNUM) is Dark pink soil class indicate 3797 SNUM, Orange (3910), Light pink (3874) and Blue (3878). Composition of these soils classes given in the below table. The soil map's relative weights are listed in Table 4.6.

Soil Texture	SNUM (FAO code)	Sand %	Clay %	Silt %	Permeability
Loamy Soil	3797	44	20	36	4.35
Loamy Soil	3910	43	21	36	3.99
Loamy Soil	3874	30	26	44	4.42
Loamy Soil	3878	44	26	30	3.55

Table 4.1: SWAT data (https://www.iirs.gov.in/)

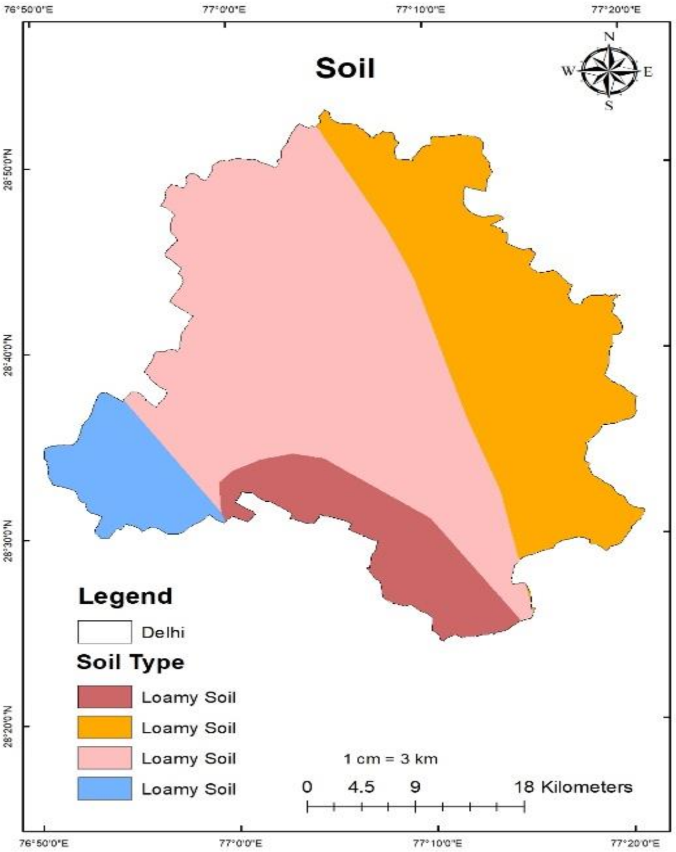


Fig 4.7: Soil cover map of Delhi, India

4.8 Rainfall

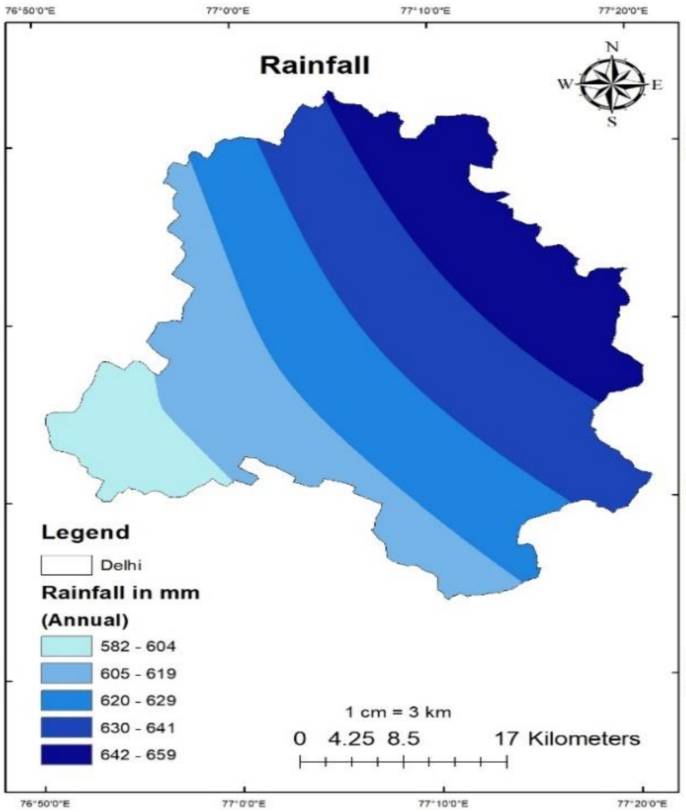


Fig 4.8: Rainfall map of Delhi, India

Rainfall is an important consideration for calculating groundwater potential zones. Higher rainfall normally causes more groundwater to be recharged, whilst lesser rainfall may cause less recharge. Rainfall data is taken from CRU as mentioned in table 3.1 for 2020 year and Kriging is used to interpolate the data and final map shows that rainfall increases from west to east. Rainfall map is divided into five subclasses from 582 mm to 659mm for the year 2020.

4.9 Geology

Delhi geological map was collected Bhuvan portal and was divided into the two categories Alluvium and Channel Delhi Super Group. Older alluvium plain(s) and younger alluvium plain(s) are indicated by Delhi Super Group. Alluvium plain covers the majority of the land (Fig. 4.8). Alluvium is loose unconsolidated sediments deposited by flowing water such as sand, gravel, silt, and clay, generally in river valleys or floodplains. Alluvium is loose, unconsolidated sediments deposited by flowing water such as sand, gravel, silt, and clay, generally in river valleys or floodplains. Alluvial deposits can store significant amounts of water within their pore spaces, contributing to groundwater storage. The porosity of alluvial sediments, which represents the volume of pore space available for water storage, varies depending on the sediment composition.

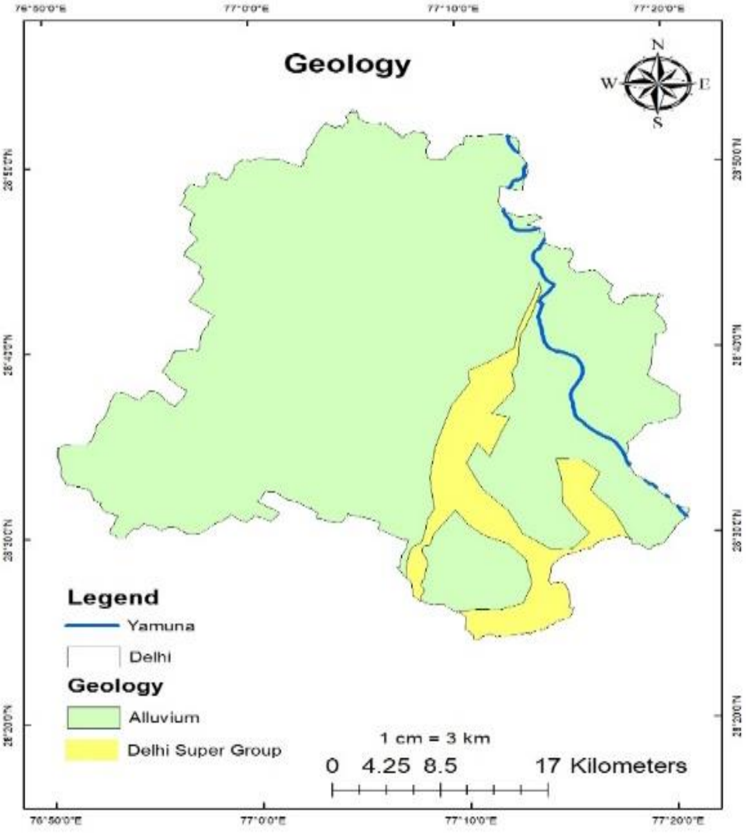


Fig 4.9: Geology map of Delhi, India

Coarser sediments have greater porosity and storage capacity whereas finer sediments have less porosity but can still hold some groundwater. Some part of south Delhi is covered with Quartzite Fig 4.8. Quartzite is a metamorphic rock composed mainly of quartz grains that have been recrystallized under high pressure and temperature. Quartzite can serve as a potential aquifer, i.e., it has the capacity to transfer and store groundwater. The interconnected pore spaces within the rock allow for the storage of water. However, the porosity of quartzite is generally low compared to other aquifer materials like sand or gravel, which may result in a lower storage capacity

Alluvium	Newer Alluvium	Unconsolidated, inter-bedded lenses of sand, silt gravel and clay confined to narrow flood plains of Yamuna River and Aeolian deposit of South Delhi.
	Older Alluvium	Unconsolidated thickness varies upto 300m. Interbedded, inter-fingering deposits of sand, clay and kankar, poor to moderately sorted.
Delhi Super Group	Alwar Quartzite	Well stratified, thick bedded, brown to buff colour, hard and compact, intruded locally by pegmatite and quartz veins interbedded with mica schist.

Table 4.2: Generalized Stratigraphic Units of NCT Delhi (CGWB)

4.10 Geomorphology

In addition to analysing earth formations, geomorphology aims to reflect inherited processes that will affect future freshwater regions as well as structural qualitiesA geomorphological map of Delhi was constructed and categorised into fourteen qualities using information from the Bhuvan website. Rivers, ponds, and other unnamed waterbodies, as well as pediment pediplain complex, flood plain, and dissected structural hills and valleys, are examples of such features. An aeolian plain refers to a flat or gently sloping landform that is formed by the deposition of sediments carried and deposited by wind.

The sedimentary deposits that form aeolian plains often consist of well-sorted, loose, and permeable materials such as sand. These sediments typically have high porosity and interconnected pore spaces, allowing for significant groundwater storage and transmission. Aeolian plains can therefore serve as potential aquifers with good permeability, facilitating the movement of water through the sediments. Aeolian plains are often characterized by relatively low surface slopes and sparse vegetation, which can enhance the infiltration of precipitation and recharge of groundwater. The permeable sediments in aeolian plains can promote rapid infiltration of water, allowing it to percolate through the soil and recharge the underlying aquifer. The open and porous nature of the sediments facilitates the vertical movement of water, contributing to groundwater recharge processes.

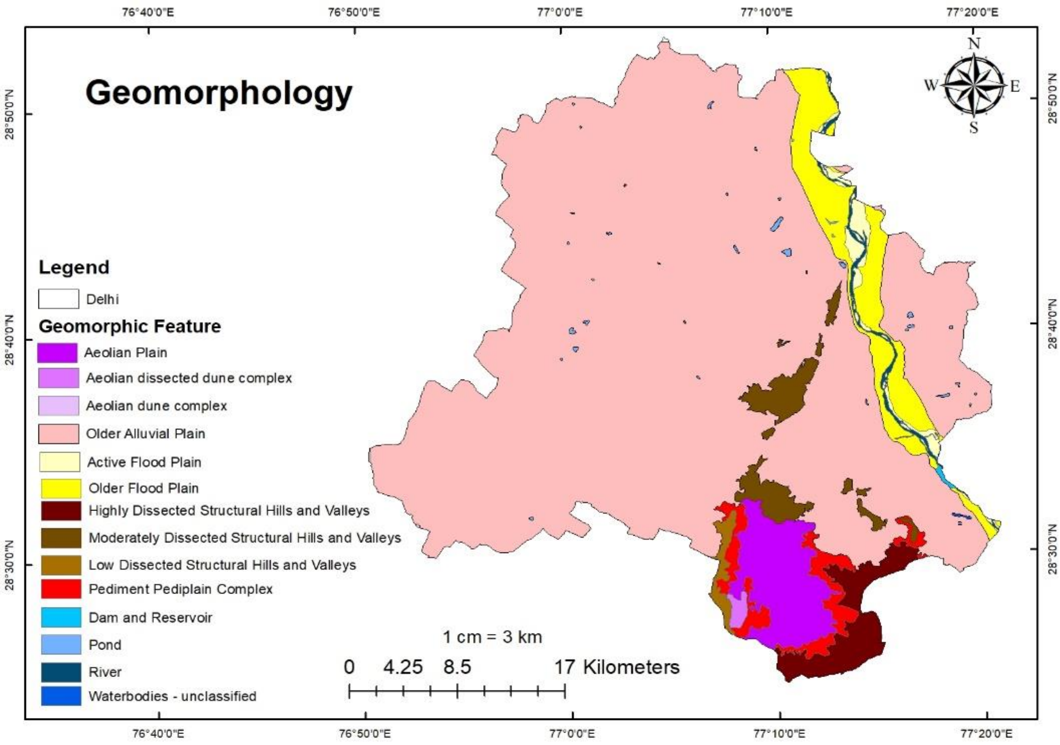


Fig 4.10: Geomorphology map of Delhi, India

Aeolian plains can provide substantial storage capacity for groundwater because of high permeability or porosity due to deposits of collected sediments. The sediments act as reservoirs, storing significant volumes of water within the pore spaces. This stored groundwater can be accessed through wells or natural springs, providing a reliable water source for human and ecological needs. A pediment-pediplain complex refers to a landscape formed by the erosion and deposition processes that shape the interaction between a pediment (a gently sloping bedrock surface) and a pediplain (a nearly flat erosional surface).

The gently sloping pediments within the complex can contribute to groundwater recharge. Precipitation falling on the pediment surface can infiltrate the soil and percolate into the underlying aquifer. The permeability of the soils and sediments atop the pediment, as well as the slope gradient, can influence the pace of recharge. Water that infiltrates the pediment can contribute to replenishing the groundwater system. The pediplain, being a nearly flat erosional surface, may have limited storage capacity for groundwater compared to other landforms.

However, the presence of sedimentary deposits, such as alluvial fans or colluvial materials, on the pediplain can provide additional storage potential. These sediments can act as aquifer materials, storing and transmitting groundwater. The extent and thickness of these deposits determine the storage capacity of the pediplain complex.

4.11 AHP Calculations

Parameter	Rainfall	Geology	Slope	Drainage Density	LULC	Lineament Density	Soil type
Rainfall	1	1	3	1	3	1	3
Geology	1.0000	1	3	1	1	1	3
Slope	0.3333	0.3333	1	1	3	1	3
Drainage Density	1	1.0000	1	1	3	1	3
LULC	0.333	1	0.3333	0.3333	1	1	3
Lineament Density	1	1	1	1	1	1	3
Soil type	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	1

Table 4.3: Matrix of pairwise comparisons for all thematic layers used

Parameter	Rainfall	Geology	Slope	Drainage Density	LULC	Lineament Density	Soil type	**Criteria weight**
Rainfall	0.2000	0.1765	0.3103	0.1765	0.2432	0.1579	0.1579	0.2032
Geology	0.2000	0.1765	0.3103	0.1765	0.0811	0.1579	0.1579	0.1800
Slope	0.0667	0.0588	0.1034	0.1765	0.2432	0.1579	0.1579	0.1378
Drainage Density	0.2000	0.1765	0.1034	0.1765	0.2432	0.1579	0.1579	0.1736
LULC	0.0667	0.1765	0.0345	0.0588	0.0811	0.1579	0.1579	0.1048
Lineament Density	0.2000	0.1765	0.1034	0.1765	0.0811	0.1579	0.1579	0.1505
Soil	0.0667	0.0588	0.0345	0.0588	0.0270	0.0526	0.0526	0.0502

Table 4.4: Thematic layer comparison matrix and criterion weightings

	Rainfall	Geology	Slope	Drainage Density	LULC	Lineament Density	Soil type	**Weighted sum**	**Ratio**
Rainfall	0.2032	0.1800	0.4133	0.1736	0.3143	0.1505	0.1505	1.5854	7.80253
Geology	0.2032	0.1800	0.4133	0.1736	0.1048	0.1505	0.1505	1.3759	7.642746
Slope	0.0677	0.0600	0.1378	0.1736	0.3143	0.1505	0.1505	1.0544	7.652597
Drainage Density	0.2032	0.1800	0.1378	0.1736	0.3143	0.1505	0.1505	1.3098	7.543718
LULC	0.0677	0.1800	0.0459	0.0579	0.1048	0.1505	0.1505	0.7572	7.228442
Lineament Density	0.2032	0.1800	0.1378	0.1736	0.1048	0.1505	0.1505	1.1003	7.312699
Soil	0.0677	0.0600	0.0459	0.0579	0.0349	0.0502	0.0502	0.3668	7.312699

Table 4.5 Calculation table for weighted sum

$\sum$ Ratio = 52.49543

$\lambda(\max) = \sum$ Ratio / n = 52.49543/ 7 = 7.5

Consistency Index (C.I,) = ($\lambda_{(\max)}$ - n) / (n-1) = 0.08322

Consistency Ratio (C.R.) = CI / RI = 0.063 **< 0.10 then OK**

Parameter	Sub class	% Influence/AHP weight	Scale Value/rank
LULC	Water body/river	11	5
	Vegetation		4
	Waterbody/Pond		5
	Cropland		4
	Settlement		3
	Build-Up land		1
	Bareland		1
Lineament Density	0-0.5	5	1
	0.51-0.99		2
	1-1.49		3
	1.5-1.98		4
	1.99-2.48		5
Drainage Density	0-0.46	18	5
	0.47-0.93		4
	0.94-1.39		3
	1.4-1.86		2
	1.87-2.32		1
Soil	Loamy (3797)	5	4
	Loamy (3810)		3
	Loamy (3874)		2
	Loamy (3878)		1
Slope	0-1.9	13	5
	1.91-3.63		4
	3.64-6.05		3
	6.06-10.55		2
	10.56-44.08		1
Geology	Alluvium	18	5
	Delhi Super Group		1
Rainfall	582-604	20	1
	605-619		2
	620-629		3
	630-641		4
	642-659		5

Table 4.6 Weightage assigned to subclasses of all thematic layer through Analytical Hierarchy Process.

4.12 Ground Water Potential Zones (GWPZ) using Overlay Analysis

One of the most often utilised methodologies for identifying ground water potential zones is weighted overlay analysis (WOA) using the Analytical Hierarchy Process. Individual thematic maps and their respective classes are assigned appropriate weightages in the WOA technique based on AHP calculations and their proportionate contribution to the result of GWPZ map production. The current study used seven characteristics to analyse the slope (in degrees), geology, rainfall, drainage density, LULC, lineament density, and soil type.

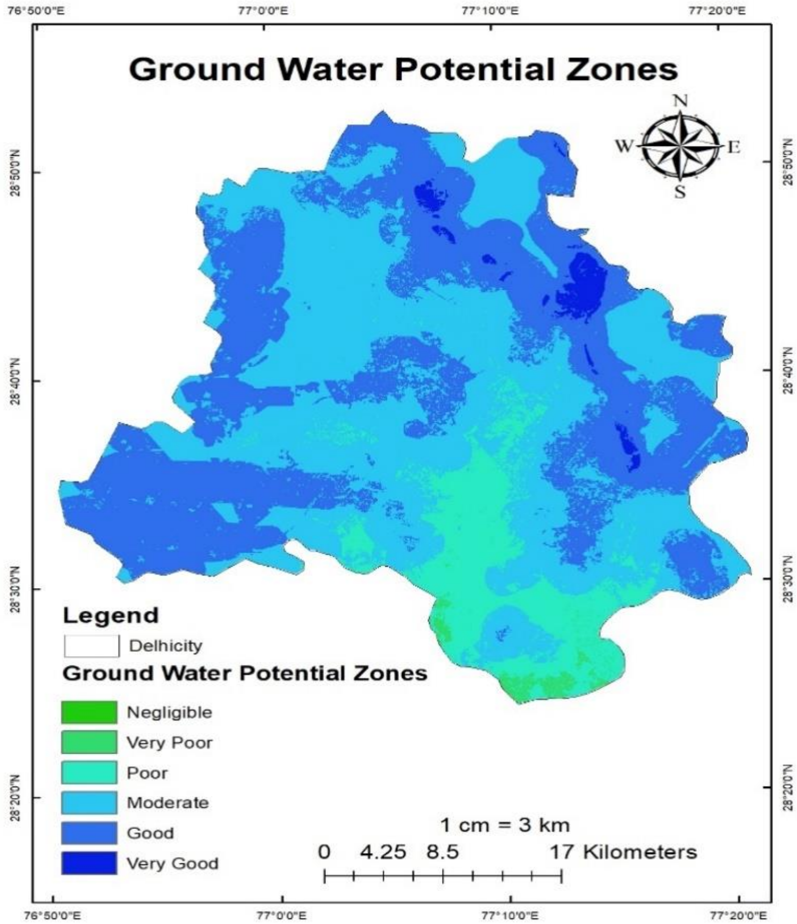


Fig 4.11: Ground Water Potential zones (GWPZs) map of Delhi, India

Output results map have been categorized into six different categories i.e. negligible, very poor, poor, moderate, good and very good on the basis of weighted overlay. Results in final map show the class – Negligible (0.01 km^2), Very poor (12.87 km^2), poor (23.08 km^2), Moderate (174.25 km^2) Good (592.61 km^2), Very Good (695.59 km^2).

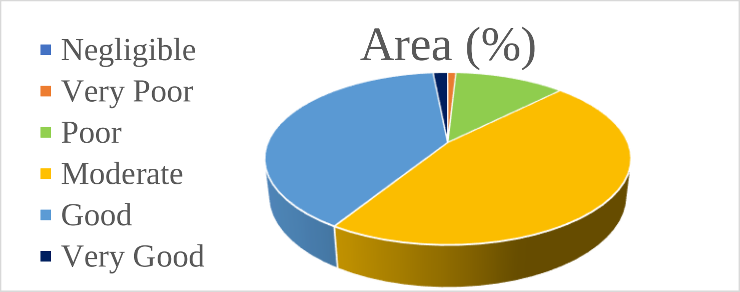


Fig 4.12 Area distribution in GWPZs in Delhi, India

The area distribution in the first category i.e. Negligible shows very less only 8 pixel count in the GWPZs map so we can neglect this class. The majority of the research region falls within the intermediate category whereas areas lying in good ground water potential zones are the second most occurring class in this analysis. Very poor class considered as the least occurring in the GWPZ analysis.

S.No.	Class	Area in km^2	Area Percentage in GWPZ
1	Negligible	0.0072	0.005
2	Very Poor	12.867	0.86
3	Poor	174.245	11.62
4	Moderate	695.58	46.62
5	Good	592.61	39.54
6	Very Good	23.08	1.54

Table 4.7: Classification and area distribution of all GWPZs (after overlay of all thematic layers)

Ground water potential index is calculated using the weights determined using AHP method for every parameter or thematic layer used in analysis. Ground Water Potential Index are as follows:

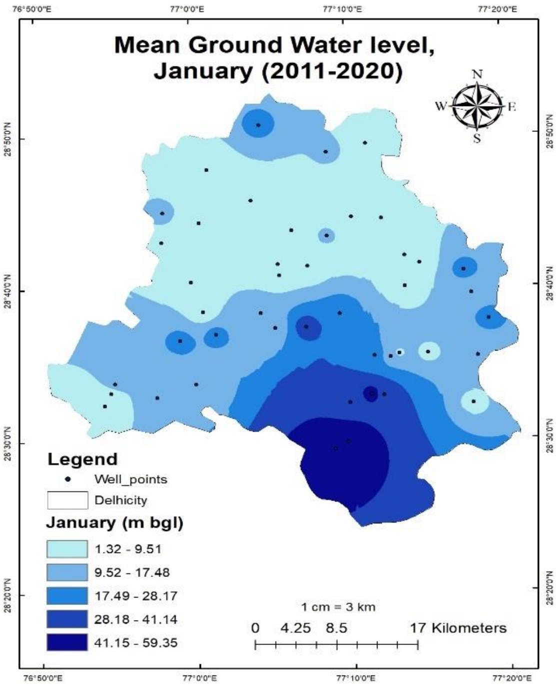
Ground Water Potential Index = Slope$_r$ * Slope$_w$ + Geology$_r$ * Geology$_w$ + Lineament density$_r$ * Lineament density$_w$ + Drainage density$_r$ * Drainage density$_w$ + Rainfall$_r$ * Rainfall$_w$ + Soil$_r$ * Soil$_w$ + Land use⌧land cover$_r$ * Land use⌧land cover$_w$

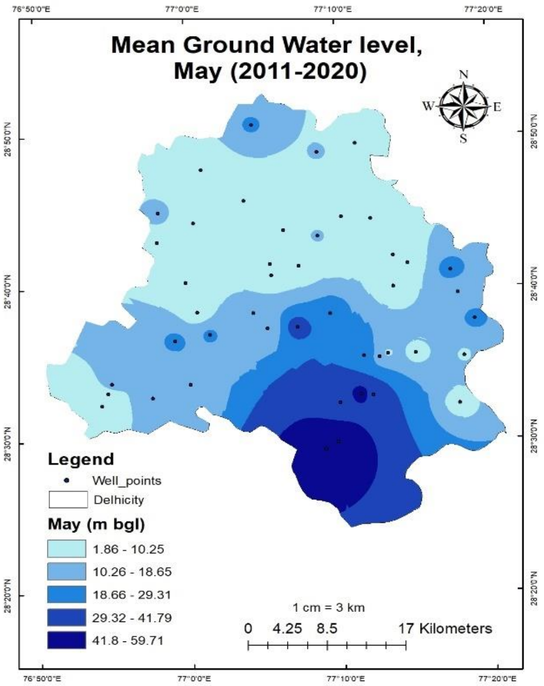
where: **r** refers as rating assigned to sub class of parameter

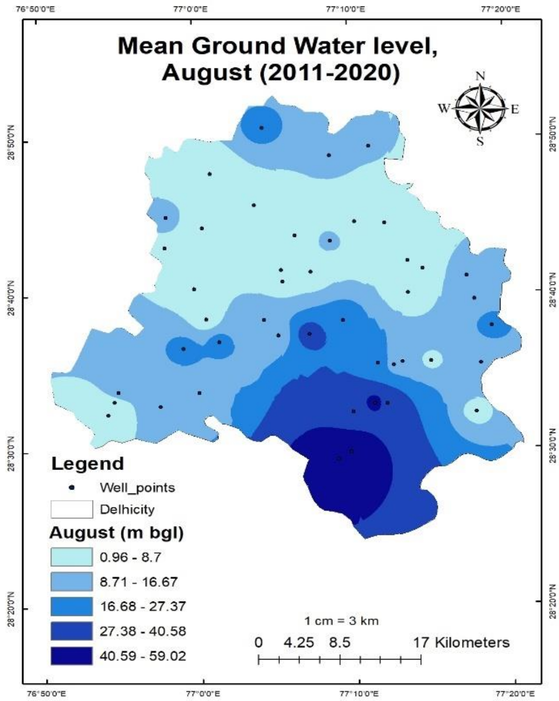
w refers as weight assigned to parameter

4.13 Validation of the Ground Water Potential Zones (GWPZ)

The water level fluctuation (WLF) is used to analyse the status of groundwater because it plays an important role in determining the groundwater level trend in Delhi. In the current study, the GWP zones defined using the proposed methodology are cross-validated using groundwater level data recorded at CGWB Network Hydrograph Stations (NHS) and monitoring wells.







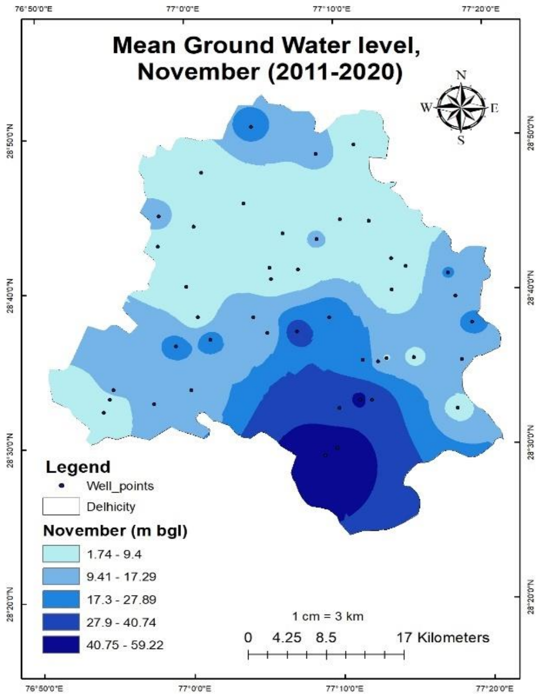


Fig 4.13: Decadal Mean ground water level variation for month of January(a), May(b), August(c) and November(d) for 2010-2020

Analytical Hierarchy Process model validation was calculated and divided into three categories as agreed (0.58), partially agree (0.3), disagree (0.1). Total 46 observation wells located in Delhi region were considered. The ground water level statistics are obtained over decadal period for January (1st-10th), May(20th-30th), August(20th-30th), November(1st-10th). During May i.e pre-monsoon period, declination in groundwater level is observed at many regions as compared to the January i.e recession stage of water level. Whereas during August i.e peak monsoon duration, increase in ground water level is observed. In November i.e. post- monsoon duration, again declination in GWL is observed.

Ground water level data is taken from CGWB Delhi annual report 2021-22. To validate the groundwater potential zone accuracy the GWL (m bgl) data of 46 wells is compared with zone. GWPZs divided into 5 categories ie very poor, poor, moderate, good, very good. Ground water level also divide into 5 categories ie very shallow, shallow, medium, deep and very deep. The stations which are showing similar level of ground water in GWPZ considered as valid and marked as agree in the given table. At some stations data is partially validated as the classification of GWPZ and GWL lies near to similar category marked as partially agree or partially valid. For regions or stations showing two different classifications marked as disagree or invalid. Bhatti, Gazi Pur Crossing, Hauz khas, Mayapuri, Sultanpur stations shows disagreement with the data and considered and invalid regions.

Location	Latitude	Longitude	Ground water level Depth (Decadal variation 2011-2020) (m bgl)				GWPZ	Ground water level	Validation
			May	Aug	Nov	Jan			
Auchandi	28.79594	77.01722	3.23	1.34	2.11	2.5	Moderate	shallow	Partially agree
Bakoli	28.8142	77.14563	10.54	11.96	10.64	10.29	Good	shallow	Agree
Balbir Nagar	28.6837	77.2904	23.34	14.27	18.25	21.28	Moderate	Medium	Agree
Bankner	28.8445	77.0737	19.51	20.9	21.06	20.25	Moderate	Medium	Agree
Baprola	28.6402	77.0104	3.99	2.7	2.87	3.28	Moderate	shallow	Partially agree
Barwala	28.7619	77.0636	5.93	5.49	5.88	5.86	Moderate	shallow	Partially agree
Bhalaswa Lake	28.743	77.171	2.19	1.23	1.78	1.66	Very good	very shallow	Agree
Bhatti	28.5483	77.1898	49.98	47.49	47.25	48.72	Moderate	very deep	Disagree
CBD Shahdara	28.6589	77.2981	10.91	11.02	11.36	11.45	Good	Medium	Partially agree
Chhawla	28.5614	77.002	14.52	13.33	13.31	13.12	Moderate	Medium	Agree
ChillaSaroda	28.5901	77.304	9.75	9.61	9.68	9.63	Good	shallow	Agree
Daryapur Khurd	28.5525	76.91073	4.34	2.74	3.49	4.29	Good	shallow	Agree
Daulatpur	28.5469	76.9598	15.6	14.81	15.03	15.55	Moderate	Medium	Agree
Dwarka S-16	28.6155	77.0241	19.98	20.11	20.52	20.47	Moderate	Medium	Agree
Gadaipur	28.4893	77.15	59.71	59.02	59.22	59.35	Poor	very deep	Partially agree
Gazi Pur Crossing	28.6302	77.3163	21	21.24	20.52	21.03	Good	deep	Disagree
Haiderpur	28.7225	77.1447	11.21	10.92	11.21	11.01	Moderate	Medium	Agree
Hauz Khas	28.5479	77.2031	33.81	33.76	33.5	33.28	Moderate	deep	Disagree
HiranKudna	28.6731	76.9984	3.01	1.68	2.31	2.58	Moderate	shallow	Partially agree
Humayu Tomb	28.5933	77.2507	6.59	6.24	6.91	6.95	Good	shallow	Agree
ISBT (Kasmiri Gate)	28.6666	77.2269	2.74	1.4	2.45	2.75	Moderate	shallow	Partially agree
J N U	28.5398	77.1664	29.99	27.45	28.01	28.71	Poor	deep	Agree
Jagatpur	28.7411	77.2033	2.35	1.01	1.74	1.6	Good	very shallow	Partially agree
Jaitpur Khadar	28.5379	77.298	6.25	5.81	6.48	6.99	Moderate	shallow	Partially agree

Janakpuri	28.6219	77.0878	11.21	10.82	11.03	11.13	Moderate	Medium	Agree
Jaunti	28.7492	76.9688	12.63	12.27	12.47	11.9	Moderate	Medium	Agree
Jhuljhuli	28.5386	76.9038	2.44	0.98	2.17	2.04	Good	shallow	Agree
Kanjhawala	28.7377	77.0075	1.86	0.96	2.27	1.32	Good	very shallow	Partially agree
Lodhi Garden	28.5931	77.2197	8.64	8.18	8.17	7.82	Good	shallow	Agree
Majnu Ka Tila	28.7003	77.2276	9.46	7.81	8.48	8.32	Good	shallow	Agree
Mangolpur	28.6923	77.0916	3.34	2.48	2.89	2.92	Good	shallow	Agree
Mayapuri	28.6231	77.1208	36.59	36.44	36.72	36.47	Good	deep	Disagree
Mundela Kalan	28.6119	76.8950	12.98	13.14	12.03	12.65	Moderate	Medium	Agree
Najafgarh	28.609	76.9855	20.78	21	20.72	20.73	Moderate	Medium	Agree
Nehru Park	28.591	77.1932	27.85	22.46	21.91	22.1	Moderate	deep	Partially agree
Nizampur	28.7167	76.9672	7.59	7.06	7.06	7.35	Good	shallow	Agree
Peeragarhi	28.6798	77.0927	5.67	4.89	4.98	4.97	Good	shallow	Agree
PUSA	28.6377	77.1571	24.1	24.13	24.87	24.22	Very poor	deep	Partially agree
Rohini Sec 11	28.7288	77.1068	6.48	5.95	6.17	5.98	Good	shallow	Agree
Safdarjung tomb	28.5893	77.2106	16.25	14.7	15.97	14.75	Good	Medium	Partially agree
SainikVihar	28.6896	77.1233	2.9	1.58	2.38	2.37	good	shallow	Agree
Sultanpur	28.4967	77.1634	57.33	57.32	57.66	57.94	Moderate	very deep	Disagree
Tiggipur	28.8236	77.188	9.05	9.37	8.74	8.66	Moderate	shallow	Partially agree
Ujwah	28.5627	76.9153	15.24	15.3	14.65	15.07	Moderate	Medium	Agree
Ushmanpur	28.6918	77.2434	4.68	2.7	3.32	4.43	Good	shallow	Agree
Vikashpuri	28.6386	77.0721	14.11	13.76	14.1	13.71	Moderate	Medium	Agree

Table 4.8: Accuracy assessment of GWPZ map with average groundwater water level (2011-2020).

4.14 Fluctuations in ground water level

Utilizing monitoring data for 46 wells, ground water depth data acquired from CGWB annual report 2021-22 for Delhi, the GWPZs map was verified. For this, the pre-monsoon and post-monsoon groundwater deviation findings were evaluated for the span of year 2011-2020 (decadal mean). Increase and declination of water table have been observed on these targeted wells, and it was classified into five different ranges according to fluctuation in ground water level for pre and post monsoon data of year 2011-2020. These ranges are -1.55 to -0.17 which suggests less volatility and leads in continual reduction of ground water in that zone because of placed in largely built up and agricultural area, where ground water is the key source of fulfilling the wants of people and also for the crop growth.

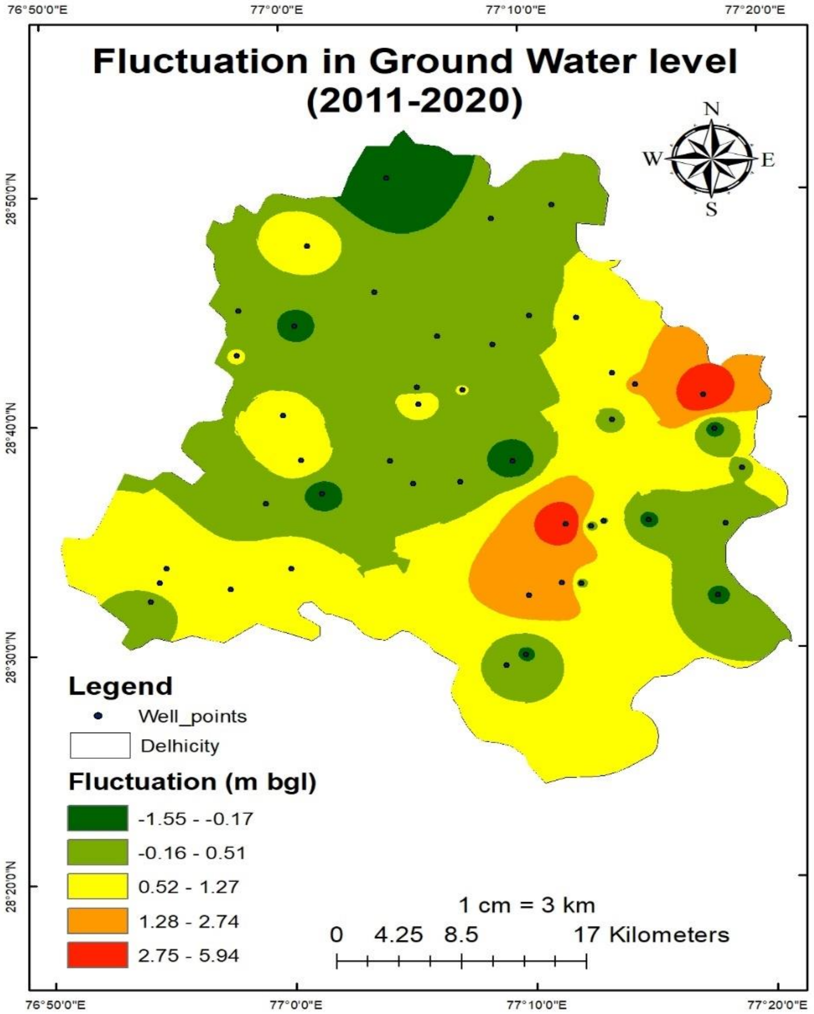


Fig 4.14: Ground water level fluctuation map (Pre-monsoon and post monsoon)

In this range total of 7 wells are found. Then ranges are -0.16 to 0.51, 0.52 to 1.27, 1.28 to 2.74 (3 wells), 2.75 to 5.94(2 wells), all these regions are in the moderate and less fluctuation zones and the ranged value 2.75 to 5.94 indicates the more fluctuation and results in recharging of ground water easily because of located in near about waterbodies and in Ganga -river vicinity and a total of 2 wells are found in this region. This remark therefore faces the reality that the technique developed for demarcating the possible groundwater region holds well and that adequate results have been obtained. Fig. 4.13 that display the spatial map.

4.15 Relevance of GWPZs study

This study on the delineation of Groundwater Potential Zones (GWPZ) is vital for a number of reasons such water resource management, in many locations, groundwater is a crucial source of freshwater for drinking, farming, and industry. Planning and managing water resources effectively depends on having a thorough understanding of the prospective zones where groundwater can be obtained and its volume. The identification of regions with a high likelihood of groundwater availability by GWPZ studies enables authorities to distribute water resources effectively and sustainably. Sustainable developmen is vital to guarantee the sustainable use of underground water resources given the expanding population and water demand. The aquifer properties, recharge areas, and groundwater flow patterns are all usefully revealed by GWPZ research. The long-term sustainability of water supplies is promoted by using this knowledge to help establish appropriate policies for groundwater extraction, recharge, and conservation. GWPZ studies assist in finding regions with high groundwater potential that are ideal for the construction of water supply projects like wells, tube wells, and boreholes. By concentrating on certain regions, the expense and labour associated with groundwater extraction can be reduced, resulting in a more effective and dependable water supply for communities. Planning for agriculture: Globally, agriculture is one of the biggest consumers of groundwater. GWPZ studies help identify regions with high groundwater potential, enabling farmers to choose crops, implement irrigation systems, and use water most efficiently. This knowledge lessens the possibility of groundwater pollution or depletion while also boosting agricultural yield.

Groundwater is essential to the maintenance of ecosystems, including wetlands, rivers, and lakes, and it is a key component of environmental conservation. Groundwater potential zone (GWPZ) studies are required for discovering places with a substantial groundwater contribution to these ecosystems. Conservation measures can be put in place to save these priceless habitats by comprehending the hydrological link between surface water and groundwater. GWPZ studies help in locating locations vulnerable to groundwater-related dangers such as contamination of groundwater, land subsidence, or saline intrusion. Authorities can take preventive action, create early warning systems, and lessen the risks connected with such hazards.

After identifying Groundwater Potential Zones (GWPZ), numerous proposed procedures can be taken to ensure the effective management and sustainable usage of groundwater resources. Establish a thorough groundwater monitoring network inside the outlined GWPZ in order to regularly evaluate groundwater levels, quality, and trends. Regular monitoring helps in understanding the changes in groundwater resources over time and facilitates informed decision-making. Encourage the use of water saving techniques and put demand management plans into action within the GWPZ. To encourage responsible water usage and decrease wastage, this can involve encouraging effective irrigation methods, water-saving devices, and public awareness campaigns. Encourage the installation of rainwater harvesting devices to collect and replenish rainwater into the earth. The GWPZ's aquifers are replenished as a result, improving groundwater accessibility. To encourage the use of rainwater collection practises, the government can offer incentives or subsidies.

Implement suitable rules and regulations for groundwater extraction inside the GWPZ. Groundwater extraction is subject to regulation and control. To prevent overexploitation and maintain sustainable use, this can involve establishing caps on abstraction rates, granting permits for groundwater extraction, and ensuring compliance. Choose appropriate locations within the GWPZ for implementation of artificial groundwater recharge. In order to replenish the aquifers, these projects channel excess surface water or treated wastewater into the subsurface. In regions where natural recharge is insufficient, artificial recharge can help supplement groundwater resources. Investigate the viability of desalination technology or the use of alternate water sources, such as brackish water or recovered wastewater. While these strategies can involve a sizable investment, they might offer a second source of water supply and lessen reliance on groundwater. Groundwater issues should be incorporated into land-use planning and zoning restrictions within the GWPZ. Avoid or limit practises including incorrect garbage disposal and storing of hazardous materials that have the potential to contaminate groundwater. Encourage environmentally friendly land management techniques that reduce soil erosion, boost infiltration rates, and improve natural recharge.

Engaging stakeholders and using participatory methods Engage local populations, water users, and pertinent parties in groundwater management decision-making processes. To inform stakeholders about the significance of sustainable groundwater usage and involve them in the execution of conservation measures, conduct awareness campaigns, workshops, and training sessions. Encourage research projects aimed at better comprehending the hydrogeological features of the GWPZ, identifying cutting-edge groundwater management strategies, and creating long-lasting solutions. To promote information sharing and technological breakthroughs, promote cooperation between researchers, water management organisations, and local communities. To ensure that these interventions are implemented successfully, it is crucial to customise them to the unique circumstances of the area and work with local stakeholders. When it comes to tackling low groundwater levels, integrated water management strategies that incorporate several treatments and involve the community frequently have the best results.

CHAPTER - 5

CONCLUSION

This study reveal that GIS approach is an effective instrument for research groundwater resources and provides proposals which are acceptable for developing strategies for groundwater recharge in Delhi, India. It shows that it is an efficient tool and approach that helps to acquire conclusions through spatial and visual perception, and enable the comparison to conventional technique of groundwater inquiry remote sensing data which offer accurate spatial information may be utilize cost effectively. Additionally proving why Satty's AHP is a viable approach for determining the weights for the groundwater study. Five classifications were used to categorise the groundwater potential zones: Very poor, poor, moderate, good, and very good. Yamuna stretch parts were assessed to have excellent groundwater potential. The South- portion of the Delhi were the locations that had demonstrated a significant decline in water level due to rock geological formation. Both, flood plain of the Yamuna River and the Alluvium are the areas belonging to the good class category in GWPZ map.

Although RS and GIS is showing favorable site for groundwater zones in North-east and North-west half of the district. Thus, an appropriate management and methods need to be implemented for exploration of this rare resource in this section of the district. The GWPZ map developed in this study will be highly beneficial for government agencies in policy making, engineers, planners, researchers and the local groundwater governing body (CGWB) to find out the suitable places for investigation for ground water. It can also be beneficial in creating appropriate groundwater exploitation methods so as to ensure the sustainable use of this essential resource. In some regions, it may be desirable to utilize artificial recharge techniques to raise the groundwater table and avoid overusing it.

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