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An Integrated Geospatial Framework for Delineating Groundwater Potential and Building Construction Suitability: A Case Study of Rautahat District, Nepal

by

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DECLARATION

I hereby declare that the thesis entitled "**An Integrated Geospatial Framework for Delineating Groundwater Potential and Building Construction Suitability: A Case Study of Rautahat District, Nepal**", submitted to the Department of Civil Engineering in partial fulfillment of the requirement for the degree of Master of Science in Construction Engineering and Management, is a record of an original work done under the guidance of Asst. Prof. Santosh Kumar Shrestha. This thesis contains only work completed by me except for the consulted material, which has been duly referenced and acknowledged.

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ABSTRACT

Shallow groundwater systems play a dual role in Nepal's Terai plains, exemplified by Rautahat District. While these aquifers support the region's agricultural livelihood, their high-water tables create significant geo-engineering constraints for infrastructure, including elevated dewatering costs, unstable excavations, and flood-prone conditions. Existing studies predominantly emphasize groundwater potential for irrigation, with limited integration of hydrogeological constraints into construction planning. This study addresses that gap by developing an integrated geospatial framework that delineates Groundwater Potential Zones (GWPZ) and evaluates construction feasibility through a Building Construction Suitability Index (BCSI). Using a GIS-based Multi-Criteria Decision Analysis (MCDA) approach supported by the Analytical Hierarchy Process (AHP), the framework incorporates eight hydrogeological factors for GWPZ and seven geo-engineering and socio-environmental factors for BCSI. Results show that 83.07% of the district exhibits Good groundwater potential, although only 0.07% falls under Very Good categories, while 14.53% is classified as Poor or Very Poor. In contrast, construction feasibility is highly constrained: 46.99% of the district is Unsuitable for building construction, and only 1.69% is Highly Suitable. Validation using discharge data from 31 deep tube wells confirms strong agreement between observed well yields and modeled potential. The integrated findings reveal a pronounced spatial conflict—areas rich in groundwater frequently overlap with zones least feasible for construction. The developed framework provides a practical decision-support tool for planners and engineers to balance groundwater utilization with safe and sustainable infrastructure development in Nepal's Terai region.

Keywords: *Groundwater Potential Zones (GWPZ); Building Construction Suitability Index (BCSI); Geographic Information System (GIS); Analytical Hierarchy Process (AHP); Dewatering Cost*

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LIST OF ABBREVIATIONS

Abbreviatio	**Full Form**
ADPC	Asian Disaster Preparedness Center
AHP	Analytical Hierarchy Process
CI	Consistency Index
CR	Consistency Ratio
BCSI	Building Construction Suitability Index
DDG	Deputy Director General
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DMG	Department of Mines and Geology
DOLID	Department of Local Infrastructure Development
DoR	Department of Roads
DWRI	Department of Water Resources and Irrigation
FAO	Food and Agriculture Organization
FRTC	Forest Research and Training Centre
GEE	Google Earth Engine
GIS	Geographic Information System
GoN	Government of Nepal

Abbreviatio	**Full Form**
GWPZ	Groundwater Potential Zones
HDX	Humanitarian Data Exchange
ICIMOD	International Centre for Integrated Mountain Development
IOE	Institute of Engineering
LRBP	Local Roads Bridge Programme
LRBSU	Local Roads Bridge Support Unit
LULC	Land Use / Land Cover
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
MSCoM	Master of Science in Construction Management
NASA	National Aeronautics and Space Administration
NLCMS	National Land Cover Monitoring System
OSM	OpenStreetMap
RI	Random Index
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission

CHAPTER ONE: INTRODUCTION

1.1 Background

The Terai region of Nepal, covering significant portions of the southern plains, is widely recognized as the country's "granary" or "breadbasket," supporting a large share of Nepal's population through extensive agricultural production (Bhandari, 2008). This region is characterized by abundant shallow groundwater resources that play a vital role in irrigation and domestic water supply (Pandey et al., 2023). The groundwater is stored within young alluvial deposits composed mainly of sand, gravel, and silt, while the Bhabar zone—consisting of coarse sediments such as boulders and pebbles—functions as a major recharge area for the Terai aquifers(Pandey et al., 2023). The depth of these aquifers varies, with shallow aquifers generally less than 60 meters deep and deeper aquifers extending beyond this depth (Bhandari, 2008). Despite this natural abundance, the Terai region is experiencing increasing water stress due to over-extraction for irrigation and drinking, land degradation, erratic monsoon patterns, deforestation, and insufficient groundwater governance (Aryal et al., 2023).

The high-water table and hydrogeological conditions pose significant challenges for infrastructure development and construction activities in the Terai. Key issues include high dewatering costs for foundations, soil instability, and increased vulnerability to flooding, which severely limit construction suitability in many areas. This paradox between groundwater availability and construction constraints has not been sufficiently addressed in regional planning frameworks. Most studies have focused on groundwater potential and irrigation needs, but the integration of hydrogeological factors with geo-engineering, economic, and infrastructural considerations remains limited .(Pandey et al., 2023)

The sustainable management of Terai's groundwater requires a comprehensive geospatial framework that can map groundwater potential zones while simultaneously assessing construction suitability. Multi-criteria decision analysis methods such as the Analytical Hierarchy Process (AHP), combined with Geographic Information System (GIS) techniques, offer robust tools for integrating multiple factors—environmental, hydrogeological, and economic—to support land use decision-making in this complex environment (Pathak, 2017). Such an integrated approach is crucial for balancing water resource management with urban and rural development, mitigating environmental risks, and ensuring socio-economic sustainability in the Terai plains.

1.2 Problem Statement

The Terai region of Nepal is underlain by highly permeable alluvial aquifers that yield substantial groundwater, making it a vital resource for irrigation, domestic supply, and rural livelihoods (Pandey et al., 2023). Despite its socio-economic significance, the shallow groundwater table presents notable geo-engineering challenges for infrastructure development. Construction activities in groundwater-rich areas often encounter high foundation dewatering costs, unstable excavation conditions, and increased susceptibility to flooding, collectively complicating the delivery of safe and cost-effective infrastructure (Maskey et al., 2023).

Several studies have delineated Groundwater Potential Zones (GWPZ) in different parts of the Terai and the broader Indo-Gangetic plain using GIS-based multi-criteria decision analysis techniques (Pathak, 2017). These studies typically integrate factors such as slope, drainage density, lineament density, lithology, and land use to map groundwater availability, mainly focusing on irrigation and domestic water supply (Pokhrel & Khanal, 2024)However, despite their methodological strengths, these assessments do not incorporate geotechnical constraints, construction-related risks, or economic feasibility parameters, which are critical for infrastructure planning in groundwater-rich environments (Timsina, 2025). As a result, no comprehensive geospatial framework currently exists that simultaneously evaluates groundwater abundance and construction suitability, limiting planners and engineers in identifying areas where high groundwater potential directly conflicts with stable, practical, and economically viable infrastructure development.

Therefore, there is a critical need to develop a GIS–AHP-based Building Construction Suitability Index (BCSI) alongside detailed GWPZ mapping. Such an integrated decision-support framework will fill the existing methodological gap and provide a more holistic basis for land-use planning in groundwater-dependent regions like Rautahat District. By harmonizing groundwater resource potential with engineering and construction constraints, this approach supports more balanced, sustainable, and technically informed development under complex hydrogeological conditions (Pandey set al., 2023).

1.3 Objectives

The objectives of this research include:

1. To delineate Groundwater Potential Zones (GWPZ) for the study area by collecting, processing, and integrating eight key hydrogeological factors (such as lithology, rainfall, slope, and drainage density) using a GIS-based Analytical Hierarchy Process (AHP) model.
2. To develop Building Construction Suitability Index (BCSI) by identifying and integrating seven critical geo-engineering and economic factors (such as soil type, dewatering cost, geomorphology, and road proximity) using the same GIS-AHP methodology.
3. To validate the GWPZ model by comparing the results with the known discharge data from existing deep tube wells within the study area.

1.4 Scope and Limitation

The scope and limitation of this research include:

1. Groundwater Potential Zones (GWPZ) are delineated using eight hydrogeological factors integrated through a GIS-based AHP model.

2. The Building Construction Suitability Index (BCSI) is developed using seven geo-engineering and economic factors, including groundwater influence.

3. The GIS–AHP framework is the only multi-criteria decision-making method applied for weighting and integration.

4. The GWPZ model is validated solely using discharge data from existing deep tube wells available within the study area.

5. The study relies primarily on secondary datasets, which may vary in accuracy, resolution, and publication year.

6. Detailed engineering parameters (e.g., bearing capacity, liquefaction susceptibility, seismic behavior) are not included due to limited field or laboratory data.

7. The selection of factors for GWPZ and BCSI is constrained by data availability, and some potentially relevant criteria could not be incorporated.

CHAPTER TWO: LITERATURE REVIEW

Understanding groundwater resources and evaluating construction suitability are increasingly important in regions experiencing rapid urbanization, agricultural expansion, and changing hydro-environmental conditions. The integration of geospatial technologies with multi-criteria decision-making approaches has emerged as a powerful framework for assessing groundwater availability, identifying potential zones, and determining the suitability of land for infrastructure development. This chapter reviews the existing body of knowledge relevant to groundwater systems, groundwater potential zone mapping, factors influencing groundwater occurrence, and the application of GIS and Analytical Hierarchy Process (AHP) in multi-criteria evaluations. The literature also highlights global and Nepal-specific studies that inform the methodological foundation of this research and identifies the research gaps addressed by the current study.

2.1 Groundwater and Groundwater Potential Zones (GWPZ)

Groundwater is one of the most vital natural resources and serves as a primary source of drinking water, irrigation, and industrial use in many parts of the world. It forms when precipitation infiltrates the soil, percolates through permeable geologic formations, and accumulates in subsurface aquifers. The availability and movement of groundwater depend on several hydrogeological factors, including lithology, soil characteristics, geomorphology, structural features, and climatic conditions (Wirth et al., 2020).

Access to reliable groundwater resources is particularly critical in regions where surface water is insufficient, seasonally variable, or difficult to store. Sustainable groundwater management requires understanding both the quantity and spatial distribution of groundwater recharge and storage potential. This has led to the increasing use of spatial groundwater potential zone (GWPZ) mapping, which identifies areas with high, moderate, or low potential for groundwater occurrence based on multiple influencing factors.(Bulbula & Serur, 2024)

Groundwater Potential Zones (GWPZ) are spatially delineated regions classified according to their likelihood of storing or yielding groundwater. These zones help decision-makers understand where groundwater extraction may be feasible, sustainable, or limited. According to (Shahid et al., 2000), GWPZ mapping integrates multiple hydrological and environmental parameters to create a composite index representing groundwater potential across a landscape.

Traditionally, groundwater assessments relied on field surveys, pumping tests, and limited hydrogeological data, which are time-consuming and costly. Advances in Remote Sensing (RS) and Geographic Information Systems (GIS) have transformed groundwater studies by enabling the integration of diverse datasets such as rainfall, slope, lithology, drainage density, and land use/land cover into a single analytical framework (Jha et al., 2007a). These technologies enhance spatial accuracy, reduce field dependency, and support large-scale assessments in data-scarce regions.

Globally, GIS-based groundwater potential mapping has been widely used in diverse environments, such as arid regions of Africa (Jha et al., 2007a), monsoon-dependent landscapes in India (Nag & Ghosh, 2013), and mountainous terrains (Pourtaghi & Pourghasemi, 2014a). Most studies combine hydrological, geological, and geomorphological variables using weighted overlay methods or multi-criteria decision tools like AHP.

In Nepal, groundwater studies have primarily focused on the Terai region due to its thick alluvial deposits and high dependency on groundwater for irrigation and drinking water. (Shrestha et al., 2018) highlights the increasing importance of groundwater mapping in the Terai where over-extraction and seasonal variability pose management challenges. Despite several localized studies, comprehensive GWPZ assessments integrating GIS and AHP remain limited, especially at district scales such as Rautahat.

2.2 Factors Influencing Groundwater Potential

Groundwater occurrence and storage are controlled by a combination of geological, hydrological, geomorphological, and climatic factors. Understanding these controlling parameters is essential for delineating Groundwater Potential Zones (GWPZ), as each factor influences infiltration, percolation, recharge, and subsurface water movement (Todd, Daniel K. Mays, 2005). GIS-based groundwater studies commonly integrate multiple thematic layers to assess the spatial variation in groundwater potential. (Jha, Manoj K. Chowdhary, V. M. Chowdhury, 2007). The major influencing factors relevant to this study are discussed below.

2.2.1 Lithology

Lithology defines the physical and mineralogical characteristics of rocks and sediments, which directly govern their porosity and permeability. Permeable lithological formations such as alluvium, sand, and weathered materials facilitate groundwater recharge, whereas impermeable units like shale, compact clay, or massive rock restrict groundwater movement (Fetter, 2001). Several GIS-based GWPZ studies highlight lithology as one of the most dominant factors influencing subsurface storage (Nag, S. K. Ghosh, 2013). In Nepal's Terai region, thick Quaternary alluvium—composed of sand, silt, and gravel—forms highly productive aquifers (Shrestha et al., 2020).

2.2.2 Slope

Slope influences surface runoff velocity and infiltration rates. Gentle slopes support infiltration and groundwater recharge, while steeper slopes promote rapid runoff and reduced percolation (Magesh et al., 2012). Studies from India, Iran, and Nepal consistently show that low-slope regions correspond to higher groundwater potential zones (Pourtaghi & Pourghasemi, 2014b). The Terai plains of Nepal, characterized by predominantly flat topography, allow substantial infiltration during the monsoon season.

2.2.3 Drainage Density

Drainage density represents the total length of streams per unit area and reflects landscape dissection. Low drainage density generally correlates with higher infiltration capacity and groundwater recharge, whereas high drainage density indicates impermeable surfaces or steep terrain with limited percolation (Sahoo et al., 2015). Numerous groundwater potential studies confirm the inverse relationship between drainage density and groundwater availability (Jha et al., 2007b)

2.2.4 Rainfall

Rainfall is the principal source of groundwater recharge in monsoon-driven regions. The amount, intensity, and spatial distribution of rainfall influence the magnitude of recharge and aquifer replenishment. Several studies highlight rainfall as a crucial input parameter in groundwater potential mapping, particularly in South Asian monsoon regions (Mishra et al., 2020; Yeh et al., 2009). In Nepal, more than 80% of annual precipitation occurs during the monsoon, making rainfall a significant recharge factor for the Terai aquifers (Department of Hydrology and Meteorology (DHM), 2021)

2.2.5 Land Use / Land Cover (LULC)

Land use and land cover influence infiltration, evapotranspiration, and surface runoff. Vegetated and agricultural areas generally show higher infiltration, while built-up and impervious surfaces reduce recharge and increase runoff (Rawat & Kumar, 2015). LULC has been widely used in groundwater studies globally (Nag & Ghosh, 2013; Yeh et al., 2009). In the Terai region, rapid urban expansion and agricultural intensification have significantly altered surface recharge patterns (S. Sharma et al., 2018)

2.2.6 Soil Type

Soil characteristics determine infiltration capacity and percolation rate of water. Coarse-textured soils such as sandy loam or loamy sand permit rapid infiltration, whereas clay-rich soils restrict water percolation (Hillel, 1998). Studies from South Asia and the Middle East have emphasized soil type as a key factor influencing groundwater availability (Magesh et al., 2012; Rahmati et al., 2015). The Terai plains typically consist of fertile alluvial soils with good infiltration capacities in many locations.

2.2.7 Geomorphology

Geomorphological features—such as floodplains, alluvial fans, terraces, and valley fills—indicate recharge zones and subsurface water movement. Features like alluvial plains and depressions are associated with higher groundwater potential, while structural hills and ridges often show low potential (Sener et al., 2005; Pourtaghi & Pourghasemi, 2014). The Terai region, dominated by alluvial plains and riverine deposits, provides favorable geomorphic conditions for groundwater accumulation.

2.2.8 Lineament Density

Lineaments—faults, fractures, and joints—provide pathways for groundwater movement, especially in hard-rock terrains. Areas with high lineament density are often linked with enhanced groundwater potential because fractures increase secondary porosity (Edet et al., 1998; Sander, 2007). Although more relevant in hilly regions, lineament mapping has been applied in flat terrains to identify buried or subsurface structural controls.

2.3 GIS and Remote Sensing Techniques in Groundwater Potential Mapping

Geographic Information Systems (GIS) and Remote Sensing (RS) have become essential tools in groundwater resource assessment, particularly in regions where field-based hydrogeological data are limited or unevenly distributed. GIS provides a robust environment for managing, analyzing, and integrating diverse thematic datasets, while Remote Sensing offers synoptic, multi-temporal, and cost-effective spatial information that aids in understanding surface and subsurface hydrological processes (Lillesand, Kiefer, & Chipman, 2015).

The integration of GIS and RS for groundwater assessment began gaining prominence in the early 1990s and has since evolved into a widely applied methodological framework across different climatic and geomorphological settings (Jha et al., 2007). These technologies allow researchers to generate thematic layers such as slope, land use, drainage, lithology, soil type, and lineament distribution, all of which contribute to groundwater occurrence and movement. By overlaying these layers through structured decision rules or weighted models, GIS facilitates the creation of groundwater potential zone (GWPZ) maps with improved spatial accuracy and reliability (Machiwal & Jha, 2015).

Remote sensing data from satellite platforms—such as Landsat, Sentinel-2, ASTER, and SRTM—are frequently used to derive geomorphological features, lineament patterns, land use/land cover, and digital elevation models (DEM). These datasets help identify recharge zones, structural controls, and surface characteristics influencing groundwater availability (Sander, 2007). For example, DEM-derived products such as slope, drainage density, and flow accumulation are commonly incorporated into groundwater studies (Magesh et al., 2012). Spectral data from multispectral satellite imagery assist in LULC classification and surface moisture assessment, further supporting groundwater analysis.

Globally, various studies have demonstrated the effectiveness of GIS-RS integration for GWPZ mapping. In India, Nag and Ghosh (2013) used IRS satellite data and GIS overlays to delineate groundwater zones in Maharashtra. In Iran, Pourtaghi and Pourghasemi (2014) applied AHP and GIS techniques to combine lithology, slope, rainfall, and lineament density to produce groundwater maps with high predictive accuracy. Similar methods have been used in Turkey (Sener et al., 2005), China, Nigeria, Ethiopia, and the Middle East.

In Nepal, the use of GIS and remote sensing for groundwater assessment has expanded in recent years, especially in the Terai region where agricultural groundwater extraction is high. DWRI, ICIMOD, and several academic researchers have used satellite data and GIS models to understand groundwater distribution and recharge potential in Nepal’s plains and Siwalik–Terai transition zones (Shrestha et al., 2020; Sharma et al., 2018). These studies highlight the importance of GIS-based multi-criteria evaluation (MCE) for groundwater planning in regions characterized by limited hydrogeological field data. type.

2.4 Multi-Criteria Decision-Making (MCDM) in Groundwater Studies

Groundwater systems are influenced by multiple physical, environmental, and anthropogenic factors that interact in complex ways. Because no single parameter can fully explain groundwater occurrence, researchers increasingly rely on Multi-Criteria Decision-Making (MCDM) techniques to integrate diverse datasets and evaluate groundwater potential in a structured and rational manner. MCDM provides a framework for assessing alternatives based on multiple criteria, making it suitable for groundwater resource evaluation, land suitability analysis, and environmental decision-making (Malczewski, 1999).

MCDM techniques enable the assignment of weights to different thematic layers based on their relative importance in influencing groundwater recharge and storage. These techniques also facilitate pairwise comparisons, ranking of factors, and the combination of weighted layers to generate composite groundwater potential maps (Malczewski, 1999). The structured nature of MCDM reduces subjectivity and improves the transparency and reproducibility of groundwater assessments.

Several MCDM approaches have been applied to groundwater studies globally, including the Analytical Hierarchy Process (AHP), fuzzy-AHP, TOPSIS, and multi-attribute utility theory (MAUT). AHP is the most widely used due to its simplicity, logical structure, and ability to incorporate expert knowledge into the weighting process (Saaty, 1980). Fuzzy logic-based approaches have also gained popularity for handling uncertainty and vagueness, particularly when expert judgments involve imprecision (Pourghasemi et al., 2014).

In groundwater potential mapping, MCDM allows researchers to integrate hydrogeological parameters such as lithology, slope, geomorphology, drainage density, lineament density, soil type, rainfall, and land use. Studies across India (Magesh et al., 2012; Nag & Ghosh, 2013), Iran (Pourtaghi & Pourghasemi, 2014), Turkey (Sener et al., 2005), and Africa (Yeh et al., 2009) have successfully applied MCDM-based GIS models to delineate groundwater zones. These works demonstrate that MCDM frameworks significantly improve the reliability of groundwater evaluations compared to single-parameter or qualitative assessments.

In the Nepalese context, the use of MCDM for groundwater analysis has grown in recent years, especially in the Terai and Inner Terai regions where groundwater plays a crucial role in irrigation and drinking water supply. Studies using GIS-AHP methods in Nepal (Shrestha et al., 2020; Sharma et al., 2018) highlight the effectiveness of MCDM approaches for integrating diverse environmental datasets in regions with limited hydrogeological field measurements. These techniques are particularly valuable in data-scarce environments such as Nepal, where comprehensive groundwater monitoring networks are limited.

2.5 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), developed by Saaty (1980), is one of the most widely used Multi-Criteria Decision-Making (MCDM) techniques in environmental and resource assessment. AHP provides a systematic framework for decomposing complex decision problems into a hierarchy of criteria and subcriteria, assigning relative weights based on pairwise comparisons, and synthesizing these weights to generate a composite index. Its simplicity, transparency, and ability to incorporate expert judgment have made AHP highly popular in groundwater studies, land suitability analysis, hazard assessment, and environmental planning (Saaty & Vargas, 2012)

In AHP, decision-making is structured into three main steps:

1. **Hierarchy development** – defining the goal, criteria, and alternatives.
2. **Pairwise comparison** – using Saaty’s 1–9 scale to compare the relative importance of each factor.
3. **Consistency evaluation** – calculating the Consistency Ratio (CR) to ensure that expert judgments are logically consistent.

A Consistency Ratio of less than 0.10 (10%) indicates an acceptable level of internal consistency (Saaty, 1980). This mathematical validation reduces subjectivity and strengthens the reliability of the final weighted model.

AHP has been widely used in groundwater potential mapping due to its strength in integrating geological, hydrological, and geomorphological factors. Numerous studies demonstrate its effectiveness in groundwater assessments. For example, Yeh et al. (2009) applied AHP to delineate groundwater potential in Taiwan, showing improved predictive accuracy compared to single-factor approaches. Pourtaghi and Pourghasemi (2014) combined AHP with GIS to map groundwater zones in Iran, integrating lithology, slope, rainfall, and lineament density. Their study confirmed that AHP provided a robust and replicable weighting structure. Similarly, Magesh et al. (2012) used AHP to identify groundwater zones in Tamil Nadu, India, demonstrating that weights derived through expert judgment closely matched actual field conditions.

AHP has also been integrated with fuzzy logic, logistic regression, random forest, and frequency ratio models to improve prediction accuracy and handle uncertainty ((Naghibi et al., 2017); Rahmati et al., 2015). Despite these advanced hybrid methods, AHP remains widely preferred because of its ease of use, minimal data requirements, and compatibility with GIS-based weighted overlay analysis (Machiwal & Jha, 2015).

In Nepal, AHP-based groundwater and land suitability studies have increased steadily due to the need for scientific decision tools in hydrological assessment and infrastructure planning. Studies by Shrestha et al. (2020) and Sharma et al. (2018) used AHP in Nepal’s Terai region to integrate multiple environmental layers such as LULC, slope, and geomorphology for groundwater and agricultural suitability mapping.

2.6 Building Construction Suitability Index (BCSI)

Building Construction Suitability Index (BCSI) represents a composite measure used to evaluate the degree to which a given land area is appropriate for construction activities based on physical, environmental, and infrastructural criteria. BCSI helps planners and engineers determine the feasibility of development by integrating diverse factors such as topography, soil characteristics, hydrological conditions, land use patterns, and accessibility. The core purpose of BCSI is to minimize construction risks, reduce costs, and ensure sustainable land development by identifying areas most suitable for infrastructure projects (Collins et al., 2001).

The concept of construction suitability has its roots in land evaluation and site suitability analysis, where spatial datasets and decision-making frameworks are used to classify areas based on their development potential ((FAO), 1976). In recent decades, the availability of GIS tools has enabled researchers to perform construction suitability analyses with high spatial accuracy, integrating multiple criteria into weighted spatial models (Malczewski, 1999). Suitability indices are widely used in urban planning, settlement development, engineering site selection, and disaster-resilient infrastructure planning.

Construction suitability assessments typically incorporate factors such as slope stability, soil bearing capacity, geomorphology, surface drainage, groundwater conditions, land use constraints, and proximity to transportation networks. These parameters influence excavation difficulty, foundation design, construction cost, and long-term performance of built structures (Bell, 2007). For example, areas with steep slopes or unstable geomorphology pose higher risks of landslides and require intensive engineering interventions. Similarly, regions with high groundwater tables can increase excavation challenges and foundation costs (Coduto, 2001).

Several global studies have adopted GIS-based Multi-Criteria Decision-Making (MCDM) methods—including AHP, Weighted Linear Combination (WLC), fuzzy logic, and machine learning algorithms—to generate construction suitability maps. In (Patil et al., 2019) applied GIS-MCE to assess suitable land for urban expansion in Navi Mumbai, integrating slope, soil type, LULC, road proximity, and geomorphology. In Iran, Boum et al. (2017) developed a suitability index for infrastructure planning by combining geotechnical and hydrological factors. Similar approaches have been applied across East Africa, China, and the Middle East for identifying optimal construction zones (Yalcin, 2008).

In Nepal, GIS-based suitability analyses have gained traction due to rapid urbanization, varied terrain, and increasing infrastructure demand. Studies such as Guragain & Bajracharya (2022) evaluated construction suitability in Mahalaxmi Municipality by integrating five spatial factors: slope, land use, geomorphology, soil type, and road access. Their findings demonstrate the utility of GIS-MCE in developing sustainable and hazard-resilient urban growth strategies. Furthermore, Nepal’s variable groundwater conditions—particularly in the Terai—make BCSI assessments critical for infrastructure development, as high groundwater levels and weak alluvial soils can significantly affect foundation performance and construction cost (K. Sharma & Maskey, 2018) .

2.7 Factors Influencing Building Construction Suitability

Building Construction suitability is governed by a combination of physical, geological, hydrological, and infrastructural parameters that determine how difficult, costly, or risky it is to build on a particular land surface. Each factor directly affects construction operations such as excavation, foundation design, drainage management, and long-term structural stability. Understanding these parameters is essential for developing a reliable Building Construction Suitability Index (BCSI) (Bell, 2007). The major factors considered in this study are discussed below.

2.7.1 Slope

Slope is one of the most fundamental parameters affecting construction feasibility. Steeper slopes are associated with increased excavation difficulty, higher earthwork volumes, slope stabilization requirements, and elevated risks of soil erosion and landslides (Yalcin, 2008). Flat and gently sloping terrain is generally preferred for construction due to easier foundation laying and lower site preparation costs. Numerous studies emphasize that slope strongly influences both suitability and construction cost (Gorse & Highfield, 2009) . In the context of Nepal, slope plays a crucial role even in the Terai due to local micro-topographic variations affecting drainage and waterlogging potential.

2.7.2 Geomorphology

Geomorphology describes the physical landscape and landforms that directly affect ground stability. Landforms such as floodplains, terraces, valley fills, and alluvial fans have distinct geotechnical characteristics that influence foundation performance (Summerfield, 1991) . Floodplains and recent alluvial deposits may contain soft soils susceptible to settlement, whereas older terraces often exhibit better compaction and bearing capacity (Mandal & Mondal, 2020) . Studies demonstrate that geomorphic units are powerful indicators of construction feasibility and hazard susceptibility (Yalcin, 2008; Chen et al., 2011). In the Terai region, extensive alluvial plains generally provide suitable ground for construction, but areas near river channels may pose risks of flooding and erosion.

2.7.3 Soil Type

Soil type determines bearing capacity, compaction properties, shrink–swell behavior, drainage characteristics, and excavation effort. Engineering-friendly soils such as sandy loam or well-graded sands provide good bearing capacity, while clayey soils may exhibit swelling, consolidation, and low permeability, requiring design interventions (Coduto, 2001). Soil classification has traditionally been one of the primary determinants in geotechnical suitability mapping worldwide (Bell, 2007). Several GIS-based suitability studies report soil as a major parameter influencing construction decisions (Gharbia et al., 2016; Guragain & Bajracharya, 2022).

2.7.4 Land Use / Land Cover (LULC)

Land use/land cover influences construction potential by indicating existing development constraints, vegetation cover, and land protection classifications. Built-up areas may already contain infrastructure that limits further construction, whereas forested areas may involve environmental restrictions or require significant clearing (Rawat & Kumar, 2015). Agricultural land may have soft soil or seasonal waterlogging, affecting foundation design. LULC is widely used in construction suitability and urban planning studies across Asia, Europe, and Africa (Chen et al., 2011; Patil et al., 2019).

2.7.5 Population Density

Population density reflects the level of anthropogenic pressure on land resources and influences demand for infrastructure, availability of free land, and land-use constraints. High-density areas often experience land scarcity, congestion, and higher land prices, making construction more challenging or restricted (Foster & Chilton, 2003). Population density is frequently used in suitability assessments as an indicator of social and development pressure, helping planners avoid overburdened zones and allocate development to less congested areas (Gharbia et al., 2016) .

2.7.6 Road Proximity / Accessibility

Proximity to road networks plays a critical role in construction suitability by affecting material transport, construction logistics, accessibility, and emergency response. Areas close to existing roads reduce transportation costs and enable faster project mobilization (Chen et al., 2011). Suitability mapping frameworks frequently use road proximity as a major factor in selecting optimal construction sites (Gharbia et al., 2016; Patil et al., 2019). In Nepal, where transport access varies across regions, road connectivity significantly influences construction feasibility.

2.7.7 Dewatering Cost / Groundwater Condition

Groundwater depth strongly influences construction feasibility in alluvial regions. High groundwater tables increase excavation difficulty, risk of slope failure, and cost of dewatering operations during foundation work (Coduto, 2001). Saturated soils have reduced bearing capacity and may require specialized foundation techniques. Studies in South Asia and Europe consistently show that groundwater conditions are a major determinant of construction complexity and cost (Bell, 2007; Sharma & Maskey, 2018). In Nepal’s Terai, shallow groundwater levels significantly affect construction suitability, especially during monsoon periods.

2.8 GIS-Based Suitability Mapping

GIS-based suitability mapping integrates spatial datasets, statistical models, and decision-making frameworks to identify areas that are optimal, moderate, or unsuitable for specific purposes such as construction, urban development, agriculture, and groundwater management. Through its ability to manage and analyze multiple layers simultaneously, GIS has become one of the most powerful tools for conducting suitability assessments in diverse environmental and engineering applications (Malczewski, 1999).

Suitability mapping typically involves generating thematic layers—such as slope, soil, geomorphology, land use/land cover, accessibility, hydrological conditions, and population pressure—and combining them through weighted overlay analysis or machine learning models. GIS enables accurate spatial evaluation by converting these factors into standardized suitability scales, assigning appropriate weights (e.g., through AHP), and producing composite suitability maps representing the relative favorability of each location (Chen et al., 2011).

Globally, GIS-based suitability mapping has been widely applied in construction and urban planning. In Turkey, Yalcin (2008) integrated slope, geology, and geomorphology to map construction suitability in landslide-prone areas. In India, Patil et al. (2019) used GIS-MCE techniques to identify suitable land for urban expansion in

Navi Mumbai by incorporating factors such as soil, slope, road proximity, and geomorphology. Similar approaches have been used in Iran (Boum et al., 2017), China (Zhang et al., 2015), and East Africa to guide settlement planning and infrastructure development.

GIS-based suitability mapping is equally important in geotechnical and hydrological contexts. Studies such as Gharbia et al. (2016) in Egypt and Chen et al. (2011) in Taiwan highlight the need to integrate hydrological factors—such as drainage conditions and groundwater depth—into suitability analysis to avoid construction risks in waterlogged or unstable areas. This is particularly relevant in flat alluvial terrains similar to Nepal's Terai, where shallow groundwater and poor drainage significantly affect construction feasibility (Sharma & Maskey, 2018).

In Nepal, GIS-based suitability mapping has gained increasing attention in recent years. Research by Guragain & Bajracharya (2022) applied GIS and AHP to determine construction suitability in Mahalaxmi Municipality, integrating slope, soil, LULC, road access, and geomorphology. Urban expansion studies in Kathmandu and Chitwan have also used GIS-MCE models to identify suitable areas for planned development and hazard mitigation (Thapa & Murayama, 2009).

The strength of GIS-based suitability analysis lies in its ability to synthesize complex datasets, reduce subjectivity through structured weighting, and provide decision-makers with visual, spatially explicit outputs. These capabilities make GIS an indispensable tool for sustainable land development, infrastructure planning, and environmental risk reduction in developing countries such as Nepal.

CHAPTER THREE: METHODOLOGY

This This chapter describes the methodological framework adopted to delineate Groundwater Potential Zones (GWPZ) and evaluate the Building Construction Suitability Index (BCSI) for Rautahat District using an integrated GIS and Analytical Hierarchy Process (AHP) approach. The methodology combines geospatial data processing, thematic layer generation, multi-criteria decision-making, and validation using field-based information. A structured workflow was designed to systematically incorporate multiple hydrogeological, environmental, and infrastructural parameters that influence groundwater availability and construction feasibility.

The overall process includes (i) data collection from satellite sources, government agencies, and field observations; (ii) preprocessing of spatial datasets, including projection, clipping, and resampling; (iii) preparation of thematic layers such as slope, lithology, geomorphology, soil type, drainage density, land use/land cover, lineament density, population density, and groundwater/dewatering conditions; (iv) determination of factor weights through AHP; and (v) generation of GWPZ and BCSI maps using weighted overlay analysis in a GIS environment. The results are later validated using well discharge data and engineering suitability considerations.

3.1. Research Framework

The research follows an integrated geospatial framework that combines Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP) to delineate Groundwater Potential Zones (GWPZ) and evaluate the Building Construction Suitability Index (BCSI) for Rautahat District. The framework is designed to incorporate multiple hydrogeological, environmental, and infrastructural factors into a structured decision-making model, enabling the generation of spatial suitability maps with high accuracy and interpretability.

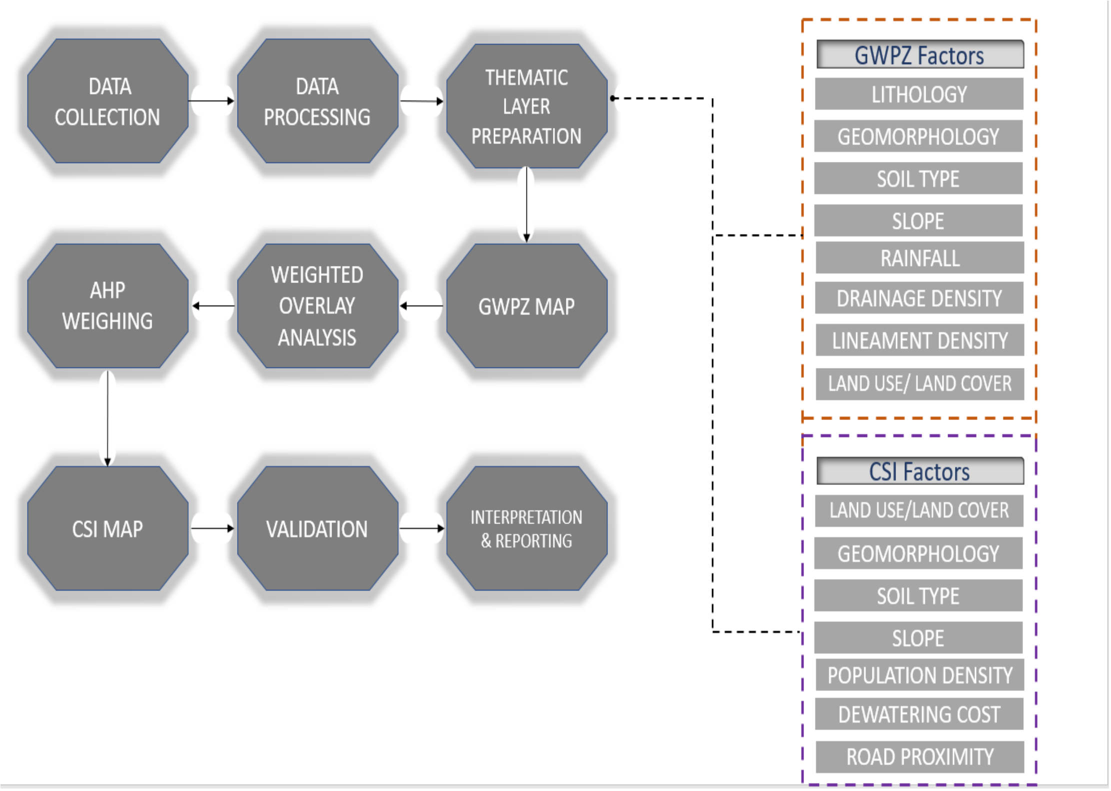


Figure3.1 Research Framework

3.2 Description of the Study Area

Rautahat District, located in the south-central part of Nepal within Madhesh Province, forms an integral section of the eastern Terai plains. Geographically, the district extends approximately from 26°44′N to 27°00′N latitude and 85°10′E to 85°30′E longitude, covering an area of around 1,126 km². It is bordered by Sarlahi District in the east, Bara District in the west, Makwanpur District and the Siwalik (Chure) foothills in the north, and the Indian state of Bihar in the south. Administratively, Rautahat comprises several urban and rural municipalities, with Gaur serving as the district headquarters.

The district is characterized by a predominantly flat and low-lying topography typical of the Terai region, with elevations gently ranging from about 60 meters in the southern plains to nearly 200 meters toward the northern Chure interface. The terrain is remarkably level, which makes it extensively suitable for agriculture but prone to drainage challenges and seasonal waterlogging in certain low-lying areas. The gradual north–south slope influences surface runoff patterns, sediment deposition, and groundwater recharge dynamics.

Rautahat experiences a humid subtropical monsoon climate, dominated by three distinct seasons: a hot and humid summer (March–June), a monsoon season (June–September), and a mild winter (December–February). More than 80% of the annual rainfall—typically between 1,800 and 2,200 mm—occurs during the monsoon months, contributing significantly to groundwater recharge, river discharge, and soil moisture conditions. Temperature variations range from above 40°C in peak summer to around 8–10°C during winter.

Hydrologically, the district is drained by several perennial and ephemeral rivers, including the Bagmati, Lalbakaiya, Manusmara, Dhansar, and Jhanjhari, which originate from the Chure hills and flow southward into the Indian plains. These rivers carry heavy sediment loads during monsoon and influence geomorphology, surface water distribution, and aquifer recharge patterns. The area is underlain by thick Quaternary alluvial deposits comprising sand, silt, clay, and gravel layers that form productive unconfined and semi-confined aquifers. Groundwater is widely used for irrigation and domestic water supply, with numerous deep tube wells and dug wells installed by the Department of Water Resources and Irrigation (DWRI) and local authorities.

Geologically, Rautahat consists primarily of Holocene and Pleistocene alluvial formations derived from fluvial processes. Coarser sediments dominate the northern belt near the Chure foothills, while finer silty and clayey deposits occur in the central and southern regions. These geological variations significantly influence groundwater storage, soil behavior, excavation characteristics, and construction feasibility. Soils in the district are mainly alluvial and vary from sandy loam to silty clay loam, providing fertile agricultural land but posing challenges in areas with high moisture content or poor drainage.

Land use in Rautahat is heavily agricultural, with rice, wheat, maize, sugarcane, and vegetables forming the dominant cropping patterns. Built-up areas are expanding rapidly, particularly along the East–West Highway corridor and in municipalities such as Chandrapur, Garuda, Maulapur, and Gaur. Population density is relatively high compared to other Terai districts, increasing pressure on land resources, groundwater extraction, and infrastructure development. Road networks consist of the national highway, district roads, rural roads, and cross-border routes, enhancing accessibility and supporting socioeconomic activities.

The district’s flat alluvial terrain, shallow groundwater table, rapid urbanization, and dynamic land use patterns make Rautahat an ideal location for integrated assessment of groundwater potential and construction suitability. Understanding its spatial characteristics is essential for guiding infrastructure development, groundwater management, and sustainable land-use planning.

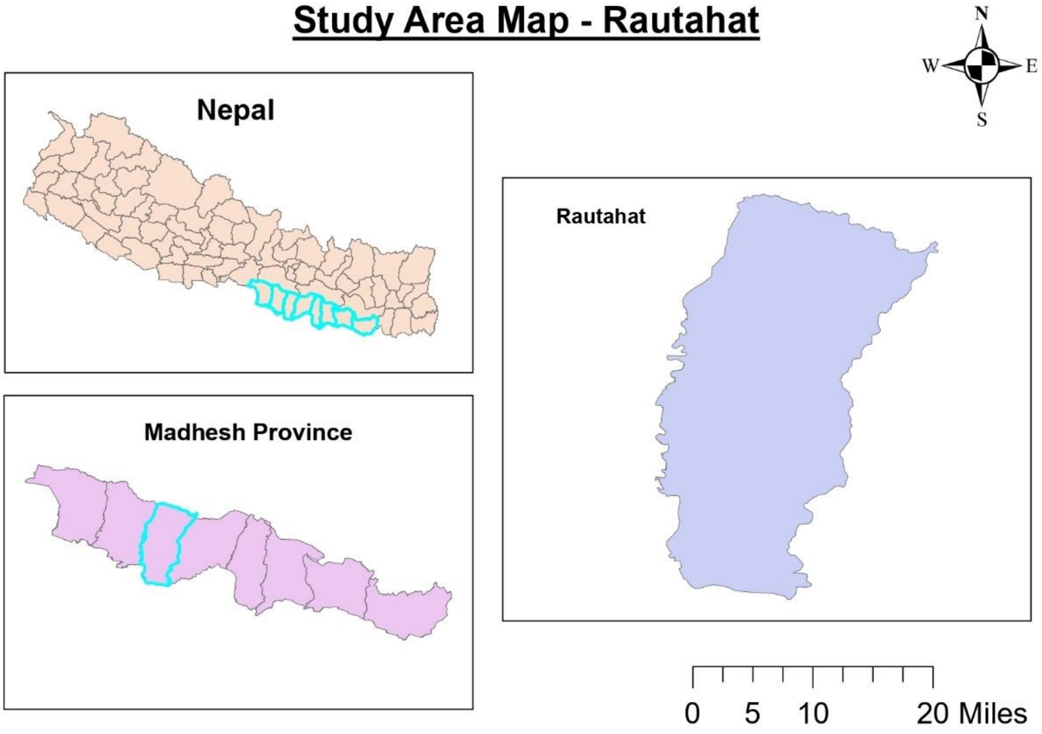


Figure 3.2 Location map of Rautahat

3.3 Data Collection and Sources

This study utilized a combination of remotely sensed data, national geospatial datasets, and governmental records to generate the thematic layers required for Groundwater Potential Zone (GWPZ) mapping and Building Construction Suitability Index (BCSI) assessment. All datasets were standardized to the WGS 1984 UTM Zone 44N coordinate system and processed at a uniform spatial resolution (30 m) for analytical consistency.

Digital Elevation Model (DEM) data were obtained from the Shuttle Radar Topography Mission (SRTM) 30 m resolution, downloaded through USGS EarthExplorer. The DEM was processed in a GIS environment to derive slope, drainage density, flow accumulation, and hillshade layers, which are essential for understanding terrain behavior and hydrological flow patterns in the study area.

Land use/land cover (LULC) data were obtained from the National Land Cover Monitoring System (NLCMS) of Nepal (2000–2022), developed by the Forest Research and Training Centre (FRTC) under the Ministry of Forests and Environment, with technical support from ICIMOD, NASA, USAID, SERVIR-HKH, SERVIR–Mekong, ADPC, and the University of Maryland's GLAD group. The dataset is produced using Landsat imagery and a cloud-based machine learning architecture within the Google Earth Engine (GEE) platform. The harmonized classification system and annual temporal coverage provide a reliable basis for LULC-based suitability and groundwater analysis.

Population density data were sourced from the Humanitarian Data Exchange (HDX) under the dataset titled Nepal: High Resolution Population Density Maps + Demographic Estimates, produced by AI and Data for Good at Meta. The geotiff grids (2018–2019) provide high-resolution (approx. 100 m) estimates of population distribution, which were resampled and clipped to represent population pressure in BCSI assessment. This dataset is widely used in humanitarian, development, and spatial planning applications.

Geology and soil (lithology) data were acquired from the ICIMOD Metadata Catalogue, specifically the dataset Geology of Nepal (scale 1:1,000,000), originally digitized from the geological map published by the Department of Mines and Geology (DMG, 1994). The dataset, curated by ICIMOD's MENRIS division, provides polygon-level geological information essential for understanding subsurface conditions, aquifer characteristics, and foundation suitability.

Rainfall data were obtained from the Department of Hydrology and Meteorology (DHM), including long-term monsoon precipitation records relevant for assessing recharge potential in GWPZ mapping. The rainfall dataset supports the interpretation of surface hydrology and infiltration processes across the Terai plains.

Drainage networks were extracted from the SRTM DEM using hydrological tools in GIS, which enabled the computation of drainage density and flow characteristics without relying on incomplete vector river datasets. This method improves spatial accuracy and ensures consistency with derived topographic variables.

Road network data were acquired from the Department of Roads (DoR) database and cross-verified with OpenStreetMap (OSM) to represent current accessibility conditions relevant for construction suitability analysis. These data provide a realistic representation of primary, secondary, and rural road infrastructure in Rautahat.

Groundwater-related information, including depth-to-water-table and deep tube well discharge data, was obtained from the Department of Water Resources and Irrigation (DWRI), which supports validation of the GWPZ model and helps quantify dewatering-related construction challenges.

All datasets underwent quality checking, projection correction, resampling, and clipping before integration into the spatial analytical framework. The combination of multi-source datasets allows for a comprehensive and reliable representation of both groundwater potential and construction suitability across the district.

3.4 Data Preprocessing

Prior to generating thematic layers and performing multi-criteria spatial analysis, all collected datasets underwent systematic preprocessing to ensure consistency, compatibility, and analytical accuracy. Data preprocessing was carried out using ArcGIS 10.x and QGIS platforms, following standard geospatial procedures involving projection, clipping, resampling, raster conversion, and dataset standardization.

All spatial datasets were transformed to the WGS 1984 UTM Zone 44N coordinate system to maintain uniformity across the study area. The district boundary of Rautahat was used as the primary mask for clipping all raster and vector datasets to the exact geographic extent of the analysis. This step avoided unnecessary processing and ensured that all subsequent layers aligned precisely.

The SRTM (30 m) Digital Elevation Model downloaded from USGS EarthExplorer was filled to remove sinks and hydrological inconsistencies. From the corrected DEM, derivative layers such as slope, flow direction, flow accumulation, and drainage density were generated using hydrological analysis tools. The slope layer was produced using a degree-based calculation, while the drainage network was derived and converted into a raster format to calculate drainage density using the line length per unit area concept.

The land use/land cover (LULC) dataset obtained from the National Land Cover Monitoring System (NLCMS) was provided in raster format at 30 m resolution. It was resampled and clipped to the study boundary and reclassified into standardized LULC classes based on their functional influence on recharge and construction feasibility.

Geological and soil-type polygons from ICIMOD (DMG geology map) were vector layers that required conversion to raster using the “Polygon to Raster” tool, with geological class codes assigned as raster values. These rasters were matched to the common 30 m resolution to maintain consistency with other datasets.

Population density data (Meta/HDX) were downloaded as GeoTIFFs with approximately 100 m resolution. These were resampled to 30 m using bilinear interpolation to align with the resolution of other thematic layers. The raster was then clipped and normalized for suitability analysis.

Rainfall data from DHM were converted from tabular form into a continuous spatial interpolated surface (e.g., Inverse Distance Weighting or Kriging), depending on the available station density. The rainfall raster was subsequently clipped and reclassified.

Road network data from DoR/OSM were processed by calculating Euclidean distance in GIS to produce a road proximity raster, which was later normalized for BCSI analysis.

Lineament features extracted from satellite imagery and geological structural data were processed by calculating lineament density using the “Line Density” tool, producing a raster indicating the concentration of structural discontinuities per unit area.

Finally, all thematic rasters were visually inspected for alignment, checked for missing values, and standardized into suitability classes (e.g., 1–5 scale) to prepare them for AHP-based weighting and weighted overlay analysis. This preprocessing ensured that all datasets were spatially harmonized, analytically compatible, and ready for multi-criteria modeling outcomes.

3.5 Preparation of Thematic Layers for GWPZ

The delineation of Groundwater Potential Zones (GWPZ) required the preparation of eight thematic layers representing the major hydrogeological and environmental factors influencing groundwater occurrence in Rautahat District. These layers were generated using GIS techniques from multiple datasets, including the SRTM DEM, geological maps, rainfall records, remote-sensing imagery, and derived hydrological features. All thematic layers were standardized to a 30 m spatial resolution and projected into WGS 1984 UTM Zone 44N, ensuring full compatibility for weighted overlay analysis.

Slope was derived from the SRTM 30 m DEM using the slope function in GIS. This layer represents the terrain steepness that directly influences infiltration and runoff. Gentle slopes promote recharge, while steeper slopes enhance runoff and reduce infiltration potential. Drainage density was calculated by extracting drainage lines from the DEM through hydrological tools and applying the line density function. Areas with low drainage density generally indicate high infiltration and thus better groundwater storage potential, whereas high drainage density areas tend to be runoff-dominant.

Lithology was prepared using the geological map obtained from ICIMOD/DMG. The polygon geology data were converted into raster format and reclassified according to the hydrogeological characteristics of each lithological unit. Coarser alluvial sediments (sand, gravel) were assigned higher groundwater potential values, while clay-rich or compact formations received lower suitability scores due to limited permeability.

Rainfall was processed from DHM precipitation records by interpolating station data into a continuous raster surface, representing long-term monsoon rainfall distribution. Since rainfall is the primary source of groundwater recharge in the Terai, areas with higher precipitation were considered more favorable for groundwater potential. Geomorphology was interpreted using a combination of DEM-derived hillshade, contours, and ICIMOD landform datasets to classify the area into geomorphic units such as alluvial plains, floodplains, and piedmont zones. These landforms significantly influence recharge behavior, sediment texture, and aquifer characteristics.

Soil type data extracted from the geological/soil maps were rasterized and reclassified based on permeability and infiltration properties. Sandy loam and mixed alluvium were assigned higher weights due to their favorable drainage and recharge potential, while clayey and fine-textured soils received lower suitability rankings. Land use/land cover (LULC) from the National Land Cover Monitoring System (NLCMS) was clipped and reclassified according to its influence on infiltration: agricultural and grassland areas were considered more favorable, while built-up areas and impervious surfaces were given low groundwater potential scores.

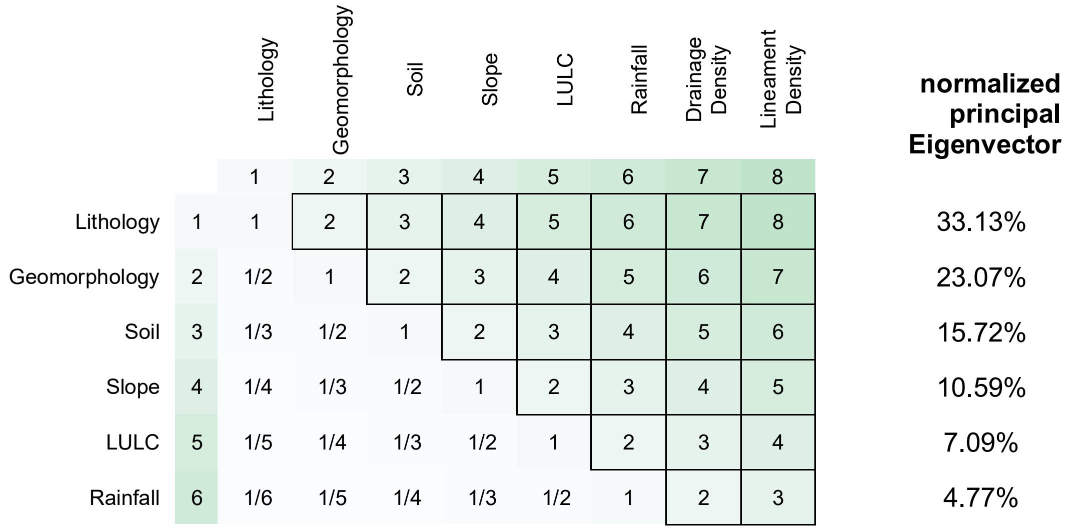
Lineament density was generated by digitizing and interpreting lineaments from satellite imagery and structural geology datasets. The lineament density raster was created using the line density tool, representing the concentration of fractures and structural discontinuities per unit area. Regions with higher lineament density indicate enhanced secondary porosity and groundwater movement pathways, thereby contributing positively to groundwater potential.

All eight thematic layers—slope, lithology, rainfall, drainage density, geomorphology, soil type, land use/land cover, and lineament density—were normalized and reclassified using a common suitability scale (e.g., 1 to 5). These standardized layers formed the input for subsequent Analytical Hierarchy Process (AHP) weighting and weighted overlay modeling to generate the final GWPZ map.

3.6 Analytical Hierarchy Process (AHP) for GWPZ

The Analytical Hierarchy Process (AHP) was applied to derive the relative importance (weights) of the eight thematic layers used for delineating groundwater potential zones—lithology, geomorphology, soil type, slope, land use/land cover (LULC), rainfall, drainage density, and lineament density. AHP is particularly suitable for groundwater studies because it converts expert judgment into numerical weights and integrates seamlessly with GIS-based weighted overlay analysis.

Pairwise comparisons were performed using Saaty’s 1–9 fundamental scale. The comparisons were made based on hydrogeological reasoning, previous groundwater potential studies, and expert understanding of alluvial aquifer systems in the Terai region. Each criterion was evaluated relative to the others to construct the pairwise comparison matrix. The resulting matrix, along with the normalized principal eigenvector representing the final weights of each criterion, is presented in Table 3.1.



		Lithology	Geomorphology	Soil	Slope	LULC	Rainfall	Drainage Density	Lineament Density	**normalized principal Eigenvector**
		1	2	3	4	5	6	7	8	
Lithology	1	1	2	3	4	5	6	7	8	33.13%
Geomorphology	2	1/2	1	2	3	4	5	6	7	23.07%
Soil	3	1/3	1/2	1	2	3	4	5	6	15.72%
Slope	4	1/4	1/3	1/2	1	2	3	4	5	10.59%
LULC	5	1/5	1/4	1/3	1/2	1	2	3	4	7.09%
Rainfall	6	1/6	1/5	1/4	1/3	1/2	1	2	3	4.77%

Drainage Density	7	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3.27%
Lineament Density	8	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2.36%

Table 3.1 Pairwise Comparison Matrix of Groundwater Influencing Factors

To assess the logical consistency of the judgments, the Consistency Index (CI) and Consistency Ratio (CR) were calculated using the maximum eigenvalue (λmax) derived from the matrix. The CI and CR were computed using the standard AHP formulas:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

where n = 8 represents the number of criteria, and RI = 1.41 is the Random Index for an 8×8 matrix. The calculated CR value (2.9%) is well below the acceptable threshold of 10%, confirming that the pairwise judgments are consistent. The detailed consistency evaluation is provided in Table 3.2.

Parameter	**Value**
Number of Criteria (n)	8
Maximum Eigenvalue (λ_{max})	8.288
Consistency Index (CI)	(λ_{max} − n)/(n−1) = 0.288 / 7 = 0.0411
Random Index (RI)	1.41
Consistency Ratio (CR)	CI / RI = 0.0411 / 1.41 = 0.029 (2.9%)
Acceptability	CR < 0.10 (Consistent)

Table 3.2 Consistency Index (CI), Consistency Ratio (CR), and Eigenvalue Parameters for the AHP Matrix

A bar chart illustrating the relative weights of all criteria is presented in Figure 3.3, which visually highlights the dominant influence of lithology, geomorphology, and soil type in controlling groundwater occurrence in the study area. These final AHP-derived weights were used in the GIS weighted overlay analysis to generate the GWPZ map.

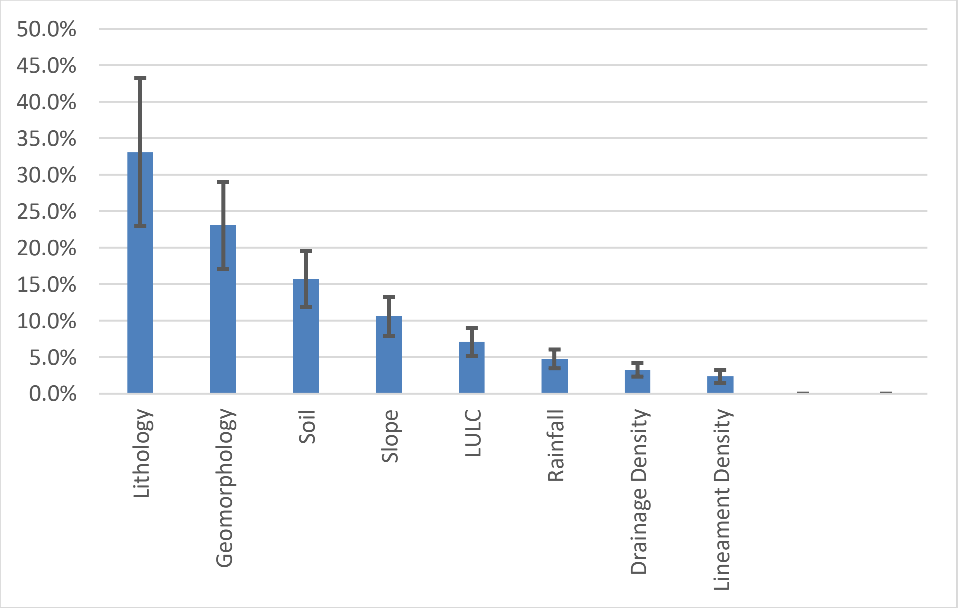


Figure 3.3 Final Weights of Groundwater Potential Criteria

3.7 Generation of Groundwater Potential Zones (GWPZ)

The final Groundwater Potential Zones (GWPZ) were generated by integrating all reclassified thematic layers using a GIS-based weighted overlay approach. The weighted overlay method combines multiple raster layers by multiplying each layer with its corresponding AHP-derived weight and summing the results to produce a composite groundwater potential index.

Each thematic layer—slope, lithology, soil type, geomorphology, land use/land cover (LULC), rainfall, drainage density, and lineament density—was first reclassified into suitability classes based on their influence on groundwater occurrence. Higher suitability values were assigned to features that promote infiltration, storage, and groundwater movement, such as gentle slopes, porous lithological units, and high lineament density. Conversely, lower suitability values were assigned to factors less favorable for groundwater accumulation. The summary of reclassification scheme for each layer is presented in Table 3.3.

Factor	**Reclassification Summary (Value → Suitability)**
Slope (%)	5 = Very High (0–2.78°); 4 = High (2.78–8.84°); 3 = Moderate (8.84–18.96°); 2 = Low (18.96–30.34°); 1 = Very Low (30.34–64.47°)
Lithology	5 = Very High (Fluvial non-calcareous); 4 = High (Fluvial calcareous); 2 = Low (Sandstone, greywacke)
Soil Type	5 = Very High (Calcaric FLUVISOL); 4 = High (Calcaric PHAEOZEM); 3 = Moderate (Cambisol / Dystric Regosol); 2 = Low (Eutric Gleysols)
Geomorphology	5 = Very High (Floodplain/Plain/Valley floor); 3 = Moderate (River terrace/Low gradient footslopes); 1 = Very Low (Structural hills/High gradient hill)
LULC	5 = Very High (Waterbody/Riverbed); 4 = High (Forest); 3 = Moderate (Cropland, Grassland/Otherwoodland); 2 = Low (Bare soil/Barren land); 1 = Very Low (Built-up area)
Rainfall (mm)	5 = Very High (>1500); 4 = High (1300–1500); 3 = Moderate (1100–1300); 2 = Low (900–1100); 1 = Very Low (<900)
Drainage Density (km/km²)	5 = Very High (0–0.61); 4 = High (0.61–1.00); 3 = Moderate (1.00–1.34); 2 = Low (1.34–1.71); 1 = Very Low (1.71–2.60)
Lineament Density (km/km²)	5 = Very High (1.06–1.77); 4 = High (0.69–1.06); 3 = Moderate (0.40–0.69); 2 = Low (0.14–0.40); 1 = Very Low (0–0.14)

Table 3.3 Summary of Reclassification Rules for Thematic Layers Used in GWPZ Analysis

After reclassification, the raster layers were converted to a common spatial resolution and coordinate system to ensure compatibility. The Weighted Overlay tool in ArcGIS was then used to combine the standardized layers according to the AHP weights derived earlier. The general form of the weighted overlay model used is:

$$GWPZ\ Index\ = \sum_{i=1}^{n}(W_i \times\ R_i)$$

$W_i =\ AHP - derived\ weight\ of\ the\ i^{th} criterion$

$R_i =\ reclassified\ raster\ score\ of\ the\ i^{th} criterion$

$n\ =\ 8\ groundwater - related\ factors$

After generating the groundwater potential index raster, the values were classified into five potential zones using the Natural Breaks (Jenks) algorithm, which groups data into statistically meaningful classes by minimizing within-class variance and maximizing between-class differences. Based on the distribution of the groundwater potential index, the study area was categorized into the following classes:

1. **Very Poor Groundwater Potential**
2. **Poor Groundwater Potential**
3. **Moderate Groundwater Potential**
4. **Good Groundwater Potential**
5. **Very Good Groundwater Potential**

These classes indicate the relative favorability for groundwater occurrence across the district, ranging from areas with very limited groundwater prospects to zones highly suitable for groundwater development.

3.8 Building Construction Suitability Index (BCSI)

The Building Construction Suitability Index (BCSI) was developed to identify zones favorable for infrastructure development based on geomorphological, hydrological, and socio-environmental conditions. Seven thematic layers—slope, geomorphology, land use/land cover (LULC), population density, groundwater condition (as a proxy for dewatering cost), soil type/geology, and road proximity—were incorporated into the BCSI model. These factors were selected based on their strong influence on construction feasibility, site stability, accessibility, and project cost, as supported by existing literature and engineering judgment.

Each dataset was pre-processed, converted to a common spatial resolution, projected into the same coordinate system (WGS 1984 UTM Zone 44N), and clipped to the study area. All thematic layers were subsequently reclassified into suitability categories ranging from low to high construction favorability. The summary of reclassification scheme for the BCSI parameters is presented in Table 3.4.

Factor	**Reclassification Summary (Value → Suitability)**
Slope (%)	5 = Very High (0–2.78°); 4 = High (2.78–8.84°); 3 = Moderate (8.84–18.96°); 2 = Low (18.96–30.34°); 1 = Very Low (30.34–64.47°)
Geomorphology	5 = Most Suitable (Plain); 4 = Suitable (Low gradient footslope); 2 = Poorly Suitable (Valley floor); 1 = Unsuitable (High gradient hill)
Land Use / Land Cover (LULC)	5 = Most Suitable (Bare soil); 4 = Suitable (Grassland); 3 = Moderately Suitable (Cropland); 2 = Poorly Suitable (Forest, Otherwoodland); 1 = Unsuitable (Built-up area, Riverbed, Waterbody)
Population Density (persons/km²)	5 = Very High (1113–1804); 4 = High (831–1113); 3 = Moderate (580–831); 2 = Low (260–580); 1 = Very Low (0–260)
Groundwater Condition (Dewatering Cost)	5 = Very Low Cost (Very Good / Low GWPZ); 4 = Low Cost (Good); 3 = Moderate Cost (Moderate); 2 = High Cost (Poor); 1 = Very High Cost (Very Poor / High GWPZ)
Soil Type / Geology	5 = Most Suitable (Sandstone, greywacke, arkose); 3 = Moderately Suitable (Fluvial, calcareous); 2 = Poorly Suitable (Fluvial non-calcareous)
Road Proximity (m)	5 = Very High (0–500); 4 = High (500–1000); 3 = Moderate (1000–2000); 2 = Low (2000–3000); 1 = Very Low (>3000)

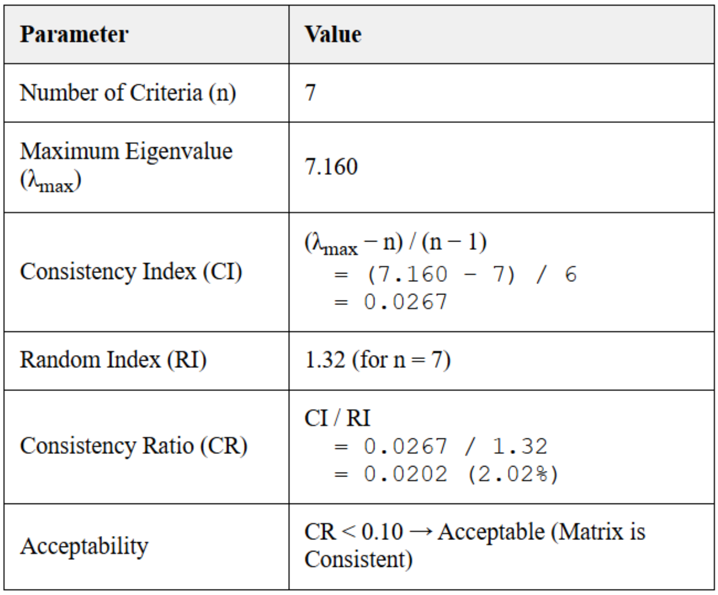
Table 3.4 Summary of Reclassification Rules for Construction Suitability Index (BCSI) Parameters

To ensure a robust weighting system, the Analytical Hierarchy Process (AHP) was applied to derive the relative importance of the seven factors. Pairwise comparisons were conducted using Saaty's 1–9 scale, considering engineering relevance and local construction challenges within the Rautahat District. The resulting pairwise comparison matrix and normalized eigenvector weights are shown in Table 3.5 with consistency verified using CI and CR calculations.

		Slope 1	Geomorphology 2	Landuselandcover 3	population density 4	Dewatering Cost 5	Soil Type 6	Road proximity 7	**normalized principal Eigenvector**
Slope	1	1	3	1/3	7	2	1/2	5	16.52%
Geomorphology	2	1/3	1	1/5	3	1/2	1/4	2	6.42%
Landuselandcover	3	3	5	1	9	4	2	7	36.05%
population density	4	1/7	1/3	1/9	1	1/5	1/7	1/2	2.60%
Dewatering Cost	5	1/2	2	1/4	5	1	1/3	3	10.23%
Soil Type	6	2	4	1/2	7	3	1	6	24.24%
Road proximity	7	1/5	1/2	1/7	2	1/3	1/6	1	3.95%

Table 3.5 Pairwise Comparison Matrix of Groundwater Influencing Factors

The detailed consistency evaluation, including the Consistency Index (CI) and Consistency Ratio (CR), is provided in Table 3.6



Parameter	**Value**
Number of Criteria (n)	7
Maximum Eigenvalue (λ_{max})	7.160
Consistency Index (CI)	(λ_{max} – n) / (n – 1) = (7.160 - 7) / 6 = 0.0267
Random Index (RI)	1.32 (for n = 7)
Consistency Ratio (CR)	CI / RI = 0.0267 / 1.32 = 0.0202 (2.02%)
Acceptability	CR < 0.10 → Acceptable (Matrix is Consistent)

Table 3.6 Consistency Index (CI), Consistency Ratio (CR), and Eigenvalue Parameters for the AHP Matrix

Once all layers were reclassified and weighted, the BCSI map was generated through a weighted overlay analysis in ArcGIS. The construction suitability index was computed using the following formulation:

$$CSI\ Index = \sum_{i=1}^{n} (W_i \times R_i)$$

$W_i = AHP - derived\ weight\ of\ the\ i^{th} criterion$

$R_i = reclassified\ raster\ score\ of\ the\ i^{th} criterion$

$n = 7\ Construction - related\ factors$

The BCSI index raster was classified into four categories using the Natural Breaks (Jenks) algorithm:

1. Highly Suitable
2. Suitable
3. Moderately Suitable
4. Poor Suitable
5. Unsuitable

3.9 Model Validation

The outputs of the Groundwater Potential Zonation (GWPZ) and Building Construction Suitability Index (BCSI) models were validated using observed field data. Tube-well locations were used to assess the accuracy of GWPZ, while existing built-up areas were used to validate BCSI.

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter presents the key outputs generated from the integrated geospatial framework developed in this study. It includes the results of the Groundwater Potential Zone (GWPZ) analysis, the Building Construction Suitability Index (BCSI) assessment, and the validation of both models using independent datasets. The thematic layers derived during the preprocessing stage—such as slope, lithology, geomorphology, land use/land cover, rainfall, drainage density, road proximity, population density, and groundwater condition—are first presented to illustrate the spatial characteristics of the factors incorporated into the suitability models.

Subsequently, the final GWPZ and BCSI maps produced through the Analytical Hierarchy Process (AHP)–based weighted overlay analysis are presented and interpreted. Area statistics for each suitability class are computed to quantify the spatial extent of groundwater potential and construction suitability across the study area. Model validation is then undertaken using deep tube-well locations for GWPZ and existing built-up areas for BCSI, enabling an assessment of the reliability and real-world consistency of the generated maps.

Finally, the chapter provides a discussion of the major findings, their implications for groundwater development and land-use planning, and a comparison with previous studies. Together, these results form the basis for understanding the spatial feasibility of groundwater extraction and construction activities within the Rautahat District.

4.1 Thematic Layers Used for GWPZ Mapping

A total of eight hydrogeological and environmental factors were used to delineate the Groundwater Potential Zones. The thematic maps generated from these factors are presented below and provide a visual representation of their spatial distribution within the study area.

4.1.1 Slope Map (Figure 4.1)

The slope map of Rautahat District (Figure 4.1) derived from the SRTM 30 m DEM, shows that the district is predominantly characterized by very gentle slopes, with values mostly between 0° and 2.78°. These nearly flat surfaces occupy the majority of the central and southern parts of the district, reflecting the typical geomorphological characteristics of the Terai alluvial plains. Such low slopes favor infiltration, reduce overland runoff, and create ideal conditions for groundwater recharge.

Moderately gentle slopes ranging from 2.78° to 8.84° occur in limited patches within the northern belt. These regions represent slightly elevated terrain transitioning toward the Siwalik foothills. Steeper slope classes (8.84°–18.96°, 18.96°–30.34°, and >30°) are present only in very small, localized areas and cover an insignificant portion of the district.

Overall, the slope distribution confirms that Rautahat is a predominantly flat district, which strongly supports groundwater accumulation and makes it favorable for irrigation, settlement expansion, and construction activities. The dominance of gentle slopes also reduces erosion potential, making slope a positively contributing factor in the groundwater potential assessment.

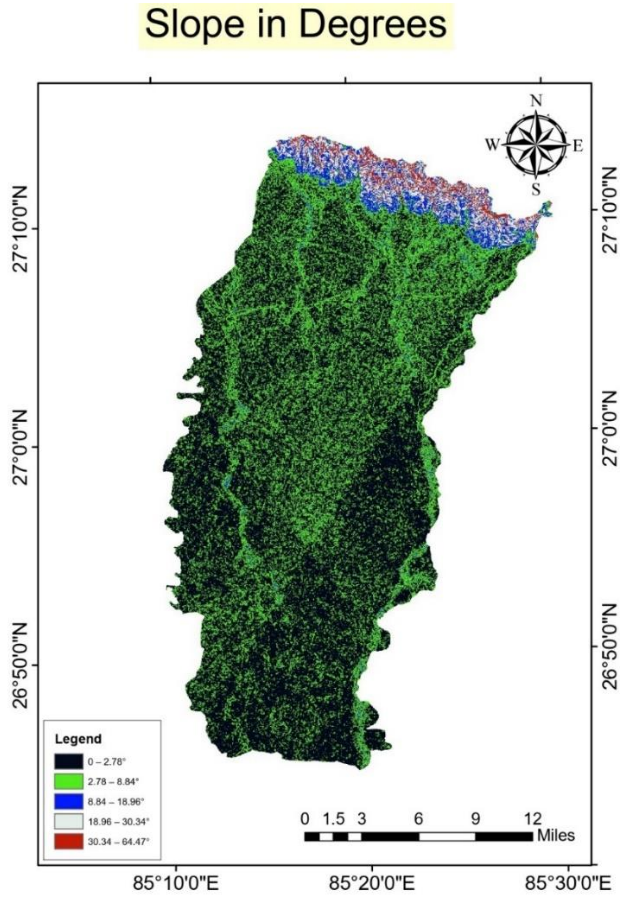


Figure 4.1 Slope Distribution of Rautahat District

4.1.2 Lithology Map (Figure 4.2)

The lithological characteristics of Rautahat District are dominated by unconsolidated fluvial deposits, which play a decisive role in shaping the groundwater conditions of the region. The central and southern parts of the district are chiefly composed of fluvial non-calcareous sediments, consisting of loose sands, silts, and gravels with minimal carbonate cementation. These materials possess high primary porosity and permeability, allowing rapid infiltration and efficient groundwater movement. As a result, they represent the most favorable lithological unit for groundwater occurrence in the district.

In contrast, fluvial calcareous deposits appear in localized patches and exhibit moderate levels of carbonate cementation. While these deposits still provide good aquifer conditions, the presence of calcium carbonate partially fills pore spaces and reduces hydraulic conductivity compared to non-calcareous alluvium. Nonetheless, they remain highly supportive of groundwater recharge and storage. Toward the northern margin of the district, the alluvial plains gradually transition into sandstone and greywacke units, which are consolidated sedimentary rocks characterized by significantly lower porosity. The compaction and cementation in sandstone, along with the fine-grained matrix material of greywacke, limit pore connectivity and restrict groundwater movement. These rock units form the least favorable zones for groundwater development and cover only a minor portion of the study area.

Overall, the lithology map illustrates that the hydrogeological setting of Rautahat is inherently favorable for groundwater potential, with the vast majority of the district underlain by permeable fluvial alluvium. The spatial dominance of these deposits explains the high recharge capability observed in the Terai region and underscores lithology’s strong influence within the GWPZ model.

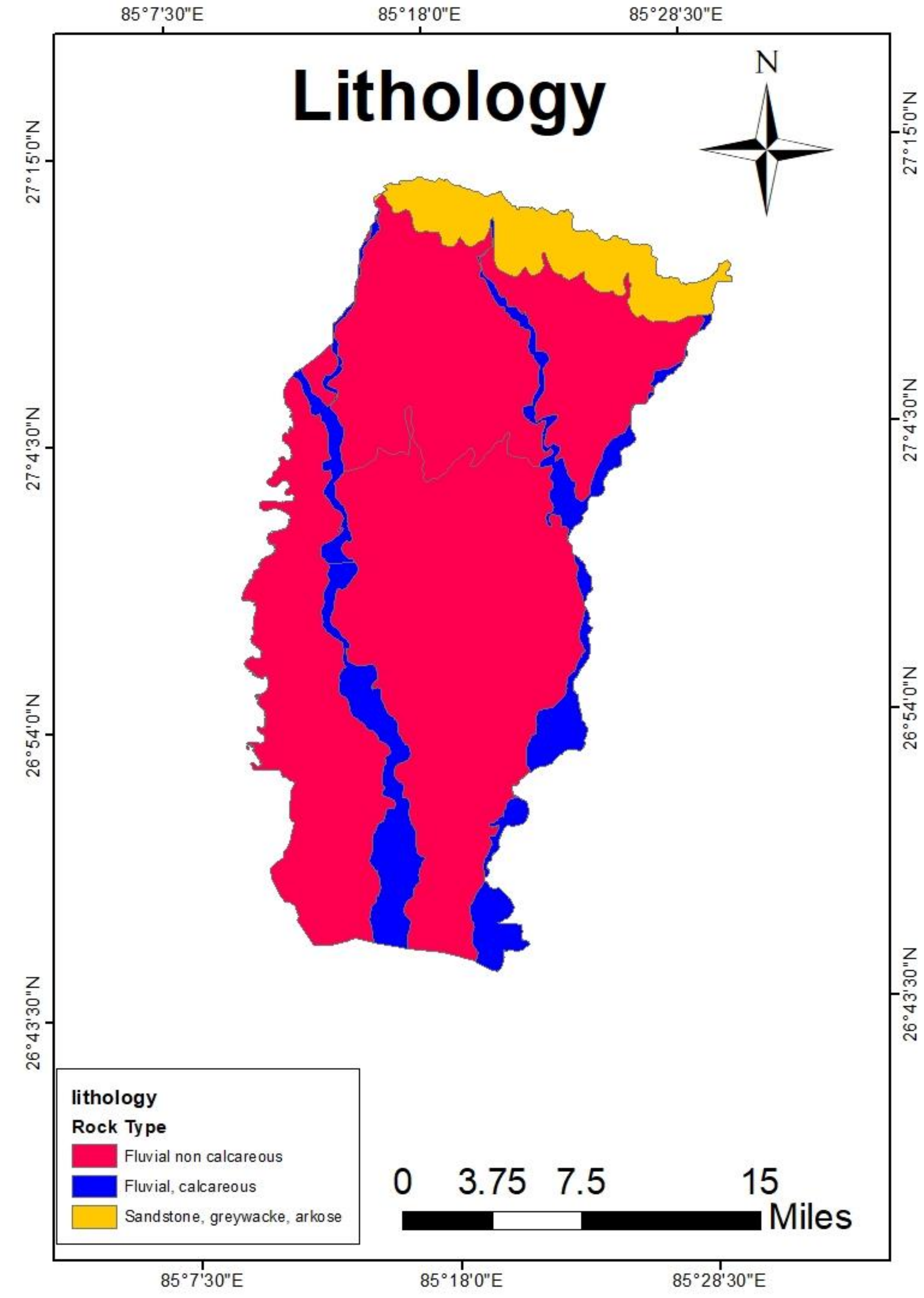


Figure 4.2 Spatial Distribution of Lithological Units in Rautahat District

4.1.3 Soil Type Map (Figure 4.3)

The soil characteristics of Rautahat District reflect the alluvial nature of the Terai plains and strongly influence infiltration capacity, recharge potential, and overall groundwater behavior. The soil type map reveals the dominance of Calcaric Fluvisols, which are young, alluvium-derived soils formed through repeated riverine deposition. These soils exhibit loose texture, high moisture-retention capability, and excellent permeability, making them highly favorable for groundwater recharge. Their combination of sandy–silty matrix and minimal compaction promotes vertical percolation and supports sustained aquifer replenishment across large portions of the district.

Adjacent to these deposits are patches of Calcaric Phaeozems, which also originate from alluvial materials but possess slightly higher organic matter accumulation and structural development. These soils retain moderate to high permeability and continue to support efficient groundwater movement, although their infiltration rate is somewhat lower than that of Fluvisols. In several transitional zones, particularly toward the northern fringes, Cambisols and Dystric Regosols appear, representing moderately developed soils with a finer texture and reduced infiltration capability. These units exhibit intermediate suitability for groundwater potential, as their partially compacted horizons and higher clay content slow down percolation.

Limited pockets of Eutric Gleysols are also present, typically associated with poorly drained environments where groundwater remains close to the surface seasonally. While these soils may support shallow groundwater tables, their lower permeability and tendency to remain saturated reduce their effectiveness in promoting deeper recharge.

Collectively, the spatial distribution of soil types demonstrates that much of Rautahat lies over highly permeable alluvial soils, reinforcing the district's natural advantage for groundwater accumulation. The predominance of Fluvisols and Phaeozems aligns with the hydro-geomorphic setting of the Terai and contributes significantly to the groundwater potential delineated in the final GWPZ map.

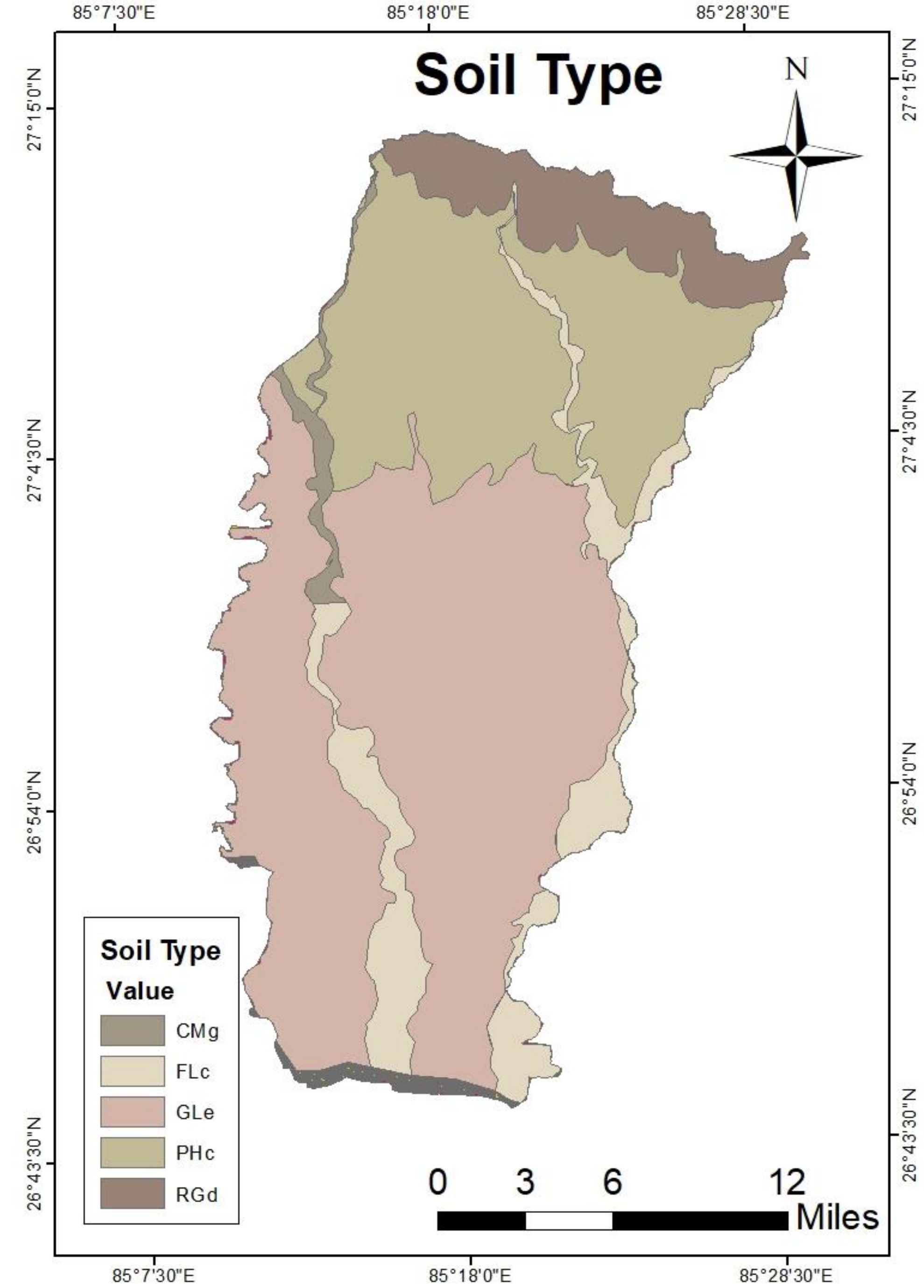


Figure 4.3 Spatial Distribution of Soil Types in Rautahat District

4.1.4 Geomorphology Map (Figure 4.4)

The geomorphological structure of Rautahat District is primarily shaped by its position within the Terai alluvial plains, resulting in landforms that are highly conducive to groundwater recharge and storage. The geomorphology map reveals that the district is overwhelmingly dominated by floodplains, low-lying plains, and valley-floor deposits, which collectively form the most suitable terrain for groundwater accumulation. These units are characterized by thick sequences of unconsolidated alluvium, gentle surface gradients, and well-developed depositional environments, all of which facilitate high infiltration and sustained aquifer replenishment. Their broad extent across the central and southern regions establishes them as the most influential geomorphic contributors to groundwater potential in the area.

In addition to the extensive plains, the district contains limited areas of river terraces and low-gradient footslopes, primarily along transitional zones toward the northern boundary. These landforms represent slightly elevated surfaces shaped by historic river channel migration and sedimentary processes. While they retain moderate permeability and support groundwater occurrence, their infiltration capacity is lower than that of the active floodplains. The terraces tend to exhibit older, more compacted sediments, which slightly reduce the rate of vertical percolation.

Toward the extreme northern margins, isolated patches of structural hills and steeper gradients emerge as the land begins transitioning toward the Siwalik foothills. These units are composed of semi-consolidated and consolidated materials, often fractured but less capable of sustaining significant groundwater storage. Their steeper slopes encourage rapid runoff and limit the development of thick sedimentary aquifers, making them the least favorable geomorphic zones for groundwater potential within the district.

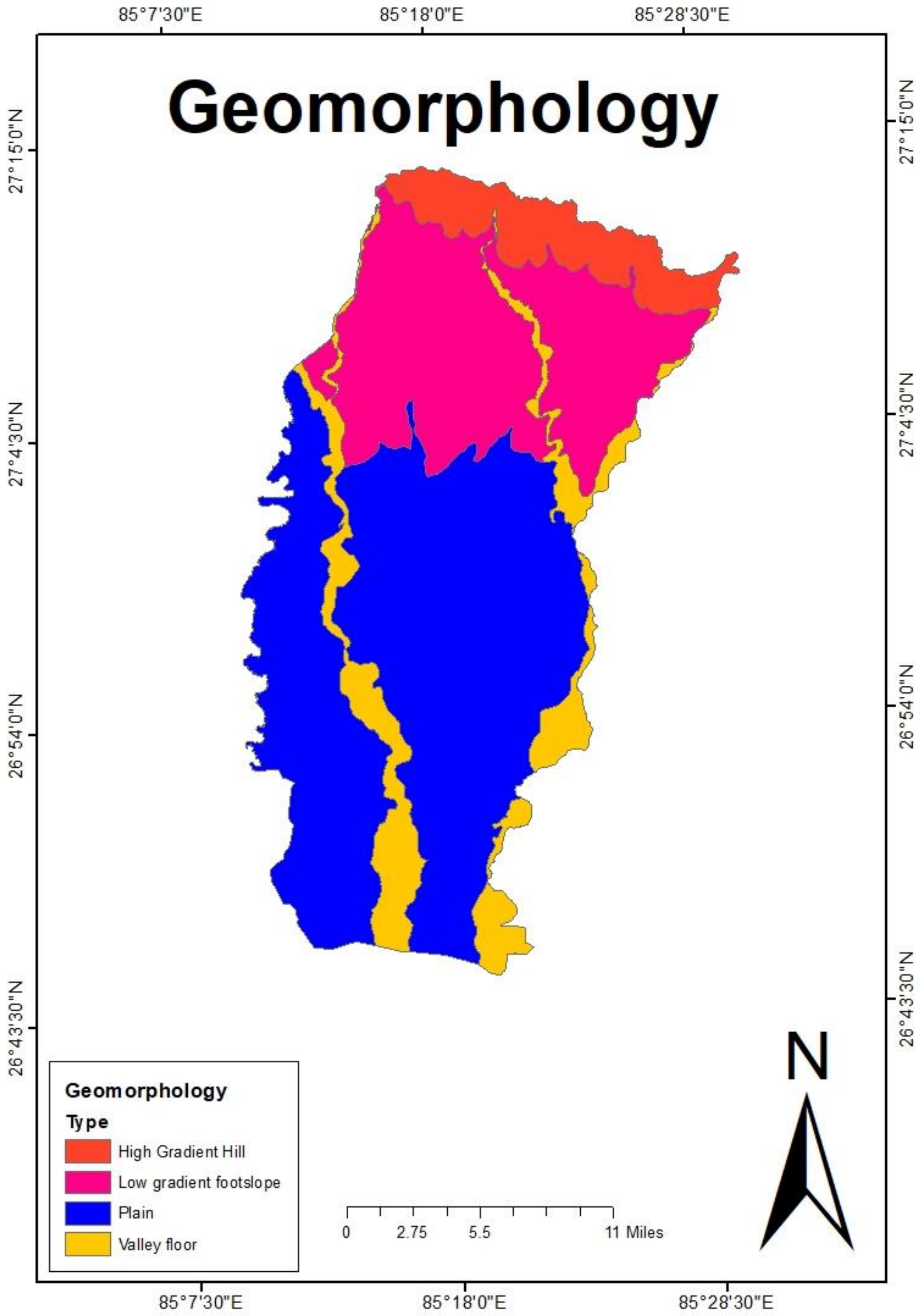


Figure 4.4 Geomorphological Distribution of Rautahat District

4.1.5 Land Use / Land Cover Map (Figure 4.5)

The Land Use/Land Cover (LULC) pattern of Rautahat District reflects the characteristic landscape of the Terai region, where agriculture and settlement expansion dominate the land surface. The LULC map shows that cropland is by far the most extensive land use category, covering the majority of the district's area. These agricultural fields, composed largely of irrigated and rainfed farmland, tend to support moderate groundwater recharge due to regular soil exposure and infiltration during irrigation cycles. Although infiltration is reduced during peak cultivation when soil compaction increases, cropland still remains a moderately favorable land use for groundwater potential.

Significant patches of forest and other wooded land occur along the northern margins and in scattered pockets. These vegetated areas enhance infiltration through root-induced soil permeability and reduced surface runoff, contributing positively to groundwater recharge. The presence of forest cover in upland transitional regions also stabilizes slopes and supports infiltration-driven aquifer replenishment.

The map also identifies riverbeds and waterbodies, particularly along the major drainage channels in the central and southern parts of the district. These zones represent locations of shallow water tables and direct interaction between surface water and groundwater. Their sandy sediment composition and high permeability make them the most favorable LULC category for groundwater accumulation.

Conversely, built-up areas are concentrated around urban centers and major transportation corridors. These regions consist of impervious surfaces such as concrete and asphalt, which significantly hinder infiltration and increase runoff. As a result, built-up land represents the least favorable category for groundwater recharge. Smaller tracts of bare soil and barren land also appear in limited areas, typically exhibiting low permeability and reduced suitability for groundwater movement.

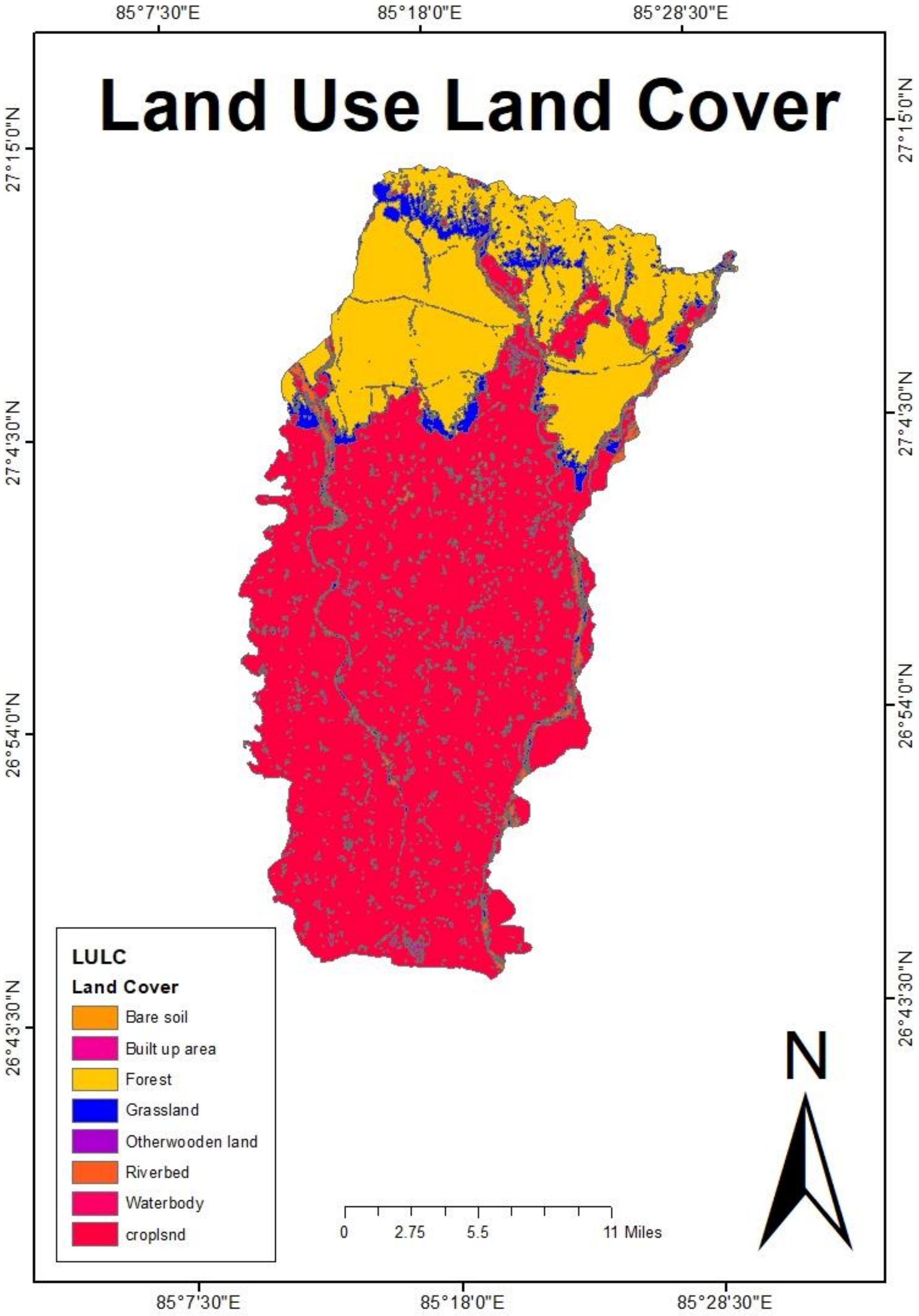


Figure 4.5 Land Use/Land Cover (LULC) Distribution of Rautahat District

4.1.6 Rainfall Map (Figure 4.6)

The rainfall distribution across Rautahat District exhibits a spatial gradient that plays a significant role in regulating groundwater recharge. The rainfall map shows that the district generally receives moderate to moderately high monsoonal precipitation, with annual totals increasing gradually from the western and central regions toward the northeastern belt. Areas receiving more than 1500 mm of rainfall represent the highest recharge potential zones, as abundant precipitation directly enhances infiltration and contributes to aquifer replenishment, especially in the highly permeable alluvial sediments of the Terai plains.

Regions experiencing 1300–1500 mm of rainfall constitute a substantial portion of the district and fall within the “high recharge” category. These areas maintain a consistent water balance that supports both shallow and deep aquifer recharge. The central belt, which predominantly receives 1100–1300 mm, represents moderate rainfall conditions. While recharge remains adequate in these zones, the combined influence of soil texture, land use, and drainage patterns determines the actual infiltration rate.

Areas receiving 900–1100 mm represent moderately low recharge potential and are generally located toward the southwestern margins. Although these areas still sustain groundwater recharge due to favorable soil and geomorphological conditions, rainfall alone contributes less significantly compared to higher precipitation zones. Very low rainfall areas (<900 mm) are minimal or nearly absent within the district.

Overall, the rainfall distribution aligns well with the hydro-geomorphic characteristics of Rautahat. The gradual northward increase in precipitation enhances groundwater recharge in the upper alluvial plains, while moderate rainfall in the central and southern regions is compensated by highly permeable soils and flat terrain. The spatial trend depicted in the rainfall map reinforces the district’s naturally favorable conditions for groundwater availability.

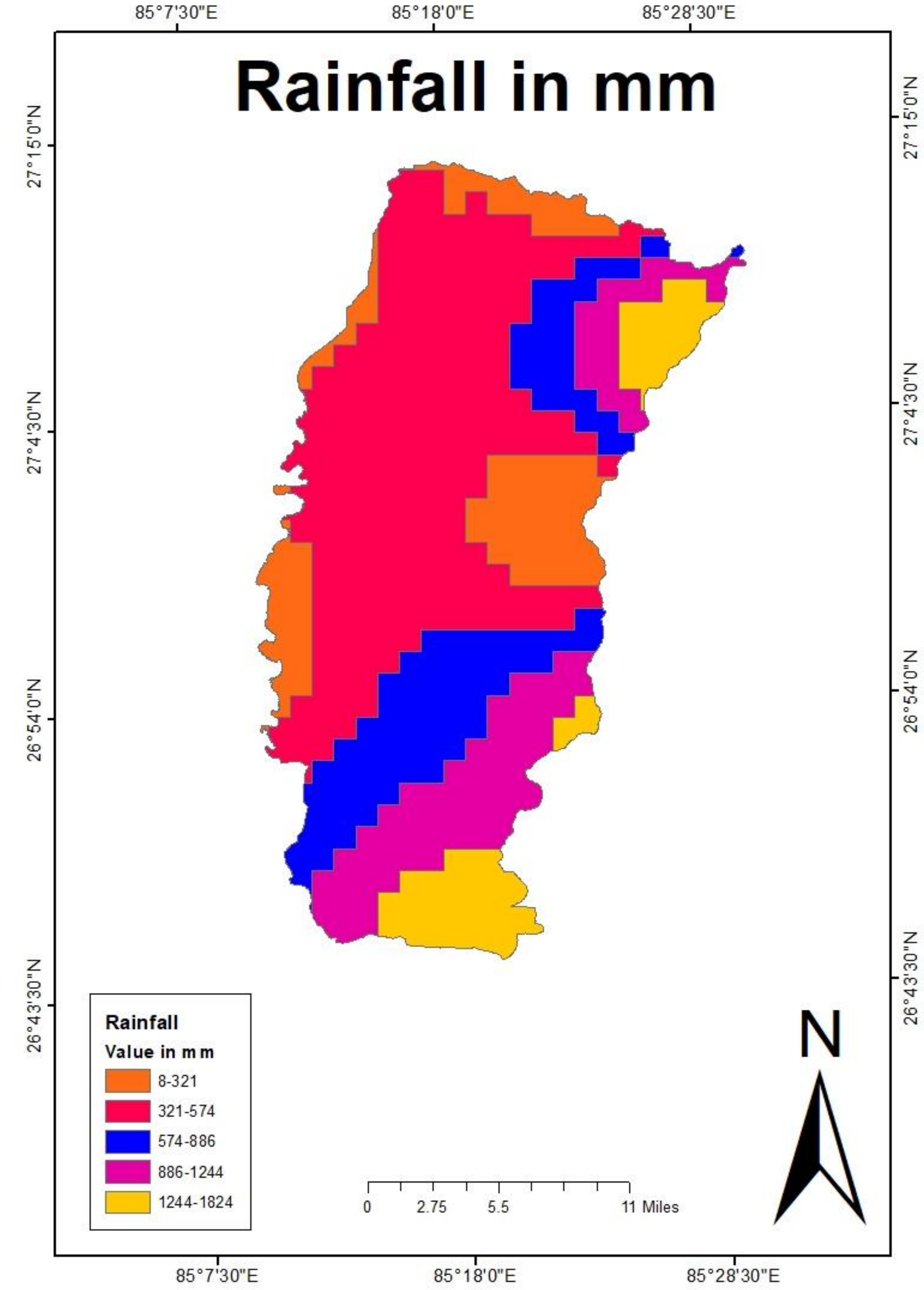


Figure 4.6 Spatial Distribution of Mean Annual Rainfall in Rautahat District

4.1.7 Drainage Density Map (Figure 4.7)

The drainage density pattern of Rautahat District reflects the interplay between surface runoff, infiltration capacity, and underlying geomorphology. The map shows that the district is dominated by low to moderately low drainage density, particularly across the central and southern plains where values generally range from 0 to 1.0 km/km². These areas exhibit permeable alluvial sediments and gentle slopes, allowing most rainfall to infiltrate rather than flow as surface runoff. Consequently, low drainage density corresponds strongly with zones of high groundwater recharge and forms one of the most favorable indicators for groundwater potential within the study area.

Moderate drainage density values between 1.0 and 1.34 km/km² occur in transitional regions, marking zones where infiltration remains feasible but is partially reduced due to either compacted soils or micro-topographic variations. These areas still contribute to groundwater recharge but to a lesser extent compared to the lower drainage density zones in the central plains.

Higher drainage density values, ranging from 1.34 to 2.60 km/km², are mostly confined to the northern fringe of the district, where slopes increase and surface runoff becomes more pronounced. These regions are closer to the foothill zones and contain relatively less permeable soils and geomorphic units, resulting in reduced infiltration and lower groundwater potential. Streams in these areas tend to be closely spaced, indicating more rapid water movement over the surface and limited opportunities for recharge.

Overall, the drainage density map underscores the favorable hydrogeological setting of the district, where **the predominance of low drainage density aligns with the extensive alluvial plains and gentle slopes**, reinforcing high groundwater availability. The spatial distribution of drainage density complements other thematic layers — particularly slope, geomorphology, and soil type — and collectively supports the groundwater potential patterns observed in the GWPZ analysis.

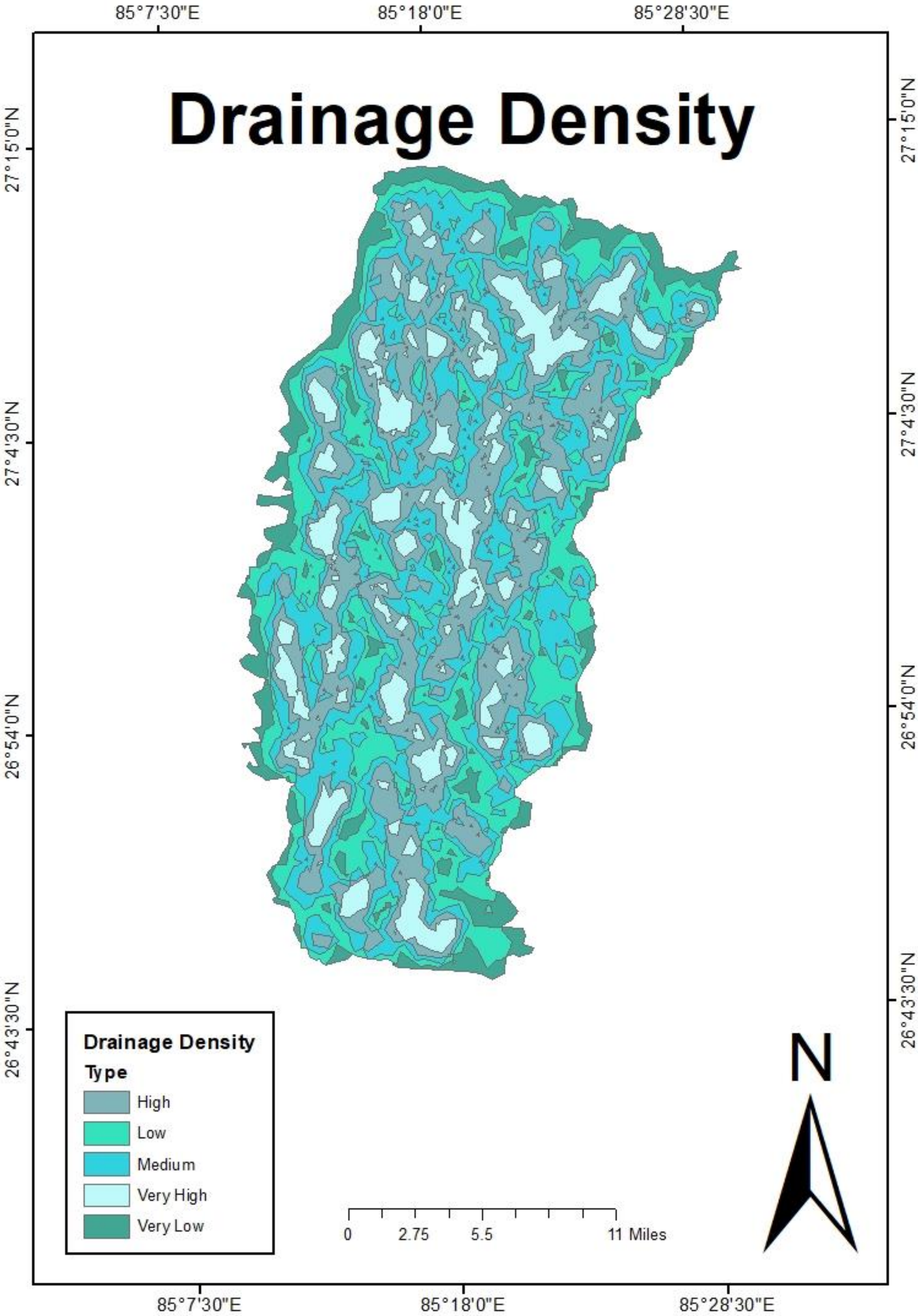


Figure 4.7 Spatial Distribution of Drainage Density in Rautahat District

4.1.8 Lineament Density Map (Figure 4.8)

The lineament density map of Rautahat District highlights the structural controls influencing groundwater movement and secondary porosity within the subsurface. Lineaments, interpreted from satellite imagery and hillshade-enhanced DEM visualization, represent fractures, joints, and linear geological features that often act as preferential pathways for groundwater flow. The map shows that the district is characterized predominantly by low to moderate lineament density, reflecting the relatively stable and gently deformed nature of the Terai alluvial plains.

Areas with the highest lineament density (1.06–1.77 km/km²) occur in localized patches, primarily toward the northern and northeastern margins. These zones are structurally more influenced by proximity to the Siwalik foothills and exhibit increased fracturing and deformation. Such areas offer enhanced secondary permeability, allowing groundwater to move more efficiently along fracture networks. Although these regions constitute a smaller portion of the district, their structural characteristics make them valuable corridors for groundwater accumulation.

Moderate lineament densities ranging from 0.40 to 1.06 km/km² are distributed across transitional zones between the northern and central plains. These regions contain a mix of subtle structural features and alluvial deposits, providing moderate opportunities for groundwater movement. While primary porosity dominates the aquifer characteristics of the Terai, the presence of moderate lineament density supports secondary porosity and can locally enhance recharge.

The majority of the central and southern plains exhibit low lineament density (0–0.40 km/km²), reflecting thick, horizontally deposited alluvium with minimal structural disturbance. In these regions, groundwater storage and movement are governed primarily by the high permeability of the sedimentary matrix rather than structural features. Although low lineament density indicates limited contribution from fractures, the thick alluvial layers in the plains compensate through strong primary porosity and infiltration-driven recharge.

Overall, the lineament density distribution emphasizes that while structural features play a supplementary role in groundwater occurrence, Rautahat's groundwater potential is largely driven by its alluvial geomorphology, permeable soils, and flat terrain. The map provides an important structural perspective that supports the spatial patterns observed in the final GWPZ analysis.

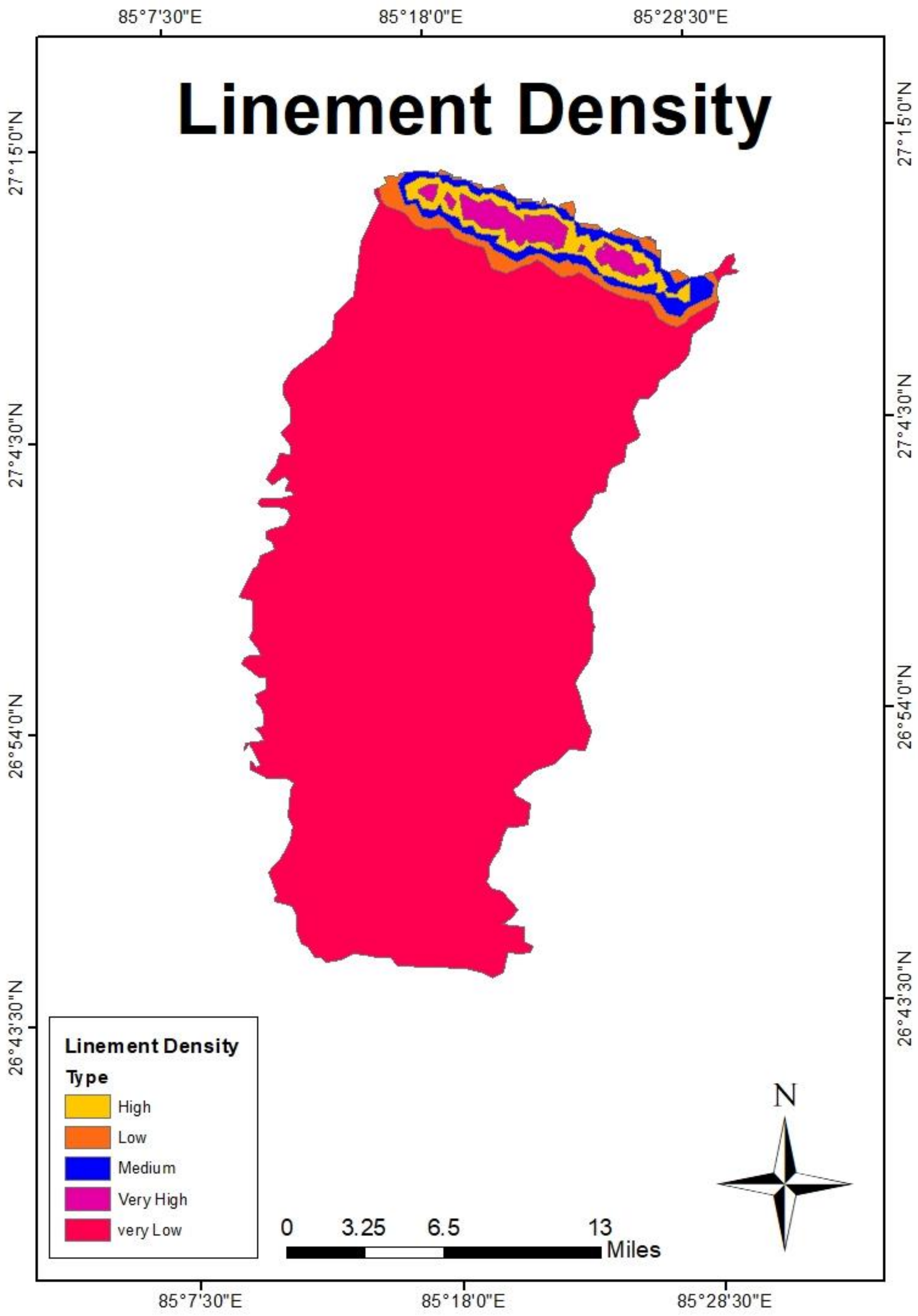


Figure 4.8 Spatial Distribution of Lineament Density in Rautahat District

4.2 Thematic Layers Used for BCSI

The thematic maps generated from these factors are presented below and provide a visual representation of their spatial distribution within the study area.

4.2.1 Slope Map (Figure 4.1)

The slope characteristics of the study area play a central role in determining construction suitability because terrain stability, excavation feasibility, and foundation performance are directly influenced by ground gradient. The slope map shows that the majority of Rautahat District consists of very gentle terrain, with slopes between 0° and 2.78°, forming the most favorable category for construction activities. These flat surfaces support low-cost site preparation, minimal earthwork requirements, and high structural stability, making them the most suitable zones for built infrastructure.

Moderately gentle slopes ranging from 2.78° to 8.84° also occupy a substantial portion of the landscape and remain highly suitable for construction. These areas may require minor grading or leveling but still offer favorable foundation conditions. Slopes between 8.84° and 18.96° represent moderately suitable terrain where construction is feasible but may demand engineered cut-and-fill operations, slope stabilization, or terracing to ensure structural safety.

Higher slope classes (18.96°–30.34° and >30°) appear only in very limited patches toward the northern region. These steeper zones are associated with increased erosion potential, greater instability, and higher construction cost due to significant earthwork and reinforcement needs. As a result, they fall within the poor or unsuitable suitability categories.

4.2.2 Land Use / Land Cover Map (Figure 4.5)

The Land Use/Land Cover (LULC) characteristics of Rautahat District significantly influence construction suitability by reflecting ground surface conditions, environmental constraints, and the cost of site preparation. The LULC map reveals that the district contains a heterogeneous mixture of agricultural land, built-up zones, forested areas, water bodies, and grasslands, each contributing differently to construction feasibility.

Bare soil areas represent the most favorable category for construction suitability. These surfaces are typically open, exposed, and free from vegetation or structural obstruction, making them ideal for development with minimal clearing costs. They also provide direct visibility of underlying soil conditions, allowing easier assessment for foundation design. Similarly, **grasslands** offer suitable conditions due to shallow-rooted vegetation and relatively undisturbed soil profiles, requiring limited effort to prepare the ground for construction.

Cropland constitutes a large portion of the district and is categorized as moderately suitable. Although the terrain is largely flat and accessible, agricultural soils may contain variable moisture levels, loose topsoil, or seasonal saturation, necessitating moderate stabilization measures before construction. These lands are feasible for development but often require careful geotechnical evaluation to account for soil strength variations.

In contrast, forest areas and other wooded lands are classified as poorly suitable due to the presence of dense vegetation, deeper root systems, and organic-rich soils. Clearing forests incurs higher environmental and economic costs, and the organic content within the soil weakens foundation stability, requiring substantial ground modification.

The least suitable classes include built-up areas, riverbeds, and waterbodies. Built-up zones are already occupied by existing infrastructure, limiting opportunities for new construction and often involving demolition or redevelopment challenges. Riverbeds and waterbodies represent dynamic or saturated environments with unstable sediment, high flooding risk, and extremely low bearing capacity, making them unsuitable for construction without major engineering intervention.

Overall, the LULC distribution indicates that while certain areas of Rautahat—particularly bare soil and grasslands—are highly favorable for construction, other land cover types impose functional, environmental, or geotechnical constraints. This spatial variability is effectively captured in the BCSI model and reflected in the district’s construction suitability pattern.

4.2.3 Geomorphology Map (Figure 4.4)

The geomorphological setting of Rautahat District exerts a significant influence on construction suitability, as landform characteristics determine terrain stability, foundation competency, and overall engineering feasibility. The geomorphology map reveals that the district is overwhelmingly dominated by plain landscapes, which constitute the most favorable construction environments. These plains are underlain by thick alluvial deposits, exhibit negligible relief, and provide uniform bearing capacity—making them highly suitable for infrastructure development with minimal stabilization requirements. As a result, the plain units form the highest suitability category within the BCSI framework.

Adjacent to these flat surfaces, areas categorized as low-gradient footslopes occur as transitional zones, primarily toward the northern segment of the district. These landforms gently merge into the plains and exhibit moderate sediment compaction with relatively stable terrain conditions. Their gentle relief and manageable engineering characteristics place them in the "suitable" category for construction, requiring only minor site preparation or localized slope treatment.

In contrast, valley-floor environments, though largely flat, are associated with seasonal water accumulation, shallow water tables, and relatively poor drainage characteristics. These conditions pose constraints for foundation design and increase the risk of moisture-related structural issues. Consequently, valley-floor geomorphic units are classified as "poorly suitable," indicating the need for ground improvement measures before construction.

Toward the northern edge, isolated patches of high-gradient hills appear, marking terrain influenced by the Siwalik foothills. These units consist of steeper slopes, irregular topography, and relatively less consolidated geological materials. Their inherent instability, combined with elevated erosion and slope-failure risk, renders them unsuitable for construction without extensive engineering intervention.

Overall, the geomorphology map indicates that Rautahat is naturally well-suited for construction, with plains and low-gradient zones dominating the district. The limited presence of high-gradient hills and valley-floor constraints ensures that geomorphology contributes positively to the BCSI model while highlighting specific zones where engineering caution is warranted.

4.2.4 Population Density Map (Figure 4.9)

Population density is an important indicator of construction suitability because it reflects land availability, development pressure, and the degree of existing urbanization. The population density map of Rautahat District exhibits a clear spatial gradient, with higher density clusters concentrated around major settlements and transportation corridors, while sparsely populated areas dominate the peripheral and agricultural regions. This pattern directly influences construction feasibility by highlighting areas where land is either constrained by existing development or remains widely open for future infrastructure expansion.

The highest suitability zones correspond to areas with very high population density (1113–1804 persons/km²), where existing urban activity and infrastructure networks create favorable conditions for new development. These zones already possess access to roads, utilities, services, and stable socio-economic activity, making them attractive for construction with minimal additional investment. Locations with high to moderate population density (580–1113 persons/km²) also demonstrate considerable construction potential. Such areas reflect transitional peri-urban landscapes where land remains partially available while still benefiting from proximity to established settlements.

On the other hand, regions with low population density (260–580 persons/km²) indicate limited development and restricted service accessibility. While open land is available, the absence of supporting infrastructure increases construction cost and reduces immediate practicality. The sparsely populated areas with very low population density (0–260 persons/km²) represent the least suitable category. These zones typically include remote agricultural lands, isolated pockets of settlement, and environmentally sensitive areas where infrastructure expansion would require substantial investment and may not align with existing development patterns.

Overall, the population density map highlights that construction suitability in Rautahat is closely linked to settlement distribution. Highly and moderately populated zones are the most practical for development due to established services and accessibility, whereas sparsely populated regions present logistical and economic challenges. These patterns are effectively integrated into the BCSI model, ensuring that suitability outcomes reflect both physical and socio-economic realities of the district.

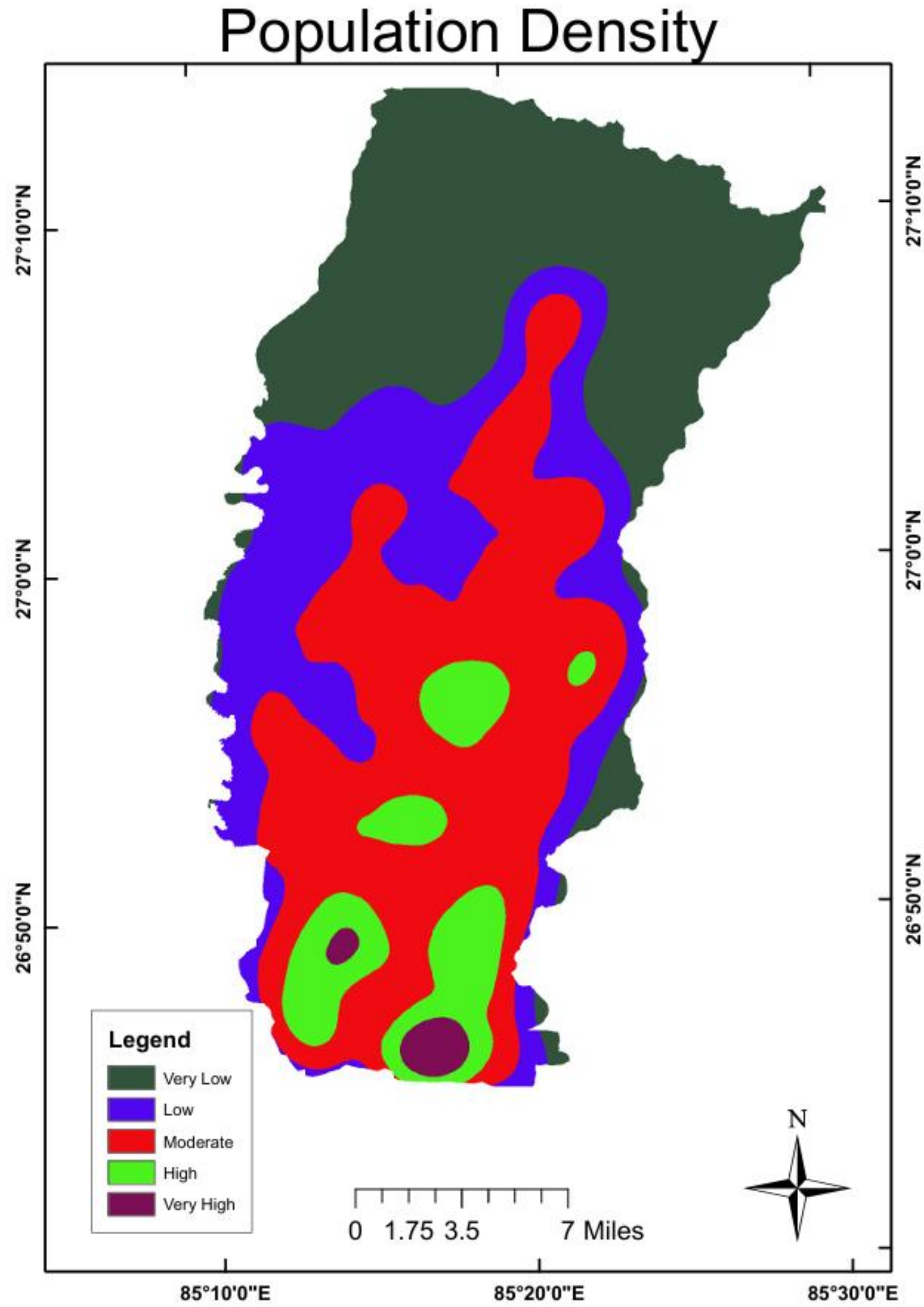


Figure 4.9 Spatial Distribution of Population Density in Rautahat District

4.2.5 Groundwater Condition (Dewatering Cost) Map (Figure 4.10)

Groundwater condition, represented indirectly through the Groundwater Potential Zone (GWPZ) classes, is a critical determinant of construction suitability in Rautahat District because it strongly influences the anticipated dewatering cost during excavation. Areas with a shallow groundwater table or high groundwater potential typically incur increased costs for foundation works, while zones with deeper groundwater levels are more favorable for construction due to reduced water-related challenges.

The groundwater condition map reveals that areas classified as “Very Good” and “Good” groundwater potential—which correspond to low dewatering cost—are the most suitable for construction. These zones exhibit deeper water tables or moderate aquifer productivity, meaning excavation pits experience minimal inflow of groundwater. Construction activities such as footing excavation, trenching, and installation of underground utilities can proceed with reduced pumping requirements and lower risk of structural instability.

Moderate groundwater potential zones present intermediate suitability. While construction is feasible, moderate inflow of groundwater may necessitate temporary pumping or localized dewatering measures. Such areas often require careful planning during the monsoon season, when groundwater levels fluctuate more significantly.

In contrast, Poor and Very Poor groundwater potential zones represent areas with a high groundwater table or highly permeable alluvial layers. These zones require substantial dewatering efforts during excavation, leading to increased construction time, higher operational costs, and potential risks such as trench collapses or soil piping. As a result, these areas are classified as the least suitable for construction within the BCSI framework.

Overall, the groundwater condition map highlights that dewatering cost is a decisive factor in evaluating construction feasibility in the Terai region. By incorporating this layer into the BCSI model, the assessment captures the true economic and engineering challenges associated with shallow groundwater conditions, ensuring that suitable zones reflect realistic construction constraints.

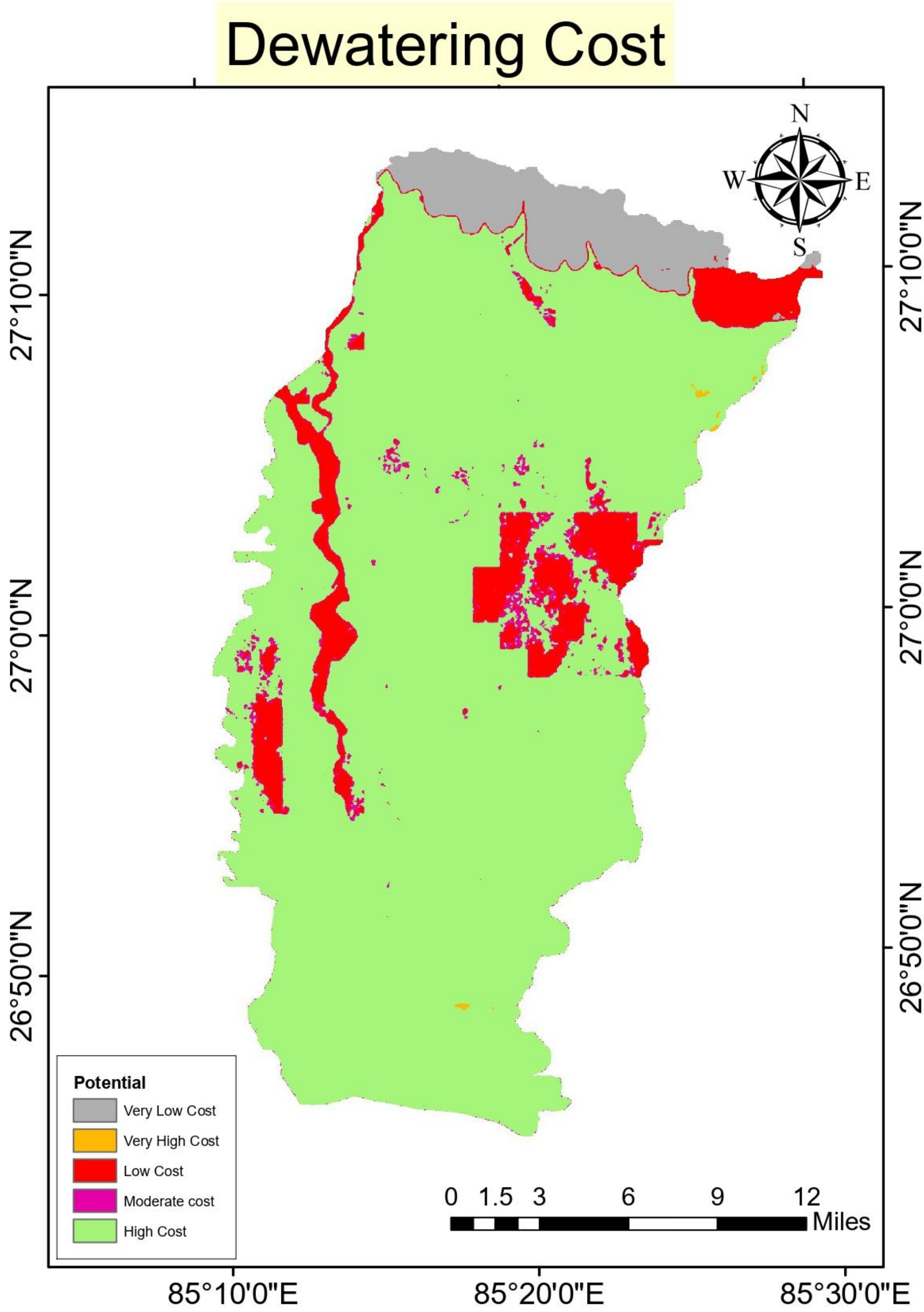


Figure 4.10 Dewatering Cost Based on Groundwater Potential

4.2.6 Soil Type / Geology Map (Figure 4.11)

Soil type and geological conditions play a foundational role in determining construction suitability, as they directly influence bearing capacity, settlement characteristics, excavation feasibility, and overall ground stability. The geological framework of Rautahat District is predominantly alluvial, yet notable variations exist across the terrain, reflecting differences in depositional history and material composition. These variations are captured in the soil type/geology map and translated into construction suitability classes.

The most favorable geological units for construction in the district are those dominated by sandstone, greywacke, and arkose materials, which collectively form the "most suitable" class. These lithological units exhibit relatively high strength, moderate permeability, and good load-bearing characteristics, making them ideal for shallow foundations and structural works with minimal ground improvement. Their consolidated nature ensures stability under load and reduced susceptibility to differential settlement.

Moderately suitable areas correspond to calcareous fluvial deposits, which consist of riverine sediments partially cemented by calcium carbonate. While generally stable, these units may exhibit variable compaction and moderate compressibility, requiring attention during foundation design. Despite these considerations, their performance remains adequate for most typical construction activities in the Terai region.

In contrast, fluvial non-calcareous deposits—classified as poorly suitable—constitute the least favorable geological units for construction. These materials are typically loose, fine-grained sands and silts deposited by active river systems. Their weak structure, higher compressibility, and low bearing capacity pose challenges for engineering works, often necessitating soil stabilization, deep foundations, or pre-loading strategies to ensure structural stability. Additionally, these deposits are more prone to settlement and liquefaction under dynamic loading.

Within the context of the BCSI model, the geological map thus serves as a critical layer that identifies where natural ground conditions inherently favor construction and where additional engineering interventions may be required. By integrating lithological variability into the suitability assessment, the BCSI framework ensures a realistic and geotechnically sound classification of construction potential across the Rautahat District.

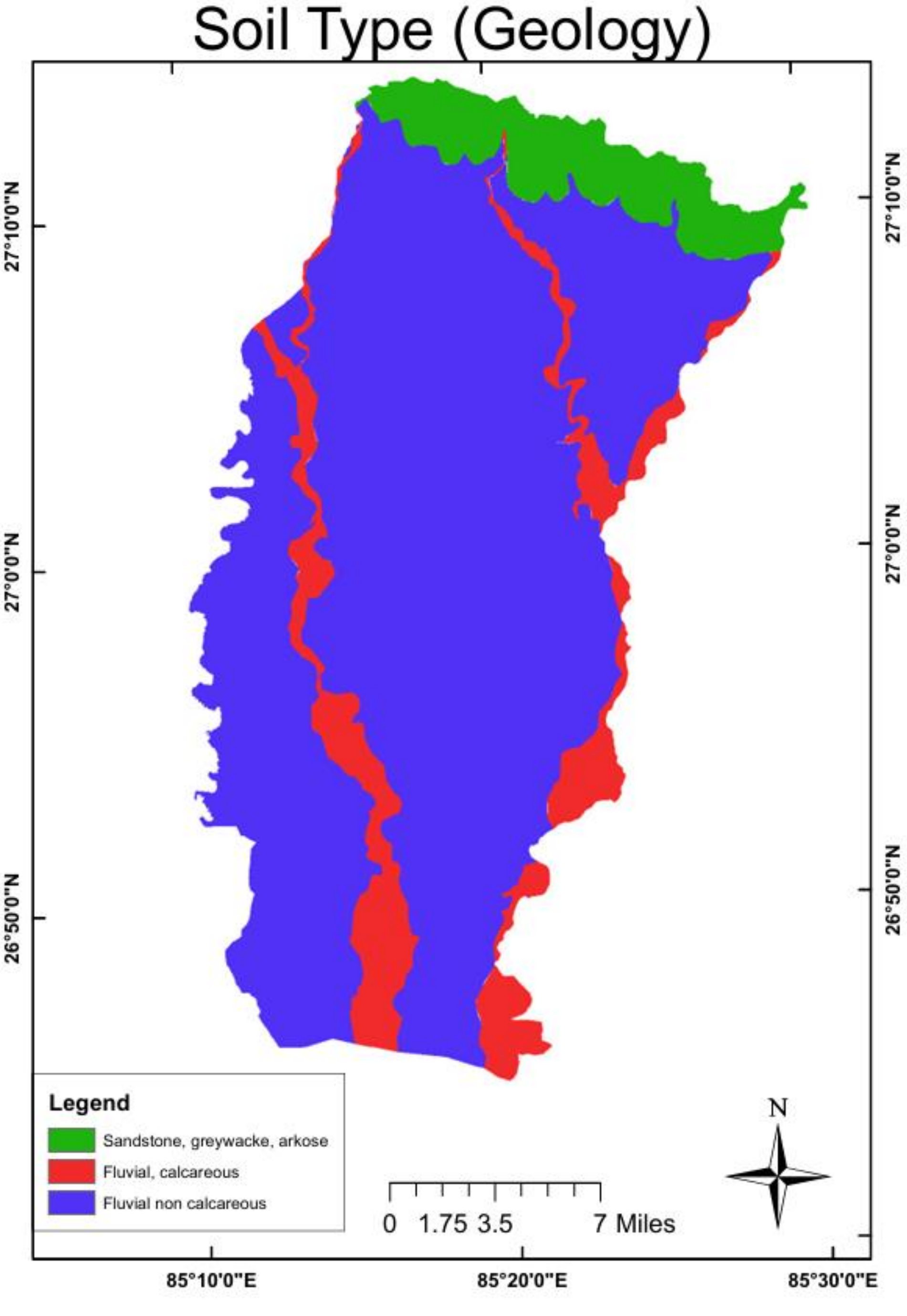


Figure 4.11 Spatial Distribution of Soil Type (Geology) in Rautahat District

4.2.7 Road Proximity / Accessibility Map (Figure 4.12)

Accessibility is a key determinant of construction suitability, as proximity to existing road infrastructure directly influences material transport, labor mobility, construction logistics, and overall project cost. In rapidly developing regions like Rautahat District, areas closer to the existing road network offer significant operational advantages, while distant or poorly connected areas pose logistical challenges. The road proximity map, therefore, plays a crucial role in the Building Construction Suitability Index (BCSI) model.

The analysis shows that land located within 0–500 meters of major or secondary roadways is classified as very highly suitable for construction. These locations benefit from minimal transport cost, ease of equipment mobilization, and efficient supply-chain connectivity. Such proximity also enhances the economic viability of development projects and accelerates construction timelines.

Zones situated 500–1000 meters from roads exhibit high suitability. While still well connected, these areas may require minor adjustments or temporary access tracks during construction. Nonetheless, they retain strong development potential because transport and logistical constraints remain relatively low.

Areas falling between 1000–2000 meters are classified as moderately suitable. These locations may require extended haulage distances or temporary road improvements, which can increase construction cost and time. However, they remain feasible for development, especially in peri-urban regions experiencing gradual expansion.

Suitability declines significantly beyond 2000 meters, where land falls into the “low” (2000–3000 m) and “very low” (>3000 m) categories. These areas face multiple logistical limitations such as long transport routes, increased vehicle operating costs, and difficulty mobilizing heavy machinery. Construction in these zones often requires the creation of new access roads, which can substantially raise the initial project cost.

Overall, the road proximity layer highlights the strong influence of infrastructure connectivity on construction feasibility. It demonstrates that accessibility is not only a matter of convenience but a fundamental engineering and economic criterion. Integrating this layer into the BCSI ensures that suitability classifications align with practical implementation realities and long-term development potential across the district.

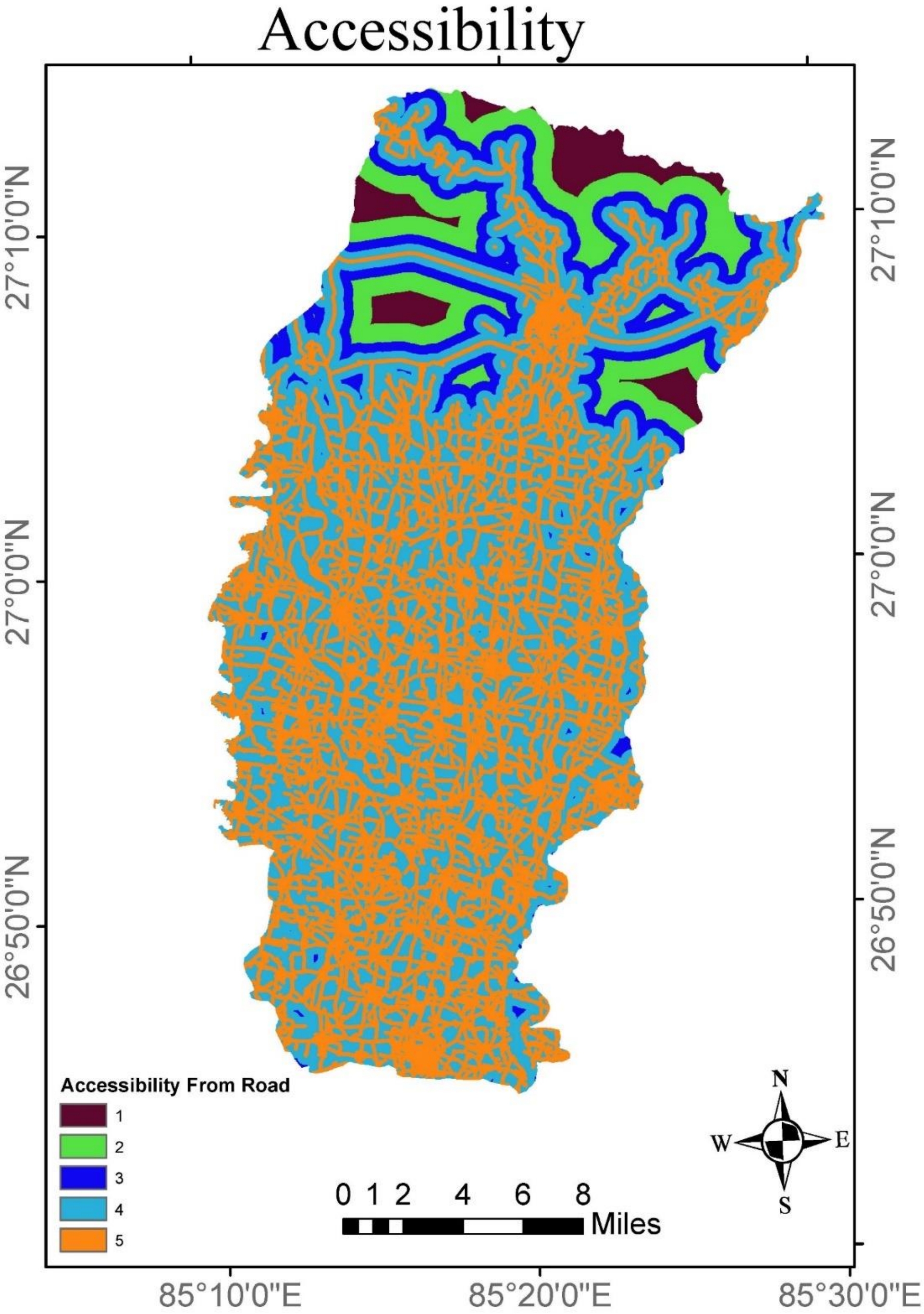


Figure 4.12 Accessibility (Road Proximity) Map of Rautahat District

4.3 Groundwater Potential Zone (GWPZ) –Results and Interpretation

The Groundwater Potential Zone (GWPZ) map of Rautahat District was generated by integrating eight hydrogeological parameters—slope, lithology, soil type, geomorphology, rainfall, drainage density, land use/land cover, and lineament density—through an AHP-weighted overlay analysis. The final map (Figure 4.13) classifies the district into five groundwater potential categories: **Very Poor, Poor, Moderate, Good, and Very Good**. These classes represent the relative spatial favorability for groundwater occurrence and reflect the combined influence of terrain characteristics, recharge conditions, subsurface lithology, and hydrological dynamics.

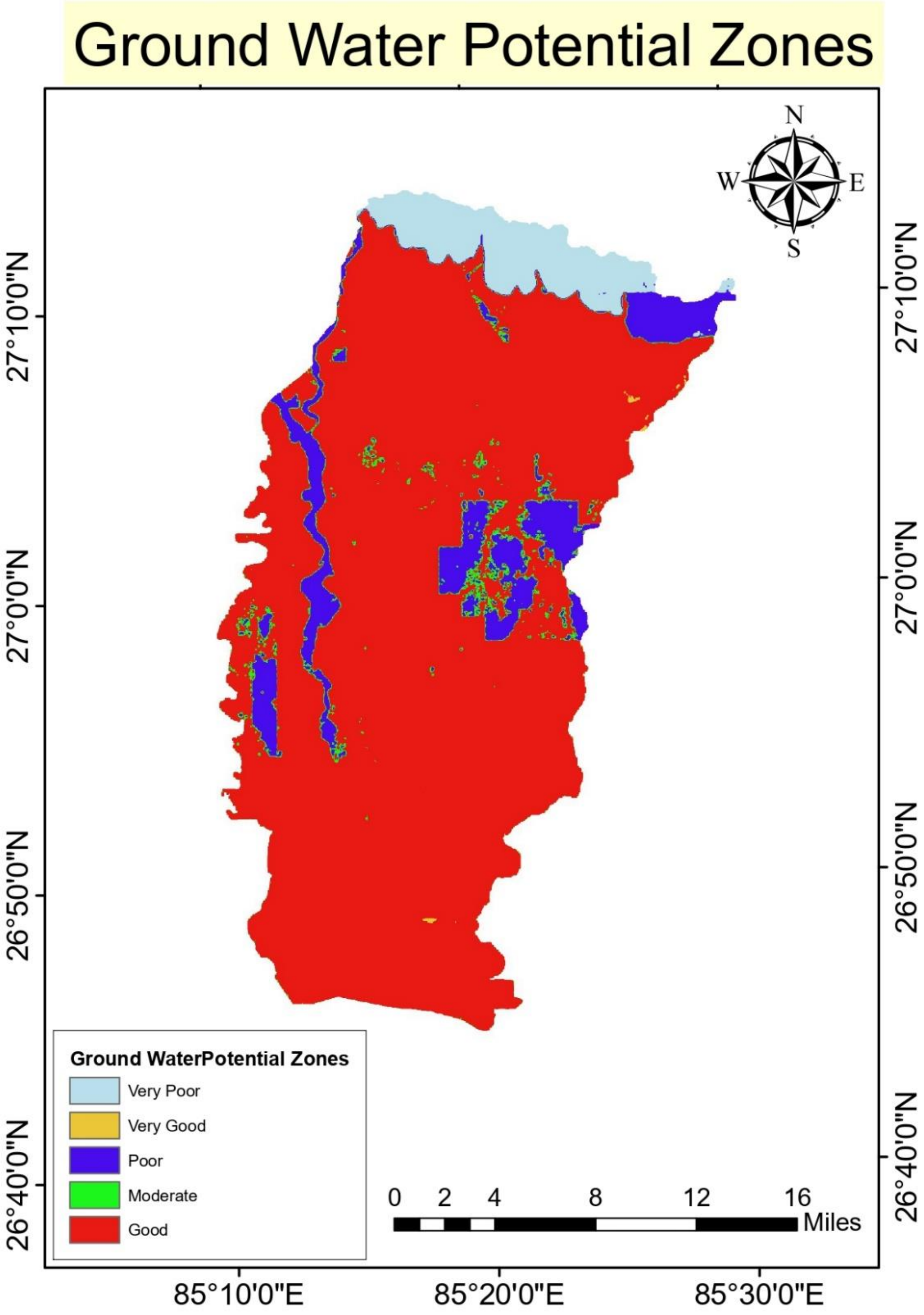


Figure 4.13 Groundwater Potential Zones of Rautahat District

The results show a strong dominance of the **Good Groundwater Potential** class, which accounts for **83.07%** of the total area. This reflects the district's typical Terai alluvial environment—characterized by flat topography, thick unconsolidated sediments, and high infiltration capacity—making it inherently favorable for groundwater storage and movement. In contrast, only **0.07%** of the area falls into the **Very Good** category, indicating that extremely high-potential zones are spatially limited and controlled by localized conditions such as high lineament density, permeable fluvial deposits, and shallow water-table dynamics.

Poor and Very Poor groundwater potential zones collectively represent **14.53%** of the district. These areas are mainly associated with regions having higher drainage density, clay-rich soil units, or less permeable lithology. The **Moderate** class covers **2.33%**, representing transitional zones between the highly favorable central plains and the relatively constrained western or southeastern pockets. Overall, the spatial distribution of GWPZ values indicates that groundwater availability is abundant across most of Rautahat District, with only a limited fraction exhibiting restrictions.

A quantitative summary of the groundwater potential distribution is provided in Table 4.1.

Groundwater Potential Class	**Pixel Count**	**Percentage (%)**	**Area (km^2)**
Very Poor	71,379	6.19	69.7
Poor	96,181	8.34	93.91
Moderate	26,828	2.33	26.23
Good	957,785	83.07	935.18
Very Good	788	0.07	0.79
Total	**1,152,961**	**100**	**1126.12**

Table 4.1 Area Distribution of Groundwater Potential Zones

4.3.1 Spatial Interpretation of GWPZ Patterns

The spatial pattern of GWPZ across Rautahat District reveals a hydrogeological environment strongly controlled by depositional setting and geomorphology. The **central and southern plains** exhibit extensive stretches of the *Good* groundwater potential class. These areas are underlain by coarse-grained to moderately sorted alluvial deposits, enabling significant percolation and movement of groundwater. The combination of high permeability soils, flat terrain, and moderate lineament density supports favorable aquifer conditions.

The **Very Good** zones, though limited in areal extent, occur in places where multiple favorable factors coincide—particularly where permeable fluvial non-calcareous sediments overlap with moderate slope and enhanced structural connectivity. These represent highly productive groundwater pockets and may serve as priority sites for deeper borewells or future groundwater development.

Areas mapped as **Poor** and **Very Poor** potential are generally confined to regions characterized by fine-textured soils, higher drainage density, reduced lineament influence, or marginally elevated terrain. These zones reflect restricted infiltration and weaker storage capacity, suggesting that wells in these areas may have lower yields or require deeper drilling.The spatial pattern thus provides a clear hydrogeological gradient, with groundwater potential improving toward the central basin-like regions and diminishing toward the margins with less permeable lithology or greater surface runoff tendencies.

4.3.2 Validation Using Tubewell Data (Figure 4.14)

Validation of the Groundwater Potential Zone (GWPZ) map was performed using **31 tubewell locations** obtained from the Department of Water Resources and Irrigation (DWRI). These wells represent actual groundwater extraction points across the Rautahat District and provide an empirical basis for assessing the accuracy of the GWPZ model. Each tubewell was spatially overlaid on the final GWPZ map to identify the corresponding groundwater potential class.

The validation results demonstrate a strong agreement between the modeled groundwater potential and the observed tubewell distribution. Out of the 31 tubewells, **29 wells (93.55%)** fall within the **Good** and **Very Good** groundwater potential zones. This indicates that the areas classified as highly favorable by the model also correspond to locations where productive groundwater structures are already functioning successfully.

Only **one tubewell** falls in the **Moderate** potential zone, and **one** in the **Poor** potential zone. Importantly, **no tubewells** were located in the **Very Poor** groundwater potential class, reflecting the model's realistic characterization of limited aquifer suitability in those areas. This distribution is consistent with hydrogeological expectations, as wells are typically constructed in areas known to yield sufficient water.

The validation map (Figure 4.Y) clearly illustrates that productive tubewell clusters align with the high groundwater potential regions identified through the AHP-based weighted overlay approach. The strong correspondence between modeled potential and field evidence confirms the **reliability and predictive strength** of the GWPZ model for groundwater development planning in Rautahat District.

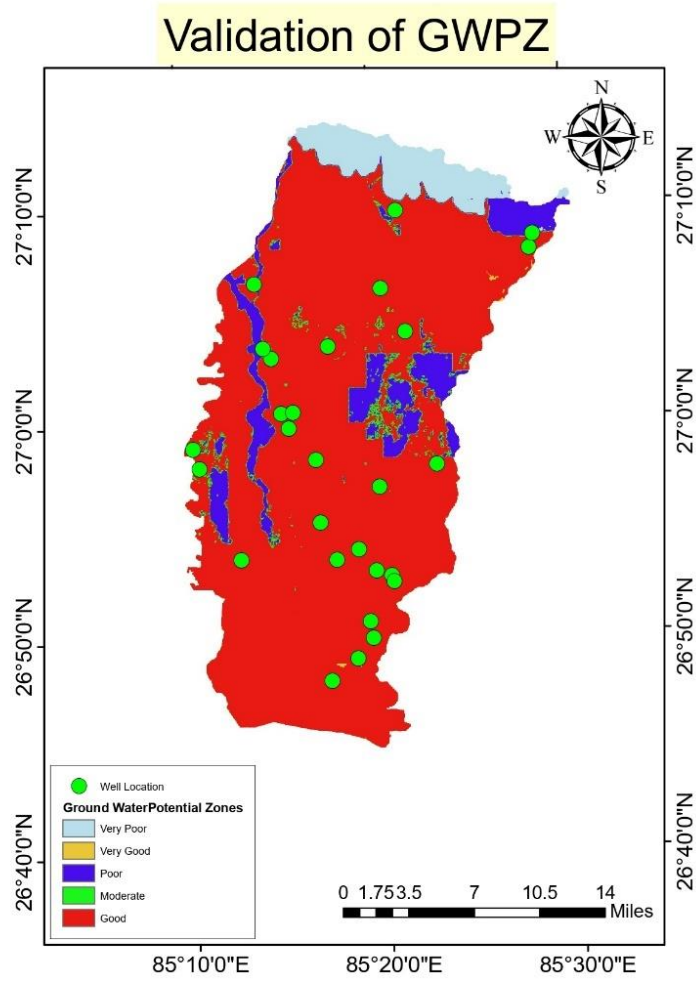


Figure 4.14 Validation of Groundwater Potential Zones Using Deep Tube-Well Locations in Rautahat District

4.4 Building Construction Suitability Index (BCSI) –Results and Interpretation

The Construction Suitability Index (BCSI) map of Rautahat District was generated by integrating seven construction-related factors—slope, geomorphology, land use/land cover, population density, groundwater condition (dewatering cost), soil type/geology and road proximity—using AHP-derived weights and a weighted overlay procedure. The final BCSI raster (Figure 4.14) was classified into five suitability classes: **Highly Suitable, Suitable, Moderately Suitable, Poor Suitable and Unsuitable**.

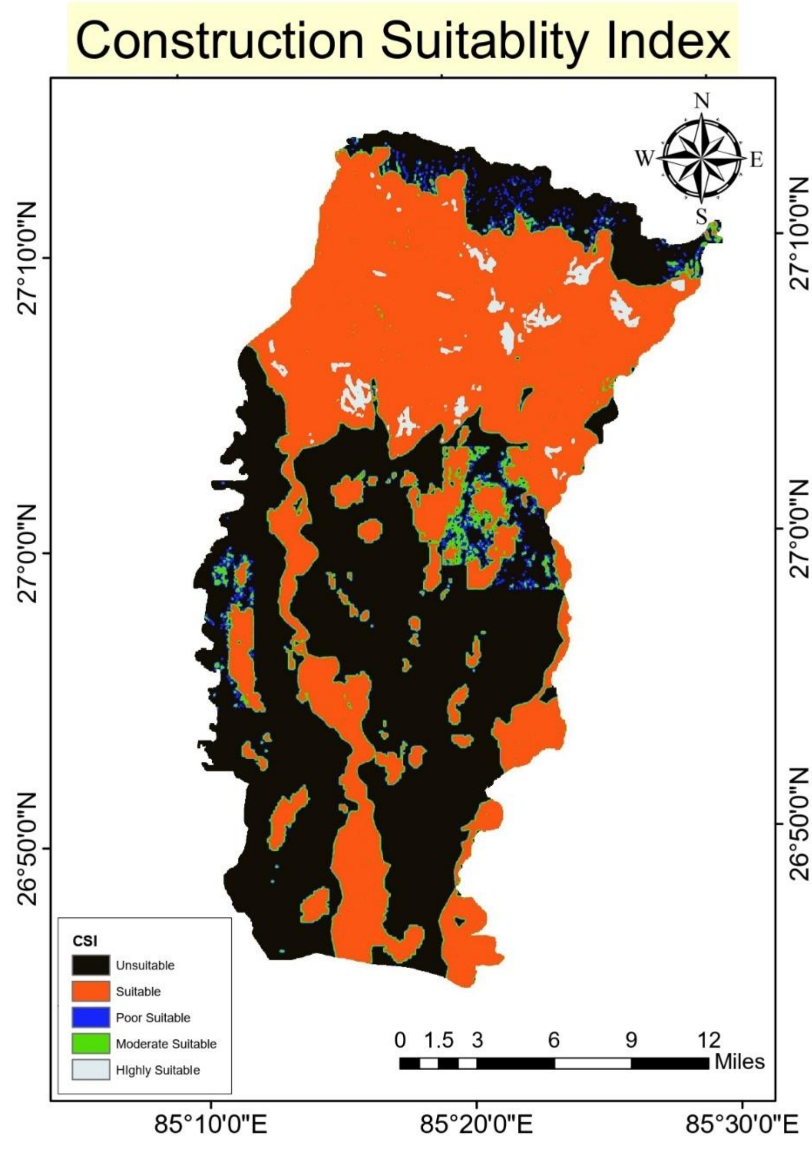


Figure 4.15 Construction Suitablity Index of Rautahat District

The results show that the district is largely divided between **Suitable** and **Unsuitable** terrain. The **Suitable** class covers **43.75%** of the total area, indicating that almost half of the district provides generally favorable conditions for construction in terms of terrain stability, accessibility and manageable dewatering cost. These areas coincide mainly with the gently sloping alluvial plains, moderate population density and good road access.The **Unsuitable** class occupies **46.99%** of the area and represents zones where one or more limiting factors are dominant—such as riverbeds and waterbodies, dense forest, high groundwater constraints, or unfavourable slope and geology. These locations would require substantial engineering intervention or are environmentally constrained, and therefore are not recommended for conventional building development.

The **Moderately Suitable** class accounts for **4.60%** of the district, forming transition belts between suitable and unsuitable terrain. In these areas construction is feasible, but may demand moderate ground improvement, drainage measures or careful site-specific design. The **Poor Suitable** zones cover **2.98%** of the area and correspond to locations where constraints such as higher slope, problematic land use or unfavourable soil conditions significantly reduce construction feasibility. Only **1.69%** of the district is classified as **Highly Suitable**, reflecting limited but exceptionally favourable pockets where flat terrain, good geology, low dewatering cost and excellent accessibility coincide.A quantitative summary of the BCSI distribution is given in Table 4.2.

BCSI Class	**Pixel Count**	**Percentage (%)**	**Area (km^2)**
Unsuitable	541,791	46.99	529.11
Poor Suitable	34,341	2.98	33.55
Moderate Suitable	52,985	4.60	51.8
Suitable	504,370	43.75	492.63
Highly Suitable	19,474	1.69	19.03
Total	**1,152,961**	**100 %**	**1126.12 km^2**

Table 4.2 Percentage Distribution of Construction Suitability Classes

4.4.1 Validation of the Building Construction Suitability Index (BCSI) Using Built-Up Area Distribution

Validation of the Building Construction Suitability Index (BCSI) was carried out by analyzing the spatial correspondence between the BCSI map and the existing built-up areas within Rautahat District. The rationale is that settlements tend to develop in locations that naturally exhibit favorable construction conditions—such as stable terrain, low flooding risk, accessible land cover, manageable groundwater conditions, and proximity to transportation networks. Therefore, if the BCSI model is reliable, a significant proportion of the current built-up area should fall within the Suitable and Highly Suitable classes.

To assess this relationship, the built-up layer was intersected with the BCSI raster, and the area of built-up land falling within each suitability class was quantified. The results are summarized in Table 4.3.

The results reveal a clear concentration of built-up development in the more favorable suitability classes. The highest share of built-up land—**7.991 km²**—falls within the *Suitable* category, demonstrating that existing settlements strongly align with areas predicted to offer favorable construction conditions. The *Highly Suitable* class, though limited in total district area, also contains **0.247 km²** of built-up land, reinforcing the model's identification of strategically favorable pockets.

BCSI Class	**Built-Up Area (km²)**	**Percentage (%)**
Highly Suitable	0.247	1.78%
Suitable	7.991	57.52%
Moderately Suitable	1.261	9.08%
Poor Suitable	0.393	2.83%
Unsuitable	4.000	28.79%

Table 4.3 Percentage Distribution of Built-Up Area Across BCSI Classes

Moderately Suitable areas contain **1.261 km²** of built-up area, indicating that some settlements lie within transitional or moderately constrained zones, likely requiring moderate engineering interventions. Conversely, only **0.393 km²** of built-up area occurs in *Poor Suitable* regions, reflecting limited expansion into marginal terrain.

A total of **4.0 km²** of built-up area is located in *Unsuitable* zones. These areas primarily correspond to locations near riverbanks, water-logged areas, or land-cover types that pose engineering challenges. Their presence suggests either historical settlement patterns predating modern planning considerations or the need for improved urban planning to prevent future exposure to geotechnical and hydrological risks.

Overall, the validation shows that **approximately three-quarters of the built-up area lies within the Suitable and Moderately Suitable zones**, confirming that the BCSI model successfully captures the spatial logic of construction feasibility within the district. This alignment between model prediction and real-world settlement distribution provides strong evidence supporting the reliability and applicability of the BCSI results for planning, zoning, and infrastructure decision-making in Rautahat District.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

This study developed an integrated geospatial framework for delineating Groundwater Potential Zones (GWPZ) and assessing the Building Construction Suitability Index (BCSI) across the Rautahat District of Nepal using GIS-based Multi-Criteria Evaluation and the Analytical Hierarchy Process (AHP). Eight hydrogeological parameters—slope, lithology, geomorphology, land use/land cover, rainfall, drainage density, soil/geology, and lineament density—were selected to derive groundwater potential, while seven factors including slope, geomorphology, land cover, population density, groundwater condition, soil type, and road proximity were used for construction suitability. All input datasets were standardized, reclassified, weighted using AHP, and integrated through a weighted overlay approach to generate final spatial outputs. The results were validated using 31 tubewell locations for GWPZ and built-up area distribution for BCSI, ensuring the reliability of the developed model.

The findings of this study indicate that Rautahat District is predominantly characterized by a high groundwater potential environment, with 83.07% of the area falling within the Good category. This is a reflection of the district's extensive alluvial plains, moderate geomorphology, and favorable recharge conditions consistent with the hydrogeological characteristics of the Terai belt. Only a small portion of the area (0.07%) exhibited Very Good potential, governed by localized combinations of highly permeable lithology and structural connectivity. Conversely, Poor and Very Poor potential zones constituted only about 14.5% of the district. Validation using tubewell locations demonstrated that 93.55% of wells occur within Good or Very Good zones, confirming the robustness of the GWPZ model. Similarly, the BCSI results revealed that 43.75% of the district is Suitable for construction, while 46.99% is Unsuitable due to factors such as flood-prone land, riverbeds, forests, and high groundwater excavation costs. The alignment between BCSI classes and existing settlement patterns further confirmed model validity, with nearly 70% of the built-up area falling within Suitable to Moderately Suitable categories.

The integrated assessment offers several practical implications for land-use planning, infrastructure development, and groundwater resource management. Areas identified as Good groundwater potential but Poor construction suitability highlight regions better suited for groundwater extraction, irrigation, or recharge enhancement rather than settlement expansion. Conversely, locations mapped as Suitable for construction but

Moderate or Poor in groundwater availability indicate that water supply infrastructure may need to be strengthened before supporting further urban growth. The combined GWPZ–BCSI analysis can guide municipal authorities, planners, and development agencies in identifying safe construction zones, prioritizing groundwater development sites, mitigating environmental risks, and preventing settlement in hazard-prone or geotechnically sensitive areas. The outputs also offer valuable inputs for future land-use zoning, disaster risk reduction, and sustainable infrastructure planning in the district.

Despite the strong results, the study has certain limitations. The accuracy of the outputs depends on the resolution and quality of available datasets such as DEM, LULC, rainfall, and geological maps, which may not fully capture local-scale variability. The analysis relied on a single temporal dataset for rainfall and land cover, which may not reflect seasonal or inter-annual fluctuations. The limited number of tubewell points (31) constrains the depth of groundwater validation. Moreover, AHP is inherently influenced by expert judgment, and thus subject to some level of subjectivity in assigning weights. Finally, the study does not incorporate temporal groundwater fluctuations or socio-economic factors that may influence future land development.

Future research can build upon this model by integrating higher-resolution datasets, machine learning classifiers such as Random Forest or Frequency Ratio models, and multi-temporal datasets to capture seasonal dynamics of groundwater and land use. Expanding field validation through pumping tests, soil sampling, and water table monitoring would improve the accuracy of groundwater potential assessment. Incorporating flood hazard mapping, climate change scenarios, and detailed geotechnical investigations could further strengthen construction suitability analysis. A dynamic multi-criteria framework combining environmental, hydrological, and socio-economic variables would provide even more comprehensive insights for long-term sustainable planning in the Rautahat District and similar regions across the Terai.

CHAPTER SIX: LIMITATIONS AND FUTURE RESEARCH SCOPE

Although the integrated GWPZ–BCSI model developed in this study provides reliable and meaningful spatial insights for groundwater assessment and construction suitability in Rautahat District, several areas can be strengthened in future research. The following recommendations are made to guide researchers, planners, and institutions working in groundwater management, land-use planning, and geospatial modeling.

1. The thematic datasets used in this study were limited by their spatial resolution and availability. Future studies should incorporate higher-resolution DEMs, updated geological maps, and multi-temporal LULC and rainfall datasets to improve model accuracy and representation of local variability.
2. The GWPZ model was validated using 31 tubewell locations due to limited availability of field data. Expanding validation through more extensive field measurements—such as pumping test data, groundwater level monitoring, and infiltration tests—would strengthen the hydrogeological reliability of the results.
3. This study employed the Analytical Hierarchy Process (AHP) for weighting criteria. Future research may explore advanced machine-learning and data-driven approaches such as Random Forest, Frequency Ratio, Logistic Regression, or ensemble models to compare, refine, or enhance groundwater potential mapping accuracy.
4. The BCSI model did not include geotechnical parameters such as soil bearing capacity, liquefaction potential, or subsurface stratigraphy. Incorporating detailed geotechnical investigations and engineering soil tests could significantly improve construction suitability assessment.
5. Seasonal variation in groundwater availability and rainfall was not analyzed due to data limitations. Future studies may integrate multi-season or multi-year hydrological datasets and climate change projections to evaluate temporal variations in groundwater potential.
6. Flood hazard zones, waterlogging-prone areas, and urban growth projections were not included in this assessment. Incorporating these layers in future models would enable more comprehensive risk-informed planning.
7. Institutional agencies such as DWRI, DHM, and local governments are encouraged to develop centralized, standardized, and openly accessible geospatial datasets, which would improve model consistency and support region-wide groundwater and land-use planning initiatives.
8. Researchers may also expand this framework to other districts of Nepal's Terai region to develop a comparative and regional-scale groundwater and construction suitability atlas, supporting evidence-based decision-making at the provincial and national levels.

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APPENDIX A: Detailed Reclassification Table for Thematic Layers Used in Groundwater Potential Zonation

Factor	**Original Class / Range**	**Value (1–5)**	**Suitability**
Slope (%)	0 – 2.78°	5	Very High
	2.78 – 8.84°	4	High
	8.84 – 18.96°	3	Moderate
	18.96 – 30.34°	2	Low
	30.34 – 64.47°	1	Very Low
Lithology	Fluvial non-calcareous	5	Very High
	Fluvial, calcareous	4	High
	Sandstone, greywacke	2	Low
Soil Type	Calcaric FLUVISOL	5	Very High
	Calcaric PHAEOZEM	4	High
	CAMBISOL / Dystric REGOSOL	3	Moderate

Factor	Original Class / Range	Value (1–5)	Suitability
	Eutric GLEYSOLS	2	Low
Geomorphology	Floodplain / Plain / Valley floor	5	Very High
	River Terrace / Low gradient footslopes	3	Moderate
	Structural Hills / High Gradient Hill	1	Very Low
Land Use / Land Cover	Waterbody / Riverbed	5	Very High
	Forest	4	High
	Cropland	3	Moderate
	Grassland / Otherwooden land	3	Moderate
	Bare soil / Barren Land	2	Low
	Built-up Area	1	Very Low
Rainfall (mm)	> 1500	5	Very High
	1300 – 1500	4	High

Factor	**Original Class / Range**	**Value (1–5)**	**Suitability**
	1100 – 1300	3	Moderate
	900 – 1100	2	Low
	< 900	1	Very Low
Drainage Density (km/km²)	0 – 0.61	5	Very High
	0.61 – 1.00	4	High
	1.00 – 1.34	3	Moderate
	1.34 – 1.71	2	Low
	1.71 – 2.60	1	Very Low
Lineament Density (km/km²)	1.06 – 1.77	5	Very High
	0.69 – 1.06	4	High
	0.40 – 0.69	3	Moderate
	0.14 – 0.40	2	Low
	0 – 0.14	1	Very Low

APPENDIX B: Detailed Reclassification Table for Building Construction Suitability Index (BCSI) Parameters

Factor	**Original Class / Range**	**Value (1–5)**	**Suitability**
Slope (%)	0 – 2.78°	5	Very High
	2.78 – 8.84°	4	High
	8.84 – 18.96°	3	Moderate
	18.96 – 30.34°	2	Low
	30.34 – 64.47°	1	Very Low
Geomorphology	Plain	5	Most Suitable
	Low gradient footslope	4	Suitable
	Valley floor	2	Poorly Suitable
	High Gradient Hill	1	Unsuitable
Land Use / Land Cover	Bare soil	5	Most Suitable
	Grassland	4	Suitable
	Cropland	3	Moderately Suitable

Factor	Original Class / Range	Value (1–5)	Suitability
	Forest	2	Poorly Suitable
	Otherwooden land	2	Poorly Suitable
	Built up area	1	Unsuitable
	Riverbed	1	Unsuitable
	Waterbody	1	Unsuitable
Population Density (persons/km²)	1113 – 1804	5	Very High
	831 – 1113	4	High
	580 – 831	3	Moderate
	260 – 580	2	Low
	0 – 260	1	Very Low
Groundwater Condition (Dewatering Cost)	Very Good (Low GWPZ)	5	Very Low Cost
	Good	4	Low Cost
	Moderate	3	Moderate Cost
	Poor	2	High Cost

Factor	**Original Class / Range**	**Value (1–5)**	**Suitability**
	Very Poor (High GWPZ)	1	Very High Cost
Soil Type / Geology	Sandstone, greywacke, arkose	5	Most Suitable
	Fluvial, calcareous	3	Moderately Suitable
	Fluvial non-calcareous	2	Poorly Suitable
Road Proximity (m)	0 – 500	5	Very High
	500 – 1000	4	High
	1000 – 2000	3	Moderate
	2000 – 3000	2	Low
	> 3000	1	Very Low

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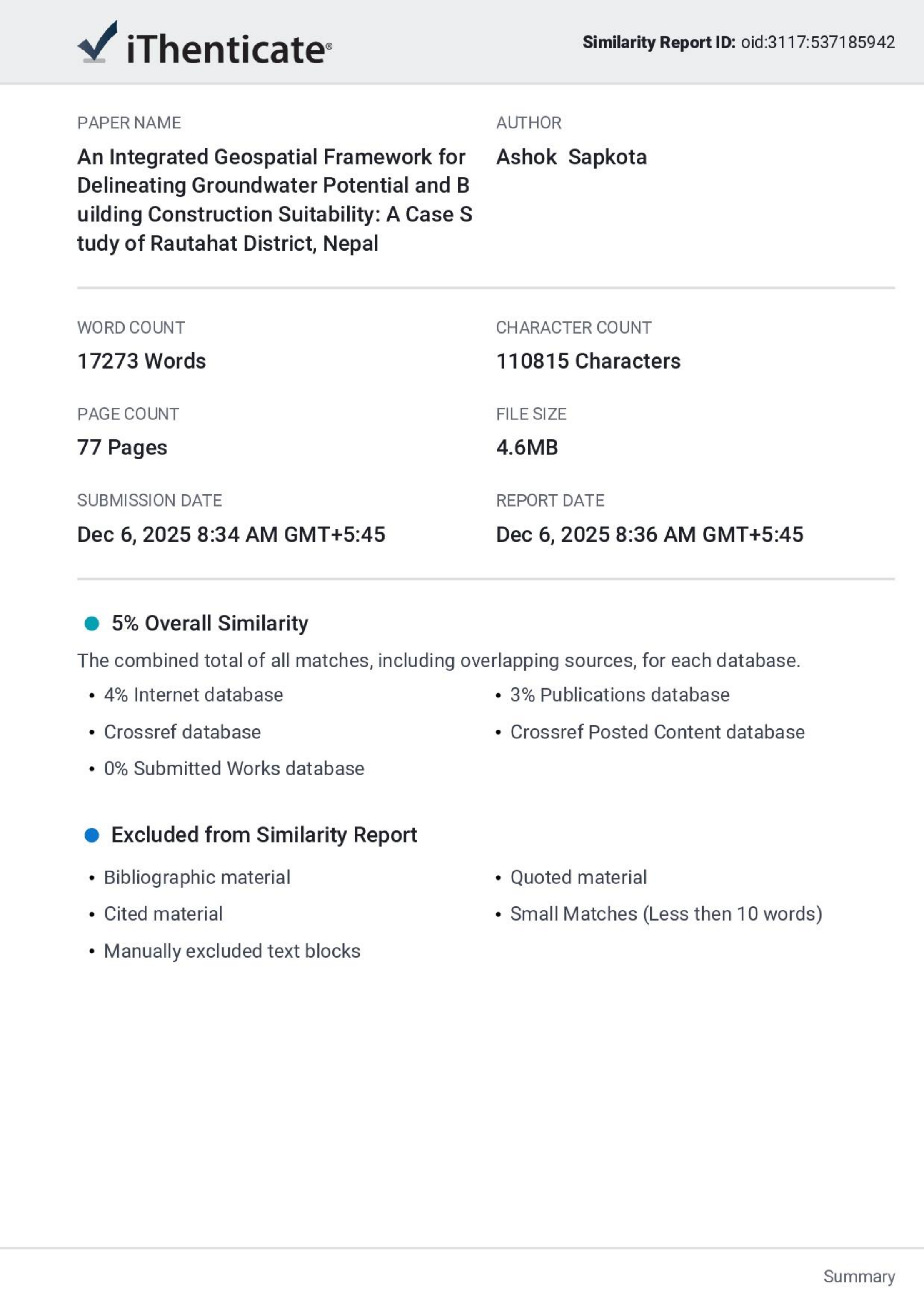

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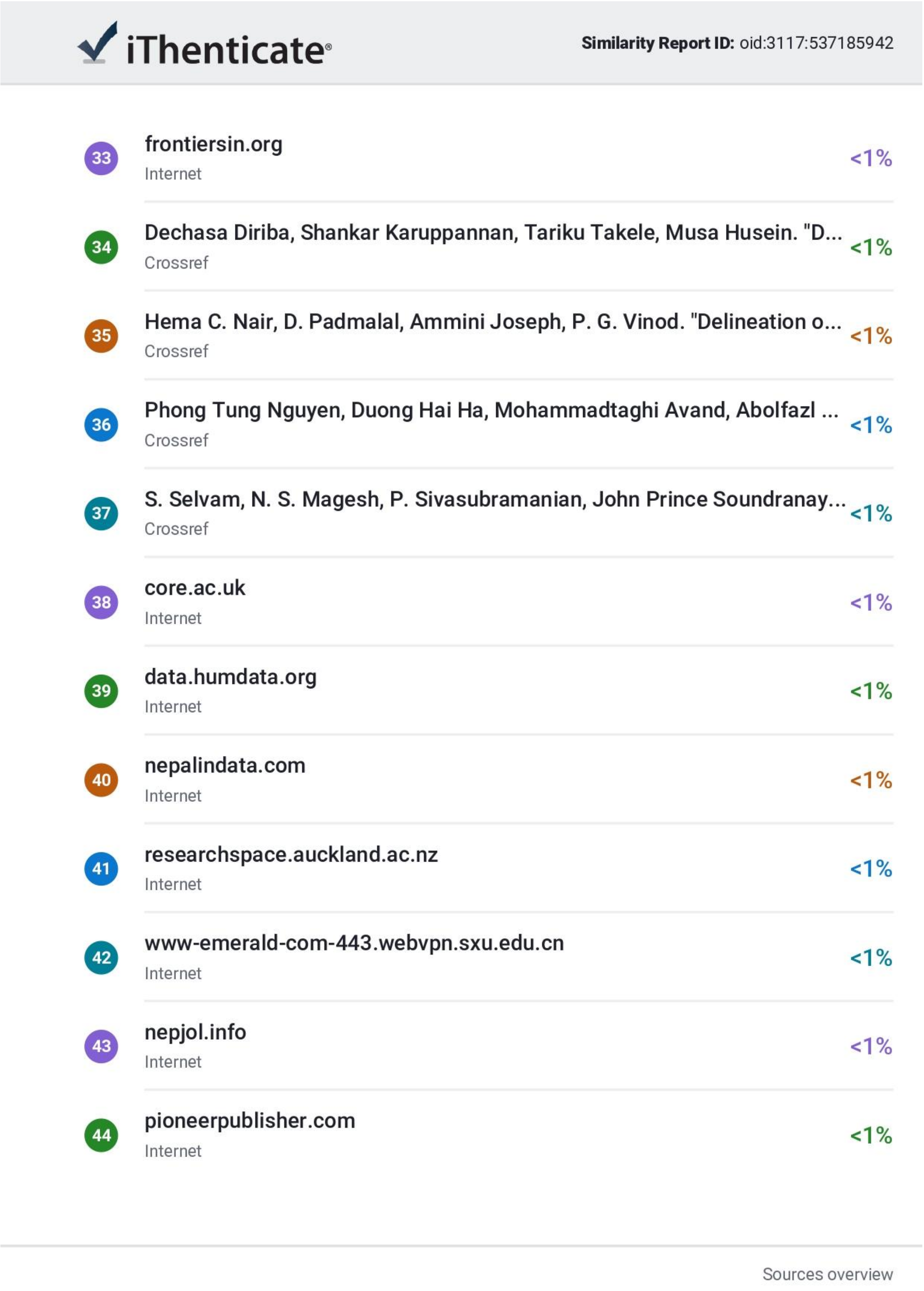

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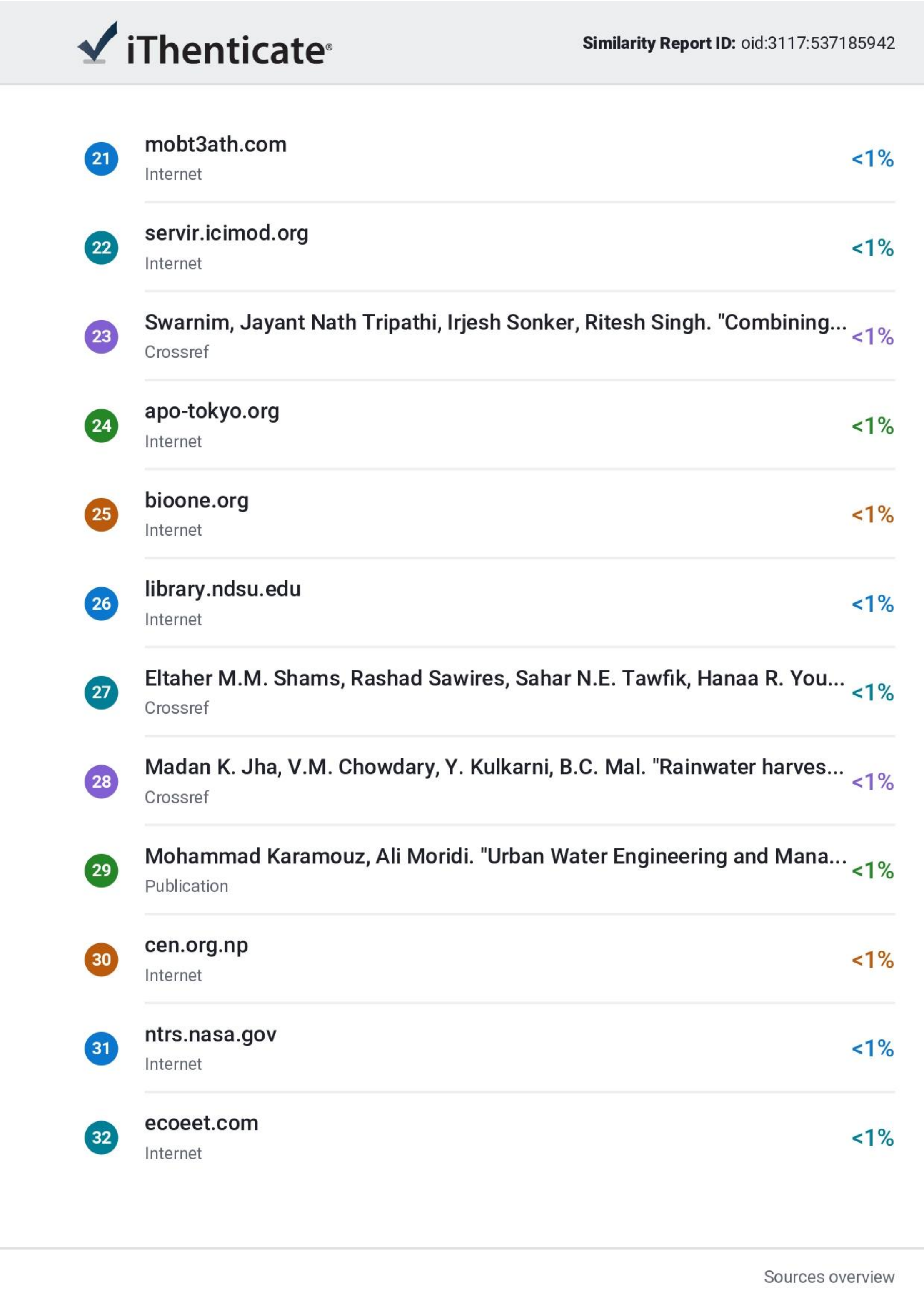

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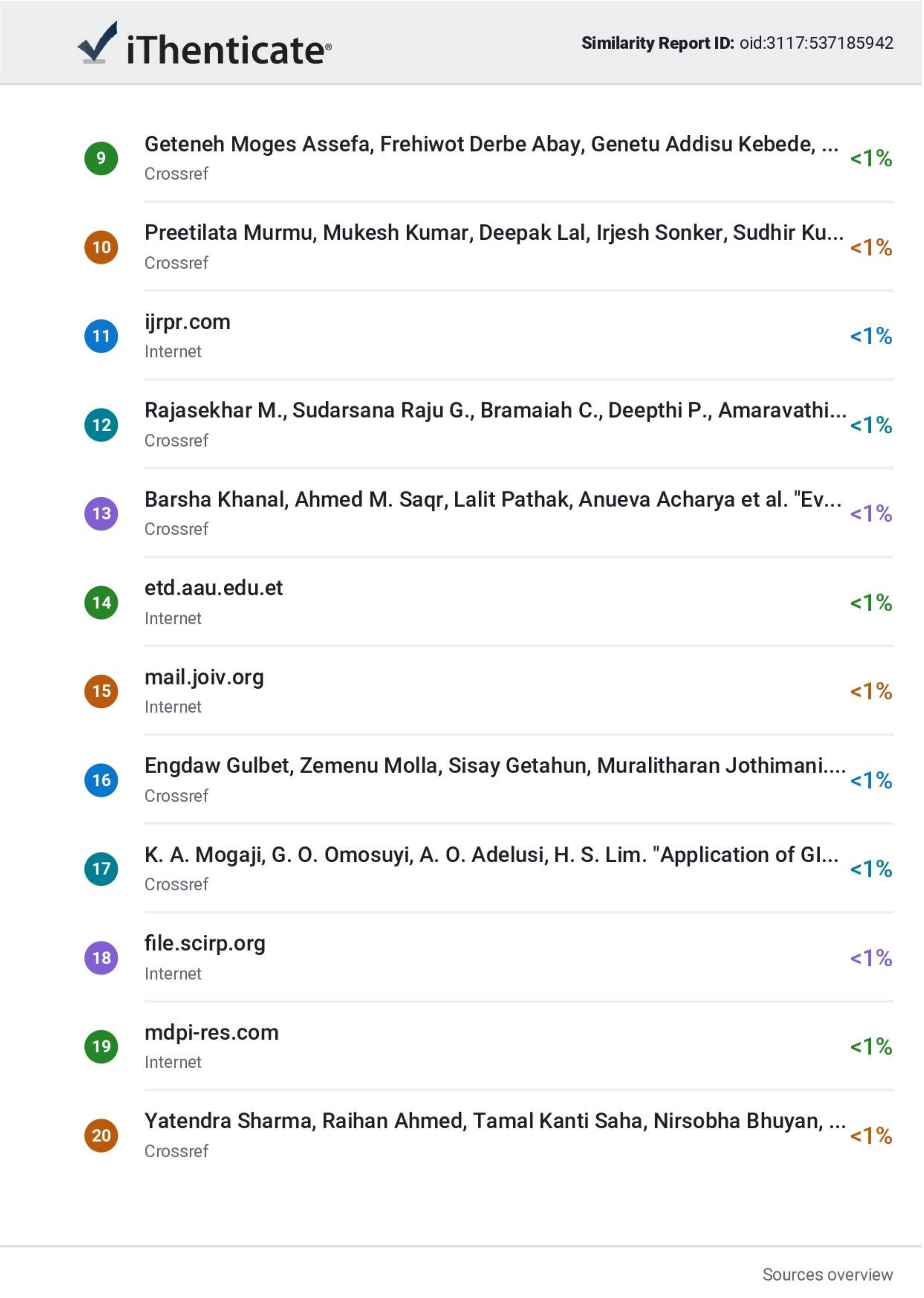

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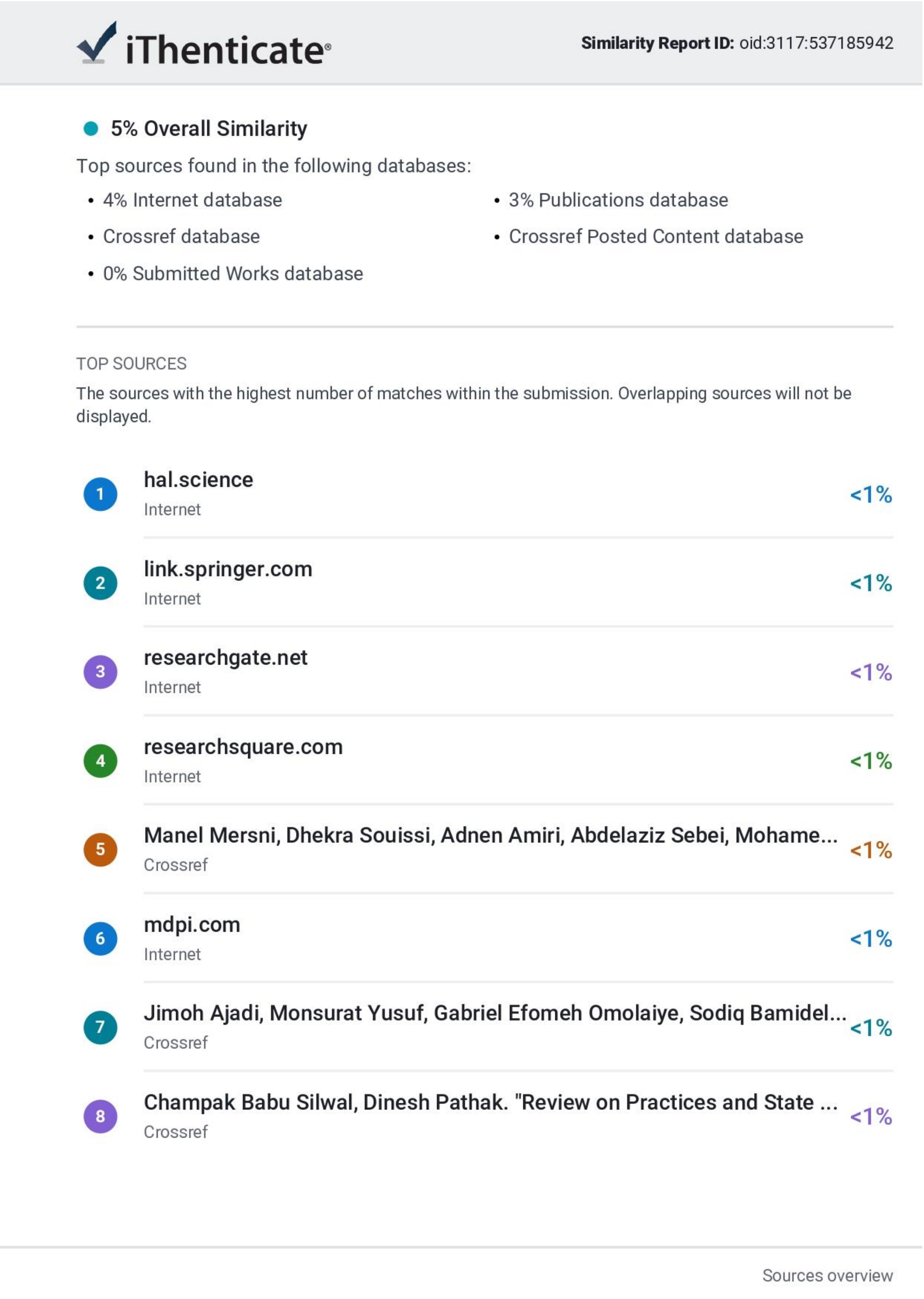

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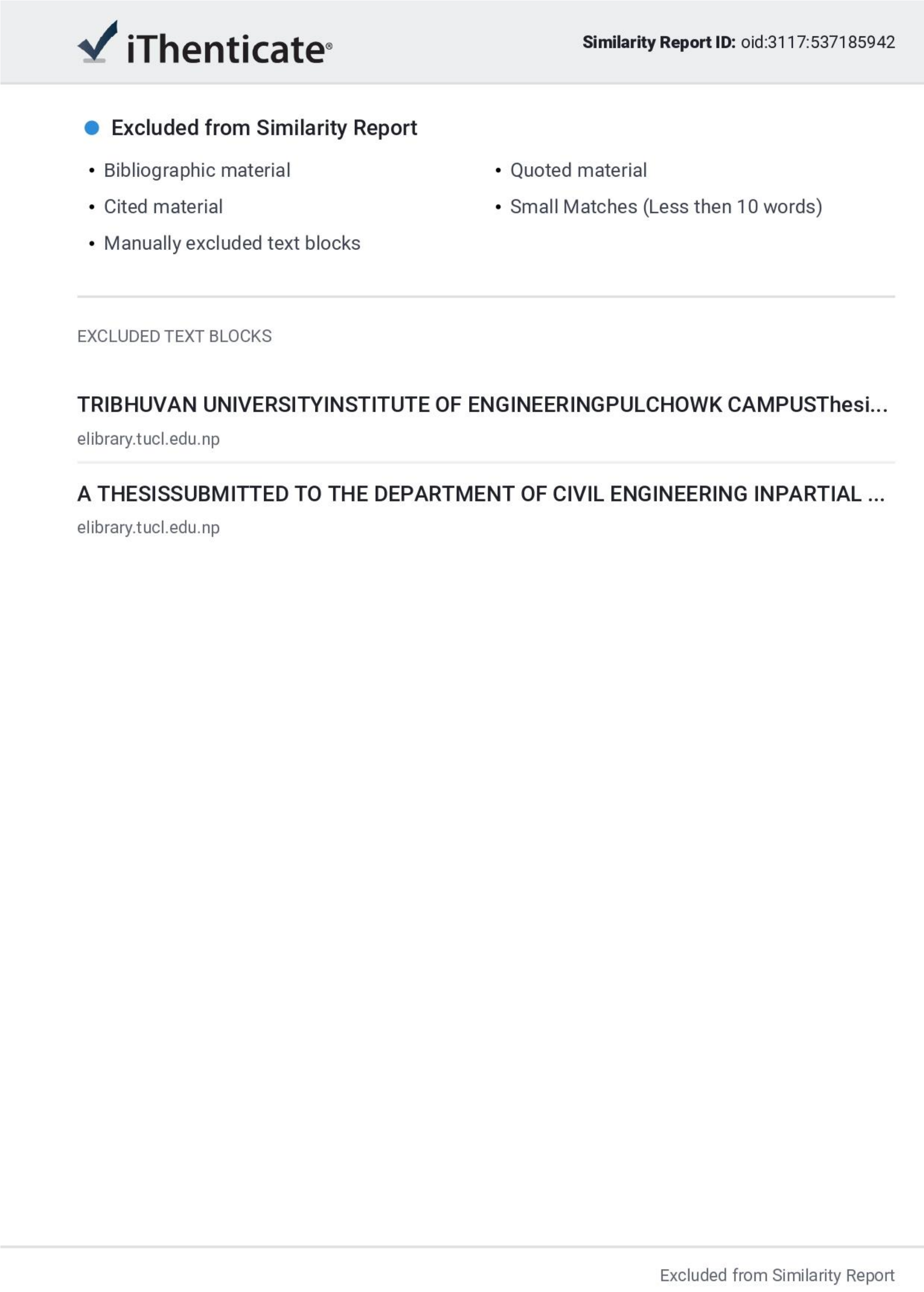

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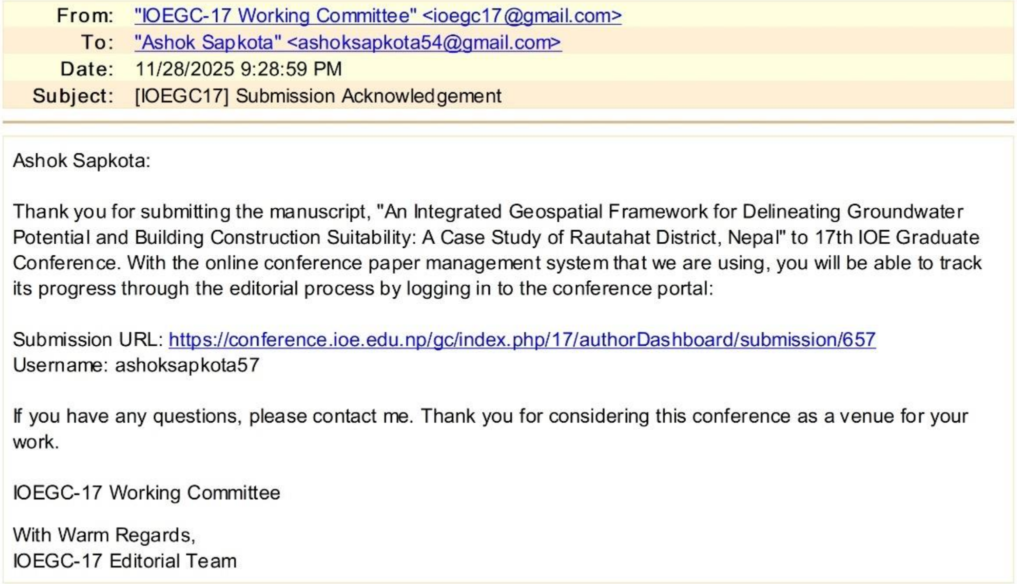

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