

Integrated Geospatial Delineation of Groundwater Potential Zones and Runoff Characteristics in the Lower-Digaru Drainage Basin, Northeast India

Debasish Chutia^{1†}, Satyajit Katak¹ and Aditya Shankar Katak²

¹*Department of Geology, Cotton University, Guwahati 781 001, Assam, India*

²*School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow, Glasgow, Scotland; United Kingdom*

(Received 16 August, 2025; Accepted 11 October, 2025)

ABSTRACT

Groundwater is a critical component of the hydrological cycle, sustaining ecosystems, baseflows, and human needs. In the Lower-Digaru Drainage Basin, Northeast India, rising groundwater dependence necessitates systematic evaluation of groundwater potential zones (GWPZs) and runoff dynamics. This study applies an integrated geospatial framework, combining Remote Sensing (RS), Geographic Information System (GIS), and Multi-Criteria Decision-Making (MCDM) with the Analytical Hierarchy Process (AHP), to delineate groundwater prospects and assess runoff behaviour. Eight thematic layers, landforms, lithology, lineament density, slope, drainage density, soil drainage, land use/land cover (LULC), and rainfall, were generated, weighted, and integrated. Results reveal that nearly level to gently sloping terrains with agricultural/vegetated cover exhibit high groundwater potential, whereas steep slopes and urban/barren sectors show poor potential and high runoff risk. The basin-average runoff coefficient ($C=0.38$) indicates a moderate hydrological response, balancing infiltration and surface flow. The derived groundwater potential map categorizes the basin into very good, good, poor, and very poor zones, with ~45% falling within moderate to high potential classes. Validation using groundwater fluctuation data and Receiver Operating Characteristic (ROC) analysis yielded an AUC of 0.79, confirming predictive accuracy. The findings provide a scientific basis for groundwater exploration, recharge structure placement, and watershed management. The study demonstrates the effectiveness of RS-GIS-MCDM integration in hydrogeological investigations, offering a replicable framework for sustainable water resource management in similar basins under increasing water stress.

Key words: *Groundwater potential, Runoff coefficient, Geospatial analysis, Multi-criteria decision making (MCDM), Analytical Hierarchy Process (AHP), Lower-Digaru Basin*

Introduction

Groundwater forms a vital component of the hydrological cycle, which governs the continuous movement of water across the planet. Beyond its role in subsurface storage, groundwater holds substantial

ecological and economic value, playing a key role in maintaining riverine flow regimes and supporting fragile ecosystems. Its occurrence and movement within a region are controlled by a complex interaction of the variables including landform features, lithology, lineaments, drainage patterns and density,

slope, soil types, rainfall pattern and landuse/landcover (Lu/Lc). Distinct geomorphic units that define the landforms within a drainage basin play a crucial role in influencing groundwater recharge potential and overall groundwater prospects. Furthermore, the physiography, surficial geology, topography, and vegetation cover of a basin collectively govern the relationship between precipitation inputs and the resultant surface and subsurface hydrological responses. Moreover, groundwater, as a primary source of drinking water, plays a critical role in advancing Sustainable Development Goal (SDG) 6.1 by ensuring universal access to safe and affordable water, and SDG 6.2 by contributing to improved sanitation and hygiene. Beyond domestic use, groundwater underpins agricultural irrigation, thereby supporting SDG 2.1 on food security and SDG 2.4, which emphasizes sustainable agricultural practices (Dwivedi *et al.*, 2024).

Groundwater potential zone maps serve as valuable tools for geologists and resource management authorities by enabling the identification of potential groundwater-bearing zones, particularly in areas facing water scarcity. These maps offer dual benefits: (1) they facilitate rapid identification of prospective sites for detailed hydrogeological investigations, and (2) they assist in selecting appropriate locations for implementing recharge structures to enhance the sustainability of drinking water sources. Consequently, the use of such maps supports more effective and targeted groundwater development and management strategies within the study area (Kataki *et al.*, 2017).

Geospatial technologies, particularly remote sensing (RS) and geographic information systems (GIS), offer significant advantages in groundwater prospect zonation. Their synoptic coverage facilitates rapid assessment of extensive and often inaccessible regions, which is especially valuable for regional-scale hydrogeological investigations. The ability to integrate multiple thematic layers, such as geology, landform features, landuse/land cover, rainfall, slope, and drainage patterns within a unified analytical framework enables comprehensive evaluation of groundwater controlling factors. These geospatial technologies provide a spatially robust platform for delineating groundwater potential zones across varied geological settings, including hard rock terrains and alluvial plains. By enabling multi-factorial analysis and spatial visualization, these tools enhance the accuracy and reliability of

groundwater exploration and management strategies. Several studies have demonstrated the utility of these technologies. For instance, Rajaveni *et al.* (2017) delineated groundwater potential zones by preparing thematic layers including slope, drainage density, landuse, geology, and lineament density through RS and GIS techniques. Similarly, Jha *et al.* (2007) emphasized the importance of integrating thematic maps- such as geomorphology, slope, and landuse- using GIS for groundwater prospecting in the Ganga alluvial plain. Krishnamurthy *et al.* (1996) and Saraf and Choudhury (1998) applied RS and GIS for groundwater zoning in hard rock terrains, highlighting a strong correlation between lineament density and groundwater yield.

In hard rock terrains, groundwater occurrence is controlled by secondary structures such as weathered zones, fractures, and faults due to inherently low primary porosity. This results in a heterogeneous and localized groundwater distribution. Remote sensing techniques are effective in identifying linear geological features (lineaments, faults, fractures) that act as conduits for groundwater movement and storage. Lineament density mapping from satellite data (e.g., ALOS PALSAR, Landsat, Sentinel-2) highlights fracture-rich zones with higher groundwater potential. Variations in vegetation, soil tone, and surface moisture also provide indirect evidence of weathered horizons. In contrast, alluvial regions, composed of unconsolidated sediments, possess high porosity and permeability, favouring groundwater accumulation and transmission, though unregulated extraction poses sustainability concerns. Integration of Digital Elevation Models (DEMs), slope analysis, LuLc, and drainage mapping within GIS helps delineate runoff and recharge zones, with low-slope areas, floodplains, and paleochannels serving as key groundwater recharge sites. These approaches collectively support sustainable groundwater resource management.

Runoff plays a critical role in the delineation and interpretation of groundwater potential zones (GWPZ) because it directly influences the partitioning of rainfall into surface flow and subsurface recharge. The runoff coefficient serves as an indicator of the integrated effect of catchment characteristics on surface runoff generation (Suharyanto *et al.*, 2021). Its value is not constant, but rather depends on the physical attributes of the basin, such as soil type, slope, landuse/landcover, and drainage density, all of which govern runoff dynamics

(Baiaomonte, 2020; Yan *et al.*, 2020). Quantification of runoff in Groundwater Potential Zonation (GWPZ) studies, is essential because it establishes the hydrological link between surface processes and subsurface storage. Runoff analysis enables the distinction between recharge-prone areas, where low runoff and high infiltration enhance aquifer replenishment, and discharge or runoff-dominated zones, where high runoff restricts groundwater recharge. It also facilitates assessment of the basin's hydrological balance, providing insights into the relative contributions of infiltration, storage, and surface flow.

Therefore, an integrated approach has been adopted to identify the key geological formations, landform features, drainage density, landuse/landcover (LuLc) characteristics, soil properties, and rainfall patterns of the study area, with the dual aim of delineating groundwater prospect zones and characterizing runoff dynamics. Satellite remote sensing data plays a crucial role in this process by offering synoptic, multi-spectral coverage that enables systematic observation and analysis of geomorphic units, rainfall-driven surface processes, and associated terrain characteristics. Incorporating runoff coefficient estimation further strengthens the assessment, as it captures the hydrological response of different landuse and slope categories, thereby linking surface flow behaviour with groundwater recharge potential. This integrated framework enhances the accuracy and efficiency of groundwater prospect mapping, particularly in diverse geological settings. Notably, this is the first study to provide a comprehensive assessment of both groundwater potential zonation and runoff characteristics in this region using geospatial technologies, offering valuable insights for integrated and sustainable groundwater management.

Materials and Methodology

Study Area

The study area lies between longitudes 91°47'28"E to 92°18'9"E and latitudes 26°1'25"N to 26°15'14"N within Survey of India Toposheets 78N/15, 78N/16, 83B/4, and 83B/8 at a 1:50,000 scale encompassing approximately 536 km². The area is situated in the Lower Brahmaputra Valley zone and is bounded by the Brahmaputra and Kolong/Kopili rivers to the north, the Kopili River to the east, the Meghalaya hills to the south, and Dispur, the capital of Assam,

to the west. The study area holds considerable geographical and strategic importance, being one of the fastest-growing peri-urban zones on the outskirts of Guwahati Metropolitan City, Assam, with a portion extending into the state of Meghalaya, India (Figure 1). Due to its proximity to Assam's capital, the region has witnessed increasing migration of both population and industrial units driven largely by the rising cost of living in Guwahati metro city and other socio-economic pressures. However, this rapid development often overlooks the region's dependence on limited and vulnerable groundwater resources. Geologically, the area forms part of the northeastern extension of the Assam-Meghalaya Plateau and is underlain by a basement composed primarily of quartz-feldspathic gneiss. This crystalline basement is overlain by unconsolidated Quaternary alluvial deposits comprising varied grades of sand and clay. Groundwater is the principal source of water for domestic, agricultural, and industrial purposes, as the Lower-Digaru River relies predominantly on rainfall from upstream regions in Meghalaya. This seasonal and spatial variability in surface water availability underscores the essential role of groundwater in meeting the area's growing water demands.

Methodological Framework for Hydrogeomorphic Zonation

The overall methodology is structured into two major components. The first component focuses on the delineation of hydrogeomorphic units by analysing parameters that influence hydrogeological properties. This involves: (a) the generation of individual thematic layers along with base map features through visual interpretation of satellite imagery, supported by limited field observations and existing data; and (b) the derivation of hydrogeomorphic units by integrating these thematic layers using a geospatial framework. The second component pertains to the evaluation of the delineated hydrogeomorphic units based on the hydrogeological characteristics of the controlling parameters, to assess their groundwater potential.

Groundwater potential zones in the study area were delineated through the integration of eight thematic layers, each representing key parameters that influence the occurrence and movement of groundwater. These thematic layers include Landform features, Lithology, Lineament Density, Slope, Landuse/Landcover (LuLc), Drainage Density,

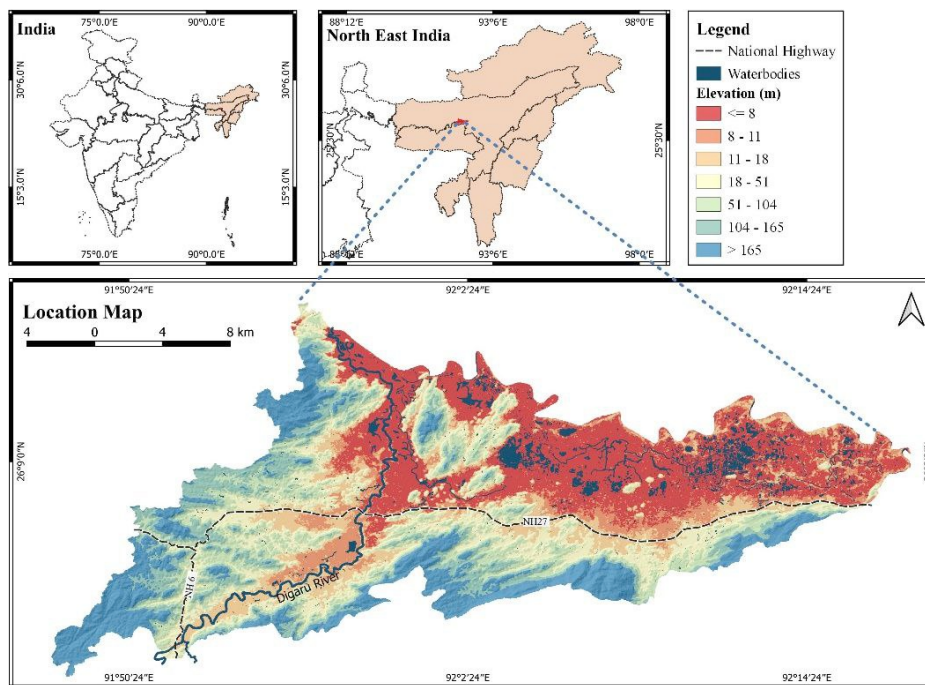


Fig. 1. Location and Elevation Map show the geographical setting of the study area within India and Northeast India. Elevation zones derived from DEM data, ranges from 8 m to above 165 m, influencing hydrological and geomorphic conditions. Major water bodies and national highways are also depicted for reference.

Rainfall, and Soil Drainage condition. The thematic layers were generated using ESRI ArcGIS software, drawing upon a combination of remote sensing and ancillary data sources, such as Sentinel-2 imagery, Survey of India Toposheets, IMD rainfall records, NBS&LUP Soil Maps of Assam, and ALOS PALSAR Digital Elevation Model (DEM).

The Analytical Hierarchy Process (AHP), a well-established method within the domain of Multi-Criteria Decision-Making (MCDM) first introduced by Saaty (1980), was applied to evaluate the relative significance of multiple thematic layers influencing groundwater occurrence. AHP is extensively applied across a wide range of scientific disciplines. Its global recognition is attributed to its efficacy in addressing complex decision-making problems (Agarwal and Garg, 2016). It is widely regarded as a versatile and robust decision-support framework, capable of integrating both quantitative and qualitative parameters in multi-criteria assessments (Lyu *et al.*, 2018). By facilitating the systematic decomposition, prioritization, and interpretation of critical factors, the method enhances comprehension of research problems and enables more informed and rational decision-making (Zewdie and Yeshanew, 2023). In the present study, eight thematic layers rel-

evant to groundwater prospect zonation were considered, each exerting a distinct level of influence on groundwater availability. To assess their relative significance, a pairwise comparison was conducted following Saaty's fundamental scale of relative importance (1-9), wherein a score of 1 signifies equal influence between two factors, while 9 reflects the extreme dominance of one factor over the other (Saaty, 1980). The resulting pairwise comparison matrix provided the basis for computing the normalized weights of the thematic layers, thereby quantifying their contribution to groundwater potential evaluation.

Table 1. Saaty's Scale (Saaty, 1980)

Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

Calculation of Normalized Weight

1. Pairwise comparison Matrix: For n criteria

C_1, C_2, \dots, C_n :

$A = [a_{ij}]_{n \times n}$, where a_{ij} is the relative importance of C_i over C_j

2. Normalization of Matrix:

$$a_{ij}^{norm} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}$$

3. Normalized Weights (W):

$$w_i = \frac{\sum_{j=1}^n a_{ij}^{norm}}{n}$$

The Priority Vector is $W = [w_1, w_2, \dots, w_n]^T$

Each thematic layer comprises multiple classes, which do not contribute equally to groundwater prospect mapping. Therefore, the classes within each layer were ranked based on their relative influence using a scale of 1 to 5, where higher values indicate greater significance in contributing to groundwater potential. The table below presents the

assigned weights of each thematic layer along with the ranks attributed to their respective classes.

Results

The integration of geospatial techniques with the Analytical Hierarchy Process (AHP-MCDM) facilitated the systematic evaluation of multiple thematic layers influencing groundwater occurrence in the study area. Each parameter- geomorphology, lithology, lineament density, drainage density, slope, land use/land cover, soil drainage, and rainfall, was analysed individually to assess its spatial variability and relative contribution to groundwater potential.

Lithology: The region is largely underlain by gneiss (49.39%), followed by sand, silt, pebble, and clay deposits (38.92%), which provide good groundwater storage potential. Porphyritic granite (3.91%) and loamy sand (7.79%) occupy smaller portions (Figure 2A).

Landform: The area is dominated by dissected hills (46.91%) and pediment-pediplain complexes (15.86%), indicating variable groundwater recharge

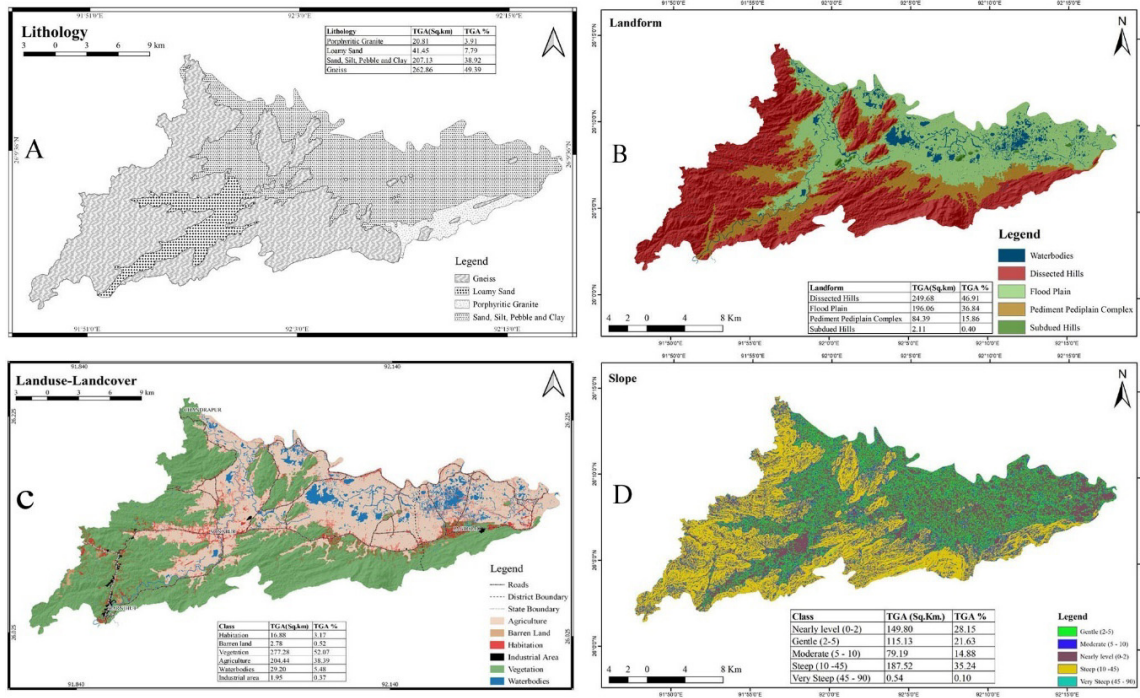


Fig.2.[A] Lithological Map of the study area illustrates the spatial distribution of major lithological units in the Lower-Digaru drainage basin.[B] Landform Map illustrates various landform categories with their spatial extent and total geographical area (TGA).[C] Landuse-Landcover Map (LULC) map of the study area, showing different land categories along with their areal extent and percentage contribution. [D] Slope classification map of the study area showing spatial distribution of five slope categories, indicating areas of varying runoff potential and groundwater recharge capability.

potential. Floodplains, though limited in extent (36.84%), represent highly favourable zones for groundwater occurrence (Figure 2B).

Landuse/Landcover (LuLc): Vegetation (52.07%) and agriculture (38.39%) dominate, both supporting moderate to good recharge conditions, while urban/ industrial areas and barren land limit groundwater prospects (Figure 2C).

Slope: Nearly level (28.15%) and gentle slopes (21.63%) favour infiltration, whereas steep (35.24%) and very steep slopes (0.10%) restrict recharge due to high runoff (Figure 2D).

Rainfall: The region receives high rainfall (1100-1339 mm) over 97% of the area, which significantly supports recharge potential (Figure 3A).

Drainage Density: Very low to low drainage density covers ~49% of the area, suggesting higher infiltration capacity and groundwater potential, while high to very high drainage density zones (~31%) imply rapid runoff and limited recharge (Figure 3B).

Lineament Density: Very low lineament density (57%) dominates the area, while zones with moderate to very high density (about 28%) are more promising for groundwater recharge and storage (Figure 3C).

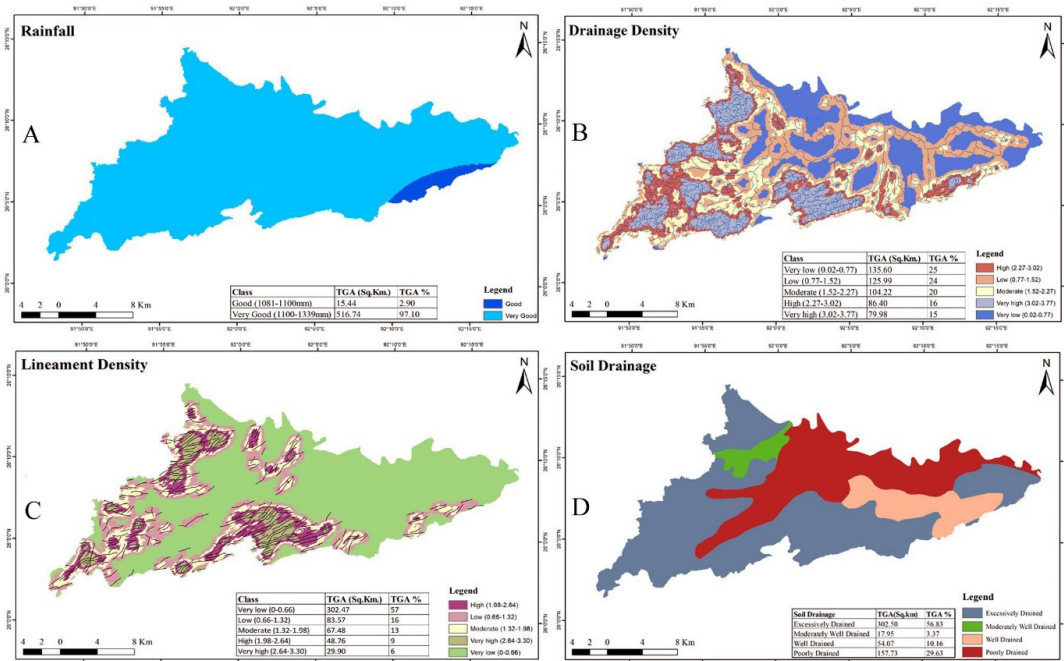


Fig. 3. [A] Rainfall distribution map of the study area. [B] Spatial distribution of Drainage Density in the study area indicating variation in surface runoff and infiltration potential. [C] Lineament Density Map illustrates spatial variations in lineament density across the area categorized into five classes ranging from very low to very high. [D] Spatial distribution of soil drainage classes in the study area, showing excessively drained, well-drained, moderately well-drained, and poorly drained zones.

Table 2. Pairwise Comparison Matrix

Comparison Matrix	Lithology	Land form	LuLc	Slope	Rainfall	Drainage Density	Lineament Density	Soil Drainage	Normalized Consistency Weight (W)	Vector (CV)
Lithology	1.00	4.00	5.00	5.00	3.00	5.00	6.00	6.00	0.36	9.302
Landform	0.25	1.00	4.00	5.00	3.00	5.00	6.00	6.00	0.25	8.985
LuLc	0.20	0.25	1.00	1.00	0.25	0.50	3.00	2.00	0.06	8.534
Slope	0.20	0.20	1.00	1.00	0.33	0.50	0.50	2.00	0.05	8.341
Rainfall	0.33	0.33	4.00	3.00	1.00	3.00	3.00	3.00	0.14	8.727
Drainage Density	0.20	0.20	2.00	2.00	0.33	1.00	2.00	3.00	0.08	8.402
Lineament Density	0.17	0.17	0.33	2.00	0.33	0.50	1.00	2.00	0.05	8.230
Soil Drainage	0.17	0.17	0.50	0.50	0.33	0.33	0.50	1.00	0.03	8.504

Soil Drainage: The area is largely excessively drained (56.83%), which may restrict prolonged water retention, while moderately well-drained and well-drained (13.53%) and poorly drained soils (6.18%) locally enhance groundwater prospects (Figure 3D).

Groundwater Potential Zonation (GWPZ) Map

The weighted overlay of these layers generated a comprehensive Groundwater Potential Zonation (GWPZ) map, delineating the area into four classes: very poor (29.7%), poor (24.7%), good (32.7%), and very good (12.9%). The “good” and “very good” zones are primarily associated with floodplains,

pediment-pediplain complexes, moderate to high lineament density, low drainage density, and gentle slopes, whereas “poor” and “very poor” zones coincide with dissected hills, steep slopes, and high drainage density areas (Figure 4).

Runoff Characteristics of the Study Area

Runoff characterization helps in identifying priority zones for management interventions, such as locating artificial recharge structures in high-runoff terrains or implementing drainage control in poorly drained regions. Runoff estimation is not only a hydrological input but also a determinant of groundwater occurrence, storage, and sustainability, mak-

Table 3. Assigned Weights and Ranks of Thematic Layers and their Classes used for Groundwater Prospect Zonation (GWPZ)

Thematic Layer	Class	Rank	Normalized Weight from AHP
Lithology	Porphyritic Granite	1.00	0.35
	Loamy Sand	4.00	
	Sand, Silt, Pebble and Clay	5.00	
	Gneissic Rocks	2.00	
Landform	Dissected Hills	2.00	0.25
	Flood Plain	5.00	
	Pediment-Pediplain Complex	4.00	
	Subdued Hills	2.00	
LuLc	Habitation	1.00	0.06
	Barren	2.00	
	Vegetation	3.00	
	Agriculture	4.00	
	Waterbodies	5.00	
Slope	Industrial Area	1.00	0.05
	Nearly level (0-2)	5.00	
	Gentle (2-5)	5.00	
	Moderate (5 - 10)	3.00	
	Steep (10 -45)	1.00	
Rainfall	Very Steep (45 - 90)	1.00	0.14
	Good	4.00	
	Very Good	4.00	
Drainage Density	Very low (0.02-0.77)	5.00	0.07
	Low (0.77-1.52)	4.00	
	Moderate (1.52-2.27)	3.00	
	High (2.27-3.02)	2.00	
	Very high (3.02-3.77)	1.00	
Lineament Density	Very low (0-0.66)	1.00	0.05
	Low (0.66-1.32)	2.00	
	Moderate (1.32-1.98)	3.00	
	High (1.98-2.64)	4.00	
	Very high (2.64-3.30)	5.00	
Soil Drainage	Excessively Drained	5.00	0.03
	Well Drained	4.00	
	Moderately Well Drained	3.00	
	Poorly Drained	1.00	

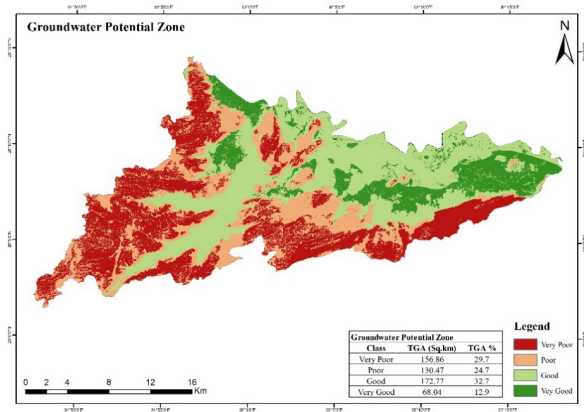


Fig. 4. Groundwater potential zonation map of the study area showing spatial distribution of the groundwater potential zones with their spatial extent and total geographical area (TGA)

ing it a key parameter in GWPZ mapping and decision-making. To estimate this parameter, researchers have developed a range of physically based and spatially distributed models. In practice, however, when data availability is limited, empirical tables and simplified equations derived from these models are often employed as practical alternatives (Dharmayasa *et al.*, 2022).

Area-weighted estimation of the basin-average Runoff Coefficient (C)

Runoff Coefficient (C) is not a fixed number but ranges with landuse landcover (LuLc), slope, soil,

and rainfall intensity. Baseline runoff coefficients (Ci) for different landuse and landcover categories were adopted from standard hydrological design references (Chow *et al.*, 1988; ASCE, 1992; Viessman and Lewis, 2003; USDA-SCS, 1986). The composite runoff coefficient for the study area was then computed using an area-weighted averaging approach, following established methods described by Mays (2010) and Bedient *et al.* (2008).

Baseline LuLc - weighted C

$$C_{LuLc} = 0.75 (0.0317) + 0.50 (0.0052) + 0.15 (0.5207) + 0.35 (0.3839) + 1.00 (0.0548) + 0.85 (0.0037) = 0.2968 (\approx 0.297)$$

Soil (HSG) adjustment (area-weighted)

$$\Delta C_{Soil} = 0.1353 (0.03) + 0.2794 (0.10) = 0.00406 + 0.02794 = 0.0320$$

(Excessively drained / HSG-A contributes 0)

Slope adjustment (area-weighted)

$$\Delta C_{slope} = 0.2815 (0.00) + 0.2163 (0.01) + 0.1488 (0.03) + 0.3524 (0.06) + 0.0010 (0.08) \approx 0.0279$$

Rainfall adjustment

$$\Delta C_{Rain} = 0.02$$

Total basin average runoff coefficient

$$C_{Total} = C_{LuLc} + \Delta C_{soil} + \Delta C_{slope} + \Delta C_{Rain} \approx 0.2968 + 0.0320 + 0.0279 + 0.0200 = 0.3767 \approx 0.38$$

Table 4. Input Parameters for Runoff Coefficient Estimation in the Study Area

Thematic Factor	Class/Category	Fraction (Area Proportion)	Remarks
Landuse/Landcover (LuLc)	Habitation	0.0317	Built-up, impervious
	Barren land	0.0052	Sparse cover, exposed soil
	Vegetation	0.5207	Forest/green cover, high infiltration
	Agriculture	0.3839	Mixed infiltration, seasonal cover
	Water bodies	0.0548	Permanent open water
	Industrial area	0.0037	Impervious surfaces
Soil Drainage / Hydrologic Soil Group (HSG)	Excessively drained (HSG-A)	0.5853	Coarse soils, very high infiltration
	Moderately well + Well drained (HSG B-C)	0.1353	Loamy to sandy loam soils, moderate infiltration
	Poorly drained (HSG-D)	0.2794	Clayey/compacted, high runoff
Slope (%)	Nearly level (0-2)	0.2815	Very low runoff potential
	Gentle (2-5)	0.2163	Low runoff
	Moderate (5-10)	0.1488	Moderate runoff
	Steep (10-45)	0.3524	High runoff
	Very steep (45-90)	0.0010	Very high runoff
Rainfall Regime	Generally high		Small Wetness Adjustment Applied

The estimated basin-average runoff coefficient for the study area is estimated at $C \approx 0.38$.

Discussion

Lithological Controls on Groundwater Potential

Lithology plays a critical role in determining groundwater potential by controlling porosity, permeability, and aquifer characteristics. In the Lower-Digaru drainage basin, four lithologic units were identified (Figure 2A). Gneissic rocks, dominant in the western and southern parts, and porphyritic granites in the southeast and central sectors, are hard and compact with negligible primary porosity, offering very poor groundwater prospects except where localized weathering and fracturing induce limited secondary porosity. In contrast, loamy sand in the south-central basin supports high infiltration and recharge. The north-eastern and north-central regions, comprising sand, silt, pebbles, and clay, exhibit the highest groundwater potential due to their loose, unconsolidated to semi-consolidated nature with well-developed pore spaces that facilitate effective infiltration and aquifer recharge.

Landform Control on Groundwater Potential

Landforms are natural physical features on the Earth's surface that results from dynamic action of various geological processes such as erosion, weathering, deposition, tectonic activity, and volcanic action. Dissected Hills are dominantly found in western and southern part of the Lower-Digaru basin area with a small patch in a northern part. These hills exhibit very poor groundwater potential because they are underlain by hard and resistant rocks which have low permeability and limits the infiltration of rainwater down to the water table and does not allow aquifer recharge thus exhibiting low groundwater potential. The steep slopes promote rapid runoff reducing the amount of water that can percolate down to recharge the aquifers. Thus, the combined effect of steep slopes and hard rock lithology results in low groundwater potential these zones.

Floodplains exhibit high groundwater potential due to their underlying unconsolidated alluvial sediments, primarily sand, silt, and gravel, which possess high porosity and permeability, facilitating infiltration and aquifer recharge. The flat topography further minimizes surface runoff and enhances

recharge during flooding events. Additionally, the presence of water bodies within these zones provides a direct source of vertical infiltration, reinforcing their role as favourable groundwater potential areas.

Pediment-Pedeplain covers the southeastern, southern and a small central part of the study area. This zone is erosion prone with lack of vegetation and very thin soil cover. Rapid erosion has resulted in exposure of hard and compact underlying lithology reducing groundwater potential. This results in lesser infiltration indicating poor to moderate groundwater potential.

Subdued-Hills occur in the eastern and northeastern parts of the study area have good groundwater potential. The reduced slopes facilitate infiltration of water, reducing runoff, allowing consequent aquifer recharge. The vegetation and soil cover retains moisture and reduces runoff. The close proximity to floodplain causes lateral subsurface flow or recharge thus increasing groundwater potential.

Landuse/ Landcover controlson Groundwater Potential

Landuse-landcover (LuLc) strongly influences groundwater dynamics by controlling infiltration, recharge, and extraction patterns. In terms of land use, agricultural areas with substantial vegetation cover are considered highly favourable for groundwater exploration (Todd and Mays, 2005). The Lower Digaru Drainage Basin comprises six major LuLc classes (Figure 2C): vegetation/forest (52.07%), agriculture (38.39%), water bodies (5.48%), habitation (3.17%), barren land (0.52%), and industrial area (0.37%). Vegetated and forested zones enhance infiltration and recharge, while agriculture supports moderate recharge but may affect quality through agrochemical inputs. Habitation and industrial areas reduce infiltration due to impervious cover and impose additional stress on groundwater resources. Water bodies serve as localized recharge and storage zones, stabilizing groundwater levels.

Slope controls on Groundwater Potential

Slope is a key topographic parameter controlling runoff and groundwater recharge. Topography, reflecting local and regional relief, provides insights into the general direction of groundwater flow and its role in influencing recharge (Gupta and Srivastava, 2010). Steep slopes (10° – 45°), covering about 35.24% of the basin, promote rapid runoff and

limited infiltration, resulting in poor groundwater prospects. In contrast, nearly level (0° – 2°) and gently sloping (2° – 5°) areas, constituting ~49.78% of the basin, enhance water retention and infiltration, making them highly favourable for recharge. Moderate slopes (5° – 10°), accounting for 14.88% of the area, represent transitional zones with balanced runoff and infiltration. Thus, slope distribution directly governs groundwater potential in the Lower-Digaruru basin (Figure 2D).

Rainfall Controls on Groundwater Potential

The rainfall map (Figure 3A) shows that 97.10% of the area receives very good rainfall (1100–1339 mm), while 2.90% falls under good rainfall (1081–1100 mm). This distribution indicates favourable recharge conditions; however, effective groundwater prospects are controlled by the interaction of rainfall with lithology and soil drainage. Permeable lithologies with sandy or fractured zones enhance recharge, while poorly drained clayey/alluvial areas restrict infiltration despite high rainfall.

Drainage Density controls on Groundwater Potential

Drainage density, defined as the total length of streams per unit area (km/km^2), is a key indicator of runoff behaviour and infiltration capacity. High drainage density reflects impermeable lithology, steep slopes, or rugged terrain, which limit infiltration and enhance surface runoff, while low drainage density indicates permeable soils and gentle slopes, favoring recharge. In the study area, drainage density is classified into five categories (Figure 3B). Very low to low drainage density zones dominate the eastern and north-eastern parts, suggesting good groundwater prospects due to higher infiltration. Moderate drainage density occurs in central areas, representing balanced runoff–infiltration conditions. High to very high drainage density zones, concentrated in the western, south-western, and isolated central patches, correspond to impermeable substrates and steep gradients, resulting in poor groundwater potential. The drainage density map quantitatively reflects the geomorphological controls over surface hydrology and is critical in assessing groundwater prospect zones. The overall dendritic drainage pattern reflects homogeneous lithology with limited structural control on channel development.

Lineament controls on Groundwater Potential

Lineaments, developed through tectonic activity, represent surface expressions of subsurface fractures that enhance secondary porosity and permeability, particularly in hard rock terrains. They act as conduits for groundwater movement, with intersections and surrounding zones serving as favourable sites for recharge and storage. Lineament density, defined as the concentration of lineaments per unit area, is a key indicator of groundwater potential. In the study area, lineament density is classified into five categories (Figure 3C), with high-density zones occurring in the western, southern, and north-central sectors. These structurally controlled regions exhibit enhanced infiltration, storage, and groundwater movement due to the abundance of fractures, faults, and joints.

Soil Drainage controls on Groundwater Potential

Soil drainage plays a vital role in delineating groundwater potential zones, as it regulates infiltration, percolation, and water retention. The soil drainage map of the Lower-Digaruru Basin (Figure 3D) shows dominance of Excessively Drained soils (58.53%), mainly over gneissic and granitic terrains, where coarse, shallow soils promote rapid percolation but poor water retention. Poorly Drained soils (27.94%) are associated with alluvial deposits of sand, silt, and clay, where finer textures restrict infiltration and cause waterlogging. Well Drained (10.16%) and Moderately Well Drained soils (3.37%) occur in sandy-loamy lithologies, offering balanced infiltration and storage, thus making them relatively favourable for groundwater recharge and agriculture.

Delineation and Interpretation of Groundwater Potential Zones

The groundwater potential zonation (GWPZ) map delineates four categories: Very Poor, Poor, Good, and Very Good (Figure 4). Very Poor to Poor zones, covering 54.44% of the basin, are associated with hard crystalline lithologies (gneiss and granite), steep slopes, and excessively drained soils, where limited secondary porosity and high runoff severely restrict groundwater storage. Good zones (32.7%) occur in moderately weathered/fractured rocks and sandy-loamy soils, exhibiting moderate infiltration and recharge potential. Very Good zones (12.9%) are concentrated in alluvial and sedimentary tracts such

as valley fills, where favourable lithology, gentle slopes, and high rainfall enhance infiltration and storage, making them highly suitable for groundwater development. Overall, while more than half of the basin exhibits poor groundwater prospects, nearly 45% (Good + Very Good zones) provides moderate to high potential, reflecting strong spatial heterogeneity governed by lithology, soil drainage, slope, and landform settings.

The basin-average runoff coefficient for the study area is estimated at $C \approx 0.38$. Considering uncertainties in baseline C_i values and adjustments for land use, slope, and soil conditions, the plausible range of the runoff coefficient is assessed to lie between 0.33 and 0.43. A basin-average C of ≈ 0.38 indicates that, under typical storm conditions in the study area, roughly 38% of effective precipitation is converted to surface runoff while the remaining $\sim 62\%$ is available for infiltration, evapotranspiration and temporary storage. This moderate C reflects the combined influence of large vegetated and agricultural cover ($\approx 91\%$ combined), which lowers baseline C_i values relative to urbanized basins; Substantial area of excessively drained (HSG-A) soils ($\approx 57\%$), which promotes vertical percolation but also increases quick interflow on steeper slopes. Considerable steep terrain ($\approx 35\%$ steep slopes), which enhances overland flow and increases the effective C locally; and non-negligible areas of poorly drained/alluvial deposits ($\sim 29\%$ HSG-D), which reduce infiltration locally and contribute to higher runoff generation in lowlands.

Assessment of Consistency

1. Calculation of Consistency Index (CI)

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

Here, (λ_{max}) = Maximum Eigen value

2. Consistency Ratio (CR)

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

RI = Random Index (Saaty, 1980)

Here,

$$\lambda_{max} = \frac{\sum_{i=1}^n CV_i}{n} = 8.627948$$

Table 5. Random Indices (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56

$$CI = 0.889707$$

$$CR = \frac{0.889707}{1.41} = 0.063622$$

As the value of CR is lesser than 0.10, the consistency of the analysis is within acceptable range. It indicates assignment of logical priority weights in pairwise comparison and justifies the reliability of the results.

Validation

Water level data from 37 dug wells were monitored during pre- and post-monsoon seasons (Figure 5). The analysis revealed a maximum fluctuation of 2.7 m. These fluctuation records were subsequently used to validate the predictive groundwater potential zonation. A threshold of 1 m was adopted to differentiate between poor and good groundwater potential zones, yielding a model accuracy of 76% under a binary classification framework. To further evaluate the predictive performance, a Receiver Operating Characteristic (ROC) curve was generated (Figure 6). The ROC curve, a widely used statistical approach, quantifies the efficiency of probabilistic and deterministic detection and prediction models (Bui *et al.*, 2019; Chepchumba *et al.*, 2019; Rajaveni *et al.*, 2017; Manap *et al.*, 2014). It was observed that the results of the predictive analysis were fairly accurate. AUC (Area under Curve) of 79 % indicates that this model can efficiently predict the groundwater availability in the study area.

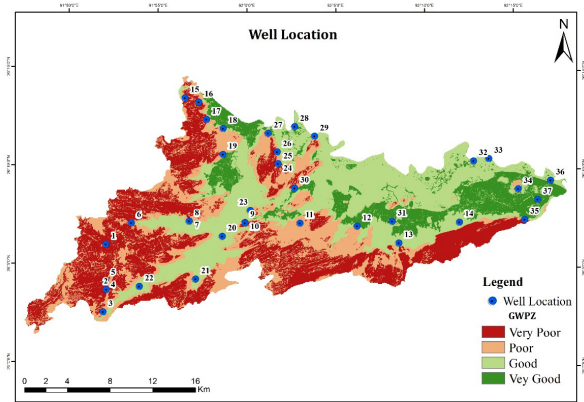


Fig. 5. Distribution of Wells over the potential zones

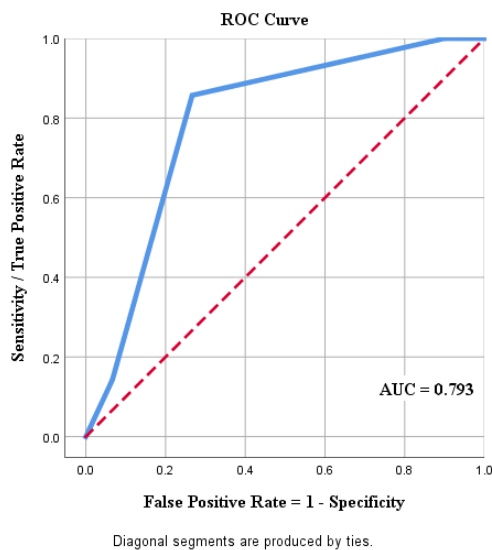


Fig. 6. Receiver Operating Characteristic (ROC) Curve

Calculation of ROC

TPR (True Positive Rate) = $TP / (TP+FN)$

FPR (False Positive Rate) = $FP / (FP+TN)$

At threshold of 1m groundwater fluctuation,

TPR = 86 %

FPR = 27 %

TP: True Positive = 6

FP: False Positive = 8

TN: True Negative = 22

FN: False Negative = 1

Conclusion

The integration of remote sensing, GIS, and AHP-MCDM techniques has proven effective in delineating groundwater potential zones within the study area. The spatial distribution of these zones reflects the combined influence of terrain characteristics, structural features, surface processes, and land use practices on groundwater occurrence and recharge dynamics. The estimated basin-average runoff coefficient ($C \approx 0.38$, plausible range 0.33–0.43) reflects a moderate hydrological response, shaped by heterogeneous land use, slope, soil drainage, and lithological conditions. This value indicates a balance between infiltration and runoff, suggesting that while significant groundwater recharge is possible in permeable uplands, challenges such as erosion in steep terrains, flash runoff, and waterlogging in alluvial lowlands persist. At the regional scale, implementing recharge structures, slope stabilization,

controlled drainage, and low-impact urban development will enhance water security, reduce sediment yield, and mitigate localized flood risks.

On a broader perspective, these findings align with watershed responses in other semi-humid to humid regions where mixed land use and variable soil-lithology combinations yield moderate runoff coefficients. The study underscores the importance of catchment-specific hydrological zoning for sustainable water management in the context of climate variability, increasing rainfall extremes, and urban expansion. Such integrated approaches contribute to the global agenda of sustainable groundwater utilization, climate-resilient agriculture, and disaster risk reduction, making this basin-level assessment relevant as a microcosm of broader hydrological challenges worldwide. Moreover, the study demonstrates how RS-GIS-MCDM integration offers a replicable framework for groundwater prospecting in data-scarce regions worldwide, contributing to global efforts toward sustainable water resource management and directly supporting the UN Sustainable Development Goals (SDGs 6.1, 6.4 & 6.5).

Acknowledgements

The authors gratefully acknowledge the Department of Geology, Cotton University, Guwahati, for providing access to the GIS Laboratory facilities that were essential for carrying out this research work.

Statement of Declarations

Conflict of Interest: The authors declare no conflict of interest.

Funding: No funding was received.

References

- Agarwal, R. and Garg P.K. 2016. Remote Sensing and GIS based groundwater potential & recharge zones mapping using multi-criteria decision-making technique. *Water Resource Manag.* 30:243-260. <https://doi.org/10.1007/s11269-015-1159-8>
- American Society of Civil Engineers (ASCE) and Water Environment Federation, 1992. *Design and construction of urban stormwater management systems* (ASCE Manuals and Reports on Engineering Practice No. 77). ASCE.
- Baiamonte, G. 2020. A rational runoff coefficient for a revisited rational formula. *Hydrological Sciences Journal.* 65(1): 112-126. <https://doi.org/10.1080/02626667.2019.1682150>.

- Bedient, P.B., Huber, W.C. and Vieux, B.E. 2008. *Hydrology and Floodplain Analysis* (5th ed.). Pearson Prentice Hall.
- Bui, D.T. 2019. A hybrid computational intelligence approach to groundwater spring potential mapping. *Water (Switzerland)*. 11(10): 1-30.
- Chepchumba, Mary Christine, James M. Raude and Joseph, K. Sang, 2019. Geospatial Delineation and Mapping of Groundwater Potential in Embu County, Kenya. *Acque Sotterranee - Italian Journal of Groundwater*. (Jica 2012): 39-51.
- Chow, V.T., Maidment, D.R. and Mays, L.W. 1988. *Applied Hydrology*. McGraw-Hill, New York.
- Dharmayasa, I.G.N.P. 2022. Investigation on impact of changes in land cover patterns on surface runoff in Ayung Watershed, Bali, Indonesia using Geographic Information System. *Environment and Natural Resources Journal*. 20(2): 168-178. <https://doi.org/10.32526/enrj/20/202100161>.
- Dunne, T. and Leopold, L.B. 1978. *Water in Environmental Planning*. W.H. Freeman and Company, San Francisco.
- Dwivedi, C.S., Mahato, A.K., Pandey, A.C., Parida, B.R. and Kumar, R. 2024. Delineation of Groundwater potential zone using Geospatial and AHP techniques in Ken River Basin (KRB) in Central India. *Discover Water*. 2024 4:60. <https://doi.org/10.1007/s43832-024-00125-6>.
- Gupta, M. and Srivastava, P.K. 2010. Integrating GIS and Remote Sensing for Identification of Groundwater Potential Zones in the Hilly Terrain of Pavagarh, Gujarat, India. *Water Int*. 35: 233-245.
- Jaiswal R., Jagannathan K., Mukharjee, S. and Saxena, R. 2003. Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development-An approach. *International Journal of Remote Sensing*. 24(5): 993-1008. DOI:10.1080/01431160210144543
- Jha, M.K., Chowdhury, A., Chowdary, V.M. and Peiffer, S. 2007. Groundwater management and development by integrated remote sensing and geographic information systems: Prospects and constraints. *Water Resources Management*. 21(2): 427-467. <https://doi.org/10.1007/s11269-006-9024-4>
- Kataki, S., Sarma, S. and Goswami, U. 2017. Groundwater prospect evaluation in the interfluvies of the rivers brahmaputra and kolong, assam using remote sensing and GIS Techniques. *International Journal of Advanced Remote Sensing and GIS*. 6(1): 2449-2457 ISSN 2320 - 0243, doi:<https://doi.org/10.23953/cloud.ijarsg.323>
- Krishnamurthy, J., Venkatesa Kumar, N., Jayaraman, V. and Manivel, M. 1996. An approach to demarcate ground water potential zones through remote sensing and a geographical information system. *International Journal of Remote Sensing*. 17(10): 1867-1884. doi:10.1080/01431169608948744
- Lyu, H.M., Shen, J.S. and Arulrajah, A. 2018. Assessment of geohazards and preventative countermeasures using AHP incorporated with GIS in Lanzhou, China. *Sustainability*. 10: 304-311. <https://doi.org/10.3390/su10020304>
- Maidment, D.R. (Ed.). 1993. *Handbook of Hydrology*. McGraw-Hill, New York.
- Manap, M.A. 2014. Application of probabilistic-based frequency ratio model in groundwater potential mapping using remote sensing data and GIS. *Arab. J. Geosci*. 7 (2): 711-724.
- Mays, L.W. 2010. *Water Resources Engineering* (2nd ed.). John Wiley & Sons.
- Rajaveni, S.P., Brindha, K. and Elango, L. 2017. Geological and geomorphological controls on groundwater occurrence in a hard rock region. *Applied Water Science*. 7: 1377-1389. DOI 10.1007/s13201-015-0327-6
- Saaty, T.L. 1980. *The Analytical Hierarchy Process*. McGraw-Hill International, New Work. P 287.
- Saraf, A.K. and Choudhury, P.R. 1998. Integrated Remote Sensing and GIS for groundwater exploration and Identification of Artificial Recharge sites. *Int J Remote Sens*. 19(10): 1825-1841.
- Sedhuraman, M., Revathy, S.S. and Babu Suresh, S. 2014. Integration of geology and geomorphology for groundwater assessment using remote Sensing and GIS techniques. *International Journal of Innovative Research in Science, Engineering and Technology*. 5:10203-10211. 3 (3): 2319-8753
- Shaw, E.M., Beven, K.J., Chappell, N.A. and Lamb, R. 2011. *Hydrology in Practice* (4th ed.). CRC Press.
- Suharyanto, A., Devia, Y.P. and Wijatmiko, I. 2021. Floodway design affected by land use changes in an urbanized area. *Journal of Water and Land Development*. 49: 259-266. <https://doi.org/10.24425/jwld.2021.137120>.
- Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology, *Am. Geophy. Union. Trans*. 38: 913-920.
- Todd, D.K. and Mays, L.W. 2005. *Ground water hydrology*. 3rd Ed., Hoboken: John Wiley & Sons.
- U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS). (1986). *Urban hydrology for small watersheds* (Technical Release 55). USDA.
- Viessman, W., & Lewis, G. L. 2003. *Introduction to hydrology* (5th ed.). Prentice Hall.
- Vittala Srinivas, S., Govindaiah, Gowda and Honne, H. 2005. Evaluation of groundwater potential zones in sub-watersheds of north Pennar river basin around Pavagada, Karnataka, India using Remote Sensing and GIS techniques. *Journal of the Indian Society of Remote Sensing*. 33(4): 473-483.
- Yan, Y. 2020. The accuracy of drainage network delineation as a function of environmental factors: A case study in Central and Northern Sweden. *Hydrological Processes*. 34(26): 5489-5504. <https://doi.org/10.1002/hyp.13963>.
- Zewdie, M.M. and Yeshanew, S.M. 2023. GIS based MCDM for waste disposal site selection in Dejen town, Ethiopia. *Environ Sustain Indic*. 18: 100228.