ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume X-5/W2-2025
Unleashing the power of Geospatial & Frontier Technologies for a Sustainable Future – GIFTS Summit 2025,
1–3 September 2025, Symbiosis International University, Pune, India

Geo-Spatial Modelling of Groundwater Potential Zones Using MIF Method and ROC Validation in Semi-Arid Pune Region

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Keywords: Groundwater, GWPZ, GIS, Multi-Influencing Factor (MIF), ROC, Pune

Abstract

Groundwater is vital for agricultural, domestic, and industrial use, particularly in semi-arid regions like Pune district, Maharashtra, India. Increasing water demand and irregular rainfall patterns resulting in water stress areas have made the identification of groundwater potential zones (GWPZs) essential for sustainable resource planning. This study aims to use the Multi-Influencing Factor (MIF) technique integrated with Remote Sensing (RS) and Geographic Information System (GIS) tools to delineate GWPZs, and statistical validation using Receiver Operating Characteristic (ROC) curve analysis. Eleven thematic layers- lithology, geomorphology, slope, elevation, rainfall, land use/land cover (LULC), soil, drainage density, lineament density, topographic wetness index (TWI), and static water level- were selected based on their influence on groundwater occurrence. Each thematic layer was assigned ranks and weights reflecting their hydrogeological relevance. These were integrated using a weighted overlay to derive the Groundwater Potential Zones, categorised into Excellent, Good, Moderate and Low. Model validation using yield data showed a good correlation, with an area under the ROC curve (AUC) value of 0.709, confirming the predictive accuracy. The study found that excellent potential zones are primarily located in the western parts of the district. The majority of areas fall under the good and moderate category. The MIF method and GIS and ROC validation provide a practical and reproducible framework for evaluating groundwater potential. The findings are a valuable tool for planners, facilitating sustainable groundwater planning and management in the Pune district and similar regions.
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1. Introduction

Groundwater is a critical, renewable natural resource in semi-arid regions, such as parts of India, and plays an even more vital role during seasonal droughts. Groundwater is one of the most vital freshwater sources globally, supplying nearly half of the drinking water needs, reinforcing agricultural productivity, ensuring drinking water supply, and supporting industrial activities worldwide. Water consumption has increased because of rapid population growth, industrialisation, urbanisation, and climate change (Singh& Devi, 2012). The definition of groundwater sustainability has moved dramatically from the previous 20th-century concept of safe yield, which primarily considered the physical system of an aquifer, to the more contemporary concept of groundwater sustainability, which encompasses people, economics, and the environment. However, due to increasing demand, poor management, and changing climate conditions, groundwater levels are declining at an alarming rate. Many parts of the world are facing severe groundwater depletion. This situation is deteriorated by urban expansion, over-extraction, and inadequate recharge, threatening ecosystems and water security (Pande et al,2021; Fildes et al,2025). India stands as the largest user of groundwater in the world. It meets over 60% of irrigation needs and 80% of rural and urban water supply (CGWB,2018). The rapid increase in borewell usage after the Green Revolution, combined with unregulated pumping and subsidised electricity, has led to over-exploitation in many regions. Punjab, Haryana, Rajasthan, and Maharashtra face acute groundwater stress. The Central Ground Water Board has identified hundreds of blocks across India where water levels are falling rapidly, pushing several areas into "critical" or "overexploited" categories (CGWB,2024). In recent times, Remote Sensing (RS)and Geographical Information Systems (GIS) have become helpful in the hydrological mapping of the region (Alrawi et al.,2022). To address groundwater inadequacies, researchers practice geospatial approaches that integrate multiple influencing factors (MIF), Analytical Hierarchy Process (AHP), and Frequency Ratio (FR), providing a comprehensive, cost-effective means to delineate groundwater potential zones over large areas (Abijith et al, 2020; Oyda et al., 2025). Such methods provide systematic, repeatable spatial analysis across various watersheds, support decision-makers with advanced planning tools, and enable rapid assessment of the regions. The MIF approach is a semi-reckonable GIS-based technique that integrates various criteria that impact groundwater storage and recharge. The MIF method represents a superlative balance between spatial complexity, data feasibility, and methodological transparency, which concerns the relevance for groundwater potential zonation mapping (Senapati &Das,2022; Shinde et.al, 2024). MIF effectively integrates diverse thematic layers, such as lithology, geomorphology, rainfall, and land use, while capturing their interrelationships through weighted scoring. This allows for a more holistic representation of groundwater dynamics. MIF enhances its applicability in resource-constrained environments.

Pune district in Maharashtra reflects this national concern at the local level. Despite receiving moderate rainfall, many areas within the district face groundwater scarcity, especially during the summer months. Factors such as increased population growth, insufficient rainwater harvesting, hard rock terrain, and excessive dependency on borewells have contributed to the problem. In certain talukas, groundwater levels have depleted significantly over the past period (GSDA 2020).

2. Study Area

Pune district covers approximately 15,600 square kilometres in western Maharashtra, with the geographical extent of 17º54' N to 19º24' N latitude and 73º19' E to 75º10' E longitude. The topography includes the Western Ghats to the west, about 1,000–1,400 meters above mean sea level, gradually descending eastward into the Deccan Plateau at elevations between 500–700 meters. The district experiences a tropical monsoon climate, with an average annual precipitation of 700 mm, largely falling during the southwest monsoon (June–September).50% of the district area falls under the Rain Shadow Zone and Drought-prone Areas. Temperatures range from 10 °C in winter to 40 °C in peak summer (GSDA,2020). Geologically, the region is predominantly comprised of Deccan Trap basalt flows. The basaltic flows, often featuring vesicular zones and fractures, serve as primary aquifer systems. Structurally, Pune district contains rifted landscapes with escarpments, plateaus, and river valleys fed by tributaries such as the Bhima, Mula-Mutha, and Pavana rivers. Soil types also vary according to the rock type. Lateritic soils dominate laterite plateaus, while alluvial and black cotton soils (vertisols) occur along valleys and plains (Figure 1).

Groundwater extraction occurs through tube wells, dug wells, and hand pumps, supplying agricultural farms, decentralised industries, and increasing peri-urban settlements. Over the past two decades, high extraction rates and suboptimal recharge interventions have resulted in declining water tables. Therefore, a data-driven spatial approach is essential for reversing the declining trend of groundwater in the study area.

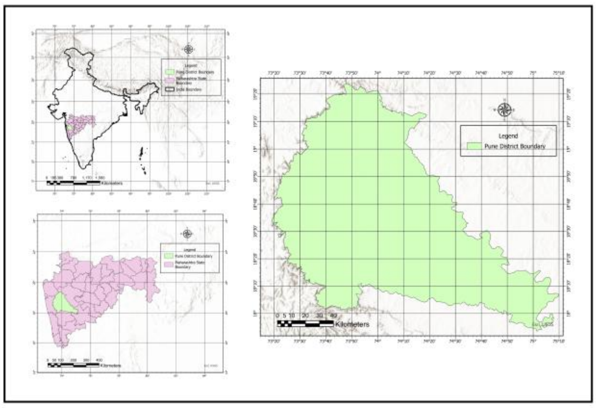


Figure 1. Location map of the Study Area

3. Methodology

3.1 Data and Method:

The Multi-Influencing Factor (MIF) technique is a knowledge-driven approach that integrates multiple thematic layers to assess groundwater potential zones (GWPZ). The method combines remote sensing-derived data with conventional field information to evaluate the spatial relationship between hydrogeological factors and groundwater occurrence (Bhattacharya et.al. 2020, Magesh et.al 2012). Figure 2 illustrates the methodology used in this research. The conventional data is derived from CartoSat DEM (30 m resolution). The slope, topographic wetness index (TWI) maps were prepared from DEM using the ArcGIS Pro environment. The elevation map prepared was obtained from the Bhuvan Portal. The rainfall data obtained from the Indian Meteorological Department (IMD) and the Inverse Distance Weighted method were used to obtain the rainfall distribution Map. Drainage and lineament density maps were prepared using the line density tool in ArcGIS. Lithology and Geomorphology maps were obtained from the Bukosh Portal. The soil map for the district was derived from the NBSSLUP (National Bureau of Soil Survey and Land Use Planning). The static water level map represents well monitor observation data obtained from the Groundwater Survey and Development Agency (GSDA) for the last 2 decades for the Pune district.

Satellite images from IRS-1C, LISS -III sensor, on scale of 1:50000 have been used to delineate various thematic layers such as lithology, geomorphology, slope, elevation, rainfall, land use/land cover (LULC), soil, drainage density, lineament density, topographic wetness index (TWI) with 30 m resolution raster format using GIS environment. The weighted overlay method was used to identify the groundwater potential zone from eleven groundwater influencing thematic layers.

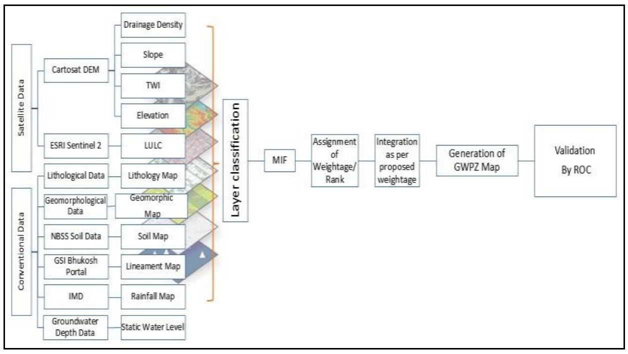


Figure 2. Flow Chart of Methodology

3.2 Multi-Influencing Factor (MIF):

The present research delineated the groundwater potential zone using a geospatial approach integrating the Multi Influencing Factor (MIF) technique. Eleven thematic layers have been identified to demarcate the GWPZ based on groundwater influencing characteristics. Figure 3 represents the interrelationship among these layers, which was determined based on influence and capacity. The weightage was assigned according to each factor and its importance. The sum of all weights from each factor is illustrative of the factor of the potential zone. A higher weightage value indicates a greater impact, where a lower value indicates a lower impact on the groundwater potential zone. All eleven thematic layers, lithology, geomorphology, slope, elevation, rainfall, land use/land cover (LULC), soil, drainage density, lineament density, topographic wetness index (TWI), and static water level, were computed through weighted overlay analysis in ArcGIS Pro.

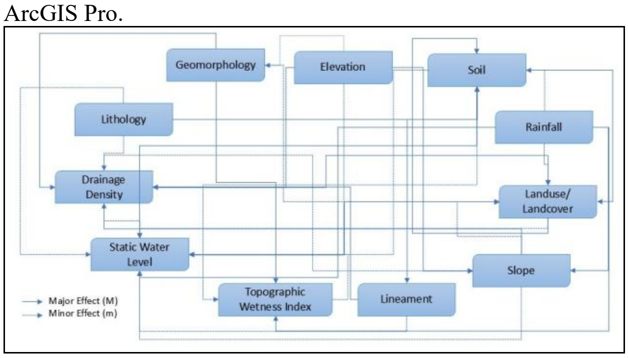


Figure 3. Interrelationship between Influencing Factors

3.3 Demarcation of Groundwater Potential Zones:

Each factor is evaluated for its relative importance and interrelationship with other factors (Figure 3). The interrelationship among the factors is categorised into major and

minor effects. The major effect represents a strong relationship among factors. It is represented by a score of 1.0, whereas the minor effect is allocated a score of 0.5, representing a weak relationship with the respective factor.
The final score is computed using the formula:

$$S = \frac{(M + m)}{\sum(M + m)} \times 100$$

Where:
S = Assigned weight (proposed score) for the thematic factor
M = Total number of major effects
m = Total number of minor effects
∑(M+m) = Total influence score across all factors
Following the calculation of weights (Table 1), all thematic layers were integrated into a Geographic Information System (GIS) platform. Using ArcGIS Pro, a Weighted Overlay Analysis was carried out, allowing spatial integration of all input layers according to their assigned influence scores.

Factor	Major Effect (M)	Minor Effect (m)	Relative Effect	Proposed Score %
Drainage Density	1	0.5+0.5	2	8.33
Elevation	1+1	0.5+0.5	3	12.50
Geomorphology	1+1	0.5	2.5	10.42
Landuse/Landcover	1	0.5	1.5	6.25
Lineament	1	0.5	1.5	6.25
Lithology	2	0.5+0.5	3	12.50
Rainfall	1+1+1	0.5+0.5	4	16.67
Slope	1	0.5+0.5	2	8.33
Soil	1	0.5+0.5	2	8.33
Topographical Wetness Index		0.5	0.5	2.08
Static Water Level	1+1		2	8.33
			∑24	∑100.0

Table 1. Proposed score of each influencing factor

4. Results and Discussion

4.1 Thematic Layers

Lithology:
Lithology plays an essential role in the groundwater potential assessment, as it indicates the nature of aquifer systems, including porosity, permeability, and groundwater storage capacity. Lithology is considered a key controlling factor influencing the occurrence, movement, and availability of groundwater. Pune district is primarily underlain by the Deccan Traps, a vast volcanic province composed primarily of basaltic flows. These flows were laid down during the Late Cretaceous to Early Eocene period. The nature of basaltic flows influences the depth and yield of groundwater. In Pune, aquifer productivity is typically higher in valleys and low-lying areas where weathered and fractured zones are better developed, allowing more recharge. The lithology map for this study was prepared using 1:50,000-scale geological maps obtained from the Geological Survey of India (GSI) Bhukosh Portal (Figure 4e).

Geomorphology:
Geomorphology is the study of landforms and their processes. It influences surface runoff, infiltration, and the recharge potential of an area. Geomorphological features help identify zones more conducive to groundwater accumulation based on terrain structure, slope, drainage, and geological formation interaction. Pune district is situated on the leeward side of the Western Ghats in Maharashtra and covers a transition zone between the Sahyadri hill ranges and the Deccan Plateau. This variation has led to the development of multiple geomorphological units, each having a different influence on groundwater recharge and storage. Pediments and Pediplains complex of Pune district are gently sloping surfaces at the foothills of the Sahyadri and other uplands. Due to their gentle gradient and surface weathering, they act as good recharge zones. Moderately and low dissected plateaus are flat to gently undulating surfaces that dominate large parts of the central Pune region, promoting infiltration and good groundwater availability capacity. Floodplains consist of layered alluvium that promotes both vertical and lateral water movement. Their flat topography and porous soil make them important for groundwater recharge. The geomorphology map of Pune district was derived from the Bhoonidhi portal of 1:50,000 scale (Figure 4 h).

Slope:
Slope is a fundamental topographic parameter that significantly influences groundwater recharge and runoff characteristics. The Slope evaluates terrain gradient affects rainwater infiltration into the subsurface. Gentle slopes support infiltration and recharge, and steeper slopes increase surface runoff, reducing groundwater accumulation. Pune district, groundwater dynamics is critical considering the varied elevation profile and range of slope conditions. The steep slope in the western parts of the district has values ranging from 26.93 to 73.82 degrees. While the gentle steepness is in the eastern parts of the district, with values ranging from 0.01 to 3.47 degrees, promoting higher chances of groundwater availability and recharge. The slope map was generated using Digital Elevation Models (DEM) Cartosat-I, data from the Indian Space Research Organisation (ISRO) with 30-meter spatial resolution (Figure 4i).

Elevation:
Elevation determines the movement of water on the surface, influencing the direction and speed of runoff. Lower elevation zones tend to collect and retain water for extended periods, enhancing infiltration. The higher elevation areas usually have steeper gradients, promoting faster runoff and limited water retention. Pune district lies on the leeward side of the Western Ghats and displays a broad elevation range, The map highlights that the northwestern southwestern part of Pune district is highly elevated with the values ranging from 916.01 to 1,416 meters which suggest that there is a chance of lower potentiality of groundwater while the lowest elevation mostly prevails in the eastern part of Pune district whose value ranges from 69.01 to 571 meters which brings out the fact that there is higher chances of groundwater being present. The variation in elevation across the district influences climatic patterns, vegetation, land use, and hydrology (Figure 4j).

Rainfall:
The rainfall thematic layer is important for GWPZ identification. Its spatial variability directly influences recharge zones and groundwater availability. Rainfall dominantly contributes to the groundwater system through infiltration and percolation—the amount, intensity, and distribution of rainfall affect groundwater recharge availability. Areas with high rainfall often exhibit better recharge conditions, provided the terrain, land use, and soil are favourable. In contrast, areas with lower rainfall require more efficient conservation measures to connect groundwater effectively. Pune district lies in the transitional zone between the humid Western Ghats and the semi-arid region of Maharashtra. This geographical position causes significant spatial variation in rainfall across the district.

The rainfall thematic layer, long-term average annual rainfall data, was collected from the India Meteorological Department (IMD). Rainfall variation across the Pune district significantly influences the groundwater recharge dynamics. Due to their abundant rainfall and natural slope towards the east, Western talukas act as source regions for surface and subsurface flows. Central and eastern zones, with relatively less rainfall, depend more on recharge through rivers, storage tanks, and artificial structures (Figure 4 b).

Land Use/Land Cover (LULC):
The Land Use and Land Cover (LULC) thematic layer is vital in understanding the surface conditions that influence groundwater recharge. LULC reflects the interaction between natural landscape and human interventions, directly affecting water infiltration, surface runoff, groundwater accumulation and evapotranspiration. Different land use and land cover types have varying water retention and infiltration capacities. Pune district exhibits diverse LULC patterns due to its combination of urban centres, agricultural areas, forests, and hill terrains. Agricultural Land is dominant in the eastern and central parts of Pune, such as Daund, Indapur, Baramati, and Shirur. Their infiltration capacity varies based on crop type and irrigation methods. Concentrated around Pune city and around regions exhibit high surface sealing due to concrete and asphalt, which restricts natural infiltration. Trees and Vegetation are mainly in the western talukas like Mulshi, Velhe, and Bhor, which form part of the Sahyadri hills. These areas are ecologically sensitive and are vital in promoting infiltration through forest lands and fractured rocks. Water Bodies and Rivers represent groundwater-surface water interaction (Figure 4a).

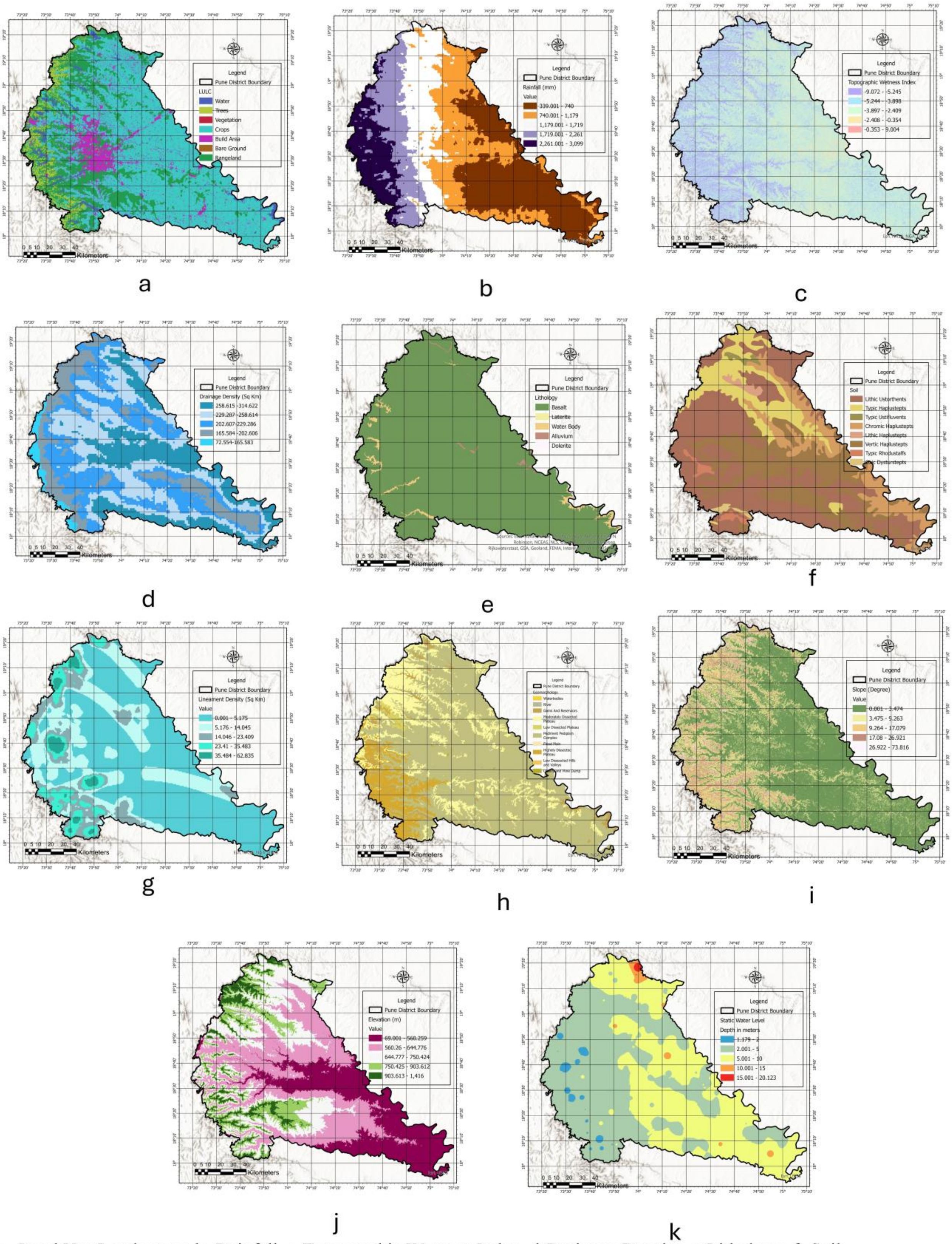
Soil:
As a thematic layer in groundwater studies, soil is critical in influencing infiltration, percolation, and water retention as key processes determining groundwater recharge. The physical and chemical properties of soil, such as texture, structure, permeability, porosity, and depth, affect the vertical movement of water from the surface to the aquifer. The soil thematic layer for the Pune district was taken from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP). Typic Ustifluvents is alluvial soil with high groundwater potential due to good permeability and proximity to water sources. Typic Rhodustalfs is iron-rich, red soil with moderate clay content that is suitable for aquifer recharge capacity.Typic Haplustepts and Vertic Haplustepts have moderate potential with characteristics of low permeability and high-water retention. In eastern talukas with clay-rich black soils, groundwater recharge is slow but can be enhanced with artificial recharge structures like farm ponds and recharge shafts (Figure 4f).

Drainage Density:
Drainage density is a hydrological parameter that influences the identification of groundwater potential zones. It reflects the closeness of spacing between channels within a basin and is defined as the total length of all the streams and rivers in a drainage basin divided by the total area of that basin. Low drainage density indicates high permeability, gentle slope, and more infiltration, making these zones favourable for groundwater recharge. The eastern and southeastern parts of the study area correspond to high groundwater potential with a range of 72.554 to 165.583 km^2, supported by alluvial deposits and flat terrain. High drainage density suggests impermeable subsurface, steep terrain, and low infiltration, making these areas less suitable for natural recharge. Western hilly areas like Velhe, Mulshi show values ranging from 258.615 to 314.622 km2, indicating low potential due to high runoff, although they may have local recharge pockets in fractured basalt (Figure 4d).

Lineament Density:
Lineament density is one of the most critical structural parameters in hydrogeological studies. Lineaments are linear or curvilinear features on the Earth's surface representing zones of structural weakness such as faults, fractures, joints, or shear zones. These features facilitate the movement and storage of groundwater, especially in hard rock terrains like that of the Pune district. The lineament density thematic layer provides a spatial assessment of these features and helps identify areas with higher secondary porosity and permeability, essential for groundwater accumulation and movement. Pune district lies within the Deccan Traps region, comprising horizontally layered basaltic flows of volcanic origin. These formations are generally low in primary porosity but contain numerous fractures, joints, and faults developed during post-volcanic tectonic activity. The lineament density thematic layer was derived from the Bhukosh Portal at a 1:50000 scale. The spatial pattern of lineament density in Pune district shows high lineament density and Excellent groundwater recharge zones, despite steep slopes indicated in talukas of Western Pune (Figure 4 g).

Topographic Wetness Index (TWI):
The Topographic Wetness Index (TWI) is an important terrain-based hydrological parameter that quantifies the spatial distribution of soil moisture and potential water accumulation. TWI is derived from Digital Elevation Models (DEMs) and combines local upslope contributing area and slope to determine the likelihood of water accumulation in the terrain. The higher the TWI value, the greater the tendency for water accumulation, indicating better groundwater recharge potential. Eastern Pune exhibits high TWI values, which correlate with favourable recharge zones. Conversely, lower TWI values correspond to well-drained or elevated regions with minimal moisture retention. Western Ghats exhibit low TWI due to steep slopes, except along valley floors. Central Pune shows moderate TWI values, suitable for managed recharge (Figure 4c).

Static Water Level:
The Static Water Level (SWL) is one of the most essential hydrogeological parameters for assessing groundwater conditions. It refers to the level at which water stands in a well when it is not being pumped and reflects the status of the groundwater table. In the context of groundwater potential zone identification, SWL directly indicates groundwater availability, recharge and aquifer condition. Thematic mapping of SWL across the Pune district provides spatial variability in groundwater storage, contributing to accurate and realistic demarcation of GWPZs. The static water level offers real-time insights into groundwater dynamics. The SWL data for the Pune district were collected from observation wells monitored by the Groundwater Surveys and Development Agency (GSDA), Maharashtra, for 24 years of data (2001 to 2024). Spatial interpolation using Inverse Distance Weighting (IDW) was performed in a GIS environment to generate a continuous SWL surface. Shallow water levels from the surface indicate good recharge and storage capacity (< 2m), while deeper levels indicate limited groundwater availability or excessive withdrawal (Figure 4k).



a- Land Use Land cover, b- Rainfall, c-Topographic Wetness Index, d-Drainage Density, e-Lithology, f- Soil, g- Lineament, h-Geomorphology , i- Slope, j-Elevation, k- Static Water Level

Figure 4.Thematic Layers of Influencing Factors

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4.2 Groundwater Potential Zones:

Demarcation of groundwater potential zones (GWPZ) is vital to sustainable water resource management, especially in areas experiencing water scarcity and increasing demand (Zghibi et al, 2020). The MIF technique provides a structured and comprehensive framework integrating eleven thematic layers representing natural and human-induced parameters influencing groundwater availability and recharge. This is achieved by assigning specific weights to selected thematic layers based on expert assessments, literature support, and local hydrogeological knowledge. (Table 1). These layers typically include lithology, geomorphology, slope, soil type, drainage density, lineament density, rainfall, land use/land cover (LULC), topographic wetness index (TWI), elevation, and static water level (SWL). The final composite map provides a spatial representation of groundwater potential across Pune district, classifying the region into four categories: Excellent, Good, Moderate, and Poor (Figure 5). A substantial portion of the district, approximately 54%, is categorised within the good groundwater potential zone, while about 41% is moderate. The excellent zone, occupying nearly 2% of the area, is predominantly situated in the western part of the district, whereas the poor zone comprises roughly 3% of the total area. GWPZ provides a strong spatial understanding of groundwater availability and contributes to making informed decisions for sustainable groundwater development and recharge planning.

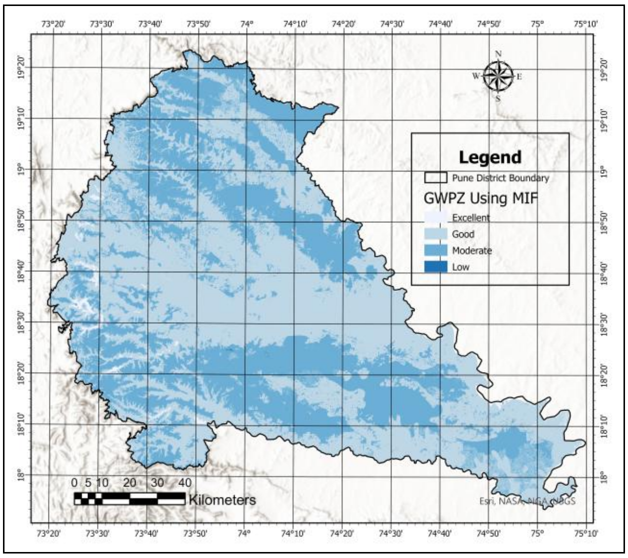

Figure 5. GWPZ using MIF

4.3 Validation of GWPZ map:

The accuracy and robustness of the groundwater potential zone delineation using the Multi Influencing Factor (MIF) technique have been validated by Receiver Operating Characteristic (ROC) curve analysis. The predictive capabilities of the model represented by this statistical validation method involve plotting the True Positive Rate (TPR) against the False Positive Rate (FPR). The Area Under the Curve (AUC) value, ranging from 0 to 1, represents the model's effectiveness. An AUC value of 1 is perfect prediction, and a value of 0.5 suggests a model with low accuracy and performance. AUC values ranging from 0.7 to 0.9 indicate good to excellent predictive performance (Agli et al, 2024; Faheem et.al, 2023). For the current research study, validation was performed using 198 observation points across the Pune district. Seventeen thousand five hundred records from pre- and post-monsoon seasons were tested using static water level data collected over 24 years (2000–2024). The dataset was obtained from the Groundwater Surveys and Development Agency (GSDA), ensuring high reliability and field relevance. The ROC curve analysis of the groundwater potential map obtained an AUC value of 0.709, confirming that the MIF model provides a practically accurate prediction of groundwater potential in the study area (Figure 6). Incorporating static water level (SWL) as one of the thematic input layers effectively supports the model output with actual field conditions. This enhances the practical significance and validity of the final GWPZ map.

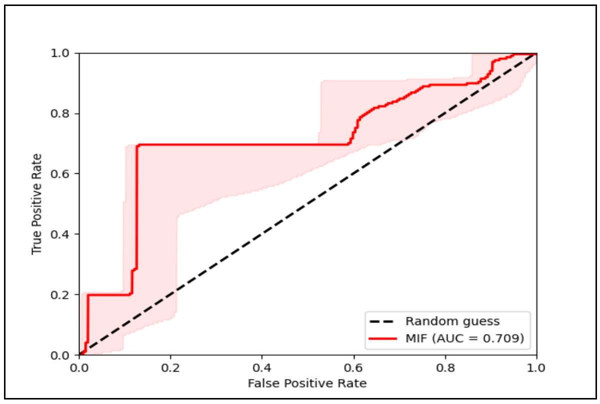

Figure 6. Validation using ROC

4.4 Conclusion

In the Pune district, rapid urbanisation and intensified agricultural practices exert increasing pressure on existing groundwater resources. The rainfall is concentrated during the monsoon months of June to September, limiting the recharge period and emphasising the importance of targeted groundwater planning. The Multi-Influencing Factor (MIF) technique has been developed as a practical, accessible, and statistically validated approach for delineating groundwater potential zones for the study area. In the present study, the geo-spatial modelling of groundwater potential zones (GWPZ) was classified into four categories: Excellent (2%), Good (54%), Moderate (41%), and Low (3%). The highest potential zones were primarily concentrated in the western part of the district, where a combination of intense lineament activity, fractured plateaus, and higher rainfall enhances subsurface infiltration and recharge capacity. In contrast, much of the central and eastern portions result in the good and moderate categories, influenced by variations in geomorphology, soil type, and drainage patterns. The validation by the ROC curve resulted in satisfactory accuracy, confirming the robustness of the geo-spatial modelling process. The groundwater potential zones maps can effectively inform the strategic locations of recharge-enhancing structures in the study area. Also, identifying suitable recharge areas to support integrated environmental conservation and long-term water security initiatives in the region. Continuous monitoring of static water levels, rainfall variability, and land use changes is essential for updating groundwater potential maps. This adaptive monitoring ensures that policies remain responsive to climatic variability and anthropogenic pressures.

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