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Remote Sensing and GIS Techniques for Groundwater Potential Zones Mapping: A Review and Methodological Framework

T. S. Chavan[1], P. G. Popale[2], S. B. Gadge3, S. A. Kadam[4] and S. K. Dingre[5]
Dept. of Irrigation and Drainage Engineering, Dr. A.S.C.A.E &T, M.P.K.V., Rahuri - 413 722 (India)
1*Correspondence : chavantanmay1112@gmail.com

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Abstract

Agriculture, being India's primary industry, faces escalating water demands amidst depleting groundwater levels. Groundwater remains a crucial source contributing to the yearly water supply. In today's era of advanced technology, agriculture leverages innovations like robotic equipment, remote sensing, and Geographic Information Systems (GIS) to enhance productivity. Remote sensing facilitates the acquisition of data from regions inaccessible for regular monitoring. GIS complements this by generating precise maps that effectively visualize the data gathered through remote sensing techniques.This article explores various methodologies for identifying groundwater potential zones using remote sensing and GIS. Mapping groundwater zones involving integrating multiple parameters such as soil characteristics, drainage density, land use/cover, geology, geomorphology, rainfall patterns, slope, and contour details are also discussed asparameters in delineating areas with varying groundwater potentials.The process utilizes both traditional and advanced techniques, incorporating additional data sources and satellite imagery. These methods involve analysing thematic layers to assess groundwater potential across a region. Each thematic layer is assigned weights and importance based on its relevance to groundwater conditions. By integrating and analysing these layers, the study aims to pinpoint areas suitable for groundwater extraction.Ultimately, this approach facilitates the identification of optimal locations for accessing groundwater resources, leveraging comprehensive spatial data to inform sustainable water management strategies.

Key words : Groundwater, Remote Sensing, Geographic Information System (GIS), Potential zones, groundwater exploitation.

Groundwater is a vital natural resource essential for maintaining biodiversity and supporting human health.Groundwater serves as a vital water source for approximately one-third of the global population, providing water for drinking, household use, and irrigation [22]. Its importance is evident in both rural and urban areas, with about 80% of rural and 50% of urban populations relying on groundwater for residential purposes. However, the increasing demand for groundwater, especially for irrigation and industrial use, raises concerns about overexploitation [49]. Groundwater is a versatile and abundant resource, but its sustainable management requires a thorough understanding of local geology and geomorphology.To preserve its significance in ecosystems and human activities, it is crucial to prevent contamination and manage its usage responsibly.The movement of groundwater is controlled by two key rock characteristics: porosity, which determines its capacity to hold water, and permeability, which governs the speed at which water can flow through the rock. Groundwater recharge primarily occurs through precipitation and surface water infiltration, while discharge occurs through processes such as springs, evaporation, pumping for consumption, and seepage of wastewater into water bodies like lakes and streams [63].

Majority of population worldwide depends on groundwateras an alternative source to surface water. Therefore, effective utilization and

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1. M.Tech Student, 2. Assistant Professor, 3. Head and 4. and 5. Associate Professor.

exploration of groundwater resources are very important. For this purpose, mapping of GW resources using advanced techniques such as RS & GIS is needed.

The combination of earth observation, satellite data and Geographic Information System (GIS) gives an information about the different effective components of groundwater existence and in movement corresponding to the geology, soil depth, geomorphology, land use land cover, drainage density and lineament density.

The RS & GIS have many advantages over the conventional methods such as time and cost effective and provide synoptic coverage.

Remote Sensing and GIS Techniques : There are different methods or tools available for finding or identifying the GWPZ, among these tools like RS & GIS are the most useful and inexpensive tools which requires very less mechanical and physical work.

Traditional methods for identification of groundwater potential zones such as geophysical resistivity surveys and on-site hydrogeological studies are well-known for their lengthy process and significant cost implications. Groundwater, located below the earth's surface, occupies the pore spaces and geological structures beneath the water table. This subterranean water moves through aquifers and eventually reaches discharge locations like wells, oceans, and lakes [1]. Remote Sensing involves acquiring information about the earth's surface without direct physical contact. It encompasses sensing, recording, analysing, and applying this information. GIS is a combination of computer hardware, software, and geographic data used for capturing, storing, analysing, and manipulating geographical information[60]. High-resolution satellite images are utilized to map groundwater zones by obtaining data on soil, land use, land cover, geology, geomorphology, rainfall, and drainage density [46]. Remote Sensing and GIS are crucial in delineating groundwater potential zones. Satellite data helps identify the water-holding capacity of various geomorphological and structural units. Additionally, by analysing land use, slope, and rainfall data, we can assess groundwater quality in the study area [51].The use of Remote Sensing and GIS techniques has demonstrated their efficiency in providing slope, drainage density, geology, and geomorphology maps in a cost-effective and time-saving manner [50].

Due to the limitations of traditional approaches, the integration of remote sensing and Geographic Information System (GIS) technologies has emerged as a promising method for delineating groundwater potential zones, offering enhanced efficiency and cost-effectiveness. The literature outlined the role of RS & GIS based multi-criteria decision making (MCDM) analysis, Analytical hierarchical process (AHP), WLC, Index overlay method, influencing factor analysis for the identification or delineation of groundwater potential zones [35][44][61].These techniques leverage the power of remote sensing and GIS to yield accurate and insightful results, marking a paradigm shift in the approach to groundwater resource assessment.

For assessment of the locations of an aquifer stratigraphy analyses and test drilling are the traditional and effective techniques but these processes are costlier and time consuming. There are some other conventional methods for delineating groundwater potential zones primarily rely onGround Surveys and Geophysical Techniques. These methods involve direct field surveys and geophysical techniques such as resistivity surveys, ground-penetrating radar (GPR), and seismic surveys. These techniques help in delineating subsurface geological structures and hydrogeological properties that influence groundwater occurrence.

Probabilistic models, such as logistic regression and statistical analyses, are also used to predict and map groundwater potential zones based on spatial datasets of geological, hydrogeological, and environmental variables. These models assess the likelihood of groundwater occurrence in different areas[28][2].

Hydrogeological studies involve monitoring groundwater levels, flow characteristics, and aquifer properties through wells and observation points. These field-based studies provide direct data on groundwater dynamics and help in understanding the spatial distribution of groundwater potential zones[13][59].

Integration of Remote sensing techniques, including satellite imagery and aerial photography, combined with GIS-based spatial analysis, are employed to identify surface features and land use patterns that indicate potential groundwater zones. These technologies facilitate the integration of multiple data layers for comprehensive groundwater potential mapping[7][39].

GIS is utilized to integrate, analyse, and visualize spatial data layers such as geology, land use, soil types, and hydrological parameters. Techniques like Weighted Linear Combination (WLC), Analytical Hierarchy Process (AHP), and multi-criteria decision analysis (MCDA) are applied to delineate and rank groundwater potential zones[21][62].

GIS functions as an effective platform capable of managing extensive datasets, merging spatial and non-spatial data seamlessly within a unified system. It provides a reliable framework for examining spatial differences, enabling the manipulation of geographic data and establishing relationships between entities based on their geographical proximity.[5]

There are six major application areas of remote sensing and GIS in groundwater hydrology [20]. They are as follows: (1) mapping and evaluation of groundwater resources, (2) identification of suitable locations for artificial recharge, (3) modelling subsurface flow and pollution using GIS,(4) assessment of groundwater pollution risks and planning for protection measures, (5) analysis of natural recharge patterns, and (6) monitoring hydrogeological processes through data analysis.

Thesemethods provide robust frameworks for understanding groundwater potential zones, integrating geological, hydrogeological, and environmental data to support sustainable groundwater management practices.

Demarcation of GWPZ

Methods based on the Remote Sensing: Delineation of Groundwater Potential Zones (GWPZ) using remote sensing and GIS techniques involves several methodologies or technologies that leverage satellite imagery and data analytics.

Visual interpretation of satellite images can identify geological features associated with groundwater occurrence such as geological structures (faults, fractures), lithological units (aquifers), and land use patterns that indicate recharge areas [52].

Analysis of multispectral or hyperspectral satellite imagery helps in distinguishing between different land covers and soil types, which can be indicative of potential groundwater zones [57].

Thermal infrared imagery can detect thermal anomalies associated with groundwater discharge areas, which can be indicative of potential groundwater zones [11].

Digital Elevation Models (DEM) Analysis : DEMs derived from satellite data can be used to analyse terrain characteristics such as slope, aspect, and drainage patterns, which influence groundwater recharge and flow [34].

GIS-based Integration : Geographic Information System (GIS) tools integrate remote sensing data with ground-based data (e.g., well logs, hydrogeological parameters) to develop predictive models for groundwater potential [29].

Multi criteria decision making (MCDM) method : Using remote sensed data different thematic maps such as lithology, landforms, drainage density, surface water bodies, slope classes, lineament density, multiband remote sensing data are prepared to demarcate the presence of groundwater.

Weighted Overlay Method : To assess groundwater potential using the Weighted Overlay Method, different thematic layers such as geology, hydrology, topography, land use, soil, and occasionally climate can be prepared in RS & GIS and normalized to a standard scale. Each layer is assigned weights based on its impact on groundwater[41]. For instance, geological factors like lithology may receive higher weights if they strongly affect groundwater dynamics. After normalization, layers are multiplied by their respective weights and summed to produce a composite suitability map. This map identifies areas with higher values as having greater groundwater potential, validated against existing data or field observations for accuracy [25]. Adjustments to weights are made based on validation results to enhance the map's reliability for groundwater management [37]. Thus, all the thematic maps are integrated and analysed through overlay techniques, where weights are assigned to each thematic layer based on its importance. Rankings are then assigned to assess and classify the groundwater potential zones [63]. The equation used for identifying groundwater potential zones integrates multiple indices, including rainfall, lithology, geomorphology, slope gradient, lineament density, drainage density, land use and land cover, and soil cover.

The equation is expressed as follows:

$$Pr = RFwRFr + LGwLGr + GGwGGr + SGwSGr + LDwLDr + DDwDDr + LCwLCr + SCwSCr$$

Where: Pr is the Groundwater Potential Index, RF is the Rainfall Index,LG is the Lithology Index,GG is the Geomorphology Index,SG is the Slope Gradient Index,LD is the Lineament Density Index,DD is the Drainage Density Index,LC is the Land Use and Land Cover Index,SC is the Soil Cover Index, w represents weight, andr represents rank [48].

Frequency ratio model : The Frequency Ratio Model is a widely used approach for mapping groundwater potential zones (GWPZ) based on the statistical relationship between the spatial distribution of known groundwater occurrences and various thematic layers. These layers typically encompass geological parameters (e.g., lithology, fault lines), hydrological features (e.g., rivers, drainage density), topographic attributes (e.g., slope, aspect), and land use/land cover types. This model operates by calculating the frequency of occurrence (FP) of each thematic parameter within areas where groundwater is present and the frequency of absence (FA) in areas without groundwater. The ratio (FR) of FP to FA is then computed, with higher FR values indicating stronger associations with groundwater occurrence. This method effectively integrates Geographic Information System (GIS) and remote sensing data to rank and classify areas into zones of varying groundwater potential, facilitating informed decision-making in water resource management and planning [25][27][3].

Analytical hierarchical process : The Analytical Hierarchy Process (AHP) is a method for multi-criteria decision-making, originally devised by Professor Thomas L. Saaty in 1980. It involves deriving relative scales from comparisons between pairs of criteria or options. These comparisons are based on both objective data, such as weights or prices, and subjective judgments or conclusions. AHP helps in structuring complex decisions by systematically analysing and prioritizing multiple factors, facilitating clearer insights into decision outcomes.

Various parameters are utilized to map groundwater potential zones, including drainage, elevation, density, geology, geomorphology, land use and land cover, lineament and dykes, rainfall pattern, slope, and soil texture. DEM data facilitated the creation of aspect, slope, and flow accumulation maps. LANDSAT ETM images are employed for land use classification. Using QGIS software, a drainage density map is generated, and weights are assigned to each parameter for analysis. These parameters are created in a GIS context, and analytical procedures are used to assign weights to each class [43].For mapping groundwater potential zones, seven key parameters are employed viz. geology, geomorphology, drainage density, slope, soil type, and a land use map. Digital Elevation Model (DEM) data is utilized to generate additional layers such as slope, aspect, and contour maps. These maps are then digitized using QGIS software, initially converting vector format data into raster format for spatial analysis. The Analytical Hierarchical Process (AHP) is applied to systematically create thematic layers, where weights are calculated and assigned to each parameter based on their significance in influencing groundwater potential. In order to compute the normalized weights parameters, an AHP analyses various datasets into pairwise matrix [4].Normalized weights in groundwater potential zone (GWPZ) mapping involve assigning relative importance to various thematic layers or parameters in a standardized manner to ensure fair and proportional contribution to the overall assessment. This process is crucial for integrating diverse spatial data layers, such as geological characteristics, hydrological features, topographic attributes, land use/land cover types, and soil properties, into a cohesive analysis. Normalization typically involves scaling weights to a common range, often from 0 to 1, based on empirical knowledge, expert judgment, or statistical methods. This standardized approach helps in creating reliable composite maps that accurately reflect the combined influence of different factors on groundwater potential [27][20].

Normalized weight = Assigned weight of parameter feature class/geometric mean

This structured approach enables the integration of diverse spatial data layers to effectively delineate areas with varying degrees of groundwater potential and resources.The groundwater potential zones are categorized into five levels: very poor, poor, moderate, good, and excellent [63].

Key Factors for ground water potential mapping : By using the integrated AHP method and geospatial technology to analyse various parameters like geology, geomorphology, slope, land use and cover, lineament density, drainage density, transmissivity of aquifer, soil permeability, and rainfall, the potential zones for groundwater recharge are investigated.

Geomorphology : Geomorphology examines the formation and characteristics of Earth's landforms, shaped largely by geological processes [63]. The geomorphological features of the area have been identified from satellite images and used as the inputs of geomorphological map. The geomorphological features of the area are classified into five categories. (1) Denudational hill: These are characterized by high surface runoff and high topography. (2) Denudational hills with moderate slope. (3) Dykes. (4) Water bodies: water bodies are lakes, ponds, streams can act as recharging zones. (5) flood plains [33]. The map identifies five distinct geomorphological features to assess water resource areas.

1. **Denudational Hills :** This area is predominantly forested with moderate slopes and a moderate flow pattern. It features numerous fractures and a drainage pattern conducive to moderate to good groundwater recharge.
2. **Pediment :** Characterized by cultivated lands, this region has steep slopes and a dendritic drainage pattern, suggesting very good groundwater recharge potential.
3. **Undulating Upland :** This area has steep slopes with moderate runoff and is associated with poor groundwater recharge capabilities.
4. **Pediment Inselberg Complex :** Covered by barren sandy lands with poor drainage patterns, this region experiences erosion due to its poor slope, resulting in a poor groundwater prospect.
5. **Peneplain :** This region consists of flat rock formations and uneven terrain, contributing to varied groundwater conditions.

Geology : Geology plays a critical role in groundwater potential zone (GWPZ) mapping as it determines the geological formations that influence groundwater occurrence, movement, and storage. Geological formations such as sedimentary rocks, fractured crystalline rocks, and alluvial deposits act as aquifers, influencing groundwater storage and availability [10]. The permeability of geological materials dictates the rate at which water can move through the subsurface, affecting groundwater recharge and flow paths [13]. Faults, fractures, and joints in geological structures create preferential pathways for groundwater flow, influencing the distribution of groundwater potential zones [16].Geologically favourable areas, such as porous limestone or sandstone formations, serve as recharge zones where precipitation infiltrates and replenishes groundwater [18].

Drainage Density : Formation of surface and subsurface characteristics is referred to as drainage pattern. Runoff increases if drainage density is higher. As a result, there will be less water intrusion. Infiltration will increase if drainage density is lower. Thus, a zone with groundwater potential may exist. The area has a dendritic-like drainage pattern [40]. The tightness of the channel spacing is known as drainage density. With the use of Arc Hydro tool 9.3 from ArcGIS, the drainage networks are built from the carto DEM. These networks have been derived from Landsat 8 image data and Google Earth photos [1].There are five classifications for drainage density: very low, low, moderate, high, and very high. The ground water prospect is very low under the range of 0-1.2 km/km2, low under the range of 1.2-2.4 km/km2, moderate under the range of 2.4-3.6 km/km2, high under the range of 3.6-4.8 km/km2, and very high under the range of 4.8-6 km/km2.Low drainage density receives high rankings because of a higher rate of infiltration [63].

Soil Depth : Soil plays a crucial role in Groundwater Potential Zone (GWPZ) mapping due to its influence on water infiltration, storage capacity, and groundwater recharge rates. Soil texture and structure determine how quickly water can infiltrate into the ground. Coarse-textured soils (e.g., sands) generally allow faster infiltration compared to fine-textured soils (e.g., clays), affecting groundwater recharge rates [19].Soil porosity and depth influence the storage capacity of groundwater within the vadose zone. Soils with high porosity and adequate depth can store more water, contributing to groundwater availability during dry periods [42]. Permeable soils facilitate vertical movement of water, enhancing groundwater recharge. Conversely, impermeable layers within the soil profile can restrict water movement and affect recharge rates [54].Soil moisture content varies seasonally and affects groundwater recharge. Wet seasons lead to higher recharge rates compared to dry seasons, influenced by soil properties and land use practices [15]. The permeability of loamy sand is quite high, while that of silt clay loam is mild to moderate. Permeability is low in clay loam and moderate to high in sandy clay loam. It flows quickly and at a high level in coarse-granule loam. Permeability is medium in coarse sandy loam [23]. The soil map depicts various elements including forest, grassland, silt, sandy loam, clay silty loam, and gravel silt loam. [38].

Land Use and Land Cover : Land Use and Land Cover (LULC) is a critical factor in Groundwater Potential Zone (GWPZ) mapping as it influences groundwater recharge rates, surface runoff, and land surface conditions. Different land cover types affect the rate of water infiltration into the ground and surface runoff. For example, forests and grasslands generally promote higher infiltration rates compared to urban areas or paved surfaces [8].Vegetation cover influences evapotranspiration rates, which directly affect the amount of water available for groundwater recharge. Dense vegetation can reduce groundwater recharge by enhancing water loss through evaporation and plant transpiration [30]. Land use practices such as agriculture and industrial activities can lead to groundwater pollution through the introduction of chemicals, pesticides, and fertilizers into the soil, impacting groundwater quality [36]. Urban areas with impervious surfaces increase surface runoff and reduce infiltration, altering natural recharge processes and potentially lowering groundwater levels [17].

As a result, vegetation and agricultural land contain fractures that allow the soil to become more pliable and accelerate soil infiltration [1]. The primary control mechanism for the process of groundwater recharge is the map of land use and cover. Land used generally refers to land that is utilized for mining or agriculture. Land cover refers to the removal of the top soil layer, which is then used to construct structures like lakes and buildings [40].The various features that can be found on a soil map include hills, crop land, bare ground, medium-density forest, and dense forest. The plantation is mostly covered in dense forest, and because of frequent rainfall, these kinds of lands are not good for groundwater recharge. First, because there is less surface and groundwater available for irrigation and residential use, cropland and barren land are given priority for groundwater recharge [23].

Rainfall : The primary source of groundwater replenishment and the source of all hydrological processes is rainfall [6]. Rainfall is a primary source of groundwater recharge, particularly in areas where infiltration rates are high and aquifers are well-connected to surface water bodies [6]. Variations in rainfall patterns across a region affect the spatial distribution of groundwater recharge zones. Areas with higher and more consistent rainfall typically exhibit higher groundwater recharge potential [12]. Seasonal variations in rainfall influence groundwater recharge rates, with wet seasons contributing significantly more to recharge compared to dry seasons [53]. Changes in rainfall patterns due to climate change can alter groundwater recharge dynamics, potentially leading to shifts in groundwater availability and recharge rates [55].

Transmissivity of Aquifer : Transmissivity of an aquifer is a critical parameter in groundwater potential zone (GWPZ) mapping as it defines the ability of the aquifer to transmit water through its pores or fractures. Aquifer transmissivity is the groundwater discharge of unit area with unit time [23]. Transmissivity (T) quantifies the rate at which water can move through a unit width of an aquifer under a unit hydraulic gradient. It is influenced by the hydraulic conductivity of the aquifer material and the thickness of the saturated zone [62]. The primary factor influencing transmissivity is the hydraulic conductivity (K) of the aquifer material, which represents its ability to transmit water. Aquifers with higher hydraulic conductivity values typically have higher transmissivity and are more productive in terms of groundwater yield [23]. Transmissivity varies spatially due to heterogeneity in aquifer materials, such as variations in grain size, sorting, and presence of fractures or conduits [10]. Transmissivity can be estimated through pumping tests, slug tests, or inferred from geological and hydrogeological data using empirical relationships and models [56].The loose layer of the geological region is called an aquifer.

Conclusion

Methodology for systematic approach towards utilising the GIS and remote sensing technique to identify groundwater potential zones are discussed. Certain techniques are quite simple and yield precise outcomes. Certain techniques necessitate additional data and involve lengthy procedures. Every strategy has benefits and drawbacks when it comes to the procedure. Groundwater potential zones can be mapped using satellite imagery by utilizing many characteristics such as geology, geomorphology, drainage density, soil, rainfall data, aquifer transmissivity, and land use and land cover.The integration of Remote Sensing (RS) and Geographic Information System (GIS) technologies has proven to be a transformative and indispensable approach in the identification of groundwater potential zones. This synergy allows for a holistic assessment by leveraging high-resolution satellite imagery, geospatial data, and advanced modelling techniques. The multi-factor analysis, incorporating geological, geomorphological, climatic, and land use considerations, provides a nuanced understanding of the complex dynamics influencing groundwater occurrence. Beyond the precision and efficiency offered by RS and GIS, the interdisciplinary nature of this methodology fosters collaboration between various scientific disciplines, enhancing the accuracy of groundwater assessments. By overcoming the limitations of traditional methods and offering a time-efficient, cost-effective, and data-driven alternative, RS and GIS contribute significantly to informed decision-making in water resource management. The RS and GIS technique is useful in identifying groundwater potential zones, a pivotal tool for sustainable water resource utilization and conservation efforts.

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