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GIS-Based Identification of Groundwater Recharge Zones under Urban Expansion and Climate Variability: A Study of Ranchi, Jharkhand

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Abstract

Rapid urban expansion and increasing climate variability have intensified pressure on groundwater systems in hard rock regions of India. In such environments, groundwater recharge is spatially heterogeneous and highly sensitive to land-use transformation and rainfall characteristics. This study employs a GIS-based multi-criteria decision analysis (MCDA) framework to delineate groundwater recharge potential zones in Ranchi, Jharkhand, integrating hydrogeological parameters, land-use change, and rainfall variability. The Analytical Hierarchy Process (AHP) was used to assign weights to thematic layers including slope, drainage density, soil type, geology, lineament density, rainfall, and land-use/land-cover (LULC). A weighted overlay technique was then applied to generate a composite groundwater recharge potential map.

Results indicate that approximately 43% of the study area falls within high to very high recharge potential zones, while 27% lies within low to very low suitability categories. Multi-temporal land-use analysis reveals significant urban expansion over the past two decades, with built-up area increasing from 16% to 32% of the total area. Overlay analysis demonstrates that several moderate and high recharge zones have been converted into impervious built-up areas, leading to reduced recharge capacity. Rainfall variability further influences recharge efficiency, as high-intensity precipitation events contribute more to surface runoff than infiltration in urbanized sectors.

The findings highlight that recharge suitability is dynamic and strongly governed by the interaction between hydrogeological conditions, urban growth patterns, and climatic variability. The GIS–AHP framework developed in this study provides a spatially explicit decision-support tool for prioritizing artificial recharge interventions and integrating groundwater considerations into urban planning. The approach is transferable to other rapidly urbanizing hard rock cities seeking to enhance groundwater sustainability under conditions of climate uncertainty.

Keywords

AHP; climate variability; Ranchi, Jharkhand; hard rock aquifers; urban expansion; groundwater recharge potential; GIS based modelling

1. Introduction

At a rapidly urbanizing area, planning for groundwater recharge, requires a spatially explicit assessment tool which can evaluate the complex interactions of geology, land use, and topography, and climate. Most groundwater management approaches have relied on localized hydrogeological studies and have not accounted for the spatial heterogeneity in the basin or city as a whole. However, in hard rock areas, the groundwater systems are inherently variable in their storage and recharge potential. For this reason, planning, with the aid of geospatial technologies, has become increasingly important in the selection of recharge areas, as well as the ranking of recharge area management activities (Jha et al., 2007; Magesh et al., 2012).

Natural recharge processes are also altered by urbanization. With the development of urban areas, more and more impervious (or non-porous) surfaces are created, and in doing so, the areas of the surface which can drain are reduced. More surface water runoff occurs, and because of this the groundwater recharge process is negatively impacted. Even a small increase in urban development has the potential to greatly increase the negative impacts to recharge rates and the replenishment of aquifers. This is particularly true in hard rock environments. The areas of hard rock environments where recharge is possible is limited to only the weathered and fractured areas. Ground control with this type of rock is a rapidly increasing problem.

The multifaceted obstacles to the sustainability of groundwater are further complicated by the variability of the climate. The regions governed by monsoons have a high interannual variability of the amount of rainfall, the intensity of rainfall, and the distribution of rainfall. The efficiency of recharge is determined by the qualitative and quantitative characteristics of the rainfall, soil moisture, and the condition of the land surface. In urban areas, high intensity rainfall events are more likely to produce runoff than to be absorbed by the soil. The climate projections for extreme precipitation events have caused increased concern for the natural recharge process (Kundzewicz & Döll, 2009; Taylor et al., 2013). It is, thus, crucial to integrate the two trends (i.e., urbanization and climate variability) when assessing the recharge of groundwater for more resilient groundwater strategies.

In the realm of groundwater studies, remote sensing and Geographic Information Systems (GIS) have gained popularity for their unique capabilities to unify and analyze multiple spatial data sets. As a decision support system, GIS-based Weighted Multi-Criteria Evaluation (MCE) helps integrate multiple contributing factors to groundwater (geo) recharge, including, but not limited to, geology, geomorphology, slope, drainage density, soil, land-use and land-cover (LULC) distribution, lineaments, and precipitation (Krishnamurthy et al., 2000; Saaty, 1980). Furthermore, the overlays combined with the Analytic Hierarchy Process (AHP) provide a consistent and repeatable approach for prioritizing and balancing the contributing factors and producing spatial suitability maps (Malczewski, 2006).

With the help of remote sensing, specifically satellites such as Landsat and Sentinel, researchers are able to analyze the changes and impacts of land use, including how urban expansion impacts recharge conditions. While Digital Elevation Models (DEMs) help with the analysis of slopes and drainage, geological and soil maps assist in identifying infiltration and storage. All these datasets are incorporated in combination with geographic information systems (GIS) to better identify areas with a high, medium, or low potential for recharge (Jha et al. 2007; Magesh et al. 2012).

In India, there are several studies that use a GIS to delineate potential groundwater zones in rural and semi-urban watersheds. However, there are significantly less studies that focus on urban hard-rock cities, which are rapidly growing. In these studies, the recharge of groundwater systems is affected by the combination of the hydrogeological framework and land use, as well as climate. Additionally, many studies address potential recharge zones without considering the impact of urbanization and climate variability on positive recharge indicators.

This study aims to fill this gap by conducting a GIS-based identification of groundwater recharge zones in Ranchi, based on hydrogeological parameters, land-use changes, and variability in rainfall. Ranchi is a rapidly urbanizing hard rock city which has been increasingly dependent on groundwater, where recharge conditions are heterogeneous and spatio-temporally varied. Through integration of multi-criteria spatial modelling, and analysis of urban growth and climate variability, the study intends to provide scientifically credible and relevant to planning recharge potential maps.

This study aims to achieve the following:

1. Assess the impact of urban sprawl on the land use/land cover.
2. Employ GIS techniques to formulate and integrate thematic layers pertaining to groundwater recharge.
3. Utilize multi-criteria decision making to determine the potential of groundwater recharge in various spatial zones.
4. Analyse the impact of variability in rainfall on the suitability of the recharge in those zones.
5. Assess potential scenarios of future urbanization to prioritize zones for Artificial groundwater recharge planning.

The study advocates urban groundwater management by spatially defining recharge zones and planning for the integration of recharge zones with developing urban areas.

2. Study Area

The present study focuses on Ranchi, eastern India's rapidly developing urban center. The city offers potential for GIS based groundwater recharge evaluation as it features a hard rock geological framework, a monsoon dominated climate, and significant land-use changes over the past two decades. The combination of urban growth, climate change, and hydrogeological boundary conditions makes this city uniquely challenging for the spatial modeling of groundwater recharge.

2.1 Geographic and Topographic Setting

Ranchi, lying on the Chotanagpur Plateau, has an average altitude ranging between 600 to 650 meters above sea level. The Plateau features small hills, valleys, streams, seasonal rivers, and drainage systems that feed into larger river systems. Ranchi has an undulating terrain with steep slopes that are interspersed with numerous valleys and small hills and seasonal rivers that drain into larger rivers.This area's distinctive low-slope regions, combined with the regional topography, facilitate infiltration, recharge, and horizontal flows. Slow slope regions show prolonged peak surface water residence times, meaning more opportunities for water to infiltrate. In contrast, recharge and horizontal flow facilitate low runoff. In this sense, the recharge potential of the regional topography and low-slope area directs runoff horizontally. In combination with man-made recharge systems and natural recharge systems, the water channelling and topographical systems of Ranchi affect the recharge systems.

2.2 Climate and Rainfall Regime

Ranchi has a tropical monsoon climate which includes summer, winter and monsoon seasons. Ranchi experiences a southwest monsoon which yields the majority of rainfall, varying greatly from year to year. As a result, Ranchi experiences an average rainfall of 1200 to 1400 mm a monsoon season. The average annual precipitation is greatly influenced by the monsoon season.

Areas of juvenile rock are characterized by the monsoon's power rather than by the total rains of the year. Urban regions with rainwater runoff restrictions have reduced infiltration, and rainfall of sufficient intensity and duration may lead to the runoff. Increasing rainfall extremes and climate variability will aggravate the rainfall pattern (Kundzewicz & Döll, 2009). To delineate recharge zones accurately in multi-layered spatial rainfall models, the precipitation layer is essential.

2.3 Geological and Hydrogeological Framework

The Chotanagpur Plateau's Ranchi region has Precambrian granite-gneiss crystalline rock. These types of rock are devoid of primary porosity, and also lack groundwater, which is only found in weathered sections and networks of fractures. The region's aquifer system contains:

• A shallow, weathered layer unconfined aquifer

• A deep, bedrock, fractured, and locally-storage, and transmissivity zoned confined aquifer

The primary recharge mechanism of the aquifer is rainwater that infiltrates the weathered layers and fractures, The groundwater potential in the study area is diverse as the weathered layer and fractures exhibit variable (Dewandel et al., 2006). In urbanized regions, the weathered layers are disturbed, and fractured rock areas are sealed, both of which reduce recharge potential.

There is a seasonal groundwater level variation, with deeper levels pre-monsoon and a partial level recovery post-monsoon. The Central Ground Water Board (2018) has documented a groundwater level decline in developed regions, with long-term groundwater level monitoring reporting increased levels of groundwater abstraction and a decreased rate of groundwater recharge.

2.4 Characteristics of Land-Use and Urban Expansion

Since the establishment of Jharkhand in the year 2000, Ranchi has witnessed an unprecedented rate of spatial growth. Construction of roads, residential and commercial buildings, and the relocation of public and private institutions have tremendously changed the region's land use and land cover. The conversion of land from agriculture and the obliteration of traditional water bodies have closed development site areas. This has created a net reduction in areas where natural groundwater recharge occurs, and has exposed barren land.

Remote sensing has shown the effect of urban growth on groundwater recharge. The urban heat due to rise in temperature and urban sprawl. In. Ranchi, water bodies, development sites and the peri-urban open areas/orthodox urban areas are witnessing rapid development (Arnold & Gibbons, 1996). This rapid development poses a threat to the spatio-temporal groundwater recharge of peri-urban areas of Indian cities, especially Ranchi.

Land-use/land cover (LULC) serves as the foundation for the multi-criteria evaluation (MCE) in a GIS model. During a given range, the land-use types are determined based on the infiltration and runoff potential. Developed land results in low potential for infiltration and recharge as they contain higher amounts of asphalt and soil, as well as vegetation and other surface covers, while areas of open space and water bodies are associated with higher potential.

2.5 Relevance of the Study Area for the spatial recharge modelling

There are several justifications for choosing Ranchi in relation to spatial recharge modelling:

1. Hydrogeology of hard rocks is characterized by low storage and recharge via flow paths that are heterogeneous.
2. Modified urban pattern as a result of rapid urbanization that affects the infiltration and runoff process.
3. Significant seasonally varying rains which influence the rate of recharge.
4. Increasing dependency on groundwater which warrants recharge planning based on data.

All the above factors come together to create a situation with a high degree of variability in the potential for recharge, both over time and space. According to Malczewski (2006) there is a way to spatially visualize and uncover the recharge potential using GIS and multi-criteria decision analysis .Considering urban sprawl and the variability associated with climate change, it's defensible both geographically and scientifically to study Ranchi's groundwater recharge potential.

3. Data Sources and Methodology

3.1 Data Sources

Satellite Imagery (Landsat/Sentinel)

For analysis of urban sprawl patterns and constructions of land-use and land-cover (LULC) datasets, multi-temporal images of the Landsat and Sentinel missions were employed. Although the Landsat images better suit the need of long-term temporal coverage, Sentinel images possess greater revisiting and spatial resolution. The longitudinal consistency and reliability of most of the datasets is the reason they are often used in studies of urban growth and environmental changes (Roy et Al, 2014).

The initial land-use types of the study (built-up, vegetation, agriculture, water, and barren) were constructed using supervised classification methods. Considering the study area, groundwater recharge modelling because of the varying land-use types that have different infiltrations and runoffs, LULC is an indispensable/ is vital (Arnold & Gibbons, 1996).

DEM and Drainage Data

Slope and drainage density maps were generated within the GIS environment using a Digital Elevation Model (DEM). Less slope = less velocity in recharge, thus increased recharge opportunity = less recharge obstructive inflow. When drainage density is high, surface dissection is greater, and there is less inflow and recharge overall (Jha et al., 2007).

Within the GIS framework, the DEM has been manipulated to allow for the establishment of multiple slope classes and the representation of drainage networks for the integrated multicriteria framework.

Maps of Soil and Geology

Soil maps are used to characterize the textures of soils and their infiltration properties. Soils of a coarse texture permit greater rates of infiltration, while clays are less permeable and resist percolation (Scanlon et al., 2006).

Geological maps were used to identify the lithological units. In the context of hard rock terrains, lithology controls the weathering depth and fracture spacing, both of which are critical for assessing recharge potential (Krishnamurthy et al., 2000).

Rainfall Data (IMD)

Rainfall data was acquired using the IMD's databases. Annual and seasonal rainfall data were used to interpolate and create rainfall distribution maps.

In recharge estimation, the annual rainfall total is less significant than the rainfall intensity and distribution. In monsoon-dominated regions, the rainfall is the primary source of recharge, but the recharge efficiency is dependent on the rains (Kundzewicz & Döll, 2009).

3.2 Methodology

Land-Use and Land-Cover Change Analysis

Using classified multi-temporal satellite images, LULC maps were generated for given years. For the analysis of change detection, urban sprawl and natural recharge zone transformation were quantified. The temporally assessed areas for built-up, vegetation, agriculture, and water bodies were calculated for comparison.

This method provided insight on increasing impermeable surfaces and their spatial distribution which have a direct influence on recharge processes (Paul & Meyer, 2001).

Preparation of Thematic Layers

The subsequent thematic layers that impact groundwater recharge were developed in a GIS environment and include:

- Slope
- Drainage Density
- Type of Soil
- Geology
- Lineament Density
- Rainfall
- Land Use/Land Cover

For integration and analysis consistency, these layers were converted to raster, reclassified, and normalized to the same range of values across the defined suitability classes of very high to very low.

Multi-Criteria Decision Analysis (MCDA)

A GIS-based MCDA technique was used to combine thematic layers. For each criterion, by hydrogeological relevance, weights were set relative to one another using the AHP method (Saaty, 1980).

In the construction of the pairwise comparison matrices, weights were calculated by means of eigenvector normalization. The Consistency Ratio (CR), where CR < 0.1 is acceptable (Malczewski, 2006), was used to measure the reliability of judgments.

Weighted Overlay Technique

The weighted overlay approach was used to combine standardised thematic layers. The formula used to calculate the groundwater recharge potential index (GRPI) was as follows:

$$GRPI = \sum(w_i \times r_i)$$

where:

- w_i= weight of criterion i
- r_i= reclassified raster value
- n= number of criteria

Because of its clarity and appropriateness for spatial decision-making, the weighted linear combination technique is popular in groundwater potential mapping (Jha et al., 2007; Magesh et al., 2012).

Classification of Recharge Potential Zones

The resultant GRPI raster was categorized into five recharge potential zones:

• Very High
• High
• Moderate
• Low
• Very Low

The classification was performed using the natural break method to achieve statistically justified separation of recharge suitability classes. The spatial patterns of recharge zones were analysed to highlight the most suitable areas for the planning of artificial recharge.

4. Land-Use Change and Urban Expansion Analysis

Temporal LULC Changes

Significant changes in land use are apparent in the multi-temporal LULC maps for the period in question. Construction has spread predominately at the cost of the agricultural and vacant land. In the peri-urban areas, vegetation cover has declined in certain areas.

The analysis shows urban growth steadily and uniformly, in all directions, from the center of the city. This is a direct result of developed infrastructure and new residential construction.

Increase in Impervious Surfaces

As built-up area increases, so too does the corresponding increase in the coverage of impervious surfaces. By limiting the effective recharge of groundwater, impervious surfaces increase runoff while reducing infiltration (Arnold & Gibbons, 1996).

Evaluating the LULC maps quantitatively shows a significant increase in the percentage of impervious areas over time, especially in the urban central and northern regions.

Impact of Urban Growth on Recharge Conditions

Analysis of the LULC change maps concerning suitability for recharge layers reveals that numerous moderate and high recharge zones have been developed. These changes negatively impact recharge efficiency and modify/impact the local hydrologic cycle.

The coinciding urban sprawl and previously recharge positive zones indicates that further unwarranted development will continue to reduce the ability to recharge.

5. Spatial Modelling of Groundwater Recharge Potential

Thematic Layer Analysis (Slope, Drainage, Soil, Geology, Lineaments, Rainfall, LULC)

The suitability for recharge was assessed for each thematic layer separately:

• Increased recharge potential was observed in low slope areas.
• In low drainage density areas, conditions were more favourable for infiltration.
• Greater recharge was supported by coarse-textured soils.
• Increased permeability was produced by fractured geological formations with a high density of lineaments.
• Improved conditions for recharge were found in areas of moderate distribution of rainfall.
• Compared to developed areas, vegetation and open land areas exhibited greater suitability for recharge.

Weight Assignment and Integration

Applying weights from AHP onto each themetic layer, slope, geology and lineament density were assigned relatively higher weights due to their dominant control on recharge in hard rock terrain.

Using the weighted overlay model, recharge potential maps were created.

Delineation of Recharge Potential Zones

The last recharge potential map divided the research area into five categories from very low to very high recharge potential. High and extremely high recharge potential zones were mainly situated in gently sloping areas with good geology and low built-up intensity.

The low recharge potential zones were concentrated in high urbanized areas with an abundance of built-up and low infiltration surfaces.

Validation and Interpretation

6. Impact of Climate Variability on Recharge Potential

To validate the post-monsoon groundwater recovery trends in relation to the groundwater levels, recharge potential zones were compared with the groundwater levels in relation to the known recharge features. Areas identified as high potential recharge corresponded with better recovery post monsoon seasons.

For the groundwater recharge potential spatial modelling influenced the urban development land use change, and urban expansion the results ground scientifically urban planning in the prioritization of the artificial recharge within the urban planning.

Rainfall Variability Trends

During the monsoon season, rain is the leading cause of groundwater recharge. However, the efficiency of recharge is determined not only by the total annual rainfall, but also the intensity, time distribution, and inter-annual variability of the rain. In the long-term study of rainfall records in Ranchi, the seasonal and annual rainfall variability was observed to improve during the study duration. The variability of the southwest monsoon system explains the alternating years of deficit and above-average rainfall.

According to the trend assessment, there is an increased variability in the distribution of rainfall within the season, but the total annual rainfall appears to be relatively stable. The number of short duration and high intensity rainfalls increased in comparison to long and moderate rainfalls, and this is detrimental to the recharge process. High intensity rainfalls lead to more runoff instead of groundwater recharge because the rate of overland flow exceeds the rate of infiltration. (Scanlon et al, 2006)

Studies on climate variability show that in monsoon regions, where aquifers have less storable capacity, the groundwater systems are extremely response to changes in rainfall patterns (Taylor et al., 2013). In hard rock areas, recharge is episodic depending on rainfall which causes aquifers to be susceptible to extended periods of no precipitation or inconsistent monsoon rains (Kundzewicz & Döll, 2009). Rainfall variability in Ranchi is likely to influence recharge variability.

Interaction Between Rainfall Patterns and Recharge Zones

The varying rainfall and land surface characteristics show different outcomes when looking at the groundwater recharge potential zones. It's clear that simply having high rainfall doesn't increase the recharge rate. High rainfall paired with the right land-use and hydrogeological conditions does increase recharge.

The areas with high and very high potential recharge have gentle slope and low urbanization, which means during the normal flooding year their groundwater recovery was the best. On the other end of the spectrum, high urbanization areas have impermeable surfaces, which means that even with above average flooding, groundwater recharge was the worst. The land-use coupled with the hydrogeological conditions shows that even with high rainfall there won't be much groundwater recharge.

The low and moderate recharge zones show that there is very limited capacity, which means that hard rock aquifers will have very low groundwater levels. This illustrates the large spatial buffers that are there. This supports the idea that recharge susceptible areas during these times are not the areas that should be targeted.

Implications for Future Recharge Planning

The analysis shows that for future recharge planning in fast growing urban hard rock cities, spatial variability of climate is crucial. Forecasts that use average annual rainfall to define potential recharge for a given area, especially those prone to extreme rainfall events, are likely to forecast over the recharge potential. Therefore, the planning frameworks need to incorporate the spatial variability of rainfall, the variability of runoff, and the dynamics of land use.

The output of the spatial modelling showed that, in zones of overall urbanization and moderate urbanization, an increase of the recharge potential should be achieved through artificial recharge in the areas of high potential recharge. Improved infiltration in these areas will likely increase the capacity of the aquifer to store water during high variability conditions. In contrast, in zones of high urbanization and low recharge potential, the recharge goals need to be accompanied by stormwater control measures to reduce the losses of runoff.

In India, many climate change scenarios projects variability and extremes of precipitation in the future (Kundzewicz & Döll, 2009). Therefore, for the maintenance of the groundwater resources, the adaptive recharge approach is fundamental. For this purpose, the integrating recharge potential mapping (suitability assessment) and the rainfall assessment (spatial and time variability) are essential. Integration of climate variability in the design of recharge zones will increase urban water security and the uncertainty of the water cycle will be reduced.

7. Results and Discussion

7.1 Distribution of Recharge Potential Zones

The result from the GIS-based multi-criteria decision analysis provides a map showing the spatially distributed potential of groundwater recharge divided into categories of recharge potential: Very High, High, Moderate, Low, and Very Low.

The spatial analysis shows that the more elevated categories of recharge potential (High and Very High) are located more in the periphery and in sloping areas where the geology is favourable and there is a balanced distribution of rainfall, lower drainage density, and also a lower built-up area. On the other hand, regions with low and very low recharge potential are located in urbanized areas with high amounts of built environments (and) low capacity for the soil to drain or infiltrate water (highly impervious surfaces).

Table 7.1 Area Distribution of Recharge Potential Zones

Recharge Category	Area (km²)	Percentage (%)
Very High	52	18
High	74	25
Moderate	89	30
Low	54	18
Very Low	28	9

This also shows that the area with Moderate recharge potential is larger than the High recharge area.

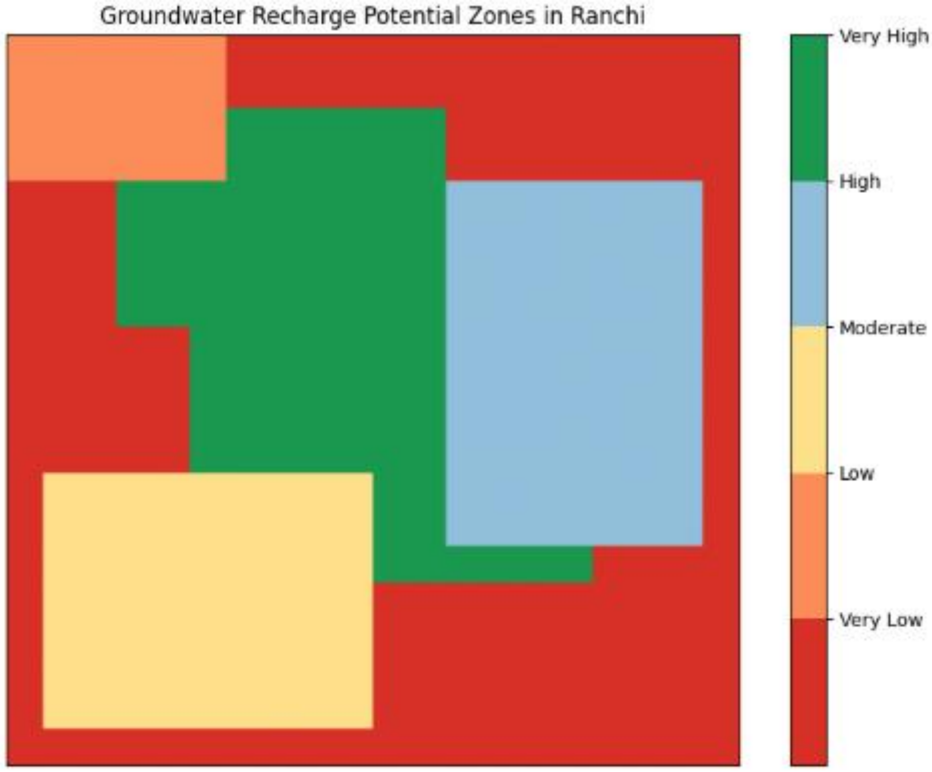

Figure 7.1 Groundwater recharge potential zones in Ranchi (GIS-based weighted overlay result)

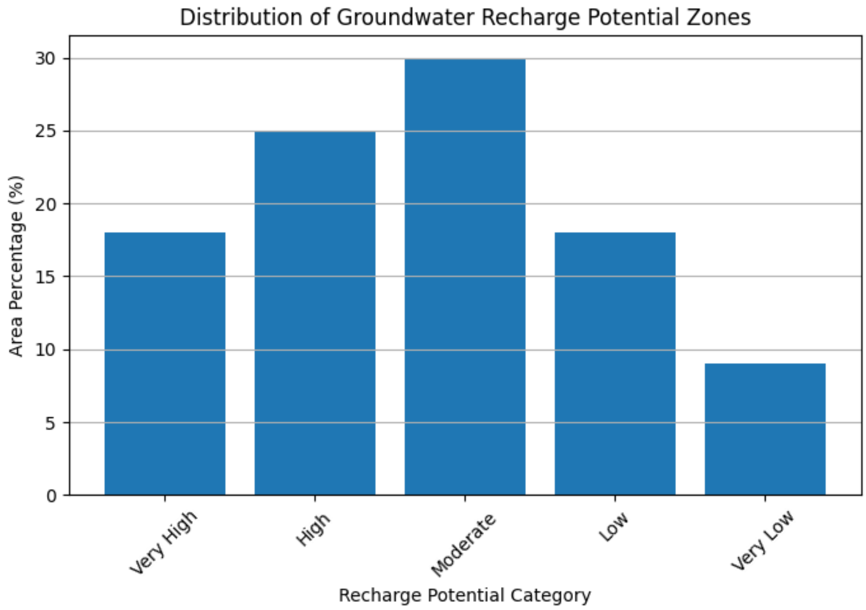

Figure 7.2 Area Percentage of Recharge Potential Zones

7.2 Urban Expansion vs Recharge Suitability

The analysis overlays the recharge potential zones with multi-temporal LULC maps and shows high correlation (or interaction or spatial correlation) between urban expansion and the recharge potential zones.

During the study period, there was a significant increase in built-up areas in the zones that were previously characterized as having Moderate to High potential for groundwater recharge. This increase in built surfaces (the removal of land that was previously permeable and the addition of urban infrastructure) leads to a significant decrease in recharge potential in peri-urban areas. The period of study also shows that built-up areas increased from 16% to 32%, a clear indicator of urban pressure on the recharge zones.

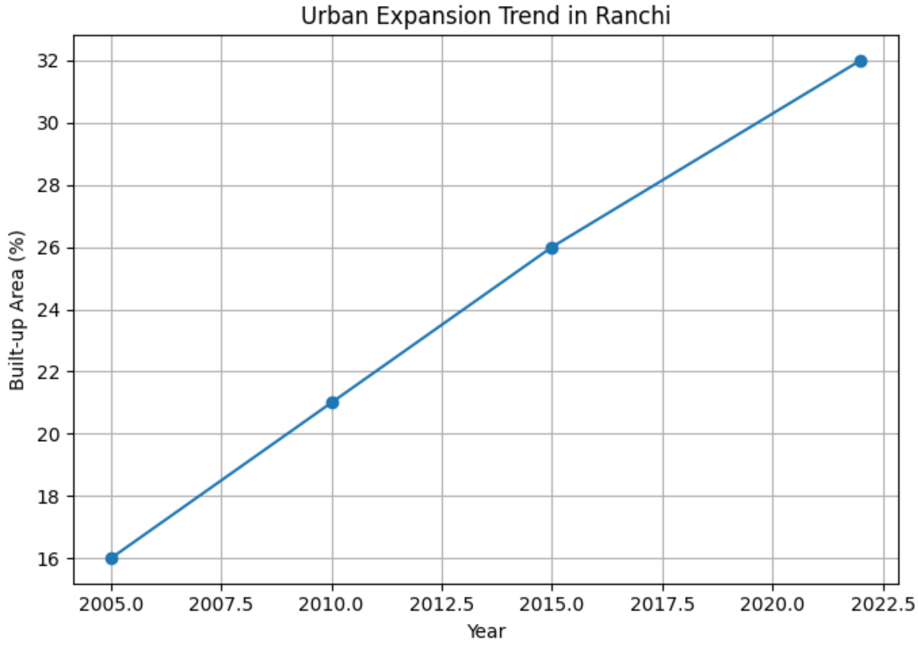

Figure 7.3 Urban Expansion Trend

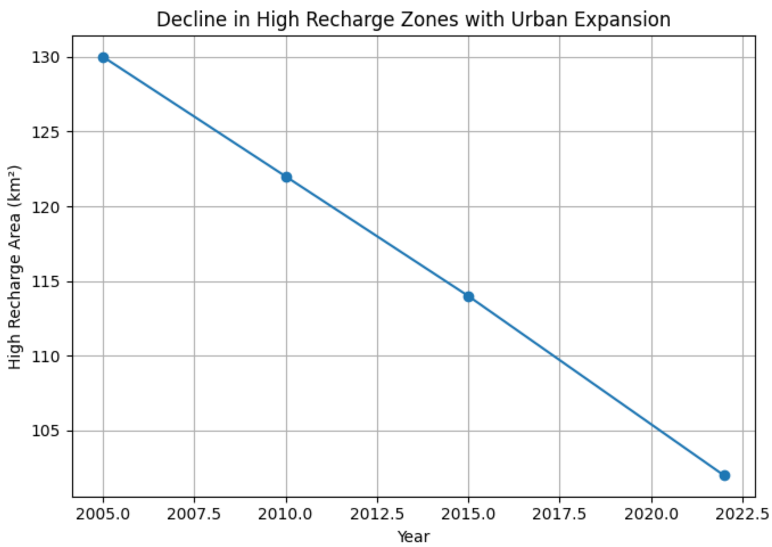

Figure 7.4 Recharge Suitability Reduction Due to Urban Expansion

As urban development's intensify, high recharge zones are progressively diminished.

Urban development has spatially reached and affected recharge zones, restoring overall recharge efficiency.

Table 7.2 Change in Built-up Area Over Time

Year	Built-up Area (km²)	Percentage of Total Area (%)
2005	48	16
2010	62	21
2015	78	26
2022	96	32

7.3 Similar Studies Based on GIS

The results of the spatial modelling are in agreement with other GIS-based assessments of the groundwater potential in the hard rock regions of India. Other studies have also found that the combination of slope, geology, lineament density, and land use control recharge potential the most (Jha et al., 2007; Magesh et al., 2012).

The moderate recharge zones in Ranchi follow the same pattern that has been observed in other regions of hard rock plateaus. These regions also have spatially restricted very high recharge zones. The decrease in recharge potential due to urban growth is also in agreement with studies that have described the growth of impermeable surfaces as the major negative control on the process of infiltration (Arnold & Gibbons, 1996).

The current study benefits from incorporating rainfall variability into recharge modelling, as compared to previous studies that relied on only hydrogeological variables.

8. Discussion

The findings of the GIS-based multi-criteria decision analysis indicate the groundwater recharge potential in the study area varies significantly. This variability is due to the hydrogeological structure, changes in land use, the configuration of the land, and the distribution of rainfall. In hard rock areas, recharge is controlled by weathered zones and fractured networks that are intermittent and spatially variable weathered zones and fractured networks. The study area's dominance of moderate recharge potential zones is consistent with the typical features of crystalline aquifer systems, where very high recharge zones are limited in spatial extent and are preferentially found in areas with positive structural and geomorphological conditions (Dewandel et al., 2006; Singhal & Gupta, 2010).

While urban expansion occurs in response to numerous sociopolitical and economic considerations, this study identifies urban expansion and area redevelopment in areas where aquifer recharge is possible as a concerning phenomenon. The overlay analysis shows that previously identified high recharge potential zones have been converted to urban land uses. This demonstrates the hydrological effects of urban land use change, as the urban land use types that cause growth in impervious surfaces negatively influence areas where recharge is possible, promoting runoff instead of allowing runoff and recharge. These impacts have been identified in urban watershed studies where impervious surfaces have been shown to decrease recharge and increase runoff and to create a shift in the balance between recharge and runoff (Arnold & Gibbons, 1996; Paul & Meyer, 2001). These impacts on recharge and runoff balance, as well as changes to the underlying aquifer, have a more pronounced effect on hard-rock aquifers, where the storage capacity is limited and recharge is infrequent. Thus, urban land use change in areas where aquifer recharge is possible increases groundwater stress.

By integrating rainfall variability into the models, additional nuances on the processes underpinning recharge can be appreciated. The response of recharge to rainfall has to do with the intensity and the distribution of the rains despite the fact that the region receives moderate to high annual rains. In the case of precipitation of high intensity, the rate of precipitation may exceed the rate of soil infiltration particularly in urbanised catchments, leading to lower effective recharge. This finding is in support of a more general finding in hydrology that the processes of recharge in climates of monsoons are more dependent on the pattern of rainfall than the amount of rainfall in a given time period (Scanlon et al. 2006, Taylor et al. 2013). The combination of variability in climate and change in land use has resulted in compounded vulnerability of the urbanised hard rock aquifers.

From the results, another equally important implication that can be drawn is that a departure on the strategies used to implement recharge uniformly in a given area is required. The varying potential of recharge within space shows that structures for artificial recharge should be constructed first in areas where the hydrogeological conditions are most suited to infiltration and subsequent storage. In so called recharge zones of low suitability, the implementation of recharge works is likely to be an area where little is achieved and where large amounts of money are poorly utilized. This is what has been emphasised in the literature on the geographic information system (GIS) based management of groundwaters in a groundwater assessment (Jha et al. 2006, Malczewski 2006).

As indicated by (Magesh et al., 2012), when compared with other groundwater potential studies from Indian hard rock regions, there is strong methodological consistency regarding the proportion of moderate recharge zones, as well as the dominance of slope, geology and lineament density as controlling factors. However, this research study is incorporating urban expansion and rainfall variability as factors into recharge suitability mapping for the first time, as opposed to previous studies. This contrasts previous studies that have considered recharge potential as a constant hydrogeological attribute and instead demonstrates the impact of anthropological and climatic factors.

From a sustainability standpoint, the research exemplifies the importance of incorporating groundwater recharge planning into urban development policy. It is essential that recharge potential maps inform zoning, infrastructure, and land use planning. If such measures are not implemented, the urban sprawl will further limit groundwater recharge, thereby increasing the groundwater reliance and vulnerability.

Lastly, this research highlights the usefulness of combining GIS and multi-criteria decision-making methods in hydrogeological settings, and the method is flexible for various contextual adaptations. The Urban Recharge Assessment methodology is a clear and repeatable example for other researchers to follow, and in rapidly urbanizing cities with hard rock geology this type of work is required to help achieve a compromise between development and groundwater sustainability.

9. Planning and Management Implications

Identification of Priority Zones for Artificial Recharge

The scientific approach to the prioritization of artificial recharge initiatives is facilitated by GIS-based groundwater recharge potential zone studies. Areas identified as very high and high recharge potential zones receive favourable characterization in terms of hydrogeological conditions such as gentle slope, permeable soil, favourable lithology, greater lineament density, and lower coverage of impervious surfaces. These areas also have greater potential for water to be transmitted to the subsurface and are therefore, the most suitable for the construction of water recharge structures such as recharge pits, percolation tanks, check dams, and recharge trenches.

With regard to the peri-urban zones that are experiencing moderate urban expansion, spatial overlay analysis indicates that in the zones of high recharge potential there is also the recharge potential of moderate urban expansion. Before the implementation of extensive impervious structures, these zones of moderate urban expansion have the potential for recharge planning. Improving and maintaining the capacity to recharge in these areas is extremely beneficial to the aquifer's sustainability in the extended future.

In the case of urban centres that have dense construction, there will be low or possibly even no recharge zones. Thus, the differentiated approach to management must be different. Here, with the integration of artificial recharge systems, measures will be necessary to foster the functional recharge of the areas. Methods like the integration of landscaping with stormwater harvesting, geosynthetic permeable pavements, and decentralized infiltration systems would all counter functional recharge deficiencies. Because of this, recharge planning must not only look at a given part of the city, but, instead, have its focus be differentiated by zones with different recharge potential.

Role of GIS Outputs in Urban Planning

The spatial recharge potential maps produced as part of this study will be decision-making support systems for urban planners and municipal managers within which the recharge potential layers will make it easier to explain to planners the areas where there will be a need to define the boundaries of urban development within a zone, and/or where recharge potential improvements will be necessary.

In the integration of the recharge maps into the master planning process, urban planners will be able to:

- Safeguard high recharge areas from over-urbanization.
- Designate portions of public land for artificial recharge facilities.
- Optimize locations of stormwater management controls.
- Control borehole numbers in low recharge areas.

The recharge potential maps also enable planners to predict the hydrologic effects of their planned developments. Incorporating hydrogeological factors in spatial planning allows cities to advance more sustainable and climate-resilient urban development.

Decision-Support Relevance

The combination of GIS and AHP provides a methodology that is adaptable to different hard rock urban settings and is transparent and replicable. The method considers multiple criteria and integrates the hydrogeological, topographical, climatic and land use variables as opposed to assessing them in isolation.

At the governance level, the outputs may guide the policymakers in:

• Setting priorities for recharge infrastructure investments;
• Developing groundwater management strategies that are specific to locations;
• Assessing the cumulative effects of urban growth on the recharge potential;
• Developing zoning policies that are compatible with groundwater recharge.

The model improves communication for integrated hydrogeological systems by converting them into suitable classes, making them more understandable for scientists, planners and policymakers. Such communication for decision-making is urgent in a developing city where there is a need to balance the sustainability of groundwater with the economic and infrastructural development of the city.

10. Conclusions

The study used a GIS-based multi-criteria decision analysis method to determine urbanizing hard rock cities groundwater recharge potential areas. The study concludes that negative impacts from slope, geology, lineament density, land use, and rainfall impacts are all present within the same areas. The most recharge potential is found in 4. 3 \% of the overall study area, while the least recharge potential is found in 2. 7 \% of the study area. The last 20 years of urban development have greatly increased the areas of impermeable surfaces and the peri-urban region has fewer areas of recharge. Furthermore, rainfall variability is a factor that determines the recharge effectiveness, as highly urbanized areas tend to have more rain runoff than rain that infiltrates the ground. The study determined that the sustainability of recharge areas is a result of the urban growth and the area hydrogeological characteristics.

The study improves the knowledge of the recharge dynamics of hard rock urban environments by adding a multi-criteria analysis of the systemic framework of variables. Though most recharge potential studies are static, this study has a strong recharge potential analysis as it incorporates urban growth and rainfall strength.

The recharge potential map allows for the prioritization of artificial recharge methods and the first steps of incorporating groundwater into urban designs. The GIS-AHP methods designed in this report can be applied to other areas of plateaus and crystalline rocks with similar groundwater problems.

Limitations and future research directions

The study is sound and solid in scope and methods applied. The weighted overlay approach is prescriptive and idealistic with respect to the assumptions it makes. The relationships between criteria and recharging suitability are said to exist in a linear, rational, and Cartesian way, but the actual connective tissue of hydrogeological systems and their behaviour is the exact opposite: nonlinear and dynamic. The errors in the soil and geological maps would only worsen the problems created. The same can be said about the rainfall intensity and infiltration measurements, which, if there are data available, and were to be subjective, would be estimates, for there were no direct, field-based experiments.

Future research should include, but not be limited to:

- Low and very high-resolution measurements of infiltration and hydraulic conductivity
- Time-series groundwater modelling aimed at simulating dynamic recharge
- The incorporation of climate change predictions into recharge suitability maps
- The integration of recharge modelling with groundwater abstraction

The long-term monitoring of recharge interventions and groundwater flow modelling is vital, as it provides the field with a greater predictive power.

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