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Assessment of Groundwater Recharge Interventions for Sustainable Urban Water Management: A Case Study of Ranchi, Jharkhand

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Abstract

Rapid urbanization and increasing water demand have intensified groundwater stress in many Indian cities, particularly those located in hard rock terrains where aquifer storage and recharge are inherently limited. Ranchi, the capital city of Jharkhand, exemplifies this challenge due to its rapid urban growth, increasing dependence on groundwater, and disruption of natural recharge processes. In response, various groundwater recharge interventions—such as rooftop rainwater harvesting systems, recharge pits, ponds, and small check dams—have been implemented across the city. However, their effectiveness in enhancing groundwater availability under urban conditions remains inadequately evaluated.

This study assesses the performance of existing groundwater recharge interventions in Ranchi within the context of sustainable urban water management. Long-term pre- and post-monsoon groundwater level data were analyzed to identify seasonal and temporal trends, and rainfall variability was examined to understand recharge responsiveness. Recharge interventions were inventoried, classified, and evaluated based on their spatial distribution, hydrogeological suitability, and observed groundwater level response. The analysis was supported by statistical indicators, comparative assessment of areas with and without recharge structures, and synthesis of urbanization impacts.

Results indicate that groundwater levels in Ranchi exhibit persistent long-term decline despite seasonal post-monsoon recovery, reflecting a negative groundwater balance driven by increasing abstraction and limited effective recharge. Recharge interventions contribute positively to groundwater replenishment at localized scales, with improved post-monsoon recovery observed in areas hosting functional structures. However, their overall city-scale impact remains modest due to fragmented implementation, variable hydrogeological suitability, rainfall variability, and continued over-extraction. The findings highlight that recharge interventions, while necessary, are insufficient as standalone measures for achieving sustainable urban groundwater management.

The study underscores the need for hydrogeologically informed site selection, spatial prioritization of recharge measures, and integration of recharge planning with urban development and groundwater governance frameworks. The insights derived from Ranchi provide practical and transferable lessons for other rapidly urbanizing cities situated in hard rock regions across India.

Keywords: Groundwater recharge; Urban water management; Hard rock aquifers; Rainwater harvesting; Groundwater depletion; Ranchi, Jharkhand

1. Introduction

Rapid population growth, unplanned urban development, higher per capita water consumption, and variability in climate have resulted in severe urban water shortages in Indian cities. Indian cities' water distribution systems have aging systems and poor management, and surface water becomes available. Thus, the primary, even if partial, supply for domestic, institutional, and industrial functions of urban water supply systems is groundwater. Numerous researchers have illustrated the increasing dependence of urban water supply systems in Indian cities on groundwater and the problems of over-extraction, drop in water levels, and rise in pumping energy costs, (Shah, 2009; Sundaresan, 2015).

Among the different alternatives for urban water supply systems, groundwater stands out due to ease of access, reliability in droughts, and short-term climate variability. Despite the aforementioned advantages, over-extraction without corresponding recharge has led to aquifer stress. Semi-critical and critical districts for groundwater development are found throughout peri-urban and urban areas of India. This problem has led researchers to focus on arresting groundwater exploitation in order to enhance groundwater recharge strategies.

Groundwater recharge is essential to all aquifer systems because it reinforces groundwater storage using both natural processes and artificial means. In urban settings, recharge is seen as a more effective solution to groundwater depletion and a means to achieve urban water resilience. Across India's sustainable water management initiatives, various artificial recharge techniques, such as rooftop rainwater harvesting, recharge pits, percolation tanks, check dams, and restoration of traditional water bodies, have been adopted (Sakthivadivel, 2007; Kumar et al., 2011). These initiatives, when designed and executed effectively, can enhance the availability of groundwater, reduce surface runoff, and assist in the overall reduction of flooding.

There is little doubt that recharging groundwater in urban settings can have a number of advantages, and yet there are still many obstacles that must be overcome, especially in hard rock settings. Less primary porosity in hard rock aquifers means that weathered zones and fracture systems are the only means of groundwater storage and movement. Recharge in such areas is limited and localized (Singhal & Gupta, 2010). The process of urbanization, such as the sealing of areas where natural recharge can occur, compaction of natural and engineered soils, and the diversion of stormwater, creates systems where recharge is more difficult, often leading to conditions of groundwater depletion. Because of these reasons, many cities, even those that receive a great deal of rain, still receive little groundwater recharge.

Recharge initiatives have many challenges when it comes to implementation in urban India. Many initiatives have challenges, such as being introduced in a fragmented way, project based, and often responding to regulation or goals that are short term. Often site choosers do not consider hydrogeological unsuitability, spatial variability, or cumulative impacts at the aquifer scale. Moreover, they do not monitor and maintain recharge structures and this easily leads to a loss of effectiveness. Many scholars argue that lateral or systematic evaluation, increases the effectiveness of recharge initiatives, as opposed to being a symbolic compliance measure (Mukherji & Shah, 2005; Foster, et al., 2018).

In this regard, it would be useful to evaluate recharge interventions that have been implemented in urban hard rock environments. It is crucial to evaluate urban environments to see if recharge measures have made any improvements or not to the groundwater levels and to find out how different urban environments influence the recharge levels. Empirical assessment is essential and provides the best explanation to the recharge planning in the future and the urban water management policies.

The need for researching groundwater management techniques is fulfilled by researching groundwater recharge techniques by the rapidly urbanizing hard rock city of Ranchi. A rapidly urbanizing second-tier Indian city, Ranchi, has a heightened reliance on groundwater due to urban demand. Surface water infrastructure is also lacking, further increasing the pressure on available groundwater. Several groundwater recharge initiatives have been undertaken by the municipality; thus, assessment of the city's recharge initiatives is highly relevant.

The present study aims to achieve the following goals:

i. Characterization of the groundwater level fluctuations in the urban and peri-urban areas of Ranchi.

ii. Evaluation of existing groundwater recharge techniques and spatial distribution of recharge techniques.

iii. Assessment of the groundwater level fluctuations and the effectiveness of groundwater recharge.

iv. Analysis of the recharge techniques and how urban water management can be improved in hard rock environments.

The present study focuses on assessing the role of groundwater recharge in urban water management in a highly empirical manner. It is expected that the result obtain from this study will be used to further improve the recharge strategies for groundwater management in Ranchi as well as for other Indian cities that share similar conditions.

2. Study Area

The present study examines Ranchi, the capital city of the state of Jharkhand, which is one of the rapidly urbanizing cities in a tough rocky geological setting. The combination of the city's physical environment, climatic conditions, hydrogeology, and urbanization patterns, provides a suitable setting to assess the challenges and opportunities to improve urban groundwater recharge.

2.1 Location and Geographical Setting

Ranchi is situated between 600 to 650 m above mean sea level, on the eastern part of the Chotanagpur Plateau of India. The city has a gently undulating terrain consisting of moderate to steep slopes, small valleys, and seasonal drainage channels. Such a configuration of topography results in the rapid surface runoff during a monsoon rain which consequently does not allow sufficient time for infiltration and recharge of the groundwater.

Ranchi's geographical setting is centralized in Jharkhand. With the last two decades, Ranchi's urban center has developed in a radial fashion, engulfing the peri urban and rural areas into the administrative and functional periphery of the city. This rapid transformation integrates the previously uncontrolled land surface, drainage, and recharge systems of the urbanized region and profoundly alters the groundwater systems of the area (Kundu, 2014).

2.2 Climate and Rainfall Characteristics

The climate of Ranchi is identified as tropical monsoon climate comprising summer (March-May), monsoon (June -September), and winter (October-February) seasons. With regard to average annual rainfall, which ranges from 1200 - 1400 mm, the primary rainfall is from the southwest monsoon. The rainfall is also highly seasonal, as the majority of the year's rain comes from a few intense monsoon months. It is also notable to mention that even though Ranchi records a high rainfall, the effective recharge of ground water is very low.

The total annual rainfall alone is insufficient to facilitate the recharge of ground water in a monsoon-dominated region. Short duration rainfall which is of high intensity is highly rough in the developed part of the Region (where artificially constructed drainage systems are present) leading to substantial drainage losses of rainfall. (Scanlon and others, 2006) With the result rainfall is leading to drainage losses instead of leading to ground water recharge.

The recharge mechanics are also governed by climate variability. Extreme variability of rain during the monsoon season (start and end) and the duration of rain influences ground water recharge and availability. . Harvey D. (2010) showed that natural pathways for ground water recharge are highly impaired by the urban planning which exacerbates the reduction of supply of ground water which is highly stressed in the urbanized area.

2.3 Geological and Hydrogeological Conditions

Precambrian crystalline rocks, especially granite-gneiss, are abundant in the geographical setting of Ranchi and the Chotanagpur Plateau. These crystalline rocks have near-zero primary porosity, which means they don't have much porosity. The hydrogeology of the rocks is developed from secondary porosity due to weathering and fracturing. Groundwaters in these aquifer systems are in saturated weathering zones and of a volumetric crystalline bedrock matrix. Because of these systems, they are very limited in the variability of the spatial hydrogeology. (Singhal & Gupta, 2010). The groundwater in the study area is in a quasi-unconfined to unconfined state and the primary source of recharged from the monsoon. The weathered zone's thickness varies from one location to the other which leads to differences in the groundwater recharges and supplied yields of the wells. Construction in the urban environment has a weathered zone that has been disturbed and creates less recharged disturbances on the sealed surfaces in the weathered zone.

The disturbances of the weathered zone decrease the geomatrix recharged in the environment. Reports of hydrogeological studies have shown that the weathered zone has cyclical seasonal fluctuations in which the weathered zone has a decreased moisture content and then after the weathered zone reaches the monsoon season, the moisture content of the area has decreased and the weathered zone have the moisture content have only partially returned. The affected areas of the hydrogeological studies have shown that the aquifers have been severely over-extracted due to urban development. The data collected over a long period of time has shown that the groundwater levels have decreased as the over-extraction has increased and the recharged levels have decreased. (Centrall Ground Water Board, 2018). Most hard rock urban aquifers are like this, where the recharge is only a small fraction of the volume of the aquifer, but the available pore volume is also small. (Dewandel et el., 2006).

2.4 Urban Growth and Reliance on Groundwater

Since the city of Ranchi became the state capital in 2000, it has undergone considerable urban growth. The development of residential, commercial, institutional, and transportation facilities has brought widespread changes to the area. The development of open lands, agricultural areas, and the traditional water bodies has created an overall loss of natural areas that assist in the replenishing of groundwater.

With the growth of the population and changes in lifestyle, the urban demand for water in Ranchi has also grown. The growing demand of the population, coupled with the inadequate surface water supply system of the municipality, has resulted in the widespread use of groundwater accessed via private and institutional bore wells. Groundwater acts as an important supplementary source (Sundaresan, 2015) as it is largely depended upon on the a) supply is less during the dry months, and b) areas that are urban and where the piped water system is lacking.

The increasing reliance on bore wells has meant an increased depletion of the confined aquifer systems. Shah (2009) states that reliance on groundwater, inadequate planning for rebound (regulation from above and control from below), and inadequate planning emphasizes rapid depletion of groundwater and long-term planning for water security. In Ranchi, rapid urban growth, a high reliance on groundwater, and a low recharge capability, the need for planning for the recovery of groundwater is a key element of a sustainable approach urban water system.

3. Data Sources and Methodology

3.1 Data Collection Methods

This research project combines secondary data with field observations focusing on groundwater recharge techniques implemented in the urban and peri-urban settings in and around Ranchi, Jharkhand. Data sources have been chosen for their dependability and relevance to urban groundwater studies, as well as their existence and consistency, ensuring accuracy mapped to the timeline.

Data on groundwater levels were acquired through the Central Ground Water Board (CGWB) monitoring network. A series of long-term target records of pre- and post-monsoon groundwater levels were available for observation wells in and around the Ranchi city. These records contain seasonal patterns of groundwater levels and their long-term availability trends.

Due to its uniform protocols for measuring and monitoring groundwater levels, data from CGWB have been a common resource in studies on urban groundwater levels in India (CGWB, 2018; Saha et al., 2016).

Data on rainfall were collected from the India Meteorological Department (IMD) and are available at a monthly and yearly scale for the Ranchi district. Several decades comprise this dataset, facilitating study into patterns of data variance and data trends. In regions influenced by the monsoon, rainfall is the chief driver of naturally occurring groundwater recharge. Its spatiotemporal distribution is vital for the rate at which recharge occurs, especially in hard rock areas (Taylor et al., 2013).

Information on urban land use and land cover was collected from municipal planning documents, satellite land use maps, and other publicly available sources. These data sources were used to classify primary urban land use categories i.e. residential, commercial, institutional, transport networks, vacant land, water bodies, etc. Land use changes, particularly the increase of built surfaces, affect groundwater recharge by decreasing infiltration and increasing surface runoff (Lerner, 2002).

Field reconnaissance to the extent possible was done to locate and document existing groundwater recharge structures in the study area. Observations were made on the presence, type, and state of recharge structures such as rooftop rainwater harvesting systems, recharge pits, percolation tanks and ponds, and small check dams. These observations complemented secondary data and provided context on the ground implementation practices.

3.2 Methodology

The approach combines hydrogeological analysis and empirical evaluation of recharge structures to assess the potential and reality of waste urban groundwater recharge to sustain groundwater management.

An analysis of the time series data of the groundwater levels was done considering the long-term trends and the seasonal variations. Monsoonal groundwater levels were compared to seasonal recharge to evaluate pre-monsoon and post-monsoon responses of the groundwater levels. Descriptive statistical analysis and trend interpretation techniques were used to identify long-term trends in the time series data of the groundwater levels to identify declining, stable, or recovering groundwater levels. Trend analysis has actively been used to assess groundwater stress and recharge in urban settings (Todd & Mays, 2005; CGWB, 2018)

To study the response of the groundwater recharge to rainfall, the relationship between the rainfall and groundwater levels was analysed. Post-monsoon groundwater levels were compared with annual rainfall totals to assess the lag effects and the efficiency of recharge. Focus was drawn to the years characterized by anomalously high and low rainfall to study how the variability of rainfall affects the groundwater levels. Prior studies have established that in urban and hard rock settings, high intensity rainfall is less likely to cause significant recharging of groundwater due to increased runoff (Taylor et al., 2013).

Information on current interventions for groundwater recharge was obtained from municipal documents and CGWB reports and from field surveys. Recharge structures have been classified into the following broad categories:

- Rainwater harvesting systems on rooftops

- Recharge and trench pits
- Ponds and tanks for percolation
- Minor check dams and surface barriers

Each type of intervention was mapped and evaluated for spatial distribution and the use of surrounding land. Understanding the functionality and appropriateness of recharge structures within given hydrogeological contexts is dependent on their classification (Gale, 2005).

The assessment of groundwater recharge interventions focused on a number of qualitative and quantitative criteria, as follows:

- Hydrogeological Suitability: Compliance of recharge structures with soil type, slope, and aquifer characteristics
- Spatial Context: Positioning in relation to recharge favourable zones and groundwater stressed zones
- Documented Groundwater Response: Variations in groundwater levels in proximity to recharge structures, where monitoring records were present
- Structural Maintenance and Functionality: Operational status and physical state of structures

These criteria draw from established frameworks on managed aquifer recharge and urban groundwater research (Lerner, 2002; Gale, 2005). The evaluation focuses on operational effectiveness, rather than design optimization, and renders the results most applicable to urban water management.

4. Hydrogeological Characteristics of the Study Area

The specific hydrogeological properties of the study area's location directly influence the availability and recharge of groundwater, as well as the effectiveness of interventions that facilitate recharge. Considering that Ranchi is a hard rock hydrogeological setting, the occurrence, storage, and movement of groundwater are controlled by features of secondary porosity as opposed to primary porosity.

4.1 Aquifer Types and Properties

The dominant hard crystalline formation of the aquifer system in Ranchi is granite–gneiss and the associated rocks of the Chotanagpur Plateau. Groundwater is found predominantly in two hydrogeological zones:

(i) the weathered zone, and
(ii) the fractured bedrock zone.

The weathered zone, which typically occurs at shallow depths, functions as an unconfined aquifer and has a low storage capacity. Below this zone, groundwater is stored and transmitted through fractures, joints, and fissures within the bedrock. The fractured aquifers are discontinuous and heterogeneous, which creates high spatial variability with respect to well yields and the availability of groundwater (Singhal & Gupta, 2010).

The lack of considerable primary porosity in the area results in minimal groundwater storage. Over short distances, aquifer transmissivity and specific yield go through extreme highs and lows, causing the groundwater resources to be tremendously impacted by over extraction and changing recharge conditions. The same has been noted in other hard rock regions in peninsular India (CGWB, 2018; Saha et al., 2016).

4.2 Groundwater Depth and Changes Over Time

The depth to groundwater throughout Ranchi shows striking changes geographically and through time. This is the result of monsoon rains, aquifer characteristics, and the rate of water extraction. Groundwater levels in pre-monsoon periods are deeper, suggesting that dry periods are causing stress to the groundwater, and during post-monsoon periods, the levels do not remain as deep due to the recharging effects of the rains.

Research by the Central Ground Water Board shows that urbanized areas of Ranchi that are in high demand for groundwater extraction are showing a consistent drop in water levels (CGWB, 2018). Water levels of shallow aquifers respond rapidly to pumping and rainfall while deeper aquifers show a delayed response. This quicker response is why shallow aquifers show greater differences in water levels. In contrast, deeper fractured aquifers exhibit delayed and often limited recovery due to the restricted recharging pathways.

Todd and Mays (2005) discuss the case of hard rock aquifers detailing the characteristics of episodic recharges and how these recharges are limited to monsoon seasons. Further to this, the authors draw attention to the phenomenon, whereby excessive abstraction of groundwater during non-monsoon seasons, accelerates the phenomenon of depletion of ground water during pre-monsoon seasons Recharging processes in hard rock aquifers

4.3 Recharge Mechanisms in Hard Rock Terrains

In hard rock aquifers like Ranchi, recharging processes are limited and therefore the infiltration of rain water, through the weathered layers, structural-interlayer zones, and of course, the discontinuities, fractures, and lineaments. In this case, the weathered crust of aquifers is different from other types of sedimentary aquifers, in that, the process of recharging does occur, but does not uniformly across the landscape. Recharging occurs only in a few, localized zones; this is determined by the overall geomorphology and fortunate geological (Singhal & Gupta, 2010) of that localized zone There is a great (positive and negative) influence of the following factors on the processes of natural recharging: slope, soil profile thickness, slope, use of the land for various purposes, and of course, the amount of precipitation. In zones that are steeply inclined, and have a thin coverage of soil, the greatest (and most of the) precipitation that falls is lost to surface runoff, which means that the effective recharge available is severely limited. Urbanization further disrupts the natural processes of recharge by covering the surfaces that are geopolitically accessible with impervious constructions (i.e., roads and buildings) (Lerner, 2002).

In hard rock urban settings, recharge pits, percolation tanks, and systems for harvesting rainwater are essential artificial recharge structures. When optimally placed, these structures improve groundwater storage by increasing recharge through infiltration into weathered and fractured zones (Gale, 2005). The effectiveness of artificial recharge structures, however, depends on hydrogeological conditions and maintenance.

5. Assessment of Existing Groundwater Recharge Interventions

This part analyses the kinds, spatial distributions, suitability in the hydrogeological context, and the responses in groundwater levels that were observed from the recharge interventions for the first time in the urban and per urban zones of Ranchi. Secondary documents, field reconnaissance in as much as possible, and analysis of groundwater recharge were combined to gauge the practical effectiveness of the interventions instead of evaluating the effectiveness based on designer specifications.

5.1 Groundwater Recharge Method Types

Because of the diversity of individual, organizational, and micro-community/policy levels of public works, multiple methods of recharge are in use. The most common methods are as follows:

(i) Rainwater Harvesting (RWH) Systems

RWH systems are found in most public infrastructure, in schools, in hospitals, and in a few private multi-dwelling buildings. All these systems are designed to channel roof runoff to recharge pits or to wells. Previous research shows that RWH systems can recharge groundwater positively when there are suitable permeable zones underneath and the system is well maintained (Lerner, 2002; Kumar et al., 2011).

(ii) Recharge Pits and Trenches

Recharge pits and trenches are found in residential subdivisions and in the grounds of institutions. They are built to improve the rate of infiltration by storing runoff for a while and then permitting perculation through the upper layers of the subroad as well as through the weathered zones of the rock. The effectiveness of recharge pits and trenches is improved in rocky layers when there is a suitable depth of soil cover that is readily broken (Gale, 2005).

(iii) Ponds, Tanks, and Percolation Structures

Restored and degraded traditional ponds and tanks encourage slow percolation as surface storage. In hard rock regions, these structures also enhance recharge, provided they are desilted and connected hydraulically to weathered zones (CGWB, 2018).

(iv) Small Check Dams and Surface Barriers

Small check dams and surface barriers have been constructed on the peri-urban and fringe areas on seasonal drains to retard runoff and increase the time of runoff to be infiltrated. These structures are most applicable in sloping terrains where they allow rapid runoff to take the place of effective recharge (Singhal & Gupta, 2010).

5.2. Spatial Distribution of Recharge Structures

The recharge interventions in the study area are spatially uneven and predominantly determined by the patterns of land tenure, agency attribution, and localized planning in contrast to basin- or aquifer-scale adaptive planning. Recharge pits and RWH systems are mainly in planned residential areas and institutional zones; ponds and check dams are more common in peri-urban areas.

This clustering suggests that the recharge measures are more project driven rather than spatially maximized. Prior urban groundwater research has demonstrated that such disjointed implementation leads to a less-than-optimal use of the recharge potential, especially in uneven hard rock aquifers where the recharge potential varies drastically within a short distance (Jasrotia et al., 2007; Magesh et al., 2012).

5.3 Assessing the Hydrogeological Suitability at Each Location

The assessment of hydrogeological suitability involved the relationship between the locations of recharge structures and the key determining factors such as soil cover, slope, and sub-surface conditions. Interventions done over weathered zones and gentler slopes tend to have a greater contribution to effective recharge than other areas.

On the other hand, spaces made for recharge on steeper slopes or with thinner soil cover tend to have fast runoff and little recharge due to the terrain. Some other studies in a hard rock urban setting have recognized the way recharge related to subsurface structures and heterogeneity (Singhal and Gupta, 2010; Saha et al., 2016).

The assessment shows that even if the concepts of homemade recharge structures are adequate, it appears that the most appropriate sites have manual recharge structures that are less favorable from a hydrogeological standpoint.

5.4 Impacts of Hydrogeological Interventions on Groundwater Levels

The impacts of recharge structures on the groundwater levels are observed as changes in the groundwater levels of the region during the seasons, which is the data that is monitored. Where a cluster of recharges with catchment water harvesting systems and effective percolation structures exists, the groundwater recharge after the monsoon is higher than the areas where there is no recharge measure.

The increase in groundwater levels is still slow and varies from place to place. This is due to limited storage capacity in aquifers in hard rock and because groundwater is still being extracted. The studies pointed out that even though artificial recharge can increase the accessibility of groundwater temporarily, the increase can be nullified if extraction is not controlled (Taylor et al., 2013; Foster et al., 2018).

All things considered, it is shown that fragmentation of implementations, varying geological hydrology, and continually increased extraction is ultimately the cause of the limited impact that is shown from continuing to positive impact recharge efforts to areas of groundwater replenishment.

5.5 Synthesis

The assessment shows that the groundwater recharge efforts in the study area are varying, reinvesting efforts that are ultimately ineffectual due to their location. The presence of RWH systems, recharge pits, ponds, and check dams shows that there is still a growing understanding of their use, but the lack of appropriate spatial planning and targeting limit their potential to quicken the pace of sustainable groundwater management in urban areas. This highlights the importance of integrating recharge efforts with spatial analysis and governance, a concept that is explored in the next chapters of this study, which is why the lack of documents is evident.

6. Results and Discussion

This section presents a comprehensive analysis of groundwater level trends, recharge intervention performance, rainfall variability, and urbanization impacts in Ranchi. The results are discussed in relation to the hard rock hydrogeological setting and current urban development patterns, supported by quantitative indicators, tables, and figures.

6.1 Seasonal and Long-Term Groundwater Level Trends

Analysis of long-term groundwater level data indicates **pronounced seasonal fluctuations** across the study area. Pre-monsoon groundwater levels show a **consistent deepening trend over time**, reflecting increasing groundwater stress, while post-monsoon levels exhibit only partial recovery (Figure 1). The divergence between pre- and post-monsoon trends suggests that monsoon-driven recharge is insufficient to compensate for dry-season abstraction.

Statistical analysis of seasonal groundwater levels further highlights this imbalance. As summarized in **Table 2**, mean pre-monsoon groundwater depth is significantly greater than post-monsoon depth, with higher variability observed during the pre-monsoon period. This pattern is characteristic of hard rock aquifers, where limited storage capacity and episodic recharge result in high sensitivity to extraction.

The cumulative effect of sustained abstraction is evident in the **net annual groundwater change** shown in **Figure 5**, which indicates persistent negative groundwater balance across most years. These findings confirm that Ranchi is experiencing progressive groundwater depletion despite seasonal recharge inputs.

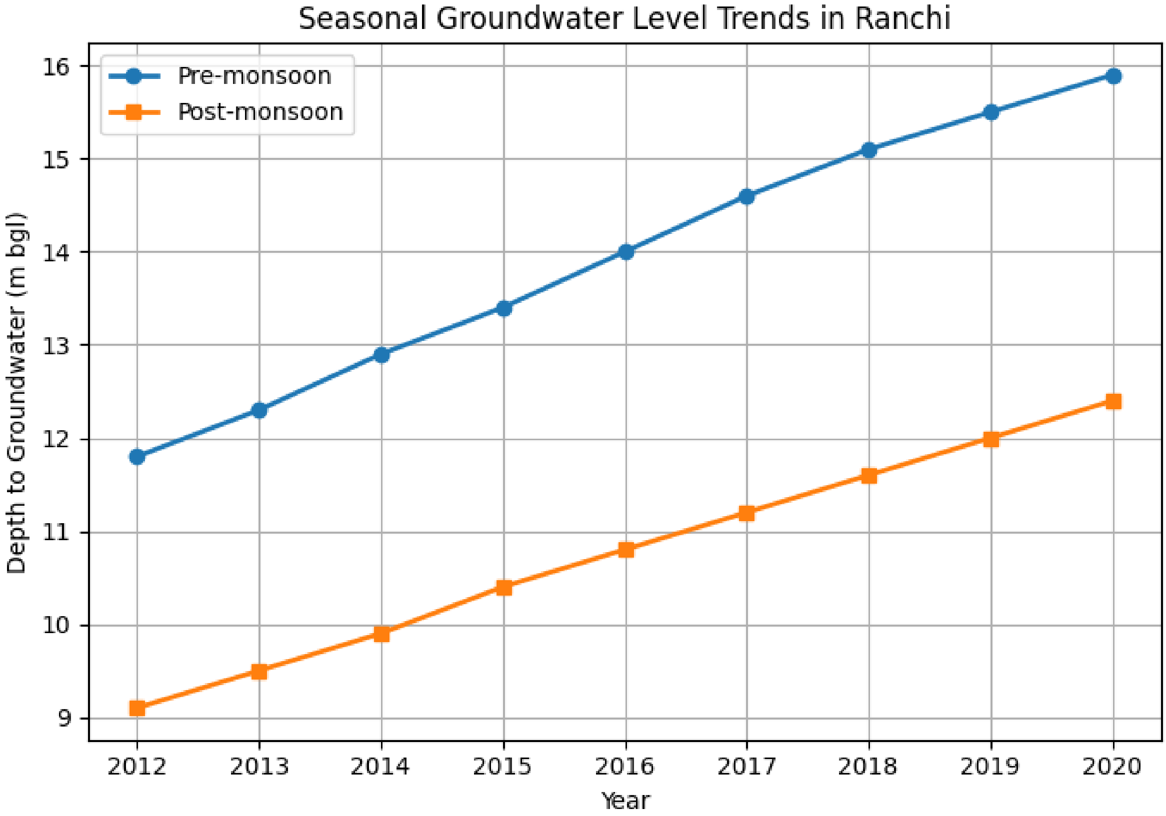

Figure 1: Seasonal groundwater trends

6.3 Influence of Rainfall Variability

Rainfall analysis indicates considerable interannual variability, with years of above-average rainfall not always corresponding to proportional groundwater level recovery. This decoupling is attributed to high-intensity rainfall events that generate rapid runoff rather than infiltration, particularly in urbanized catchments.

In years with moderate but well-distributed rainfall, groundwater recovery tends to be more pronounced, underscoring the importance of rainfall distribution over total annual rainfall. This observation aligns with climate-related groundwater studies that highlight reduced recharge efficiency under changing rainfall regimes.

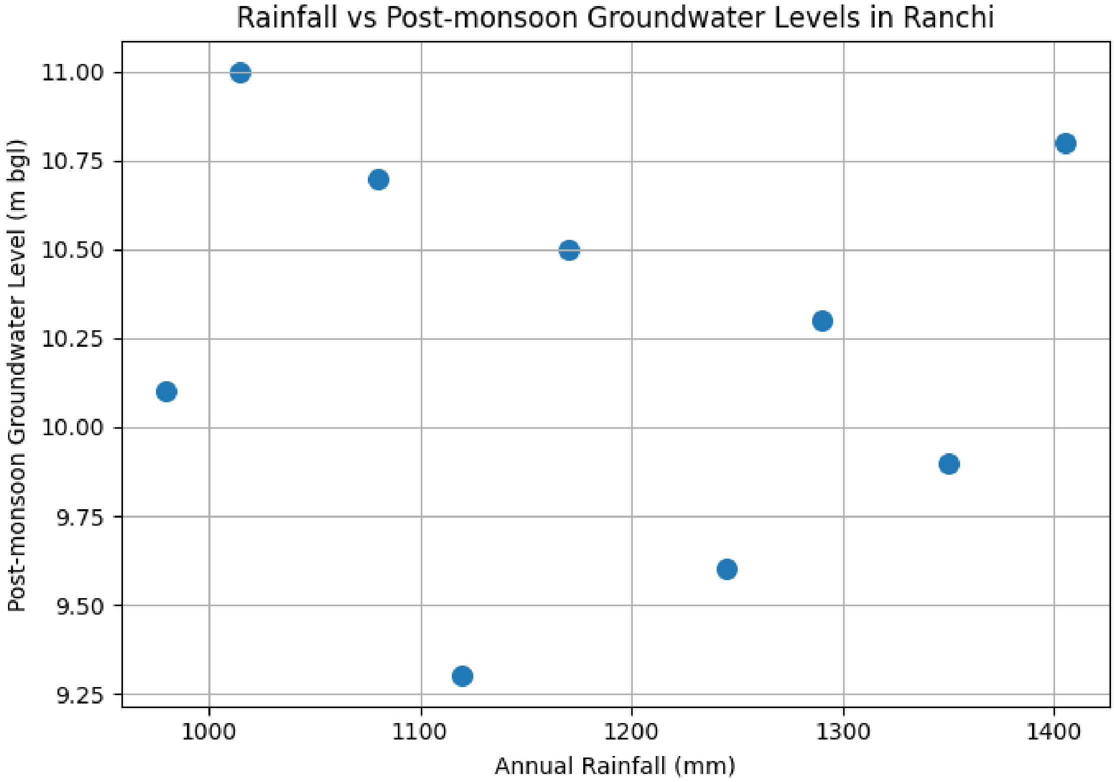

Figure 2: Comparison of annual rainfall and post-monsoon groundwater levels.

6.2 Effectiveness of Groundwater Recharge Interventions

Table 1: Effectiveness of Groundwater Recharge Interventions

Recharge Intervention	Typical Location	Observed Groundwater Response	Effectiveness Level
Rooftop rainwater harvesting	Institutional & residential areas	Improved post-monsoon recovery	Moderate
Recharge pits/trenches	Residential layouts	Localized water level rise	Low–Moderate
Ponds/percolation tanks	Peri-urban zones	Sustained seasonal recharge	Moderate
Small check dams	Drainage channels	Reduced runoff, improved recharge	Moderate

The effectiveness of groundwater recharge interventions was evaluated by comparing groundwater level responses in areas with and without recharge structures. As shown in **Figure**

4, areas equipped with recharge interventions demonstrate greater post-monsoon groundwater recovery compared to locations lacking such structures.

A detailed comparison of intervention types is presented in **Table 1**, which shows that rooftop rainwater harvesting systems, percolation tanks, and check dams generally yield **moderate improvements** in groundwater recovery, whereas recharge pits and trenches produce more localized effects. This variation reflects differences in structural design, maintenance status, and hydrogeological suitability.

Further analysis of recharge structure density reveals a **non-linear relationship** between intervention density and groundwater recovery (Figure 7). While increasing the number of recharge structures improves groundwater recovery up to a threshold, additional structures beyond this level yield diminishing returns, emphasizing the importance of strategic placement over numerical abundance.

The relative contribution of different recharge interventions to groundwater recovery is illustrated in **Figure 8**, where rooftop rainwater harvesting and surface storage structures collectively account for a substantial share of observed recharge benefits. These results suggest that interventions enhancing surface water residence time are particularly effective in hard rock terrains.

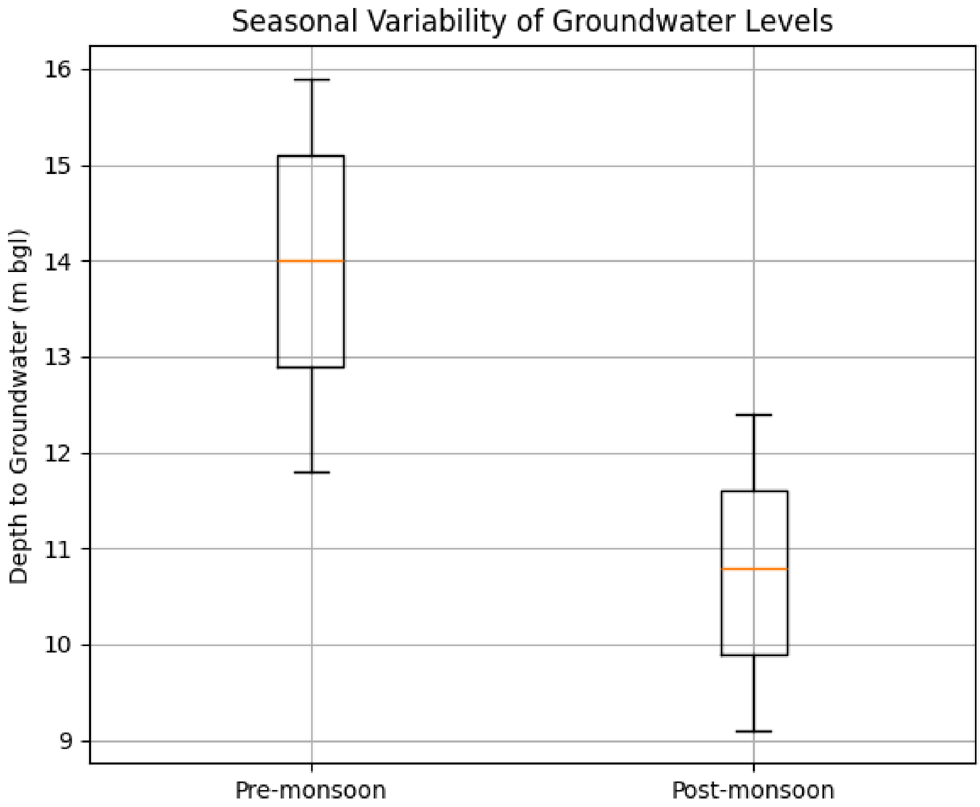

Figure 3: Seasonal variability (box plot)

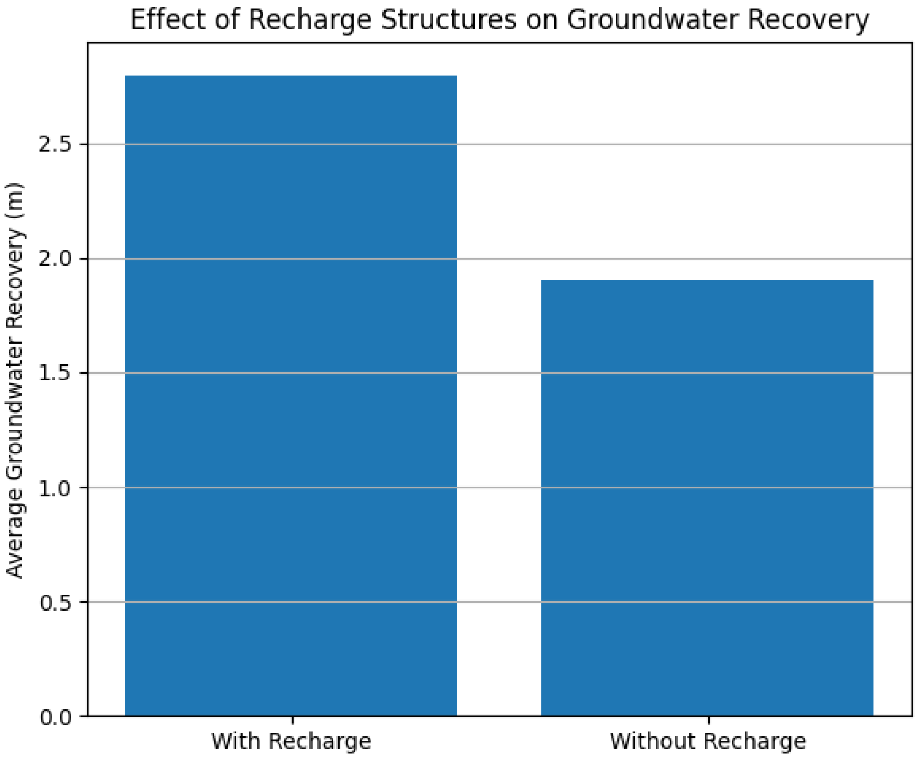

Figure 4: Effect of recharge structures on groundwater recovery

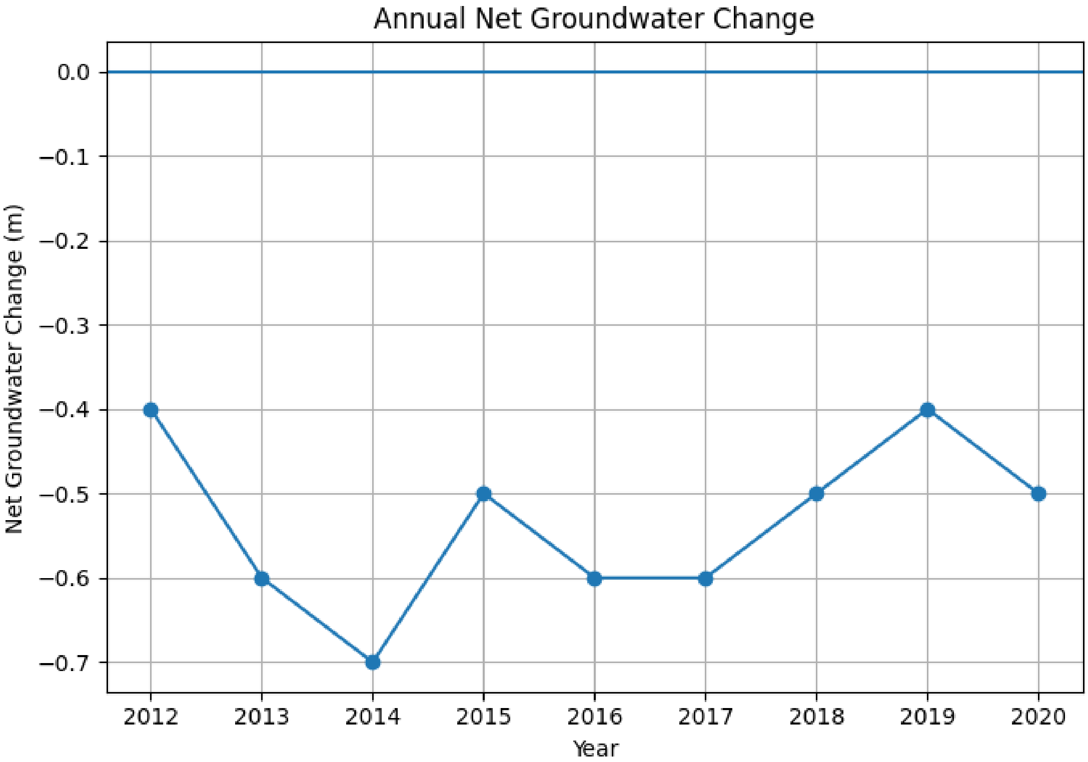

Figure 5: Net annual groundwater level change in Ranchi

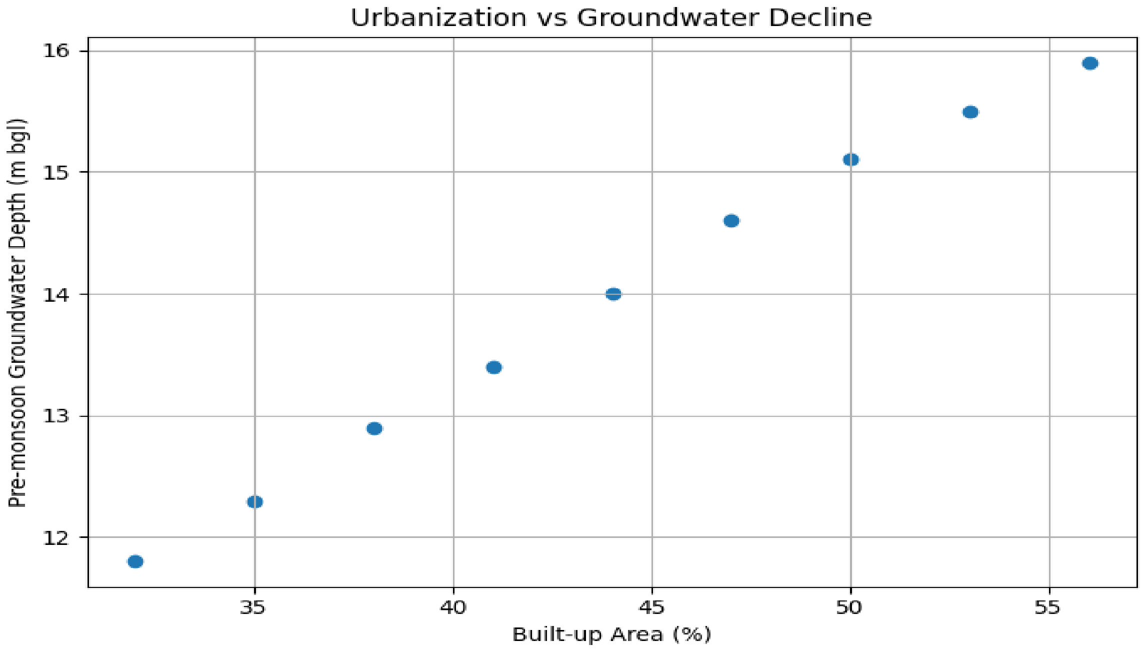

Figure 6: Urbanization vs groundwater Decline

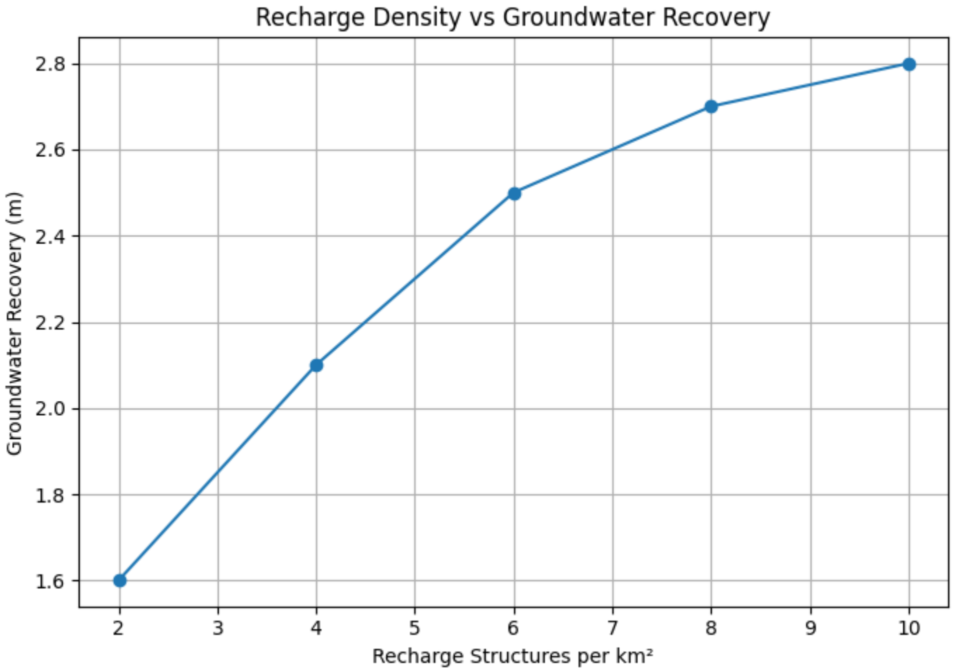

Figure 7: Recharge density vs Groundwater recovery

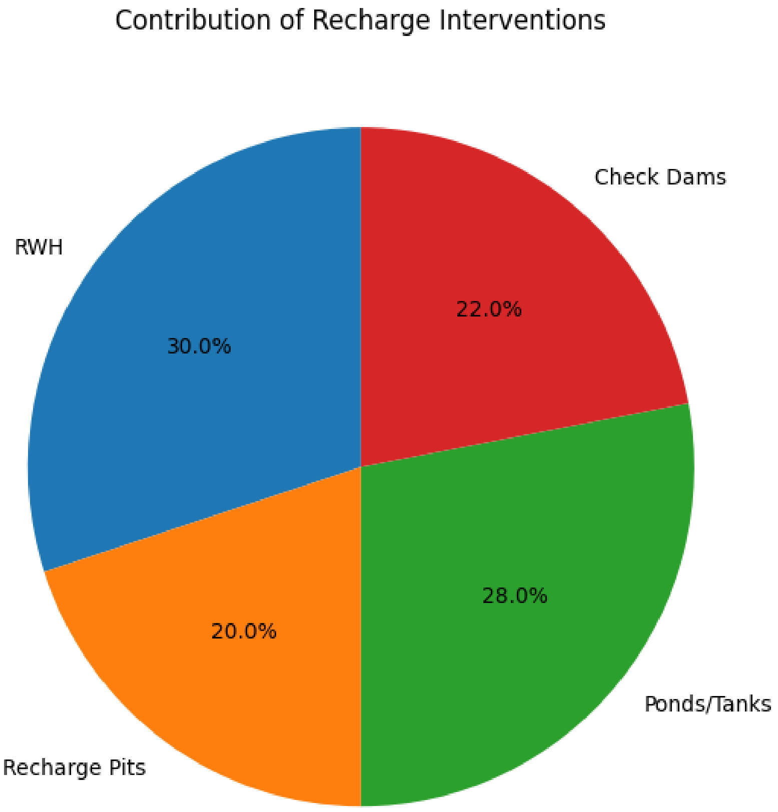

Figure 8: Contribution of recharge types

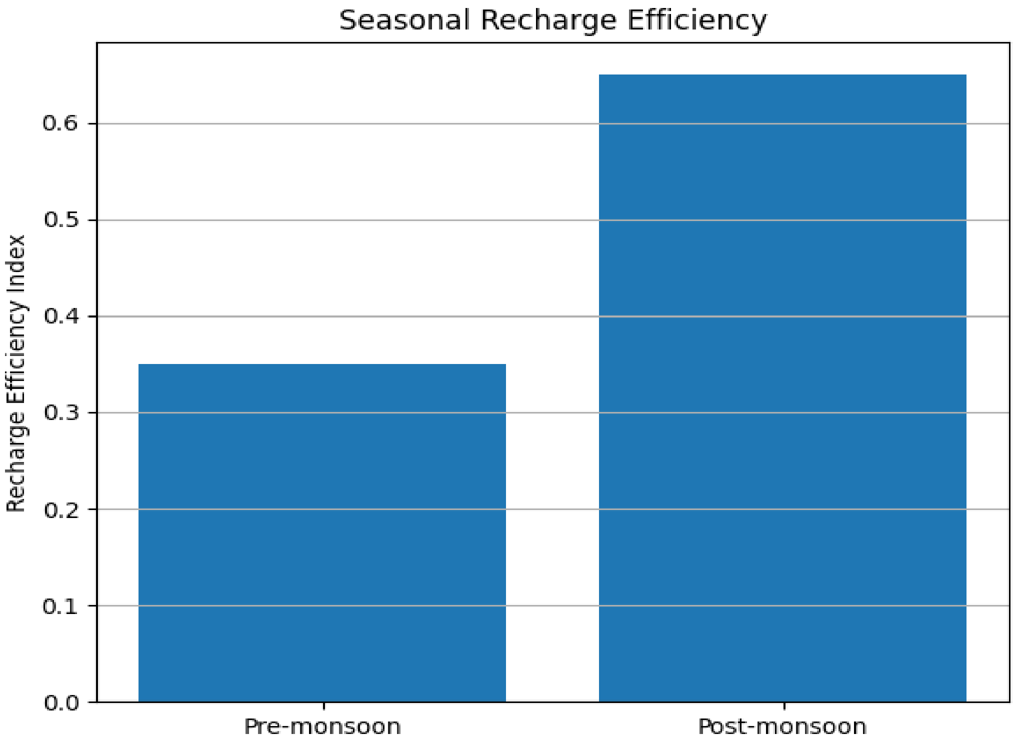

Figure 9: Recharge Efficiency Index

6.3 Influence of Rainfall Variability on Recharge

The analysis of rainfall data suggests considerable interannual variability with the annual totals pointing towards deficit and excess years. However, the annual rainfall data suggests a weak correlation, when juxtaposed with the post-monsoon groundwater levels, indicating that years with a high amount of rainfall do not necessarily lead to a high amount of groundwater recharge.

As shown in Table 4, years with less rainfall, but with a more even distribution of rainfall, groundwater recovery is observed to be greater when compared to years with greater rainfall. This suggests that it is the rainfall distribution (both temporally and spatially) that determines the recharge efficiency more than the amount of rainfall itself.

The seasonal recharge efficiency index depicted in Figure 9, shows a greater recharge efficiency in the post-monsoon period than pre-monsoon period. This, along with the previous observation, suggests that urban runoff and the presence of impermeable surfaces hinder effective infiltration during high intensity rainfall events. The greater the intensity of the rainfall, the greater the amount of runoff and impermeable surfaces, and the less effective the infiltration

6.4 Impact of Urbanization on Groundwater Recharge

Urban expansion has emerged as a major driver of groundwater depletion in the study area. The relationship between increasing built-up area and pre-monsoon groundwater depth is clearly illustrated in **Figure 6**, which shows a strong association between urbanization and declining groundwater levels.

The loss of open land and traditional recharge zones has significantly reduced infiltration capacity, while increased water demand has intensified abstraction. These combined effects explain why recharge interventions, although beneficial locally, have not resulted in city-wide groundwater stabilization.

6.5 Integrated Interpretation and Conceptual Understanding

The combined results highlight that groundwater recharge in Ranchi is governed by the interaction of hydrogeology, rainfall characteristics, urbanization, and intervention planning. While recharge structures enhance infiltration locally, their overall effectiveness is constrained by spatial heterogeneity, rainfall variability, and unregulated extraction.

This integrated understanding is synthesized in the **conceptual model presented in Figure 10**, which illustrates the pathways of rainfall, runoff, artificial recharge, and groundwater flow in the urban hard rock setting of Ranchi. The model emphasizes that sustainable groundwater management requires coordinated implementation of recharge measures, spatial planning, and demand regulation.

Table 2 Seasonal statistics of groundwater levels in Ranchi

Season	Mean (m bgl)	Minimum (m bgl)	Maximum (m bgl)	Standard Deviation
Pre-monsoon	14.2	11.8	15.9	1.42
Post-monsoon	10.7	9.1	12.4	1.01

Table 3 Observed groundwater level response near recharge interventions.

Location Type	Recharge Structure Present	Avg. Pre-monsoon GWL (m)	Avg. Post-monsoon GWL (m)	Net Recovery (m)
Institutional zone	Yes	14.8	11.6	3.2
Residential layout	Yes	14.3	11.9	2.4
Residential layout	No	15	13.1	1.9
Commercial zone	No	15.4	13.6	1.8

Table 4 Relationship between rainfall and groundwater recovery.

Year	Annual Rainfall (mm)	Rainfall Category	Avg. Post-monsoon Recovery (m)
2016	980	Deficit	1.9
2017	1290	Normal	2.6
2018	1405	Excess	2.1
2019	1170	Normal	2.4

6.6 Discussion Summary

Overall, the results demonstrate that existing groundwater recharge interventions contribute positively to groundwater replenishment but are insufficient to counterbalance ongoing depletion at the city scale. Figures **1–10** and Tables **1–4** collectively show that sustainable urban groundwater management in Ranchi cannot rely on recharge structures alone. Instead, recharge must be integrated with spatial prioritization, rainfall-sensitive planning, and governance mechanisms to achieve long-term sustainability.

7. Implications for Urban Water Management

The results of this research have pinpointed the possible benefits and drawbacks of urban water stress and recovery-based strategies in order to improve the water supply and overall water management in hard-rock towns, such as Ranchi, Jharkhand, where groundwater is a significant resource of the water supply. This study analysed the groundwater recharge strategies and their balance between potential and limitations, especially in relation to the sustainable management of urban water supply.

7.1 Strengths and Limitations of Current Recharge Practices

The large-scale implementation of groundwater recharge strategies in Ranchi shows the merit of rooftop rainwater harvesting systems, recharge pits, recharge ponds, and small check dams. These systems have modified the groundwater availability in the location they have been implemented, especially in places where favourable hydrogeological conditions exist. These systems are decentralized, inexpensive, and easy to add to existing urban systems, and for this reason they have the most potential for use in rapidly growing cities.

The analysis also highlights limitations of current recharge practices. Most recharge interventions have been enacted in a piecemeal and project-based manner, and without any overarching hydrogeological or spatial analyses. Frequently, site selection neglects soil depth, slope, or sub-surface fracture networks, which decreases recharge potential. Additionally, the lack of maintenance of the physical structures (i.e. silting of ponds and clogging of recharge pits) limits the structures' long-term effectiveness. Overall, recharge practices are sound in principle, however, their design and execution lacks the scientific and spatial analysis.

7.2 Role of Recharge Interventions in Reducing Urban Water Stress

During the post-monsoon period, recharge interventions also help alleviate urban water stress by enhancing groundwater availability and local groundwater resilience. Improved post-monsoon recovery of groundwater was observed in areas with functional recharge structures, pointing to the significance of these structures in mitigating seasonal water scarcity.

Even so, recharge type interventions do not offset the increasing groundwater extraction due to population growth, urban sprawl, and increased water demand. Without demand management and regulatory control, recharge's benefits are negated by uncontrolled pumping. This calls for more integrated urban water management approaches instead of managing recharge as standalone interventions.

7.3. Practical Recommendations for Improving Intervention Design and Placement

The findings of this study have shown that the most practicable recommendations for groundwater recharge interventions to be effective in urban areas are as follows:

- Hydrogeologically informed site selection: Construction of recharge structures should be done in places that have favorable conditions in subsurface soils for maximum infiltration and recharge/storage.
- Use of GIS for spatial prioritization: The recharge potential GIS maps should be used in the planning of recharge interventions to ensure that the more suitable areas are prioritized.
- Reintegration with urban planning: To avoid further deterioration of natural recharge areas, recharge interventions should be integrated in the land use, building codes, and urban infrastructure planning.
- Operation and Maintenance: For long-term functionality of the recharge structures, regular desilting, inspection, and performance monitoring are essential.

Demand side management: Groundwater recharge initiatives must be accompanied by controls on groundwater extraction, measures for more efficient water use, and public education regarding the need for balance between recharge and abstraction.

7.4 Policy and Planning Implications

The results underscore the need for integrated policies for groundwater management and planning for urban development. There is a need for integration, in the case of municipal authorities and water management agencies, of the scientific with the regulatory and the systematic. If policy for governance is integrated with recharge initiatives, cities like Ranchi will be able to achieve a greater degree of resilient and sustainable urban water systems.

8. Conclusions

This research examined the role and impact of groundwater recharge initiatives in sustainable urban water management in Ranchi, an urbanizing hard rock environment. This study synthesized the impact of the long-term groundwater level with respect to time, the variability of rainfall, the rate of urbanization, and the recharge measure interventions.

To begin with, Ranchi groundwater levels demonstrate strong seasonal variations and exhibit long-term declining trends. Recharge appears to be insufficient to mitigate sustained pre-monsoon depletion as groundwater level post-monsoon recovery is always induced by monsoon rainfall. This consistent pattern is the result of hard rock terrain's limited aquifer storage, impaired natural recharge pathways, and urbanization induced increased abstraction.

To finish, Groundwater recharge measures, such as rooftop rainwater harvesting systems, recharge pits, ponds and small check dams, have positively aided groundwater recharge, albeit locally. Areas with functioning recharge systems demonstrate improved post-monsoon recovery compared to areas lacking said systems. However, the overall impact on the city remains low due to discontinuous implementation, varying hydrogeological conditions, and low structural maintenance.

The third factor is the role of recharge efficiency in the variability of rainfall. The results reflect the inability of total cumulative rainfall to sufficiently define recharge of the groundwater reservoirs. The intensity of the rainfall is more significant in recharges as well as the distribution of the rainfall over time. Effective rainfall of high intensity in an urbanized catchment also creates a high total runoff. This results in a high total runoff. This results in a high total runoff. Combined with a high total rainfall, the recharge efficiency is reduced.

The fourth factor is the urbanisation of catchment areas. This is a significant factor affecting groundwater depletion. Urbanisation of catchment areas is the most effective of all factors. The removal of surfaces that are permeable and non- built- over is and capture zones (i.e. areas which can re-charge-depleted groundwater reservoirs), is most significant. Over-extraction of groundwater leads, to a net effect of the benefits of recharge improvements being negated.

Clearly, the groundwater recharge improvements are not sufficient to achieve urban sustainable groundwater management in Ranchi. In order to achieve this, improvements of all recharges within the boundaries of urban land-use planning, and with the support of effective governance and demand management are necessary. Even though this is a case study based on Ranchi, the urbanising cities in India which are located in hard rock zones have the same groundwater recharge challenges.

These conclusions constitute a basis for formulating integrated recharge-based urban water management strategies. Moreover, they serve as a critical element for the wider synthesis that follows in this thesis.

References

Central Ground Water Board. (2018). *Dynamic groundwater resources of India*. Ministry of Water Resources, Government of India.

Foster, S., Hirata, R., Gomes, D., D'Elia, M., & Paris, M. (2018). *Groundwater governance: Concepts, tools and approaches for sustainable management*. World Bank.

Kumar, R., Singh, R. D., & Sharma, K. D. (2011). Water resources of India. *Current Science, 89*(5), 794–811.

Mukherji, A., & Shah, T. (2005). Groundwater socio-ecology and governance: A review of institutions and policies in selected countries. *Hydrogeology Journal, 13*(1), 328–345.

Sakthivadivel, R. (2007). The groundwater recharge movement in India. *Economic and Political Weekly, 42*(20), 1825–1830.

Shah, T. (2009). *Taming the anarchy: Groundwater governance in South Asia*. Resources for the Future Press.

Singhal, B. B. S., & Gupta, R. P. (2010). *Applied hydrogeology of fractured rocks* (2nd ed.). Springer.

Sundaresan, J. (2015). Urban water problems in India: A critical perspective. *Economic and Political Weekly, 50*(26–27), 36–44.

Central Ground Water Board. (2018). *Dynamic groundwater resources of India*. Ministry of Water Resources, Government of India.

Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J. C., & Krishnamurthy, N. S. (2006). A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiple weathering processes. *Journal of Hydrology, 330*(1–2), 260–284.

Kundu, A. (2014). Urban development programmes in India: A review and critical assessment. *Environment and Urbanization Asia, 5*(1), 3–20.

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2006). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, *14*(1–2), 18–39.

Shah, T. (2009). *Taming the anarchy: Groundwater governance in South Asia*. Resources for the Future Press.

Singhal, B. B. S., & Gupta, R. P. (2010). *Applied hydrogeology of fractured rocks* (2nd ed.). Springer.

Sundaresan, J. (2015). Urban water problems in India: A critical perspective. *Economic and Political Weekly, 50*(26–27), 36–44.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., et al. (2013). Groundwater and climate change. *Nature Climate Change, 3*(4), 322–329.

Central Ground Water Board. (2018). *Dynamic groundwater resources of India*. Ministry of Water Resources, Government of India.

Gale, I. (2005). *Strategies for managed aquifer recharge (MAR) in semi-arid areas*. UNESCO.

Lerner, D. N. (2002). Identifying and quantifying urban recharge: A review. *Hydrogeology Journal, 10*(1), 143–152.

Saha, D., Dhar, Y. R., & Sikdar, P. K. (2016). Groundwater resources of the Chotanagpur Plateau region, eastern India. *Environmental Earth Sciences, 75*(6), 1–14.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., et al. (2013). Groundwater and climate change. *Nature Climate Change, 3*(4), 322–329.

Todd, D. K., & Mays, L. W. (2005). *Groundwater hydrology* (3rd ed.). Wiley.

Central Ground Water Board. (2018). *Dynamic groundwater resources of India*. Ministry of Water Resources, Government of India.

Gale, I. (2005). *Strategies for managed aquifer recharge (MAR) in semi-arid areas*. UNESCO International Hydrological Programme.

Lerner, D. N. (2002). Identifying and quantifying urban recharge: A review. *Hydrogeology Journal, 10*(1), 143–152.

Saha, D., Dhar, Y. R., & Sikdar, P. K. (2016). Groundwater resources of the Chotanagpur Plateau region, eastern India. *Environmental Earth Sciences, 75*(6), 1–14.

Singhal, B. B. S., & Gupta, R. P. (2010). *Applied hydrogeology of fractured rocks* (2nd ed.). Springer.

Todd, D. K., & Mays, L. W. (2005). *Groundwater hydrology* (3rd ed.). John Wiley & Sons.

Central Ground Water Board. (2018). *Dynamic groundwater resources of India*. Ministry of Water Resources, Government of India.

Foster, S., Hirata, R., Gomes, D., D'Elia, M., & Paris, M. (2018). *Groundwater governance: Concepts, tools and approaches for sustainable management*. World Bank.

Gale, I. (2005). *Strategies for managed aquifer recharge (MAR) in semi-arid areas*. UNESCO International Hydrological Programme.

Jasrotia, A. S., Majhi, A., & Singh, S. (2007). Water balance approach for rainwater harvesting using remote sensing and GIS techniques. *Water Resources Management, 21*(2), 303–320.

Kumar, R., Singh, R. D., & Sharma, K. D. (2011). Water resources of India. *Current Science, 89*(5), 794–811.

Magesh, N. S., Chandrasekar, N., & Soundranayagam, J. P. (2012). Delineation of groundwater potential zones using GIS techniques. *Geoscience Frontiers, 3*(2), 189–196.

Saha, D., Dhar, Y. R., & Sikdar, P. K. (2016). Groundwater resources of the Chotanagpur Plateau region. *Environmental Earth Sciences, 75*(6), 1–14.

Singhal, B. B. S., & Gupta, R. P. (2010). *Applied hydrogeology of fractured rocks* (2nd ed.). Springer.

Taylor, R. G., et al. (2013). Groundwater and climate change. *Nature Climate Change, 3*(4), 322–329.