# Impact of Land Use Changes on Groundwater Recharge in Deccan Basaltic Aquifers from Western India

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**Abstract**

Groundwater, a critical freshwater resource, is under increasing pressure from rapid urbanization and environmental changes, especially in India, where declining levels threaten water and food security. These challenges are made worse by a lack of integrated management strategies and the overarching impacts of climate change on hydrological patterns. This research investigates the dynamic changes in land use and land cover (LULC) within parts of the Pune and Satara districts of Maharashtra. We used remote sensing data and geospatial techniques from 2015 to 2024.

Our study used multitemporal Landsat 8 Operational Land Imager (OLI) data, processed and analyzed on the Google Earth Engine (GEE) cloud computing platform. We classified five main LULC categories: Water Body, Vegetation (Forest), Agricultural Area, Barren Land, and Built-up. The accuracy of the LULC maps was carefully assessed. The overall accuracy improved from 85% in 2015 to 89% in 2024, and the Kappa coefficient increased from 0.768 to 0.867, showing robust classification performance.

The findings show a substantial LULC transformation. Over the nine-year period, Built-up areas expanded significantly by 7.99%, reflecting rapid urbanization. At the same time, Agricultural areas also increased by 4.99%. In contrast, both Forest cover and Barren Land declined by 2.38% each, while Water bodies had a minor net decrease of 0.49%. These significant conversions highlight the impact of factors such as population growth, accelerated urban expansion, economic development, and the growth of industrial and commercial activities.

These findings highlight an urgent need for formulating and rigorously implementing effective land-use policies and regulations. These policies are essential for ensuring sustainable urban development and balancing the competing demands on finite land resources. The GEE-based approach proved to be a powerful and efficient method for examining LULC changes, offering actionable insights for urban planning and land-use management strategies. This research emphasizes the critical need for robust policies to foster sustainable development amidst the complex interplay of competing land demands and the ongoing challenges of urbanization.

## 1. Introduction

Groundwater, a critical part of Earth's hydrological cycle, is a vital freshwater source for domestic, agricultural, and industrial use. However, this essential resource has been strained in recent decades by human activities and environmental shifts. In India, diminishing groundwater levels are particularly concerning, posing a severe threat to the nation's water and food security.

Rapid urban expansion has led to the widespread loss of natural vegetation, disrupting the processes that naturally replenish groundwater (Dangar et al., 2021). The problem is worsened by a lack of integrated watershed management strategies, which often results in groundwater overexploitation—a phenomenon known as the "tragedy of the commons" (Chinnasamy et al., 2015).

Climate change significantly intensifies groundwater depletion by altering precipitation patterns, affecting aquifer recharge rates, and increasing the frequency of extreme weather events like droughts and floods (Kumar et al., 2020; IPCC, 2021). The global temperature rise from elevated greenhouse gas emissions introduces uncertainty into hydrological cycles, complicating sustainable groundwater management (Al-ghussain, 2019). These climate shifts, largely caused by human activities, have profound implications for groundwater sustainability, especially in developing countries like India, where livelihoods rely heavily on agriculture and infrastructure can be limited (Nandhitha and Mishra, 2018; Singh et al., 2010).

Changes in Land Use and Land Cover (LULC), along with climate variability, are crucial in shaping groundwater recharge patterns. Climate change is advancing at an unprecedented rate (Petrovic, 2021), and the conversion of land for urban development, agriculture, or industrial uses further disrupts the natural hydrological balance. Many studies have shown how changes in land cover—such as deforestation and urban sprawl—interfere with water movement and storage, increasing watershed vulnerability (Bisht et al., 2018; Singh et al., 2015). While sustainable land management, including forest preservation and optimized agricultural practices, could help mitigate these effects, such efforts are often overshadowed by land conversion driven by developmental pressures (Patra et al., 2018; Singh, 2016). It is important to distinguish between land cover, which refers to natural features like forests and water bodies, and land use, which describes human-driven activities such as farming, construction, or mining (Ali et al., 2012; Setti et al., 2020).

This research investigates the relationship between LULC changes and groundwater recharge in the Satara district, Maharashtra. This agriculturally important region faces significant water stress. Understanding how these changes influence subsurface water dynamics is critical for developing effective groundwater management strategies and strengthening the region’s resilience to climate change.

To perform this assessment, we used Google Earth Engine (GEE) as our main geospatial analysis tool. GEE provides a cloud-based platform with access to petabytes of satellite imagery and geospatial datasets, allowing for large-scale, advanced spatial analysis. Its robust processing capabilities, tools for cloud and haze removal, and integrated machine learning classifiers enable efficient land use mapping, change detection, and time-series analysis (Velastegui-Montoya et al., 2023). GEE also promotes reproducible and collaborative research through standardized processing frameworks and shared code environments.

GEE has been invaluable in addressing global environmental challenges, from real-time deforestation monitoring to drought forecasting, climate impact assessment, and disaster response

(Amani et al., 2020). It also plays a vital role in monitoring agricultural health, urban planning, and natural resource conservation. With the growing availability of high-resolution sensors and satellite products, GEE effectively manages the complexity of analyzing large-scale geospatial datasets (Suryawanshi et al., 2021; Wangchu et al., 2024), making it a powerful tool for understanding LULC dynamics and their implications for groundwater recharge (Singh et al., 2024; Suryawanshi et al., 2023).

This study uses GEE's capabilities to analyze LULC changes from 2015, 2020, and 2024 with Landsat-8 satellite imagery. By integrating geospatial analytics with climate considerations, this research provides actionable insights for sustainable groundwater management in Satara and similar semi-arid regions.

### 1.1 Study Area

Our study focuses on a specific region within the Upper Bhima River Basin, including parts of Bhor Taluka in the Pune district and Khandala Taluka in the Satara district, Maharashtra. This area is the BM-82 sub-watershed, located between latitudes 18°01'20"N and 18°09'25"N and longitudes 73°52'00"E and 74°59'30"E. We delineated the sub-watershed using Survey of India (SOI) toposheet 47F/16 at a 1:50,000 scale, covering approximately 126.56 square kilometers.

The terrain is predominantly hilly and undulating, characteristic of the Western Ghats. These varying elevations significantly influence surface runoff patterns and groundwater recharge processes. The region receives an average annual rainfall of approximately 600 mm, with over 80% occurring during the southwest monsoon season from June to September. This seasonal precipitation is crucial for aquifer replenishment and local agriculture.

Climatically, the area is classified as tropical sub-humid, with average temperatures ranging from a minimum of 11.6°C to a maximum of 37.5°C. Agriculture is the primary livelihood, with land use patterns closely tied to seasonal cycles. The farming calendar includes two main cropping seasons: kharif (monsoon, June to October), for crops like paddy, maize, bajra, jowar, soybean, and sugarcane; and rabi (post-monsoon, October to February), for crops such as wheat, barley, and gram. Common crop rotation systems include paddy–mustard–fallow and maize–potato–onion.

The Nira River, a major tributary of the Bhima River, flows through the study region and is a vital water source for both domestic and agricultural needs. It originates in the Sahyadri Hill range near Shirgaon village (Bhor, Pune district) at an altitude of 623 meters above mean sea level and flows southeast through a thriving agrarian zone with densely populated riverbanks. The larger Nira River basin, with a drainage area of approximately 6,879.60 km², lies between 18°13.528' N and 17°58.237' N latitude and 73°32.357' E and 75°08.458' E longitude. This basin has a hot semi-arid climate, bordering on tropical wet and dry, with average temperatures between 20°C and 28°C. Most of its 722 mm average annual rainfall occurs between June and September, with July typically being the wettest month.

The region's reliance on seasonal monsoon rainfall, its complex Western Ghats terrain, and intensive agricultural practices make it an ideal location for assessing the impacts of LULC changes on groundwater recharge. Understanding these connections is essential for developing sustainable watershed and groundwater management strategies amid ongoing environmental and climatic challenges.

### 1.2 Methodology and Data Acquisition

This study employed multitemporal Landsat 8 Operational Land Imager (OLI) data from 2015, 2020, and 2024 to conduct Land Use Land Cover (LULC) classification and detect temporal changes. All satellite imagery was accessed and processed using the Google Earth Engine (GEE) cloud computing platform, which proved essential for efficiently handling large geospatial datasets. Landsat 8 imagery, with its 30-meter spatial resolution and 16-day revisit interval, is well-suited for regional-scale environmental monitoring. To ensure data quality and consistency, only cloud-free (less than 10% cloud cover) surface reflectance scenes from Path 144, Row 45 were selected. Pre-processing steps, including cloud and shadow masking, were applied using the pixel quality attributes (QA_PIXEL band) available in GEE. For spatial consistency, the Universal Transverse Mercator (UTM) projection, Zone 44N, was uniformly adopted across all image processing. The LULC classification identified five dominant land cover categories relevant to the study area: Water Body, Built-up, Barren, Forest, and Agriculture.

### 1.3 Land Use Land Cover Classification and Change Detection

The classification process involved a series of sequential steps executed entirely within the GEE environment. Initially, multitemporal Landsat 8 images for 2015, 2020, and 2024 were filtered to include only dry-season months (February to May) to minimize vegetation interference and ensure optimal cloud-free coverage. Following image selection, cloud and shadow masking were applied using the QA_PIXEL band to eliminate atmospheric noise and enhance data integrity. Regions of Interest (ROIs) for each land cover class were systematically collected based on visual interpretation. Subsequently, supervised classification was performed to categorize the images into the five specified Land Use Land Cover classes. After classification, the generated images underwent post-processing to refine and merge the results, thereby improving thematic coherence and overall map quality.

The accuracy of the classified maps for each year was rigorously assessed using a confusion matrix generated within GEE. Independent validation points were utilized to calculate the Kappa Coefficient, which provides a robust measure of classification reliability by accounting for agreement that may occur by chance. All validation procedures were executed using GEE’s integrated functions.

Finally, Land Use Land Cover change analysis was conducted by comparing the classified maps of 2015, 2020, and 2024. This post-classification comparison approach enabled the clear and quantitative identification of transitions among the various land cover categories over the study period, such as the conversion of agricultural land to built-up areas or forest to barren land. The entire methodological workflow, from data acquisition and classification to accuracy assessment and change detection, was implemented and visualized within the ArcGIS environment.

## 2. Result and Discussion

The Land Use Land Cover (LULC) classification within the designated study area, delineating categories of Water Body, Vegetation (Forest), Agricultural Area, Barren Land, and Built-up, revealed substantial spatiotemporal shifts between 2015, 2020, and 2024. The region, being a developing landscape, has historically featured agricultural land as a dominant component of its total land cover.

| Class | 2015 (%) | 2020 (%) | 2024 (%) | Change (%) (2015–2024) |
|---|---|---|---|---|
| **Agriculture** | 38.29 | 43.04 | 43.28 | 4.99 |
| **Barren** | 25.16 | 23.85 | 22.78 | -2.38 |
| **Forest** | 25.16 | 23.85 | 22.78 | -2.38 |
| **Water** | 4.88 | 3.94 | 4.39 | -0.49 |
| **Built-up** | 8.35 | 14 | 16.34 | 7.99 |

**Table 1: LULC Area & Change (2015-2024)**

Table 1 provides a detailed overview of the 1.3 Land Use Land Cover area distribution and percentage change for each category across the study period.

A detailed examination of the Land Use Land Cover maps consistently indicated discernible trends in land transformations over the nine-year period. In 2015, agricultural land comprised 38.29% of the total classified area. Both vegetation (Forest) and Barren Land each occupied 25.16%, while Built-up areas accounted for 8.35%, and Water bodies constituted 4.88%. These spatial distributions are visually presented in Fig. 1.

By 2020, a notable alteration was observed, as shown in Fig. 2 agricultural land expanded to 43.04% of the total area. Conversely, both vegetation (Forest) and Barren Land experienced a decline, each reducing to 23.85%. Settlement (Built-up) areas continued their pronounced expansion, reaching 14.00%, while Water bodies slightly decreased to 3.94%.

Further analysis for 2024, depicted in Fig. 3, indicated a marginal, yet continued, increase in agricultural land, estimated at 43.28%. However, vegetation (Forest) cover saw a further reduction to 22.78%, mirroring a similar contraction in Barren Land, which also stood at 22.78%. The most significant change by 2024 was the substantial growth in Settlement (Built-up) areas, which surged to 16.34%. Water bodies demonstrated a slight recovery, registering 4.39% of the total area.

Collectively, these findings distinctly highlight a clear pattern of urban expansion and a concurrent reduction in natural land covers throughout the study duration. Fig. 4 graphically illustrates the magnitude of these LULC transformations. Specifically, the Built-up area experienced a considerable net increase of 7.99% from 2015 to 2024. Simultaneously, the Agricultural area also expanded by 4.99%. In contrast, both Barren Land and Forest cover significantly diminished by 2.38% each during the same period. Water bodies registered a minor net decrease of 0.49%. These pronounced land conversions strongly suggest a rapid pace of urbanization within the region, consistent with broader global trends driven by factors such as population growth and economic development. The burgeoning industrial and commercial activities, coupled with the expansion of transportation networks, appear to be primary catalysts in the transformation of natural and agricultural landscapes into urbanized settlements.

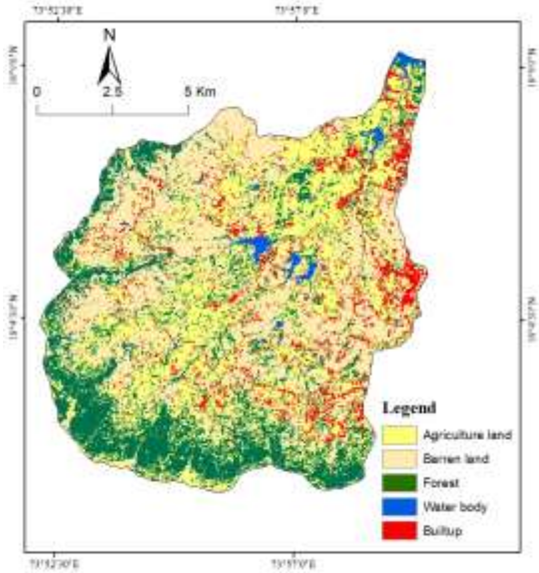


**Fig.2: Land Use Land Cover Map (2015)**

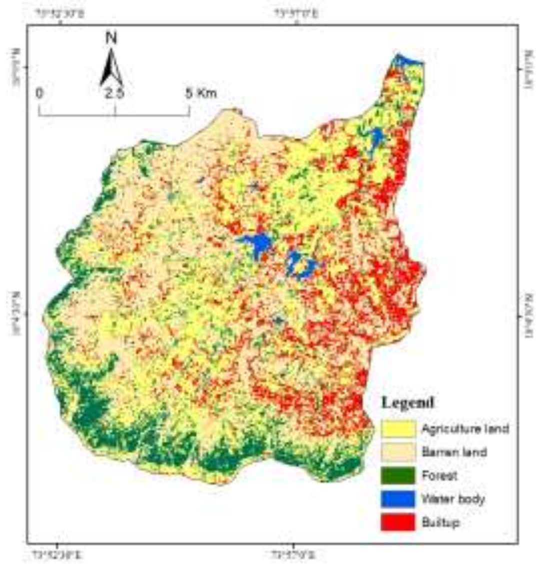


**Fig.3: Land Use Land Cover Map (2020)**

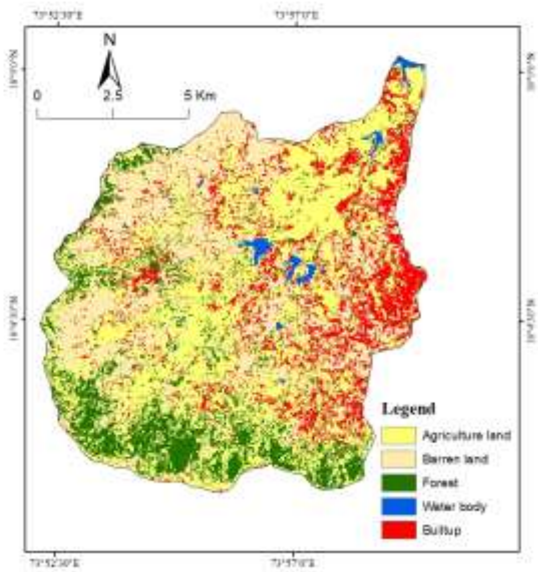


**Fig.4: Land Use Land Cover Map (2024)**

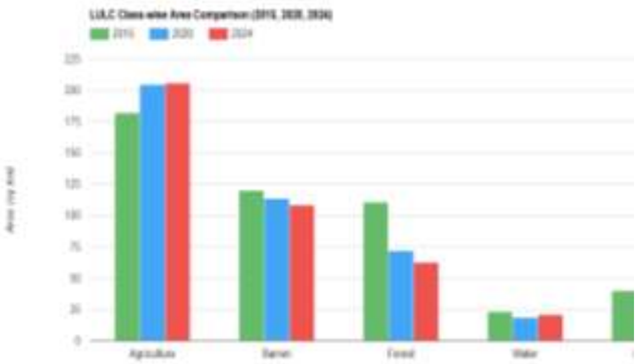


**Fig.5: LULC Change Trends (2015-2024)**

### 3. Accuracy Assessment

The reliability of the classified LULC maps for each study year (2015, 2020, 2024), as presented in Fig. 2 (2015), Fig. 3 (2020), and Fig. 4 (2024), was rigorously evaluated through a confusion matrix generated within the Google Earth Engine (GEE) platform. The overall classification accuracy demonstrated an improvement from 85% in 2015 to 89% in 2024, indicating enhanced performance over time. The Kappa coefficient, a robust measure of agreement beyond chance, similarly increased from 0.768 in 2015 to 0.867 in 2024. This notable increase signifies a substantial improvement in the classification's ability to accurately predict outcomes throughout the study period. These findings collectively confirm the effective and reliable performance of the LULC classification using GEE.

### 4. Conclusion

The principal aim of this research was to examine the dynamic alterations in land use and land cover (LULC) within the study area, leveraging remote sensing data and geospatial techniques from 2015 to 2024. The findings unequivocally demonstrate a substantial expansion in Built-up areas accompanied by a corresponding decline in Forest and Barren Land, as quantitatively detailed in Table 1: LULC Area & Change (2015-2024) and visually represented in Fig. 5: LULC Change Trends (2015-2024). These trends clearly signify profound urbanization and widespread Land Use Land Cover transformations. Such observed urbanization aligns with a broader global phenomenon where rapid urban growth frequently leads to the reduction of natural spaces and agricultural areas, directly impacting the hydrological cycle and, crucially, groundwater recharge mechanisms.

This study offers critical insights into both the magnitude and the underlying characteristics of urbanization within the study area. It identifies key drivers of these LULC changes, including population growth, accelerated urban expansion, and on-going economic development. The increasing urban population has demonstrably fuelled a heightened demand for housing and infrastructure, converting permeable surfaces into impervious ones. Concurrently, the expansion of the transportation network has further contributed to the growth of Built-up areas by opening up previously undeveloped regions for development. Moreover, the research determined that the proliferation of industrial and commercial activities has served as a significant catalyst for the conversion of both natural and agricultural lands into urbanized spaces, thereby reducing natural infiltration zones crucial for groundwater replenishment.

The implications of these findings underscore an urgent necessity for the formulation and rigorous implementation of effective land-use policies and regulations. These measures are fundamental to ensuring sustainable urban development and to adeptly balance the competing demands on finite land resources, specifically with a focus on maintaining and enhancing groundwater recharge potential. The study implicitly suggests that current land-use planning and management practices in the region may be inadequate, potentially contributing to uncontrolled and chaotic urbanization and further exacerbating groundwater depletion. Consequently, we strongly advocate that local authorities prioritize enhancing the efficiency and efficacy of land-use planning and management, integrating principles that protect and restore groundwater recharge areas. Such a focus is paramount for effectively addressing the complex challenges posed by urbanization and for actively fostering sustainable development and water security in the region.

The adoption of a GEE-based approach in this study proved to be a powerful and efficient methodology for examining LULC changes, showcasing its considerable potential for replication in other cities and regions confronting similar developmental pressures. The actionable insights derived from this research, including the detailed LULC maps (Fig. 1, Fig. 2, Fig. 3) and change trends (Fig. 4), can significantly inform urban planning initiatives and guide land-use management strategies. These insights can direct efforts towards promoting sustainable development and mitigating the adverse consequences of urbanization on groundwater resources. Furthermore, the GEE-based approach provides an invaluable tool for continuous monitoring of future LULC changes and for proactively identifying areas that demand immediate intervention to ensure sustainable development and effective groundwater management. In conclusion, this research paper contributes significantly to understanding the intricate LULC dynamics and urban sprawl within the study area, emphatically highlighting the critical need for robust land-use policies and regulations to foster sustainable urban development amidst the complex interplay of competing land demands and the urgent imperative of safeguarding groundwater sustainability.

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