RESEARCH PAPER

Ecological Assessment of Ecosystem Service Decline in the Changing Landscape of the Aravalli Hills: A Dpsir-Based Approach

Biswas, S.[1*], Pandey, D.[2] and Khuman Y. S[3]

Amity University Haryana, India
Indira Gandhi National Open University (IGNOU), New Delhi, India
***Corresponding Author:** zoe.biswas@gmail.com*

Received: 24th April, 2026; Revised: 20th May 2026; Accepted: 30th June, 2026; Available Online: 10th July, 2026

ABSTRACT

This study examines the degradation of ecosystem services in the foothills of the Aravalli Range in Haryana using the Ecosystem Services Approach and the DPSIR (Driver–Pressure–State–Impact–Response) framework. The research focuses on six foothill villages—Baghanki, Chandla Dungerwas, Kherki, Fazalwas, Gwaliar, and Kukrola—located in the Manesar Block of Gurugram district, which are undergoing rapid socio-economic and environmental transformation due to urbanization and industrial expansion. The study evaluates temporal changes in agricultural land, groundwater levels, air pollution, and population growth to understand the relationship between human activities and ecosystem degradation over time.

A descriptive and trend-based analytical methodology was adopted using both primary and secondary data sources. Land Use/Land Cover (LULC) analysis for the period 2005–2016 reveals a steady decline in cropland and scrub forest areas alongside increasing urban and rural built-up land. Agricultural land across all villages showed a continuous reduction between 2010 and 2024, indicating conversion of productive land into settlements and infrastructure. Simultaneously, groundwater depth increased in most villages from 2020 to 2024, reflecting declining groundwater availability and reduced recharge capacity. Air quality analysis from Sector 2 IMT Manesar and Sector 6 Manesar demonstrates increasing concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants (NO_2, SO_2, and O_3), indicating deteriorating environmental conditions associated with industrialization and vehicular emissions. Population data further reveal rising demographic pressure, with Baghanki recording the highest growth rate of over 82% between 2011 and 2020.

The comparative trend analysis highlights a strong association between population growth, expansion of built-up areas, groundwater depletion, loss of agricultural land, and rising pollution levels. Through the DPSIR framework, population growth, urbanization, and industrial development are identified as major drivers creating environmental pressures that alter ecosystem states and reduce provisioning and regulating ecosystem services. The study concludes that unplanned development and ecological degradation are significantly weakening the resilience of the Aravalli ecosystem. It emphasizes the urgent need for sustainable land-use planning, groundwater conservation, pollution control measures, afforestation, and protection of remaining agricultural and natural landscapes to maintain ecological balance and ensure long-term environmental sustainability in the region.

Keywords: Agricultural Land Decline, Air Pollution, Aravalli Hills, DPSIR Framework, Ecosystem Services, Land Use/Land Cover, Urbanization

How to cite this article: Biswas S, Pandey D, Khuman YS, Ecological Assessment of Ecosystem Service Decline in The Changing Landscape of The Aravalli Hills: A Dpsir-Based Approach. Int J Drug Deliv Technol. 2026;16(7): 26-38. DOI: 10.25258/ijddt.16.7.4
Source of support: Nil.
Conflict of interest: None

1. INTRODUCTION

Aravalli Hills and its Ecological Significances

The Aravalli Hills, formed during the Precambrian era, are among the world's oldest mountain ranges and are of high biogeographic and evolutionary significance. The present range is a remnant of a much larger system that has been reduced by prolonged weathering, erosion, and human activities. The Aravallis are rich in metallic minerals such as zinc, gold, silver, copper, and lead, as well as marble, limestone, silica, and quartz (Rathore, 2009). Evidence suggests that copper and other metals have been mined here since at least the 5th century BCE (Gandhi, 2000; Shrivastva, 1999).

The forests of the Aravallis provide timber, fuelwood, fodder, medicinal plants, and essential ecosystem services. They help prevent desertification, regulate climate and precipitation, recharge groundwater, conserve soil, and support biodiversity. Forest patches facilitate groundwater infiltration of approximately 1.54 million litres per hectare annually, with an average percolation rate of 25.2–36%

**Author for Correspondence: zoe.biswas@gmail.com*

(Agarwal, 2016). In southern Haryana, particularly around Gurgaon, the Aravalli foothills have historically sustained dense forests, seasonal streams, and agricultural settlements while providing critical ecosystem services, including groundwater recharge, carbon sequestration, soil conservation, and biodiversity conservation (Rai & Kumar, 2013).

Ecosystem Services in Semi-Arid Region

According to the Millennium Ecosystem Assessment (MA, 2005), ecosystem services (ES) are the goods, processes, and functions provided by ecosystems that directly or indirectly benefit humans. These services are fundamental to human well-being and sustainable development (Zhao et al., 2006; Wu, 2013). The MA classifies ES into four categories: provisioning, regulating, supporting, and cultural services.

Arid and semi-arid regions, which cover about 40% of the Earth's land surface, are characterized by scrubland and dry deciduous forests that exhibit strong seasonal variation. Unsustainable exploitation of natural resources in these regions has resulted in groundwater depletion, desertification, soil salinity, vegetation loss, and increased pollution (Zhu et al., 2016). Widespread ecosystem degradation (Lu et al., 2015; Zhou et al., 2015) threatens sustainable socio-economic development (Peng et al., 2019), with similar challenges emerging in rapidly urbanizing developing countries (Abd-Elaty et al., 2020; Azaiez et al., 2020; Haghighi et al., 2020; Sharafatmandrad and Mashizi, 2021).

Agriculture, the largest human-managed ecosystem, occupies nearly one-third of the Earth's land surface (about 4.9 billion hectares) (FAO, 2018). It both depends on and provides a wide range of ecosystem services (Zhang et al., 2007; Duguma et al., 2019). However, agricultural practices, livestock grazing, resource extraction, and land-use change can degrade ecosystem quality and reduce the availability of ecosystem services (Roy et al., 2022).

Aravalli Changing Landscape

The study villages are located in Manesar town, Gurugram district, Haryana, a region that has experienced rapid peri-urban growth over the last decade, leading to substantial changes in the Aravalli landscape (Dutta, 2012). Urbanization threatens ecosystems through deforestation, groundwater overextraction, hydrological disruption, habitat destruction, and ecological imbalance (Alberti, 2005). Expansion of built-up areas, infrastructure, and agriculture has reduced forest cover and contributed to the degradation and loss of the Aravalli hills (Rathore, 2002; Celestine, 2012; Yadav & Sehrawat, 2019), resulting in significant biodiversity loss (Shashi Mehta, 2016; Mukherjee & Rajvanshi, 2016). Satellite-based studies estimate that nearly 8% of the Aravalli hills disappeared between 1975 and 2019. Urban expansion directly drives land-use change, while population growth acts as an indirect driver (Lambin et al., 2001; McDonald et al., 2013). Increasing built-up areas and population density have adversely affected natural resources, open spaces, and ecosystem services in the Delhi–NCR region (Mohan et al., 2011; Nagendra et al., 2014; Turner et al., 1994). These land-use changes also contribute to climate change, pollution, and ecosystem alteration across multiple scales (Grimm et al., 2008), while unplanned development has further intensified pressure on natural resources (Kulkarni & Ramachandra, 2009).

OBJECTIVES

- To examine the decline in agricultural land as an indicator of provisioning ecosystem services.
- To assess groundwater depletion trends as a measure of regulating ecosystem services.
- To evaluate the increase in air pollution levels as an indicator of declining air quality regulation.
- To analyze population growth trends as a key driver of environmental change.
- To interpret the relationship between human pressures and ecosystem degradation using the DPSIR framework.

2. MATERIALS AND METHODS

2.1 Conceptual Framework

Ecosystem Services Approach

Ecosystem services are the tangible and intangible benefits humans obtain from ecosystems. The Millennium Ecosystem Assessment (MA) framework classifies these services into four categories:

Provisioning Services: Provide essential goods such as food, freshwater, timber, fuel, medicinal plants, fibers, fodder, and genetic resources.

Regulating Services: Maintain environmental balance through climate regulation, air and water purification, erosion control, pollination, and pest and disease regulation.

Supporting Services: Include fundamental ecological processes such as nutrient cycling, soil formation, primary productivity, and oxygen generation that sustain other ecosystem services.

Cultural Services: Offer non-material benefits, including recreation, tourism, aesthetic, spiritual, educational, and cultural values.

The ecosystem services approach aims to promote sustainable ecosystem management, conserve biodiversity, and enhance awareness of nature's role in supporting long-term human well-being and resilience.

DPSIR Framework

This study adopts an integrated approach to assess the decline of ecosystem services in the foothills of the Aravalli Range by linking landscape transformation with environmental and socio-economic indicators. It is based on the Ecosystem Services Framework, which classifies ecosystem services into four categories and highlights their importance for human well-being.

An indicator-based assessment is used, where measurable environmental variables act as proxies for ecosystem service change. The analysis is further guided by the DPSIR (Driver–Pressure–State–Impact–Response) framework, which explains human–environment interactions through cause–effect relationships.

Within the DPSIR framework, population growth and urbanization are identified as the main drivers, creating pressures such as land-use change, expansion of built-up areas, and increased air pollution. These lead to state changes, including loss of agricultural land, groundwater depletion, and declining air quality, resulting in the degradation of ecosystem services, particularly provisioning (food production) and regulating (water regulation and air quality) services. Responses include conservation measures, sustainable resource management, and environmental policies aimed at restoring ecosystem services and maintaining ecological balance.

2.2 Study Area

The Aravalli Hills span Haryana, Rajasthan, Delhi, and Gujarat, featuring rocky terrain, scrub forests, semi-arid conditions, and rich biodiversity that supports both human and wildlife populations. To study ecosystem services and human–environment interactions, six foothill villages—Baghanki, Chandla Dungerwas, Kherki, Fazalwas, Gwaliar, and Kukrola—were selected, located around 28.3173° N and 76.9145° E in Manesar Block, Gurugram, Haryana. Collectively known as Pachgaon (excluding Baghanki), these villages were chosen for their ecological importance, increasing urbanization, population growth, livelihood changes, and accessibility, as well as their ongoing socio-economic transformation.

2.3 Research Design

The study follows a descriptive, trend-based analytical design to examine temporal changes in environmental and socio-economic indicators over a ten-year period. It evaluates historical patterns and recurring trends through logical interpretation rather than spatial or statistical correlation. To assess the relationship between human activities, environmental change, and community well-being, the study integrates both primary and secondary data sources. The analysis is based on environmental and socio-economic indicators representing these dimensions. The key variables used in the study include:

- Land Use/Land Cover (LULC) data derived from satellite imagery
- Agricultural land extent
- Groundwater level data
- Air pollution indicators (e.g., $PM_{2.5}$, PM_{10})
- Population data

Data Framework

Variable	Type	Role in Framework
LULC images (10 years)	Environmental	Pressure
Agriculture decline	Environmental	Provisioning service indicator
Groundwater data	Environmental	Regulating service indicator
Air pollution data	Environmental	Regulating service indicator
Population data	Socio-economic	Driver

Indicator-Based Assessment of Ecosystem Services

Given the lack of direct ecosystem service measurements, the study uses proxy indicators to represent changes in key services:

- Provisioning Services: Decline in agricultural land is used as an indicator of reduced food production capacity.
- Regulating Services: Groundwater depletion reflects declining water regulation and recharge capacity, while increasing air pollution indicates reduced air quality regulation.

This approach enables the assessment of ecosystem service degradation in a data-constrained environment while maintaining conceptual rigor.

Ecosystem Services Linkage

Using the Ecosystem Services Framework:

Indicator	Ecosystem Service
Agriculture decline	Food provisioning
Groundwater decline	Water regulation
Air pollution increase	Air quality regulation

Land Use/Land Cover Analysis

LULC data over the study period (2005 – 2016) are classified into major categories such as agricultural land, built-up area, and vegetation cover. Changes in these categories are quantified using percentage change and rate of change calculations. The analysis focuses on identifying major transitions, particularly the conversion of agricultural land into urban or built-up areas.

Trend Analysis

Temporal trends are analyzed for all key variables to identify patterns of increase or decline over the study period. Line graphs and percentage change calculations are used to examine:

- Reduction in agricultural land
- Decline in groundwater levels
- Increase in population
- Rise in air pollution levels

The annual rate of change is calculated to provide a clearer understanding of the intensity of these trends.

Comparative Trend Interpretation

In the absence of statistical correlation or spatial modelling, the study employs comparative trend analysis to infer relationships between variables. Trends are examined side-by-side to identify consistent patterns, such as:

- Increasing population alongside declining agricultural land
- Expansion of built-up areas coinciding with groundwater depletion
- Rising pollution levels associated with urban growth

These relationships are interpreted cautiously, focusing on logical consistency rather than causal inference.

3. RESULT AND DISCUSSION

3.1 Trend Analysis - Result

1. Land Use Change – Decline in Agriculture Land Area

The graph shows a clear declining trend in the area (in hectares) across all six villages—Baghanki, Chandla Dungerwas, Fazalwas, Gwaliar, Kukrola, and Kherki—between 2010 and 2024. Baghanki consistently has the largest area, starting at around 285 hectares in 2010 and gradually decreasing to about 270 hectares by 2024. Gwaliar also shows a noticeable reduction, dropping from approximately 255 hectares to around 195 hectares over the same period, marking one of the steepest declines. Chandla Dungerwas and Kherki exhibit moderate decreases, while Fazalwas and Kukrola maintain comparatively smaller areas with steady but less pronounced reductions.

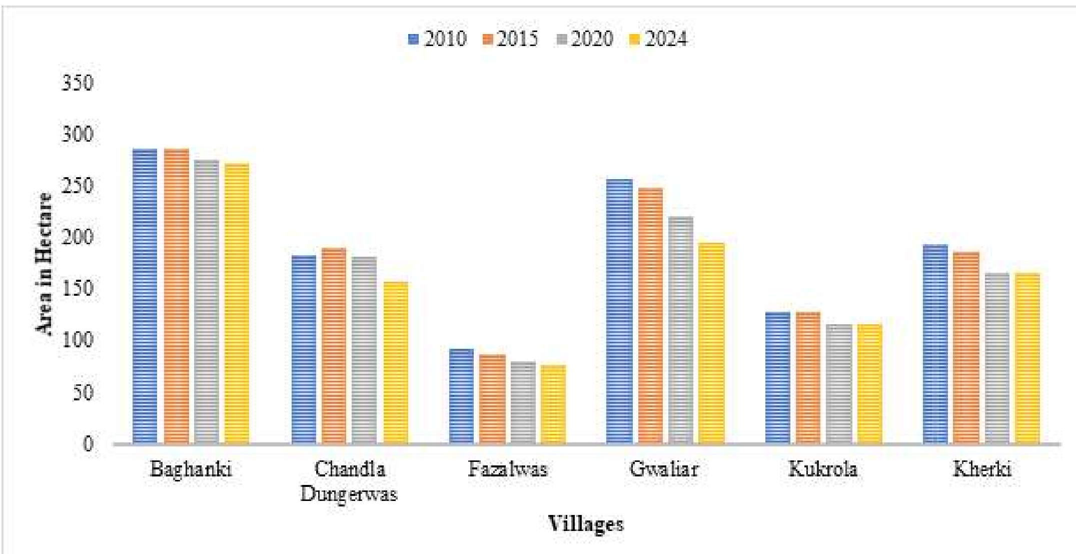

Figure 1: Change in agriculture land area across villages (2010 - 2024)

(*Source:* Manesar Tehsil Office, Municipal Corporation Manesar**)**

Temporal Change in LULC

The Land Use/Land Cover (LULC) graph shows changes across three periods: 2005–2006, 2011–2012, and 2015–2016. Cropland consistently dominates the landscape, though it declines from about 11.8% in 2005–2006 to roughly 9.8% in 2015–2016. Scrub forest is the second most prevalent class, decreasing from around 5.4% to 4.5% over the same period. Rural areas show a gradual increase, rising from approximately 0.5% to about 1.0%. Scrubland and urban areas are minimal in earlier years but increase slightly by 2015–2016, with urban areas reaching around 1.3%. Grasslands/grazing lands remain negligible or absent throughout the study period.

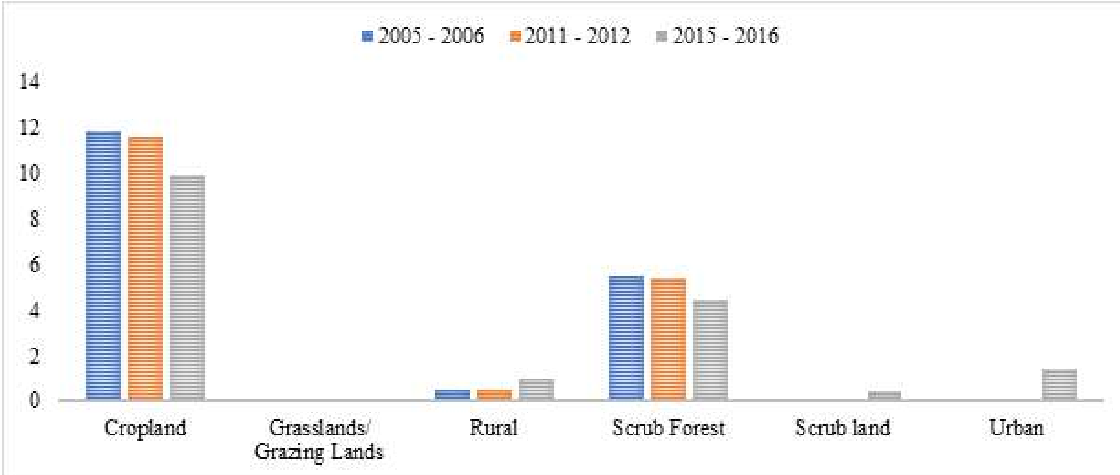

Figure 2: LULC Spatial Analysis Report for selected AOI, study Area (17.891 Sq. Km.)

(***Source:*** Bhuvan NRSC Website**)**

2. Environmental Trends - Ground Water Depletion

The graph represents the groundwater depth (in meters) in the month of June from 2020 to 2024 across six villages: Baghanki, Kherki, Fazalwas, Kukrola, Gwalior, and Chandla Dungerwas. A general increasing trend in water level depth is observed in most villages over the five-year period. Baghanki, Kukrola, and Gwalior show relatively high depths, increasing gradually from about 47.5 m in 2020 to around 49 m in 2024. Fazalwas shows a steady rise from approximately 47.5 m to about 48.5 m while Kherki remains comparatively stable, with only a slight increase around 43.3–43.6 m. Chandla Dungerwas consistently shows the lowest depth values (around 37 m), with minimal variation over the years. Overall, most villages show a slow but consistent increase in groundwater depth.

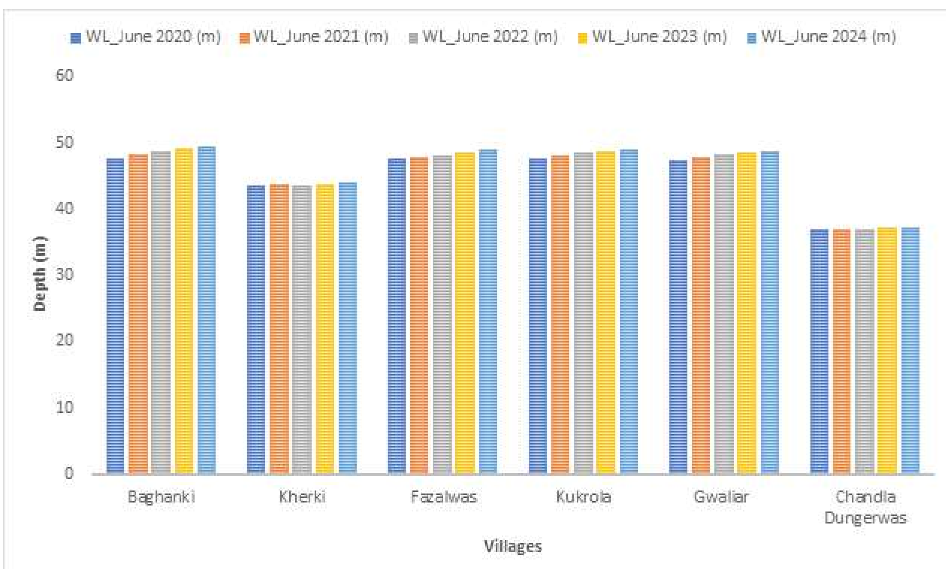

Figure 3: Groundwater Level across Study Villages (2020 – 2024)

(***Source:*** Groundwater Cell of the Irrigation & Water Resources Department of Haryana)

Rising Pollution

NOTE - Sector 2 (IMT Manesar) and Sector 6 (Manesar) were selected as data monitoring stations to enable a meaningful comparison of air quality across areas with different land-use characteristics within the same urban setting. Sector 2, located within the industrial hub of IMT Manesar, represents a zone with significant industrial activity, heavy vehicular movement, and multiple emission sources, making it suitable for assessing industrial pollution impacts. In contrast, Sector 6 is relatively more residential and mixed-use, reflecting population exposure in a less industrialized environment. Additionally, both monitoring stations are situated within a short distance (less than 7 km) from nearby villages, which makes them highly relevant for understanding not only urban air quality but also its spillover effects on rural communities. This proximity ensures that the observed pollution levels are likely to influence surrounding villages, allowing for a more comprehensive assessment of environmental and public health impacts across both urban and rural settings.

Figure 4: Temporal Variation of Particulate Pollution Indicators (AQI, PM2.5, PM10) in Sector 2 IMT Manesar and Sector 6 Manesar (2020–2024)

(*Source:* AQI.in)

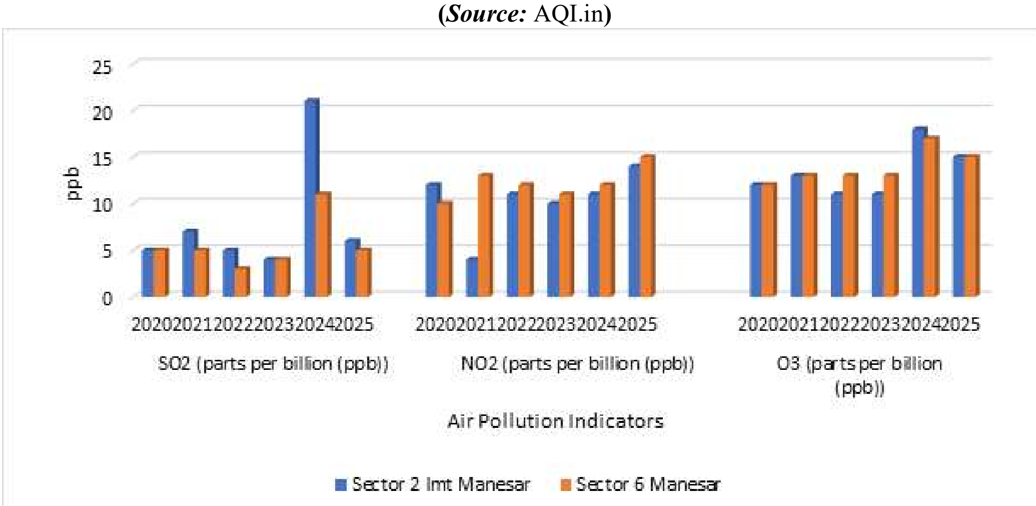

Figure 5: Temporal Variation of Gaseous Air Pollutants (SO_2, NO_2, O_3) in Sector 2 IMT Manesar and Sector 6 Manesar (2020–2024)

(Source: AQI.in**)**

The graphs show a clear decline in air quality in both Sector 2 (Industrial Manesar) and Sector 6 (Manesar) from 2020 to 2025. Concentrations of gaseous pollutants such as SO_2, NO_2, and O_3 generally increase over time, with NO_2 and O_3 showing consistent upward trends in both sectors, indicating rising emissions and enhanced atmospheric reactions. A noticeable spike in SO_2 in Sector 2 around 2024 suggests episodic industrial discharge. Particulate pollution indicators, including AQI, PM2.5, and PM10, remain high throughout the study period, often exceeding safe limits. AQI values indicate moderate to poor air quality, with Sector 2 typically recording higher pollution levels. PM2.5 and PM10 show fluctuations but remain elevated, with peak concentrations observed around 2021–2022 and only slight reductions thereafter.

3. Socio- Economic Trends - Population Growth

Table 1: Population Growth and Density Changes in Selected Villages of the Aravalli Hills (2011–2020)

Villages	Total Village Geographical Area km2	Population :2011	Population: 2020	Population density/ km2 2011	Population density/ km2 2020	Population increase percentage
Baghanki	4.17	3356	6116	805 people	1467 people	82.24076281

Chandla dungerwas	2.81	1997	2299	711 people	818 people	15.12268403
Kherki	2.49	1648	1866	662 people	750 people	13.22815534
Fazalwas	1.89	1866	2148	987 people	1137 people	15.11254019
Gwaliar	6.17	1259	1512	204 people	245 people	20.09531374
Kukrola	3.08	1819	2094	591 people	680 people	15.11819681

Source: Municipal Corporation Manesar

The data shows a consistent increase in population across all selected villages between 2011 and 2020. Baghanki experienced the highest population growth, rising from 3,356 to 6,116, with an increase of about 82.24%, and a sharp rise in population density from 805 to 1,467 persons per km². Other villages such as Chandla Dungerwas, Fazalwas, and Kukrola recorded moderate growth rates of around 15%, while Kherki showed a slightly lower increase of 13.23%. Gwaliar, despite having the largest geographical area (6.17 km²), maintained the lowest population density, increasing from 204 to 245 persons per km², with a growth rate of about 20.09%. Overall, population density increased in all villages, indicating growing pressure on land resources.

3.2 Interpretation of Trend Analysis using DPSIR Framework

D — Drivers (Underlying causes)

The main drivers in the Aravalli hill region are socio-economic and demographic:

- Population growth in villages such as Baghanki, Kukrola, and Fazalwas increases demand for land, water, and resources.
- Economic shifts and livelihood changes are pushing communities away from agriculture toward settlement expansion and non-farm activities.
- Urban expansion and regional development pressure from nearby urban centres intensify land demand.
- Industrialization and mining activities (as noted in Sector 2 and Sector 6) add further developmental pressure.

P — Pressures (Direct human stresses on the environment)

From the discussion, several clear pressures emerge:

1. Land conversion and land use change

- Decline in cropland across villages reflects conversion of agricultural land into built-up areas.
- Expansion of rural and urban land indicates settlement growth and infrastructure development.
- Reduction in scrub forests and near disappearance of grasslands shows vegetation clearing and ecosystem simplification.

2. Vegetation loss

- Deforestation, encroachment, and degradation of scrub forests reduce green cover.
- Loss of vegetation weakens soil stability and natural recharge processes.

3. Resource extraction pressure

- Increased agricultural pumping and water demand due to population growth.
- Mining and land disturbance in the Aravalli region intensify environmental stress.

4. Emissions and pollution

- Urbanization and industrial growth increase air pollutant emissions (PM2.5, PM10, NO_2, SO_2).
- Loss of forest cover reduces pollutant absorption capacity.

I — Impacts (Effects on ecosystems and society)

These environmental changes directly translate into ecosystem service decline:

1. Decline in provisioning services

- Reduced agricultural land leads to lower food production capacity.
- Groundwater depletion reduces water availability for irrigation and domestic use.

2. Decline in regulating services

- Reduced vegetation cover weakens:
  - Groundwater recharge regulation (less infiltration, more runoff).
  - Air purification capacity, leading to worsening air quality.
  - Climate regulation, contributing to local temperature rise.

3. Supporting service degradation

- Habitat loss from scrub forest and grassland decline reduces biodiversity and ecological stability.
- Soil degradation and erosion increase due to loss of root systems.

4. Human and health impacts

- Increased air pollution contributes to respiratory risks.
- Water scarcity intensifies livelihood stress.
- Reduced agricultural viability affects rural economies.

R — Response (Implied or needed interventions)

Although not strongly detailed in the text, implied responses include:

- Sustainable land-use planning to control urban expansion.
- Afforestation and restoration of scrub forests in degraded Aravalli zones.
- Regulation of mining and encroachment activities.
- Improved groundwater management (rainwater harvesting, reduced extraction).
- Promotion of climate-resilient and water-efficient agriculture.

3.3 Comparative Trend Analysis - Result

1. Population vs. Agricultural Land

The comparative analysis of population growth and agricultural land trends in the Aravalli villages of Haryana reveals a significant transformation in land use and demographic structure between 2010 and 2024. Population increased in all selected villages between 2011 and 2020, accompanied by a rise in population density. Simultaneously, agricultural land area showed a declining trend across all villages.

Among the villages, Baghanki recorded the highest population growth, increasing from 3,356 in 2011 to 6,116 in 2020, representing an increase of 82.24%. Its population density also rose sharply from 805 people/km² to 1,467 people/km². During the same period, the agricultural area declined from approximately 288 hectares in 2010 to 272 hectares in 2024.

Gwaliar experienced the most substantial decline in agricultural land, decreasing from nearly 256 hectares in 2010 to about 194 hectares in 2024. Although its population growth was comparatively moderate (20.09%), the reduction in cultivated land was significant, indicating severe land-use transformation.

The villages of Chandla Dungerwas, Fazalwas, Kherki, and Kukrola also showed continuous reduction in agricultural land along with moderate population growth ranging from 13% to 15%. Fazalwas recorded the highest population density among the villages in 2020 (1,137 people/km²), reflecting intense pressure on limited land resources.

Overall, the results demonstrate a negative relationship between increasing population and agricultural land availability in the Aravalli region villages.

2. Expansion of built-up areas coinciding with groundwater depletion

The temporal Land Use/Land Cover (LULC) analysis from 2005–2006 to 2015–2016 reveals a significant transformation of the landscape characterized by declining natural and agricultural land and increasing human settlement areas. Cropland, which remained the dominant land-use category throughout the study period, decreased from approximately 11.8% in 2005–2006 to around 9.8% in 2015–2016. Similarly, scrub forest cover declined from nearly 5.4% to 4.5%, indicating gradual degradation of vegetative cover associated with the Aravalli ecosystem. In contrast, rural and urban built-up areas exhibited continuous expansion. Rural settlements increased from nearly 0.5% to 1.0%, while urban areas, although initially negligible, expanded to about 1.3% by 2015–2016. The increase in scrubland and built-up categories indicates growing anthropogenic pressure and land transformation within the region. Grasslands and grazing lands remained minimal throughout the study period, suggesting reduced ecological resilience and declining open natural habitats.

The groundwater depletion analysis for the period 2020–2024 demonstrates a consistent increase in groundwater depth across most villages, indicating declining groundwater availability. Villages such as Baghanki, Kukrola, and Gwalior recorded comparatively deeper groundwater levels, increasing from around 47.5 m in 2020 to approximately 49 m in 2024. Fazalwas also showed a gradual increase from nearly 47.5 m to 48.5 m. Kherki remained relatively stable with minor fluctuations between 43.3 m and 43.6 m, while Chandla Dungerwas consistently exhibited the shallowest groundwater levels at around 37 m. Overall, the trend reflects progressive groundwater depletion across the study area.

A comparative assessment of both datasets suggests a close relationship between expansion of built-up areas, degradation of Aravalli vegetation cover, and declining groundwater levels. The reduction in cropland and scrub forest alongside increasing urban and rural settlements indicates conversion of permeable natural surfaces into impervious built-up land, thereby reducing groundwater recharge potential. Simultaneously, degradation of the Aravalli landscape, particularly the loss of scrub forests and natural vegetation, likely weakened ecological functions such as water infiltration, soil conservation, and moisture retention.

3. Rising pollution levels associated with urban growth

The temporal analysis of air pollution indicators in Sector 2 IMT Manesar and Sector 6 Manesar from 2020–2024 reveals a progressive deterioration in environmental quality associated with rapid urbanization and industrial expansion in the Manesar region adjoining the Aravalli landscape. The observed trends indicate increasing atmospheric pollution loads and significant land use transformations, both of which contribute to ecological stress and degradation of the Aravalli ecosystem.

The particulate pollution data (AQI, $PM_{2.5}$, and PM_{10}) show consistently high concentrations across both sectors throughout the study period. AQI values remained within moderate to poor categories, with Sector 6 initially recording higher AQI levels during 2020–2021, while Sector 2 maintained persistently elevated pollution levels in later years. $PM_{2.5}$ concentrations showed a marked rise in 2021, especially in Sector 6, followed by moderate fluctuations but remaining above permissible standards. PM_{10} concentrations also remained critically high in both sectors, indicating sustained emissions from vehicular movement, industrial activity, road dust, and construction processes linked with urban growth.

The gaseous pollutant analysis further demonstrates declining air quality conditions. NO_2 concentrations increased steadily in both sectors from 2020 to 2025, reflecting rising vehicular emissions, fossil fuel combustion, and industrial operations. O_3 levels also showed a continuous upward trend, indicating enhanced photochemical reactions driven by urban atmospheric conditions and increasing precursor pollutants. SO_2 concentrations remained relatively moderate but displayed a significant spike in Sector 2 during 2024, likely associated with episodic industrial emissions and fuel combustion activities.

The Land Use/Land Cover (LULC) analysis indicates substantial landscape transformation over the examined periods (2005–2006, 2011–2012, and 2015–2016). Cropland, which formed the dominant land cover, declined noticeably over time, while scrub forest area also reduced significantly. Simultaneously, rural settlements, scrubland, and urban areas expanded gradually. Urban land increased from negligible levels to approximately 1.3% by 2015–2016, reflecting rapid urban encroachment around the Aravalli foothill region. The decline in scrub forests and croplands suggests fragmentation of natural and semi-natural ecosystems due to infrastructure development, industrialization, and settlement expansion.

These changes collectively indicate increasing anthropogenic pressure on the Aravalli region. The reduction in vegetative cover and scrub forest weakens the natural ecological barrier function of the Aravallis, which traditionally acts as a sink for dust and pollutants and regulates the regional microclimate. Simultaneously, expanding urban and industrial activities contribute to increased particulate matter and gaseous emissions, accelerating environmental degradation.

3.4 Interpretation of Comparative Trend Analysis

1. Population vs. Agricultural Land

The observed trends suggest that rapid population growth is one of the major factors contributing to land-use change and environmental degradation in the Aravalli region of Haryana. Increasing population creates greater demand for housing, infrastructure, transportation, and other developmental activities, which often lead to the conversion of agricultural land into residential and non-agricultural uses.

The case of Baghanki clearly reflects the impact of demographic pressure on land resources. The exceptionally high population increase corresponds with a steady decline in agricultural land, indicating expansion of settlements and intensified human activities. Similarly, the decline in agricultural area in Gwaliar may be associated not only with population growth but also with environmental degradation, deforestation, and possible mining or developmental activities in the Aravalli landscape.

The reduction of agricultural land has serious ecological implications for the Aravalli region. Continuous land conversion contributes to: Loss of vegetation cover, Soil erosion, Declining groundwater recharge, Reduction in biodiversity, Increased land degradation.

Higher population density further intensifies pressure on natural resources. Villages such as Fazalwas and Baghanki, with very high population density, are likely experiencing greater stress on land and water resources. The shrinking agricultural area may also affect local livelihoods, food security, and the sustainability of traditional farming systems.

The findings indicate that the degradation of the Aravalli ecosystem is closely linked with unplanned population expansion and unsustainable land-use practices. Without proper management, continued demographic growth may accelerate ecological imbalance in the region.

2. Expansion of built-up areas coinciding with groundwater depletion

The observed increase in built-up areas reflects rapid urbanization and rural expansion in the region adjoining the Aravalli hills. Such land transformation is often associated with infrastructure development, population growth, mining activities, and encroachment into ecologically sensitive zones. The decline in scrub forest and cropland demonstrates increasing anthropogenic pressure on natural landscapes. Since the Aravalli range acts as an important ecological barrier and groundwater recharge zone, degradation of its vegetation cover can directly influence hydrological processes.

The increasing groundwater depth recorded in most villages indicates excessive groundwater extraction combined with insufficient recharge. Expansion of urban surfaces such as roads, buildings, and settlements reduces infiltration of rainwater into the subsurface. Consequently, groundwater recharge declines while water demand simultaneously increases due to domestic, agricultural, and industrial activities. Villages exhibiting greater groundwater depletion, such as Baghanki, Kukrola, and Gwalior, may be experiencing higher developmental pressure and groundwater abstraction compared to relatively stable areas like Kherki and Chandla Dungerwas.

The relationship between Aravalli degradation and groundwater depletion is environmentally significant. The Aravalli hills traditionally support groundwater recharge through forest cover, natural drainage systems, and porous geological formations. Reduction in scrub forests and associated ecological degradation can accelerate soil erosion, reduce infiltration capacity, and disturb local hydrological balance. Moreover, shrinking cropland may indicate conversion of agricultural land into settlements or degraded barren land, further intensifying ecological stress.

The comparative trend analysis therefore suggests that urban expansion and degradation of the Aravalli ecosystem are interconnected drivers contributing to groundwater depletion in the region. The findings highlight the cumulative environmental impact of unplanned development and ecological degradation on water resources sustainability.

3. Rising pollution level associated with urban growth

The observed increase in particulate and gaseous pollutants in Manesar reflects the broader environmental consequences of rapid urban growth occurring along the Aravalli corridor. The Aravalli range plays a critical ecological role in northwestern India by controlling desertification, regulating local climate, conserving biodiversity, and acting as a natural buffer against dust transport from the Thar Desert. However, extensive urbanization and industrialization in areas surrounding Gurugram and Manesar have intensified pressure on this fragile ecosystem.

High $PM_{2.5}$ and PM_{10} concentrations indicate significant dust generation and suspended particulate emissions associated with road construction, mining remnants, industrial operations, and vehicular traffic. The degradation of scrub forests and natural vegetation in the Aravalli region reduces dust retention capacity and exposes soil surfaces to erosion, thereby increasing atmospheric particulate loads. This explains the persistently high PM levels observed in both sectors.

The increasing trend of NO_2 and O_3 further highlights the influence of expanding transportation networks and industrial emissions. NO_2 is closely linked with combustion sources such as diesel vehicles, factories, and power generation activities. Elevated NO_2 concentrations contribute to secondary ozone formation, particularly under high temperature and sunlight conditions typical of the region. The rise in O_3 levels therefore reflects intensifying urban photochemical pollution.

The temporary spike in SO_2 concentrations in Sector 2 suggests localized industrial discharge events, possibly linked with manufacturing units operating within IMT Manesar. Industrial clusters situated near the Aravalli foothills contribute significantly to atmospheric pollution due to fuel combustion and inadequate emission controls.

The LULC changes strongly support the air pollution trends. The decline in cropland and scrub forest demonstrates conversion of natural and agricultural landscapes into built-up areas. Urban expansion fragments ecological habitats and weakens the ecological resilience of the Aravalli system. Loss of vegetation also reduces carbon sequestration capacity and increases surface temperatures, which may further intensify ozone formation and urban heat island effects.

The expansion of urban areas and reduction of natural vegetation indicate a transition from a semi-natural landscape toward a highly urban-industrial environment. Such transformations are characteristic of peri-urban regions undergoing rapid economic development without adequate environmental safeguards. In the context of the Aravalli region, these changes threaten groundwater recharge zones, biodiversity habitats, and the ecological continuity of the hill system.

Overall, the results suggest a strong relationship between urban growth, land degradation, and deteriorating air quality in the Manesar region. The environmental stress observed in the study area reflects ongoing degradation of the Aravalli ecosystem due to anthropogenic activities.

4. POLICY IMPLICATIONS

Need for Sustainable Land-Use Planning

Rapid urban expansion and unregulated development often lead to the loss of agricultural land, ecological imbalance, and pressure on infrastructure. Sustainable land-use planning is therefore essential to balance economic growth with environmental protection. Policies should promote compact urban development, zoning regulations, mixed land use, and the preservation of green belts and open spaces. Integrating environmental impact assessments into planning processes can help reduce long-term ecological degradation.

Groundwater Conservation Strategies

Excessive extraction of groundwater for domestic, industrial, and agricultural purposes has caused declining water tables and water scarcity in many regions. Effective conservation strategies should include rainwater harvesting, artificial groundwater recharge, efficient irrigation methods, wastewater recycling, and regulation of borewell extraction. Public awareness campaigns and community participation are also important for promoting responsible water use and ensuring long-term water security.

Pollution Control Measures

Industrialization, urbanization, and increasing vehicular emissions contribute significantly to air, water, and soil pollution. Strong pollution control policies are necessary to protect public health and environmental quality. These measures may include stricter enforcement of emission standards, treatment of industrial effluents, promotion of clean energy, improved waste management systems, and regular environmental monitoring. Encouraging sustainable industrial practices and green technologies can further reduce pollution levels.

Protection of Remaining Agricultural and Natural Areas

Agricultural lands, forests, wetlands, and other natural ecosystems provide essential ecological and economic benefits. Their conversion into urban or industrial areas threatens biodiversity, food security, and climate resilience. Policies should focus on conserving fertile agricultural land, protecting biodiversity-rich zones, and restoring degraded ecosystems. Establishing protected areas, promoting sustainable farming practices, and limiting encroachment into ecologically sensitive regions are important steps toward environmental sustainability.

Acknowledgement

I would like to express my sincere gratitude to Dr. Deepika Pandey & Yanglem sharatchandra khuman whose guidance and insightful feedback greatly contributed to the development and completion of this research. Her expertise played a crucial role in shaping the direction and quality of this research. We also thank Amity University Haryana for providing the necessary resources and support throughout the study.

I also extend my appreciation to all willingly participated villagers who helped in the survey.

Statement of Declaration

Competing Interests and Funding: No funding from any agency was involved in the present research work.

Author Consent: All authors have read, understood, and complied with the statement on "Ethical Responsibilities of Authors" as outlined in the Instructions for Authors. Each author has made a significant contribution to the research and has approved the final version of the manuscript.

Ethical Consent: This research was conducted in accordance with all relevant ethical guidelines. Participation in the survey was voluntary, with face-to-face interviews conducted only with willing participants who provided informed consent. The study design and submission adhere to the University Ethical Committee guidelines. Human ethics approval and consent to participate are not applicable.

Ethics Approval: Not applicable.

Clinical Trial Number: Not applicable.

The research presented is original, has not been published previously, and is not under consideration for publication elsewhere. The manuscript contains no plagiarism and there are no conflicts of interest associated with this paper.

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