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RESEARCH

Mapping Gully Erosion Dynamics Near Ahilyanagar, Maharashtra: A Cloud-Based Geospatial Analysis Using Google Earth Engine

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Abstract
Gully erosion represents a significant global environmental challenge, severely impacting land productivity, water resources, and ecological sustainability. The Nagar tehsil and the surrounding area of Ahilyanagar city in Maharashtra belong to semi-arid regions where gully erosion is a major threat to agriculture and water resources. This study used the Google Earth Engine (GEE) platform to map and assess gully erosion dynamics. By analyzing multi-temporal Sentinel-2 imagery, NDVI, Digital Elevation Models (DEMs), and other environmental data, researchers were able to accurately map gully-affected areas and identify the main factors contributing to their formation. A spatial analysis using a 5 km multi-ring buffer around Ahilyanagar city identified six gully erosion hotspots, revealing that about 40 villages in Nagar Tahsil are highly susceptible to erosion. The study found that the northeastern part of the region had the highest concentration of gullies, while the southern and southeastern parts had very few. The main causes were identified as both human activities, such as deforestation and unsustainable farming, and natural factors like steep slopes and drainage density. This research demonstrates that GEE is an effective, large-scale, and cost-efficient tool for mapping erosion. The findings provide a valuable framework for policymakers to implement targeted conservation strategies, directly supporting global Sustainable Development Goals (SDGs) and India's Land Degradation Neutrality (LDN) mission.

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Statement of Sustainability: This research offers a novel, scalable, and remote sensing-driven framework for gully erosion assessment, moving beyond conventional, resource-intensive techniques. Its distinct contribution lies in leveraging Google Earth Engine to provide highly detailed, reproducible insights into land degradation dynamics in semi-arid zones. This innovative methodology directly bolsters SDG 15 (Life on Land) by facilitating targeted restoration and sustainable land management practices. Moreover, it indirectly supports SDG 2 (Zero Hunger) by protecting arable land and SDG 6 (Clean Water and Sanitation) by minimizing sediment pollution, fostering enhanced environmental and agricultural sustainability.

1. Introduction

Gully erosion is a problem of Indian land resources, but it is unevenly spared in districts (Majhi et al., 2025). Gully erosion, a severe form of soil degradation, is a pervasive environmental issue with profound socio-economic and ecological consequences globally (Shrestha, 2018). It is characterized by the formation of deep, incised channels that can rapidly expand, leading to irreversible land loss, reduced agricultural productivity, decreased water quality due to increased sediment loads, and damage to infrastructure (Poesen et al., 2003; Vanmaercke et al., 2014). Semi-arid regions, in particular, are highly susceptible to gully erosion due to their fragile ecosystems, sparse vegetation cover, and vulnerability to intense, episodic rainfall events (Valentin et al., 2005; De Girolamo and Gentile, 2016). In India, land degradation, including gully erosion, remains a significant challenge, with a 2025 scientific report highlighting that 77 districts are particularly affected, primarily concentrated in eastern and southern India (Majhi et al., 2024a). The Deccan Plateau, specifically the Ahilyanagar district in Maharashtra, is highly susceptible to land degradation due to its undulating terrain and seasonal monsoons. This problem is worsened by rapid deforestation, which has led to a decrease in protective vegetation and increased erosion.

The advent of cloud-based geospatial platforms like Google Earth Engine (GEE) has revolutionized environmental monitoring by providing unparalleled access to petabytes of satellite imagery and powerful computational capabilities (Gorelick et al., 2017). GEE enables large-scale, multi-temporal analyses that were previously computationally prohibitive, offering a cost-effective and reproducible framework for addressing complex environmental challenges. The application of advanced geospatial technologies, particularly cloud-based platforms and machine learning, has significantly progressed gully erosion research internationally. The capability of platforms like GEE to process vast amounts of satellite data efficiently has enabled large-scale, long-term monitoring that would be computationally intensive with traditional methods. Studies in diverse semi-arid regions, such as Iran and Ethiopia, have effectively demonstrated the integration of GEE with machine learning algorithms, including Random Forest (RF) and Support Vector Machine (SVM), to generate highly accurate gully erosion susceptibility maps (GESM) (Lei et al., 2020; Titti et al., 2022).

These international studies frequently utilize high-resolution satellite imagery (e.g., Sentinel-2), Digital Elevation Models (DEMs), and a variety of derived terrain indices, all readily available within the extensive GEE data catalog (Huang et al., 2023). A common methodological trend observed is the increasing adoption of Object-Based Image Analysis (OBIA) over traditional pixel-based methods for mapping complex geomorphic features like gullies, due to its enhanced capability in delineating irregular shapes and reducing salt-and-pepper noise (Blaschke, 2010; Karami et al., 2015; Liu et al., 2018). The UAV and multi-source remote sensing data play a very crucial role in the multi-scale level gully mapping (Liu et al., 2016; Wang et al., 2016). Within India, gully and ravine erosion represent widespread challenges, particularly prevalent in states like Madhya Pradesh, Uttar Pradesh, Gujarat, and significant parts of the Deccan Plateau and the Shivalik Hills (Majhi et al., 2024b). Rill and gully erosion in Pravara River basin of the Deccan trap region of Maharashtra, triggered by agricultural land use changes and indicating rapid gully expansion and significant annual loss of soil (Joshi, 2014; Joshi, 2020)

The present study's focus on Ahilyanagar, Maharashtra, aligns directly with national priorities concerning land degradation assessment and sustainable land management. Substantial national research has been conducted utilizing geospatial techniques for soil erosion mapping. For instance, studies in the Chambal River basin have successfully employed GEE in conjunction with the Revised Universal Soil Loss Equation (RUSLE) to estimate soil loss, providing valuable insights for regional planning (Renard et al., 1997; Kumar et al., 2022). Consistent findings from national research highlight key drivers of gully erosion, including intense monsoonal rainfall, steep slopes, high soil erodibility (K-factor), and significant land use and land cover changes (LULC) (Pal and Chakrabortty, 2019). The strategic shift towards cloud computing platforms such as GEE in Indian research is pivotal for facilitating large-scale, dynamic, and multi-temporal analyses crucial for comprehensive erosion monitoring and prediction. The object-based image analysis (OBIA) approach is also contemporary to be used for gully detection (Aliramaee et al., 2024).

This study contributes to the existing body of international and national research by employing advanced methodologies in a regionally specific context, namely the semi-arid Ahilyanagar area. The leveraging of GEE offers distinct advantages, including the capacity for multi-temporal analysis of gully expansion, which can yield critical insights into erosion rates and patterns over time. To ensure the scientific rigor and robustness of the findings, the selection and justification of gully erosion conditioning factors are meticulously based on local physiographic and environmental conditions. Furthermore, rigorous validation of the generated gully maps and susceptibility models through targeted field surveys and comparisons with very high-resolution imagery is essential to confirm accuracy. Embracing an Object-Based Image Analysis (OBIA) approach within the GEE environment is considered a crucial step to further refine the precision of gully extraction and mapping, enhancing the overall scientific contribution.

Therefore, this study aims to address the critical need for comprehensive and high-resolution spatial mapping of gully erosion around Ahilyanagar City in Nagar Tahsil, Maharashtra. By leveraging the advanced capabilities of GEE and integrating diverse Earth Observation (EO) datasets, this research seeks to: Accurately identify and map the spatial distribution of gully-affected areas; Assess the relationship between gully erosion distribution and proximity to the urban core; Identify and delineate prominent gully erosion hotspots within Nagar Tahsil; Quantify the number of villages affected by these erosion hotspots; Provide evidence-based insights to support sustainable land management and erosion control planning in the region, contributing to both national Land Degradation Neutrality (LDN) targets and global Sustainable Development Goals (SDGs).

2. Materials and Methods

2.1. Study Area

The study focuses on the area adjacent to Ahilyanagar City within Nagar Tahsil, located in the Ahilyanagar District of Maharashtra, India (Figure 1). Geographically, the tahsil is situated between 19°05' N to 19°15' N latitude and 74°30' E to 74°50' E longitude, encompassing an approximate area of 1,200 square kilometers, which constitutes about 5% of Ahilyanagar District's total landmass. The region is characteristic of the semi-arid zone of the Deccan Plateau, featuring an undulating terrain, naturally sparse vegetation, and a climate dominated by seasonal monsoonal rainfall. Despite the often-erratic nature of these rainfall events, their intensity significantly contributes to soil erosion, particularly gully formation. Historical and contemporary evidence suggest frequent soil erosion problems in the study area, largely attributable to a complex interplay of intense rainfall events, unplanned land use, localized deforestation, unsustainable agricultural practices, and various anthropogenic interventions. Nagar Tahsil comprises 108 villages and 6 towns as per the 2011 District Census Handbook, making it one of the more densely populated tahsils in Ahilyanagar District. Ahilyanagar City itself functions as both the district and Tahsil headquarters, facilitating critical governance and administrative coordination for the wider region. This geographical and administrative positioning renders Nagar Tahsil a significant nexus for agricultural, commercial, and administrative activities, thereby increasing its vulnerability to environmental changes such as gully erosion due to concentrated human footprint.

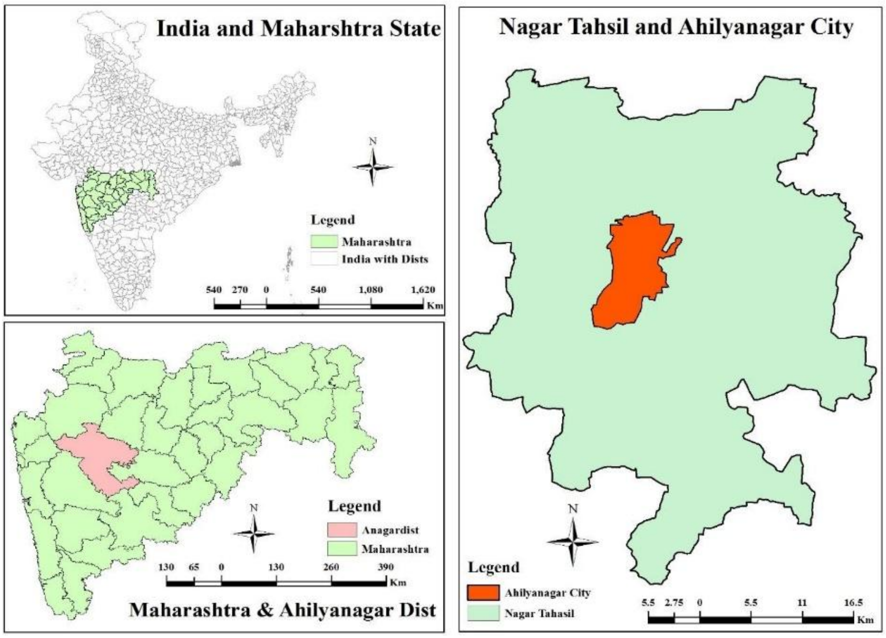


Figure 1. Location map of the study area in Nagar Tahsil, Maharashtra, India.

The selection of this study area is grounded in its dual significance: both environmental sensitivity and practical relevance. Its semi-arid climate, coupled with increasing anthropogenic pressures from urbanization and agricultural expansion, creates a highly dynamic environment for soil degradation. The application of contemporary geospatial analysis, particularly using high-resolution Earth Observation (EO) data and GEE, offers a unique opportunity for an accurate and comprehensive spatial assessment of gully-affected areas, providing valuable insights for local environmental monitoring and planning efforts.

2.2. Dataset and Methodology

This study adopts a multi-pronged data integration and analysis approach within the Google Earth Engine (GEE) cloud computing platform to comprehensively map and analyze gully erosion dynamics near Ahilyanagar. The methodology relies on robust remote sensing techniques combined with ancillary environmental datasets.

2.3. Datasets

The following datasets were systematically integrated within the GEE environment: a) High-Resolution Optical Imagery of Sentinel-2 collected by the Multi-Spectral Instrument (MSI) in the year 2023. Sentinel-2 has 13 spectral bands out of which B3 (Green), B4 (Red), and B8 (Near-Infrared (NIR)) bands have been used in present analysis which have spatial resolution of 10 m. These bands are particularly vital for to determine NDVI to use in distinguishing bare soil and exposed gully features from vegetated areas (Drusch et al., 2012). The Normalized Difference Vegetation Index (NDVI) is a crucial input for identifying gullies. It has been calculated from Sentinel-2 data using bands 8 (Near-Infrared) and 4 (Red). This index is a powerful tool in remote sensing for assessing vegetation cover and health. The Bare Soil Index (BSI) is calculated using four bands, i.e., B2, B4, B8, and B11 of Sentinel-2. It is incorporated to identify gullies in the area under investigation. b) The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) is a vital dataset for gully identification, as its 30-meter resolution enables the derivation of key terrain variables. By calculating slope, it pinpoints areas of steepness where water runoff has high erosive power. Aspect provides insight into moisture and radiation conditions that influence soil stability. Furthermore, hydrological indices like Flow Accumulation and Stream Power Index (SPI) reveal channels where water concentrates, marking high-risk zones for gully formation. Together, these derived variables from the SRTM DEM provide a comprehensive framework for mapping and understanding gully systems. CHIRPS precipitation data and Soil grids data are two key datasets for modeling gully erosion risk. CHIRPS provides high-resolution daily rainfall records, which are crucial for linking gully formation to specific, intense rainfall events. Simultaneously, SoilGrids offers detailed soil property information, including texture and erodibility (K-factor) (Funk et al., 2015; Hengl et al., 2017).

2.4. Methodology

The methodological workflow within GEE involved several integrated steps to achieve comprehensive gully erosion mapping and hotspot identification:

2.4.1. Cloud-Based Geospatial Analysis using Google Earth Engine (GEE)

The first phase of the methodology involves using the Google Earth Engine (GEE) platform and its JavaScript API to process and analyze geospatial data. The process begins by defining the region of interest (ROI) using the shapefile of the Nagar tehsil, sourced from the Survey of India (SOI) (Figure 2a,b). This ensures all subsequent analyses are confined to the study area. Next, two primary datasets are loaded: Sentinel-2 imagery for calculating the Normalized Difference Vegetation Index (NDVI), which is calculated using the formula that is (Band 8 - Band 4) / (Band 8 + Band 4).

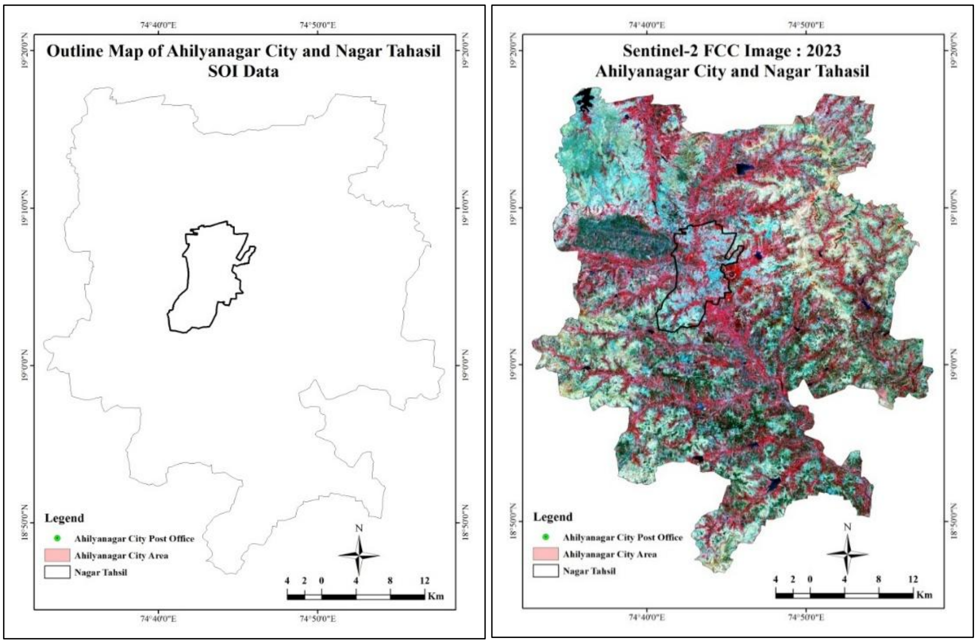
Higher NDVI values indicate healthier vegetation, which helps in identifying areas with less vegetation, often associated with gullies, to identify barren land, and the SRTM 30 DEM for deriving slope data (Figure 3a,b). The NDVI helps to pinpoint areas with little to no vegetation, which are often susceptible to erosion. Simultaneously, the slope data identifies steep terrain, a key factor in gully formation due to high runoff velocity. A critical step is to combine these two layers by creating a composite map that highlights areas that are both barren and steep, as these represent the highest potential for gully development. The final step in this phase is to visualize the results within the GEE code editor and export the final map of Gully Affected Areas as a JPEG file for further processing.

2.4.2. Geographic Information System (GIS) Mapping and Analysis

The second phase of the methodology shifts to GIS software, specifically ArcGIS, to refine and finalize the maps generated in GEE. The exported Gully Affected Areas map is imported into ArcGIS, where basic cartographic elements like a title, legend, scale bar, and north arrow are added to produce a publication-quality map. This stage also includes a quantitative analysis of the identified gullies. The raster calculator in ArcGIS is used to determine the total area under the gully-affected zones. To provide a more detailed and localized understanding of the impact, a village map is then overlaid on the gully-affected map. This overlay analysis allows for the identification of specific villages that are most affected by gully erosion.

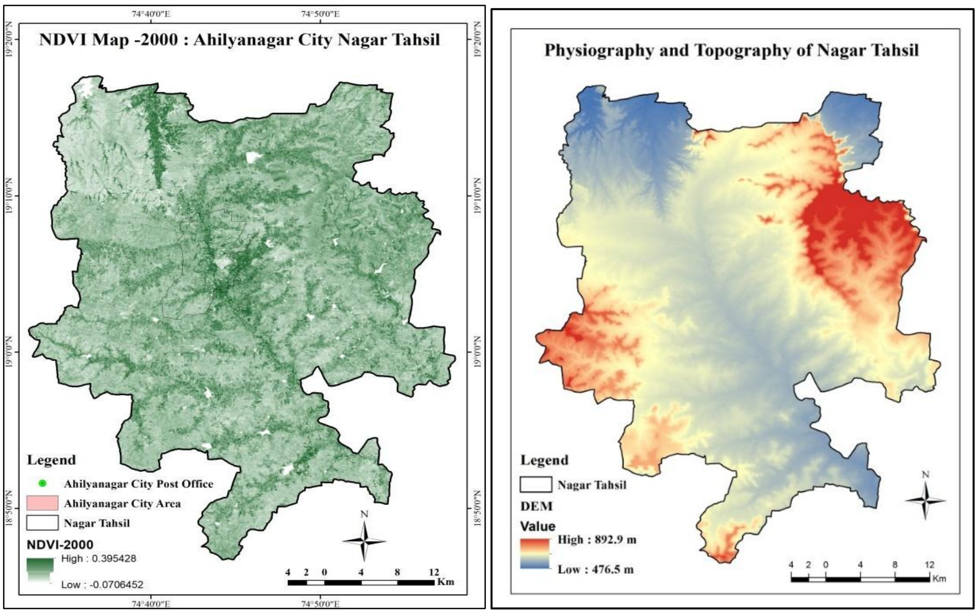
To analyze the spatial distribution of gully erosion, the delineated gully areas were first converted into a vector format for GIS analysis. A multiple-ring buffer analysis was then performed from the geographical center of Ahilyanagar City Post Office, using 5 km concentric rings extending outwards to 30 km. This helped to quantify the distribution of gullies relative to the urban core. Following this, gully erosion hotspots were identified based on areas of high gully density. Six distinct Gully Erosion Hot Spots (GEHS A-F) were delineated using this approach, with high-resolution Google Earth imagery used for visual validation.

To assess the impact on local communities, these hotspot polygons were overlaid with the village boundary map of Nagar Tahsil. A spatial join operation was performed to identify and quantify the villages intersecting with each hotspot, ultimately providing a clear picture of the villages most affected by gully erosion (Table 1). This integrated methodology, leveraging GEE's capabilities, ensures a detailed, multi-scale, and robust assessment of gully erosion dynamics in the study area. Finally, the affected areas per village are used to create an Excel spreadsheet. This data is then used to generate a bar graph that visually represents the gully hotspots, highlighting the most severely impacted villages within the study area.



(a) (b)

Figure 2. a) SOI outline map of the study area and b) Sentinel-2 satellite FCC image of Ahilyanagar City and Nagar Tahsil (2023).



(a) (b)

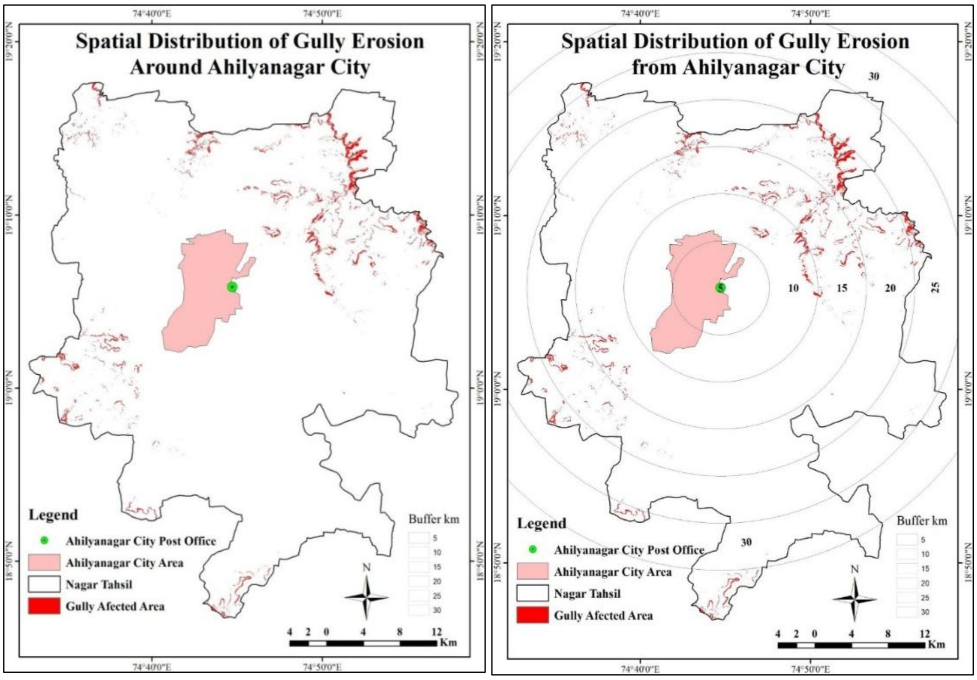
Figure 3. a) SRTM digital elevation model (DEM) - 30-meter resolution of Ahilyanagar City and b) NDVI Map of Nagar Tahsil (based on Sentinel-2 imagery).

3 Results and Discussion

3.1. Spatial Distribution of Gully Erosion

The comprehensive mapping of the spatial distribution of gully erosion within Nagar Tahsil, focusing on areas around Ahilyanagar City. As illustrated in Figure 4a, significant gully erosion (shown in red) is predominantly concentrated in the northern and southern extremities of the tahsil, with smaller, dispersed patches also visible towards the western boundary. The urban core of Ahilyanagar City, depicted in light pink, exhibits a remarkably low incidence of gully erosion, suggesting that built-up areas and possibly better land management practices within the city may act as deterrents to extensive gully formation. This initial mapping provides a clear visual overview of the spatial extent and intensity of land degradation across the study area. Further analysis involving a multi-ring buffer approach from the Ahilyanagar City Post Office, depicted in Figure 4b, quantitatively confirms these observations.

The concentric buffer rings, extending at 5 km intervals up to 30 km, distinctly show that the majority of severe gully erosion is located in the outer buffers. Specifically, a high concentration of gully features is observed between the 15 km and 25 km buffers in the northern region, and a substantial portion is also present beyond the 20 km buffer in the south.



(a) (b)

Figure 4. a) Spatial Distribution of gully buffer and b) spatial Distribution of gully and 5 km erosion around Ahilyanagar city.

In contrast, the areas surrounding the city center, within the 5 km and 10 km buffers, show minimal to no gully erosion. This spatial pattern strongly suggests that land degradation is more prevalent in the rural, outlying parts of the tahsil, where agricultural activities, natural terrain, and potentially less intensive land management interventions likely contribute to erosion vulnerability, as opposed to the more developed urban core.

3.2. Gully Erosion Hotspots

The analysis identified six distinct Gully Erosion Hot Spots (GEHS) within Nagar Tahsil, indicating areas of significantly concentrated land degradation (Figure 5).

These hotspots represent critical zones requiring prioritized intervention:

- **Hotspot 'C'**: Located in the north-eastern part of Tahsil, GEHS C is the most prominent and extensive area of gully erosion. It encompasses a vast, intricate network of gullies, indicating a high degree of long-term land degradation.

- **Hotspot 'A'**: Situated in the north-western region, GEHS A is another significant area of concern, characterized by a large cluster of gullies, suggesting considerable impact on the local landscape.
- **Hotspot 'F'**: Positioned in the western part of the tahsil, GEHS F represents a substantial area of gully erosion, though spatially smaller than GEHS C and A.
- **Hotspot 'E'**: Found in the southern part, GEHS E also signifies a notable concentration of gullies.
- **Hotspot 'B'**: A smaller yet distinct concentration of gullies, GEHS B is located immediately north of the Ahilyanagar City area.
- **Hotspot 'D'**: Representing a localized cluster of gullies, GEHS D is found in the south-eastern part of the map.

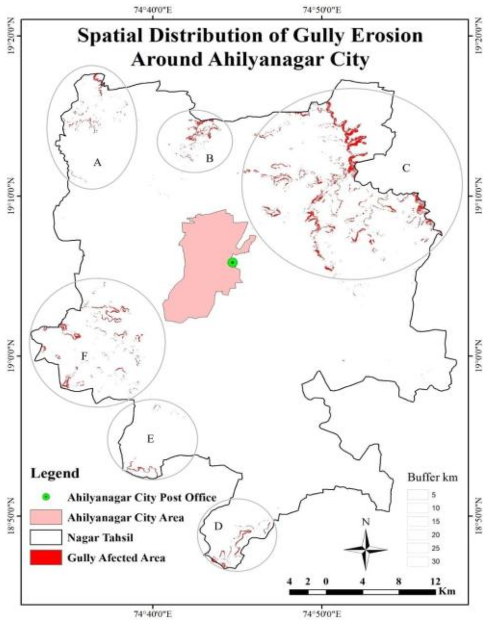


Figure 5. Gully erosion hot spots around Ahilyanagar City.

The persistent absence of gully erosion in the central urban area of Ahilyanagar City further reinforces the findings. The high concentration of gully erosion in the northern and western rural regions may be intrinsically linked to specific topographic characteristics, such as steeper slopes and more extensive drainage networks, or prevalent land use practices (e.g., rain-fed agriculture, limited terracing) that exacerbate erosion processes in those zones (Ganasri and Ramesh, 2016; Xu et al., 2025). The detailed visual inspection of these hotspots using high-resolution Google Earth imagery (Figure 6) strongly validates the presence and extent of these gully networks, confirming the accuracy of the GEE-based delineation.

3.3. Gully Erosion Hotspot and Affected Villages

The GEE-based analysis revealed that gully erosion poses a significant and widespread threat to villages within Nagar Tahsil surrounding Ahilyanagar City. The identification of six distinct Gully Erosion Hot Spots (GEHS A-F) and the quantification of affected villages, as detailed in Table 1 and visualized in Figure 7, highlight a clear spatial pattern of impact severity. GEHS C emerges as the most critical area, directly impacting 17 villages, which accounts for 42.5% of the total 40 confirmed affected villages. This significant concentration underscores a severe and localized erosion problem, likely driven by specific physiographic features (e.g., steep slopes, highly erodible black cotton soils, concentrated runoff pathways) and intense land use pressures characteristic of that region. GEHS F is the second most significant hotspot, affecting 9 villages (22.5%), representing another major area of concern requiring focused conservation interventions. GEHS A and B each affect 5 villages (12.5% each), indicating substantial but less extensive erosion problems compared to C and F. Lastly, GEHS D and GEHS E represent more localized erosion problems, affecting only 1 village (2.5%) and 3 villages (7.5%), respectively, though still critical for the specific communities involved. Overall, the findings demonstrate that gully erosion is a widespread environmental challenge, directly impacting 40 out of the 108 villages (approximately 37%) in Nagar Tahsil. This substantial proportion highlights gully erosion as a major environmental and socio-economic issue for the region surrounding Ahilyanagar city. The remaining 68 villages may either be unaffected by gully erosion or experience erosion below the detection/severity threshold employed in this study, which warrants further localized investigation (Figure 8).

Table 1. Gully erosion hotspots and number of affected villages in Nagar Tahsil

Gully Erosion Hot Spot (GEHS)	Number of Affected Villages	Percentage of Total Affected Villages (%)
A	5	12.5
B	5	12.5
C	17	42.5
D	1	2.5
E	3	7.5
F	9	22.5
Total villages affected in Nagar Tahsil	40	100

Total villages in Nagar Tahsil = 108.

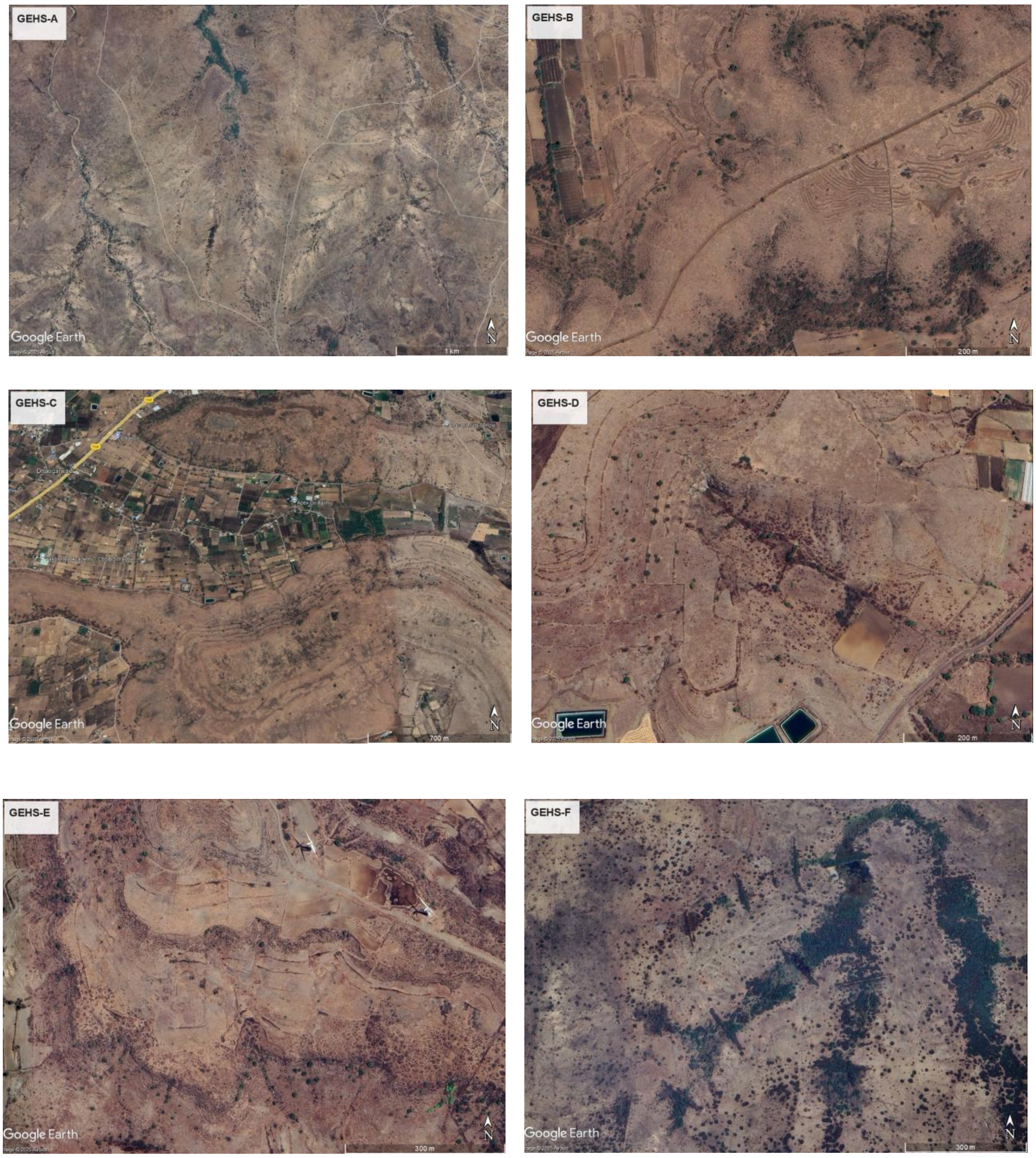


Figure 6. Google Earth images of gully erosion hot spots (GEHS-A to GEHS-F) identified in Nagar Tahsil.

3.4. Future Directions

The precise identification of affected villages and hotspots enables a strategic prioritization of conservation efforts, allowing for the allocation of resources to areas where they are most urgently needed. By offering an evidence-based understanding of the problem's spatial dynamics and drivers, this study empowers the development and implementation of effective mitigation and management strategies, contributing directly to sustainable land management, improved water security, and the long-term ecological and socio-economic resilience of the Ahilyanagar region. This aligns seamlessly with both India's commitment to Land Degradation Neutrality (LDN) and the broader objectives of the United Nations' Sustainable Development Goals (SDGs), particularly those related to land restoration and climate action. Based on the detailed analysis of gully erosion dynamics in Nagar Tahsil, a multi-tiered approach is recommended to effectively mitigate the problem. Immediate measures should include structural interventions like constructing check dams and gabions to slow water flow and implementing contour trenching and bunding to increase infiltration and reduce runoff (Sheng, 1990). Bioengineering solutions are also crucial, such as planting Vetiver grass for soil binding and using native shrubs and bamboo for stability on gully banks (Truong and Dao, 2008; Stokes and Greenwood, 2008). For long-term management, promoting sustainable farming practices like zero-tillage, crop rotation, and contour plowing is essential to reduce soil disturbance and vulnerability to erosion (Lal, 2015). These efforts should be part of an integrated watershed management plan with active community participation to ensure local ownership. On a policy level, Gully Erosion Risk Zoning maps derived from the geospatial analysis can be used to guide land use planning, while a GEE-based automated monitoring system can provide timely alerts for intervention (Belgiu and Drăguţ, 2016). Finally, further research is needed, including high-resolution UAV surveys for micro-topographic details, climate-resilient soil studies on Vertisols, and socio-economic impact assessments to inform future strategies and secure funding (Nex and Remondino, 2014). The success of these recommendations depends on strong inter-departmental collaboration to ensure coordinated implementation. These comprehensive recommendations, grounded in geospatial analysis, aim to provide a pragmatic and scientifically informed pathway toward effective gully erosion management and land restoration in the Ahilyanagar region.

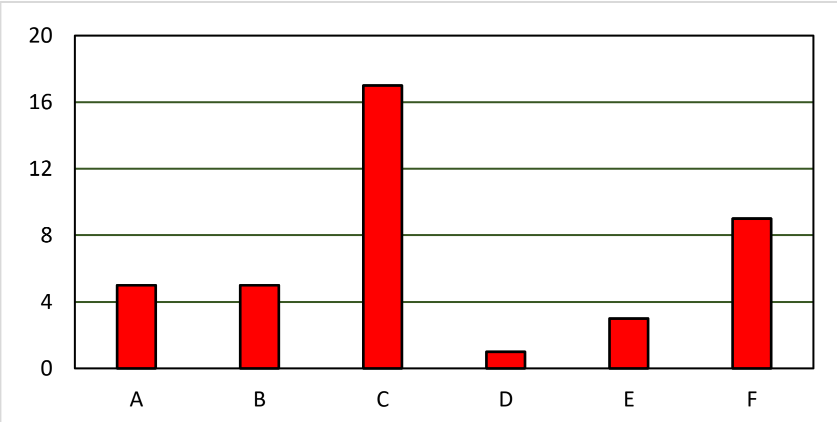
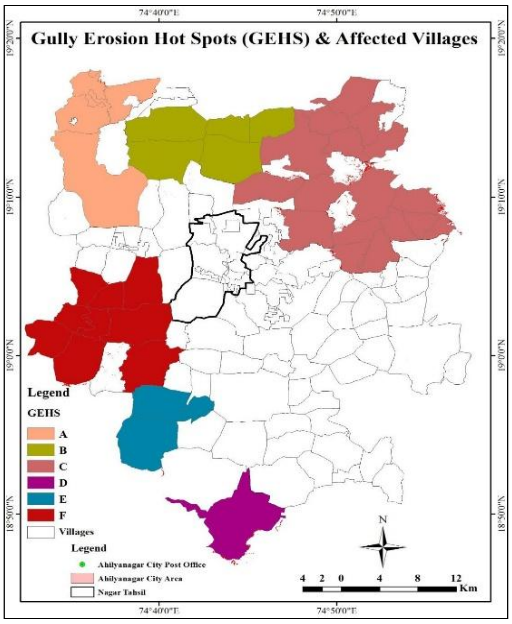


Figure 7. Spatial distribution of gully erosion hotspots (GEHS) and affected villages in Nagar Tahsil.

4. Conclusions

This study conclusively demonstrates that gully erosion in Nagar Tahsil, Ahilyanagar District, is a significant and escalating environmental challenge, driven by a complex interplay of natural geomorphic processes and human-induced land disturbances. Natural drivers, notably the intensity of monsoonal rainfall and the inherent erodibility of black cotton soil types, create a conducive environment for gully formation. However, anthropogenic activities, including rampant deforestation, the expansion of unsustainable agricultural practices, and unplanned land use changes, are identified as critical accelerators of gully initiation and expansion. The high-resolution spatial mapping and buffer analysis, effectively conducted using Google Earth Engine, provided unprecedented detail in identifying the distribution and severity of gully erosion. The pronounced spatial clustering of erosion hotspots, particularly in the northern and western rural areas of the tahsil, definitively highlights the imperative for targeted, localized interventions rather than broad, generalized approaches. Multi-temporal analysis using GEE confirms an increasing trend in erosion rates in unprotected or poorly managed areas over the past two decades. Conversely, areas where pre-existing conservation measures, such as check dams and afforestation programs, have been implemented demonstrate discernible signs of gully stabilization and reduced erosion. The findings of this research provide a crucial, data-driven guide for local policymakers, agricultural departments, and community stakeholders.



Class	Color	Location Description
A	Orange	Northwest region
B	Peach	Western region
C	Olive Green	Central-north region
D	Red	Southwest region
E	Teal Blue	South-central region
F	Magenta	Southernmost and southeastern region

Figure 8. Spatial distribution of gully erosion hotspots (GEHS) and affected villages in Nagar Tahsil.

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Institutional/Ethical Approval: Not applicable.

Data Availability/Sharing: The datasets used and analyzed during the current study will be made available from the corresponding author upon a reasonable request.

Supplementary Information Availability: Not applicable.

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