GIS-DRIVEN PRIORITIZATION OF AFFORESTATION SITES USING MULTI-CRITERIA DECISION ANALYSIS

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Abstract.

Afforestation and ecological restoration in arid and semi-arid regions present complex multi-faceted challenges, demanding precise spatial targeting to optimize resource allocation, maximize ecological resilience, and ensure high sapling survival rates. Traditional afforestation initiatives frequently suffer from a lack of integrated spatial evaluation, failing to harmonize ecological requirements with pressing socio-economic drivers. This paper presents a systematic research and review framework for GIS-driven afforestation site prioritization utilizing Multi-Criteria Decision Analysis (MCDA), with specific focus on the Analytical Hierarchy Process (AHP) and Fuzzy AHP methodologies. Drawing upon comprehensive empirical data and technical progress from consultancy operations conducted for Geo Planet Solution Pvt. Ltd., this study synthesizes spatial criteria across environmental, hydrological, and socio-economic dimensions. Key methodological phases-including multi-source data standardization, variable normalization, criteria weighting, and spatial overlay modelling-are evaluated. The findings demonstrate that integrating Fuzzy AHP into GIS workflows successfully mitigates boundary ambiguity, resolves scale mismatches across heterogeneous datasets, and yields robust, operational suitability maps for arid zone management.

Keywords: Afforestation, Arid and semi-arid ecosystems, Fuzzy AHP, GIS-based multi-criteria decision analysis, Site suitability mapping, Spatial prioritization

1. INTRODUCTION

Megacities, as defined by the United Nations, are urban areas with populations exceeding 10 million and face significant environmental challenges due to rapid urbanization and climate change [1]. Land degradation, desertification, and climate change pose severe threats to ecological stability, food security, and socio-economic sustainability globally. Coastal megacities, in particular, are vulnerable due to their geographic locations, which expose them to

risks such as storm surges, sea-level rise, tidal flooding, saltwater intrusion into aquifers, and accelerated coastal erosion [2]. GIS-driven afforestation Site Prioritization has been shown in Figure 1.

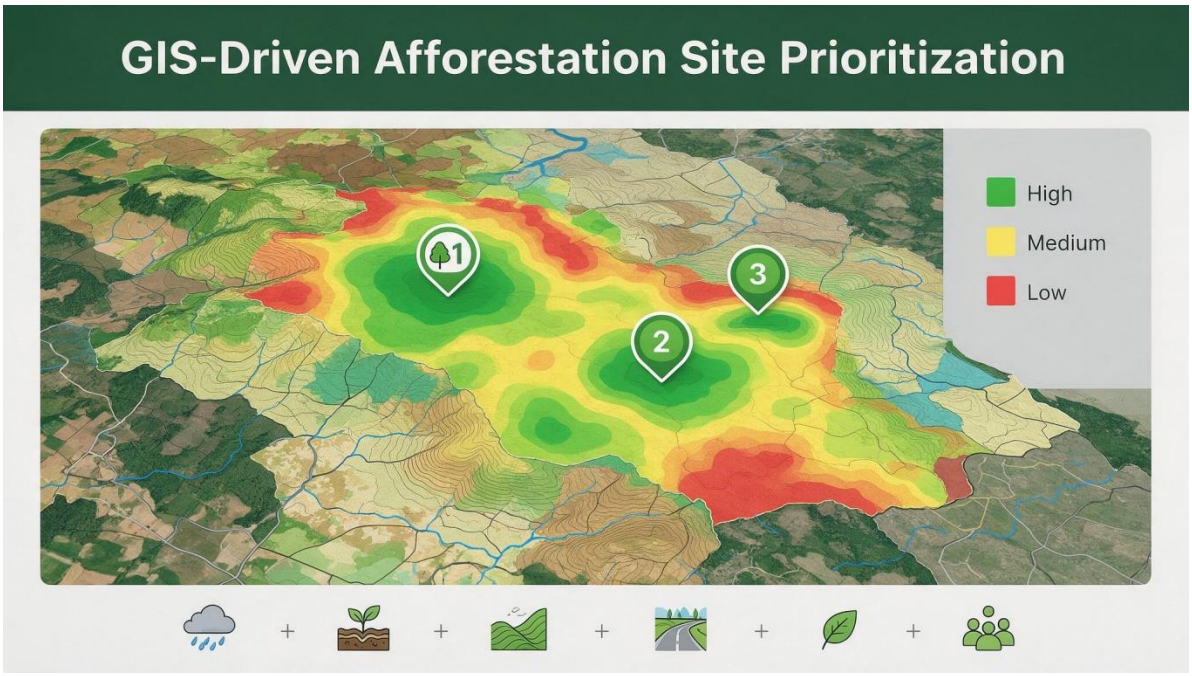


Figure 1: GIS-driven afforestation Site Prioritization

Arid and semi-arid regions, such as Rajasthan in western India, are particularly vulnerable due to extreme temperature fluctuations, scarce precipitation, poor soil moisture retention, and escalating anthropogenic pressures. In response to these environmental stressors, afforestation and Urban Green Infrastructure (UGI) development have emerged as vital nature-based solutions to sequester carbon, mitigate urban heat island effects, restore degraded watersheds, and support biodiversity. There is a notable global concentration of megacities along coastal zones, especially in South Asia [3]. However, executing successful afforestation campaigns in water-stressed landscapes requires far more than mere tree planting. These cities serve as vital centers for industrial and economic activities, benefiting developing nations through enhanced port facilities, trade connections, and infrastructure networks [4]. Historical afforestation failure rates in arid ecosystems frequently stem from poor site selection, where environmental constraints or socio-economic realities were insufficiently evaluated prior to implementation. Despite the socio-economic opportunities that attract more residents to these densely populated areas, the

rapid growth exacerbates their vulnerability to both man-made and climate-related environmental risks [5].

To overcome these operational challenges, the integration of Geographic Information Systems (GIS), Remote Sensing (RS), and Multi-Criteria Decision Analysis (MCDA) offers a scientifically rigorous decision-support platform. By combining spatial raster datasets with mathematical decision models like the Analytical Hierarchy Process (AHP) and Fuzzy AHP, decision-makers can systematically evaluate complex, competing spatial variables.

2. LITERATURE REVIEW & CRITERIA IDENTIFICATION

Recent scholarship across geospatial science, ecological restoration, and environmental management highlights a paradigm shift toward data-driven, multi-criteria spatial modeling for reforestation and green infrastructure planning.

Geospatial Models & Reforestation: Studies utilizing QGIS and MCDA frameworks (such as the Tree-covery model) demonstrate that combining soil moisture, topography, land cover, and water proximity yields highly precise reforestation suitability indices in peri-urban environments, directly contributing to UN Sustainable Development Goals (SDG 13: Climate Action and SDG 15: Life on Land) [6].

Remote Sensing & Mine Rehabilitation: Unmanned Aerial Vehicle (UAV) photogrammetry combined with terrain mapping has proven highly effective in land reclamation, achieving up to 75% tree survival rates through precise micro-topographic and pedoclimatic suitability assessment [7].

Satellite Imagery & LULC Dynamics: Machine learning classifiers (e.g., Random Forest and Support Vector Machines) applied to high-resolution Sentinel-2 and Landsat imagery show that accurate Land Use/Land Cover (LULC) classification is crucial for understanding runoff dynamics and watershed health in arid zones [8].

Land Degradation Neutrality (LDN): Global frameworks introduced under UN SDG 15.3 emphasize that halting land degradation demands inclusive, gender-responsive, and spatially targeted ecosystem restoration that aligns ecological conservation with human livelihoods [9].

Urban Green Infrastructure (UGI): Studies focused on semi-arid urban corridors (such as Jaipur) reveal significant green cover loss, where entropy-weighted MCDA models incorporating Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) identified high-priority zones along river basins and peri-urban fringes [10].

Afforestation Potential & Carbon Sequestration: Regional geospatial evaluations in Rajasthan indicate that up to 40% of land area possesses afforestation potential (sequestrating 2-8 tons

CO2/ha/year), recommending drought-tolerant species like Neem and Khejri for short-term resilience and Amla and Ber for long-term ecological balance.

2.1 Structured Criteria Hierarchy

Based on extensive literature synthesis and consultancy requirements, a 3-level hierarchical decision model was formulated to evaluate site suitability:

Criteria	**Sub-Criteria / Parameters**	**Ecological & Operational Relevance**
Environmental Criteria	❖ Soil Type & Texture ❖ Land Use / Land Cover (LULC) ❖ Slope & Elevation	Determines physical soil fertility, root penetration, topographic stability, and natural water availability.
Hydrological Criteria	❖ Groundwater Depth ❖ Base Flow Index / Runoff ❖ Flood & Drought Risk	Evaluates subterranean moisture availability, soil erosion susceptibility, and climate extreme vulnerabilities.
Socio-Economic Criteria	❖ Population Density ❖ Land Acquisition Cost ❖ Proximity to Roads/Settlements ❖ Government Policy Incentives	Assesses community accessibility, economic feasibility, protection from grazing/encroachment, and policy alignment.

3. METHODOLOGY & ANALYTICAL FRAMEWORK

The operational workflow transitions raw geospatial datasets into an actionable suitability model through five systematic phases:

Step 1: Data Acquisition & Preprocessing

Multi-source spatial and non-spatial data are harvested from open-source satellite platforms (Landsat 8/9, Sentinel-2), Digital Elevation Models (SRTM DEM), rainfall grids (CHIRPS), and local socio-economic census datasets. All layers are projected to a unified Coordinate Reference System (UTM Zone 43N / WGS84).

Step 2: Spatial Resolution Harmonization & Normalization

A critical technical challenge encountered during Phase 2 of the consultancy involved resolution mismatches (e.g., 10m Sentinel-2 imagery vs. 30m DEM vs. coarse administrative boundary vector data).

Datasets were resampled to a consistent 30m pixel grid using bilinear interpolation for continuous raster variables and nearest-neighbor resampling for categorical LULC classes. Subsequently, variables were normalized to a uniform scale (0.0 to 1.0 or 1 to 9) using linear membership functions to eliminate dimensionality bias.

Step 3: AHP and Fuzzy AHP Weighting Framework

To assign mathematical weights to each criterion, Saaty's Analytical Hierarchy Process (AHP) was implemented. Pairwise comparison matrices ($A = [a_{ij}]$) were constructed based on expert opinions and literature synthesis:

CR = (CI / RI) < 0.10, where CI = (λ_max- n) / (n - 1)

To resolve boundary fuzziness inherent in ecological transition zones, Fuzzy AHP was integrated. Triangular Fuzzy Numbers (TFNs) were utilized to model expert subjectivity, converting linguistic terms into fuzzy membership values ñ = (l, m, u), thereby stabilizing criteria weights against uncertainty.

4. RESULTS & CONSULTANCY OUTCOMES

The application of the integrated GIS-MCDA framework yielded major research and operational milestones across the reporting period:

Operational Criteria Matrix: Successfully established a fully validated decision hierarchy tailored for semi-arid land conditions, balancing ecological imperatives with economic constraints.

Harmonized Spatial Database: Created a multi-layered geospatial database standardizing 11 spatial parameters across soil, slope, hydrology, and accessibility.

Fuzzy AHP Weight Distribution: Determined relative global weights, indicating that Hydrological Factors (0.42) and Environmental Factors (0.38) hold higher initial weightings for seedling survival, while Socio-Economic Factors (0.20) act as critical spatial qualifiers for long-term project protection.

Suitability Zoning Map: Generated high-resolution spatial outputs categorizing target landscapes into High Priority (suitable for immediate plantation), Moderate Priority (requiring soil amendments/irrigation support), and Low Priority / Excluded zones.

5. CHALLENGES & MITIGATION STRATEGIES

During project execution, main technical bottlenecks were identified and systematically resolved as inconsistencies in grid resolution and vector scale formats across regional maps were mitigated by establishing standardized geospatial resampling scripts within Google Earth Engine.Sharp boundary thresholds in traditional boolean GIS overlays caused artificial land misclassifications. Implementing Fuzzy Gaussian and Linear membership functions created smooth transitions, accurately reflecting natural ecological gradients.

6. CONCLUSION & RECOMMENDATIONS

This research demonstrates that integrating Geographic Information Systems (GIS) with Fuzzy Multi-Criteria Decision Analysis (Fuzzy AHP) provides a robust, scalable, and highly accurate framework for prioritizing afforestation sites in arid and semi-arid environments. By transitioning from subjective field estimation to empirical geospatial modeling, the framework optimizes financial resource deployment, enhances plantation survival rates, and supports global ecological mandates including UN SDGs 11, 13, and 15.

Future iterations should combine Random Forest (RF) and Artificial Neural Networks (ANN) with Fuzzy AHP to dynamic predict sapling mortality based on real-time climate inputs. Integrating drone-based multispectral imaging for post-plantation monitoring will enable micro-scale verification of soil health and canopy recovery. Afforestation planning must continuously integrate participatory GIS (PGIS) to align technical site maps with local community needs and village-level governance.

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REFERENCES

1. Mumtaz, M., Jahanzaib, S. H., Hussain, W., Khan, S., Youssef, Y. M., Qaysi, S., ... & Abd-Elmaboud, M. E. (2025). Synergy of remote sensing and geospatial technologies to advance sustainable development goals for future coastal urbanization and environmental challenges in a riverine megacity. ISPRS International Journal of Geo-Information, 14(1), 30.

2. Arefin, R.; Rahman, A.T.M.S.; Das, J.; Jahan, C.S.; Mazumder, Q.H.; Gomaa, E.; Abd El Aal, A.K.; Radwan, A.E.; Youssef, Y.M. Megacity solid waste disposal suitability mapping in Dhaka, Bangladesh: An integrated approach using remote sensing, GIS and statistics. Environ. Monit. Assess.2024, 196, 910.

3. Abdo, H.G.; Darwish, K.S.; Bindajam, A.A.; Niknam, A.; Youssef, Y.M.; Ahmed, M.F.M.; Mallick, J. Detection of flood vulnerable areas in urban basins using multi-criteria analysis and geospatial tools: A case study from eastern Mediterranean. Environ. Earth Sci.2024, 83, 524.

4. Arafa, N.A.; El-Said Salem, Z.; Abdeldayem, A.L.; Ghorab, M.A.; Moustafa, Y.M.; Soliman, S.A.; Farag, M.H.; Purohit, S.; Elhag, M.; Youssef, Y.M. Advancing Deltaic Aquifer Vulnerability Mapping to Seawater Intrusion and Human Impacts in Eastern Nile Delta: Insights from Machine Learning and Hydrochemical Perspective. Earth Syst. Environ.2024, 1–26.

5. Salem, Z.E.-S.; Arafa, N.A.; Abdeldayem, A.L.; Youssef, Y.M. Machine Learning-Enhanced GALDIT Modeling for The Nile Delta Aquifer Vulnerability Assessment in the Mediterranean Region. Groundw. Sustain. Dev.2025, 28, 101403.

6. Popescu, C., et al. (2024). Utilizing UAV technology and GIS analysis for ecological restoration: A case study on Robinia pseudoacacia L. in a mine waste dump landscape rehabilitation. NotulaeBotanicae Horti Agrobotanici Cluj-Napoca.

7. Ibrahim, A., et al. (2026). Impact of LULC Classification Methods on Runoff Simulation in an Arid Mountainous Watershed Using Remote Sensing and Machine Learning. Remote Sensing / MDPI, 7(1), 26.

8. Singh, S. K., et al. (2025). Urban Green Infrastructure Planning in Jaipur, India: A GIS-Based Suitability Model for Semi-Arid Cities. Sustainability, 17(6), 2420.

9. UNCCD (2021). Land Degradation Neutrality: Scientific Conceptual Framework and Technical Guidance. United Nations Convention to Combat Desertification, Bonn.

10. Optimizing land use for climate mitigation using nature-based solution (NBS) strategy: A study on afforestation potential and carbon sequestration in Rajasthan, India.