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GIS and Remote Sensing-Based Site Suitability Analysis for Wastewater Treatment Plants in Urban Regions

Jhumpa Lahiri

Saiva Bhanu Kshatriya College, Aruppukottai, India

ABSTRACT: Site selection for urban wastewater treatment plants (WWTPs) is a critical planning task, balancing environmental protection, public health, infrastructural feasibility, and cost constraints. Geographic Information Systems (GIS) combined with Remote Sensing (RS) offer powerful tools for multi-criteria site suitability analysis. This paper reviews pre-2017 studies where GIS and RS have been applied for WWTP site selection in urban contexts. Case studies from Omdurman (Sudan), Muscat (Oman), Shollinganallur (India), Debre Berhan (Ethiopia), and general methodologies highlight workflows using multi-criteria decision analysis, weighted overlay, AHP (Analytic Hierarchy Process), and fuzzy logic integrated within GIS. These studies combine layers such as slope, elevation, land use, proximity to roads and water bodies, soil type, groundwater depth, and land cover to generate suitability maps. Remote sensing data (e.g., DEMs, land cover imagery) support spatially accurate layer creation. The proposed general methodology features spatial data collection, criterion standardization, weight assignment via AHP, raster overlay analysis, and constraint masking. Key findings include enhanced precision in identifying optimal sites, improved environmental safeguards, and stakeholder-supported transparency. Benefits include spatially explicit decision support, replicability, and integration of physical and technical factors. Drawbacks involve data availability issues, subjective weight assignments, and limitations in spatial resolution. This synthesis provides a structured workflow and policy insights for planners aiming to deploy GIS/RS-based site selection systems for urban WWTP planning.

KEYWORDS: GIS site suitability, remote sensing, wastewater treatment plant, urban planning, multi-criteria analysis, AHP, suitability mapping.

I. INTRODUCTION

Urban wastewater treatment is essential for sustainable urban growth, especially in developing regions facing infrastructure constraints and environmental stress. Locating appropriate WWTP sites involves navigating complex spatial, environmental, technical, and regulatory landscapes. Traditional siting methods often lack spatial precision and transparency, leading to suboptimal outcomes.GIS and Remote Sensing (RS) enable planners to integrate and analyze multiple geospatial criteria—such as land use, hydrology, terrain, soil, proximity to roads and water bodies, groundwater depth, environmental sensitivity, and socio-economic factors. Layered overlay techniques facilitate objective suitability modeling, while RS—such as multispectral satellite imagery and DEMs—provides data for land cover, topography, and hydrological mapping.Pre-2017 applications exemplify these capabilities. For instance, the Omdurman, Sudan study deployed RS/DEM and land cover layers alongside AHP to rank candidate WWTP sites. Muscat, Oman used AHP and weighted overlays in GIS to assess land-use, environmental, economic, and technical criteria. Additional cases in India and Ethiopia applied similar approaches to generate suitability indices. Fuzzy logic-enhanced tools and spatial decision support systems (SDSS) have also been proposed to handle uncertainty and decision-maker preferences.This paper synthesizes these studies to propose a robust, replicable methodology for GIS/RS-based WWTP site suitability analysis in urban areas. It aims to bridge technical rigor with practical planning needs, enabling data-informed decision-making grounded in spatial analysis and stakeholder engagement.

II. LITERATURE REVIEW

Several pre-2017 studies demonstrate the application of GIS and RS in WWTP site selection:

1. **Omdurman, Sudan**
2. Abdalla & El Khidir (2017) used multispectral RS imagery, DEM, land use/cover layers, and GIS to model suitability for WWTP sites. They applied AHP to weight criteria, identifying three high-suitability areas ranked by composite scores. repository.neelain.edu.sd.

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3. **Muscat, Oman**
4. AHP-based multi-criteria decision-making (MCDM) was used within GIS to rank suitability across social, economic, environmental, and technical dimensions, leveraging weighted overlay analysis. MDPI.
5. **Shollinganallur, India**
6. A GIS-based overlay approach was used to select appropriate WWTP technology types and potential sites, considering land use, hydrogeology, and environmental pollution metrics. IJser.
7. **Debre Berhan, Ethiopia**
8. Spatial analysis combined factors like slope, elevation, soil, groundwater, roads, water bodies, and land use—using weighted overlay suitability mapping—to identify highly suitable WWTP locations. Science and Education PublishingSciepub.
9. **SDSS with Fuzzy Logic**
10. A fuzzy logic–MCDM spatial decision support tool integrated ArcView GIS, MATLAB, and Excel to accommodate inspector risk attitudes and uncertainty in site suitability modeling for new urban developments. Taylor & Francis Online.
11. **General RS-GIS Insights**
12. The integration of RS with GIS supports hydrological characterization: slope, elevation, drainage, and land cover are essential for assessing wastewater site suitability. Wikipedia.

Taken together, these works underscore the efficacy of GIS/RS and MCDM/AHP techniques in spatially driven WWTP site suitability studies in urban contexts.

III. RESEARCH METHODOLOGY

1. **Data Collection**
   - RS data: multispectral satellite imagery, DEMs for elevation/slope.
   - GIS layers: land use/cover, roads, water bodies, soil types, groundwater wells.
2. **Criteria Selection and Standardization**
3. Define restrictive (no-go) factors—e.g., protected areas, steep slopes—and selective factors such as proximity to water bodies, roads, terrain, groundwater vulnerability.
4. **Weight Assignment via AHP**
5. Conduct expert pairwise comparisons to determine criterion importance and generate normalized weights. MDPI+1repository.neelain.edu.sdTaylor & Francis Online.
6. **GIS Weighted Overlay Modeling**
7. Reclassify raster layers to comparable scales and perform weighted overlay to generate composite suitability maps. MDPIIISTEScience and Education Publishing.
8. **Constraint Masking**
9. Apply exclusion masks to remove unsuitable areas (e.g., steep terrain, protected zones). MDPITaylor & Francis Online.
10. **Fuzzy Logic Integration (Optional)**
11. Incorporate fuzzy membership functions to handle criterion uncertainty and nuance in suitability thresholds. Taylor & Francis Online.
12. **Site Ranking and Selection**
13. Identify high, moderate, and low suitability zones; extract and rank candidate sites for further evaluation.
14. **Validation and Sensitivity Analysis**
15. Use field verification, scenario testing, or sensitivity analysis to test robustness of weights and criteria.

IV. KEY FINDINGS

- **RS-Derived Terrain Attributes are Crucial**
- DEM-based slope and elevation layers are foundational in identifying flat, constructible areas. repository.neelain.edu.sdScience and Education PublishingIWA Publishing.
- **Proximity Factors Influence Cost and Impact**
- Distance to water bodies, roads, and built-up zones are standard determinants to balance accessibility, environmental risk, and construction feasibility. IISTEIWA Publishing.
- **AHP Enhances Decision Transparency**

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- Weighted analyses via AHP translate expert judgment into quantifiable weights, enabling structured decision-making. MDPI+1repository.neelain.edu.sd.
- **GIS Overlay Delivers Visual and Analytical Utility**
- Composite maps clearly demarcate suitability classes, facilitating stakeholder communication. IISTEScience and Education Publishing.
- **Fuzzy Logic Manages Uncertainty**
- SDSS integrating fuzzy logic enables handling of ambiguity in parameter thresholds, enriching decision resilience. Taylor & Francis Online.
- **RS+GIS Methods are Transferable**
- The workflow has been successfully adapted in diverse urban contexts—Sudan, Oman, India, Ethiopia—demonstrating methodological adaptability. repository.neelain.edu.sdIISTEIJser.

V. WORKFLOW

1. **Define Objectives and Study Area**
2. Outline goals (e.g., environmental protection, cost-efficiency) and set city boundary.
3. **Collect and Prepare Data**
4. Acquire RS imagery and GIS datasets; harmonize projections and preprocess.
5. **Define Criteria**
6. Identify constraints (protected zones, flood zones) and suitability parameters (slope, proximity to infrastructure, groundwater risk).
7. **Build AHP Framework**
8. Use expert surveys to conduct pairwise comparisons and compute normalized weights.
9. **Create Criterion Maps**
10. Reclassify spatial layers into suitability scores (e.g., 1–5 scale).
11. **Perform Weighted Overlay**
12. Combine layers in GIS to generate composite suitability map.
13. **Apply Masking**
14. Exclude restricted areas from analysis.
15. **Generate Final Suitability Map**
16. Classify into suitability classes: high, moderate, low.
17. **Extract Candidate Site Polygons**
18. Identify and rank top-suitability parcels.
19. **Validate and Refine**
20. Cross-check with site realities, conduct sensitivity checks.
21. **Document and Recommend**
22. Present maps, site recommendations, and policy guidance.

VI. ADVANTAGES & DISADVANTAGES

Advantages
- Spatially explicit decision-making enhancing transparency.
- Scalable and replicable across different urban contexts.
- Facilitates integration of multiple technical, environmental, and social factors.
- Visual output aids stakeholder buy-in and planning rationales.

Disadvantages
- Quality depends on data accuracy; resource-constrained cities may lack data.
- AHP weighting introduces subjectivity; inconsistency affects outcomes.
- Spatial resolution limits may obscure micro-variations.
- RS imagery may not capture dynamic factors like odor plumes or effluent dispersion.

VII. RESULTS AND DISCUSSION

Combined analysis confirms that GIS and RS-based methodologies enable rational, transparent WWTP site selection. For example, Omdurman's analysis pinpointed three optimal zones; Muscat's model integrated technical and socio-

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economic factors for robust planning. Indian and Ethiopian applications indicate that even peri-urban and mid-size cities benefit from data-driven site suitability mapping.

Challenges include selecting appropriate criterion thresholds and ensuring stakeholder consensus on weight assignments. Addressing these requires participatory planning, multi-sectoral collaboration, and sensitivity analyses to test assumptions. Additionally, integration with WBGT zoning, hydrological modeling, and future urban growth scenarios can extend the utility of these models.

Nevertheless, the core GIS/RS-AHP workflow provides a solid foundation for evidence-based urban infrastructure planning, improving alignment between technical feasibility, environmental safety, and institutional planning.

VIII. CONCLUSION

GIS and Remote Sensing, combined with multi-criteria decision-making tools such as AHP and fuzzy logic, provide powerful frameworks for urban WWTP site suitability analysis. Pre-2017 case studies establish that careful layering of environmental, infrastructural, and technical criteria leads to objective, spatially informed decision outputs.

The generalized methodology—mobilizing RS/DEM data, GIS overlays, AHP weighting, and constraint masking—can be applied across diverse urban contexts to enhance planning robustness. Limitations remain in data availability, subjectivity, and resolution; yet participatory approaches and sensitivity testing mitigate these concerns.

Ultimately, adopting geospatial decision support systems for WWTP siting elevates planning from heuristic to evidence-driven, aiding municipalities in achieving sustainable infrastructure deployment.

IX. FUTURE WORK

- **Incorporate Temporal Remote Sensing**
- Use multi-temporal RS to detect urban expansion, hydrological changes, and evolving land use.
- **Integrate Hydrodynamic and Flood Modeling**
- Combine GIS with hydraulic simulation to ensure WWTP resilience to flooding and climate variability.
- **Advance Stakeholder Engagement Tools**
- Develop participatory GIS (PGIS) platforms for real-time community feedback on site preferences.
- **Leverage High-Resolution Data**
- Incorporate LiDAR and high-res satellite data to refine micro-site suitability.
- **Automate Workflow via Open-Source Tools**
- Utilize PyLUSAT or QGIS models for reproducible, efficient analysis.
- **Expand to Combined Stormwater and Wastewater Design**
- Apply guidelines from Water-Sensitive Urban Design (WSUD) to create integrated wastewater management.

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