

## GIS-BASED LANDFILL SITE SUITABILITY ANALYSIS USING MULTI-CRITERIA WEIGHTED OVERLAY IN SUNGAI PENUH CITY

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### ABSTRACT

Rapid increase in solid waste generation has created significant challenges for environmentally safe landfill planning in many Indonesian cities. Kota Sungai Penuh faces particularly strong constraints due to limited land availability, concentrated settlement patterns, steep terrain, and high hydrological sensitivity. This study evaluates landfill suitability by integrating fifteen environmental and social criteria through the Analytic Hierarchy Process combined with Weighted Overlay Analysis in a geographic information system (GIS) environment. The criteria include terrain conditions, climatic and hydrological variables, land surface characteristics, accessibility, and population related factors. AHP was used to assign weight values and ensure consistency of the pairwise comparison matrix, and all criteria were standardized for weighted spatial integration. The results show four suitability classes, namely Suitable, Moderately suitable, Unsuitable, and Very unsuitable, with no areas categorized as Very suitable. Suitable locations appear only as small and isolated patches on transitional foothill areas, while most of the central basin is unsuitable due to intensive human activity, river proximity, and agricultural land use. Very unsuitable areas dominate the steep mountain slopes surrounding the valley. The findings demonstrate that landfill development in Kota Sungai Penuh is strongly limited by the interaction of terrain, hydrology, climate, and land use factors. The study provides a reproducible spatial framework for supporting informed waste management decisions and can guide planning in other environmentally sensitive regions with similar physical constraints.

**Keywords:** Landfill Site; AHP; Weighted Overlay; Multi-criteria; Waste Management; Sungai Penuh City

### INTRODUCTION

Municipal solid waste generation has increased sharply in recent decades as a direct consequence of rapid urbanization, population growth, and changing consumption patterns. This trend has created substantial environmental and public health challenges at the global scale. According to the World Bank, global waste production is projected to reach 3.40 billion tons per year by 2050, which is nearly double the volume recorded in 2016, and the fastest growth is occurring in low- and middle-income countries (Kaza et al., 2018). In many of these regions, limited waste handling infrastructure and continued dependence on uncontrolled dumping intensify groundwater contamination, air pollution, disease transmission, and ecological degradation (Guerrero et al., 2013; Ferronato and Torretta, 2019). Therefore, the identification of environmentally safe and socially acceptable landfill locations has become an essential component of sustainable solid waste management systems.

The selection of landfill sites is a complex decision that requires careful consideration of environmental, hydrological, topographical, socio economic, and infrastructural constraints (Kontos et al., 2005; Gorsevski et al., 2012). Landfills that are not properly located can generate leachate, degrade the quality of surface and groundwater, produce methane emissions, alter landscapes, and decrease surrounding land values (El Fadel et al., 1997; Abdel-Shafy, 2024). Numerous epidemiological studies have documented elevated risks of respiratory illnesses, cancers, reproductive disorders, congenital anomalies, and vector borne diseases among communities located near inadequately managed disposal facilities (Vrijheid, 2000; Porta et al., 2009). For these reasons, the selection of suitable landfill locations is necessary to ensure operational efficiency and to safeguard both environmental conditions and public health.

Geographic Information Systems (GIS) have become essential analytical tools for identifying potential landfill sites through the integration of

multiple spatial datasets. GIS supports the combination of hydrological, geological, topographical, demographic, and infrastructural information to produce transparent and reproducible spatial suitability maps (Sumathi et al., 2008; Malczewski, 2006). Multi criteria decision analysis frameworks such as the Analytic Hierarchy Process, fuzzy AHP, TOPSIS, and Weighted Linear Combination have been widely applied in landfill siting studies (Ali and Ahmad, 2020; Karimi et al., 2019; Beskese et al., 2015). Weighted Overlay Analysis is frequently selected because it is conceptually simple, straightforward to interpret, and compatible with raster-based GIS workflows once all criteria are normalized to a common suitability scale (Kontos et al., 2005; Gorsevski et al., 2012). Weighted Overlay Analysis has also demonstrated strong performance in environmental suitability modeling, including groundwater vulnerability mapping, flood hazard assessment, and waste management planning (Alharbi, 2024; Shrestha et al., 2017, Roy et al, 2022).

Although GIS based landfill siting is well established at the global level, many medium sized cities in Indonesia still lack comprehensive spatial assessments. Kota Sungai Penuh in Jambi Province is an example of a city experiencing significant pressure. The city covers approximately 366 square kilometers of mountainous terrain and had an estimated population of 102,000 residents in 2024 (BPS Kota Sungai Penuh, 2024). Recent assessments reported household waste generation of 0.328 kilograms per person per day, equivalent to approximately 31,938 tons per year, and the waste stream is dominated by food waste with a proportion greater than 57 percent, which increases the potential for high leachate production and greenhouse gas emissions when disposal facilities are inadequate (Rahmadhani et al., 2024). Waste handling infrastructure in the city remains limited. Sixteen TPS 3R facilities are available, but only three facilities operate at a medium performance level, and the remaining facilities are categorized as less or very low performance (Rahmadhani et al., 2024). The city also does not possess an engineered sanitary landfill and depends on a temporary disposal site covering 1.6 hectares in Renah Padang Tinggi Village. The rapid expansion of built-up areas, the steep topography, the limited availability of suitable land, and the increasing proximity between residential areas and unsuitable disposal locations further intensify the need for a scientifically supported landfill siting framework.

This study addresses this gap by developing a GIS based landfill suitability model that incorporates

fifteen environmental, hydrological, topographical, socio economic, and accessibility criteria. These criteria include slope, elevation, land use and land cover, rainfall, temperature, distance to rivers, proximity to major roads, distance to agricultural zones, sensitivity of environmental areas, and population exposure. These variables have been used widely in previous GIS based landfill siting studies (Sumathi et al., 2008; Ali and Ahmad, 2020). All criteria are combined through a Weighted Overlay Analysis framework that provides consistent evaluation across spatial layers. The resulting model offers a replicable, transparent, and data driven decision support tool that is specifically adapted to the environmental and socio-economic characteristics of Kota Sungai Penuh. This approach provides local authorities with a scientific basis for selecting environmentally appropriate, technically feasible, and socially acceptable landfill candidate sites that can support long term waste management planning and sustainable urban development.

## RESEARCH METHOD

### Research Design

This research uses a quantitative descriptive design that integrates Geographic Information Systems and multicriteria spatial analysis to produce a landfill suitability model for Kota Sungai Penuh. A quantitative descriptive approach is appropriate because landfill site selection requires objective evaluation of spatial variables, numerical scoring of criteria, and systematic interpretation of suitability values across geographic space. GIS based quantitative designs have been widely applied in landfill siting studies because they enable spatial integration of biophysical, socio economic, and infrastructural factors within a reproducible analytical framework (Sumathi et al., 2008; Kontos et al., 2005; Ali and Ahmad, 2020).

The research was conducted from June to October 2025 and focused on the administrative area of Kota Sungai Penuh, located in Jambi Province, Indonesia. The city has a total area of approximately 366 square kilometres and is characterised by a combination of mountainous ridges and alluvial valleys. Elevation data obtained from the Shuttle Radar Topography Mission (SRTM) and supported by regional documentation from the municipal government indicate that the elevation of Kota Sungai Penuh generally ranges between 500 metres and 1,500 metres above sea level, which reflects its position within the Bukit Barisan mountain system.

**Table 1.** Evaluation Scale (1–5) Used for All Criteria

Score	Interpretation	Description in Suitability
1	Very suitable	Meets all environmental, social, and technical requirements
2	Suitable	Acceptable for landfill development with minor constraints
3	Moderately suitable	Usable with mitigation; moderate environmental or technical limitations
4	Unsuitable	Strong constraints present; high risk or conflict zone
5	Very unsuitable	Must be excluded due to safety, environmental, or legal restrictions

### Research Target/Subject

The main target of this research is the identification of suitable locations for the development of a new municipal solid waste landfill within the administrative boundary of Kota Sungai Penuh. The research focuses on evaluating all land parcels in the region based on environmental, hydrological, topographical, socio economic, and accessibility constraints that influence their appropriateness for landfill development. This type of spatial evaluation is consistent with the approach commonly used in GIS based landfill siting studies, where each spatial unit functions as the analytical subject (Sumathi et al., 2008; Gorsevski et al., 2012). The subjects of this research consist of raster cells generated from the thematic spatial layers that represent the entire landscape of Kota Sungai Penuh. Each raster cell acts as an individual analytical unit that contains information on slope, elevation, land use and land cover, rainfall, temperature, population distribution, and distance to infrastructure or sensitive areas. The use of raster based spatial units is essential for multi criteria decision analysis in GIS, because it allows the consistent evaluation of all geographic locations under a uniform resolution (Malczewski, 2006).

### Research Procedure

#### Pre-Processing Data

The research procedure followed a sequence of analytical stages consistent with established GIS based multi criteria evaluation methods. The work began with the acquisition and preparation of thematic datasets representing environmental, hydrological, topographical, socio economic, and accessibility conditions within Kota Sungai Penuh. Each dataset was projected into a common coordinate system, clipped to the administrative boundary, and converted into raster format in order to build a uniform analytical structure suitable for Weighted Overlay Analysis. This preprocessing step is consistent with the recommendations of earlier landfill suitability studies that emphasize the importance of spatial harmonization before multi

criteria analysis (Sumathi et al., 2008; Karimi et al., 2019).

Each criterion was then standardized through reclassification into a suitability scale with values ranging from one to five. This numerical scale reflects five levels of appropriateness and is commonly used in spatial decision support systems because it facilitates direct comparison between heterogeneous variables (Kontos et al., 2005). The reclassification thresholds were determined by combining national environmental standards with suitability rules reported in previous GIS based landfill assessments.

#### Analytic Hierarchy Process (AHP)

A central component of the analysis was the determination of weights for each criterion. Weight determination was conducted using the Analytic Hierarchy Process, which evaluates the relative importance of criteria through pairwise comparisons. The AHP output was normalized and subsequently converted into percentage influence values so that it conformed to the input requirements of the Weighted Overlay tool in ArcGIS. The AHP method is one of the most widely adopted approaches in landfill suitability modeling due to its transparency, reproducibility, and strong theoretical foundation (Gorsevski et al., 2012; Ali and Ahmad, 2020).

The methodology relies on three fundamental principles: decomposition, comparative judgment, and synthesis of priorities (Saaty, 1980). The core mechanism of AHP involves a pairwise comparison matrix where each criterion is compared against every other criterion using Saaty's fundamental scale of 1 to 9 (Saaty, 1980). On this scale, a value of 1 indicates equal importance, 3 represents moderate importance, 5 denotes strong importance, 7 signifies very strong importance, and 9 indicates absolute dominance (Saaty, 1990). If criterion A is assigned a value of 5 when compared to criterion B, then criterion B is automatically assigned the reciprocal value of 1/5 (Saaty, 1980).

To ensure the reliability of the weighted results, AHP incorporates a validation process through the Calculation of the Consistency Ratio (CR). The CR is determined by comparing the

Consistency Index (CI) of the judgment matrix with a Random Index (RI) derived from a large sample of random matrices. Mathematically, the CI is calculated as:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where  $\lambda_{max}$  is the principal eigenvalue and  $n$  is the number of criteria. A CR value of less than or equal to 0.1 (10%) is the standard threshold. Any result exceeding this value indicates inconsistent judgments that require the decision-maker to revise the pairwise comparisons (Saaty, 1990).

#### **Weighted Overlay Analysis**

All reclassified and weighted criteria were integrated using the Weighted Overlay tool in ArcGIS. Weighted Overlay Analysis is widely recognized as an effective method for environmental suitability mapping because it calculates a weighted linear combination of input layers and produces a continuous suitability surface (Rahmati et al., 2016; Malczewski, 2006). The resulting suitability map provided a spatial distribution of candidate locations for landfill development, classified into multiple suitability zones based on score ranges. These zones were evaluated in the context of terrain constraints, land use patterns, and environmental protection requirements.

#### **Instruments, and Data Collection Techniques**

The research employed a combination of secondary geospatial datasets, satellite derived products, and limited field verification to support the development of the landfill suitability model. All data collection activities were conducted digitally using official geospatial repositories. The datasets consisted of fifteen spatial criteria that were prepared in accordance with the requirements of Weighted Overlay Analysis in ArcGIS. These criteria included slope, elevation, rainfall, temperature, soil moisture, land use and land cover, distance to rivers, distance to primary and secondary roads, built environment characteristics, agricultural areas, restricted zones, sensitive facilities, and population density. The inclusion of population density and proximity to sensitive facilities reflects the socio-economic dimension of the model, in line with the recommendations of previous GIS based landfill siting studies.

Spatial preprocessing and analysis were performed using ArcGIS. These platforms served as the primary instruments for georeferencing, projection standardization, raster conversion, reclassification of criteria, production of distance surfaces, and execution of the Weighted Overlay Analysis. The Spatial Analyst extension in ArcGIS

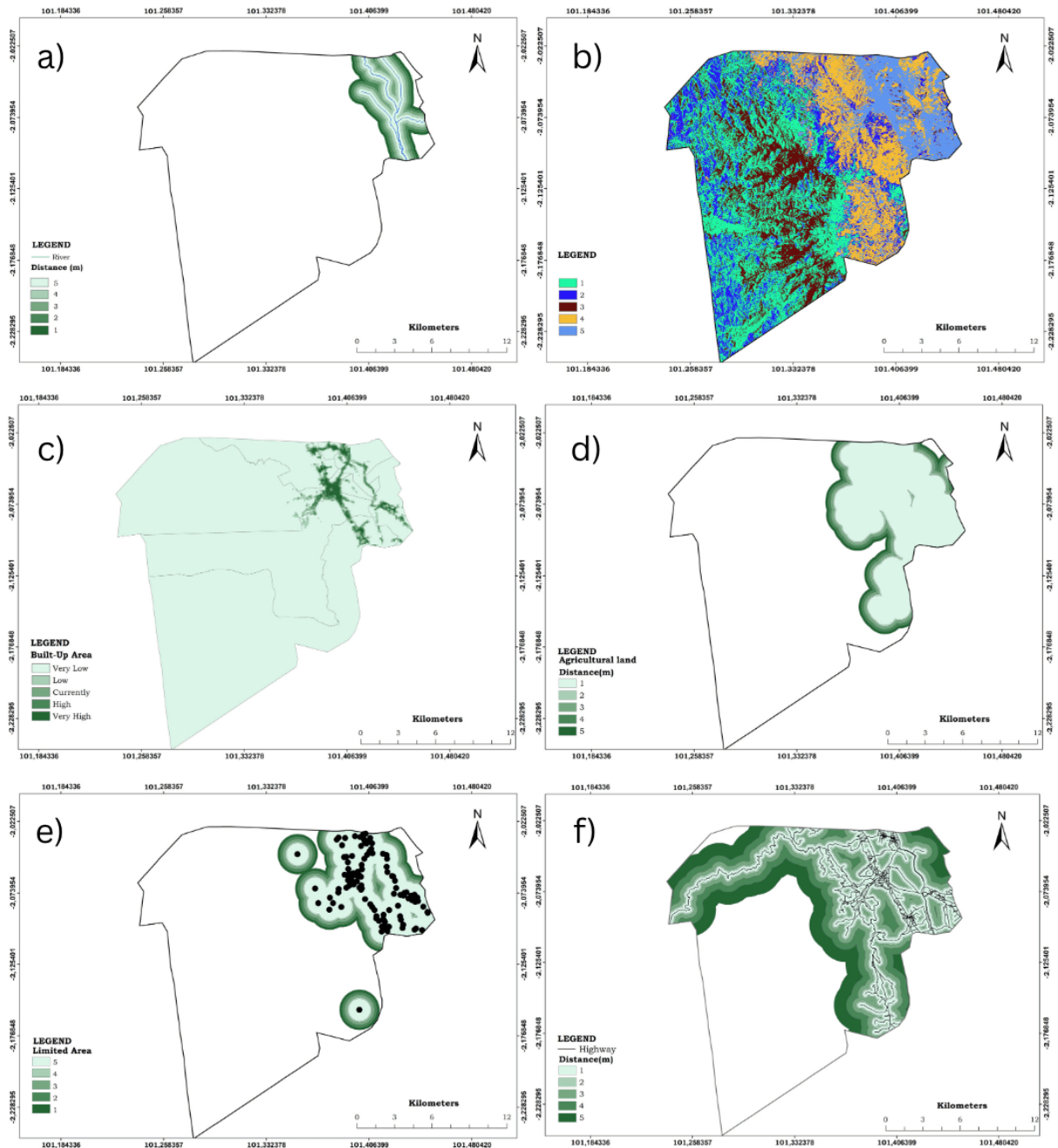
was used to generate slope and elevation derivatives from SRTM data, compute Euclidean distance layers for rivers and transportation networks, and standardize all thematic layers prior to weighting. Satellite derived elevation datasets from the Shuttle Radar Topography Mission and land surface information from Sentinel imagery were incorporated to complement the national datasets obtained from the Badan Informasi Geospasial, Badan Pusat Statistik, BMKG, and the Ministry of Environment and Forestry.

#### **Data analysis technique**

The Weighted Overlay Analysis produced a continuous raster surface representing the overall suitability score for every location within the study area. These scores were interpreted as a cumulative measure of environmental safety, engineering feasibility, and social acceptability. Higher scores indicate areas that satisfy the required distance buffers from rivers and settlements, occur on acceptable slopes, fall within compatible land use categories, and avoid environmentally sensitive or restricted zones. Lower scores indicate locations where environmental hazards, physical constraints, or socio-economic conflicts make landfill development unsuitable. Each criterion in this analysis is classified into an ordinal scale from 1 to 5, where a value of 5 indicates the highest suitability and 1 indicates areas that must be excluded or are highly unsuitable (Kontos et al., 2005).

Primary criteria in landfill site selection include the protection of water resources, where the distance from surface water bodies must be more than 100 meters and the site must not be in a groundwater recharge area (SNI, 1994). Furthermore, the slope factor is a critical determinant of construction stability, where gentle slopes (less than 10 percent) are considered highly ideal, while slopes above 20 percent should be avoided due to erosion and mass movement risks (Moon, 2020; SNI, 1994). From a social perspective, a minimum safety distance from settlements of 1,500 meters is required to protect residents from noise, odor, and vector-borne diseases (SNI, 1994; Karimi et al., 2019). Integrating these criteria into a Weighted Overlay model allows for the simultaneous evaluation of these various limiting factors (Malczewski, 2006).

Interpretation of the suitability map was conducted by directly relating the spatial patterns of suitability scores to the research problem and objectives. The main research problem concerns the absence of a spatially informed, scientifically grounded method for identifying suitable landfill sites in Kota Sungai Penuh. The objective of the study is to



**Figure 1.** The selected criteria: a) the river proximity map; b) land use and land cover; c) built-up area; d) agricultural areas; e) limited area f) distance from major and primary roads.

determine suitable locations for a new landfill that minimize environmental risk, avoid social conflict, and meet technical requirements. Therefore, areas classified with high suitability were interpreted as potential candidate locations because they meet these criteria simultaneously. Conversely, low suitability areas were interpreted as zones that should be excluded from consideration because they conflict with environmental protection requirements, violate regulatory buffers, or present engineering limitations. This interpretive process involved evaluating suitability zones relative to actual

landscape conditions, land availability, and municipal development constraints. High suitability areas were cross-checked with field observations to confirm the accuracy of land cover, accessibility, and terrain characteristics. This step ensured that the GIS-derived suitability scores accurately reflect ground conditions and can be used reliably by decision makers. Through this interpretive framework, the analysis directly answers the research objective by identifying specific locations that are scientifically justifiable, environmentally safe, and socially feasible for landfill placement in Kota Sungai Penuh.

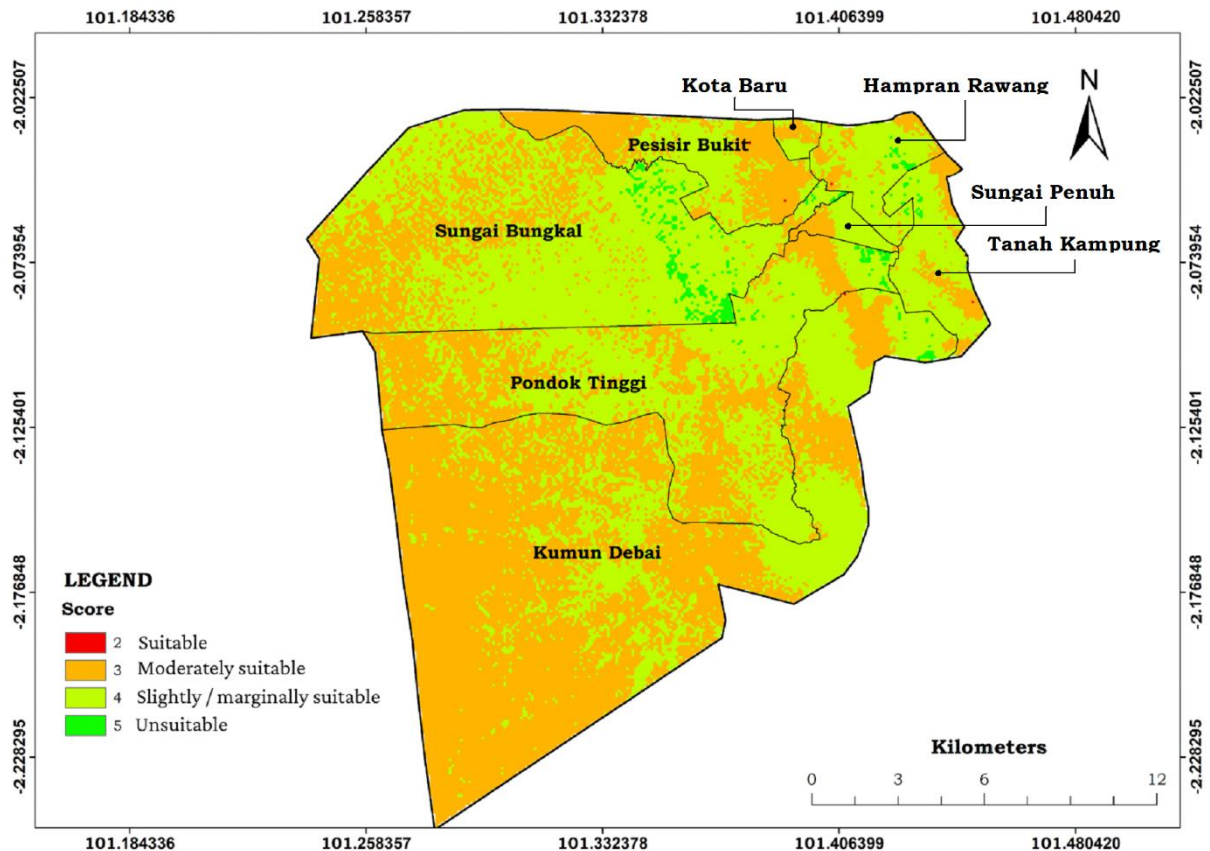


Figure 2. The Suitability Map of Landfill in Sungai Penuh City Using Multi-Criteria Weighted Overlay

**RESULTS AND DISCUSSION**

**Criteria Analysis**

The spatial distribution of the fifteen criteria shows that landfill suitability in Kota Sungai Penuh is shaped by the combined influence of terrain conditions, hydrology, climate, land surface properties, accessibility, and human settlement patterns. The slope and elevation in this region is dominated by steep mountainous terrain belonging to the Bukit Barisan range, while flat relief is present only in a narrow valley. Steep slopes are unsuitable for landfill development because unstable terrain increases the risk of erosion, mass movement, and structural failure, which is consistent with previous assessments in mountain environments (Sumathi et al., 2008; Gorsevski et al., 2012). Climatic variables such as rainfall, humidity, temperature, and soil moisture indicate that the area experiences a humid tropical climate with high rainfall intensity and elevated surface moisture. These conditions increase the potential for leachate formation and reduce soil stability, which complicates landfill operation and increases environmental risk (El Fadel et al., 1997; Lou and Nair, 2009; Krause et al, 2013).

Hydrological constraints are clearly reflected in the river proximity map (Figure 1a), which shows dense river networks that flow across the central valley. Areas near river channels must be excluded because rivers act as pathways for contaminant movement. Leachate can migrate rapidly from landfills into surface water and groundwater systems, especially in permeable alluvial deposits (Winter et al., 1998; Chabuk et al., 2017). Land surface factors further reduce the number of feasible locations. Maps of land use and land cover (Figure 1b), settlement/ built-up area distribution (Figure 1c), agricultural areas (Figure 1d), and limited area (Figure 1e) show that much of the accessible land is already occupied by residential development, farmland, or ecological conservation areas. These zones cannot be used for landfill development due to environmental protection requirements, health considerations, and land use conflict (Karimi et al., 2019; Ali and Ahmad, 2020).

Accessibility map representing distance from major and primary roads indicate that moderate distances are ideal (Figure 1f). Locations too close to roads can create disturbance and discomfort for nearby communities, while distant areas increase

transportation cost and reduce operational efficiency (Sener et al., 2011). Social criteria, represented by population density and sensitive facilities, highlight that the central basin is densely settled and contains numerous schools, hospitals, and worship facilities. These areas require strict protection buffers to avoid exposure to pollution and health hazards. Epidemiological studies show a clear relationship between landfill proximity and elevated risk of respiratory and reproductive disorders (Porta et al., 2009; Guerrero et al., 2013).

### Weighted Calculation Result

Based on the AHP calculations, the model demonstrated a high degree of consistency with a Consistency Ratio (CR) of 0.0028, which is well below the 0.1 threshold, indicating a valid and consistent judgment matrix. The final weight structure adhered exactly to the framework used in the analysis. The highest influence values, between thirteen and fourteen percent, were assigned to criteria associated with high environmental risk and public safety. This includes land use and land cover, distance to rivers, restricted zones, population exposure, and environmentally sensitive areas. These criteria are frequently identified as priority determinants in landfill siting because they strongly influence contamination potential and community exposure (El-Fadel et al., 1997; Porta et al., 2009)

Medium influence values, approximately six percent, were allocated to slope, soil moisture, and built environment characteristics. These parameters influence engineering feasibility, stability, and construction requirements, which align with earlier findings in multi criteria environmental evaluation (Fatoyinbo et al, 2020; Durlević et al, 2023).

The lowest influence values, between one and three percent, were assigned to climate related factors and general accessibility variables because they exert a lesser but still relevant effect on final suitability outcomes. The total weight was maintained at one hundred percent to satisfy the operational rules of Weighted Overlay Analysis.

The AHP results show that land use, rivers, limited area, built-up area density, and sensitive facilities received the highest weight values. These criteria are widely recognized as the most restrictive factors because they define where landfills must not be placed under any circumstance (Kontos et al., 2005; Chabuk et al., 2017). Medium weight criteria include slope, soil moisture, and settlement patterns, which reflect engineering and environmental feasibility. Rainfall, temperature, elevation, and road distance received lower weights because their influence on suitability is indirect.

The distribution of weights strongly affects the spatial pattern of the suitability map. Because high weight criteria dominate the central valley, an area that is heavily settled, highly agricultural, and exhibiting high drainage density, most of the flat land becomes unsuitable. The mountainous terrain surrounding the basin is steep and therefore cannot host a landfill. As a result, only a few patches remain where all criteria align at favorable levels. This pattern is consistent with previous studies in mountain basins and other environmentally constrained regions (Chang et al., 2008).

### Suitability Class

The Weighted Overlay Analysis produced four suitability classes (figure 2): Suitable (Class 2), Moderately suitable (Class 3), Unsuitable (Class 4), and Very unsuitable (Class 5). No areas were classified as Very suitable (Class 1). The spatial distribution is dominated by Class 3 and Class 4, with limited areas of Class 2 and extensive coverage of Class 5 in the higher mountain slopes.

Class 2 areas appear as small, scattered patches located mainly on the western and southwestern foothills and in a few central interior locations. These patches occur in gentle terrain that is sufficiently distant from river channels and human settlements, while also avoiding agricultural land and protected zones. Their fragmented nature reflects the narrow availability of moderately stable land between steep slopes and densely used valley floors. Similar patterns have been documented in landfill studies conducted in other mountain regions with limited land resources (Karimi et al., 2019).

Class 3 areas form a continuous belt across much of the region. These zones generally have acceptable slope and elevation but are affected by moderate hydrological or land use constraints. They represent potential candidates for landfill siting if mitigation measures are applied, such as engineered liners or improved drainage systems.

Class 4 areas dominate the central basin, where residential communities, agricultural land, and major river channels are concentrated. These zones are unsuitable due to a combination of settlement exposure, land use conflict, and hydrological risk.

Class 5 covers most of the mountain slopes surrounding the city. These areas are steep, elevated, and frequently associated with protected land, making them completely inappropriate for landfill development.

### CONCLUSION

This study assessed landfill suitability in Kota Sungai Penuh by integrating fifteen environmental

and social criteria through a combination of Analytic Hierarchy Process and Weighted Overlay Analysis within a geographic information system environment. The resulting suitability map contains four suitability classes, with no areas classified as Very suitable. Suitable areas occur only in small, fragmented patches located primarily on transitional foothill terrain, where slope, hydrological separation, and land use conditions are moderately favorable. Moderately suitable zones are more widespread but still require mitigation measures such as engineered containment and controlled drainage. The dominance of Unsuitable and Very unsuitable classes reflects the limited land resources of the intermontane basin, indicating that landfill development must be planned with strict environmental considerations and may require regional cooperation beyond the city boundaries.

Overall, the findings demonstrate that successful landfill planning in Kota Sungai Penuh depends on understanding the interaction between terrain, hydrology, climate, land use, and human settlement patterns. The methodology developed in this study provides an effective and reproducible framework for evaluating landfill suitability in environmentally sensitive and topographically constrained regions. Future work should include site-specific field surveys, subsurface investigations, and assessments of alternative waste management strategies to support long term sustainability.

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