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RESEARCH ARTICLE

MCDA-AHP-GIS-Based Site Suitability Assessment for a Multi-Utility Tunnel in Panakkukang Sub-district, Makassar City , Indonesia

Ade Nirwani Abdurahman Muthalib [1,*], Nini Apriani Rumata[1], Fathurrahman Burhanuddin[1], Muhammad Faisal [2] ,Firdaus[1], Rahmania[3], Rizki Yusliana Bakti [2]
[1] Department of Urban and Regional Planning, Universitas Muhammadiyah Makassar, Indonesia
[2] Department of Informatics, Universitas Muhammadiyah Makassar, Indonesia
[3] Department of Electrical Engineering, Universitas Muhammadiyah Makassar, Indonesia

* Corresponding author: 105851100422@student.unismuh.ac.id
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Abstrak

This study develops a transparent MCDA–AHP–GIS framework to screen Multi-Utility Tunnel (MUT) corridor suitability in Panakkukang Sub-district, Makassar City, using 2024 baseline datasets and five criteria: utility/network density (C1), road functional class and corridor capacity (C2), flood susceptibility (C3), activity intensity (C4; proxied by kelurahan-level population density), and spatial planning compatibility with RTRW/RDTR (C5). All layers were standardized and reclassified (1–3 or 1–5) and integrated using Weighted Linear Combination (WLC) with AHP-derived weights (CR = 0.028), where C1 (0.26) and C5 (0.24) were highest, followed by C2 (0.19), C4 (0.16), and C3 (0.15). The 2,918.3-ha study area was classified into Very Unsuitable (88.2 ha; 3.0%), Unsuitable (405.8 ha; 13.9%), Moderately Suitable (764.9 ha; 26.2%), Suitable (935.8 ha; 32.1%), and Highly Suitable (723.6 ha; 24.8%). A corridor-focused overlay shows that 436.9 ha fall within the Suitable–Highly Suitable mask, of which 127.3 ha (29.1%) intersect high flood-hazard zones, indicating that some priority segments require attention during detailed planning. Uncertainty mainly arises from buffer distances and reclassification thresholds and from non-differentiating attributes in some utility layers; however, a ±10% weight sensitivity test yields only minor shifts in class areas and preserves the main priority-corridor pattern.

Keywords: Multi-Utility Tunnel, GIS, MCDA-AHP, WLC, Land Suitability, Panakkukang Sub-district

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1. Introduction

Rapid urban growth necessitates utility management that is more orderly, safe, and resilient to environmental disturbances. In many urban areas, utility installation using open-cut excavation is increasingly constrained because it can disrupt traffic, trigger land-use conflicts, and increase restoration and operation and maintenance costs (Bergman et al., 2022; Z. Deng et al., 2023; Thakre et al., 2025). Fragmented development of electricity, telecommunications, potable water, and drainage networks often produces overlapping utilities, repeated excavation along the same road segments, and coordination challenges among agencies (Bergman et al., 2022; Jorjam et al., 2024; P. Zhang et al., 2025). In this context, Multi-Utility Tunnels (MUT) provide an integrated underground corridor to accommodate multiple utilities, reducing re-excavation and improving service efficiency and resilience (Zhu and Zhang, 2025; Z. Deng et al., 2023).

MUT implementation depends on corridor conditions particularly activity density, road functional class and capacity, and flood exposure which collectively influence utility integration requirements, construction feasibility, and long-term safety and performance (Zhang et al., 2023; Peng, F. Le et al., 2023; Oh et al., 2025; Z. Deng et al., 2023). Outside surface conditions, MUT corridor feasibility in Panakkukang is also influenced by subsurface geology dominated by Quaternary coastal alluvial deposits (Qac) and the Camba Formation (Tmc) (Center for Geological Research and Development, Bandung, 1982). The unconsolidated Qac unit is more prone to compressibility and differential settlement, while Tmc is relatively more competent but heterogeneous; therefore, priority segments especially within Qac-dominated zones should be verified through geotechnical and hydrogeological investigations at the detailed design stage. (Zhao et al., 2022; Ullah et al., 2024; Oh et al., 2025). To integrate these interacting constraints, GIS-based MCDA–AHP is widely used to derive consistency-checked expert weights (CI/CR) and, through data standardization, proximity analysis, and multi-layer integration, generate regional suitability maps via weighted overlay (Faisal, Irmawati, et al., 2025; Waheeb et al., 2023; Ullah et al., 2024; Mati et al., 2021).

Integration between figures and text is demonstrated by the study area context in each figure (showing the study area boundaries), the spatial distribution of the five MUT criteria in Figure 2, and the resulting MUT corridor suitability map in Figure 3, enabling readers to trace the relationship between criterion patterns and derived priority zones. (Zhang and Peng, 2024; Yin and Wang, 2022; P. Zhang et al., 2025). At a broader scale, Urban Underground Space (UUS) research emphasizes data integration and spatial modeling for underground infrastructure planning, including multi-criteria risk and reliability assessments for utility corridors (S. Wang and Fu, 2022; Vujovi et al., 2025; Zhao et al., 2022). Nevertheless, a clear research gap remains, as GIS-based MCDA–AHP applications for MUT corridor suitability screening at the sub-district scale in Indonesian cities that are explicitly linked to statutory spatial planning (RTRW) are still limited in the literature (Pu et al., 2024; Taki and Maatouk, 2018).

Addressing this gap, Panakkukang Sub-district exhibits high activity density, overlapping utilities, limited space, and recurrent road excavations that disrupt mobility, highlighting the need for an integrated utility corridor arrangement aligned with the RTRW. Accordingly, this study develops an MCDA-AHP-GIS framework to identify MUT corridor suitability zones in Panakkukang Sub-district using five criteria: existing utility density, road functional class and corridor capacity, flood susceptibility, activity intensity, and spatial planning compatibility (F. Deng et al., 2023; Getachew et al., 2025; Pu et al., 2024; Oh et al., 2025). This study contributes by proposing a reproducible GIS-based MCDA–AHP screening approach for MUT corridor suitability at the sub-district scale, integrating five planning-relevant criteria into a single suitability index, and linking the resulting priority corridors to the RTRW to support planning and targeted verification at the detailed design stage (e.g., flood risk and subsurface constraints).

2. Literature Review

2.1 Concept and Benefits of Multi-Utility Tunnels

A Multi-Utility Tunnel (MUT) is an integrated, accessible underground corridor that accommodates multiple utility networks for inspection and maintenance (Faisal, Sahabuddin, et al. 2025). MUT can reduce network fragmentation, limit repeated excavation, and improve operation and maintenance efficiency (Bergman et al., 2022; Thakre et al., 2025). Within the Urban Underground Space (UUS) framework, MUT are particularly relevant for high-density cities because they optimize subsurface space and reduce surface disruptions in high-activity areas (Z. Deng et al., 2023; Z. Peng et al., 2023; Peng, F. Le et al., 2023; P. Zhang et al., 2025). Bibliometric evidence also shows a shift toward data-driven management and stronger planning, construction, and operation agendas for underground infrastructure (Zhang and Peng, 2024; Yin and Wang, 2022).

2.2 Multi-Criteria Decision Analysis (MCDA) and the Analytic Hierarchy Process (AHP) in Spatial Planning

MCDA, especially the Analytic Hierarchy Process (AHP), is widely used in spatial evaluation because it converts qualitative judgments into quantitative weights through pairwise comparisons (Faisal, Hasiri, et al. 2025). AHP helps structure complex criteria and assess judgment consistency (Ullah et al., 2024). In infrastructure studies, AHP has been applied for facility site selection (Frimpong et al., 2025; S. Wang and Fu, 2022), flood risk mapping, and Development prioritization based on expert input (Waheeb et al., 2023; Rekik and El Alimi, 2023). Consistency testing using CI and CR strengthens decision transparency and accountability, including for underground network evaluation (Hosen et al. 2025).

2.3 GIS-Based Spatial Decision-Making for Infrastructure Planning

Infrastructure planning requires geospatial data that represent location, distance, connectivity, and activity patterns. GIS enables the management, visualization, and analysis of multilayer datasets (e.g., road networks, zoning, activity distribution, existing utilities, and environmental conditions) to support more measurable and evidence-based planning (Z. Peng et al. 2023). GIS is also widely used for overlay, buffering, and proximity-based analyses in flood hazard mapping and in identifying safer and more efficient infrastructure corridors (Gao et al., 2021). This is directly relevant to MUT planning, where corridor selection must jointly consider activity density, flood risk, utility density, road network function, and spatial planning suitability within an integrated platform (Peng, F. Le et al., 2023).

2.4 Integration of MCDA-AHP and GIS in Urban Infrastructure Studies

Recent MUT research increasingly emphasizes utility integration, reduced surface disruption, and sustainable management of underground infrastructure (Z. Deng et al., 2023). Integrating MCDA–AHP with GIS enables expert-based weighting alongside regional-scale spatial evaluation: GIS supports normalization, spatial analysis, and weighted overlay, while AHP provides standardized priority weights (Frimpong et al. 2025). This combined approach has been practical for renewable energy site selection, flood hazard mapping, landfill site selection, and green space planning (Popescu and Alina, 2023; Ullah et al., 2024; Gao et al., 2021). In underground contexts, GIS-based MCDA with AHP supports the identification of suitable areas for UUS Development, including MUT corridors, by integrating activity factors, spatial planning, existing utilities, and environmental risks (Hosen et al., 2025; Zhang et al., 2023; Z. Peng et al., 2023; P. Zhang et al., 2025). However, applications explicitly designed to delineate MUT corridors in developing cities remain limited and warrant further expansion.

2.5 Research Gap and Study Contributions

Three key gaps are identified. First, many MUT studies focus on technical, operational, and managerial aspects, while MCDA-AHP-GIS-based spatial evaluation for MUT corridor selection in developing cities remains underreported (Bergman et al., 2022; Z. Deng et al., 2023). Second, data-driven and spatial modeling UUS frameworks have been less tested in developing city contexts facing data limitations, informal utilities, and regulatory constraints (Zhang and Peng, 2024; M. Wang and Yin, 2022). Third, comprehensive integration of five criteria, flood risk, utility density, activity density, road functional class, and spatial planning suitability into a single spatial suitability model for MUT corridors remains rarely discussed (Rekik and El Alimi, 2023; Waheeb et al., 2023). To address these gaps, this study:

(i) Develops an MCDA-AHP-GIS framework for MUT corridor identification at the sub-district scale.
(ii) Operationalizes five criteria relevant to Panakkukang.
(iii) Produces an MUT corridor suitability map that can be integrated into the RTRW.

3. Methodology

3.1 Research Framework

This study integrates GIS-based MCDA with the Analytic Hierarchy Process (AHP) to assess the suitability of MUT corridors. The workflow includes: (i) defining criteria and indicators; (ii) deriving criterion weights using AHP; (iii) standardizing and reclassifying spatial layers; (iv) combining weighted criteria using the Weighted Linear Combination (WLC) method; and (v) classifying the

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composite index into suitability classes to produce the corridor suitability map (Figure 1). This GIS-based MCDA-AHP workflow (criteria definition, AHP weighting with consistency checking, layer standardization, and weighted overlay integration) follows established spatial decision-making practice in geoscience and infrastructure planning (Taki and Maatouk, 2018; Iskandar, Zannah and Anshari, 2023).

3.2 Criteria Identification

Criteria were selected to capture key spatial determinants of MUT feasibility, based on theoretical considerations, MUT/UUS practice, and the availability of spatially quantifiable data. Each criterion was operationalized as measurable indicators for AHP weighting and GIS-based analysis, thereby enabling consistent assessment of the technical, environmental, and regulatory dimensions. The selection of corridor-related indicators (road hierarchy/capacity and activity intensity) is consistent with land-use–transport integration concepts used to structure TOD and corridor planning evaluations (Taki et al. 2017).

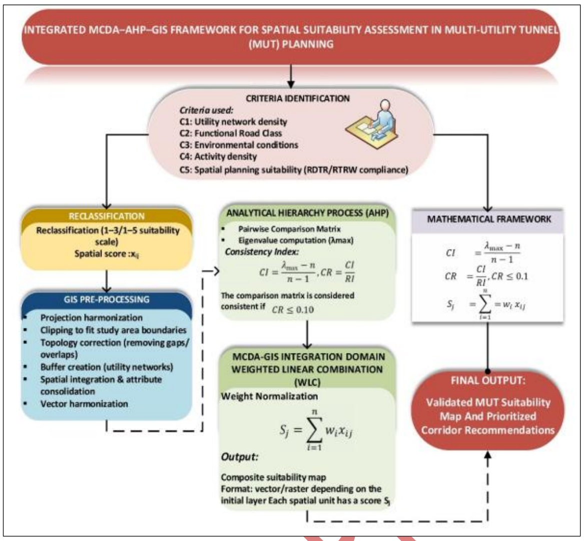

Fig. 1. Research Framework for MUT Corridor Location Selection

Table 1. Data sources and primary uses of the datasets applied in this study.

Target	Main Criteria	Criteria Selection (Indicators)	Spatial detail (vector)	Data Format	Data Source	Key Literature
Utility Tunnel Priority Index	Utility / Network Density (C1)	Telecommunications (fixed network: fiber-optic), BTS; electricity (Medium Voltage Cable Channel/MVCC); potable water pipelines (active distribution); primary drainage; road segment length	Linear network features; buffered corridors (criterion and class-specific distances; see Tables 5–6)	Polyline Buffer	RTRW; sectoral agencies (Public Works/PU, PLN, PDAM, Telkom)	(Z. Deng et al., 2023; Bergman et al., 2022)
	Road Functional (C2)	Road functional class; road width	Road segments (analysis unit for scoring and overlay)	Polyline Buffer	RTRW	(Z. Deng et al., 2023; Getachew et al., 2025; Oh et al., 2025)
	Environmental Conditions (C3)	Flood susceptibility level	Flood/hazard zoning polygons	Polygon	RTRW	(Getachew et al., 2025; Ullah et al., 2024)
	Activity Density (C4)	Population density, road network density (mobility intensity), and activity zones (commercial, offices, public facilities)	Administrative/activity-zone polygons (joined/aggregated to study units)	Polygon	Statistics Indonesia (BPS) and RTRW	(Z. Deng et al., 2023; Bergman et al., 2022; Z. Peng et al., 2023)
	Spatial Planning Suitability (C5)	Land-use zoning (commercial, offices, infrastructure); road right-of-way as legal utility corridor; exclusion of protected/heritage areas under RTRW	Zoning and constraint polygons	Polygon	RTRW	(Gao et al., 2021; Hao et al., 2024)

Note: All datasets used in this study refer to the 2024 baseline (RTRW 2024, BPS 2024, and sectoral utility inventory available in 2024), and are aligned with the same study boundaries and coordinate reference systems before analysis. Map scale/nominal position accuracy 1:20.000.

3.3 Suitability Scoring (Reclassification)

Suitability scoring harmonized all criteria (C1-C5) into an ordinal scale for integration in the MCDA-GIS model. Indicators were reclassified to a 1-3 or 1-5 scale based on data characteristics, following established spatial suitability practice (Mati et al., 2021; Waheeb et al., 2023; Ullah et al., 2024). Higher scores indicate higher suitability, and class thresholds were set based on activity intensity, utility density, flood risk, road corridor constraints, and spatial planning suitability (Rekik and El Alimi, 2023).

At the road-corridor segment level, C1 (Utility/Network Density) was derived from buffered utility proxies telecommunications (fiber-optic lines and BTS), electricity (MVCC), potable water pipelines (active distribution), and primary drainage using criterion- and class-specific buffer distances (Tables 5-6) to compute density measures (e.g., km/km^2 and BTS/km^2), reclassify them to a common suitability scale (1–3), and aggregate them into a composite

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C1 layer via a weighted sum with internally normalized weights (∑w = 1). C4 (Activity Density) was constructed in the same manner from population density, road-network density, and RTRW activity zones (reclassified to 1–5), and the resulting composite C1 and C4 layers were then integrated with the remaining criteria using WLC to produce the final corridor suitability index.

3.4 Spatial Data Processing (GIS)

Spatial data processing was performed to ensure that all layers were analysis-ready and geometrically consistent. Polygon and polyline datasets included the road network, utility corridors, river buffer boundaries, land use, protected areas, water bodies, and RTRW zoning. All layers were standardized by harmonizing the coordinate reference system (UTM WGS 84 Zone 50S), clipping to the study boundary, and conducting topology checks to minimize gaps, overlaps, and disconnected features. All spatial processing steps were carried out using ArcGIS 10.8 (GIS) (Hosen et al., 2025; Frimpong et al., 2025; Majid and Mir, 2021).

Key modeling parameters were explicitly defined to ensure methodological transparency. These include: (i) criterion and hierarchy-specific buffer distances representing utility and road-corridor influence zones (Tables 5-6), (ii) reclassification thresholds transforming each criterion into an ordinal suitability scale (Tables 4-8), (iii) inverse scoring for flood susceptibility (higher hazard = lower suitability), (iv) AHP settings (Saaty 1-9 scale, geometric-mean aggregation, and CR < 0.1), and (v) WLC integration followed by classification of the composite suitability index into five classes using Jenks natural breaks (Table 12). Buffer distances were differentiated across criteria and road classes to reflect different spatial footprints and corridor capacities; a single uniform buffer would homogenize influence zones and reduce discrimination among candidate corridors. Uncertainty related to expert weighting was evaluated via a ±10% weight sensitivity test (Section 3.7), while remaining uncertainty associated with buffer distances and threshold choices is acknowledged as a modeling limitation. Data harmonization (common CRS, clipping, topology/geometry checks) and transparent documentation of dataset spatial detail (nominal scale/accuracy where available) follow good practice in multi-source GIS mapping studies (Irawan et al., 2025; Iskandar, Zannah and Anshari, 2023).

3.5 Pairwise Comparison for Determining Criteria Weights Using the Analytic Hierarchy Process (AHP)

AHP weighting was conducted through pairwise comparisons among criteria using the 1-9 intensity scale (Mulyadi et al., 2024; Taki and Maatouk, 2018). Weights were derived from the eigenvector, and the consistency of judgments was evaluated using $^{\lambda}$max, the Consistency Index (CI), and the Consistency Ratio (CR). The judgments were considered consistent when CR < 0.1, indicating that the resulting weights were acceptable for use in the weighted overlay stage (Ullah et al., 2024; Waheeb et al., 2023; Frimpong et al., 2025). The pairwise comparison procedure and the CI/CR consistency evaluation are applied following standard AHP implementations in JGEET spatial-planning studies (Taki and Maatouk 2018).

Table 2. Scale for pairwise comparisons in AHP.

Value (n)	Definition
1	The two elements are equally important.
3	One element is slightly more important than the other.
5	One element is more important than the other.
7	One element is strongly more important than the other.
9	One element is absolutely more important than the other.
2,4,6,8	Compromise values between two adjacent judgments

Criteria weights were computed using the eigenvector approach, with inter-expert aggregation performed using the geometric mean. Judgment consistency was tested using the Consistency Index (CI) and Consistency Ratio (CR) as follows:

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

Where: CI = Consistency Index; λ_{max} = maximum eigenvalue of the pairwise comparison matrix; n = number of variables.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (2)$$

Where: CR = Consistency Ratio; CI = Consistency Index; RI = Random Index. The pairwise comparison matrix is considered consistent when the Consistency Ratio (CR) value is < 0.1.

Table 3. The random index (RI) is used to assess consistency.

n	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

n, number of criteria; RI, random index

3.6 MCDA-AHP-GIS Integration (Weighted Linear Combination, WLC)

All criterion maps (C1-C5) were first standardized by reclassifying them into a suitability scale (e.g., 1-5). Each criterion map was then multiplied by its corresponding AHP weight to generate a weighted criterion map $(w_i \times x_{ij})$ In the final step, all weighted maps were summed using the Weighted Linear Combination (WLC) method to obtain the overall suitability score (S_j) for each spatial unit. Higher (S_j) values indicate locations that are more prioritized as potential MUT corridors (Gao et al., 2021; Ullah et al., 2024; Frimpong et al., 2025).

$$S_j = \sum_{i=1}^{n} w_i x_{ij} \quad (3)$$

where $w_i$represents the weight of criterion i and x_{ij}represents the reclassified score of criterion i for spatial unit j. The WLC output was then classified into five suitability classes to identify priority zones for MUT corridors (Waheeb et al., 2023; Ullah et al., 2024).

3.7 Model Validation and Sensitivity Analysis

Validation was conducted through field verification (ground truthing) and spatial checks by comparing the suitability map against existing zones, flood-prone zones, constraint zones (river buffer zones and protected areas), and the land-use directives of the RTRW/RDTR. Sensitivity analysis was performed by varying each criterion's AHP

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weight by ±10%, re-normalizing the weights so that $\sum w_i = 1$, and recalculating the suitability map. Changes in class areas and spatial distribution patterns were examined to assess model stability. Overlay-based spatial checks against constraint layers and sensitivity testing are commonly used to assess robustness and to flag segments requiring detailed ground verification in applied geospatial studies. (Iskandar, Zannah and Anshari, 2023; Zamroni et al., 2020).

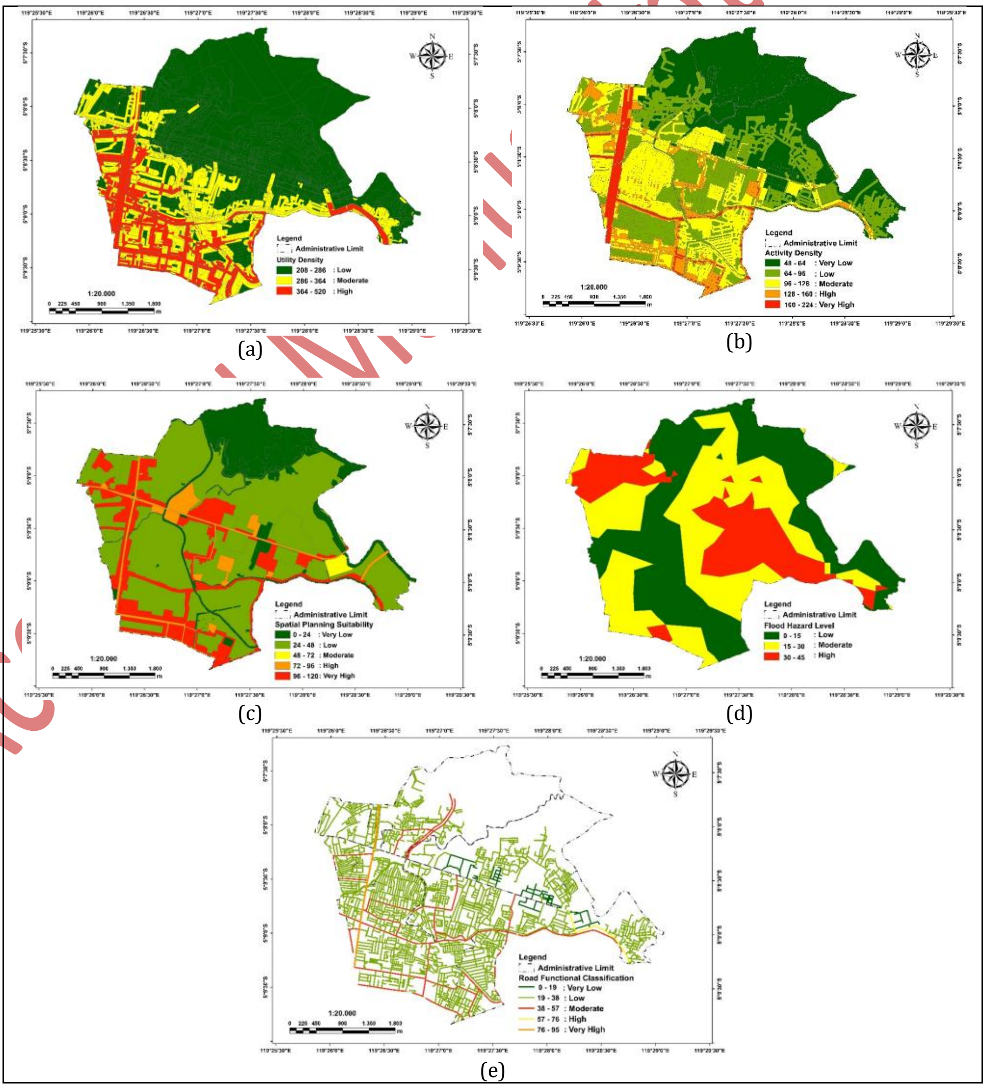
4. Results and Discussion

4.1 Spatial Criteria Analysis for the MUT Suitability Model

Each criterion layer (C1–C5) was reclassified to a common ordinal suitability scale (1–3 or 1–5) and, together with AHP-derived weights, integrated in GIS using Weighted Linear Combination (WLC) to produce a composite suitability index, which was then classified into five classes from Very Unsuitable to Highly Suitable (Figure 3). In this integration, C3 (flood susceptibility) was scored inversely (higher hazard = lower suitability; Table 4), C1 summarizes corridor-level utility concentration by integrating four utility sub-layers (Table 5), C2 represents corridor feasibility based on road class/width/segment characteristics while prioritizing arterial and collector roads (Table 6), C5 ensures consistency with RTRW zoning and excludes restricted areas (Table 7), and C4 uses kelurahan-level population density as a proxy for activity intensity (Table 8). Area statistics in Tables 4–8 represent the spatial coverage of each classified criterion layer within the study boundary. Because several corridor-related criteria are expressed as buffered influence zones (e.g., utilities and road corridors), their coverage may not exactly match the total administrative area; however, all layers were standardized consistently to provide comparable inputs for the subsequent WLC integration.

Table 4. Summary of suitability classification and scoring for the environmental variable (flood-prone areas).

Environmental Conditions	Score	Area	
		Ha	Percentage (%)
Low flood hazard	3	303.4	20.2
Moderate flood hazard	2	584.2	39.0
High flood hazard	1	610.1	40.8
Total		1498.6	100%



(a) (b) (c) (d) (e)

Fig. 2. Spatial Suitability Criteria for MUT: (a) Utility Density, (b) Road Functional Class, (c) Environmental Conditions, (d) Activity Density, (e) Spatial Planning Suitability.

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Table 5. Summary of suitability classification and scoring for the utility/network density variables.

Criterion	Indicator	Class	Network length category (km/km^2)	Buffer radius (m)	Score	Area	
						Ha	Percentage (%)
Utility/Network Density	Telecommunications (Fiber, BTS)	High	> 5 BTS/km^2 or > 8 km fiber/km^2	0–150	3	416.8	36.5
		Moderate	2-5 BTS/km^2 or 4-8 km fiber/km^2	150–250	2	477.5	41.8
		Low	< 2 BTS/km^2 or < 4 km fiber/km^2	> 250	1	248.6	21.7
	Total					1142.8	100%
	Electricity (MVCC)	High	Network length (km/km^2) >8	0–100	3	236.2	19.6
		Moderate	Network length (km/km^2) 4-8	100–200	2	416.5	34.5
		Low	Network length (km/km^2) < 4	> 200	1	554.6	45.9
	Total					1207.2	100%
	Active distribution of water pipes	High	Network length (km/km^2) > 10	0–75	3	989.7	100
		Moderate	Network length (km/km^2) 5-10	75–150	2	0	0
		Low	Network length (km/km^2) < 5	> 150	1	0	0
	Total					989.7	100%
	Primary drainage	High	Network length (km/km^2)> 2	0–50	3	164.7	29.1
		Moderate	Network length (km/km^2) 1-2	50–100	2	200.1	35.4
		Low	Network length (km/km^2) < 1	> 100	1	200.7	35.5
	Total					565.5	100%

Note: For the water pipe dataset, the entire study area was classified as the High category because the distribution network data were available as a single connected system without density-differentiating attributes; therefore, the Moderate and Low classes were not generated.

Table 6. Summary of suitability classification and scoring for the road network variable.

Road Type	Class	Lane Width (m)	Average Width (m)	Segment Length Category (m)	Buffer distance (m)	Score	Area	
							Ha	Percentage (%)
Toll Road	Very High	3.50 – 3.75	> 20	> 1000	100 – 150	5	5.5	2.4
Primary Collector Road	High	3.25 – 3.50	11 – 20	200-1000	75 – 100	4	1.7	0.7
Secondary Collector Road	Moderate	3.00 – 3.25	7 – 10	200-1000	50 – 75	3	22.7	9.8
Jalan Secondary Local Road	Low	2.50 – 3.00	5 – 7	< 200	25 – 50	2	193.7	83.5
Special Road	Very Low	< 2.50	< 5	< 200	10 – 25	1	8.0	3.5
Total							231.5	100%

Table 7. Summary of spatial planning suitability (RTRW)/land-use zoning suitability.

No	Spatial Planning Category	Class	Score	Area	
				Ha	Percentage (%)
1	Trade and Services Area	Very High	5	196.0	13.2
2	Office Area	Very High	5	47.8	3.2
3	Road Right-of-Way	High	4	36.2	2.4
4	Public Facilities and Social Facilities Area	High	4	28.6	1.9
5	Urban Infrastructure Area	High	4	13.6	0.9
6	Power Generation Area	Moderate	3	11.1	0.7
7	Defense and Security Area	Low	2	71.8	4.8
8	Residential Area	Low	2	816.3	54.8
9	Water Bodies	Very Low	1	40.4	2.7
10	Green Belt	Very Low	1	9.7	0.6
11	Mangrove Ecosystem Area	Very Low	1	50.9	3.4
12	Local Protection Area	Very Low	1	149.3	10.0
13	Cemetery	Very Low	1	14.4	1.0
14	Sub-district Park	Very Low	1	2.0	0.1
15	City Park	Very Low	1	2.2	0.1
16	Neighborhood Park	Very Low	1	0.8	0.1
Total				1491.1	100%

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Table 8. Summary of population density by kelurahan in Panakkukang Sub-district.

No	Subdistrics	Population Density (persons/km^2)	Class	Score	Area	
					Ha	Percentage (%)
1	Karuwisi	42.072.00	Very High	4	24.7	1.7
2	Tamamaung	20.907.44	Very High	4	121.0	8.1
3	Karuwisi Utara	12.625.76	High	3	66.2	4.5
4	Pandang	17.867.74	High	3	61.5	4.1
5	Paropo	13.233.59	High	3	127.9	8.6
6	Karampuang	8.366.93	Moderate	2	126.5	8.5
7	Masale	8.166.67	Moderate	2	119.7	8.0
8	Sinrijala	8.168.89	Moderate	2	45.4	3.1
9	Pampang	5.267.57	Low	1	332.8	22.4
10	Panaikang	6.494.59	Low	1	295.9	19.9
11	Tello Baru	6.930.54	Low	1	166.6	11.2
Total					1488.2	100%

4.2 Criteria Weights and Expert Consistency

AHP Results (Pairwise Comparison Matrix and Weights).

Table 9. Results of the Analytic Hierarchy Process (AHP).

Criteria	Weight (w)
Utility Density (C1)	0.26
Road Functional Class (C2)	0.19
Environmental Conditions (C3)	0.15
Activity Density (C4)	0.16
Spatial Planning Suitability (C5)	0.24
Total	1.00

Based on the matrix, the relative weight of each criterion was computed as the geometric mean of its row and then normalized so that the total weight equals 1. The resulting AHP weights reflect the relative priority of criteria for MUT corridor suitability.

Table 10. Consistency Test of the Criteria Pairwise Comparison Matrix.

λ_{max}	N	RI	CI	CR
5,124	5	1.12	0.031	0.028

The consistency test indicates that CR = 0.028 (< 0.1); therefore, the expert judgments are considered Consistent and the resulting weights are acceptable for use in the weighted overlay process in GIS.

4.3 Spatial Criteria Maps

This section presents the spatial reclassification results for each criterion, including suitability classes, scores, area, and percentage coverage. These reclassified values serve as standardized inputs for the MCDA-AHP-GIS integration through weighted overlay. The maps are presented in the Figure 3.

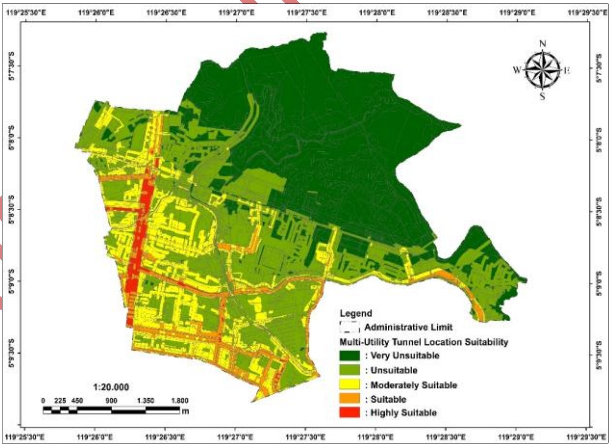

Fig. 3. Multi-Utility Tunnel (MUT) Corridor Suitability Map in Panakkukang Sub-district.

Table 11. Multi-Utility Tunnel (MUT) suitability criteria.

Indicator	Parameter	Suitability Class	Rank	Weight	Area	
					Ha	Percentage (%)
Utility/Network Density	208 - 286	Low	1		1338.0	58.3
	286 - 364	Moderate	2	0.26	598.0	26.1
	364 - 520	High	3		358.0	15.6
Total					2294.0	100%
Road Functional Class	0-19	Very Low	1		8.0	3.5
	19-38	Low	2		193.7	83.5
	38-57	Moderate	3	0.19	22.7	9.8
	57-76	High	4		1.7	0.7
	76-95	Very High	5		5.5	2.4
Total					231.5	100%
Environmental Conditions	0-15	Low	1		303.4	20.2
	15-30	Moderate	2	0.15	584.2	39.0
	30-45	High	3		610.9	40.8
Total					1498.6	100%
Activity Density	48-64	Very Low	1		504.0	31.2
	64- 96	Low	2		474.8	29.4
	96-128	Moderate	3	0.16	389.0	24.1
	128-160	High	4		171.0	10.6
	160-224	Very High	5		75.0	4.6
Total					1613.8	100%
Spatial Planning Suitability	0-24	Very Low	1		269.7	18.1
	24-48	Low	2		888.1	59.6
	48-72	Moderate	3	0.24	11.1	0.7
	72-96	High	4		78.4	5.3
	96-120	Very High	5		243.8	16.4
Total					1491.1	100%

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4.4 MUT Corridor Suitability Map

The weighted overlay (MCDA–AHP–GIS) produced five suitability classes (Table 12): Highly Suitable 25% (724 ha), Suitable 32% (936 ha), Moderately Suitable 26% (765 ha), Unsuitable 14% (406 ha), and Very Unsuitable 3% (88 ha). Spatially, higher-suitability classes generally follow arterial and collector corridors in areas with dense utilities and high activity.

Table 12. Distribution of final MUT corridor suitability classes.

Target	Parameter	Suitability Class	Area	
			Ha	Percentage (%)
	314 - 451	Very Unsuitable	88.2	3.0
	452 - 589	Unsuitable	405.8	13.9
MUT	590 - 727	Moderately Suitable	764.9	26.2
	728 - 865	Suitable	935.8	32.1
	866 -1004	Highly Suitable	723.6	24.8
Total			2918.3	100%

The concentration of the Suitable–Highly Suitable classes along arterial and collector corridors reflects the combined effect of higher corridor capacity and right-of-way feasibility (C2), stronger planning compatibility in activity-supporting zones under the RTRW (C5), and higher corridor-level integration demand where utility concentrations are dense (C1). Conversely, Unsuitable–Very Unsuitable areas tend to cluster in spatial and environmental constraint zones (e.g., protected areas, river buffers, water bodies, and higher flood-hazard zones), where regulatory restrictions and flood exposure (C3) systematically lower suitability by increasing construction and service-life risks for underground infrastructure. Overall, this corridor-aligned pattern indicates that the model differentiates implementable higher-order corridors from constrained spaces by balancing network demand, technical feasibility, environmental constraints, and statutory planning directives. In this study, priority zones are delineated based on the Suitable and Highly Suitable classes. The final suitability pattern is mainly driven by the two highest-weight criteria utility/network density (C1) and spatial planning compatibility (C5) followed by road functional class/corridor capacity (C2). Accordingly, higher suitability concentrates along arterial collector corridors where utilities co-locate and RTRW/RDTR zoning/right-of-way indicates fewer regulatory conflicts, which is consistent with common MUT planning logic that prioritizes higher-order roads for accessibility and serviceability. In contrast, lower suitability clusters in zones penalized by high flood susceptibility (C3) and restricted land-use categories (very-low C5 classes), implying higher construction/lifecycle risk and lower planning permissibility for underground corridors.

4.5 Spatial Consistency Validation and Sensitivity Analysis

This assessment evaluated the spatial consistency of the WLC outputs through overlay analysis with key constraint layers (flood hazard and RTRW). To focus on implementable road-corridor segments, the analysis was performed on the extracted road-corridor mask, where the Suitable-Highly Suitable classes cover 436.9 ha. With respect to flood hazard, 127.3 ha (29.1%) of this priority-corridor mask overlaps high flood-hazard zones, while the remaining 309.6 ha (70.9%) lies outside the high flood-hazard zone (Table 13). These results indicate that the suitability map is appropriate for initial corridor screening; however, segments intersecting high flood-hazard areas should be addressed at the detailed planning stage through route refinement and enhanced design measures (e.g., waterproofing, drainage control, and construction staging). Taken together, the suitability map should be interpreted as a screening output aligned with the RTRW, where the Suitable-Highly Suitable segment represents candidates for the next feasibility confirmation rather than the final design. Key limitations include the use of village-level population density as activity proxies (C4), non-differentiating attributes in some utility datasets (e.g., water pipe layers uniformly classified as "High"), and modeling assumptions embedded in buffer distances and reclassification thresholds. This uncertainty was partially mitigated by the AHP weight sensitivity test ±10%, which showed that the main priority corridor pattern remained stable under moderate variation in expert weighting. Comparable international MUT/UUS studies also highlight.

Table 13. Overlap of Suitable-Highly Suitable MUT classes with the high flood-hazard zone.

MUT WLC Class	Flood Zone	Area	
		Ha	Percentage (%)
Suitable-Highly Suitable	High flood-hazard	127.3	29.1
Suitable-Highly Suitable	Outside high flood-hazard zone	309.6	70.9
Total Suitable-Highly Suitable		436.9	100%

In the spatial planning context, overlaying the MUT suitability map with the RTRW zoning shows a consistent pattern: low-suitability RTRW zones are not concentrated in the higher-priority MUT classes; instead, they predominantly occur in the lower MUT classes. Of the total study area (2,918.3 ha), the largest overlaps of low-suitability RTRW zones are found in the Very Unsuitable class (254.0 ha; 8.7%) and the Unsuitable class (99.0 ha; 3.4%), whereas overlaps in the higher-priority classes are relatively small (Moderately Suitable 49.0 ha; 1.7%, Suitable 3.0 ha; 0.1%, and Highly Suitable 0.0%). These results indicate that prioritized corridors tend to fall within RTRW zoning that is more compatible with MUT development, while low-suitability RTRW zones correspond to lower MUT priority classes, demonstrating that the modeling outcomes are aligned with spatial planning directives. These results are presented in Table 14.

Table 14. Overlay results of MUT suitability classes against RTRW zoning.

Suitability Class MUT	RTRW Zone	Area RTRW	
		Ha	Percentage (%)
Very Unsuitable	Very Low	254.0	8.7
Unsuitable		99.0	3.4
Moderately Suitable		49.0	1.7
Suitable		3.0	0.1
Highly Suitable		0.0	0.0
Grand Total		405.0	13.9
MUT coverage area (Ha)		2918.3	

Validation and spatial consistency checks were conducted to assess the robustness of the model results to

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variations in expert judgment and to their alignment with environmental conditions and spatial planning directives. The AHP weight variations satisfied the consistency criterion (CR < 0.1), and the ±10% weight sensitivity test showed that the priority-corridor pattern remained stable. The changes in class areas were relatively small. They did not meaningfully alter the primary spatial pattern of priority corridors, indicating that the model remains stable under moderate variations in weight and can serve as an initial basis for delineating MUT corridors.

5. Conclusion

This study developed the MCDA-AHP-GIS framework to screen the suitability of the Multi-Utility Tunnel (MUT) corridor in Panakkukang District, Makassar, by integrating five criteria: utility/network density (C1), road functional class and corridor capacity (C2), flood vulnerability (C3), activity intensity (C4), and RTRW/RDTR spatial planning compatibility (C5). The AHP weights resulted in consistent ratings (CR = 0.028) with the highest weights given at C1 (0.26) and C5 (0.24), followed by C2 (0.19), C4 (0.16), and C3 (0.15). The final suitability map classifies the study area of 2,918.3 ha as Very Unsuitable (3.0%), Unsuitable (13.9%), Fairly Suitable (26.2). Practical implications: The proposed workflow provides a reproducible, RTRW/RDTR-consistent screening tool that can support early-stage corridor prioritization, inter-agency coordination, and targeted allocation of detailed surveys by identifying (i) candidate MUT corridors where integration benefits and planning compatibility are high and (ii) segments that require additional risk treatment, especially in flood-prone areas. Key limitations: The model relies on kelurahan-level population density as an activity proxy, some utility datasets contain non-differentiating attributes (e.g., uniformly high water-pipe classification), and suitability outcomes depend on buffer distances and reclassification thresholds. Although a ±10% AHP weight sensitivity test indicates that the main priority-corridor pattern remains stable, residual uncertainty related to data granularity and parameter assumptions remains. Future research: Further work should incorporate higher-resolution activity indicators (e.g., POI density, traffic intensity, land-use intensity), improved utility asset inventories with richer attributes, and additional subsurface variables (e.g., groundwater depth and geotechnical constraints) to strengthen constructability screening. Future studies may also apply multi-scenario parameter sensitivity (buffers/thresholds) and validation against actual excavation records or infrastructure plans to better quantify model performance and support implementation-ready corridor design.

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