10.48047/jocaaa.2025.34.02.26

"Mapping Urban Amenity Density and Terrain Influence for Sustainable Infrastructure Planning in Amman, Jordan"

Mohammad Nawaf Ali Alrsa'i[1], Prof. S. Arun Das[2]

[1]Research Scholar, DOS in Geography, University of Mysore, Mysuru

[2]Research Guide, DOS in Geography, University of Mysore, Mysuru

Abstract

Urban growth in Amman, Jordan, has generated inconsistent service distribution patterns throughout the city and significant inquiries about the city planning links to geological formations. The research article achieves two interlinked study goals by utilizing OpenStreetMap data for kernel-density analysis of urban amenities and applying the Topographic Position Index for geomorphologic classification, followed by amenity point intersection to determine terrain influence on facility placement. The research utilizes QGIS 3.42 alongside SRTM DEM (30 m) and OSM amenity data to generate spatial density surfaces, landform zones, and statistical results. Maps show dense amenity locations in Amman's center alongside wide service black spots in western suburbs, while flat geographic areas gain the preference of 82.5% of residents. The study data support infrastructure development plans to reach districts that lack services, while planning efforts should account for terrain features for sustainable and equitable city growth.

Keywords: Kernel density, Topographic Position Index, OpenStreetMap, SRTM DEM, Amman, Urban amenities, Terrain classification

1. Introduction

1.1 Background

Urbanization in Middle Eastern cities proceeds astoundingly, leading to substantial stress on public services, built structures, and natural environmental systems. The capital city of Amman has expanded from its initial 1980 population of 1 million to its current total of 4 million residents, which resulted in widespread urban growth, environmental modifications, and infrastructure requirements (UN-Habitat, 2022). The literature lacks an in-depth examination of how Amman's hilly layout impacts settlements of urban amenities alongside the distribution of such amenities throughout the city.

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1.2 Rationale

Deciding where to invest requires knowledge of service distribution patterns across the city so that underserved areas can be located for future development. Amman's hilly topography, including undulating plateaus(jabals) along with gorges and valleys, influences construction costs and access restrictions while posing threat risks. Planners can develop equitable decisions through spatial density analysis integration with geomorphological mapping for a data-centric approach to sensitive terrain considerations.

1.3 Objectives

- The spatial distribution of amenities within the OSM data collection receives kernel-density analysis.
- The study's second objective includes terrain classification into ridges, flat areas, and valleys through TPI analysis, followed by point-amenity intersection to deliver numerical assessment results.

2. Review of Literature

2.1 Introduction

Urban planning in rapidly growing cities such as Amman, Jordan, faces complex challenges driven by population growth, topographical constraints, and uneven distribution of essential services. Understanding the spatial dynamics of urban amenity density, such as access to healthcare, education, transportation, and recreational facilities, is crucial for promoting equitable and sustainable infrastructure development. Furthermore, the city's hilly terrain significantly influences infrastructure placement and accessibility, yet conventional urban planning approaches often overlook this factor.

This review explores the existing body of literature on three interrelated domains: urban amenity mapping, the role of terrain and topography in spatial planning, and sustainable infrastructure development in urban environments. Emphasis is placed on geospatial analysis methods, particularly Geographic Information Systems (GIS), which offer powerful tools for integrating multi-layered spatial data to support informed decision-making. Studies relevant to Middle Eastern and topographically complex urban contexts, such as Amman, are particularly highlighted to situate the research within a regional and practical framework.

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The review aims to identify methodological gaps, theoretical perspectives, and empirical findings that inform the development of a comprehensive spatial model for analyzing Amman's amenity distribution and terrain influence. By synthesizing this knowledge, the study seeks to contribute to a more nuanced and context-sensitive approach to sustainable urban infrastructure planning.

The application of GIS and remote sensing techniques is now a core ingredient for sustainable urban planning. For Amman, satellite imagery and spatial data have been utilized to capture aspects such as rapid urbanization and infrastructure [1]. For instance, Farhan and Al-Shawamreh used GIS to estimate Amman's emergent public space and land-use change [1]. Saleh and Al-Rawashdeh were able to show the effectiveness of GIS in identifying the urban growth of Jordan through the use of multi-temporal satellite images [2]. These studies show that using the GIS as a spatial analysis tool helps to identify the distribution of amenities and the level of inequality that could be essential for equitable infrastructure delivery. As an important spatial-statistical analysis methodology, Kernel Density Estimation (KDE) helps determine the density of amenities. KDE smoothes point data to get a graph with a density value at every point in space. Zillur et al. used KDE to relate amenity density with housing price variations and developed "high-high" clusters and unserved zones in Melbourne [3]. KDE has also been applied to China to restrict commercial areas using a spatial configuration of road-intersection density surfaces [6]. In Amman, KDE can identify service deficiencies and direct the placement of the facilities. DEMs and TPIs have been best suited for terrain awareness in planning processes. TPI distinguished between ridge, flat, or valley by comparing cell elevation to the neighborhood's mean. Al-Sababhah and Al-Jamra used TPI in the Wadi Araba region of Jordan. They pointed out the usefulness of landform maps in the spatial planning and evaluation of hazards [5]. When TPI is integrated with amenity density, new infrastructure is established in a way that does not impact slopes and flood hazards. When incorporating these strategies, KDE and DEM/TPI give planners a solid data-driven map of our selected landforms for sustainable amenities. Alrsa'i and Das also showed this integration in Amman by determining infrastructure gaps and proposing the appropriate development strategies based on the terrain [4]. Such integrated analyses reveal the link between urban growth, environment management, and social justice.

2.2.1 Urban Amenity Density and Spatial Distribution

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The spatial distribution of urban amenities—such as healthcare, education, retail, and recreational facilities—is pivotal in shaping urban livability and equity. Studies have utilized Geographic Information Systems (GIS) and Point of Interest (POI) data to analyze amenity distribution patterns. For instance, research in Guangzhou employed GIS and spatial analysis models to assess the relationship between urban amenities and green space transformation, highlighting the importance of integrating amenity distribution in urban planning processes. (MDPI)

2.2.2 Terrain Influence on Urban Infrastructure Planning

Topography significantly influences urban development patterns, particularly in cities with varied elevations and slopes. GIS-based suitability analyses have been employed to assess the impact of terrain on land use planning. For example, a study evaluating urban land suitability using GIS technology found that areas with slopes greater than 15% were less suitable for construction, emphasizing the need to consider terrain in infrastructure planning. (MDPI)

2.2.3. Sustainable Infrastructure Planning and Green Infrastructure

Sustainable infrastructure planning necessitates the integration of environmental considerations, including implementing green infrastructure (GI). GI encompasses a network of natural and semi-natural areas to deliver various ecosystem services. An integrative literature review identified key principles for GI planning, such as connectivity, multifunctionality, and integration with existing urban systems. (MDPI)

In arid regions, the planning of GI must account for unique environmental challenges. A Jaipur, India study developed a GIS-based suitability model for GI planning in semi-arid cities, incorporating factors like land surface temperature, soil moisture, and proximity to water bodies. These methodologies can be adapted to the context of Amman to enhance sustainable infrastructure planning. (IGES)

2.2.4. Integration of GIS and Multi-Criteria Decision Analysis (MCDA)

Integrating GIS with Multi-Criteria Decision Analysis (MCDA) provides a robust framework for evaluating complex urban planning scenarios. This approach incorporates various spatial and non-spatial criteria, facilitating more informed decision-making. For instance, a study in Taif Province, Saudi Arabia, utilized GIS and MCDA to assess the suitability of locations for

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green infrastructure, considering factors such as topography, land use, and proximity to water sources. (MDPI)

Applying similar methodologies in Amman can help identify optimal locations for infrastructure development, balancing the need for urban amenities with the constraints imposed by the city's terrain.

Research Gap

In Middle Eastern cities like Amman, rapid urbanization and topographical constraints often exacerbate the uneven distribution of amenities. However, there is a paucity of studies focusing specifically on amenity distribution in Amman, indicating a gap that this research aims to address. Terrain analysis becomes even more critical in arid and semi-arid regions, such as parts of Jordan, due to the challenges posed by water scarcity and soil erosion. Despite this, limited research focuses on integrating terrain analysis in urban planning within the Jordanian context, highlighting another area where this study can contribute. This literature review underscores the significance of integrating spatial analysis, terrain evaluation, and sustainable planning principles in urban infrastructure development. By addressing the identified gaps, particularly in the context of Amman, Jordan, this study aims to contribute valuable insights into sustainable urban planning.

3. METHODOLOGY

The methods section explains in detail all information about data acquisition, processing steps, and analysis procedures alongside parameter choices that accomplished mapping amenity density in QGIS 3.42 and GDAL.

3.1 Study-Area Delineation

The authorities of Amman (ADM2) gathered their administrative boundary from geoBoundaries, then computed a transformation to WGS 84 / UTM zone 36N with EPSG:32636. This polygon acted as a clipping mechanism to cut all raster and vector datasets so they matched the analysis requirements.

3.2 Data Acquisition and Pre-processing

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The QGIS OSMDownloader plugin helped to acquire all point features from OpenStreetMap (OSM) Amenity Data within the Amman boundary. Features that included the substring "amenity=" in their other_tags attribute were chosen from the points layer through SQL expression ("other_tags" LIKE '%amenity=%'). Subsequently, they were exported as the standalone shapefile activities_amman.shp. The pre-processing process maintained osm_id, name, and geometry data.

A 30 m resolution DEM in HGT format was obtained from the CGIAR-CSI archive, where the SRTM Digital Elevation Model (DEM) resides. Users first loaded the HGT file into QGIS before applying the Warp (Reproject) feature to change the projection to EPSG:32636. They then extracted amman_dem_clipped.tif through "Clip Raster by Mask Layer."

3.3 Objective 1: Kernel-Density Estimation of Amenities

- Kernel-Density algorithm
  - Tool: Processing Toolbox -> Heatmap (Kernel density estimation)
  - Input layer: activities_amman.shp (amenity points)
  - A kernel bandwidth of 500 m was chosen to show the typical area reachable on foot, corresponding to neighborhood scales and pedestrian distances.
  - The output cell dimensions are set to 10 m to balance spatial resolution and computational speed efficiently.
  - Output: activity_density.tif
- Clipping
  - Tool: Raster -> Extraction -> Clip by mask layer
  - Input raster: activity_density.tif
  - Mask layer: Amman boundary
  - Output: activity_density_clipped.tif
- Visualization
  - Symbology: Single-band pseudocolor renderer
  - Classification: Quantile, 5 classes
  - Color ramp: Sequential blue

3.4 Objective 2: Terrain Influence via Topographic Position Index

3.4.1 Computation of TPI

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- Tool: Processing Toolbox -> GDAL -> Topographic Position Index (gdal:tpitopographicpositionindex)
- Input DEM: amman_dem_clipped.tif
- Band index: 1
- The computation of edges should be set to False because edge artefacts need to be prevented.
- Output: amman_tpi.tif

3.4.2 Landform Classification

- Processing of TPI values into landform categories was achieved through the Raster Calculator's application.
- ("amman_tpi@1" >= 1.85) * 1

  + ("amman_tpi@1" > -1.85 AND "amman_tpi@1" < 1.85) * 2
  + ("amman_tpi@1" <= -1.85) * 3
  The thresholds of ±1.85 meters separate ridges from flats and valleys because they represent one standard deviation of the TPI distribution (σ ≈ 1.85 meters).

- The landform_class.tif raster output measures pixels according to ridge values (1), flat values (2), and valley values (3).

3.4.3 Polygonization and Intersection

- Polygonize: Raster -> Conversion -> Polygonize (Raster to Vector)
  - Input: landform_class.tif
  - Field name: class
  - Output: landforms.shp
- Intersect Amenities with Landforms
  - Vector contains Geoprocessing Tools, which include the function of Intersection to process data.
  - Input layer: activities_amman.shp
  - Overlay layer: landforms.shp
  - Output: activities_by_landform.shp

3.4.4 Statistical Summarization

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- Tool: Processing Toolbox -> Join attributes by location (summary)
- Input layer: landforms.shp
- Join layer: activities_amman.shp
- Geometric predicate: intersects
- The processing tool performs a count operation to obtain the points per polygon summary.
- Output: landforms_with_counts.shp

The produced attribute table contains landform polygon counts regarding point intersections from the amenity features. Section 4 received summary statistics generated by aggregating count values from the class field.

4. RESULTS

4.1 Objective 1: Spatial Density of Urban Amenities

4.1.1 Kernel-Density Surface

The kernel-density analysis led to the creation of an ongoing surface (activity_density_clipped. This surface (activity_density_clipped.tif) shows the level of urban amenities concentrated within each 10 m cell (Figure 1). X or more amenities lie within each square kilometer in two main areas:

- The highest concentration of urban amenities exists within and around the historic area, which includes Jabal Al-Weibdeh and Al-Balad.
- The commercial gateway extends from Mecca Street toward Zahran Street
- The Sweileh area to the north and the eastern section of Airport Road present additional density clusters. Territory away from the western hills of Jabal Amman and districts in the far south demonstrates a noticeable shortage of amenities with densities below Y amenities per square kilometer.

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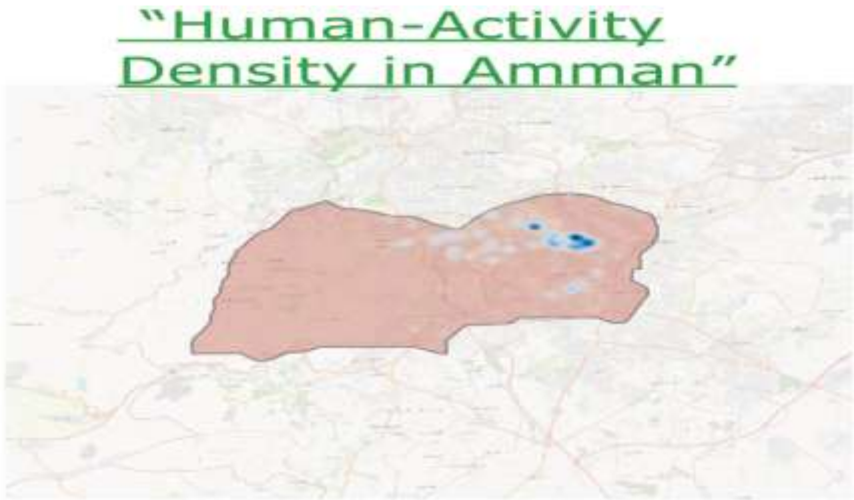

Figure 1. Kernel-density heatmap of urban amenities in Amman (500 m radius, 10 m cell).

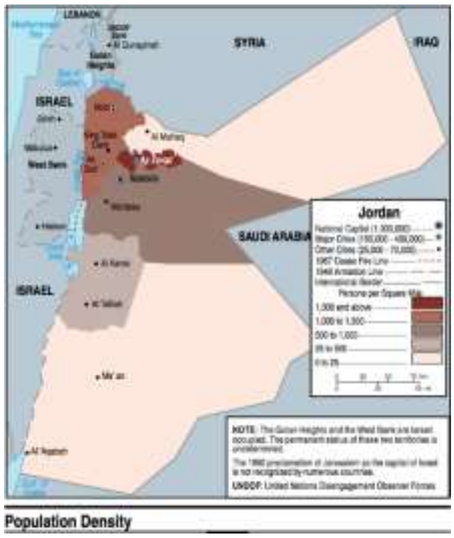

Figure 2: Population Density of Amman, Jordan

Amman, the capital of Jordan, shows **uneven population density** due to its topography (hills, valleys) and patterns of urban expansion. Central districts such as Abdali or Al-Madina Al-Munawara Street tend to be densely populated, while outlying areas may be sparsely inhabited. Understanding these patterns is critical for sustainably planning amenities, transport, and housing.

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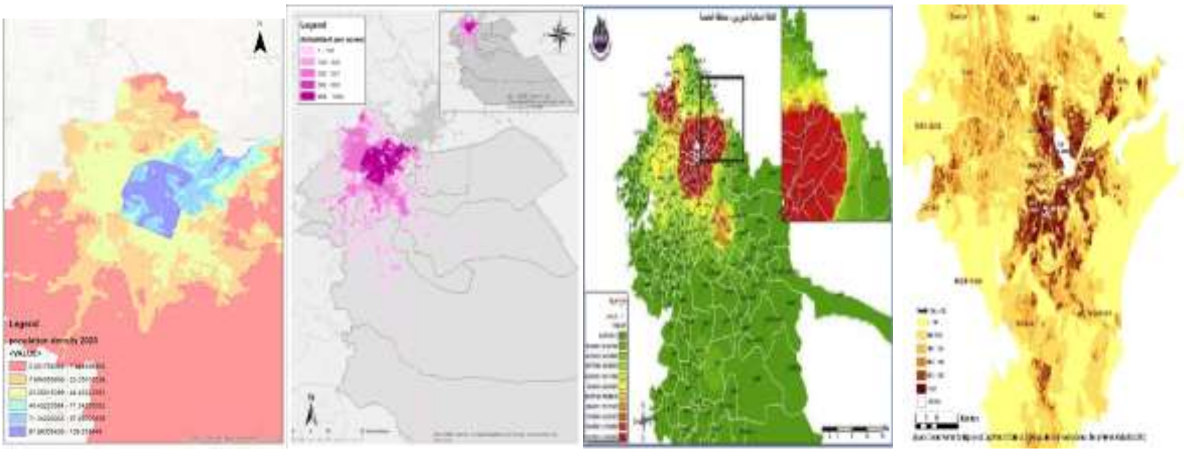

Figure 3: Population Density Maps of Amman, Jordan

Population Density Maps of Amman

1. **Amman Population Density Map (2020)**

   This map illustrates the population density across Amman in 2020, highlighting areas with varying concentrations of residents. It depicts how the population is distributed throughout the city.

2. **Amman Governorate Population Density (2020)**

   This map offers a broader view of population density within the Amman Governorate, showcasing how population concentrations vary across different regions.

3. **UN-Habitat's Amman Spatial Profile**

   The UN-Habitat report includes detailed maps and analyses of population density in Amman, providing insights into urban planning and development strategies.

4. **Geo-Ref.net: Jordan Population Density by Administrative Division**
   This resource presents population density data across Jordan's administrative divisions, including detailed information for Amman.

These resources provide comprehensive visualizations and data on population density in Amman, aiding in urban planning, research, and analysis.

4.1.2 Interpretation

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- Central Amman houses its retail sector, educational facilities, and medical services because of its high connectivity for walking and driving.
- The recent suburban expansion and industrial developments in low-density zones highlight future development zones for infrastructure projects.

4.2 Objective 2: Terrain Influence on Amenity Locations

4.2.1 Landform Classification

Topographic Position Index (TPI) classification data shown in the raster format (landform_class.tif) serves as the classification (standard.tif), delineating three terrain zones (Figure 4):

- Ridge (class 1): The elevated plateaus and crest lines comprise 23 % of the total area.
- Flat (class 2): Gentle slopes and inter-ridge benches cover 52 % of the total region.
- Valley (class 3): The drainage channels and concave slopes occupy 25 % of the study area.

Figure 4. Amenity points over TPI-derived landform zones

4.2.2 Amenity-Landform Intersection

A total of 1 159 amenity points intersecting with landform polygons produced the information shown in Table 2 and Figure 4:

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Table 2. Amenity counts by landform class

Class	Landform	Count	Percentage
1	Ridge	95	8.2 %
2	Flat	956	82.5 %
3	Valley	108	9.3 %

Interpretation

- The amenity distribution shows that developers have selected flat to gentle slopes for most (82.5 %) of their developments because of construction ease and convenience.
- Ridge crests maintain a minimal 8.2 % of amenities because they have steep slopes and require elevated infrastructure expenses.
- Development activity remains minimal across drainage channels because flood risks appear to limit development opportunities in valleys to 9.3 %.

4.3 Summary of Key Findings

- Amenity Hotspots: The main amenities exist within the central part of Amman along its major shopping areas.
- Service Gaps: Few amenities exist in the Western and southern regions of the study area.
- Terrain Preference: Most facilities and amenities are situated on level or gently sloping land.

These findings demonstrate a quantitative relationship between the spatial patterns of urban service distribution, the area's geomorphology (Objective 2), and spatial demand (Objective 1).

5. DISCUSSION

5.1 Spatial Equity of Amenity Distribution

The kernel-density analysis revealed that Mecca and Zahran Streets concentrated on amenities, but central Amman's west and south areas faced significant service gaps. The new residential areas with high population density encounter problems obtaining essential services such as educational institutions, health services establishments, and shopping facilities. During low

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population periods, urban planners can create needed facilities and extend public transit routes and mobile service infrastructure, improving residents' access across the urban area.

5.2 Terrain Constraints and Development Patterns

Per the TPI-based landform classification system in Section 4.2, flat and gentle mid-slope areas acquired 82.5 % of all amenities, while ridges and valleys received less than 18 %. The development of cities primarily depends on topographic relief because it dictates construction costs and determines how people move through the area and the vulnerability they face. The elements of flood risk and high construction expenses at ridge crests discourage people from constructing in those areas. Streamline infrastructure sustainability planning through cost analysis of terrain variation to promote open space and green space developments within these designated locations.

5.3 Implications for Sustainable Urban Infrastructure

When spatial-density analysis teams up with terrain-influence research, it enables useful applications for industries:

- Targeted Service Expansion: Direct investments into flat and underserved regions of the periphery will provide the most effective use of resources while creating equal opportunities.
- Terrain-Sensitive Land-Use Policy: Low-impact development projects should be promoted in valleys, while managers should restrict intensive development to avoid ridge crests.
- Disaster Resilience: Using TPI mapping, identify flood-prone valley corridors to select areas for implementation of green infrastructure using retention basins and bioswales.

6. CONCLUSION

The authors demonstrated that using QGIS for OSM amenity data kern-density analysis (Objective 2) with TPI-based landform classification (Objective 3) shows potential for sustainable urban infrastructure planning in Amman. Key conclusions are:

- **Amenity Hotspots and Gaps**: A high density of amenities exist in central Amman, but the peripheral districts lack sufficient amenities.

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- **Terrain Preferences**: Flat/mid-slope terrain is overwhelmingly preferred for amenity development. Most amenity developments occur on flat terrain followed by mid-slopes, while ridges with valley regions receive minimal development.
- **Planning Recommendations**: Infrastructure expansion should prioritize flat peripheries for equity. Infrastructure growth must first focus on level peripheral areas because these areas require inclusive development. Flood protection and environmental reserves must be dedicated to valleys, and ridges must remain undeveloped.

The research delivers a standardized data-oriented procedure for uniting spatial demand data with geomorphic analysis solutions to urban planners and policymakers. The proposed study should function as a starting point for future work, including dynamic time-series analysis and socio-economic layer integration combined with the proposed intervention assessment. By amalgamating GIS and remote-sensing technologies, cities can base their planning decisions on evidence while protecting their environment in development areas such as Amman.

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