ISSN: 2093-5374 / E-ISSN: 2093-5382

GIS Based Analysis of Urban Street Network Evolution and Morphological Patterns in Kufa City

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Received: March 12, 2026; Revised: April 17, 2026; Accepted: June 05, 2026; Published: June 30, 2026

Abstract

The street network can be seen as the backbone of any urban system. This paper will consider the city of Kufa in Iraq, which is an urban agglomeration whose growth was heavily dependent on the presence of the Great Mosque in it. This rapid expansion and the presence of the organic, radial, irregular, and grid patterns of streets have caused complex urban morphology, which calls for spatial analysis in order to comprehend the urban pattern. The research problem in this paper is the absence of spatial modeling techniques that would help understand changing patterns of streets in historically layered cities. The methodology of this study lies in the Geographic Information System (GIS) approach through the use of ArcMap. Apply the georeferencing method, where the UTM coordinate system shall be used, along with other processes such as data integration, creating a spatial database, and multi-layering maps. The data sources to be used will include historical maps, remote sensing images, field surveys, and urban data. Street networks are classified based on spatial geometry, connectivity, accessibility, and urban development phases to examine structural variation across the city. Four distinct street configurations dominate the findings: organic formation in the historical centers, radial configuration around the Great Mosque, irregular transitional regions, and grid formation in the modern expansion area. In terms of time trend analysis, the trends show an organic pattern dominating prior to 1870, followed by a combination of radial and irregular street systems between 1920 and 1970, and a structured grid pattern since 2003. The grid pattern is a clear indication of improved connectivity and accessibility over previous street formations. The current paper provides an analysis of the morphological development of the streets of Kufa via the use of GIS in the context of the Future Internet, characterized by such attributes as smart urban system, geospatial connectivity, and digital infrastructure. This study highlights the importance of GIS-based spatial systems and digital mapping frameworks in analyzing urban street networks and supporting data-driven urban planning and sustainable development strategies.

Keywords: GIS Analysis, Street Networks, Urban Morphology, Kufa City, Spatial Mapping, Urban Planning, Geospatial Modeling.

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA), volume: 17, number: 2 (June-2026), pp. 821-839. DOI: *10.58346/JOWUA.2026.I2.046*

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1 Introduction

The street network represents the basic structure of any urban settlement and has shaped the way in which people move to and from cities, how people have settled in cities, accessibility within a city, and the whole structure of urban settlement. Street patterns are influenced by the terrain (e.g., ridges and valleys), the raw material available, and the long processes of history through which cities have grown, which create their overall form and function (de Gruchy et al., 2021). Street patterns help to shape whether and how cities grow, how they function in the world, and whether they can maintain the complex economic and social activities for which they were designed.

The Great Mosque is positioned in the heart of the ancient city of Kufa, in the province of Najaf, Iraq, and acts as an important physical marker that affects the urban form and development of the surrounding area (Mohsen Kizar et al., 2022). The street pattern of the city of Kufa will be discussed with respect to the historical development of the city and modern interventions in urban planning and layout of streets, with their implications for urban mobility and growth. Street pattern is one important component for planning the city, in which a clear understanding of urban space and ordering, spatial efficiency, planning for effective mobility, land utilization, and urban growth dynamics can emerge (Mohammed & Alrobaee, 2024). Urban planning research on street patterns enables planners to find how to establish efficient road networks so as to reduce traveling costs and time, create good accessibility, and minimize the possible noise and air pollution. However, organic patterns that exist without comprehensive plan development and growth often lead to traffic congestion, ineffective traffic services, and limited access.

Kufa's street pattern is a mixed form, that is, organic, radial, irregular, and rectangular/grid, which can make a good reference for discussing the relationship between history and modern planning methods. There are some difficulties for historic cities in incorporating new types of land uses and new infrastructure requirements that have appeared as a result of modern development in the city's function. Due to the increasing scale and complexity of cities, more and more people turn to spatial tools such as software-based geospatial infrastructure for urban analysis, such as GIS, to explore patterns and organize, in general. This work sets out to make better use of street pattern mapping as a GIS-based tool in analyzing Kufa's morphology to highlight some aspects of spatial organization for effective planning Desta et al., (2025). The context for urban street networks as Future Internet enabled spatial systems, whereby geographic information systems, intelligent sensing, and digital mapping can be used to comprehend the development of Kufa in terms of its morphology, accessibility, and sustainability.

Key Contribution

1. Created a spatial framework for the analysis and classification of urban street networks in Kufa using GIS, which involved the use of georeferencing, spatial databases, and digital mapping.
2. Mapped four types of street patterns (organic, radial, irregular, and grid), highlighting how these have evolved over time in Kufa since 1870 to the post-2003 expansion era.
3. Showed the application of temporal GIS overlays in determining how the city of Kufa developed over time by clearly noting the shift from organic structure to hybrids and ultimately a planned grid structure.

The structure of this paper is as follows. Section I contains introduction, problem statement, and objectives. Section II gives an overview of the literature. Section III describes the methodology used along with data collection and GIS analysis. Results and street pattern classification are discussed in

Section IV. Implications, limitations, and further research are provided in Section V. Section VI concludes the study.

2 Literature Review

Recent publications point to the significance of spatial analysis based on GIS in studying urban environmental and structural features. Environmental risk due to heavy metal contamination in urban soils of Kufa was studied through geospatial methods (Muslim et al., 2023). Transportation planning in Iraqi cities proves the potential of intelligent mobility systems in increasing the accessibility and urban efficiency (Al-Jameel & Abdabas, 2018). Thus, recent studies prove that spatial technologies play an increasingly important role in studying urban environments.

Transformation and sustainable development of urban land use are also popular themes among recent publications. It is proven that urban land use has a significant impact on the functional structure and urban development pattern in cities (Albasri et al., 2023). Sustainable urban housing and greening in Najaf City are other examples proving the significance of considering environmental issues in planning frameworks (Hamza & Alrobaee, 2024). Publications on satellite cities prove the necessity of structured urban growth with the help of planning strategies (Al-Nasrawy et al., 2023). Moreover, sustainability assessment of urban street networks proves the significance of spatial indicators in planning analysis (Abrah et al., 2025).

Historical and cultural aspects of urbanism offer more perspectives regarding the development of the street network system. The study on pilgrim movement systems shows how pilgrimage activities affect spatial and infrastructural development over time (Dauphin et al., 2015). Research on the cultural and religious urbanism of Karbala illustrates the link between cultural identity and the urban spatial pattern (Parkes, 2021). Historical urban planning practices stress the need for a balance between maintaining heritage sites and ensuring urban functionality and safety (Alrobaee et al., 2023). These studies collectively demonstrate how historical processes shape contemporary urban morphology.

Environmental and infrastructural issues still form the core of urban sustainability research. Papers related to road systems at the regional level underline the necessity of enhancing transport efficiency in urban network (Abid, 2020). Papers on soil classification and environment reveal the effect of natural factors on the urban development pattern (Al-Bayati et al., 2019). Studies on climatic effects on traditional buildings stress the issue of adaptation in urban design (Alhilo & Ismael Kamoona, 2024). Papers on urban sustainability models and connectivity focus on structural efficiency of city networks (Al-Abayechi et al., 2024). Research on alternative connectivity and historical path ways sheds light on the changing mobility structure (Gambash et al., 2024). Research on environmental pollution, especially those related to wastewater and emissions, stresses the need for an urban environmental management system (Al-Yasery et al., 2025). Industrial environmental research papers also support the idea (Hadi et al., 2022). The literature review emphasizes GIS applications in urban areas based on the Future Internet principles such as smart mobility, spatial intelligence, IoT enabled mapping, and digital urban analytics concerning heritage cities, sustainability, and optimization of transport networks research methodology (Batty, 2018).

According to the literature review, it is quite clear that urban street patterns are significantly impacted by the historical development, environment, and planning intervention. Moreover, spatial analysis using the GIS tool is a vital component of urban morphology. Sustainable transportation, land-use, and the environment collectively affect the strategy of urban development.

3 Methodology

Future Internet–Enabled GIS Data Framework for Urban Morphology Analysis

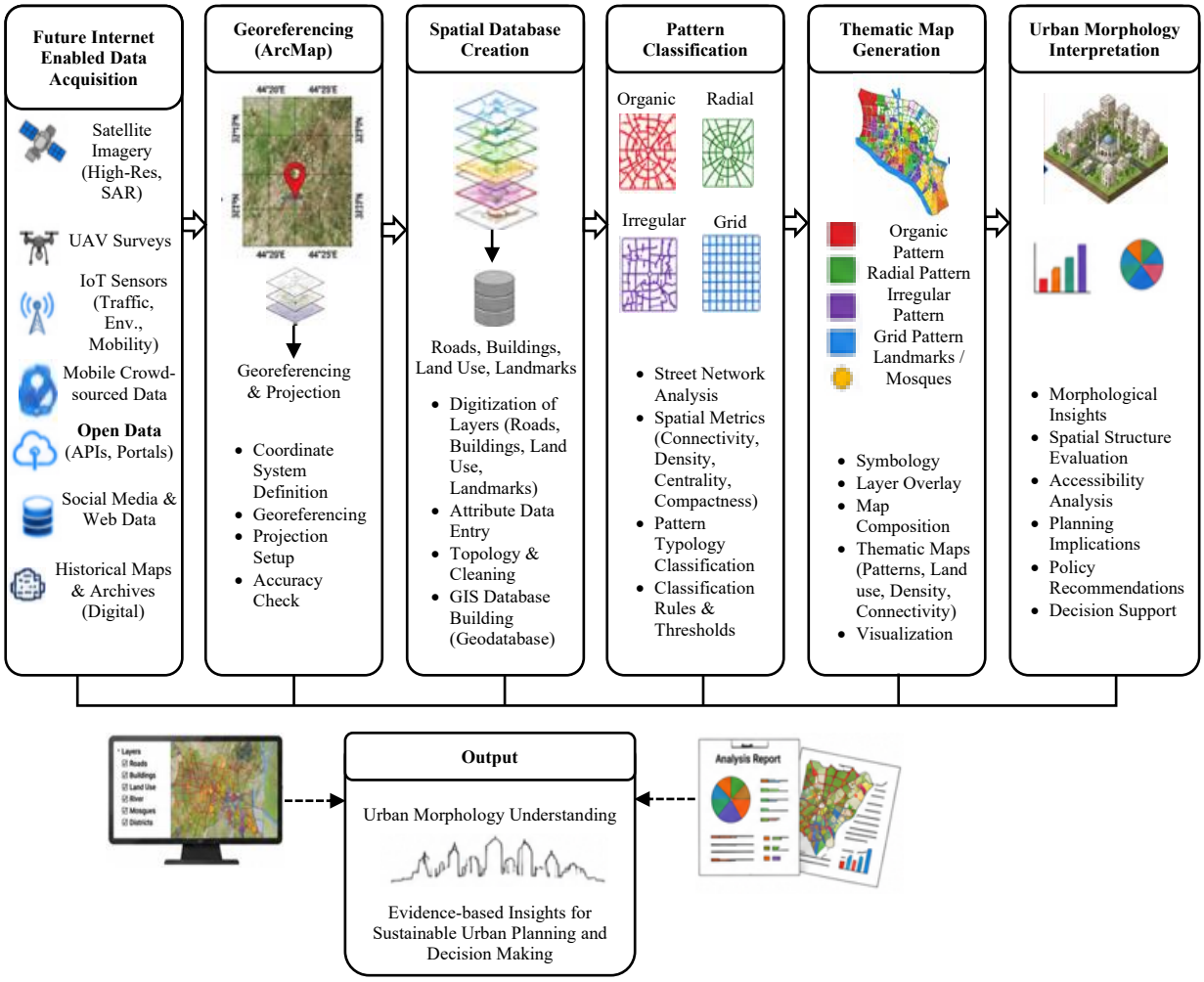

Figure 1: GIS-based urban analysis framework for kufa city

The framework that will be used to analyze the Holy City of Kufa consists of a GIS that is enabled by the Future Internet technology. This GIS involves the integration of heterogeneous, real-time, and multi-source urban data. It uses IoT sensing (traffic, mobility, and environment), UAV and satellite imagery, crowdsourced data from mobile sources, open web APIs, social media feeds, and historic geospatial archives as inputs. They are then georeferenced and preprocessed on a cloud GIS platform using the Universal Transverse Mercator (UTM) coordinate system in ArcMap. A scalable cloud GIS database is established for the storage, integration, and management of spatial layers. Spatial analysis is carried out through AI-enabled spatial metrics and pattern recognition techniques to classify the urban street network into organic, radial, irregular, and grid patterns. The processed data are visualized in Web GIS thematic mapping and 3D urban modeling. Lastly, the framework enables the analytics of urban morphology and decision support systems in urban planning through the Future Internet enablers like IoT, cloud computing, big data analytics, AI & ML, and cyber-physical systems.

This figure 1 shows the overview of the proposed GIS-based analysis framework to understand the urban morphology of Kufa City which encompasses several sequential steps, including: data collection, georeferencing and database building, street pattern classification, thematic map creation and analysis, and the generation of the urban morphology maps of the area concerned, based on the analysis. GIS spatial analysis and cartographic modeling approaches allow effective visualization of the spatial pattern of urban expansion, characteristics of the connectivity network of urban areas for decision support, and, as mentioned, contribute to the planning process in the context of the new urbanism and sustainable urban development.

Figure 2: Georeferenced master plan of kufa city using arcmap

The georeferenced master plan of Kufa City generated using ArcMap under the UTM coordinate system is represented through the current figure 2. This figure indicates the distribution of residential, commercial, institutional, green spaces, and road network as well as the course of river within the city of Kufa.

GIS Software and Tools Used

Kufa City spatial analysis was done using a GIS-based analysis methodology. The methodology includes visualization of the spatial layer using ArcMap (ArcGIS Desktop Environment); the analysis is based on the utilization of Arc Toolbox Spatial Statistics Tools to implement quantitative analysis on spatial data. The analysis was made based on the assumption of the Universal Transverse Mercator (UTM) coordinate system to obtain the accuracy of positioning and GIS digitization, along with layer classification tools to create structured data on spatial data. Kufa City is one of the important religious, Historical, administrative, and trading centers for Muslims within the center of Najaf Governorate; it lies between 32°00′15″ N and 32°04′26″ N, and between 44°20′39″ E and 44°26′28″ E on a global scale. This framework, using GIS, helps to achieve accuracy regarding the analysis of urban morphology and street patterns.

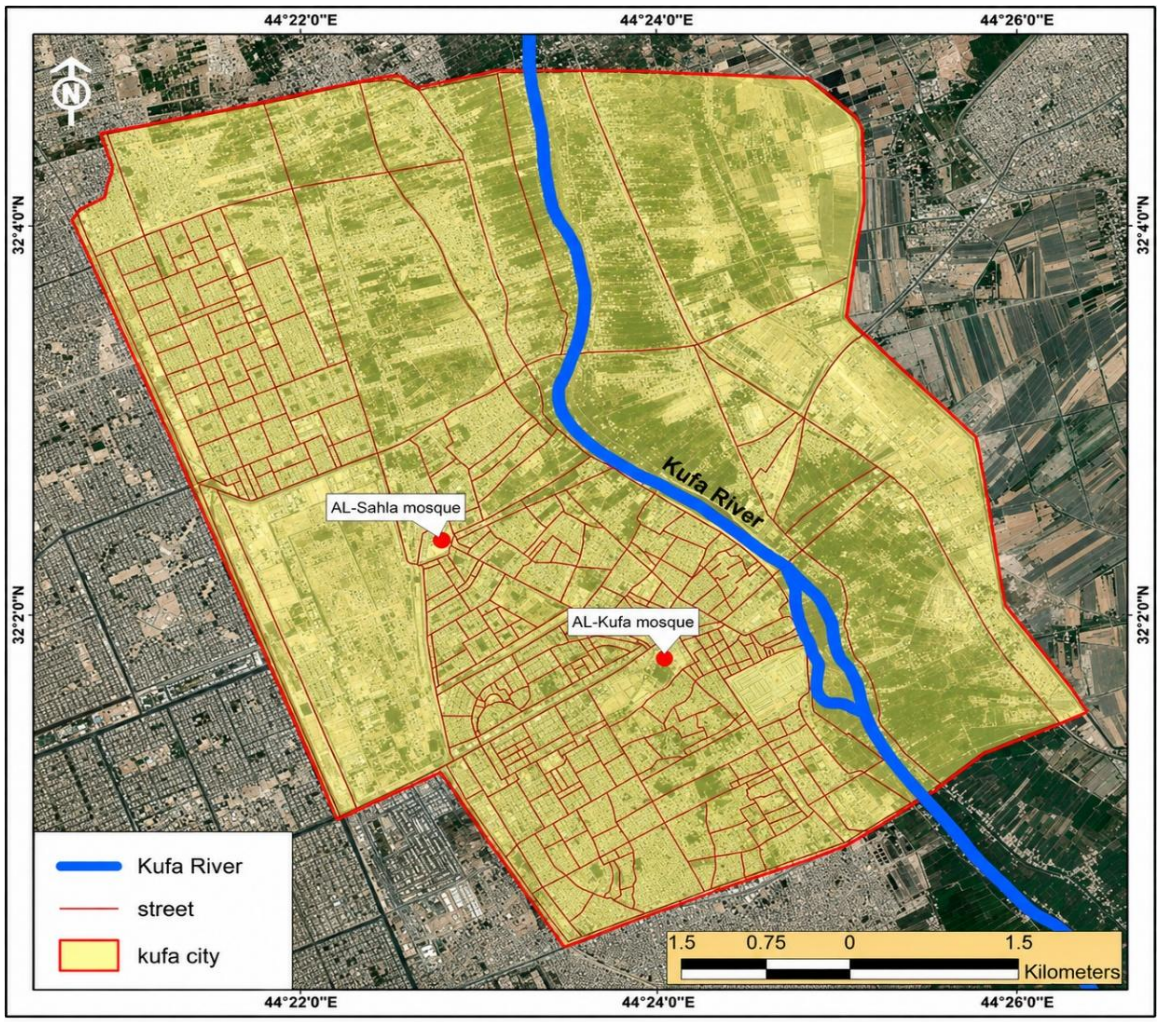

Figure 3: Study area mapping of kufa city

In figure 3 shows the georeferenced spatial map of Kufa illustrating the administrative boundary, Road Network, Kufa River, and religious landmarks. It also shows the distribution of urban land uses and the GIS-based Street Pattern Structure for morphology analysis, spatial analysis, and the study region's morphology.

Criteria for Street Pattern Selection

Great Mosque of Kufa (GMK) the urban framework determines how urban density is dispersed or centralized on the land. There are an estimated 203,065 inhabitants of the city of Kufa, as for 2026. The surface occupied by the Kufa city comprises of 49.44 km where population density decreased from urban core to the urban peripheral zones, thus these districts evolved over time-starting from the core, pre-1870 to post-2003 informal areas, consisting of 26 residential districts. The study on street patterns was carried out on KFA using a GIS approach including geometric aspects, connectivity density, stages of construction, function use of the land, accessibility index which revealed four types of street patterns in the Kufa city; namely organic, radial, grid and irregular types.

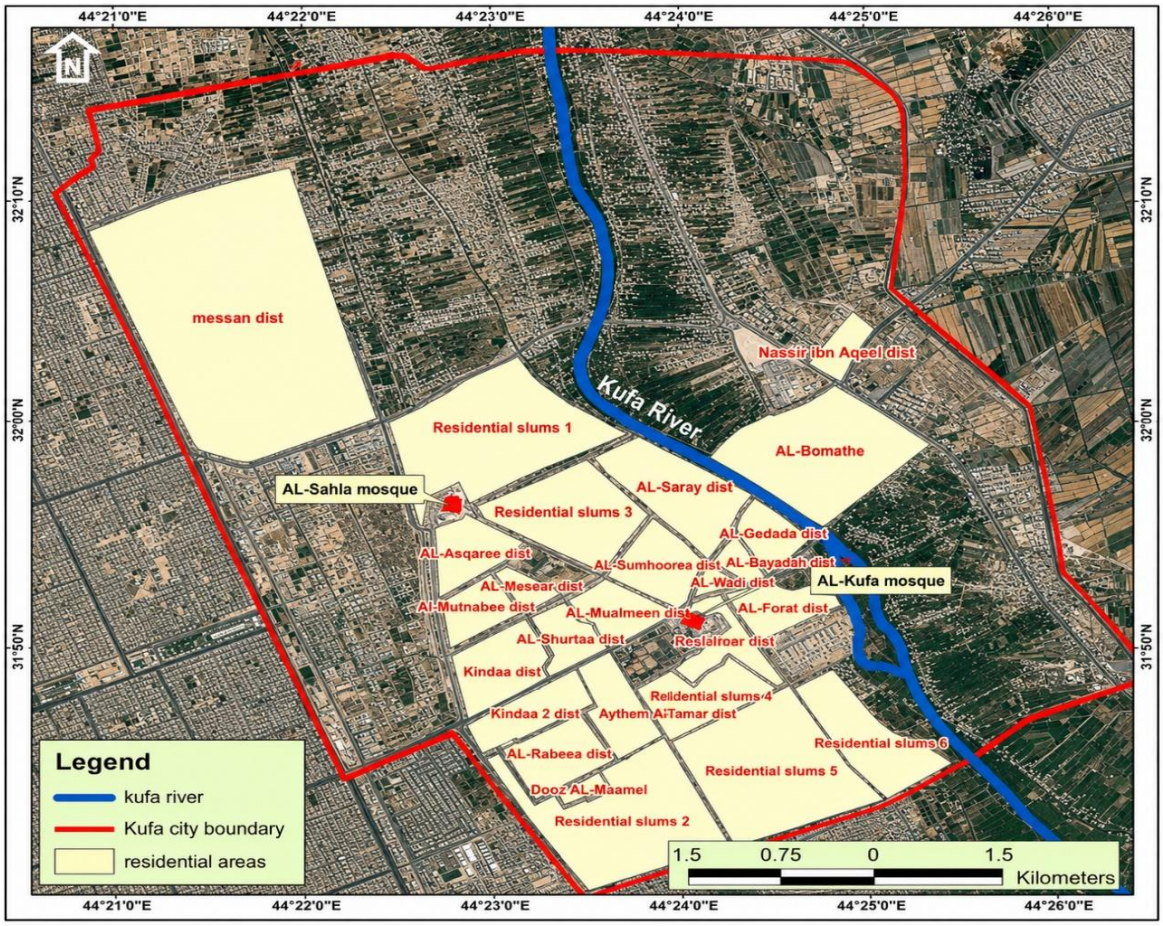

Figure 4: Residential district distribution in kufa

In figure 4 demonstrates the distribution of residential districts in the city of Kufa, displaying the spatial layout of neighborhoods, slums, important districts, and land uses in relation to the Kufa River. It provides information about the pattern of urban development, boundaries, and association with important landmarks.

4 Results

From the results, it is evident that the Kufa streets have been grouped under four main morphological patterns based on GIS: Organic Pattern, Radial Pattern, Irregular Pattern, and Grid Pattern, depending on the various stages of urban development. The results have been discussed with regard to the Future

Internet urban analytics approach, which helps us gain insight into assessing connectivity and evaluating spatial efficiency.

GIS-Based Analysis of Street Patterns

Street pattern maps have a very important role in urban planning since they are important for illustrating the street networks and regularity within cities spatially and historically. The street pattern represents the evolving shape of the city as influenced by its environmental, historical, economic, and social attributes. By GIS analysis, it is observed that Kufa displays a mixed morphological street system, being created from natural growth, along with modern urban planning intervention; therefore, analyzing these patterns is a tool for optimal decisions in mobility, environment, as well as accessibility between the districts.

Organic Street Pattern

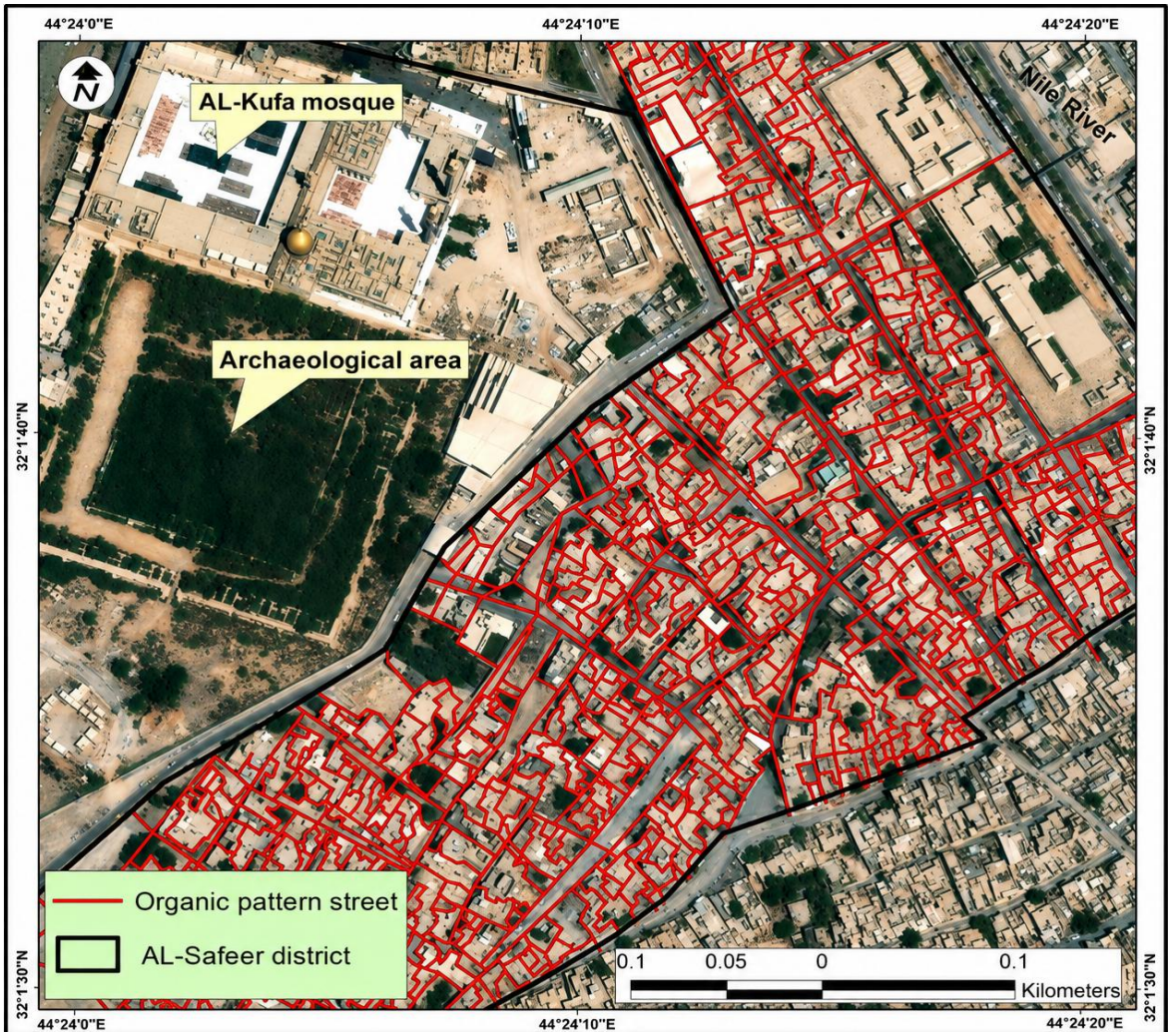

Figure 5: Maps illustrating the organic street pattern in the al-safeer district. (Kufa city)

The organic streets pattern is defined by narrow irregular alleys and a non-straight pattern. Also known as 'winding and random' pattern, which grows gradually through informal and organic development of the city itself through self-organization of bottom-up design. In Kufa, the dominant areas with organic

patterns are the old Kufa quarters (Al-safeer) along with informal residential areas which contain informal settlements (Residential Slum 4-6). These areas generally have low degree of accessibility and high value of spatial entropy, hence limited mobility.

This figure 5 illustrates the organic street pattern of the Al-Safeer neighborhood of the Kufa city, emphasizing irregular and unplanned street networks within the archeological site and the Al-Kufa Mosque. It represents dense and non-orthogonal urban development that is characterized by low accessibility and high spatial fragmentation.

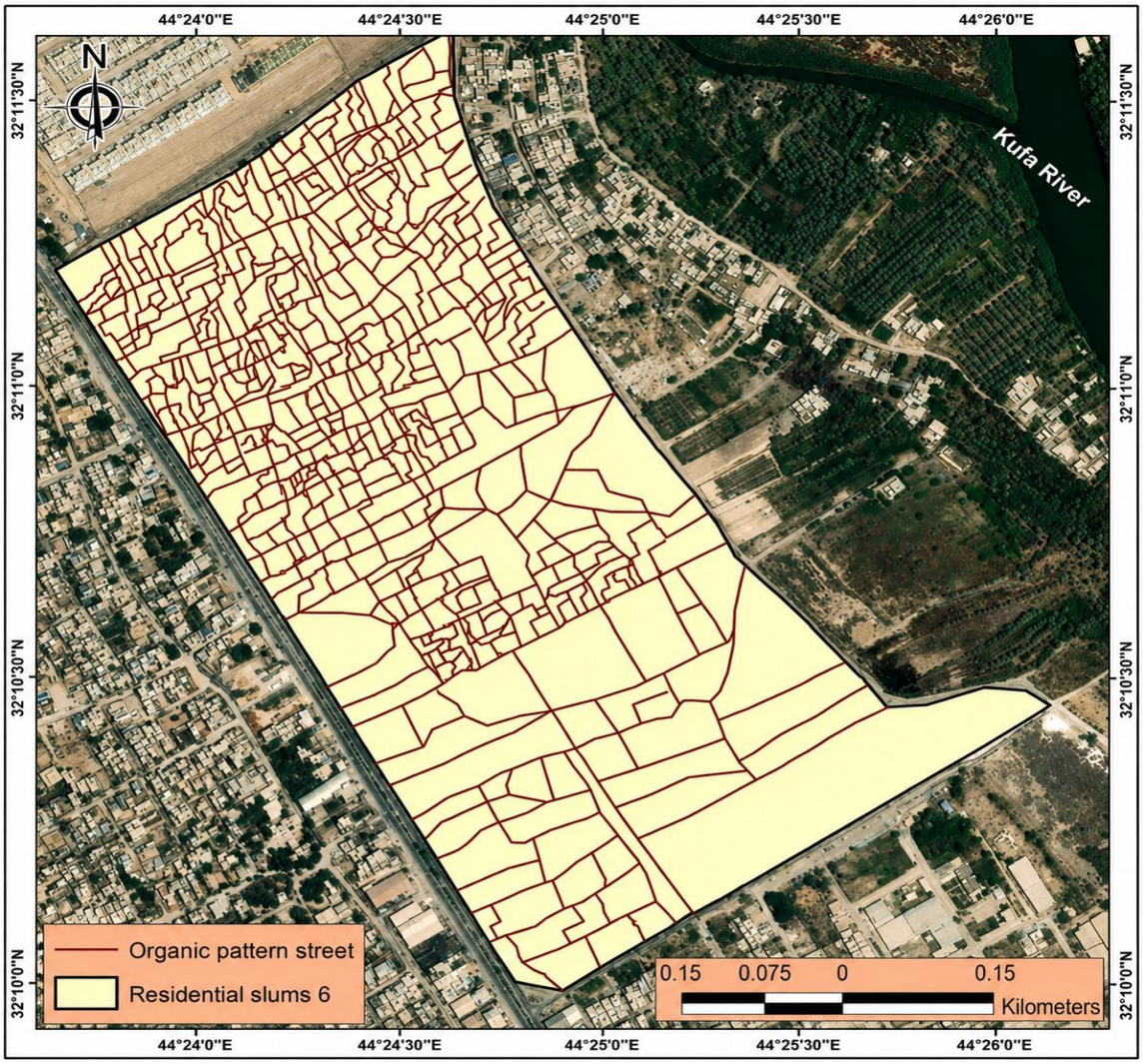

Figure 6: Maps illustrating the organic street pattern slums 6 (Kufa city)

In figure 6 demonstrates the organic street pattern in RS 6, Kufa City, showing fragmented and irregular road networks, which are characterized by many dense and narrow streets that reveal a weak structure and rapid organic sprawling and fragmenting urban form of the study area.

Radial Street Pattern

A radiating street network consists of streets branching out from a central area, the focal point in the city, which can be a commercial or religious institution in the city, resulting in a hierarchical spatial

system. Kufa features the great mosque of Kufa as the core, which radiates roads in the region, major arteries, and connections into the city, like Kufa-Najaf Street, Sahla Street, Bridge Street, and Railway Street, can be used in order to access the region for a religious trip. On the other hand, concentration in the central area might create a traffic congestion issue. The Central business district accentuates this type of radial urban pattern.

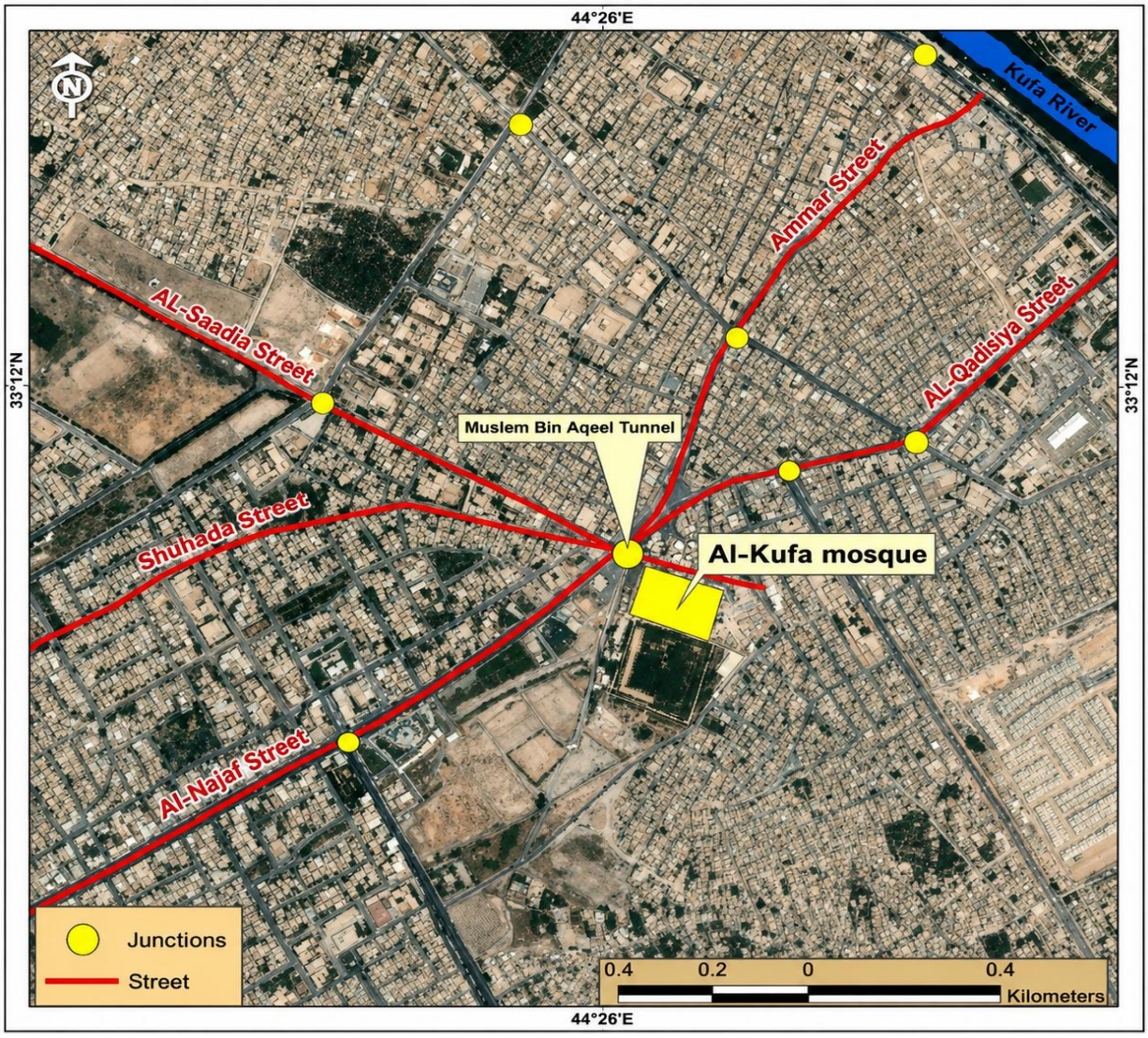

Figure7: Radial street pattern of kufa

In figure 7 shows the radially oriented plan of Kufa with its focus at the Al-Kufa Mosque and illustrates its primary arteries radiating outward, the central arterial routes, the principal intersections (nodes), and connectivity hierarchy. It is an urban analysis showing aspects of city centrality, transportational flows and the organizational structure imposed by religious and mercantile centers.

Irregular Street Pattern

An irregular pattern is characterized by a layout that lies between the non-uniform, semi-formed arrangement (street) and comprises curved and cul-de-sac-type streets; it is a transitional pattern between the 'organic' and 'planned' grid layouts. It can be recognized in some Kufa districts like Al-Sarai,

Al-Jadidat, Al-Rashadiyah, and Al-Waqf, which have moderate interconnectedness, moderate accessibility, and mixed access to the community and roads. Planning and servicing it may present difficulty due to irregular street configuration, but at the same time, it reduces the speed and congestion on streets, creating a more livable and quiet community.

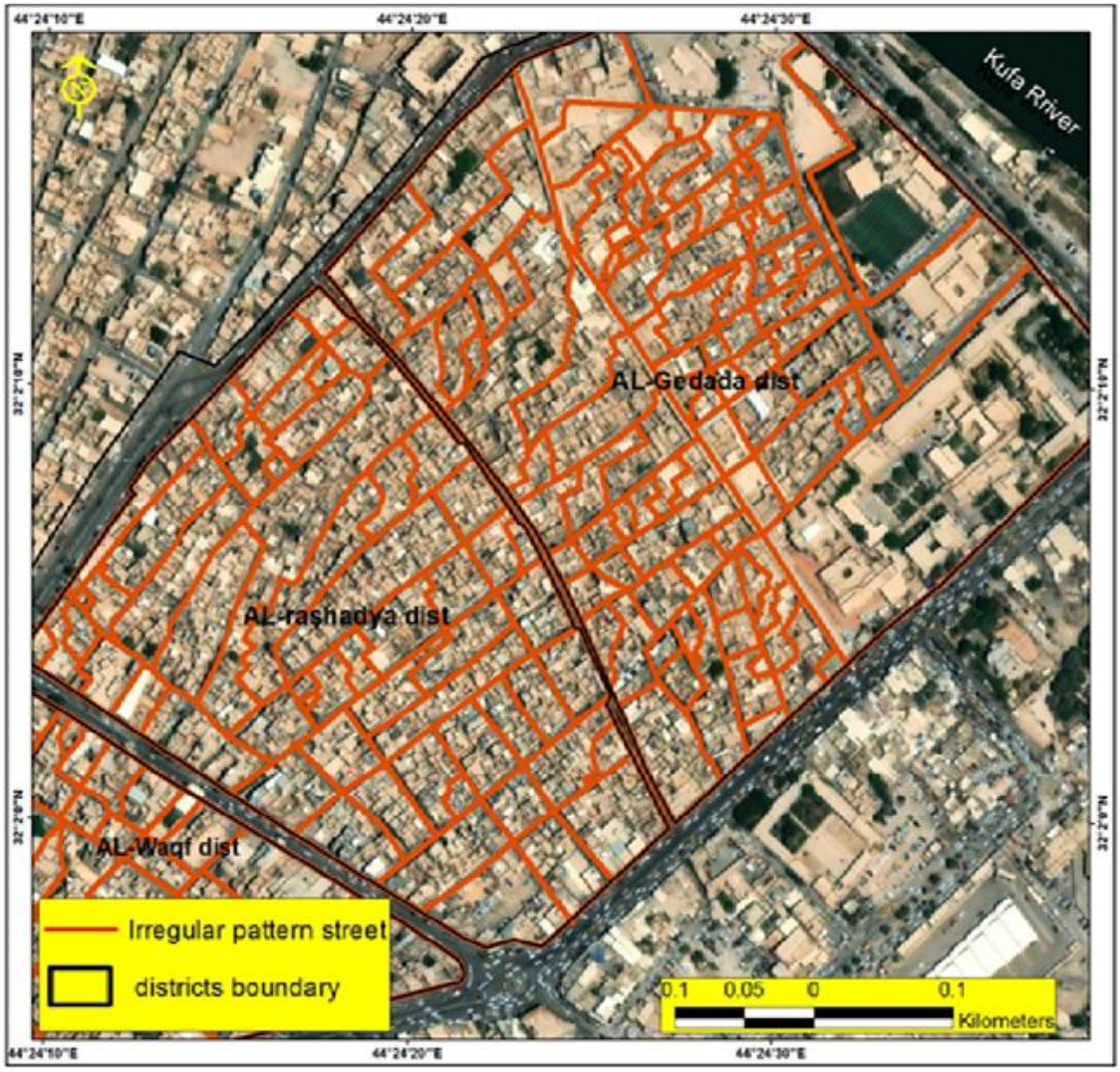

Figure 8: Map illustrating the irregular street pattern

In figure 8 depicts the irregular city form of the city of Kufa, including partially structured and disorganized streets in various forms throughout different urban districts of Al-Rashadiyah, Al-Gedada, and Al-Waqf, indicating partial integration, curved street layouts, and transitional urban fabric between planning and informality.

Grid Street Pattern

Grid plan Street layout the street network of this type of arrangement is organized orthogonally (streets intersecting one another at a 90° angle), which can greatly help in organizing space. In Kufa city, this can be seen most effectively in some modern sectors like Mesan, Al Askari, Al Gameaa, and Al Mutanabbi. The system is consistent with current urban planning and policy strategies to enhance access

and facilitate traffic movement with an effective allocation of land uses. However, this type system has its drawbacks, in that it limits the shade to certain urban areas, causing lower-level climatic satisfaction; the buildings are mostly exposed to the wind and sun. Yet it is considered the most optimal design system.

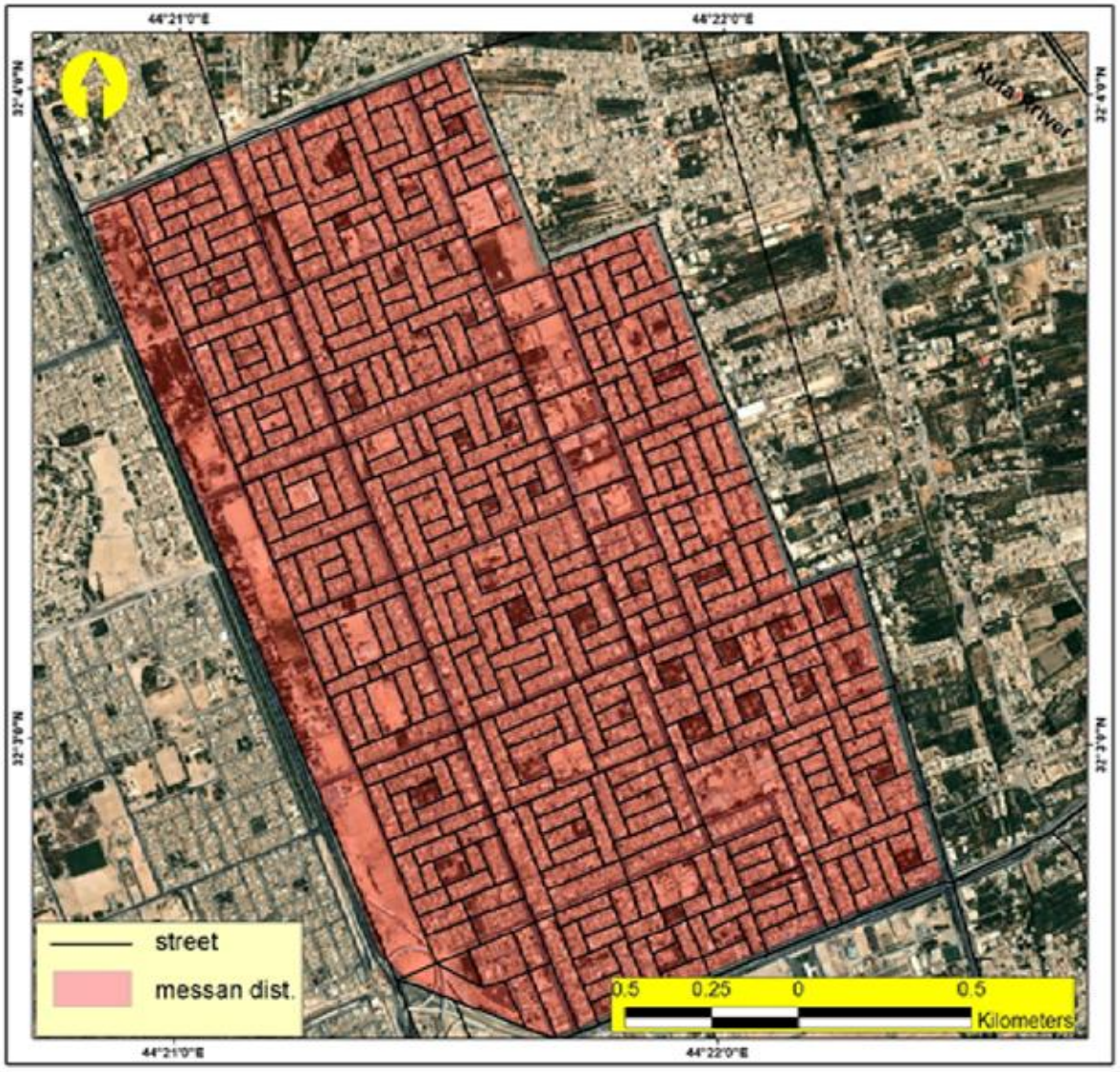

Figure 9: Maps illustrating the grid street pattern in the messan district

The figure 9 represents urban organization for a block in a specific planning district which named Messan district, Kufa city, illustrating orthogonal arrangement of roads, and a high block density with integrated blocks in addition to clear organized land-use inside and outside the block boundary which is designed using the street pattern design of blocks which leads to efficient connection of roads & traffic, increased blocks number, improved access & permeability through the area.

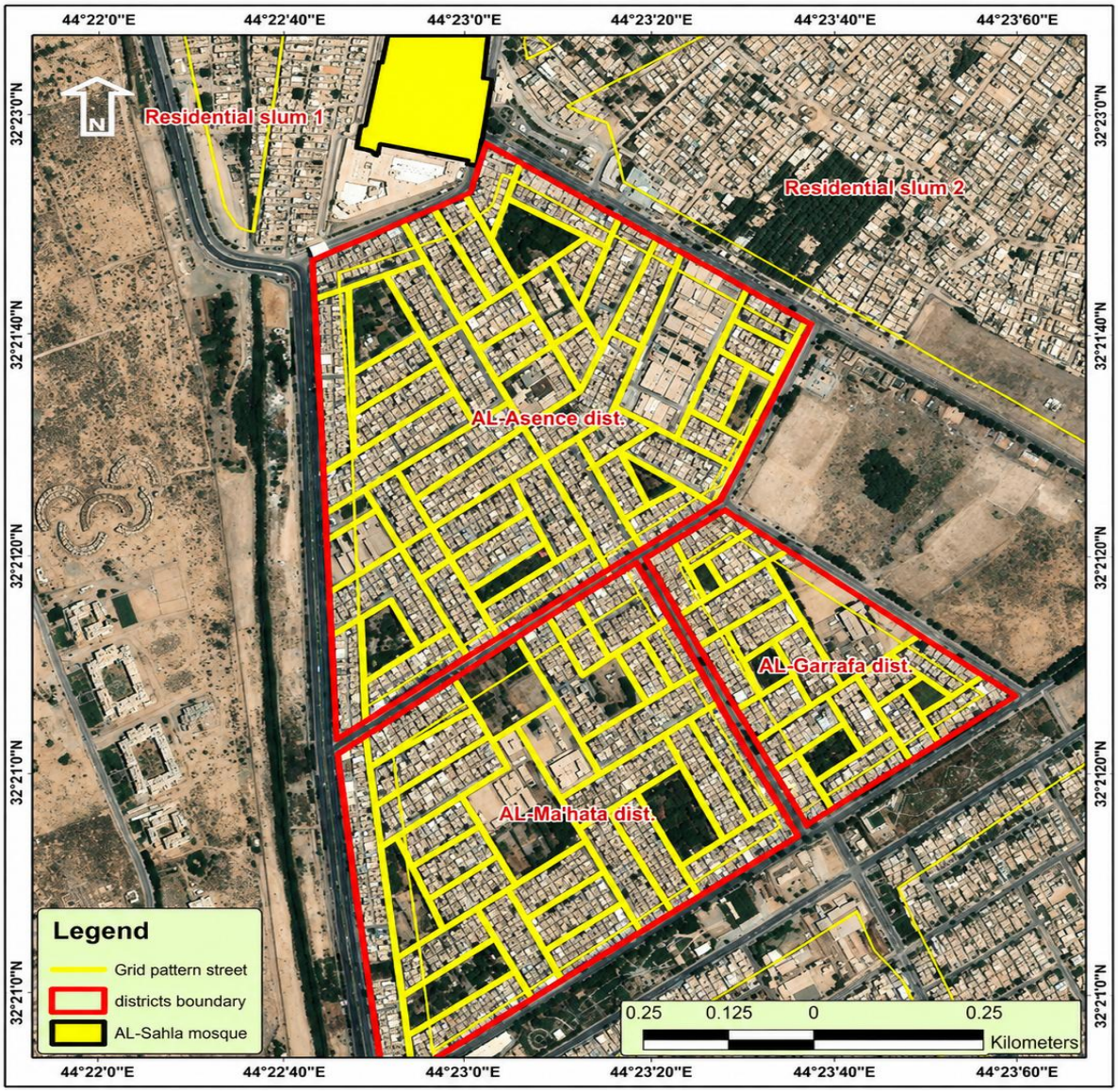

Figure 10: Maps illustrating the grid street pattern in a-asqaree district al-gameaa district al-mutnabee district

In figure 10 shows the grid urban street network of selected districts in the City of Kufa, with rectangular blocks, an orderly grid of orthogonal road networks, and strong connectivity. In the planned zone around Al-Sahla Mosque, it is clear to show an optimal land use plan and good accessibility in the adjacent residential area, which indicates spatial regularity.

Table 1: Comparative characteristics of street patterns in kufa

pattern type	Geometry	Connectivity	Planning type	Functional efficiency
Organic	Irregular	Low	Spontaneous	Low vehicular access
Radial	Centralized	High (core)	Semi-planned	High central access
Irregular	Semi-structured	Medium	Mixed	Moderate
Grid	Orthogonal	High	Planned	High efficiency

The table 1 outlines a Comparison between four styles of streets within Kufa: organic (unstructured, organic street, less access) road designs offer a high central connectivity; a layout consisting of a series

of radial and curvilinear avenues, or a network comprising a certain level of organization of a series of straight street at certain directions which would allow connectivity at different points; a simple, rectilinear pattern and orthogonal (a well-articulated network of orthogonal avenues allowing vehicular movement with a central origin).

Comparison of Historical and Current Street Layouts

Kufa City urban structure based on GIS overlay analysis shows clearly the transformation of temporal characteristics from its historic period to the present, as influenced by old and new development approaches. Before 1870, the most prevalent urban design feature was the organically formed structure with irregular layouts. From 1920 to 1970, it was transformed gradually under expanding influences and limited planned development, which took radial patterns along with existing irregular networks, and following 2003 and intense urbanization, the growth is characterized by a systematic and grid planning-based development. In general, the Kufa urban morphology shows a transitional stage starting from an organic pattern and evolving into the planned structure with the adoption of grid networks after a mixed stage.

Table 2: Temporal evolution of street patterns in kufa city

Period	Dominant street pattern	Urban characteristics
Pre-1870	Organic	Irregular, unplanned, historical core
1920–1970	Radial & Irregular	Expansion phase, mixed structure
Post-2003	Grid	Planned development, high accessibility

In table 2 represents the changes in Kufa street pattern through time Before 1870: Irregular pattern (organic street plan) was characterized in old town. 1920-1970: radial pattern and irregular pattern as a result of urban growth. 2003-present: Grid pattern as a result of planned growth and facility enhancement.

Key Findings and Trends

Kufa city has been developed according to different physical characteristics which reflects four kinds of morphological types (Kufa Great Mosque the spatial and urban centrality, modern planning, the formal city, slum, the informal city, and the modern road system), Kufa's morphology, in general, is characterized by a combination of physical and administrative components. It is divided into different morphological sub-components, such as Kufa Mosque, which has a clear spatial center of the entire city structure and has major impacts on the distribution and accessibility of activities and the degree of density in various ways. Grid the structure of new planning, which had better connectivity. While the street system is not highly functional in the areas of slums, as their street systems are organically characterized. Road connectivity in the city is strengthened through strengthening the hierarchy system.

5 Discussion

Implications for Urban Planning in Kufa

This confirms a set of crucial implications for sustainable development and city planning in Kufa. The unstructured/organic settlements suffer badly from problematic access and inefficient access to the emergency systems owing to the tight unstructured street network. Inwards and the radially expanded cities from central points, such as from the Great Mosque, create an excess accumulation in the urban center as there is pressure in the congestion on the city center. From this a hybrid development planning concept would create equilibrium between modernization of the city, however for its heritage protection

and city planning would benefit from modern city planning tools like those applied using a GIS to enhance traffic mobility and land development to solve the problem of congestion in and outside the study area.

Comparison with Other Historical Cities

The morphology of Kufa aligns closely with that of the other traditional Islamic Cities. It exhibits the universal religious-core based model of the transformation of a traditional settlement form. Baghdadis' circular plan with organic core surrounded by old city remains. The plan of Cairo is one where organic sprawl occurs with later grid urban expansion and the morphological pattern of Damasus has elements of organic growth alongside radially ordered urban sectors that are influenced by factors. These provide evidence of the pattern of the Middle-Eastern tradition where development occurs outwards of religious/cultural focal points and gradual introduction of a more rigidly grid pattern of urban growth is incorporated to the peri-urban areas.

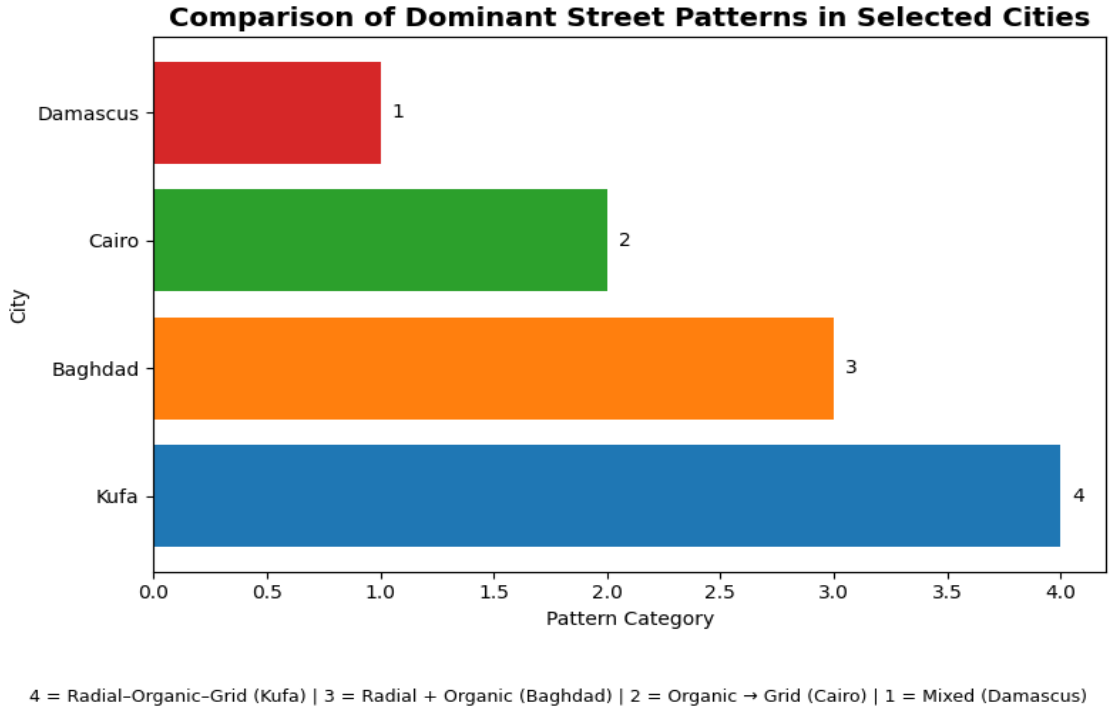

Figure 11: Comparison of dominant street patterns in kufa, baghdad, cairo, and damascus

These figure 11 shows the distribution of predominant street patterns in the four cities as categories. In Kufa, the complex urban form (radial, organic & grid), while in Baghdad it is radial & organic; in Cairo, it changed from organic to grid, Damascus revealed a mixed urban form through a hybridization process.

Limitations of the Study

There are a few limitations to this study. First, a coarse spatial scale is given due to the low temporal resolution of the available historical and satellite images, limiting urban change analysis. Second, the study does not include advanced graph-theoretic or mathematical network metrics for quantifying street connectivity and accessibility. The analysis is limited to GIS-based spatial interpretation and visual

classification. Thirdly, an accurate forecast of urban future growth cannot be obtained as it was not within the scope to build a predictive model of urban change. Lastly, a static analysis based on ArcGIS is performed, but there is no element of automation and incorporation of advanced analytic tools, such as AI and machine learning models, for improving accuracy and reliability for the automated pattern identification and spatial prediction.

Future Research Directions

Future work includes adoption of sophisticated computational methods to improve the analysis of urban morphology using Street network modeling with graph theory to compute different metrics like connectivity, centrality and spatial efficiency, Machine learning to classify urban pattern automatically, time-series imagery of satellites for ongoing monitoring of the urban growth, GIS analysis for comparative study for cities in Iraq and in middle east, and application of Spatial AI and Deep learning models for future predictive urban planning.

6 Conclusion

The study investigated the evolution of spatial patterns of street networks in the city of Kufa employing a GIS-based approach. It is evident that the results show that Kufa has four morphologies, which include organic, radial, irregular, and grid. Organic morphology occurs in the historical parts of the city, with high fragmentation and inaccessibility of streets, with radial morphology being found around the Great Mosque as a focal point in space. Irregular morphology occurs as a transition from historical to modern urban fabric, while grid morphology occurs in modern areas with planning and high connectivity of roads. In the GIS overlay analysis, there is a clear temporal transition from dominance of organic morphology prior to 1870, to radial and irregular growth between 1920-1970, and grid-based growth since 2003.

Grid-based districts demonstrate improved accessibility and better-organized street connectivity compared to organic and irregular areas, based on GIS spatial interpretation, while the organic districts are limited in terms of their level of accessibility, as it is affected by their narrowness and discontinuity of street networks. The radial districts have moderate connectivity, yet higher central congestion in the mosque districts, while irregular districts have intermediate levels of spatial efficiency. It is evident that morphological variation plays a crucial role in influencing urban function and movement. Based on GIS-based spatial interpretation, urban accessibility in grid-based districts appears significantly higher compared to organic and irregular areas, reflecting the impact of modern planning interventions.

All things considered, the importance of GIS-based spatial computing technologies, geospatial urban data bases, and digital cartography systems is highlighted by this research. All these are at the heart of the methodology adopted in this paper. The conclusions made in this study are of high value to urban planners since they serve as a basis for sustainable urban planning, heritage-conscious urban reconfiguration, and transportation network optimization. This methodology is consistent with other approaches applied to analyze complicated urban environments in terms of effective planning and intelligent decision making. The use of GIS in morphological analysis, transitional urban growth can be seen in Kufa, where the principles of the Future Internet play a part in increasing knowledge on spatial connectivity for smart planning and urban governance.

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