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Markov Chain-Based Modeling and Prediction of Functional Urban Land-Use Transformation: A Case Study of An-Najaf City, Iraq

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Abstract: Changes in the functional use of urban land have become an important challenge affecting urban structure and sustainable development. An-Najaf City, Iraq, has experienced substantial functional transformation over the past two decades, including residential expansion, commercial growth, industrial development, and the emergence of informal settlements. This study analyzes functional land-use changes in An-Najaf City and predicts future transformation using a Markov chain model. Land-use data for 2005, 2015, and 2025 were obtained from official records, geographic information system (GIS)-based land-use maps, recent satellite imagery, and field verification. Transition probability matrices were constructed for the 2005–2015 and 2015–2025 periods, and the 2015–2025 matrix was used to predict the functional land-use distribution for 2035. The results show that residential and commercial land uses increased substantially from 2005 to 2025, with commercial land recording the largest increase, from 200.30 ha to 2,204.30 ha. Informal settlements were also identified as an important factor affecting urban functional change. Based on the Markov prediction, residential land is projected to increase to approximately 5,204.7 ha by 2035, slum areas to 482.3 ha, and industrial land to 876.4 ha. By contrast, commercial land is projected to decline to approximately 1,816.1 ha, while the "Others" category is expected to decrease to 204.5 ha. Since the prediction is applied within the defined 2025 study boundary, the total land area remains constant, and the results represent internal functional transformation rather than further physical urban expansion. The findings highlight the need for planning policies that control informal settlement growth, manage residential and industrial expansion, protect supporting urban functions, and promote balanced urban development in An-Najaf City.

Keywords: Markov chain model; Functional land-use change; Urban land-use dynamics; Land-use prediction; Informal settlements; GIS; An-Najaf City

1 Introduction

Urban land use is dynamic and changes in response to population growth, economic restructuring, infrastructure development, and planning policies [1]. Factors continuously interacting with each other reshape the spatial distribution of activities in urban areas by changing land from one functional use to another. In other words, the functional structure of a city evolves over time, influencing urban efficiency, service provision, and sustainability. In urban planning, it is essential to understand the drivers of functional land-use change. Otherwise, uncontrolled land conversion may lead to urban sprawl, inefficient provision of services, environmental degradation, and expansion of informal settlements [1, 2]. As a result, the monitoring of historical land-use transitions and the prediction of future functional changes have become useful tools for evidence-based planning and sustainable urban management [1, 2].

The emergence of advanced spatial analysis tools, such as the geographic information system (GIS), remote sensing, and spatial modelling techniques, has greatly improved the monitoring, classification, and prediction of urban land-use change [3, 4]. Based on these spatial datasets, several quantitative models have been developed for land-use prediction, including Cellular Automata, Artificial Neural Network, Logistic Regression, Random Forest, and Markov chain models [5–8]. Among these methods, the Markov chain model is widely used because it provides a simple and effective mathematical framework for estimating transition probabilities among land-use categories based on historical land-use changes [6–10].

The Markov chain model is based on the idea that the future state of a land-use system depends primarily on its present state and the transition probabilities derived from previous changes. These probabilities are organized in a transition probability matrix, which is calculated from observed historical land-use transitions [6–8]. Using this property, the future distribution of land use can be projected while maintaining the statistical behavior of past transition patterns. Although the ordinary Markov model does not directly show the spatial configuration of future land-use change, it remains a useful tool for evaluating temporal land-use dynamics. For this reason, it has often been integrated with GIS and other spatial simulation techniques in urban planning studies [6–8]. Recent studies show that Markov-based techniques remain effective for land-use prediction when supported by reliable historical data and field-based observations [7–10].

An-Najaf City in Iraq has experienced rapid urban and functional transformation over the past two decades [11, 12]. Rapid population growth, religious tourism, commercial development, and increasing development pressure have accelerated changes in the city's functional land-use structure. The rapid expansion of informal settlements and the conversion of residential land to commercial and industrial uses have created serious challenges for urban planning and land management [11, 12]. Previous studies have applied Markov or Cellular Automata–Markov (CA–Markov) models to analyze urban spatial change and urban expansion in Al-Najaf City [11, 12]. However, these studies mainly focused on historical urban spatial change or physical urban expansion, while the present study further examines updated functional land-use transformation using the 2025 field-survey dataset and predicts the functional land-use distribution up to 2035.

Building on this previous research, the present study develops a Markov chain-based prediction framework using functional land-use data derived from official records, GIS-based analysis, recent satellite imagery, and an intensive field survey. Unlike many previous studies that rely mainly on remote sensing for land-cover classification, this study focuses specifically on functional urban land-use categories, including Residential, Slums, Commercial, Industrial, and Others. It explicitly examines the transformation of residential land into commercial, industrial, informal settlement, and other urban functions. Transition probability matrices are constructed for the 2005–2015 and 2015–2025 periods, and the 2015–2025 matrix is used to predict the functional land-use distribution of An-Najaf City in 2035. The results provide quantitative evidence for planners and decision makers to support sustainable urban land management and the control of informal expansion in An-Najaf City.

Thus, this study aims to analyze the temporal dynamics of functional land-use change, construct Markov transition probability matrices, and predict the future functional land-use distribution of An-Najaf City by 2035. The proposed framework enhances the understanding of transitions among urban functions and provides a scientific basis for planning policies that regulate informal urban expansion, guide commercial development, and promote a more balanced functional structure within the city.

The original contribution of this study lies in three aspects. First, it incorporates newly collected 2025 field-survey data together with GIS analysis, recent satellite imagery, and official planning records. Second, it develops a new transition probability matrix for the 2015–2025 period, extending the historical baseline established in the previous study. Third, it predicts the functional land-use distribution up to 2035, thereby providing updated evidence for future urban planning in An-Najaf City. Accordingly, the previous study provides the methodological and historical baseline, whereas the updated dataset, transition matrix, functional land-use analysis, and future prediction presented in this paper constitute the main original contribution of the current research.

2 Literature Review

Numerous studies have applied Markov chain-based models to analyze historical land-use transitions and predict future urban growth. These models are widely used because they can quantify transition probabilities among different land-use categories and require relatively limited input data compared with more complex spatial simulation models [6–10]. However, many previous studies have focused mainly on land-cover changes derived from remotely sensed images, rather than on functional urban land-use changes verified through field investigation [3, 4, 8].

Kushwaha et al. [8] integrated Earth observation datasets with the CA–Markov model to simulate urban growth in Jhansi City, India. Their method combined satellite-image classification and urban spatial metrics to examine historical urban sprawl and future growth scenarios. The results showed that Markov transition probabilities combined with Cellular Automata could effectively improve the representation of urban growth patterns and support sustainable planning. However, the study mainly focused on physical land-cover dynamics and did not examine functional urban land-use transformation.

Fathizad et al. [13] applied the Markov chain model to detect and predict land-cover change in the semi-arid rangelands of western Iran. Their findings showed that transition probability matrices provide an effective mathematical framework for describing temporal land transitions and generating reliable forecasts when historical transition patterns remain relatively stable. Although the model was effective, the study focused on environmental land-cover classes and did not address functional transformations within urban land-use systems.

In Iraq, Albasri et al. [11] used GIS and the Markov chain model to investigate urban spatial change in An-Najaf

City. The study quantified functional land-use changes during 2005–2015 and used the Markov model to predict future spatial-functional patterns. Its results indicated notable changes in residential, slum, commercial, industrial, and other land-use functions, confirming the usefulness of transition probability matrices in urban planning. However, that study was mainly limited to the 2005–2015 period and did not include more recent observed data. Similarly, AL-Ruwashdi and AL-Khakani [12] applied a CA–Markov model to simulate and predict urban expansion in Al-Najaf City, but their focus was mainly on physical urban expansion rather than detailed functional land-use transformation.

The present study should therefore be regarded as a direct extension of previous research rather than a repetition of it. While earlier studies established the baseline for Markov chain-based analysis of urban spatial change in An-Najaf City, the current research introduces a newly compiled functional land-use database based on the 2025 field survey, develops a new transition probability matrix for the 2015–2025 period, and extends the prediction horizon to 2035. Consequently, only the methodological framework and historical baseline are adopted from the previous study, whereas the updated dataset, transition probabilities, functional land-use analysis, and prediction results presented in this manuscript constitute new contributions.

Marey et al. [10] recently developed a multi-scenario model that links Patch-generating Land Use Simulation (PLUS) with the Markov chain model for urban land-use forecasting. Their results showed that combining statistical transition probabilities with spatial simulation can improve the prediction of future land-use patterns. The authors also emphasized that the accuracy of prediction models depends heavily on the quality of historical transition data and that detailed field observations should be incorporated whenever available. This finding supports the use of the updated field-survey dataset in the present study.

Overall, previous studies have mainly focused on remote-sensing-based land-cover dynamics, CA–Markov urban expansion simulation, or general land-use prediction models [6–10, 13]. In contrast, the present study focuses on functional urban land-use transformation by incorporating the updated 2025 field-survey dataset, recalibrating the 2015–2025 transition matrix, and extending the prediction of major functional land-use categories, including slums, to 2035. This approach provides a more specific assessment of functional land-use transformation in An-Najaf City and forms the principal contribution of the present study.

3 Methodology

3.1 Study Area and Data Collection

An-Najaf City lies in central Iraq, roughly 160 km southwest of Baghdad, and is the capital of An-Najaf Governorate. The city is one of Iraq's important religious, cultural, and economic centers because of the Holy Shrine of Imam Ali (PBUH), which attracts large numbers of visitors every year. This religious and economic significance has contributed to urban growth, increased demand for residential and service land, and changes in the city's functional urban structure [11, 12].

An-Najaf City lies on the western edge of the Euphrates River plain, between the alluvial plain and the western desert plateau. During the past two decades, the city has experienced rapid urban expansion and functional land-use transformation. Residential areas have expanded toward the urban fringe, commercial activities have increasingly concentrated along major transport corridors and central urban districts, and informal settlements have become an important challenge for urban planning and land management [11, 12]. The study area covers the urban boundary of An-Najaf City as defined by recent municipal planning documents. As shown in Figure 1, the study area is located in Iraq and represents the administrative boundary used for the spatial analysis.

The analysis was conducted using functional land-use datasets for three benchmark years: 2005, 2015, and 2025. The 2005 and 2015 datasets were derived from official land-use maps, municipal planning documents, cadastral records, and the previous study [11]. These earlier data were used as the historical baseline. The 2025 dataset was newly developed for the present study through field survey, updated planning documents, recent satellite imagery, and GIS-based verification.

Urban land use was classified into five major functional categories for Markov chain modelling: Residential, Slums, Commercial, Industrial, and Others. The "Slums" category was treated as an independent functional category because informal settlements have become a significant form of unplanned urban transformation in An-Najaf City. Although slums are not an official land-use category in the master plan, they were identified through field observation, satellite-image interpretation, and comparison with official planning maps. The "Others" category represents the residual functional category retained in the reclassified Markov model dataset. This simplified five-category classification was adopted to construct a manageable transition matrix and to focus the analysis on the dominant functional transformations in the study area.

Functional land-use transitions were identified by comparing successive datasets for 2005–2015 and 2015–2025. The converted areas among the five functional categories were quantified and used to construct functional change matrices. Areas that remained within the same category were also retained as persistence values and included in the diagonal cells of the transition matrix. These matrices were then transformed into Markov transition probability matrices for predicting future functional land-use distribution.

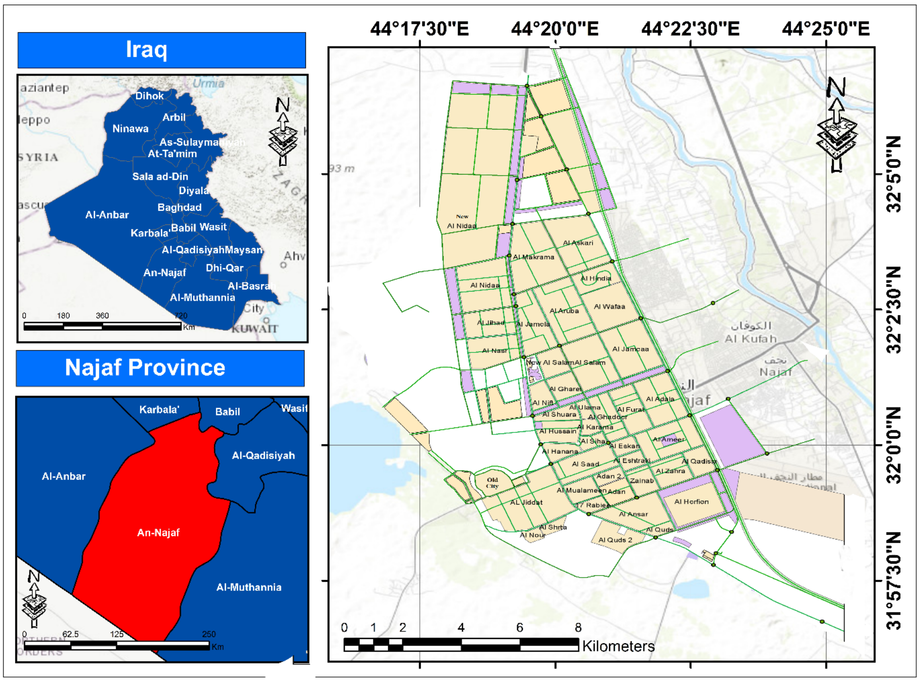

Figure 1. Location of Najaf City and the administrative boundary of the study area, reproduced from Ref. [11] under the Creative Commons CC BY 4.0 license

To update and verify the urban functional land-use database for the 2025 reference year, field verification was conducted across the entire study area and cross-checked with 2025 satellite imagery, official planning maps, and records obtained from relevant local authorities. The verification focused on identifying the functional status of urban land uses, especially newly developed areas and informal settlements. Field observations were systematically recorded and integrated into the GIS environment for spatial checking, database updating, and area calculation. The finalized 2025 GIS database was then used to calculate the areas of the five functional land-use categories, construct the 2015–2025 transition matrix, and provide the input vector for the Markov chain prediction for 2035.

3.2 Markov Functional Change Matrix

The Markov chain model was applied to measure the temporal dynamics of functional urban land-use change and to predict the future distribution of land-use categories. The model assumes that the future state of a land-use system depends mainly on its current state and on the transition probabilities observed during a previous period. In this study, the transition probabilities were derived from observed functional land-use conversions during the calibration period [6–10, 13].

Unlike conventional land-cover studies, this research focuses on functional urban land-use transitions. A transition was recorded only when land changed from one functional category to another, such as from Residential to Commercial or from Residential to Slums. Areas that remained within the same category were treated as persistence and were represented by diagonal elements in the transition probability matrix. Therefore, the transition matrix includes both inter-category conversions and persistence probabilities [6–8, 13].

The future functional land-use state can be estimated using the following Markov chain equation:

$$B_{t+1} = B_t P \tag{1}$$

where, B_t is the functional land-use state vector at time t; B_{t+1} is the predicted functional land-use state vector at time $t+1$; and P is the row-normalized transition probability matrix.

The transition probability matrix is expressed as:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \tag{2}$$

where, p_{ij} represents the probability that land-use category i changes to land-use category j, p_{ii} represents the persistence probability of category i, and n is the number of functional land-use categories.

The transition probabilities were calculated from the observed functional land-use changes as follows:

$$p_{ij} = \frac{A_{ij}}{\sum_{j=1}^{n} A_{ij}} \tag{3}$$

where, A_{ij} is the observed area converted from land-use category i to category j, including A_{ii}, which represents the area that remained unchanged within the same category.

The transition matrix satisfies the following condition:

$$\sum_{j=1}^{n} p_{ij} = 1, \qquad 0 \leq p_{ij} \leq 1 \tag{4}$$

which ensures that the total transition probability from each land-use category equals one [10].

The prediction process was conducted using the observed functional land-use datasets for 2005, 2015, and 2025. The 2005–2015 transition matrix was used as a historical baseline and was adapted from the previous study [11]. The 2015–2025 transition matrix was newly constructed in the present study based on the updated 2025 field survey and GIS database. Because the purpose of this study is to predict future functional land-use changes, the 2015–2025 transition matrix was used as the calibration matrix for the 2035 prediction.

The 2035 prediction was calculated as follows:

$$B_{2035} = B_{2025} P_{2015-2025} \tag{5}$$

where, B_{2025} is the observed functional land-use distribution obtained from the 2025 field survey; $P_{2015-2025}$ is the transition probability matrix derived from the observed functional land-use changes between 2015 and 2025; and B_{2035} is the predicted functional land-use distribution for 2035.

This prediction assumes that the transition probabilities observed during 2015–2025 will remain statistically stable during the forecast period. Therefore, the predicted 2035 land-use distribution should be interpreted as a trend-based projection rather than an exact forecast [7, 10, 13]. In this study, the Markov chain prediction was applied to the 2025 functional land-use distribution within the defined study boundary. Accordingly, the total land area was kept constant in the 2035 prediction, and the results represent internal functional land-use transformation rather than further physical expansion of the urban area. Based on the recent transition patterns observed in the study area, the Markov chain model estimates the expected functional land-use distribution of An-Najaf City in 2035 under this assumption.

4 Results

This section presents the results of the functional land-use analysis and Markov chain prediction. First, the reclassified baseline land-use data for 2005 and 2015 are presented, followed by the historical functional change matrix and transition probability matrix. The updated 2015–2025 land-use changes are then analyzed and used to construct the 2015–2025 transition probability matrix for predicting the 2035 functional land-use pattern. The 2005–2015 results are used as the historical baseline, while the main new results of the present study are based on the updated 2025 dataset, the 2015–2025 transition matrix, and the 2035 prediction.

The reclassified baseline data for 2005 and 2015 are presented in Table 1. These data provide the starting point for examining historical functional land-use changes and for comparing earlier urban transformation patterns with the updated 2015–2025 dataset.

Table 1. Reclassified land-use areas and percentages used in the present Markov chain model (2005–2015)

Land Use	2005 Area (ha)	2005 Share (%)	2015 Area (ha)	2015 Share (%)
Residential	3,156.82	71.88	3,912.50	67.83
Slums	177.03	4.03	277.71	4.81
Commercial	200.30	4.56	645.70	11.19
Industrial	702.41	15.99	739.52	12.82
Others	155.00	3.53	193.00	3.35
Total	4391.56	100.00	5768.43	100.00

Note: The values represent the selected functional land-use categories used as baseline input data for the present Markov chain model. The 2005–2015 data were adapted and reclassified from Ref. [11]. These totals refer only to the categories retained for the Markov model and should not be interpreted as the complete urban land-use area reported in the original 2005–2015 dataset. Minor discrepancies in the percentage totals are due to rounding.

After establishing the reclassified baseline distribution, the actual functional transitions from 2005 to 2015 were identified. Table 2 presents the historical functional change matrix, showing the areas converted from one functional land-use category to another. The off-diagonal cells represent inter-category conversions, while persistence within the same category was considered when constructing the corresponding Markov transition probability matrix. This matrix is used as a historical reference for understanding earlier transformation patterns and for constructing the corresponding transition probability matrix.

Table 2. Functional land-use change matrix in the study area (2005–2015), adapted from Ref. [11]

From/To	Residential	Slums	Commercial	Industrial	Others
Residential	–	277.71	47.69	7.84	1.89
Slums	124.96	–	21.33	24.37	6.37
Commercial	12.11	19.46	–	15.60	12.9
Industrial	130.00	34.00	13.40	–	2.00
Others	2.10	4.20	54.00	3.33	–

Note: Values indicate converted land-use areas in hectares. The symbol "–" denotes within-category persistence, i.e., land that remained in the same functional category, which is not shown in this change matrix.

The off-diagonal changes shown in Table 2, together with the corresponding persistence values, were used to construct the Markov transition probability matrix. As shown in Table 3, the historical 2005–2015 transition probability matrix is adapted from Hasach et al. [11] and is presented in a row-normalized From/To format for consistency with the prediction equation used in this study. Each row represents the probability distribution of transitions from a given original land-use category, and the row sums are equal to one, except for minor rounding differences.

Table 3. Markov transition probability matrix for functional land-use changes in the study area (2005–2015), adapted from Ref. [11]

From/To	Residential	Slums	Commercial	Industrial	Others	Sum
Residential	0.931	0.032	0.003	0.033	0.001	1.000
Slums	0.448	0.344	0.070	0.122	0.015	0.999
Commercial	0.074	0.033	0.788	0.021	0.084	1.000
Industrial	0.011	0.033	0.021	0.931	0.005	1.001
Others	0.010	0.033	0.067	0.010	0.880	1.000

Note: Values are row-normalized transition probabilities. Each row represents the probability distribution of transition from the original land-use category to other categories. Minor deviations from 1.000 are due to rounding.

After the historical baseline was examined, the functional land-use distribution was updated using the 2015 and 2025 datasets. Table 4 presents the observed changes in the five functional land-use categories during this period. These data represent the updated urban functional conditions in An-Najaf City and form the empirical basis for constructing the new 2015–2025 transition matrix.

Table 4. Functional land-use area changes and shares of total change during 2015–2025

Land Use	2015 Area (ha)	2025 Area (ha)	Change (ha)	Share of Total Change (%)
Residential	3,912.50	4,870.30	957.80	34.02
Slums	277.71	411.00	133.30	4.73
Commercial	645.70	2,204.30	1,558.60	55.36
Industrial	739.52	786.40	46.90	1.67
Others	193.00	312.00	119.00	4.23
Total	5,768.43	8,584.00	2,815.60	100.00

Note: Minor discrepancies in the percentage total are due to rounding.

As shown in Table 4, commercial land use recorded the largest increase during 2015–2025, accounting for 55.36% of the total observed area change. This indicates the growing importance of commercial activities in the urban structure of An-Najaf City during this period. Residential land use ranked second, contributing 34.02% of the total change, which reflects continued demand for housing and urban expansion. Slums accounted for 4.73% of the observed change, indicating the continued spread of informal settlements. The "Others" category accounted for 4.23%, while industrial land use showed the smallest increase, at 1.67%. Overall, commercial and residential land-use changes together accounted for approximately 89.38% of the total observed change, indicating that these two categories were the main drivers of functional urban transformation during 2015–2025.

To identify the direction and magnitude of recent functional conversions, a functional land-use change matrix was constructed for 2015–2025. Table 5 shows the areas converted among the five functional categories, including both persistence within the same category and conversion to other categories. These values provide the basis for calculating the 2015–2025 transition probabilities used in the Markov chain prediction model.

Table 5. Functional land-use change matrix in An-Najaf City (2015–2025)

From/To	Residential	Slums	Commercial	Industrial	Others	Total
Residential	3,609.11	243.00	50.14	8.24	2.01	3,912.50
Slums	187.55	6.32	40.39	34.88	8.57	277.71
Commercial	112.00	12.00	484.70	23.00	14.00	645.70
Industrial	11.00	23.00	8.00	681.52	16.00	739.52
Others	25.00	65.00	19.00	7.00	77.00	193.00

Note: Values indicate converted land-use areas in hectares. Diagonal values represent persistence within the same land-use category, while off-diagonal values indicate conversion from one category to another.

Following the quantification of the 2015–2025 functional transitions, the observed converted areas, including both inter-category conversions and persistence values, were normalized to construct the Markov transition probability matrix. As shown in Table 6, residential, industrial, and commercial land uses show relatively high persistence probabilities, indicating that large portions of these categories remained stable during the observation period. In contrast, slums and the "Others" category show lower persistence and higher probabilities of conversion to other land uses, reflecting greater instability under urban expansion and development pressure. The 2015–2025 transition probability matrix therefore provides the main calibration basis for predicting the functional land-use distribution in 2035.

Table 6. Markov transition probability matrix for functional land-use changes (2015–2025)

From/To	Residential	Slums	Commercial	Industrial	Others	Sum
Residential	0.922	0.062	0.013	0.002	0.001	1.000
Slums	0.675	0.023	0.145	0.126	0.031	1.000
Commercial	0.173	0.019	0.751	0.036	0.022	1.001
Industrial	0.015	0.031	0.011	0.922	0.022	1.001
Others	0.130	0.337	0.098	0.036	0.399	1.000

Note: Values are row-normalized transition probabilities and are rounded to three decimal places. Minor deviations from 1.000 are due to rounding.

After constructing the complete row-normalized 2015–2025 transition probability matrix, the calibrated Markov chain model was applied to predict the functional land-use distribution of An-Najaf City in 2035. The prediction was obtained by multiplying the observed 2025 land-use vector by the 2015–2025 transition probability matrix, under the assumption that the transition probabilities observed during 2015–2025 remain stationary during the forecast period. The predicted results are presented in Table 7. The revised prediction suggests that residential land use will increase from 4,870.30 ha in 2025 to 5,204.70 ha in 2035, representing an increase of 334.40 ha. Slum areas are expected to increase from 411.00 ha to 482.30 ha, while industrial land use is projected to rise from 786.40 ha to 876.40 ha. By contrast, commercial land use is projected to decrease from 2,204.30 ha to 1,816.10 ha, and the "Others" category is expected to decline from 312.00 ha to 204.50 ha. The total urban area remains 8,584.00 ha, indicating that the predicted changes represent internal functional transformation rather than further physical expansion of the study area.

Table 7. Predicted functional land-use areas and changes in the study area for 2035

Land Use	Area 2025 (ha)	Predicted Area 2035 (ha)	Change (ha)
Residential	4,870.3	5,204.7	+334.4
Slums	411.0	482.3	+71.3
Commercial	2,204.3	1,816.1	−388.2
Industrial	786.4	876.4	+90.0
Others	312.0	204.5	−107.5
Total	8,584.0	8,584.0	0

5 Discussion

The prediction results indicate that An-Najaf City is likely to continue experiencing internal functional land-use transformation by 2035. The most notable trends are the continued expansion of residential land, slum areas, and industrial land use, together with a projected decline in commercial land use and the "Others" category. These changes suggest that housing demand, informal urban expansion, industrial development, and the conversion of supporting urban functions may remain important forces shaping the future urban structure of the city.

The projected increase in residential land use reflects the continuing demand for housing and urban accommodation in An-Najaf City. Residential areas are expected to remain one of the dominant functional land-use categories, indicating that population growth, household formation, and urban expansion pressure may continue to influence the spatial structure of the city. This result also suggests that residential land may remain relatively persistent in the urban system, while also receiving land converted from other categories.

The predicted expansion of slum areas is another important finding of the model. Unlike officially planned land-use categories, slums represent unauthorized or unplanned occupation of urban land. Their continued increase suggests that current planning policies, housing provision, and development-control measures may be insufficient to meet the growing demand for urban land and services [14, 15]. If this trend continues, informal settlements may increasingly encroach upon planned residential and service areas, creating additional pressure on infrastructure networks, public facilities, and environmental quality [15].

The moderate increase in industrial land use indicates the gradual expansion of productive and industrial activities. This trend may reflect the continued role of industrial land in supporting the economic base of the city. By contrast, the projected decline in commercial land use does not necessarily indicate a weakening of commercial activity. Rather, it may reflect a redistribution of commercial areas within the fixed study boundary, or the conversion of part of the commercial land into residential, industrial, or other functional uses under the transition patterns observed during 2015–2025. Similarly, the decline in the "Others" category suggests that several supporting urban functions, such as transportation, services, open spaces, and infrastructure-related uses, may be increasingly transformed into more dominant land-use categories during the prediction period. This finding is important because the reduction of supporting and public-service land may weaken the functional balance of the urban system if not properly controlled [16].

Overall, the findings show that the Markov chain model can provide a useful quantitative framework for identifying dominant patterns of functional land-use transition and forecasting future urban development trends. However, the results should be interpreted as scenario-based projections rather than fixed outcomes, because they depend on the assumption that the 2015–2025 transition probabilities will remain stable during the forecast period [17, 18]. The predicted trends emphasize the need to strengthen land-use planning policies, improve monitoring mechanisms, and control informal urban expansion while maintaining a balanced distribution of residential, commercial, industrial, and public-service functions.

6 Conclusions and Recommendations

6.1 Conclusions

This study applied the Markov chain model to analyze past functional land-use changes and predict future land-use patterns in An-Najaf City. Based on functional land-use datasets for 2005, 2015, and 2025, the study constructed transition probability matrices and used them to forecast the distribution of major functional land-use categories in 2035. The results indicate that, although the total urban area is expected to remain unchanged in the prediction period, significant internal functional transformations are likely to occur among the five land-use categories.

The prediction results show a continued increase in residential, industrial, and slum areas, together with a projected decline in commercial land use and the "Others" category. The increase in residential land use indicates the continuing importance of housing demand in shaping the future functional structure of An-Najaf City. The projected decline in commercial land use does not necessarily indicate a weakening of economic activity, but rather suggests a possible redistribution or conversion of commercial areas within the fixed study boundary. At the same time, the projected increase in slum areas highlights the continuing challenge of informal urban expansion and the limited effectiveness of existing land-use control measures.

The findings suggest that future functional land-use dynamics in An-Najaf City will not be driven only by population growth, but also by competition among land-use functions, especially the pressure exerted by residential expansion, informal settlements, and industrial development. Therefore, proactive planning policies are required to guide urban growth, reduce unplanned land conversion, and maintain a more balanced functional structure within the city.

6.2 Recommendations

Based on the findings, urban planning authorities should strengthen the enforcement of land-use regulations to control informal urban expansion and reduce unplanned functional land-use changes. Greater attention should be given to managing residential expansion, preventing the spread of informal settlements, and protecting public-service, open-space, and infrastructure-related land from excessive conversion into other uses.

It is also recommended that planning authorities incorporate GIS-based monitoring systems and predictive models, such as the Markov chain model, into regular urban planning practice. These tools can support evidence-based decision-making, continuous land-use monitoring, and early identification of areas vulnerable to rapid informal settlement growth and the loss of supporting urban functions.

Future planning policies should aim to maintain a balanced distribution of residential, commercial, industrial, public-service, and infrastructure-related land uses. In addition, future studies may integrate the Markov chain model with CA–Markov, artificial intelligence, or machine-learning techniques to improve spatial prediction accuracy and generate more comprehensive planning scenarios for the sustainable development of An-Najaf City.

7 Limitations and Future Research

Although the Markov chain model is useful for examining historical functional land-use changes and forecasting future trends, this study has several limitations. First, the model assumes that the transition probabilities observed during 2015–2025 will remain constant throughout the forecast period. In reality, future land-use dynamics may be affected by unexpected socio-economic, political, environmental, or regulatory changes. Therefore, the prediction results should be interpreted as a projection based on current trends rather than as a definitive forecast.

Second, the Markov chain model mainly captures temporal transition probabilities and does not directly represent the spatial interactions among adjacent land-use categories. As a result, it can estimate the expected amount of land-use change, but it does not fully explain the spatial configuration or precise location of future changes. Third, the accuracy of the prediction depends on the quality, consistency, and classification of the historical and updated functional land-use datasets. Any uncertainty in the field survey, GIS database, or reclassification process may influence the final prediction results.

In addition, the 2035 prediction was conducted within the fixed 2025 study boundary. Therefore, the model represents internal functional land-use transformation rather than further physical expansion of the urban area. Future studies should consider incorporating newly urbanized or non-urban land as an additional transition category if the objective is to predict both urban expansion and internal functional change.

Future research should consider integrating the Markov chain model with spatial simulation approaches such as CA–Markov to improve the representation of spatial land-use patterns. Incorporating additional variables, such as population growth, transport accessibility, land prices, socio-economic conditions, and planning policies, could further improve the reliability of future predictions. Advanced artificial intelligence and machine-learning techniques may also be used to compare forecasting performance and develop more robust urban development scenarios. Finally, applying the same methodology to other Iraqi cities would allow comparative analysis and provide broader evidence for improving urban planning strategies across Iraq.

Author Contributions

Conceptualization, N.A.R.H.; methodology, N.A.R.H.; software, N.A.R.H.; investigation, N.A.R.H.; data curation, N.A.R.H.; formal analysis, N.A.R.H. and A.M.D.; validation, A.M.D.; visualization, N.A.R.H.; writing—original draft preparation, N.A.R.H.; writing—review and editing, A.M.D. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflicts of interest.

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