Urban Sprawl and Collective Land Vulnerability in Irrigated Perimeters: A Geospatial and Predictive Modeling Approach Using LCM in Sidi Kacem, Morocco

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Abstract. Land management and territorial planning are central challenges for sustainable governance, particularly in irrigated areas under growing urban and agricultural pressures. This study evaluates the projected vulnerability of collective lands in the irrigated perimeter of Sidi Kacem, Morocco, under future urbanization scenarios. Geographic Information Systems (GIS), remote sensing, and the Land Change Modeler (LCM) within TerrSet were applied to simulate urban expansion for the horizons 2040 and 2050. The analysis combines collective farmlands with projected built-up surfaces, producing a vulnerability index expressed as a ratio. Four vulnerability classes were established: very low (0–5%), low (5–15%), moderate (15–30%), and high (>30%). Results indicate a moderate increase in built-up areas, from 1,353 ha in 2022 to 2,123 ha in 2040 and 2,303 ha in 2050, reflecting both development pressures and regulatory controls. By generating vulnerability maps and decision-support tools, this research demonstrates the potential of geospatial technologies to support rural planning, safeguard high-value agricultural lands, and align urban growth with the principles of good land governance and the melkisation reform.
Keywords: urban sprawl, geospatial analysis, predictive modelling, collective lands, Sidi Kacem, melkisation, GIS, Land Change Modeler

1 Introduction

Urbanization is one of the defining processes of the twenty-first century, particularly in developing countries where rapid population growth often outpaces the capacity of urban planning and infrastructure development [1, 2]. Morocco illustrates this trend, with urban areas hosting 62.8% of the population according to the 2024 General Population and Housing Census (RGPH) [3]. This accelerated urban transition raises significant challenges for

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sustainable land management, as agricultural and rural spaces are increasingly absorbed by urban expansion.

Among the most affected are collective lands, which represent a crucial resource for food security, social stability, and rural development [4]. In Morocco's irrigated perimeters, collective lands hold a strategic position due to the considerable public investments in hydro-agricultural infrastructure, which aim to boost productivity and improve the living standards of rural communities. Although irrigated agriculture represents only about 15% of the total cultivated area, it contributes nearly 45% of the sector's added value on average and accounts for approximately 75% of agricultural exports [5]. However, the unchecked spread of urban areas threatens to compromise these efforts, creating a spatial competition between urban growth and agricultural preservation [6].

To address this, Morocco has embarked on the melkisation process, which consists of the privatization of collective lands to secure land tenure, enhance agricultural performance, and mobilize them for high-value-added agriculture [7]. While this reform is framed as a tool of good land governance and rural development, it is increasingly confronted with the realities of urban sprawl that risk undermining its objectives [8].

In this context, geospatial technologies and predictive spatial modelling emerge as indispensable tools. Geographic Information Systems (GIS), remote sensing, and dynamic models such as the Land Change Modeler (LCM) integrated in TerrSet provide the means to map land-use dynamics, identify driving factors, and simulate future scenarios of land transformation [9,10]. These approaches not only make it possible to visualize trajectories of urban growth but also to quantify the vulnerability of collective lands to urbanization, thus providing decision-makers with evidence-based insights for strategic land management [11].

This study applies such an integrated geospatial approach to the irrigated perimeter of Sidi Kacem. Specifically, it seeks to analyze historical land-use dynamics (1985–2022), simulate urban expansion to 2040 and 2050, and evaluate the projected vulnerability of collective lands to urban sprawl. By doing so, it contributes to the growing body of knowledge on the interactions between urban growth, agricultural land preservation, and land governance in Morocco.

2 Study area

The province of Sidi Kacem, situated in the Gharb region of northwestern Morocco, extends over 4,060 km². It lies at latitude 34°13' N and longitude 5°42' W, corresponding to the projected coordinates of 468 km West and 430 km North. Since the 2015 administrative division, it has been part of the Rabat–Salé–Kenitra region. Geographically, the province occupies a strategic location where the Rdom River descends from the Meknès plateau into the Gharb plain. It is traversed by the Sebou River and its tributaries, Ouergha and Beht, and is bordered by Ouezzane to the north, Meknès and Sidi Slimane to the south, Taounate and Moulay Yaacoub to the east, and Kenitra to the west.

Within this territory, two irrigated perimeters intersect the province: Sebou Inaouen and Gharb. The Sebou Inaouen perimeter, which forms part of Morocco's Petite et Moyenne Hydraulique (PMH), covers a total of 15,000 hectares, of which 512 hectares are located in the southeastern part of Sidi Kacem. Its irrigation was initiated in 1998 under a participatory management framework involving Water Users Associations [12]. The Gharb irrigated perimeter stands as one of the largest irrigation schemes in Morocco, covering a total of 388,000 hectares of cultivable land, of which approximately 114,000 hectares are already equipped for irrigation [13]. A considerable share of this perimeter extends into the province of Sidi Kacem, reinforcing its central role in agricultural production and highlighting the province's strategic importance within the broader irrigated system of the Gharb.

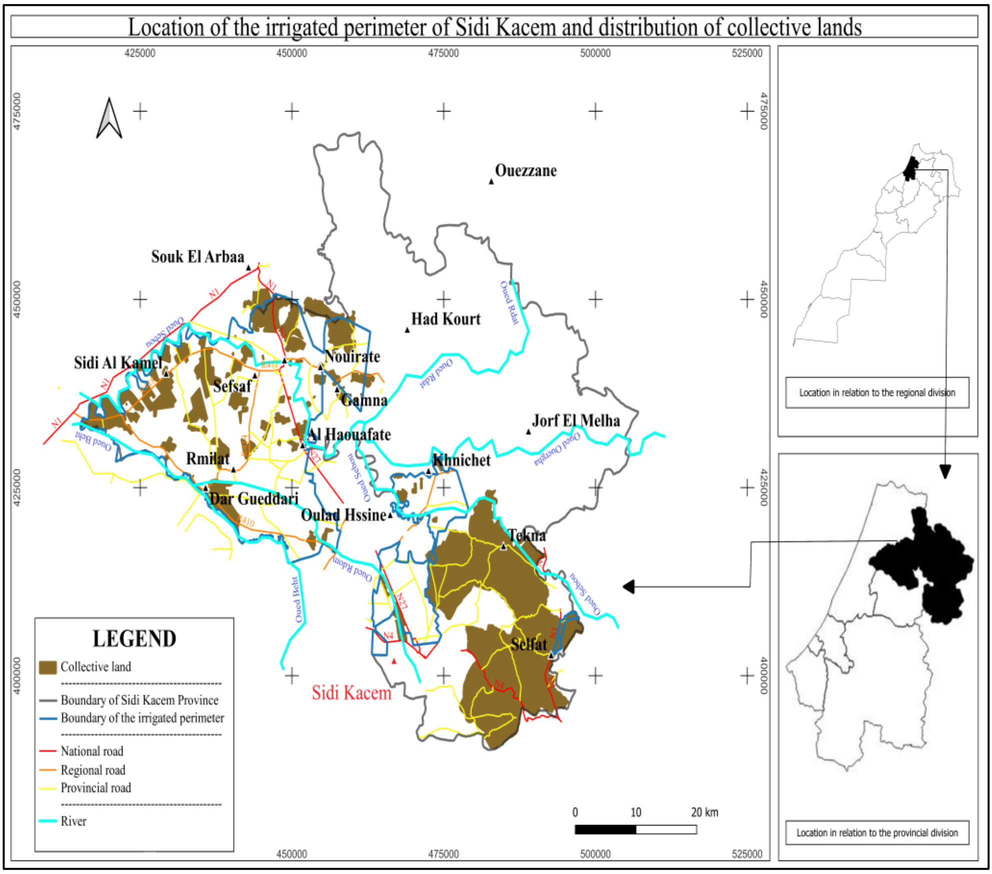

Figure 1. Study area: irrigated perimeter of Sidi Kacem and collective lands

The collective lands within the irrigated perimeter represent a considerable share of the province's land tenure structure. In the Gharb perimeter alone, they account for approximately 42% of the total area, or nearly 60,000 hectares. This proportion highlights their weight in the overall distribution of agricultural land and their essential role in the productive system of the province. As the primary focus of this study, these lands stand at the center of ongoing debates on land governance, irrigation development, and the challenges of balancing modernization with local socio-economic realities.

3 Data and methodology

3.1 Data sources

Satellite imagery from Landsat (1985, 2005, and 2022) was used to track land use changes. Additional data, such as slope maps derived from Digital Elevation Models (DEM) and proximity to infrastructure (roads, hydrographic networks), were integrated into the analysis. These datasets were complemented by demographic data from the RGPH 2024, providing a comprehensive view of urban growth trends and population dynamics.

Table 1. Summary of datasets used for geospatial analysis and predictive modelling in the irrigated perimeter of Sidi Kacem

Data Type	Source / Provider	Details	Acquisition Date / Year	Use in Study
Satellite Imagery (Landsat)	USGS EarthExplorer	Landsat 5 TM (1985, 2005), Landsat 8 OLI/TIRS (2022) – Path/Row: 201/036	06/03/1985, 20/04/2005, 08/04/2022	Land use/land cover classification and change detection
Digital Elevation Model (DEM)	USGS EarthExplorer	30 m resolution	Accessed online	Extraction of slope, aspect, and hillshade maps
Digitized Topographic Maps	Cartographic archives, processed with QGIS	Vector layers: roads (national, regional, provincial), rivers, public facilities	Digitization during study	Spatial variables influencing urban sprawl
Population and Housing Census (RGPH 2024)	Haut-Commissariat au Plan (HCP), Morocco	Demographic and housing data	2024	Population density and demographic dynamics

3.2 Methodology

This study combines remote sensing, GIS analysis, and spatial modeling to evaluate land use/land cover (LULC) dynamics and assess the vulnerability of collective lands to urban expansion within the irrigated perimeter of Sidi Kacem. The methodological workflow integrates (i) pre-processing of multi-date satellite images and supervised classification, (ii) preparation of explanatory driver variables, (iii) implementation and validation of the Land Change Modeler (LCM) for prospective simulations, and (iv) derivation of vulnerability maps through spatial overlay with collective lands. This integrated approach ensures both temporal comparability of LULC maps and robust prospective analysis of urban sprawl pressures.

3.2.1. Pre-processing and Supervised Classification

The satellite images from 1985, 2005, and 2022 were first calibrated radiometrically and atmospherically in ENVI in order to remove sensor- and atmosphere-related distortions and to guarantee inter-date comparability. This calibration step was essential for ensuring that the reflectance values of the images could be reliably compared over time. Once corrected, the images were geometrically aligned through co-registration, resampled to a uniform spatial resolution, and finally clipped to the study area boundary for subsequent analysis.

Land use/land cover (LULC) maps were generated using a supervised Maximum Likelihood classifier with three classes [14]: Built-up, Agricultural land, and Bare soil. The choice of these classes was motivated by the study's focus on modeling urban expansion, where the dynamics of built-up areas are best captured through their transitions with the two other dominant land uses. Training samples were digitized directly from false-color composites of the USGS Landsat images, with balanced sampling across classes to ensure stable and reliable classification statistics.

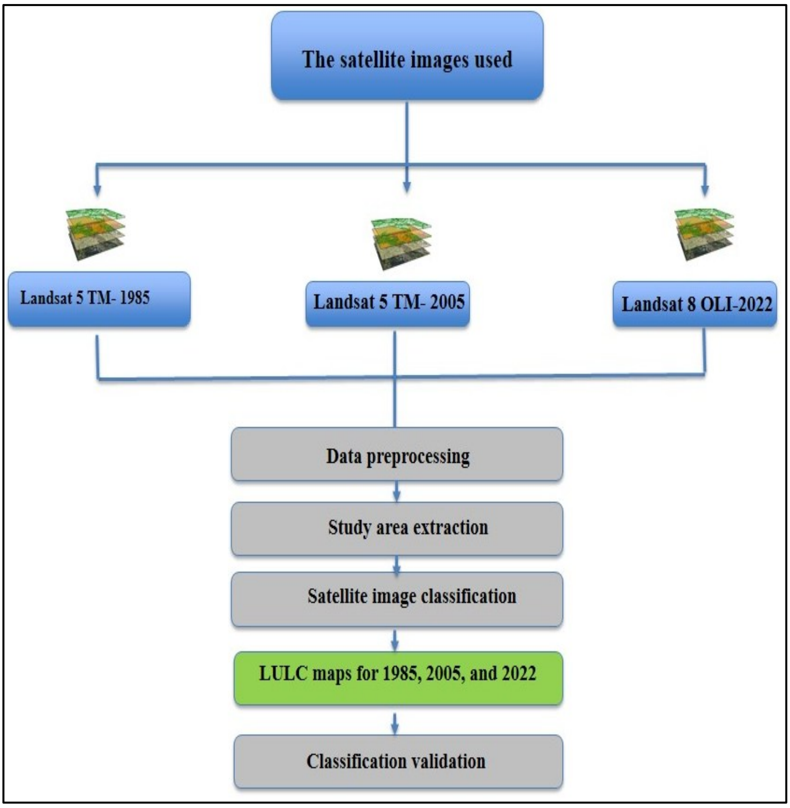

Figure 2. Workflow of LULC mapping from satellite images (1985–2022)

The validation process combined visual interpretation with confusion matrices derived from independent points. Accuracy was expressed in terms of User's and Producer's Accuracies, Overall Accuracy (OA), and the Kappa coefficient. Results indicate OA values ranging from 76.8% to 82.1% and Kappa values between 0.65 and 0.72, reflecting a substantial but not perfect agreement. These outcomes are consistent with the limitations of medium-resolution satellite sensors, particularly for earlier dates, while remaining sufficiently reliable for analyzing land use/land cover dynamics and supporting subsequent modeling.

Table 2 : Validation metrics of supervised classification (1985, 2005, 2022)

Year	Overall Accuracy (OA %)	Kappa Coefficient
1985	76.8	0.65
2005	79.4	0.69
2022	82.1	0.72

3.2.2. Preparation of Driver Variables

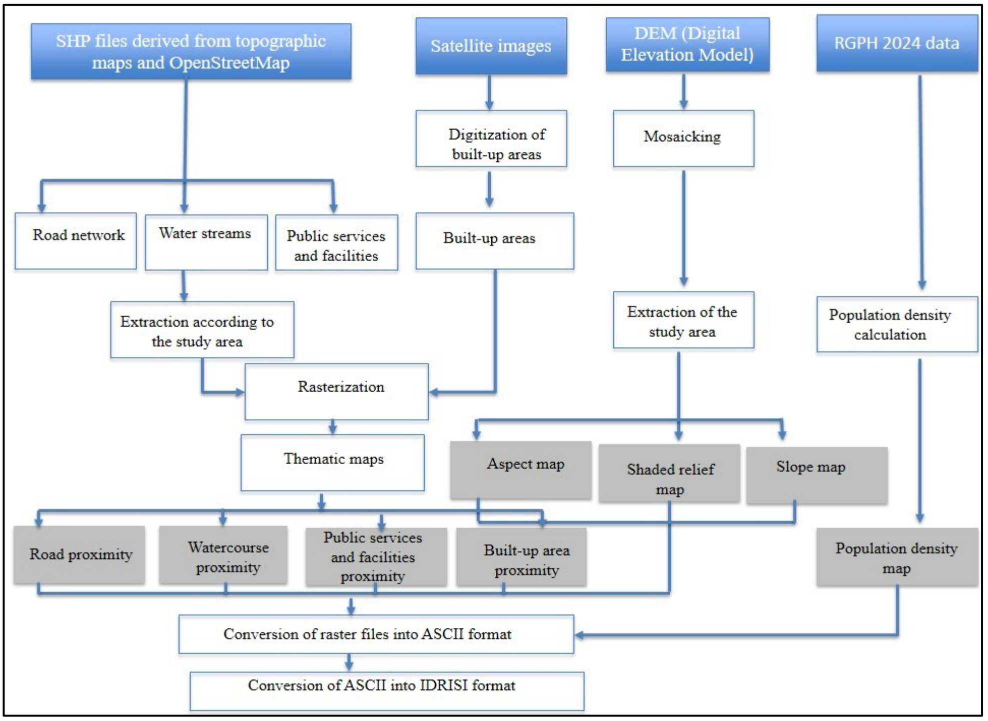

Figure 3. Workflow for the Preparation of Explanatory Variables for LCM

Spatial drivers of urban expansion were generated as standardized raster layers. These included distance-to maps (roads, rivers, built-up areas, public facilities), topographic derivatives (slope, aspect, hillshade from DEM), and population density derived from the 2024 Population and Housing Census (RGPH).

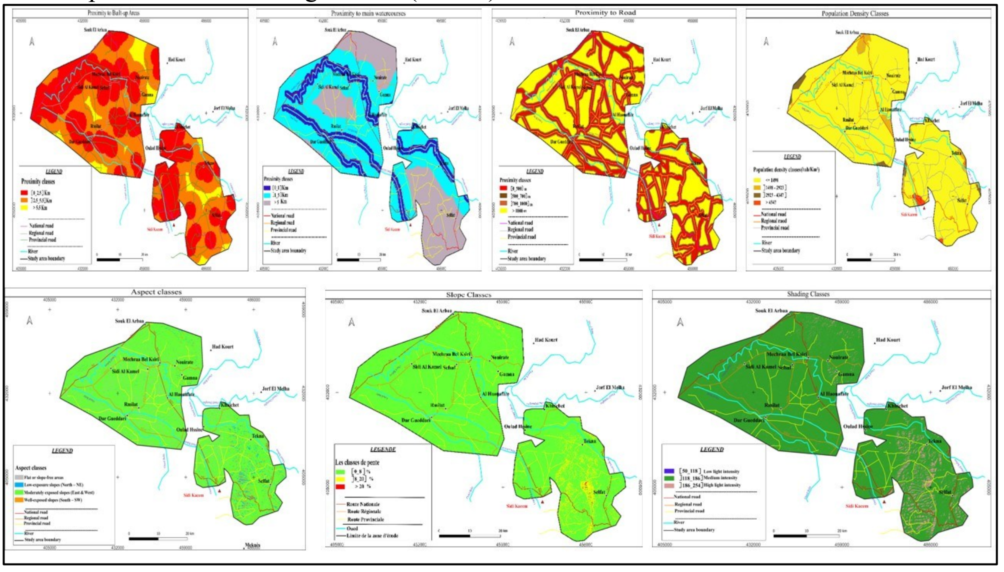

Figure 4. Driver Variables for Land Change Modeling

Their explanatory power was assessed using Cramer's V coefficient, which identified proximity to built-up areas (0.3283), population density (0.2878), and public services and facilities (0.2839) as the most influential drivers.

Table 3. Cramer's V coefficients of explanatory variables in the built-up dynamics submodel

Explanatory Variables	Cramer's V Coefficient (Built-up Dynamics Submodel)
Proximity to Built-up Areas	0.3283
Population Density	0.2878
Proximity to Public Facilities	0.2839
Proximity to Main Watercourses	0.2124
Proximity to Roads	0.2042
DEM	0.1682
Slope	0.0823
Aspect	0.0321

3.2.3 Land Change Modeling and Vulnerability Assessment

The Land Change Modeler (LCM) in TerrSet was applied to analyze past land use/land cover dynamics and to simulate future urban expansion within the study area. The modeling workflow comprised three main stages: (i) change analysis for the periods:1985, 2005 and 2022 to extract transition samples, (ii) development of transition potential maps using a Multilayer Perceptron (MLP) trained with the explanatory driver variables, and (iii) Markov chain projections to estimate the demand and spatial allocation of built-up areas for the horizons 2040 and 2050.

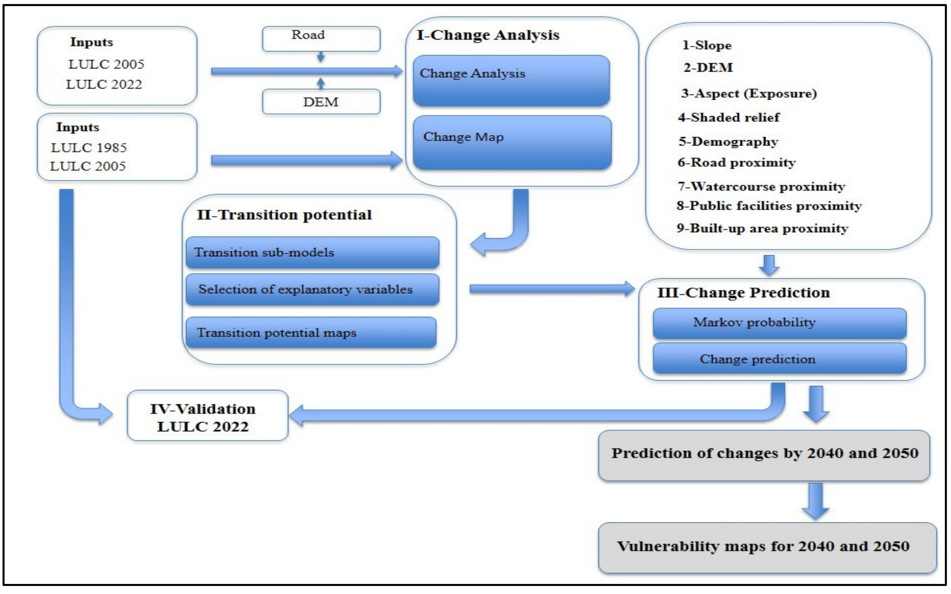

Figure 5. Workflow of the Land Change Modeler and Vulnerability Assessment

Model performance was tested through a hindcasting procedure, comparing the simulated 2022 map with the observed classification. The results showed acceptable levels of accuracy, with Kno = 0.71, Klocation = 0.69, and Kstandard = 0.64. These values reflect substantial, though not perfect, agreement, which is consistent with the limitations of medium-resolution satellite imagery and the inherent spectral confusion between built-up areas and bare soils.

The validated projections were then intersected with collective-land polygons to assess their exposure to urban expansion. For each polygon, a vulnerability ratio was computed (built-up area / total polygon area × 100) and categorized into four classes: very low (0–5%), low (5–15%), medium (15–30%), and high (>30%). This procedure enabled the identification of collective lands most at risk from urban encroachment in future scenarios.

4 Results and discussion

4.1 Future Dynamics of Built-up Areas

The sub-model developed in this study specifically targeted the dynamics of built-up expansion, integrating explanatory variables selected according to the characteristics of this land-use class. Once validated against observed land cover maps, the model was applied to generate predictive maps for 2040 and 2050. These projections highlight the areas most likely to undergo urban transformation, thereby illustrating the trajectories of spatial reorganization driven by demographic and infrastructural pressures.

The predictive maps (Figure 5) and corresponding graphs emphasize a steady but moderate increase in built-up areas across the irrigated perimeter of Sidi Kacem. While the expansion is not exponential, it indicates a continuous trend of urban growth, suggesting a progressive encroachment on agricultural and collective lands. This dynamic underscores the mounting challenge of balancing urban development with the preservation of fertile irrigated lands, which remain a strategic asset for regional agricultural production.

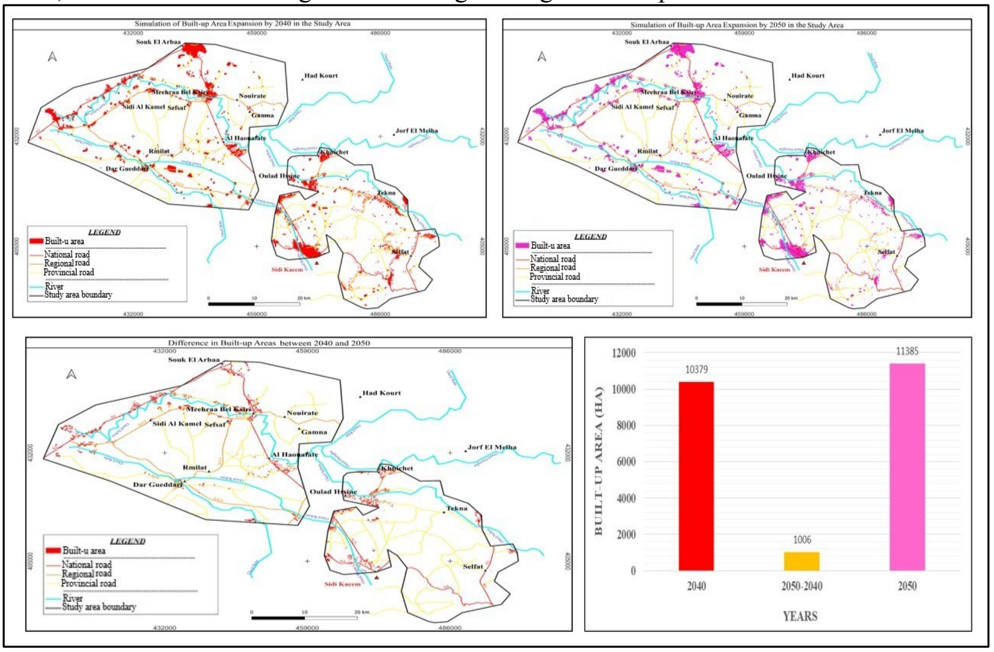

Figure 6. Simulated Built-up Area Expansion and Differences between 2040 and 2050 in the Study Area

4.2 Urban Expansion within the Irrigated Perimeter

To contextualize these results, a longitudinal analysis of urbanization was performed from 1985 through 2050. The synthetic map (Figure 6) integrates both historical and simulated data, providing a comprehensive view of past transformations and future projections.

Between 1985 and 2050, built-up areas increased more than fourfold, from 2,537 hectares in 1985 to an estimated 11,385 hectares by 2050. The most significant acceleration is expected after 2040, with urban growth spreading outward from established nuclei such as Sidi Kacem, Mechraa Bel Ksiri, and Dar Bel Amri. This expansion trajectory illustrates not only demographic growth but also the impact of infrastructural development in shaping settlement patterns.

Such projections reinforce the urgency of adopting sustainable land-use planning strategies, particularly in peri-urban zones where the competition between urban and agricultural functions is most pronounced.

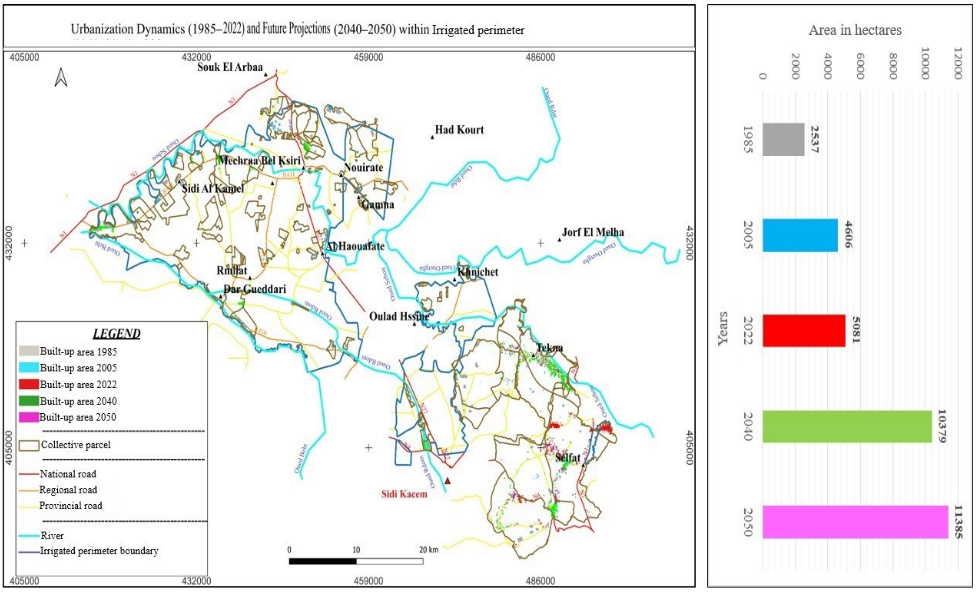

Figure 7. Evolution and Projection of Built-up Areas (1985–2050) within the irrigated perimeter

4.3 Expansion over Collective Lands

A specific focus was placed on the evolution of built-up areas within collective lands, which represent a crucial component of the irrigated perimeter. These lands, long dedicated to agricultural production and communal use, are increasingly exposed to urban pressures.

Spatial overlay analyses revealed a progressive increase in urban occupation of collective lands over the study period (Figure 7). In 1985, built-up areas covered approximately 924.8 hectares, rising to 1,289.3 hectares in 2005 and 1,353.7 hectares in 2022. This relatively modest growth during the first decades suggests a contained process of urbanization, largely consistent with the protective function attributed to these lands.

However, the projections indicate a marked acceleration after 2040. Built-up areas are expected to reach 2,123.4 hectares in 2040 and 2,303.8 hectares in 2050. This sharp increase illustrates a turning point in the dynamics of land occupation, reflecting broader patterns of urban sprawl and the expansion of settlement areas at the expense of agricultural and communal functions.

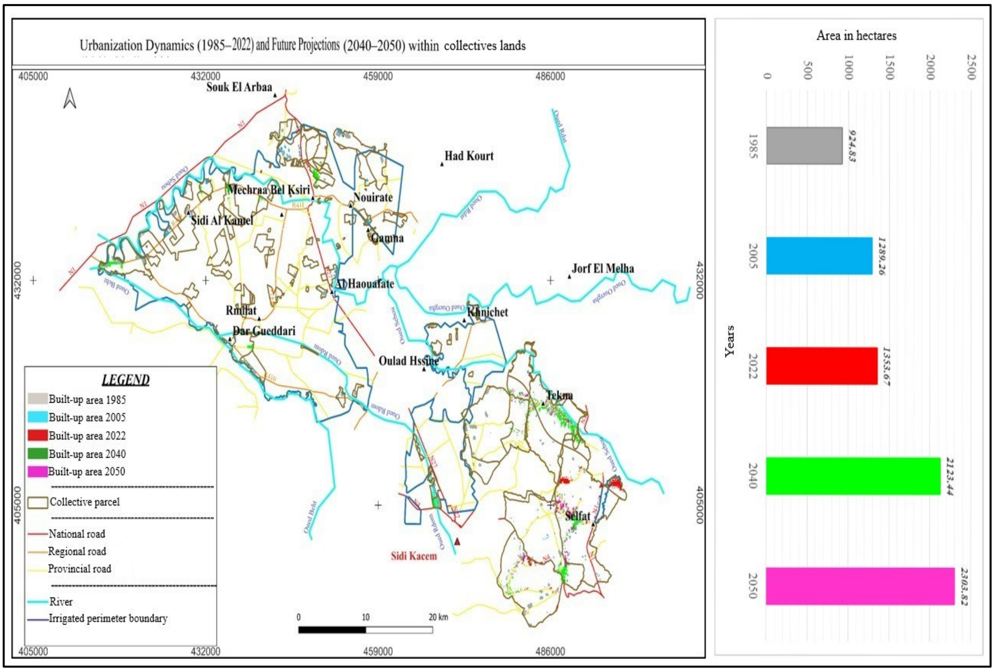

Figure 8. Evolution and projection of built-up areas within collective lands (1985–2050)

These findings highlight the growing pressure on collective lands in the irrigated perimeter of Sidi Kacem. While urban encroachment was relatively limited in earlier decades, the anticipated intensification underscores the urgency of integrating these trends into land management and planning strategies, in order to ensure a sustainable balance between urban growth and agricultural preservation.

4.4 Vulnerability of Collective Lands to Urbanization

To assess exposure, a vulnerability index was calculated for each collective land polygon, based on the ratio of projected built-up areas to total polygon area. This ratio was then classified into four levels: very low (0–5%), low (5–15%), medium (15–30%), and high (>30%).

– By 2040, the analysis (Figure 8) shows that very low vulnerability dominates (76% of total area, ~46,000 ha), reflecting a limited presence of projected urban encroachment. However, about 22% (13,377 ha) falls into the low vulnerability class, and smaller but critical shares (1–2%) exhibit medium to high vulnerability, concentrated around strategic urban centers.

– By 2050, the situation intensifies (Figure 8): very low vulnerability still prevails (80%, ~48,000 ha), but low vulnerability decreases to 17%, while medium vulnerability increases (2%), and high vulnerability persists (1%), highlighting localized but significant threats near rapidly urbanizing hubs.

These findings demonstrate that while most collective lands remain relatively safeguarded from direct urbanization, a non-negligible fraction is highly vulnerable, particularly those adjacent to dynamic urban centers. This calls for targeted governance measures, balancing urban development demands with the strategic protection of irrigated agricultural lands.

The results of the predictive modelling show a significant expansion of urban areas into the collective lands of the Sidi Kacem perimeter by 2050. The simulations revealed two distinct phases of urban growth: an initial rapid expansion until 2040, followed by a stabilization phase as the city approaches its spatial limits.

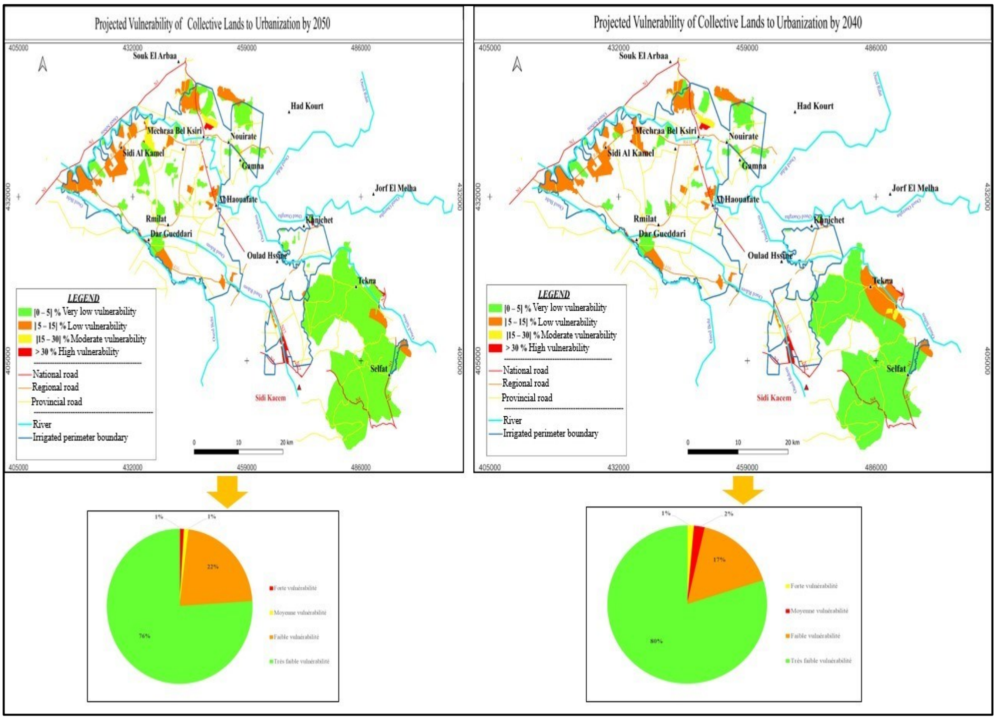

Figure 9: Projected Vulnerability of Collective Lands to Urbanization in 2040 and 2050 ***(Source: map by author)***

5 Conclusion

This study has demonstrated the decisive contribution of geospatial technologies, namely Geographic Information Systems (GIS), remote sensing, and empirical simulation models such as the Land Change Modeler (LCM), in analyzing, managing, and planning territorial dynamics. By integrating these tools, it was possible to design a geo-decisional framework capable of evaluating the vulnerability of collective lands within the irrigated perimeter of Sidi Kacem to urban expansion.

The modeling results reveal a moderate but continuous growth of built-up areas, increasing from 1,353 ha in 2022 to 2,123 ha in 2040, and 2,303 ha in 2050. This relatively contained trajectory reflects ongoing efforts by public authorities to regulate and monitor construction within irrigated perimeters. Beyond the descriptive aspect, the predictive maps and vulnerability indices produced provide strategic decision-support material that can guide land-use planning and strengthen territorial governance.

From the perspective of good land governance, these results offer decision-makers a solid empirical basis to adapt planning strategies, reconcile housing demand with the preservation of high-value agricultural land, and mitigate risks of uncontrolled urban sprawl. Urban Development Master Plans (SDAU) covering these areas could rely on such outputs to delineate rational zones for urbanization and to preserve agricultural resources critical for food security and rural development.Furthermore, the tools developed in this research enable stakeholders to act proactively, particularly in areas identified as highly vulnerable, by aligning land management policies with the broader objectives of sustainability, tenure security, and agricultural land valorization.

Finally, after having addressed the spatial, modeling, and decision-support dimensions of collective lands, this research points to the importance of reinforcing the institutional lever of melkisation. The methodological advances achieved here, including the agricultural potential mapping and urbanization vulnerability mapping, are not ends in themselves but rather strategic instruments. They are designed to support inclusive and forward-looking land governance, ensuring that the transformation of collective lands unfolds in a way that is economically efficient, socially equitable, and environmentally sustainable.

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