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Managing Agricultural Water Resources through Spatial Mapping and Cropping Pattern Reallocation in Egypt

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Abstract

- **Purpose:** This research presents a comprehensive Geographic Information Systems (GIS) based Spatial Decision Support System (SDSS) integrating spatial analysis and Multi-Criteria Decision Analysis (MCDA) to address severe agricultural water scarcity in Egypt through the strategic spatial reallocation of wheat-cultivated areas.
- **Methods:** To evaluate climatic water demands, the study applies the standardized FAO-56 Penman–Monteith method to estimate reference evapotranspiration (ET_0) and crop evapotranspiration (ETc) across key agricultural regions. Furthermore, spatial suitability across eight major governorates Al-Sharqia, Al-Beheira, Dakahlia, Minya, Assiut, Sohag, Fayoum, and Matrouh was evaluated using the Analytic Hierarchy Process (AHP) by integrating key environmental, topographic, and soil criteria including soil permeability, drainage, and irrigation water availability. A multi-regional reallocation scenario was successfully developed to shift wheat cultivation from high-water-demand zones toward highly suitable expansion lands in Matrouh, while rigorously maintaining national production continuity and food security targets.
- **Results:** The spatial reallocation resulted in significant localized reductions in seasonal crop water requirements, reaching 2.83% in Al-Sharqia, 2.10% in Al-Beheira, 1.90% in Sohag, 1.40% in Assiut, 1.10% in Dakahlia, 1.08% in Minya, and 0.86% in Fayoum.
- **Conclusions:** These findings conclusively demonstrate the efficacy of integrating spatial modeling, MCDA, and targeted crop reallocation as a robust framework for optimizing agricultural water management and enhancing water use efficiency under arid conditions.

KEYWORDS: AHP; Evapotranspiration; GIS; MCDA; SDSS; Wheat

1. Introduction

Egypt is facing increasing pressure on its limited freshwater resources due to rapid population growth, climate change, rising temperatures, and increasing water demand across the agricultural, domestic, and industrial sectors. The country's population was approximately 115 million in 2023, and recent United Nations projections indicate that Egypt's population could reach approximately 122 million by 2050 under the medium scenario (United Nations, 2022). This continued population growth is expected to further increase pressure on water resources and food production systems. Egypt already faces a substantial gap between available freshwater resources and total water demand, while agriculture represents the largest water-consuming sector, accounting for approximately 80–85% of freshwater use. Therefore, improving the efficiency of agricultural water allocation is becoming increasingly important for maintaining food production under growing water scarcity.

Climate change further intensifies this challenge through rising temperatures and increasing atmospheric evaporative demand. Higher temperatures can increase reference evapotranspiration (ET_0), resulting in higher estimated crop water requirements and greater agricultural water demand, particularly in regions characterized by high evaporative losses. Moreover, agricultural water demand is not spatially uniform across Egypt because climatic, topographic, soil, and water-availability conditions vary considerably among regions. This spatial variability creates differences in estimated crop water requirements and agricultural suitability, highlighting the potential for reallocating crops toward areas where similar agricultural production can be supported under relatively lower water requirements.

Wheat (*Triticum aestivum* L.) is one of Egypt's major strategic cereal crops and plays a central role in national food security. However, conventional wheat cropping patterns do not necessarily account for spatial variations in evapotranspiration and environmental suitability. Consequently, spatially reallocating wheat cultivation from areas with relatively higher estimated crop water requirements toward more suitable areas with lower water requirements could provide an alternative approach for improving agricultural water allocation.

GIS-based Spatial Decision Support Systems (SDSS), integrated with Multi-Criteria Decision Analysis (MCDA), can support this process by combining climatic, agricultural, soil, topographic, and water-resource factors to identify suitable areas for spatial crop reallocation (e.g., Ashour et al., 2021).

1.1. Literature Review and Background

Recent studies have strengthened the application of geospatial technologies, evapotranspiration modeling, and water management approaches to agricultural water management in Egypt. Ezz and Abdel Wares (2025) integrated GIS, remote sensing, and the FAO-56 Penman–Monteith equation to produce high-resolution ET_0 maps for Egypt, demonstrating their potential for supporting regional water allocation. Saffan et al. (2025) developed adjusted wheat crop coefficients (Kc) using energy-balance techniques to improve the estimation of seasonal crop evapotranspiration (ETc). Elsayed et al. (2025) highlighted the importance of location-specific strategies for balancing agricultural productivity and water conservation across agro-climatic zones, while Maharjan et al. (2025) demonstrated the utility of remote sensing and machine learning for climate-resilient agricultural planning. Abdelaziz et al. (2025) evaluated water management plans under arid conditions using simulation modeling and irrigation scenarios in the Western Nile Delta, highlighting the importance of integrating climatic, crop, soil, and water-management factors in agricultural water planning. In 2024, Roushdi investigated the implications of climate change for crop water requirements in the Western Nile Delta, Egypt, emphasizing the effects of changing climatic conditions on agricultural water demand. Mostafa et al. (2024) examined wheat production under water-scarce conditions in Sinai, Egypt, highlighting the importance of irrigation management and water-saving approaches for sustaining wheat productivity. Makar et al. (2024) used GIS-based AHP to assess wheat land suitability in El-Beheira Governorate, Egypt, demonstrating the applicability of multi-criteria spatial analysis to agricultural land evaluation. El-Shirbeny and Ali (2024) identified distinct spatial patterns of crop water consumption using satellite data, further demonstrating the importance of spatial variability in agricultural water requirements. Furthermore, research on canal rehabilitation and lining has highlighted the relationship between irrigation infrastructure, groundwater conditions, and water availability, emphasizing the need for improved management of irrigation-water resources.

In 2023, Mansour et al. investigated water productivity and irrigation-water distribution under different agricultural management practices, demonstrating the potential of improved irrigation and field-management techniques to enhance agricultural water use. Abd El Moneam (2023) assessed groundwater suitability for irrigation in the South Nile Delta using a groundwater quality index, highlighting the importance of evaluating water-resource suitability for sustainable agricultural use. In 2022, Sobh et al. validated the reliability of the FAO-56 Penman–Monteith method under Egyptian climatic conditions, supporting its application for estimating reference evapotranspiration in agricultural water-management studies. In 2021, Omar et al. examined the impacts of climate change on Egypt's water resources and food security, emphasizing the increasing challenges facing agricultural water management. Ashour et al. assessed the reuse of agricultural drainage water for irrigation in El-Beheira Governorate, highlighting the importance of alternative water resources in supporting agricultural water management. In 2020, Yassen et al. emphasized the importance of incorporating regional variations in ET_0 into irrigation planning. Furthermore, Abd El-Hafez and Hammad (2020) and El-Marsafawy et al. demonstrated that rising temperatures increase seasonal irrigation water requirements, highlighting the need for adaptive water management strategies. At the regional scale, Dawoud et al. (2017) confirmed substantial spatial variability in irrigation performance across the Nile Delta using remotely sensed evapotranspiration. El Baroudy (2016) established a GIS-based land suitability analysis using multi-criteria evaluation to identify suitable agricultural land. Allen et al. (2007) demonstrated the application of satellite-based estimates of actual evapotranspiration to support field- and regional-scale agricultural water management. These developments build upon earlier agricultural planning and optimization approaches, including the goal programming framework presented by Bazaraa and Bouzaher (1981).

1.2. Research Gap

Although substantial progress has been achieved in GIS-based agricultural assessment, evapotranspiration modeling, land suitability analysis, and Multi-Criteria Decision Analysis (MCDA), important research gaps remain. Previous studies have commonly addressed individual components, such as reference evapotranspiration (ET_0) estimation, crop water requirement assessment, land suitability evaluation, or irrigation planning, rather than integrating these components within a comprehensive spatial decision-support framework for crop reallocation (e.g., Santos Pereira et al., 2025).

Moreover, limited attention has been given to multi-regional spatial reallocation of wheat cultivation based on

the combined influence of climatic conditions, land suitability, topographic and soil characteristics, water-resource availability, existing cultivated-area distribution, and regional crop water requirements.

In particular, there is a need for an integrated GIS-based framework capable of identifying spatially suitable areas for wheat reallocation while considering differences in estimated crop water requirements among agricultural regions. Such an approach can provide a practical basis for evaluating potential water savings through spatial redistribution of wheat cultivation without relying solely on localized improvements in irrigation management. Therefore, the present study addresses this gap by integrating FAO-56 evapotranspiration estimation, AHP-based criteria weighting, MCDA, and GIS-based weighted overlay analysis within a Spatial Decision Support System to support multi-regional wheat reallocation and agricultural water demand management in Egypt.

1.3. Scientific Novelty and Contribution

The primary contribution of this study is the development of an integrated GIS-based Spatial Decision Support System (SDSS) that links spatial land suitability with regional evapotranspiration variability (ET_0 and ETc), cultivated-area distribution, and strategic crop reallocation. Unlike conventional GIS-AHP studies that primarily focus on identifying suitable agricultural areas, the proposed framework extends this approach to the spatial reallocation of existing wheat cultivated areas between governorates according to crop water requirements and land suitability.

Specifically, the framework evaluates the reallocation of wheat cultivation from Al-Sharqia, Al-Beheira, Dakahlia, Minya, Assiut, Sohag, and Fayoum, where relatively higher estimated crop water requirements are identified, toward Matrouh Governorate, which exhibits relatively lower estimated crop water requirements. Importantly, the reallocation is not based solely on evapotranspiration; it also considers slope, water availability, soil permeability, drainage conditions, and elevation (DEM) to assess the suitability of the receiving area.

The proposed framework therefore provides a multi-criteria, spatially explicit approach for evaluating the redistribution of existing wheat cultivation while maintaining the total national wheat cultivated area and reducing estimated crop water requirements. Its open-source GIS-based workflow can also be adapted to other crops, regions, and agricultural water-management scenarios in Egypt.

2. Study Objectives

The primary aim of this study is to develop an open-source GIS-based Spatial Decision Support System (SDSS) framework for the spatial reallocation of agricultural crops from areas with higher evapotranspiration and crop water requirements to areas with lower evapotranspiration, with wheat used as the case study for demonstrating this approach in Egypt. The framework is designed to support agricultural water demand management by maintaining the cultivated area while spatially reallocating wheat cultivation toward locations with lower crop water requirements.

The specific research objectives are:

- To estimate baseline reference evapotranspiration (ET_0) and crop evapotranspiration (ETc) using the FAO-56 Penman–Monteith formulation to quantify spatial variations in wheat crop water requirements across the target governorates.
- To develop an AHP-driven multi-criteria land suitability model integrating climatic, soil, topographic, water availability, and environmental parameters.
- To model a multi-regional spatial reallocation scenario that transfers cultivated wheat areas from governorates with higher evapotranspiration, namely Al-Sharqia, Al-Beheira, Dakahlia, Minya, Assiut, Sohag, and Fayoum, to Matrouh governorate, identified as a relatively lower-evapotranspiration and suitable receiving area.
- To quantify the resulting regional reduction in estimated crop water requirements and assess the framework's potential to support national agricultural water demand management.

3. Materials and Methods

3.1. Study Area and Environmental Setting

The study area encompasses eight strategic Egyptian governorates representing diverse agro-climatic zones across the Nile Delta, Middle Egypt, Upper Egypt, and the Western Coastal Desert: Al-Sharqia, Al-Beheira, Dakahlia, Minya, Assiut, Sohag, Fayoum, and Matrouh. These governorates exhibit substantial spatial variability in climatic conditions, soil characteristics, topography, and agricultural water availability, providing a suitable basis for

assessing spatial variations in wheat crop water requirements and land suitability.

3.2. Methodological Framework

The methodological framework establishes an integrated GIS-based Spatial Decision Support System (SDSS) designed to evaluate spatial variations in wheat crop water requirements and identify strategic opportunities for agricultural water demand management through targeted spatial reallocation. The methodology is systematically organized into four interconnected stages, beginning with the rigorous estimation of reference evapotranspiration (ET_0) and crop evapotranspiration (ETc) using multi-decadal climatic data. This is followed by a detailed assessment of the baseline spatial distribution of wheat-cultivated areas and their corresponding water consumption volumes across contrasting agro-climatic zones. The subsequent stages integrate multi-criteria environmental and agricultural suitability mapping incorporating topographic, soil, and drainage parameters with spatial optimization modeling. Ultimately, this enables the identification of optimal receiver zones where wheat can be sustainably cultivated under comparatively lower crop water requirements, as illustrated in Figure 1.

Stage 1: Estimation of Evapotranspiration and Crop Water Requirements

The first stage focuses on estimating the climatic water demand associated with wheat cultivation. Reference evapotranspiration (ET_0) is estimated using the FAO-56 Penman–Monteith method based on the available climatic variables, including temperature, relative humidity, wind speed, and solar radiation. The estimated (ET_0) is then combined with the wheat crop coefficient (Kc) to calculate crop evapotranspiration (ETc) according to the relationship $ETc = ET_0 \times Kc$ (Allen et al., 1998).

The resulting (ETc) values represent the estimated climatic crop water requirement and are spatially represented within the GIS environment to identify differences in wheat water requirements among the studied governorates. The (ET_0) estimation procedure is additionally evaluated against CROPWAT results using selected reference stations, with CROPWAT used for model validation rather than as the primary spatial processing tool.

Stage 2: Baseline Wheat Area and Water Demand Assessment

The second stage establishes the baseline condition by incorporating the existing spatial distribution of wheat-cultivated areas. The wheat area in each governorate is spatially associated with its corresponding ETc values to estimate the baseline crop water requirement before any spatial reallocation. This stage provides the reference scenario against which the effects of the proposed reallocation are evaluated. Accordingly, the analysis quantifies the estimated crop water requirement associated with the existing wheat-cropping pattern and identifies areas where wheat cultivation is associated with relatively higher estimated crop water requirements.

Stage 3: Spatial Suitability Assessment and Reallocation

The third stage evaluates the suitability of different locations for wheat cultivation using a GIS-based Multi-Criteria Decision Analysis (MCDA). The assessment incorporates climatic water requirement and relevant environmental, soil, topographic, and water-availability criteria, including ETc, slope, water-source availability, soil permeability, drainage conditions, and elevation. The Analytic Hierarchy Process (AHP) is used to derive the relative importance of the selected criteria based on expert judgments, followed by a weighted-overlay procedure to generate a spatial suitability map. The suitability assessment is integrated with the spatial reallocation procedure to identify potential receiving locations characterized by comparatively favorable conditions and lower estimated crop water requirements. The spatial reallocation is implemented while respecting the defined administrative boundaries and suitability requirements and while preserving the total wheat-cultivated area considered in the scenario.

Stage 4: Post-Reallocation Water-Demand Assessment and Water-Saving Estimation

In the final stage, the post-reallocation wheat areas are reassessed using the corresponding spatial (ETc) values and compared with the baseline condition to quantify the reduction in estimated crop water requirements. The difference between the baseline and post-reallocation requirements is used to estimate the potential agricultural water savings and assess the contribution of spatial reallocation to agricultural water demand management.

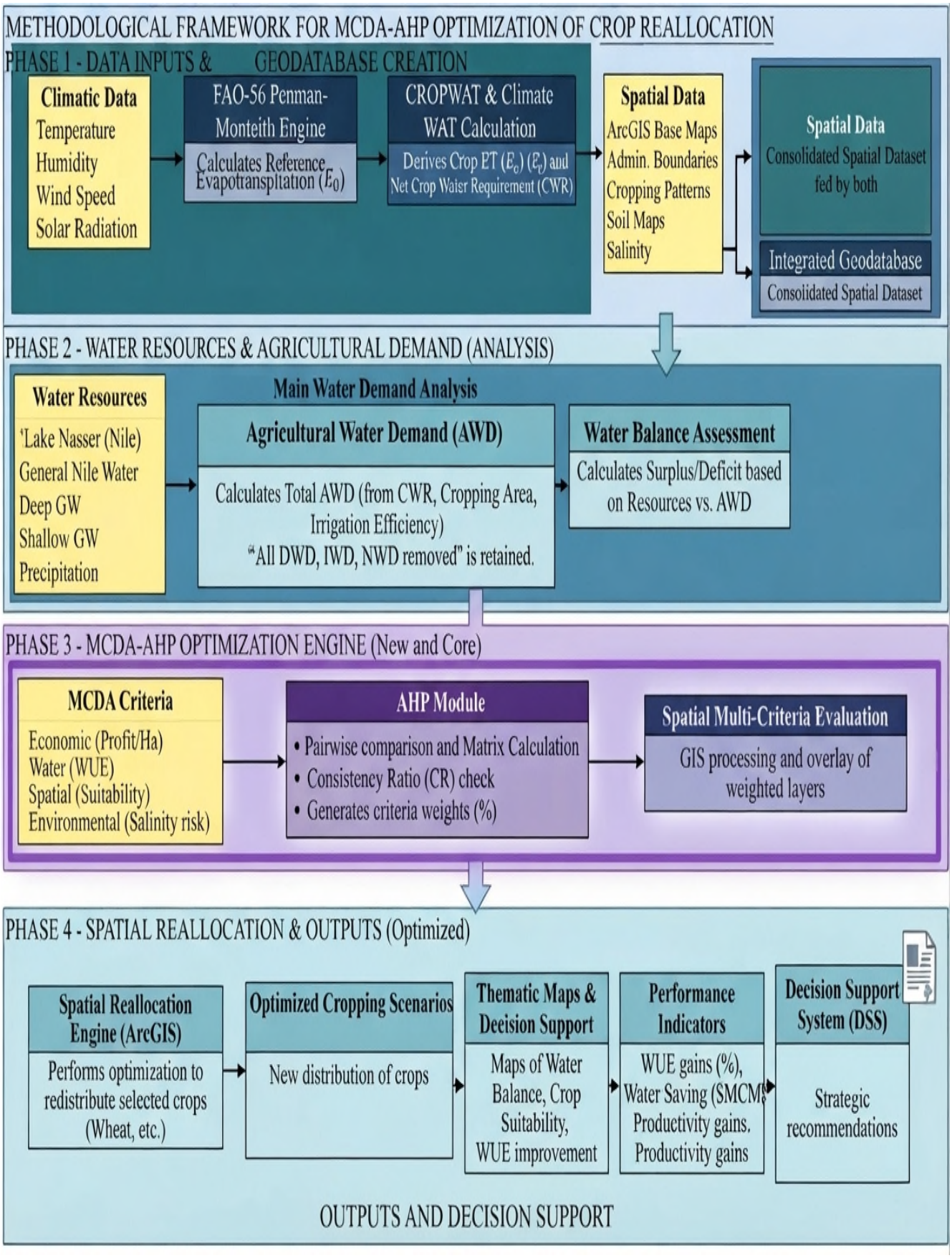


Fig. 1 Methodological Framework of the GIS-Based (SDSS) Integrating (MCDA) for Wheat Spatial Realloca

3.3. Quantification of Evapotranspiration (ET_0 and ETc)

$$ET0 = \frac{0.408\Delta((Rn - G) + \gamma(\frac{900}{T + 273})u2(e - ea)}{\Delta + \gamma(1 + 0.34u2}$$

Reference evapotranspiration (ET_0) was calculated using the standardized FAO-56 Penman–Monteith equation (Allen et al., 1998).

Where:

- ET_0 is reference evapotranspiration (mm/day),
- R_n is net radiation at the crop surface (MJ/m²·day),
- G is soil heat flux density (MJ/m²·day),
- T is mean daily air temperature at 2 m height (°C),
- u_2 is wind speed at 2 m height (m/s), e_s - e_a is vapor pressure deficit (kPa),
- Δ is the slope of the vapor pressure curve (kPa/°C),
- and γ is the psychrometric constant (kPa/°C).

3.4. Data Collection and Preparation

Climatic, agricultural, environmental, and geospatial datasets were collected from national and international sources and processed within the ArcGIS Pro environment. Climatic variables, including temperature, relative humidity, wind speed, solar radiation, elevation, and latitude, were obtained from CAPMAS for 2021 (Central Agency for Public Mobilization and Statistics [CAPMAS], 2021) and used to estimate reference evapotranspiration (ET_0) using the FAO-56 Penman–Monteith equation. Wheat cultivation areas and related agricultural statistics were obtained from the Ministry of Agriculture and CAPMAS (Central Agency for Public Mobilization and Statistics [CAPMAS], 2021) and used to establish the baseline spatial distribution of wheat cultivation across the study area. Additional spatial datasets representing soil, topographic, drainage, and irrigation-water conditions were prepared to support the multi-criteria suitability assessment. The selected criteria included soil permeability, drainage, slope, DEM, and irrigation water availability, which were standardized and integrated within the GIS environment to ensure their compatibility for subsequent spatial analysis and weighted-overlay processing. The DEM was obtained from the USGS at a spatial resolution of 90 m, while soil permeability and drainage datasets were obtained from the FAO at a spatial resolution of 250 m (United States Geological Survey [USGS], 2024). Before analysis, the datasets were subjected to spatial preprocessing, including projection, resampling, clipping to the study-area boundary, and conversion to a common raster framework. This preprocessing ensured spatial consistency among datasets with different resolutions, formats, and source characteristics and minimized inconsistencies during the overlay analysis. The processed datasets were then integrated within the GIS Model Builder workflow to provide a reproducible sequence from data preparation and (ETc) estimation to suitability assessment and spatial reallocation. The datasets were subsequently prepared and harmonized to support the (ETc) assessment, suitability analysis, and spatial reallocation procedure, as summarized in Table 1.

Table 1 Source, Year/Period, Resolution, and GIS Processing

Data	Source	Year/Period	Resolution	GIS Processing
Climatic Data	CAPMAS	2021	—	IDW spatial interpolation and raster generation
DEM	USGS	—	90 m	Clipping to the study area and spatial analysis
Water Sources	GIS data	—	—	Spatial analysis and raster conversion
Drainage	FAO	—	250 m	Clipping and reclassification
Soil Permeability	FAO	—	250 m	Clipping and reclassification
Agricultural Statistics	CAPMAS	2021	—	Statistical/spatial processing

The GIS preprocessing procedures included clipping all spatial datasets to the study area, spatial interpolation of climatic variables, raster conversion, and reclassification of thematic layers according to their suitability levels. The resulting spatial criteria were standardized to a common raster cell size of 250 m before integration within the MCDA/Weighted Overlay analysis.

3.5 GIS-Based Multi-Criteria Decision Analysis (MCDA)

The spatial suitability model was developed using a GIS-based Multi-Criteria Decision Analysis (MCDA) approach. The selected criteria included ET_0, soil permeability and drainage, DEM, slope, and irrigation water availability. The criteria were standardized according to their suitability characteristics and converted to a common 250 m raster resolution. They were then integrated in ArcGIS Pro using the Weighted Overlay tool and normalized AHP weights.

The final suitability map was generated as a weighted sum of the standardized criteria and used to identify areas with comparatively favorable conditions for wheat cultivation. The resulting suitability zones provided the spatial basis for identifying potential locations for wheat reallocation toward areas with relatively lower estimated crop water requirements.

$$CI = \frac{\lambda max - n}{n - 1}$$

$$CR = \frac{\{CI\}}{RI}$$

The relative importance of the selected criteria was determined using the Analytic Hierarchy Process (AHP) proposed by Saaty (Saaty, 1980). Pairwise comparisons were conducted using the standard nine-point Saaty scale based on the judgments of 30 experts from engineering faculties and research institutes. The consistency of the comparison matrix was assessed using the Consistency Index (CI) and Consistency Ratio (CR), where λmax is the maximum eigenvalue, n is the number of criteria, and RI is the Random Index. A matrix is considered acceptable when CR < 0.10. In this study, the calculated CR was 0.01, indicating excellent consistency of the expert judgments and supporting the reliability of the derived criterion weights, as shown in Tables 2.

Table 2 The final normalized weights obtained from the AHP analysis

No.	Criteria	Weight
1	ETc	0.369
2	DEM	0.051
3	Water Source	0.193
4	Drainage	0.097
5	Permeability	0.097
6	Slope	0.193
Total		**1.000**

3.6 Model Validation

To assess the reliability of the estimated reference evapotranspiration (ET_o), an additional comparative validation was conducted using FAO crop Water Requirements (CROPWAT 8.0). Climatic data were obtained from the Climatic and Water Database (CLIMWAT 2.0) and processed through CROPWAT 8.0 to estimate ET_o for representative stations corresponding to the study areas. The selected stations were Bilbeis for Sharqia, Alexandria/Beheira for Beheira, and Dabaa for Matrouh. The ET_o estimates obtained from CROPWAT 8.0 were compared with those generated by the proposed GIS-based FAO-56 Penman–Monteith methodology. As shown in Figure (2), the spatial distribution of meteorological stations available in CLIMWAT 2.0 was examined to select representative stations covering the study area and supporting the validation of the estimated reference evapotranspiration (ET_o) model. The agreement between the two approaches was quantitatively evaluated using the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). The resulting values were 0.675 mm/month, 0.567 mm/month, and 11.53%, respectively.

These results indicate generally acceptable agreement between the proposed GIS-based methodology and the CROPWAT 8.0 estimates, supporting the reliability of the estimated ET_o values used in the spatial analysis as shown in Figure 2.

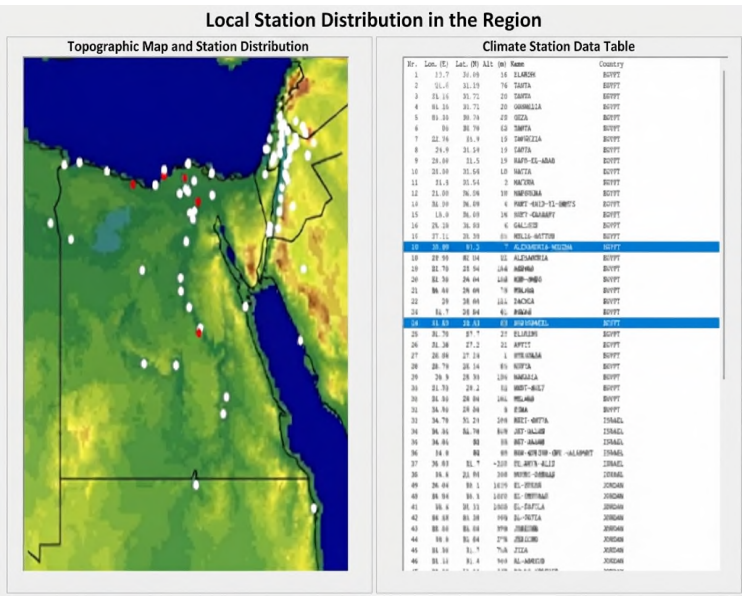


Fig. 2 Spatial distribution of CLIMWAT 2.0 meteorological stations and selection of representative stations for model validation in Egypt

4. System Design and Spatial Analysis

The proposed research framework combines Geographic Information Systems (GIS) with climatic, agricultural, soil, topographic, and water-availability datasets to develop a spatial decision-support approach for wheat cultivation

reallocation and agricultural water management. The system is structured as an integrated sequence of analytical procedures that transform the input datasets into spatial suitability information and reallocation scenarios. The framework comprises four principal stages:

(1) preparation and integration of the required climatic, agricultural, and spatial datasets;

(2) estimation of reference and crop evapotranspiration (ET_0 and ETc) to characterize spatial variations in wheat crop water requirements;

(3) assessment of land suitability and existing wheat cultivation patterns using GIS-based multi-criteria spatial analysis; and

(4) development of a spatial reallocation scenario based on the resulting suitability assessment to identify alternative locations with lower estimated crop water requirements.

The framework establishes a direct link between the spatial distribution of wheat cultivation and the corresponding estimated crop water requirements across the study area. The evapotranspiration assessment provides the climatic basis for comparing water requirements among different locations, while the multi-criteria analysis incorporates additional spatial factors affecting agricultural suitability. The resulting suitability maps are then used to identify areas that can accommodate wheat cultivation under more favorable spatial conditions. The reallocation stage focuses on redistributing the existing cultivated wheat area toward locations with relatively lower estimated crop water requirements rather than increasing the total cultivated area. Accordingly, the framework provides a GIS-based analytical pathway for evaluating potential reductions in estimated crop water requirements resulting from alternative spatial distributions of wheat cultivation.

4.1 Integrated Wheat Structural Analysis

This section presents the detailed spatial analysis of wheat within the System Design and Spatial Analysis framework. The analysis examines the spatial distribution of wheat cultivation and its relationship with the main factors considered in the proposed decision-support framework. The spatial analysis integrates climatic, environmental, soil, topographic, and water-related information to provide a comprehensive representation of the existing wheat production pattern. The resulting spatial layers are processed and combined to identify areas with different levels of suitability for wheat cultivation and water demand management. This analysis provides the spatial basis for assessing the current distribution of wheat and identifying potential areas for spatial reallocation. The results presented in this section support the subsequent assessment of potential water savings while maintaining the overall cultivated area. The main spatial-analysis results and outputs are presented in Figures 3–11.

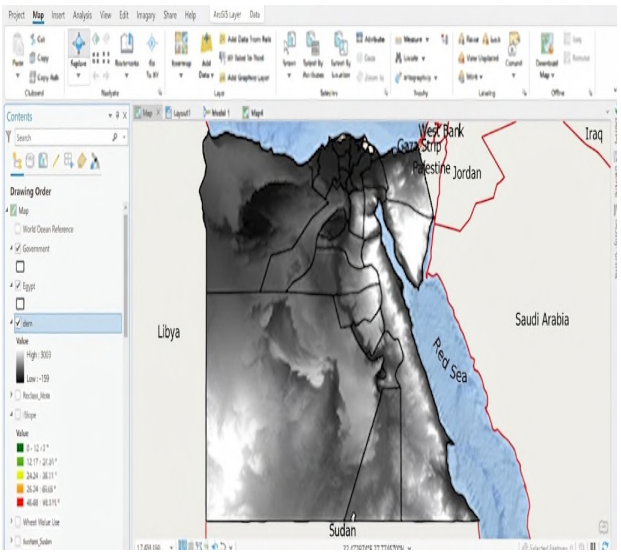


Fig. 3 Digital Elevation Model (DEM) of the Study

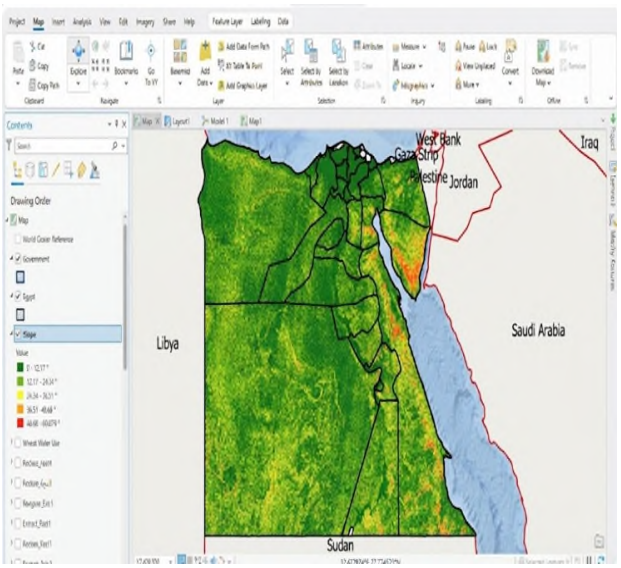


Fig.4 Area Spatial Distribution of Slope Grades

4.1.1 Reference Evapotranspiration (ET_o)

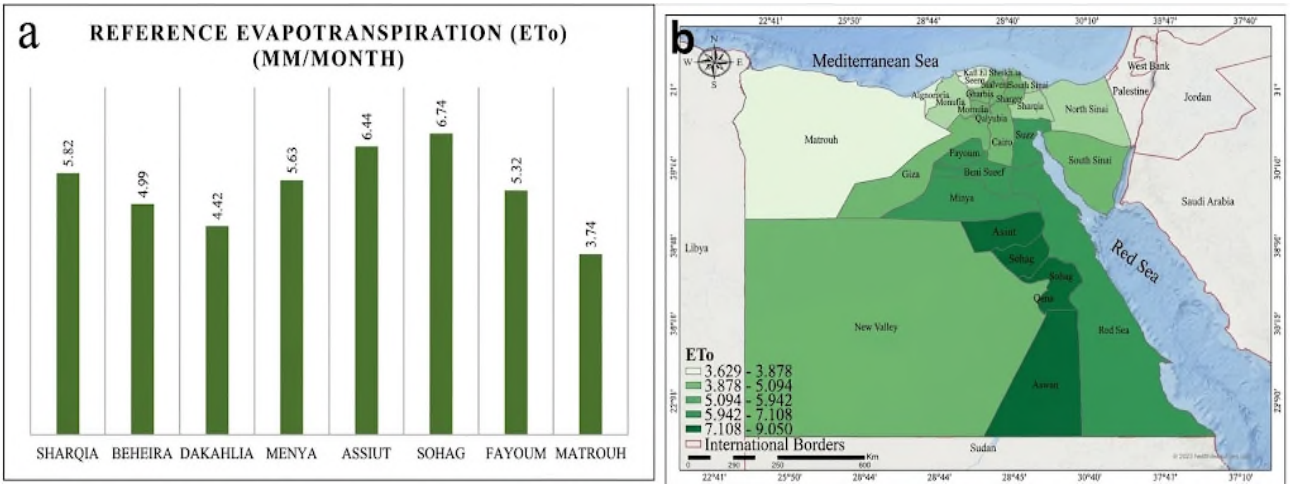


Fig. 5 Reference evapotranspiration (ET_o): (a) monthly baseline rates for each governorate, and (b) spatial distribution map of (ET_o) intervals.

4.1.2 Crop Evapotranspiration (ETc)

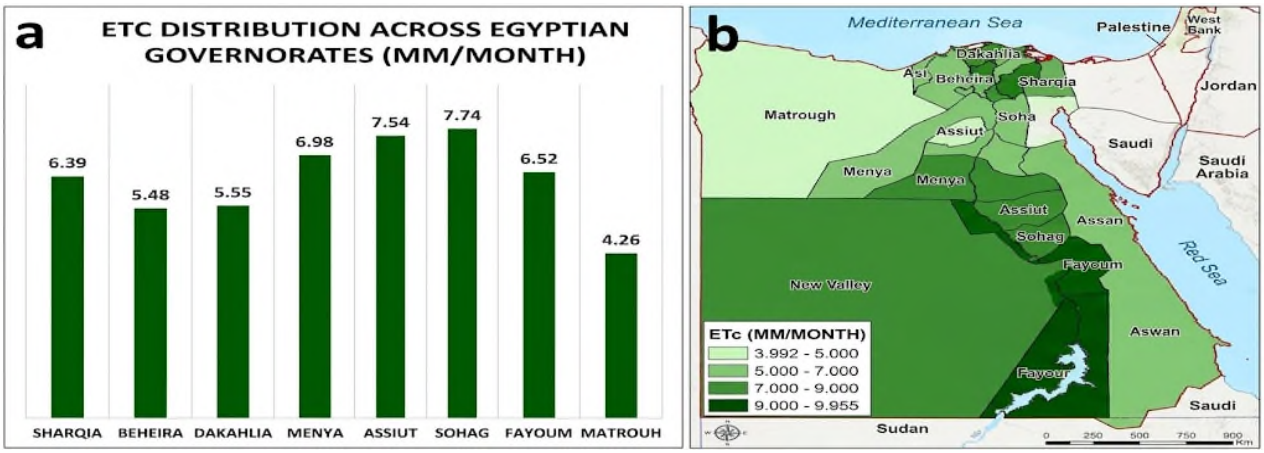


Fig. 6 Crop evapotranspiration (ETc): (a) monthly values (mm/month) per governorate, and (b) spatial distribution map

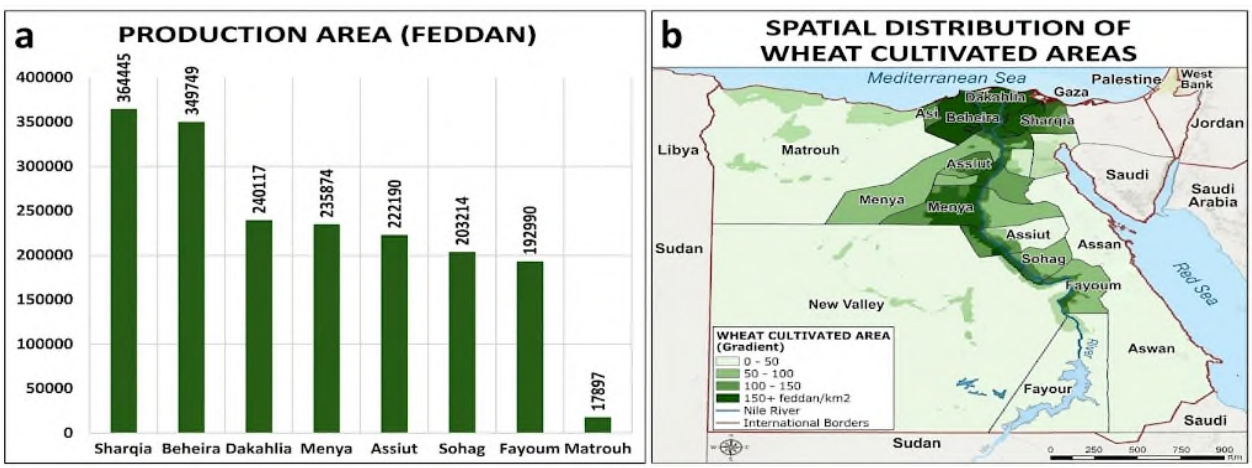


Fig. 7 Baseline wheat cultivated areas: (a) Area by governorate (feddans); (b) GIS spatial distribution map

4.1.4 Water Use Before Reallocation

The baseline water use was estimated based on the existing spatial distribution of wheat cultivation before applying the proposed reallocation scenario. It represents the estimated crop water requirement (ETc) associated with the current cultivated wheat areas in the study region. The spatial distribution of the estimated water use provides a baseline for comparison with the results obtained after reallocation. The corresponding spatial results are presented in the following figures.

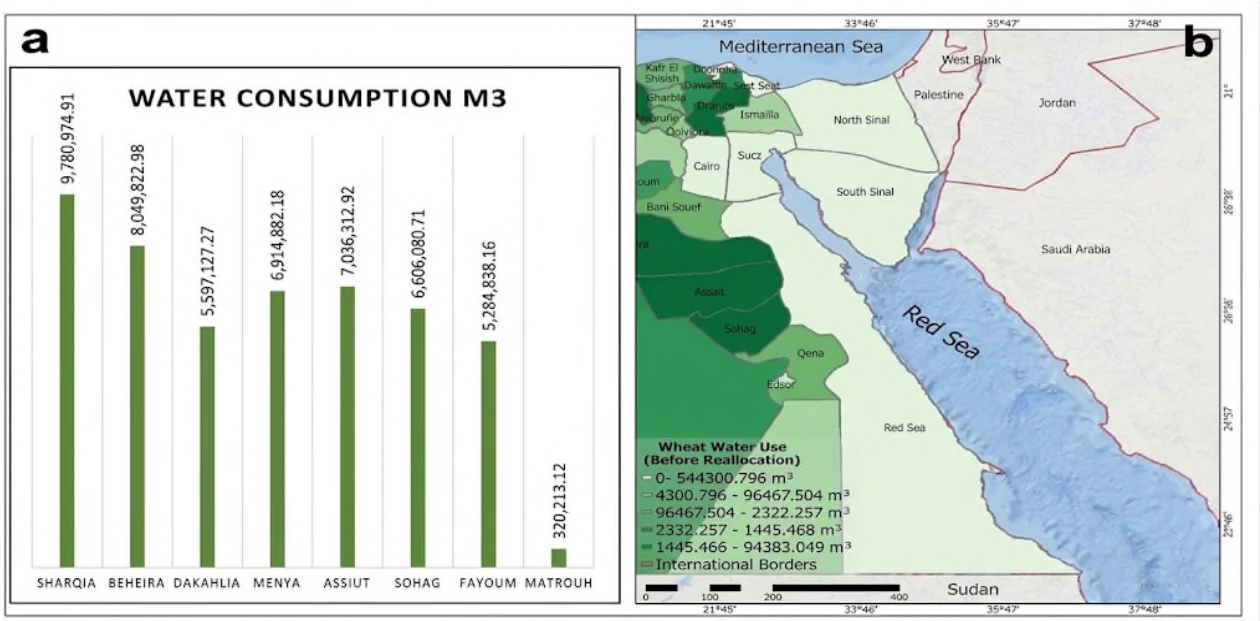


Fig. 8 (a) Total volumetric water use by governorate (m3); (b) Spatial distribution map across Egypt

4.1.5 Wheat Cultivated Area After Reallocation

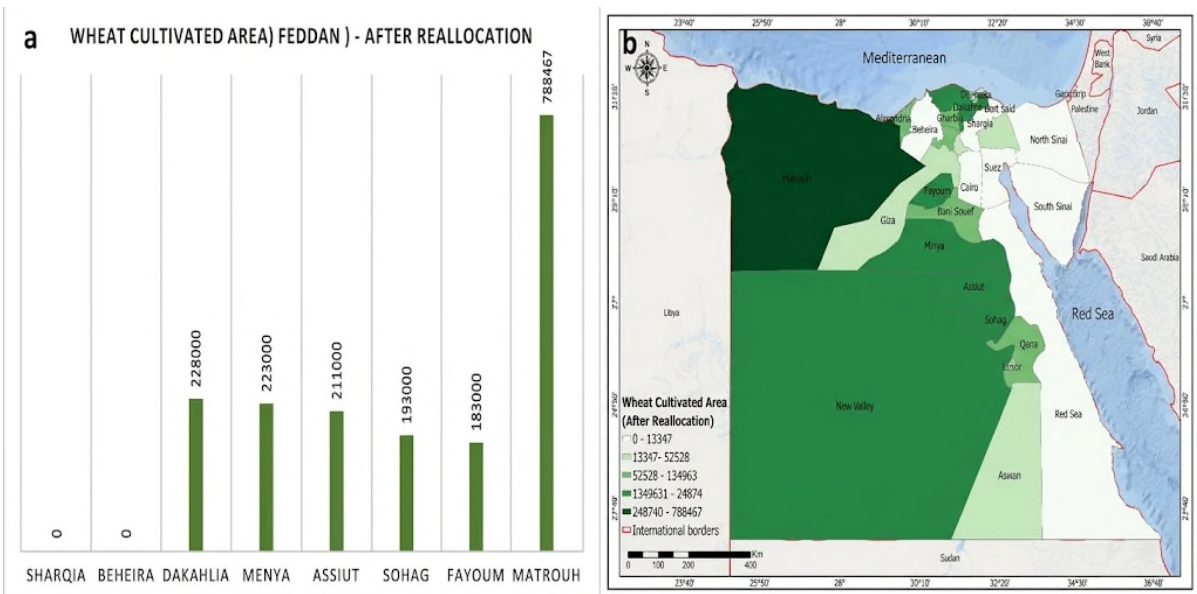


Fig.9 Post reallocation wheat cultivated areas: (a) Area by governorate (feddans); (b) GIS spatial distribution map

4.1.6 Water Use After Reallocation

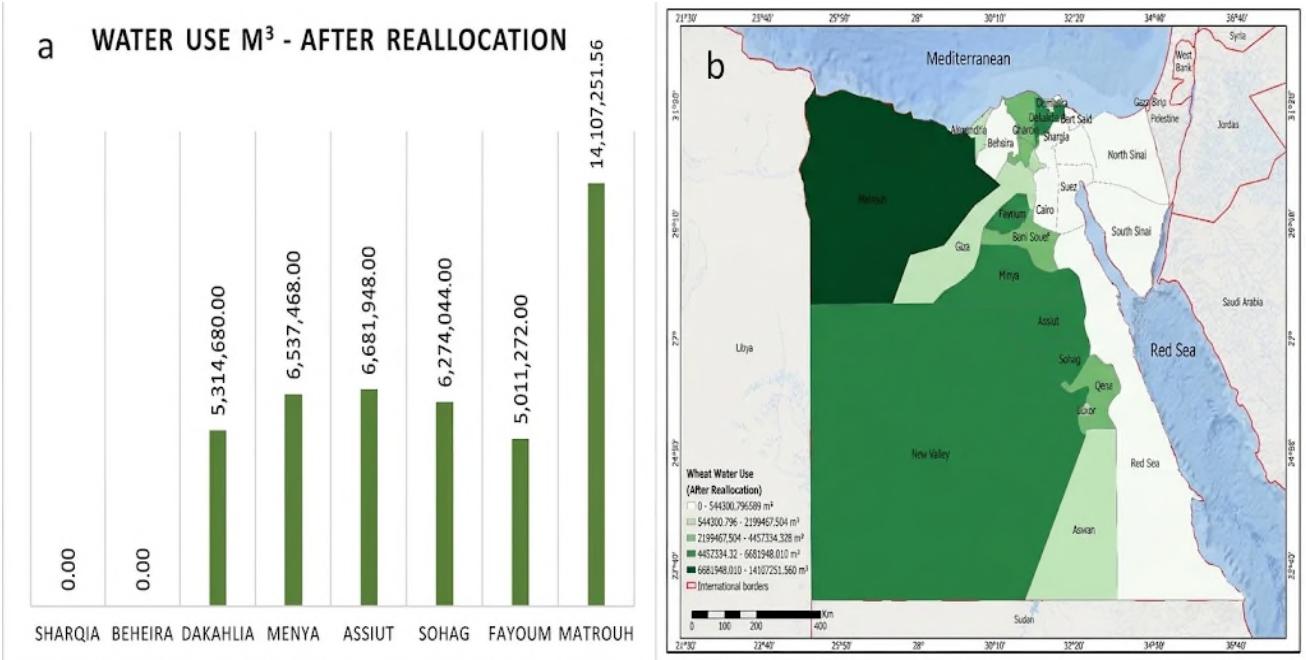


Fig. 10. Post-reallocation wheat water use: (a) Water use by governorate (m³); (b) GIS spatial distribution map

4.1.7 Final Multi-Criteria Evaluation of Agricultural Water Savings

This section illustrates the final multi-criteria evaluation outputs for agricultural water savings across the studied governorates. The spatial distribution map highlights land suitability classes for crop reallocation (Fig. 11a), while the line chart compares water consumption levels before and after implementation alongside the resulting water savings (Fig. 11b).

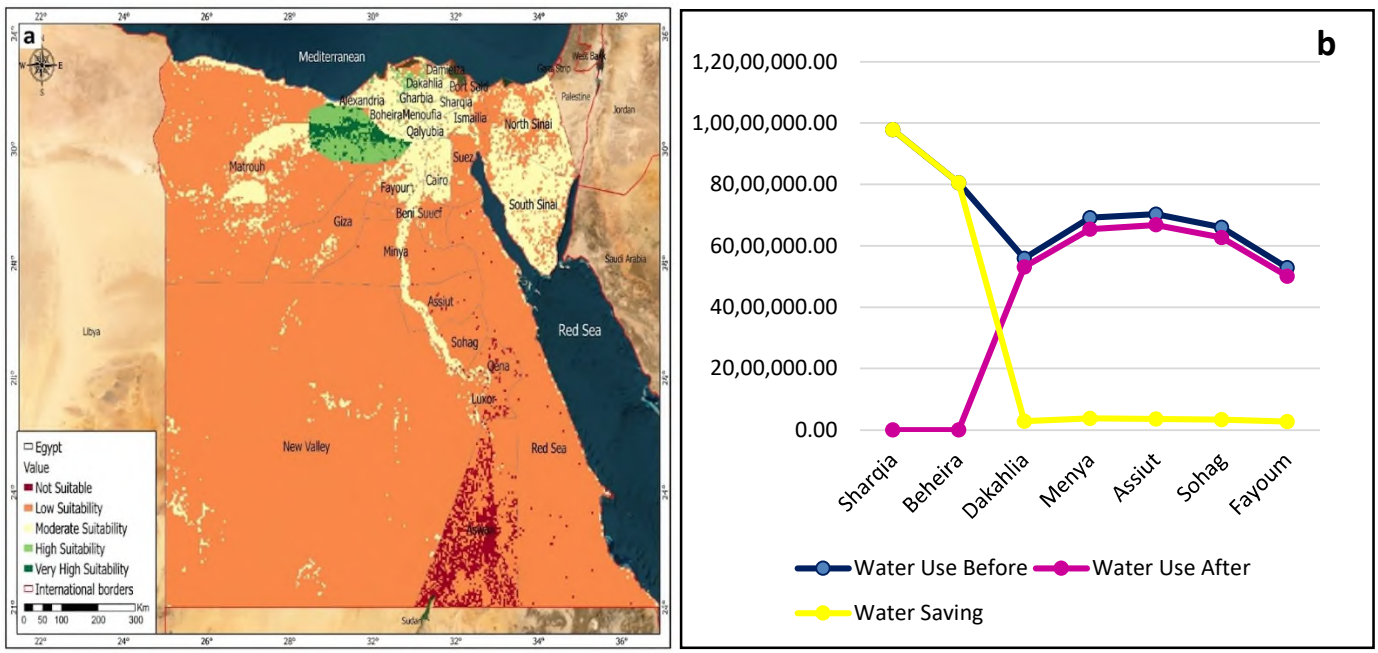


Fig. 11 Multi-criteria evaluation outputs: (a) land suitability/reallocation map, and (b) comparison of wheat water use

5.Results and Discussion

The multi-criteria spatial reallocation model redistributed a cumulative wheat area of 1,877,340 feddans toward Matrouh Governorate, while strictly maintaining the national baseline wheat area at 4,351,220 feddans. Constrained by socioeconomic and logistical factors, Al-Sharqia and Al-Beheira governorates were reallocated in their entirety, whereas remaining regions underwent targeted partial adjustments.

Matrouh emerged as the optimal receiver zone through a comprehensive evaluation of multi-criteria parametersspanning soil, topography, drainage, and climate rather than relying solely on evapotranspiration (ET) metrics. This optimization directly aligns with Egypt's Vision 2030 and the mega national project, "The New Delta."

Consequently, this spatial redistribution reduced estimated crop water requirements across the study area. Reductions varied by baseline footprint and agro-climatic conditions: Al-Sharqia accounted for 2.83% of the overall national reduction, followed by Al-Beheira at 2.10%, Sohag (1.90%), Assiut (1.40%), Minya (1.08%), and Fayoum (0.86%). Ultimately, these findings demonstrate that targeted spatial reallocation significantly enhances agricultural water use efficiency while safeguarding national food security and total cultivated acreage.

6. Conclusion

This study developed an integrated GIS-based Spatial Decision Support System (SDSS) to facilitate spatially differentiated agricultural water demand management through the strategic reallocation of wheat cultivation. By combining the FAO-56 Penman–Monteith methodology, multi-criteria spatial analysis, and the Analytic Hierarchy Process (AHP), the framework successfully links crop water requirements with comprehensive land and water suitability conditions. This integration establishes a systematic mechanism for identifying optimal relocation pathways that reduce estimated crop water consumption while strictly preserving national agricultural footprints.

Spatial variations in crop water requirements must be explicitly embedded into agricultural land-allocation planning rather than treating farming zones as uniform entities. The framework translates heterogeneous climatic, topographic, soil, drainage, and water-availability parameters into actionable geospatial decision support. Instead of enforcing rigid reductions in cultivated acreage, the approach utilizes targeted spatial reallocation as an alternative pathway to capture water-saving efficiencies under growing climate pressures and fixed freshwater constraints.

Furthermore, the developed SDSS offers a highly adaptable analytical architecture that can readily accommodate updated climatic, agronomic, and hydrological datasets. Because the underlying criteria, weights, and suitability thresholds can be modified according to evolving regional policies, the framework provides a robust baseline for broader applications.

Future research endeavors could significantly enhance this decision-support process by expanding the spatial scope to evaluate additional governorates for wheat cultivation or by extending the model to other vital strategic crops, such as barley and rice. Incorporating comprehensive economic valuations, farm-level return analyses, irrigation system efficiencies, groundwater sustainability metrics, and future climate change scenarios will further refine the assessment of trade-offs between agricultural production and water resource management.

Ultimately, the proposed framework provides scientific spatial evidence to support policymakers in identifying potential water-saving opportunities and optimizing agricultural land distribution under escalating water scarcity.

6.1 Study Limitations

While the developed GIS-based Spatial Decision Support System (SDSS) provides a robust, reproducible framework for evaluating agricultural water demand management through spatial crop reallocation, several structural, methodological, and operational limitations should be explicitly acknowledged. Specifically, while geospatial modeling effectively identifies macro-level optimization potentials, translating these digital scenarios into physical agricultural transformations introduces complex, multi-scale realities. These practical boundaries span from institutional governance and hydrometric constraints at the irrigation canal level to the socio-economic vulnerabilities of local farming communities, necessitating a transparent appraisal of the model's operational boundaries before scaling policy interventions:

1. **Baseline Data Dependency:**

   The evapotranspiration and spatial suitability modeling rely on baseline climatic and agricultural statistics (CAPMAS 2021). Future multi-decadal climatic shifts, seasonal temperature anomalies, and inter-annual hydrological variability may influence absolute evapotranspiration rates and water-saving estimates.

2. **Administrative, Scale Dependent, and Socioeconomic Constraints:**

   The proposed spatial reallocation scenario models optimal land suitability and crop water requirement reductions within existing governorate boundaries. However, practical implementation must carefully account for real-world land tenure dynamics, farmer adoption rates, localized cropping preferences, and regional supply chain logistics. Crucially, a distinct methodological and operational divergence exists between governorates subjected to total spatial reallocation (such as Al-Sharqia and Al-Beheira) and those undergoing partial adjustments:

- **Total Reallocation (Al-Sharqia and Al-Beheira):**

  Involves a comprehensive spatial restructuring of targeted cropping patterns across the entire administrative territory. Under this total reallocation framework, the GIS model evaluates overall land capability and territorial suitability across the whole governorate scale, directing complete cropping pattern shifts out of these areas to maximize volumetric water savings. However, implementing such complete territorial shifts necessitates structural administrative intervention, macro-level policy alignment, and phased adoption schedules to manage potential short-term disruptions in regional agrarian markets and crop delivery chains.

- **Partial Reallocation & Spatial Reorganization (Remaining Target Governorates):**

  Focuses on targeted, incremental reallocations constrained to low-suitability or hydrologically inefficient zones within Dakahlia, Minya, Assiut, Sohag, and Fayoum, while explicitly safeguarding high-yield traditional cropping cores. Conversely, suitable expansion zones such as Matrouh act as receiving territories for optimized spatial reallocation rather than sources of crop reduction. While partial reallocation is operationally more feasible and socially adaptable for local farming communities, it yields more conservative volumetric water savings and requires precise spatial targeting. Methodologically, the decision support system isolates low-performing spatial units to execute localized adjustments without disturbing core agricultural lands, allowing regional authorities to manage water reallocation smoothly while maintaining market stability and local farming livelihoods.

3. **Model Parameter Scope:**

   While the AHP-MCDA framework incorporates critical soil, topographic, and water-availability parameters (DEM, slope, soil permeability, drainage, water source proximity, and ETc), subsequent operational planning would benefit from embedding dynamic groundwater extraction sustainability rates, canal conveyance efficiencies, and detailed microeconomic farm-level profitability metrics.

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