كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
PRINT ISSN 3009-6049
ONLINE ISSN 3009-6022

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (54),Issue (3)
July 2025, pp:25-34
https://erjsh.journals.ekb.eg

Impact of Water-Reduction Scenarios on Crop-Productivity, Soil Salinity, and Unofficial Water Reuse in Eastern-Nile Delta

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Abstract: Water scarcity, driven by population growth, overuse, pollution, and climate change, threatens agriculture in Egypt due to limited Nile water allocations. This study examines the effects of water shortages on crop productivity, soil salinity, and unofficial water reuse in Eastern Nile Delta governorates using the SIWARE model under 0%–50% water reduction scenarios. Data sources include agriculture, irrigation, meteorology, drainage reuse, and groundwater from relevant ministries and institutes. The model was calibrated based on data from the year 2020. The results reveal that the crop productivity remained stable under moderate water reductions (10%–15%) but declined sharply under a 50% reduction. On average, 85% of cultivated areas in North Sinai, Port Said, and Damietta were classified within the critical range of average relative evapotranspiration (25%–50%), while Sharkia and Qalyubiyya had 30% of their cultivated areas falling within this specified range. However, none of the governorates reached the lowest productivity threshold (0%–25%). Soil salinity remained stable under reductions of up to 25% but increased significantly under a 50% reduction. Port Said and Ismailia saw their moderately saline areas increase from an average of 31% to 55%, while Suez, Damietta, and Qalyubiyya showed newly emerging salinity concerns. Unofficial water reuse declined in most governorates, with Sharkia and Dakahlia recording an average decrease of 31%, whereas Port Said and North Sinai exhibited a 13% rise. These findings emphasize the need for region-specific water management strategies to sustain agricultural productivity, mitigate salinity risks, and optimize water use under growing water scarcity challenges.

Keywords: Eastern Nile Delta, SIWARE model, soil salinity, crop productivity, unofficial water reuse

1. Introduction

Water scarcity, which is defined as the inadequate availability of freshwater resources to meet regional demands, has become a critical global challenge. This issue is worsened by population growth, excessive water consumption, pollution, and the impacts of climate change, affecting billions of people worldwide [1-3]. In Egypt, water scarcity is an important concern due to the growing demand for water across various sectors. The fixed annual allocation of 55.5 billion cubic meters (BCM) from the Nile River is insufficient to meet the current demand of approximately 72.4 BCM [4,5].

The scarcity of water in Egypt has led to adverse consequences, including reduced crop productivity, increased soil salinity, and the rise of unofficial water reuse practices. For instance, farmers often use localized pumps to redirect agricultural drainage water back to their fields [5,6]. Actual evapotranspiration is the real water loss from soil and vegetation to the atmosphere under prevailing moisture and climate conditions, whereas potential evapotranspiration represents the maximum possible loss driven by atmospheric demand when water is not limiting. Crop productivity can be assessed using relative evapotranspiration (RET), which is the ratio of actual to potential evapotranspiration. RET serves as a key parameter in the hydrological cycle and as a physical input in crop water productivity functions and yield modeling [7-10].

Soil salinity, another major issue linked to water scarcity, poses a significant threat to agricultural productivity on a global scale. The accumulation of salts in the soil's root zone or on its surface diminishes soil fertility, alters soil properties, reduces water retention capacity, and disrupts ecological functions [11,12]. Soil salinization affects over 100 countries and is expanding by approximately 2 million hectares annually, resulting in estimated agricultural losses of up to $27 billion per year [13-16].

In Egypt, soil salinization has become a growing concern, particularly in the Nile Delta region, where intensive irrigation practices and the reuse of drainage water worsen the problem. Research has highlighted the critical need for effective water and salinity management strategies. Aziz et al. (2019) used the MODFLOW model to simulate the impact of reduced surface water availability caused by the Grand Ethiopian Renaissance Dam (GERD) on soil salinity in the Eastern Nile Delta. Their findings revealed that a 50% reduction in surface water over ten years would significantly increase soil salinity, reducing crop productivity and economic output [4].

Similarly, Hammam and Mohamed (2020) employed Geographic Information Systems (GIS) to evaluate soil salinity in a pilot area of the Eastern Nile Delta, emphasizing the importance of salinity management in improving water management practices [17]. In the Western Delta, El-Moneim et al. (2018) used the SIWARE model to assess the effects of unofficial drainage water reuse on soil salinity and crop water usage. The study highlighted the severe water shortages driving farmers to adopt these practices, which in turn contribute to soil salinization [6].

This research aims to investigate the effects of various water scarcity scenarios, ranging from 0 to 50%, on crop productivity, soil salinity, and unofficial water reuse practices in the Eastern Nile Delta.

2. Study Area

The study examines eight governorates in the Eastern Delta region, which is situated east of the Damietta branch and extending from Cairo to Lake Manzala, bordered by the Eastern Desert. These governorates include North Sinai, Port Said, Ismailia, Suez, Damietta, Dakahlia, Sharkia, and Qalyubiyya, as illustrated in Figure 1. Their cultivated land area are as follows: 296,813.6; 1,471,578; 5,245,556; 1,166,888; 432,609.7; 4,877,969; 10,487,079; and 1,829,351 feddans, respectively.

The Eastern Delta region is supplied by seven main canals: Ismailia, Rayah El Tawfiki, Mansouria, Basousia, Sharkawia, El Salam, and Abu El-Manga, all of which are directly derived from the Damietta Branch. The irrigation in this area is provided through the branches of these canals. Additionally, the region is served by five major drains: Belbies, Qalyubiyya, Bahr El-Baqar, Saft El-Kbeley, and Bahr Hadus. The Ministry of Water Resources and Irrigation (MWRI) has installed pump stations in these drainage systems for water lifting and reuse, as shown in Figure 2.

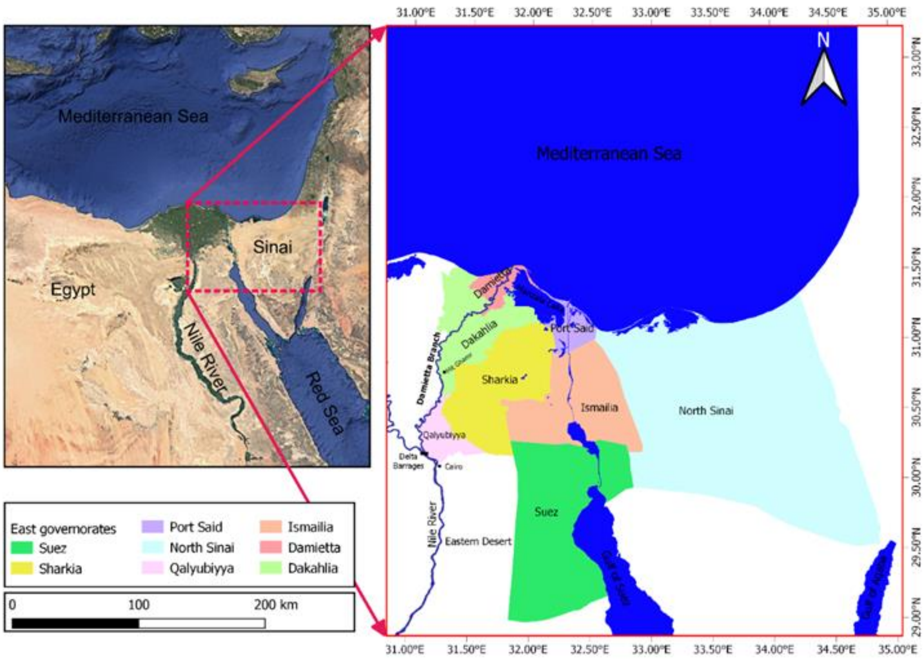


Figure 1. The eight governorates in the Eastern Delta region.

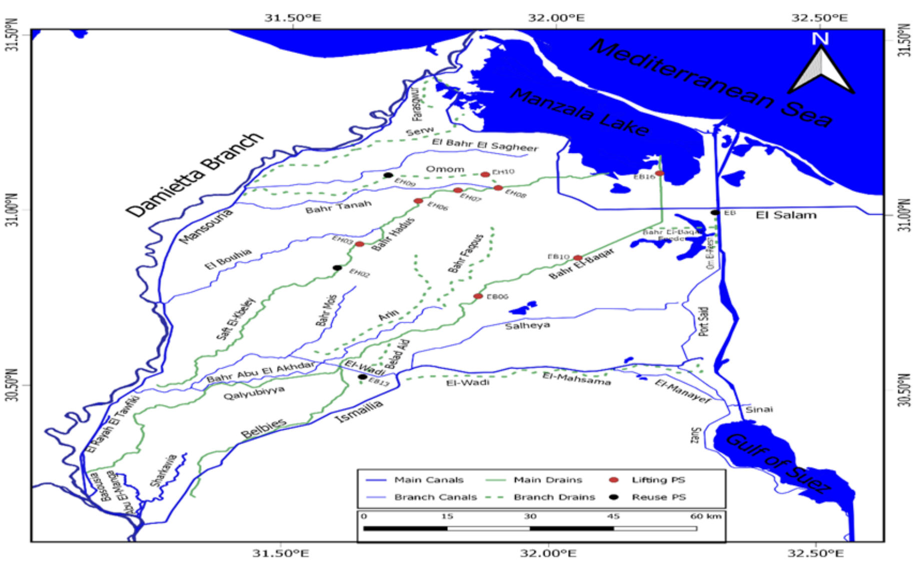


Figure 2. Network of main and branch canals, drains, and pump stations for reuse and lifting in the Eastern Delta.

3. Methodology

The SIWARE model, which stands for simulation of water management in Egypt [5,6], was employed to simulate the eight governorates in the Eastern Delta. This model was created to predict the alterations resulting from various factors, including shifts in the practices of water management, variations in hydrological, hydraulic, and meteorological conditions [18]. The SIWARE system is composed of four sub-modules: design, water duty, water distribution, and reuse [19].

4. Model Configuration and Data Acquisition

The Eastern Delta region was divided into 115 calculation units (CUs) as illustrated in Figure 3, where each unit is characterized by a singular canal, drain, and uniform soil conditions. Crop pattern data, which was provided by the Ministry of Agriculture and Land Reclamation (MALR), was initially provided at the Governorate scale, then downscaled to the CUs scale using the Quantum Geographic Information System (QGIS) to estimate the cultivated area percentage for each CU. Daily meteorological data gathered over a decade, encompassing parameters like precipitation, evaporation, average temperature, solar radiation, sunshine hours, relative humidity, and wind speed, were employed to compute the maximum evaporative requirement based on crop height and the adjustment factor for inadequate soil coverage utilizing the Rijtema method [19]. Fifteen types of crops were represented in the model. This number was chosen by grouping crops with similar properties, such as crop height, irrigation salinity, soil cover, rooting depth, and maximum ponding. The irrigation water duties for the preceding crops, the primary canals, and the total water supply allocated to the studied area were sourced from MWRI and used in the model in accordance with the irrigation schedules. Data regarding the volume and salinity of reused water was supplied by the Drainage Research Institute (DRI) and incorporated into the model for all reuse pump stations located in the eight governorates. The Ground Water Research Institute (GWRI) provided information for all CUs about groundwater extraction, clay cap depth, aquifer thickness, piezometric head, hydraulic permeability, and aquifer salinity.

5. Results and Discussion

5.1 Calibration

The model was calibrated based on the dataset from the year 2020. Simulated results for water allocation to main canals were graphed and compared with observed data. Additionally, the discharge and salinity values in the drains were calibrated using the same approach. The average deviation (Av.dev.), as defined by Equation 1, served as the benchmark for comparing modeled results to observed values. This performance criterion evaluated how closely SIWARE's simulated results aligned with actual measurements, permitting average deviations of 30% for drain discharge and water allocations to main canals, as well as 50% for drain salinity, as determined by the Steering Committee for the reuse of drainage water project, which includes DRI, MWRI, and the Egyptian government [6,19].

$$Av._{dev.} = 100 * \frac{\sum(P_m - P_c)}{\sum\left(\frac{P_m + P_c}{2}\right)} \qquad \text{Equation 1}$$

where Pm represents measured values, and Pc denotes simulated values for water allocations, discharge, and salinity. The calibration points are located on the El Rayah El Tawfiki Canal at coordinates (30.19°N, 31.13°E), the Mansouria Canal at (30.74°N, 31.26°E), and the Sedqa Pump Station on Bahr Hadus at (30.91°N, 31.64°E). The calibration results are shown in Figures 4 and 5. Figure 4 highlights that the average deviation for water allocation is 15.25% for El Rayah El Tawfiki and 6.39% for the Mansouria Canal. Figure 5 indicates that the average deviation values for discharge and salinity at the Sedqa Pump Station are 9.10% and 8.90%, respectively. These findings demonstrate that the average deviation remains within acceptable limits.

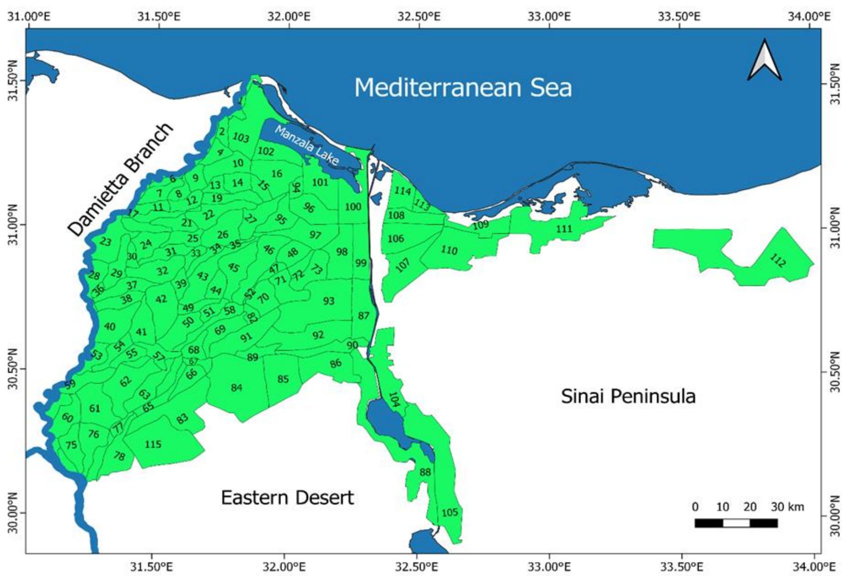


Figure 3. Eastern Delta Calculation Units (CUs).

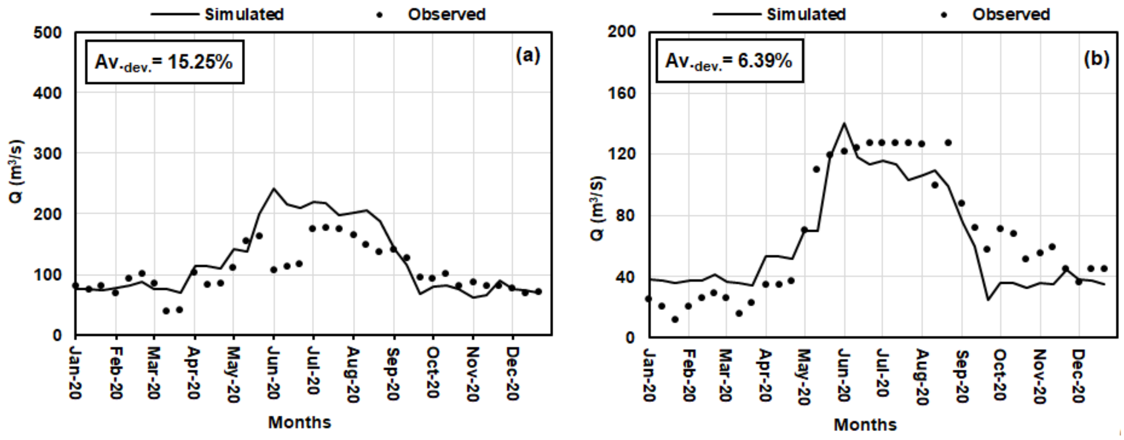


Figure 4. The comparison between the simulated and observed values of water allocation in the year 2020: (a) for El Rayah El Tawfiki, (b) for the Mansouria Canal.

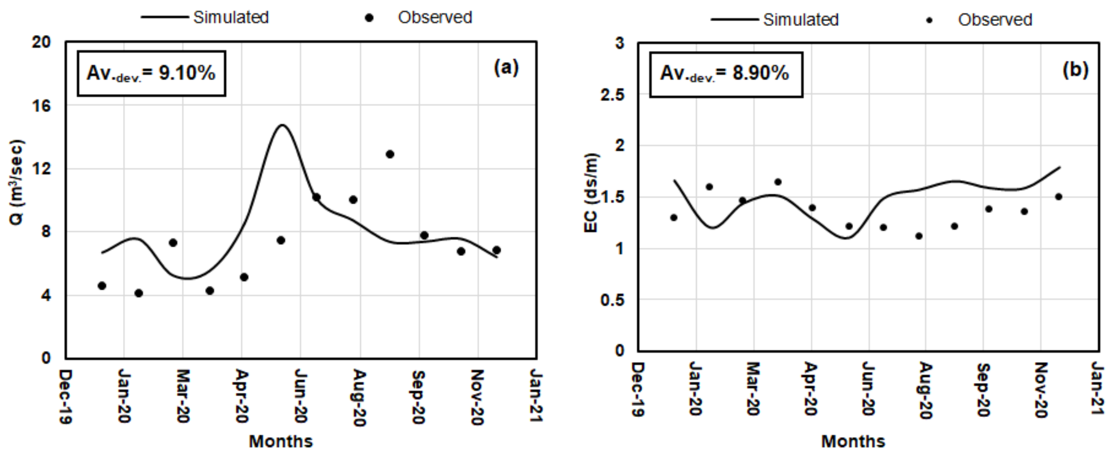


Figure 5. Simulated versus observed monthly values of discharge and salinity at Sedqa pump station during the year 2020: (a) for discharge, (b) for salinity.

5.2 Impact of Water Supply Reduction Scenarios on Eastern Delta Governorates

5.2.1 Effect on crop productivity

Crop productivity was evaluated by analyzing crop water consumption and determining the percentage of average relative evapotranspiration (RETav.) for the fifteen major agricultural crop types across all CUs. RETav. served as a productivity indicator, with a value of 100% indicating that crops were free from water stress.

In the base case (no water reduction), as shown in Figure 6 (a), most cultivated areas (69.9%) had RETav. in the 75%–100% range, which reflecting optimal water availability, while smaller proportions (26.3% and 3.8%) fell into the 50%–75% and 25%–50% ranges, respectively, with no areas experiencing critical water stress (0%–25% RETav.). Under the 25% water reduction scenario, as shown Figure 6 (b), water stress became more obvious as the areas with RETav. of 25%–50% and 50%–75% increased to 14.4% and 39.3%, respectively, and the share of high-productivity areas (75%–100% RETav.) declined to 46.3%. In the 50% water reduction scenario, as shown in Figure 6 (c), the trend of increasing water stress continued, with 34.2% of cultivated areas shifting to the 25%–50% RETav. range, 52.9% to the 50–75% range, and only 12.2% maintaining RETav. levels between 75%–100%. Across all scenarios, no areas experienced RETav. in the most critical range of 0%–25%, indicating that even under severe water reductions, the crops retained some level of productivity, albeit with significant declines in high performance areas.

For further analysis, Figure 7 (a-h) demonstrates the effects of water reduction scenarios on RETav. percentages for each governorate separately. In North Sinai, as shown in Figure 7 (a), crop productivity was resilient up to a 10% water reduction, but the share of areas with 50%–75% RETav. fell from 37% at baseline to 18% at 15% reduction, with all areas experiencing severe stress (25%–50% RETav.) beyond 20% reduction. In Port Said, 16% of the cultivated area had RETav. in the 25%–50% range at baseline, remaining unchanged up to 10% reductions, as shown in Figure 7 (b). However, with a 50% reduction, areas in the (25%–50% RETav.) range expanded to 73%, indicating severe water stress (exceeding 50%). In Ismailia, 80.7% of areas exhibited high productivity (75%–100% RETav.) at baseline, remaining stable up to 10% reductions, as shown in Figure 7 (c). By 50% water reduction, 33% of cultivated land shifted to severe stress (25%–50% RETav.). Suez, as shown in Figure 7 (d), initially entirely in the 75%–100% RETav. range, saw all areas move to moderate stress (50–75% RETav.) by 35% reductions. In Damietta, as shown in

Figure 7 (e), high-productivity areas (75%–100% RETav.) were 16.7% at baseline but transitioned rapidly to severe stress (25%–50% RETav.), reaching 83% by 50% reduction. Dakahlia and Sharkia, as shown in Figure 7 (f, g), faced steep declines in high-productivity land, dropping from 64% and 75%, respectively, at baseline to 28% and 38%, respectively, under 50% reductions, with significant portions falling into severe stress. Qalyubiyya, as shown in Figure 7 (h), began with 87.4% high-productivity land (75%–100% RETav.), dropped to 27% by 50% reduction, with 31% shifting to severe stress (25%–50% RETav.). These results demonstrate that extended water shortages have a substantial impact on crop productivity in the Eastern Nile Delta. While some areas show initial resistance under mild stress, prolonged scarcity causes a notable decline in high-productivity regions. Severe stress becomes widespread, highlighting the urgent need for sustainable water management to protect agricultural production.

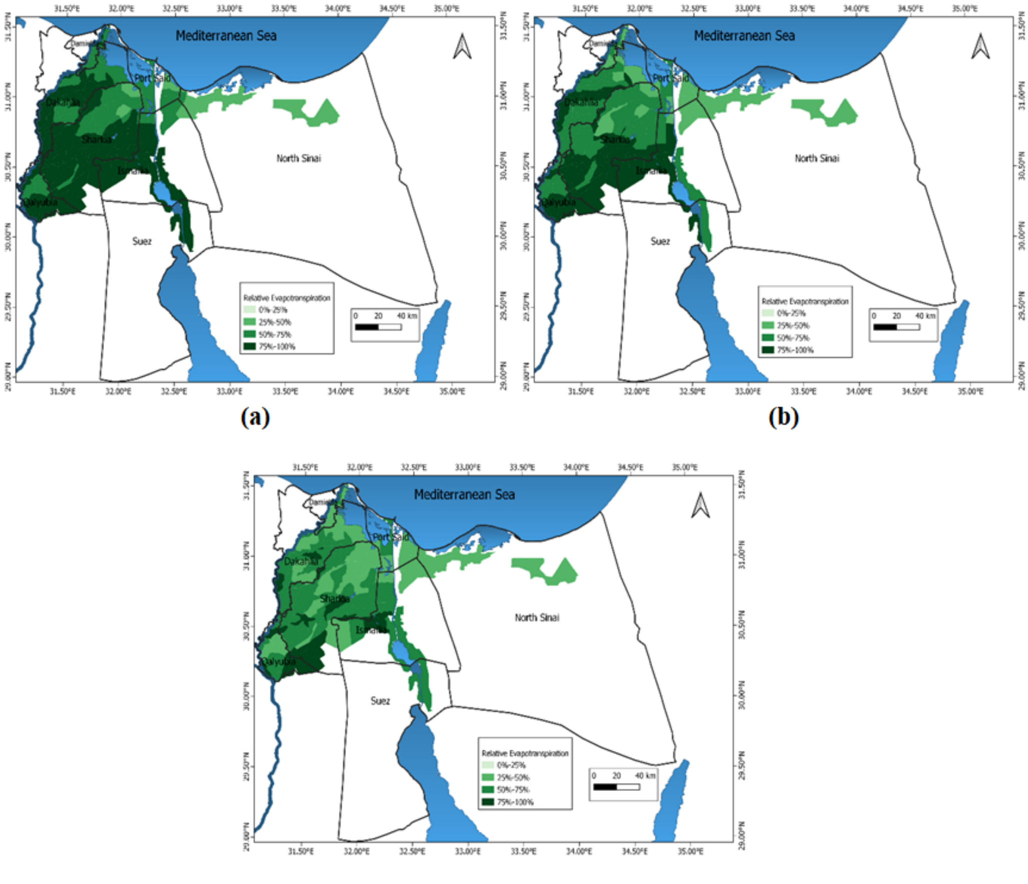
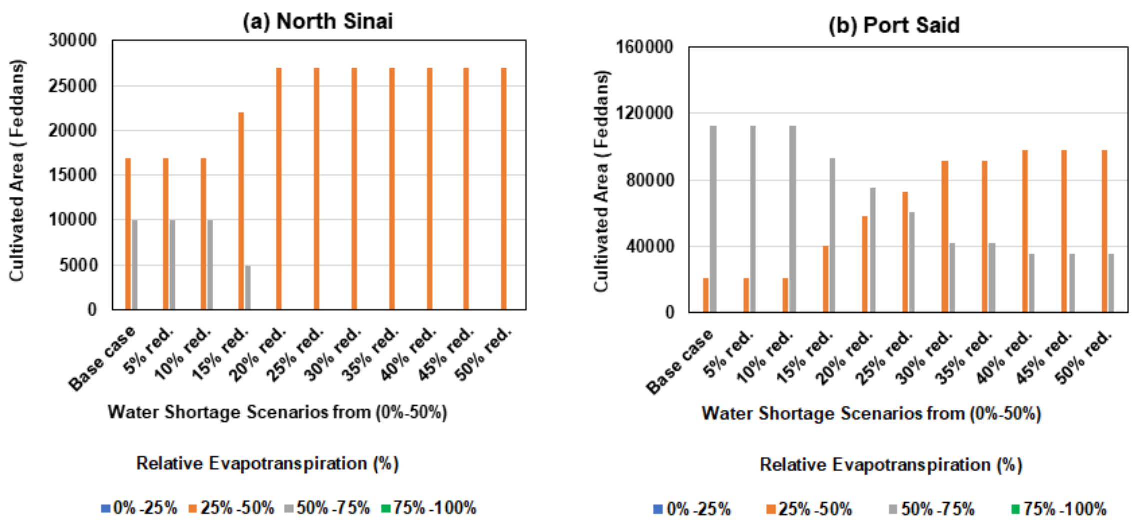


Figure 6. The simulated spatial distribution of RETav. percentages across cultivated areas in the eight governorates of the Eastern Delta, illustrating three water reduction scenarios: 0% (a), 25% (b), and 50% (c).



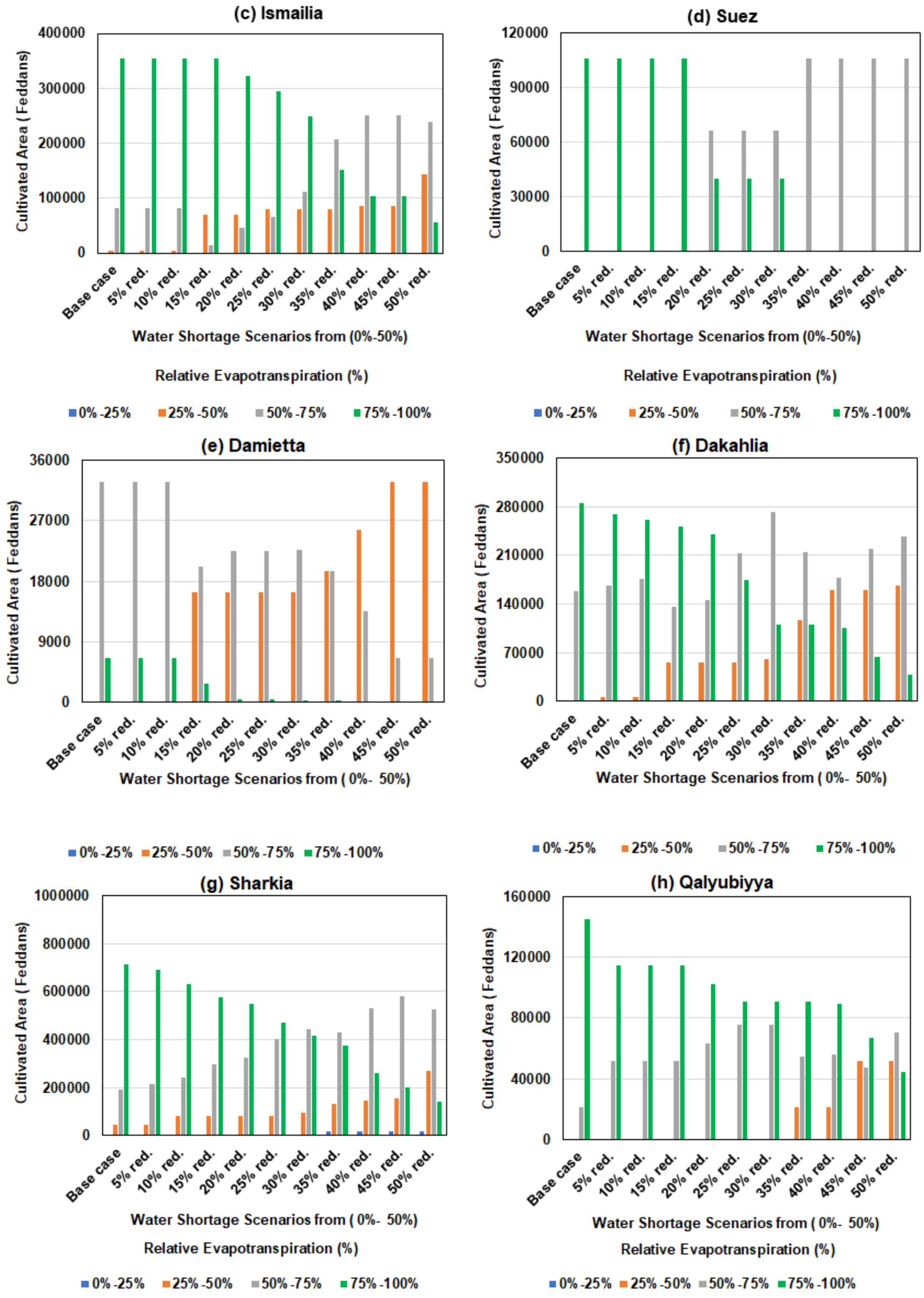


Figure 7. Modeled cultivated areas affected by RETav. under water shortage scenarios ranging from 0% to 50%. Panels a–h corresponds to the governorates of North Sinai, Port Said, Ismailia, Suez, Damietta, Dakahlia, Sharkia, and Qalyubiyya, respectively.

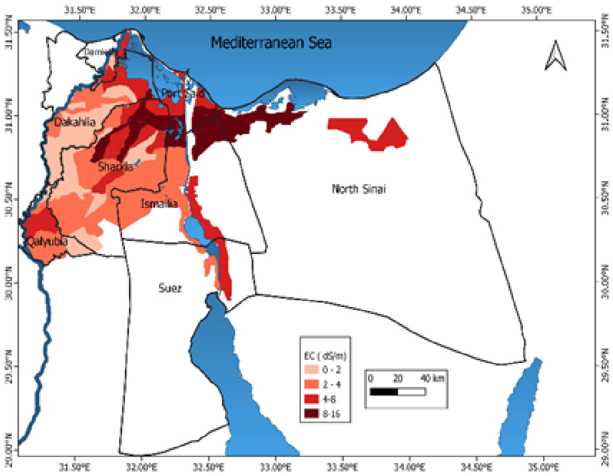
5.2.2 Impact on soil salinity

Soil electrical conductivity (EC) measures the ability of soil water to conduct an electrical current, which is commonly used in agriculture to assess soil salinity. Table 1 outlines the soil salinity classifications according to the Natural Resources Conservation Service (NRCS) [20].

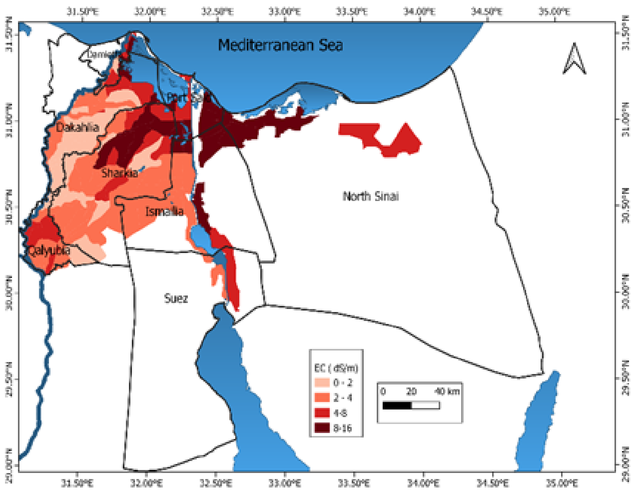
Table 1: classes of soil salinity

Salinity Class	EC (dS/m)
Non-saline	< 2
Very slightly saline	2-4
slightly saline	4-8
Moderately Saline	8-16
Strongly Saline	>16

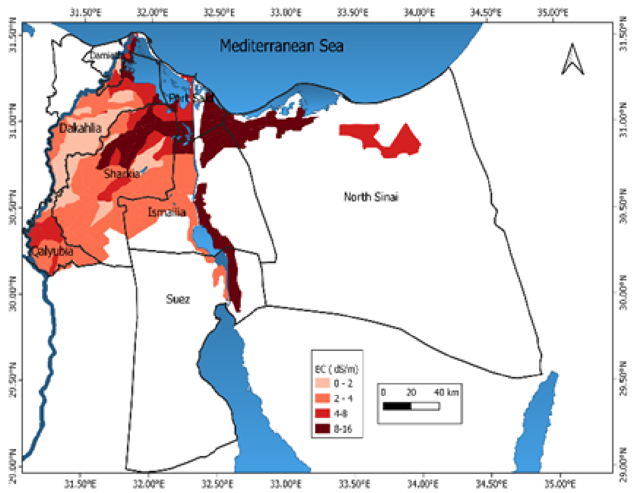
The spatial distribution of soil salinity across cultivated areas in the Eastern Delta under varying water reduction scenarios was demonstrated in Figure 8 (a-c). Under the baseline scenario, as shown in Figure 8 (a), 20.2% of the land remains non-saline, while 43.15% is classified as very slightly saline, 24.06% as slightly saline, and 12.5% as moderately saline. As water availability decreases by 25%, as shown in Figure 8 (b), non-saline areas shrink to 18%, and very slightly saline areas expand to 45%. Slightly saline areas reduce to 18%, while moderately saline regions increase to 19%, indicating an upward trend in salinity levels. At a 50% water reduction, as shown in Figure 8 (c), non-saline areas drop further to 17%, very slightly saline areas grow to 47%, and slightly saline areas decline to 14%. Moderately saline regions surge to 23%, emphasizing the progressive salinization of soils as water scarcity intensifies. These patterns highlight a clear correlation between reduced water supply and increased soil salinity, underscoring the potential risks to agricultural productivity in the region.



(a)



(b)



(c)

Figure 8. The spatial distribution of simulated soil salinity across the cultivated regions in the eight governorates of the Eastern Delta, showing three scenarios of water reduction: 0% (a), 25% (b), and 50% (c).

For further examination, Figure 9 (a–h) illustrates the impact of water reduction scenarios on soil salinity levels in each governorate individually. In North Sinai, as shown in Figure 9 (a), 90%–95% of the cultivated area consistently faced moderate salinity regardless of water reduction. Similarly, Port Said, as shown in Figure 9 (b), saw a shift from slightly to moderately saline soils, with moderately saline areas increasing from 43% in the base year to 72% under a 50% reduction. In Ismailia, as shown in Figure 9 (c), moderately saline areas doubled from 19% to 37% as water reductions reached 50%. Suez, initially dominated by very slightly and slightly saline soils (38% and 62%), experienced a shift to predominantly moderate salinity levels after reductions exceeding 30%, as shown in Figure 9 (d). In Damietta, as shown in Figure 9 (e), soil salinity levels remained stable up to a 20% reduction, but beyond 25%, slightly saline areas began transitioning to moderate salinity. Dakahlia maintained relatively stable salinity up to 15% reduction. However, non-saline areas declined from 58% to 52% under 50% reduction, with moderate salinity was slightly increased, as shown in Figure 9 (f). In Sharkia, as shown in Figure 9 (g), very slightly saline areas (50%) dominated, with only a modest increase in moderate salinity (13% to 16%) under severe water shortages. Lastly, Qalyubiyya, as shown in Figure 9 (h), exhibited minor shifts, as very slightly saline areas increased by 7%, while other salinity levels remained largely unchanged, highlighting minimal impact compared to other governorates. Overall, these findings underscore the progressive salinity challenges linked to water scarcity, with moderate salinity becoming more prevalent in most governorates.

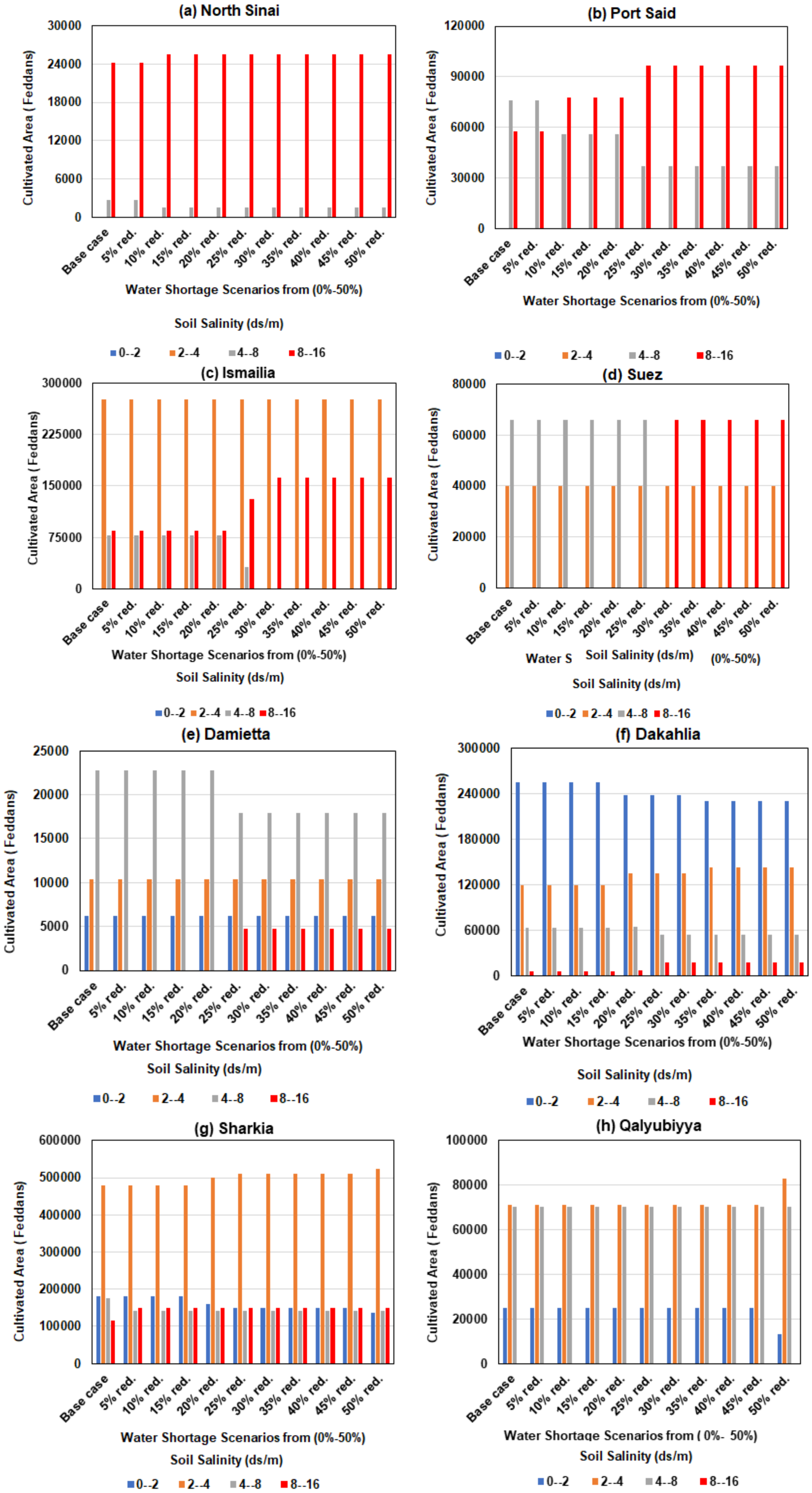


Figure 9. Simulated cultivated area classified by soil salinity levels under water shortage scenarios ranging from 0% to 50% water reduction. Panels a–h represents the governorates of North Sinai, Port Said, Ismailia, Suez, Damietta, Dakahlia, Sharkia, and Qalyubiyya, respectively.

5.2.3 Impacts on unofficial water reuse practices

In the base year, the total annual volume of unofficial water reuse (VUWR) across the Eastern Delta governorates was 2,671.24 MCM. However, under a 50% water reduction scenario, this volume decreased by 25.4% to reflect reduced drainage discharges due to declining canal water supplies. Sharkia exhibited the highest VUWR (41.5%), which is consistent with its significant share (41.3%) of the cultivated area in the Eastern Delta. Dakahlia ranked second, contributing 31.5% of VUWR despite covering only 19.2% of the cultivated area. This is due to its high percentage of rice cultivation, which requires extensive irrigation and generates substantial drainage flows.

Following the 50% water reduction scenario, most governorates experienced significant declines in VUWR. Sharkia's VUWR fell by 24.6%, and Dakahlia's by 37.4% which was driven by diminished drainage flows resulting from reduced irrigation inputs. Similar trends were observed in Ismailia (23.1%), Qalyubiyya (37.5%), Suez (74.6%), and Damietta (50.5%). The water reductions in Suez and Damietta highlight the pronounced impacts of decreased water availability on drainage discharges in areas already simulated under water scarcity. Conversely, VUWR increased in Port Said and North Sinai by 17.1% and 9.2%, respectively. This anomaly is likely due to their locations at the end of the irrigation system, which required increased dependence on drainage water to meet demands as canal discharges declined.

6. Conclusion

The calibrated SIWARE model was utilized to assess crop productivity, soil salinity, and unofficial water reuse across eight governorates in the Eastern Delta under various reductions water scenarios, up to 50%. The analysis highlights the diverse impacts on each factor as follows.

Crop productivity exhibited resilience under moderate water reductions, with most governorates maintaining baseline productivity up to a 10%–15% reduction. However, under a 50% water reduction scenario, productivity significantly declined. In North Sinai, 100% of the cultivated area shifted to the lowest productivity range (25%–50% $RET_{av.}$), while in Port Said and Damietta, 73% and 83% of cultivated areas, respectively, fell into the same range. Sharkia and Qalyubiyya also faced substantial declines, with 28% and 31% of their cultivated areas moving to lower productivity categories. Despite this stress, no governorates experienced critical productivity levels (0%–25% $RET_{av.}$), demonstrating some resilience to extreme conditions.

Soil salinity remained stable under moderate water reductions (up to 15%–25%) but increased significantly under a 50% reduction. North Sinai, with 90%–95% of its area moderately saline in the base year, showed little change. However, Port Said saw its moderately saline area expand from 43% to 72%, and Ismailia experienced an increase from 19% to 37%. Suez transitioned almost entirely to moderate salinity, and Damietta recorded its first substantial increase after 25% reductions. Dakahlia, initially with only 1% moderate salinity, rose slightly to 4%, while Sharkia and Qalyubiyya reached 16% and newly observed salinity, respectively. These trends highlight the widespread exacerbation of salinity under severe water scarcity.

VUWR responded variably to water reductions. Most governorates experienced significant declines, driven by reduced irrigation inputs and drainage flows. Sharkia and Dakahlia, which initially accounted for 41.5% and 31.5% of total VUWR, saw reductions of 24.6% and 37.4%, respectively. In contrast, Port Said and North Sinai experienced VUWR growth of 17.1% and 9.2%, respectively, attributed to their strategic positioning at the irrigation system's terminus, necessitating reliance on drainage water.

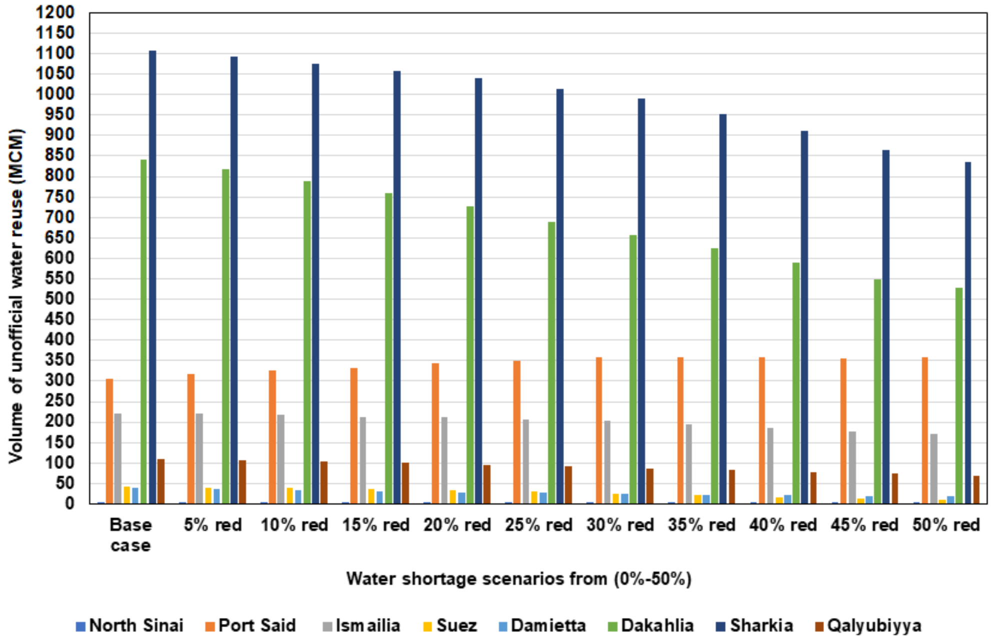


Figure 10. The modeled amounts of unofficial water reuse under various water shortage scenarios across the eight Eastern Delta governorates.

This study underscores the need for sustainable water management to cope with increasing resource pressures. Practical steps include aligning cropping patterns with local water availability, encouraging the reuse of treated drainage and municipal effluents, and applying salinity control in sensitive areas. These measures can collectively enhance efficiency, protect soil productivity, and strengthen the resilience of water management systems.

ACKNOWLEDGEMENTS

Sincere gratitude is extended to the staff of the Drainage Research Institute (DRI) and its director, Professor Dr. Mohamed Shaban, for their invaluable support in providing all the necessary data and information. Additionally, heartfelt thanks go to the Ministry of Agriculture and Land Reclamation (MALR), the Ministry of Water Resources and Irrigation (MWRI), and the Ground Water Research Institute (GWRI) for their ongoing support and provision of data.

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