Climate Change And Irrigation Water: A Vulnerability Assessment Of Egypt's Governorates

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The mounting impact of climate change on the livelihoods and agricultural sectors of both developed and developing nations underscores the need to identify and prioritize the regions and communities that are most vulnerable to its effects at a sub-national level. In this regard, irrigation technologies represent a highly recommended adaptation option to effectively address the proposed changes. Given the limited funding available for climate change adaptation plans in Egypt, it is essential to determine the most vulnerable governorate in terms of Irrigation Water Requirements (IWR) to climate change. The main objective of this study is to evaluate the vulnerability of Irrigation Water Requirements (IWR) to the effects of climate change at the governorate level. To accomplish this objective, we employed reference evapotranspiration (ET_o) and precipitation change as exposure factors, in addition to sensitivity factors such as soil type and the economic value of irrigation water. Furthermore, we considered adaptive capacity factors, including poverty, education, and organizational capacity. To enhance the robustness of our results, we incorporated data from six different climate models under various shared socioeconomic pathway scenarios (namely, SSP126, SSP245, SSP370, and SSP585) for the period spanning 2040 to 2060. Based on the research results, the central and northern regions of the country were found to exhibit the greatest and most significant degrees of vulnerability across nine governorates. Meanwhile, four governorates demonstrated the lowest vulnerability degrees under the climate change scenarios (SSP126, SSP245, and SSP370), and Aswan was identified as having the lowest vulnerability degree under the SSP585 scenario. These findings hold significant value for informing decision-making processes by pinpointing the areas of highest vulnerability and facilitating the implementation of effective mitigation strategies.

Keywords: Climate change, Irrigation water requirement, Vulnerability, SSP scenarios, Egypt

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1. Introduction

Global climate change is a crucial environmental concern with far-reaching consequences. It poses significant challenges to infrastructure, agriculture, and other sectors critical to human survival. Addressing this issue is essential for society's continued progress and prosperity and the preservation of our natural environment [1]. Several studies have identified Egypt's northern region as an area with a high susceptibility to the effects of climate change [2, 3]. The effects of climate change are also observed in the Middle East and North African countries [4]. Egypt has a rapidly growing population densely concentrated around the Nile River [5], making it vital to understand how climate change interacts with other challenges to develop effective adaptation strategies.

Assessing vulnerability is a valuable tool for determining the extent to which climate change affects human and ecological systems and their capacity to respond to potential impacts [6]. This tool identifies the places or communities most susceptible to the effects of climate change and the primary drivers of their vulnerability [7]. Consequently, vulnerability assessment has become an indispensable aspect of climate change research, as it facilitates the development of effective and appropriate adaptation and mitigation strategies [8]. Despite its widespread use, there still needs to be more agreement on the most appropriate definition of vulnerability in the context of climate change research [9].]. As a result, various efforts have been made to establish a structured vulnerability model, which can be categorized into three approaches: the endpoint approach, the starting point approach, and the third approach based on the IPCC Third Assessment Report (TAR) [10].

The most widely adopted approach in climate change research for assessing vulnerability is based on the IPCC Fourth Assessment Report (AR4) [11, 12]. According to this approach, vulnerability is defined as "the extent to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability depends on the character, magnitude, and pace of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" [11]. This definition emphasizes that vulnerability is determined by exposure, sensitivity, and adaptive capacity. Exposure (EX) pertains to the rate of change in the climate, while sensitivity (SE) refers to the degree to which a system is affected by a given climate change exposure, either adversely or beneficially. Finally, adaptive capacity (AC) is the system's ability to adapt to climate change [8]. By considering these three factors, vulnerability assessment provides a comprehensive and accurate understanding of how climate change can affect human and ecological systems and their capacity to cope with its impacts.

The agricultural sector is a vital component of Egypt's economy, accounting for approximately 20% of its Gross Domestic Product (GDP) and utilizing over 85% of the country's total water demand, with around 40% of the workforce employed in this sector [13]. Nonetheless, Egypt is confronted with a critical issue of water scarcity, whereby the water demand surpasses the available resources by approximately 20 billion cubic meters per annum [14]. Because the agricultural sector is highly susceptible to the impacts of climate change, [15]; Many research studies have been conducted to address the potential impacts of climate change on the agricultural sector, including the investigation of irrigation technology and the effects of climate change on water availability. For instance, Elshamy and al. [16] investigated anticipated flow of the Nile River in response to climate change and determined that the rise in flow was negligible when compared to the projected increase in evaporation rate. Moreover, studies indicate that crop yields are likely to decrease significantly under climate change [17]. According to these studies, by the year 2050, crop yield reductions could range from 11% for rice to 28% for soybeans. Looking ahead to 2100, these reductions could intensify, with wheat potentially experiencing a 36% decrease, and maize facing a 20% decline [18]. Consequently, to mitigate the potential impacts of climate change, it is essential to implement adaptation plans, and among the suggested adaptation options, the use of irrigation technology is significantly mentioned approaches [19]. To that end, the present study aims to identify the governorate that is most vulnerable to climate change in terms of Irrigation Water Requirements (IWR) at the governorate level.

2. Materials and methods

2.1. Study area

Egypt, a country situated in the northeast corner of the African continent, has a vast area of about 1 million km2, xperiences a unique climate characterized by its desert landscape and the Nile River, which is the lifeblood of the country. The climate in Egypt is predominantly arid, with hot and dry summers and mild winters. The Nile River's annual flooding, essential for irrigation, has historically supported Egypt's agriculture, with main crops such as wheat and rice reaping the benefits [20]. According to [21], the geographical delineation of Egypt comprises twenty-seven governorates in total. However, it's worth noting that four of these governorates (numbered 2, 14, 22, and 24) exhibit negligible agricultural activity. Thus, to carry out this study, the focus is on the remaining 22 governorates, as shown in Fig. 1. These 22 governorates cover all eight agro-climatic zones that have been identified in Egypt [22].

2.2. Framework and data collection

The vulnerability assessment approach in this study adheres to the definition presented in the IPCC Third Assessment Report [23] and follows the standardized guidelines for vulnerability assessment developed by [24]. The initial step of this study involves constructing the IWR impact chain for assessing vulnerability to climate change. Seven distinct factors are taken into account for evaluating vulnerability, contingent upon data availability. These factors encompass two facets related to exposure, two associated with sensitivity, and three tied to adaptive capacity. The exposure factors, specifically ET_0 and precipitation,

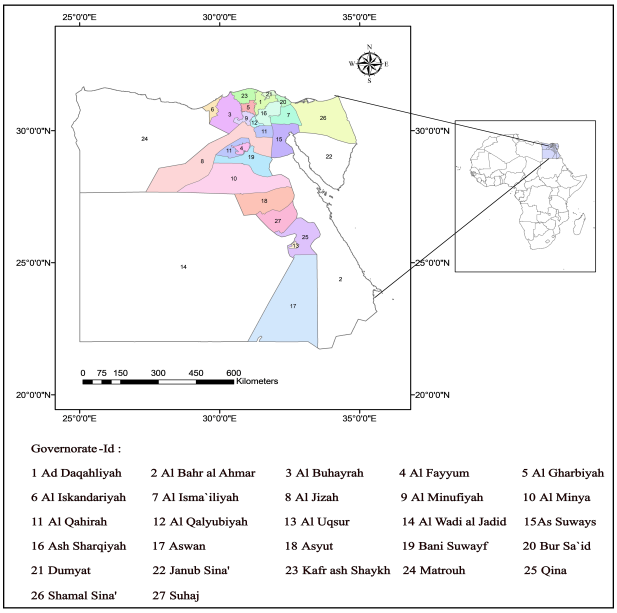

Fig. 1. The study area.

directly exert influence on irrigation water requirements. ET_0 serves as a vital indicator of the atmosphere's evaporative demand, signifying the potential water loss from the soil-plant system [25]. Likewise, precipitation, as a primary water input, significantly affects the availability of water for irrigation [26].

Conversely, the sensitivity factors, namely soil type and the economic value of irrigation water, play pivotal roles in shaping the system's responsiveness to changing conditions. Distinct soil types possess varying water-holding capacities and drainage characteristics, thereby impacting irrigation water requirements for different crops [27]. Additionally, the economic value of irrigation water highlights its significance in determining the allocation and efficiency of water use [28]. Lastly, the adaptive capacity factors, namely education, poverty, and organizational capacity, reflect the society's ability to cope with and respond to changes in the irrigation system [24]. Education and awareness play a pivotal role in promoting sustainable water practices, while poverty levels can impact access to resources for irrigation improvement. Furthermore, the organizational capacity of institutions and governance structures can influence the implementation of adaptive measures for efficient irrigation water management.

Fig. 2 illustrates the assessment framework employed to evaluate IWR vulnerability to climate change. The study meticulously identified a set of indicators for each of the seven factors, as presented in Table 1. This table also provides information on the units of measurement, functional relationships with vulnerability, and data sources associated with each indicator.

For the exposure factors, the study selected ET_0 and precipitation, which are known to have a significant impact on IWR [29]. Regarding the sensitivity factors, two distinct variables were chosen due to their significant impact on IWR vulnerability. Firstly, soil type was selected, given its well-established correlation with irrigation in prior research [30]. Secondly, the economic value of irrigation water was chosen. This multifaceted variable encompasses the overall cost (LE/Feddan) associated with various aspects, such as land preparation, irrigation, seed selection, fertilization, agricultural services, harvesting, pest management, crop transportation, public expenditures, and their comparison with revenue [31, 32]. Taking this into account is a crucial aspect to consider, as the economic value of irrigation water directly affects the investment and allocation of resources towards IWR management. Moving on to the adaptive capacity factors, we selected three variables, namely education, poverty, and organizational capacity. These variables were chosen based on their availability of data and their positive relationship with IWR vulnerability. Improving education and reducing poverty levels can enhance the capacity of individuals and communities to cope with climate change impacts on IWR. On the other hand, organizational capacity can help in the development and implementation of effective IWR management strategies.

After developing the assessment framework for IWR vulnerability to climate change, the next step is to carefully select the indicators for each factor and manage the data acquisition process effectively. Table 1 presents the different indicators for the study's factors, including their units, purposeful affiliation with vulnerability, and data source. In terms of exposure factors, the historical climate data used in the study was monthly data for the period from 1970 to 2000 [33]. The study used monthly future climate data from 2040 to 2060, which was obtained from the most recent Shared Socioeconomic Pathway (SSP) scenarios (SSP126, SSP245, SSP370, and SSP585) [34]. The period is selected as it's referred to the near-future period, which holds significant relevance for decision-makers in updating plans to adapt to climate change. Shared Socioeconomic Pathways (SSPs) serve to delineate potential future developmental routes for human societies, designed particularly for application in sophisticated Integrated Assessment Models. These models encompass assumptions regarding shifts in population, education, energy consumption, technology, and more over the next century. These projections are then interwoven with considerations of climate change mitigation ambitions. The amalgamation of socio-economic variables and mitigation aspirations cul-

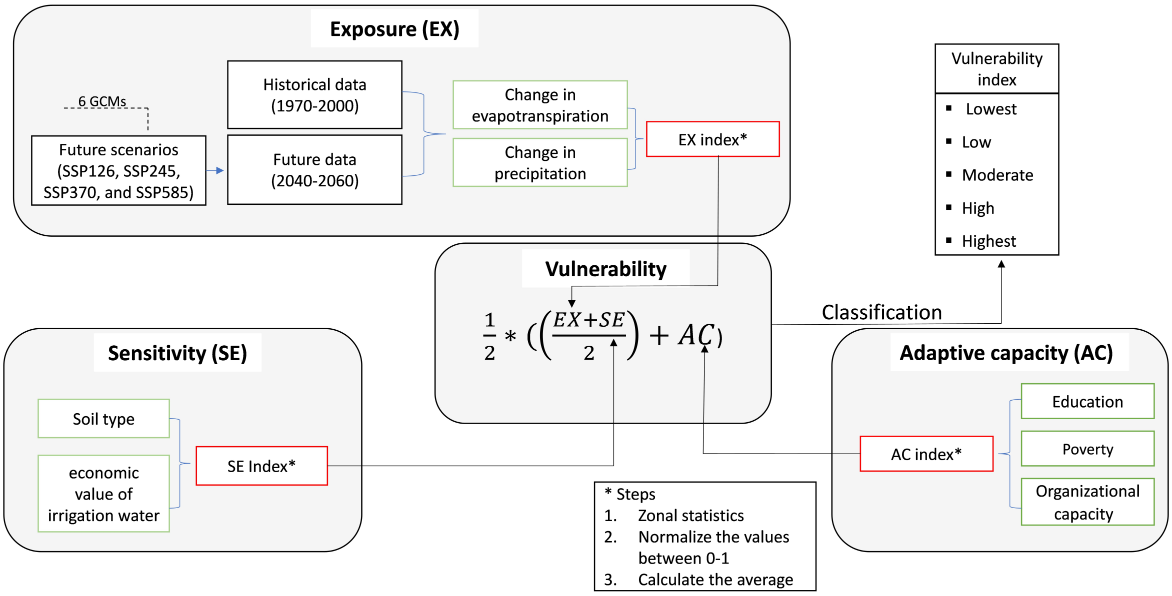

Fig. 2. Framework for Assessing the Vulnerability of Irrigation Water Requirement to Climate Change. The framework is structured into four primary boxes, within which the outputs culminate to form the ultimate vulnerability index. The study incorporates seven factors, represented by rectangular green boxes, while the red boxes signify the outputs for the three vulnerability components: Exposure, Sensitivity, and Adaptive Capacity.

minates in scenarios illustrating greenhouse gas emissions trajectories. Consequently, the climate projections stemming from these scenarios encompass an array of conceivable future climatic conditions, [34–36]. To generate this data, six different climate models were employed, namely BCC-CSM2-MR [37], CanESM5 [38], CNRM-CM6-1 [39], IPSL-CM6A-LR [39], MIROC-ES2L [40], MRI-ESM2-0 [41]. The Penman-Monteith method [25] was used to calculate the ET_0, which has been proven to be effective for estimating ET_0 in Egypt by El Afandi & Abdrabbo (2015) [42]. The study computed the average annual ET_0 and precipitation for both the historical and future periods and determined the percentage difference between them. Another aspect addressed in this study involves determining the functional relationship, which pertains to the quantitative or qualitative connection among distinct factors or components contributing to the vulnerability of a system or entity. This relationship elucidates how alterations in a single factor can exert an influence on, or impact, the overall vulnerability of the entire system [24].The functional relationship between ETo and IWR vulnerability to climate change is positive, as an increase in the percentage difference for ET_0 results in higher vulnerability. On the other hand, the relationship between precipitation and IWR vulnerability is negative, as an increase in precipitation leads to more available water for irrigation. As for the sensitivity factors, the average Total Available Water (TAW) for the different soil types in each governorate was calculated, [43, 44]. Studies have shown a negative correlation between vulnerability and TAW, indicating that higher TAW results in improved irrigation efficiency, as evidenced by previous research [30]. The economic value of irrigation water is another sensitivity factor that negatively impacts IWR vulnerability, indicating that a higher return per unit input of water results in lower vulnerability to climate change. On the other hand, the adaptive capacity factors exhibit a positive correlation with IWR vulnerability, implying that an increase in the percentage of illiteracy, percentage of poverty, and the total agricultural area for a government office raises the IWR vulnerability to climate change.

2.3. Data normalization

Table 1 displays a variety of indicators that are measured on diverse scales, necessitating the use of normalization to convert them to a standardized scale. In this study, the Human Development Index (HDI) methodology was used to achieve this normalization, as detailed by [45]. In this study, ‘0’ is defined as ‘optimal, no improvement necessary

Table 1. Components utilized in the vulnerability assessment process, indicators, and data sources of factors that contribute to vulnerability.

Comp.	Factors	Indicators	Unit	Functional Relationship	Source of data
Exposure	Reference evapotranspiration (ET_0)	Difference percentage between historical and future values	%	+	Worldclim (Fick & Hijmans, 2017), CMIP6 data (WorldClim, 2020)
	Precipitation	Difference percentage between historical and future values	%	-	Worldclim (Fick & Hijmans, 2017), CMIP6 data (WorldClim, 2020)
Sensitivity	Soil type	Total available water (TAW)	%	-	FAO(Nachtergaele et al., 2009)
	Economic value of irrigation water	Return per unit input of water	LE/m^3	-	Decision support system for the economic value of irrigation water (El-Gafy & El-Ganzori, 2012)
Adaptive capacity	Education	Percentage of illiteracy	%	+	Egypt in Figures 2018 (Egypt, 2018)
	poverty	Percentage of poverty	%	+	Handbook of the most important indicators of Income Egypt (Egypt, n.d.-b)
	Organizational capacity	Total agricultural area (Fed) to government irriga-tion offices	Fed/irrigation office	+	Egypt Geoinformatics portal (Egypt, n.d.-a)

or possible' and '1' as 'critical, system no longer functions. Eq. (1) was applied to the indicators that have a positive relationship with vulnerability while, Eq. (2) was utilized for the indicators that exhibit an inverse association with vulnerability (as shown in Table 1). The two equations are used to ensure that the indicators' values increase in the right direction. In other words, lower values should reflect positive conditions in terms of vulnerability, while higher values should indicate more negative conditions.

$$X_i, 0 \text{ to } 1 = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

$$X_i, 0 \text{ to } 1 = 1 - \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{2}$$

where X_i : the indicator (i) actual value, X_{min}: the indicator (i) minimum value, X_{max}: the indicator (i) maximum value X_i, 0 to1: the normalized value of the indicator (i).

2.4. Weighting and aggregating of indicators

In this stage, we assign weights to each indicator for the three vulnerability components in the study and then combine the normalized values using Eq. (3) [24].

$$CI = \frac{(I_1 \times W_1 + I_2 \times W_2 + I_n \times W_n)}{n \sum W} \tag{3}$$

where CI: the composite indicator, I: an individual indicator, W: the assigned weight to that indicator.

The Nile river is crucial for Egypt's irrigation water resources (IWR), which constitute approximately 90% of the country's water supply, while precipitation accounts for less than 10% [14]. As a result, we assigned a weight nine times higher to the ET_o factor than to the precipitation factor for the exposure assessment. In other words, changes in precipitation won't significantly affect the irrigation water requirements compared to the reference evapotranspiration change. Conversely, for the sensitivity and adaptive capacity assessments, all factors were granted the same weight.

2.5. Final vulnerability index assessment

In the final step of the study, the two vulnerability components, exposure (EX) and sensitivity (SE), were amalgamated to create the potential impact [46]. This resultant potential impact was then harmonized with adaptive capacity (AC) through an equal-weight approach, a method previously employed in numerous studies [10, 47, 48]. The average value of EX and SE was computed to determine the possible consequences of climate change, and AC was added to this value using Eq. (4). The resulting values were then categorized into five levels: lowest, low, moderate, high, and highest [49].

$$\frac{1}{2} \times \left(\left(\frac{EX + SE}{2} \right) + AC \right) \tag{4}$$

3. Results and discussion

3.1. ET_o

Calculating the average monthly ET_o for Egypt's governorates on a sub-national scale was a crucial component of this study, as it provided insight into the historical and future trends of this variable under the four SSP scenarios and across six different models. In order to achieve this, a meticulous process was followed, which involved averaging the ET_o results for each governorate and then combining the averages from all six models. Additionally, to make the data more understandable, the average annual ET_o is presented in Fig. 3. To further use the data in the vulnerability assessment, the difference percentage between future and historical calculations was determined and concise in Table 2. However, it should be noted that this analysis excluded four governorates - Al Bahr al Ahmar, Janub Sina', Matrouh, and Al Wadi al Jadid - due to their lack of significant agricultural areas, as confirmed by [21].

According to the study, the most remarkable percentage difference between future and historical reference evapotranspiration (ET_o) values was observed under the ssp585 scenario, as indicated in Table 2. Specifically, the highest percentage difference of 12.17% was observed at Shamal Sina' under the ssp585 scenario, while the lowest difference of 4.71% was found at Aswan under the ssp370 scenario. Notably, the results suggest that the northern coastal areas of Egypt are particularly vulnerable to climate change, with the highest ET_o difference percentages found in this region, contrary to previous studies that highlighted the south as more susceptible. These findings hold significant implications for policymakers and researchers, offering valuable insights into the potential impact of climate change on Egypt's irrigation water requirement.

Table 2. ET_o difference percentage (%) between future and historical calculations.

Gov. name	2040-2060			
	ssp126	ssp245	ssp370	ssp585
Ad Daqahliyah	7.18	7.07	7.85	9.88
Al Buhayrah	7.36	7.15	8.07	10.03
Al Fayyum	7.69	7.34	8.39	10.31
Al Gharbiyah	7.02	6.92	7.59	9.62
Al Iskandariyah	7.60	7.49	8.38	10.39
Al Isma'iliyah	7.93	7.86	8.81	10.86
Al Jizah	7.78	7.58	8.66	10.51
Al Minufivah	7.36	7.19	8.01	10.04
Al Minya	7.71	7.38	8.47	10.33
Al Qahirah	7.71	7.45	8.42	10.40
Al Qalvubivah	7.62	7.56	8.39	10.46
Al Uqsur	6.93	6.70	7.31	8.96
As Suways	8.63	8.63	9.60	11.75
Ash Sharqiyah	7.58	7.52	8.32	10.41
Aswan	6.59	6.58	7.08	8.47
Asyut	7.97	7.76	8.76	10.65
Bani Suwayf	7.70	7.39	8.39	10.30
Bur Sa'id	8.08	8.10	9.07	11.18
Dumyat	7.61	7.58	8.42	10.49
Kafr ash Shaykh	7.17	7.09	7.93	9.89
Qina	7.29	7.09	7.77	9.49
Shamal Sina'	8.95	8.90	10.13	12.17

According to the results obtained, it has been observed that the southern region of the country exhibits the highest ET_o. These findings corroborate the results of previous studies [50, 51]. Additionally, the climate model data demonstrates that the south region has the country's highest temperature. Thus, it can be inferred that a positive relationship exists between the change in evapotranspiration and the mean air temperature, which is the primary factor in the alteration of ET_o, as reported by [52].

Conversely, the percentage difference in ET_o change shows the highest value in the northern governorates. This outcome coincides with the previous study by [3], which identifies that the trend of ET_o between 1983 and 2017 in the southeastern and northwestern regions is most affected due to climate change. Therefore, it can be concluded that the north of the country is more susceptible to changes in evapotranspiration. The implication of this finding is that climate change may have a more pronounced impact on the northern regions, warranting further investigation into the matter.

3.2. Exposure, sensitivity, and adaptive capacity

In the upcoming section, we will thoroughly expound upon the evaluation outcomes conducted for Egypt. Our approach entails utilizing various colors to portray the adaptive capacity, sensitivity, and exposure of the irrigation requirement to the effects of climate change (refer to Figs. 4 and 5). Additionally, we shall showcase the ultimate vul-

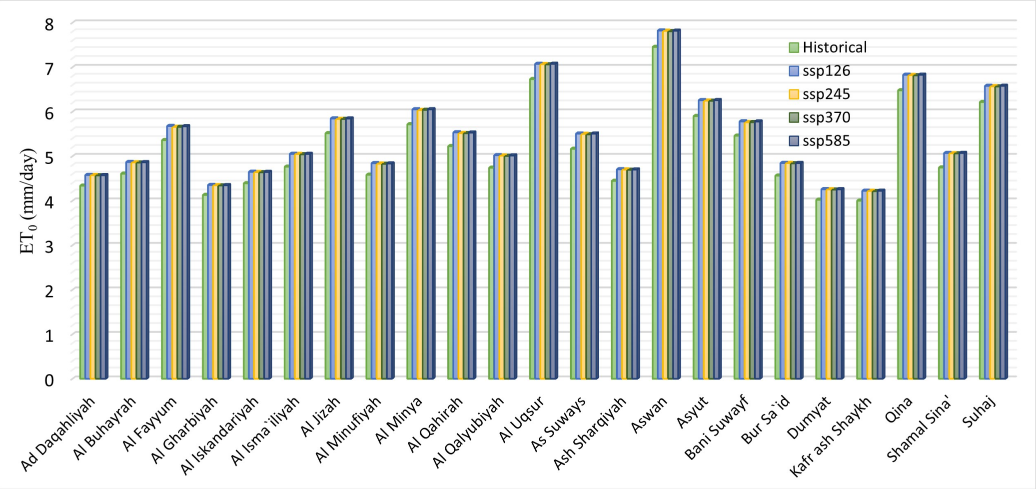

Fig. 3. Average annual ET_0 (mm/day) for the period (2040-2060) under the four SSP scenarios and the historical period (1970-2000) for Egypt's governorates.

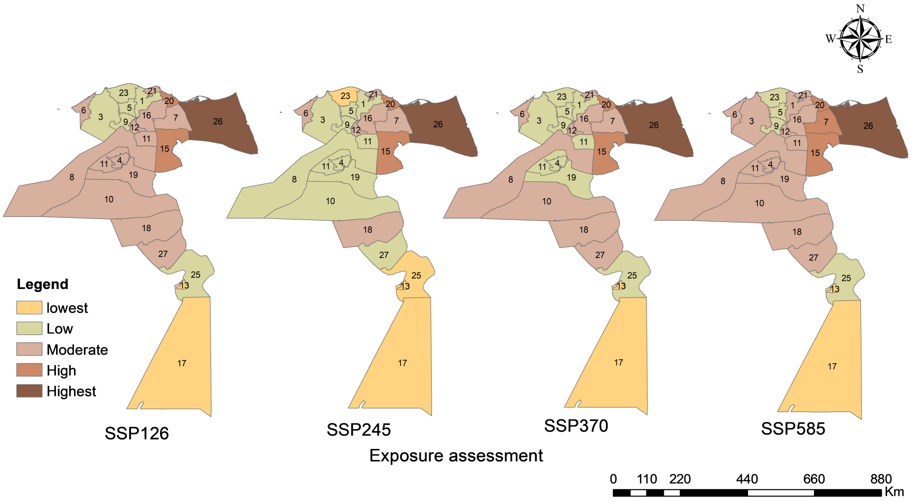

Fig. 4. Assessment of exposure levels under the four climate change scenarios.

nerability index for each governorate (Fig. 6), considering the four different climate change scenarios.

As shown in Fig. 4, the exposure assessment was conducted under four different SSP scenarios. According to the study's results, the governorates located in the northeast of the country, specifically Shamal Sina, As Suways, and Bur Said, demonstrated the greatest and high levels of exposure across all four scenarios. Meanwhile, Al Ismailiyah governorate exhibited high exposure levels under the SSP370 scenario. Conversely, Aswan and Luxor governorates situated in the southern region of the country were found to have the lowest levels of exposure across all four scenarios. Additionally, Kafr ash Shaykh and Qina governorates were identified as having the lowest exposure levels under the SSP245 scenario. The exposure levels of the remaining governorates varied from low to moderate. The northeastern region exhibited high exposure levels primarily due to the substantial changes in ET_0 caused by climate change. Previous studies have consistently identified the Mediterranean region as a hotspot for climate change, and have emphasized that the northern part of the country is particularly susceptible to its impacts [2, 3].

The results of the sensitivity and adaptive capacity assessments are shown in Fig. 5. According to the sensitivity assessment, most governorates in the country exhibit high and moderate sensitivity levels. Al Ismailiyah governorate is unique in that it has the most elevated level of sensitivity, whereas Al Buhayrah, Al Gharbiyah, and Ad Daqahliyah

Table 3. The most vulnerable governorates with their vulnerability components degree.

Governorate (Id)	Vulnerability	Exposure	Sensitivity	Adaptive capacity
Al Minya (10)	Highest	Moderate (high under SSP245)	High	High
Asyut (18)	Highest	Moderate	High	high
Shamal Sina' (26)	Highest	Highest	High	Low
Suhaj (27)	Highest (high under SSP370)	Moderate	High	High
Al Buhayrah (3)	High (highest under SSP585)	Low (moderate under SSP585)	Low	Highest
Al Faxxum (4)	High	Moderate (low under SSP245 & SSP370)	Moderate	Moderate
Al Isma iliyah (7)	High	Low (high under SSP585)	Highest	Low
Ash Sharqiyah (16)	High (moderate under SSP245)	Low	High	Moderate
Bani Suwayf (19)	High	Moderate (low under SSP245 & SSP370)	High	Moderate

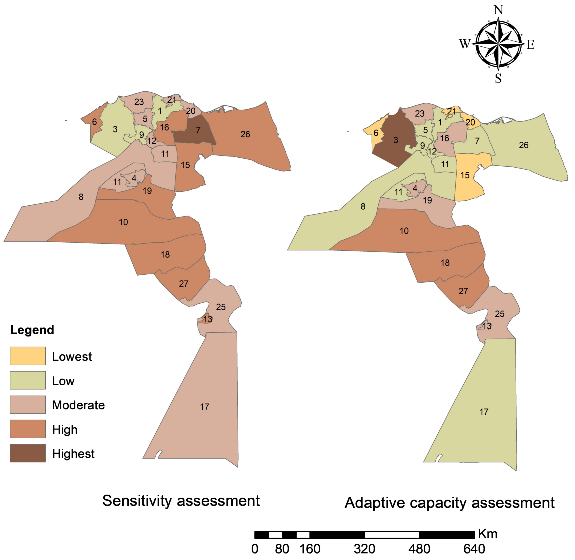

Fig. 5. Sensitivity and adaptive capacity assessment.

exhibit low levels of sensitivity. No governorates were found to have the lowest levels of sensitivity. The reason for the high and moderate sensitivity levels observed throughout the country can be attributed to the prevalence of soil types such as sand, sandy-clay, and sandy-loam, which possess low levels of Total Available Water (TAW) [44]. Furthermore, the prevalence of traditional irrigation systems in most governorates has resulted in low economic productivity of irrigation water, contributing to the high levels of sensitivity [53].

According to the results of the adaptive capacity assessment, it is evident that Al Buhayrah governorate has the highest degree of adaptive capacity. Additionally, three other governorates, namely Al Minya, Ash Sharqiyah, and Suhaj, exhibit high levels of adaptive capacity. This can be attributed to various factors such as low levels of education, high poverty rates, and inadequate government capacity, all of which result in a weaker ability to cope with the proposed effects of climate change. In contrast, the remaining governorates demonstrate lower degrees of adaptive capacity, falling within the lowset, low, and moderate range (as illustrated in Fig. 5).

3.3. Vulnerability Index assessment

Various drivers can be attributed to the causes of vulnerability, each unique to the respective governorates. Therefore, the final study outcome is the result of calculating the vulnerability assessment, which takes into account the exposure, sensitivity, and adaptive capacity assessments (as depicted in Figs. 4 and 5). To further elaborate, Fig. 6 presents the vulnerability assessment results across different climate change scenarios (SSP126, SSP245, SSP370, SSP4, and SSP585). Interestingly, despite applying these different scenarios, the outcomes indicate no significant variation. The explanation clarifies that vulnerability, as illustrated in Eq. (4), is calculated with equal weighting assigned to exposure and sensitivity relative to adaptive capacity. Consequently, exposure's impact on the vulnerability assessment is relatively minor, and changes among the four scenarios only become apparent when there are significant variations in the exposure assessment between these scenarios. This is further compounded by the close

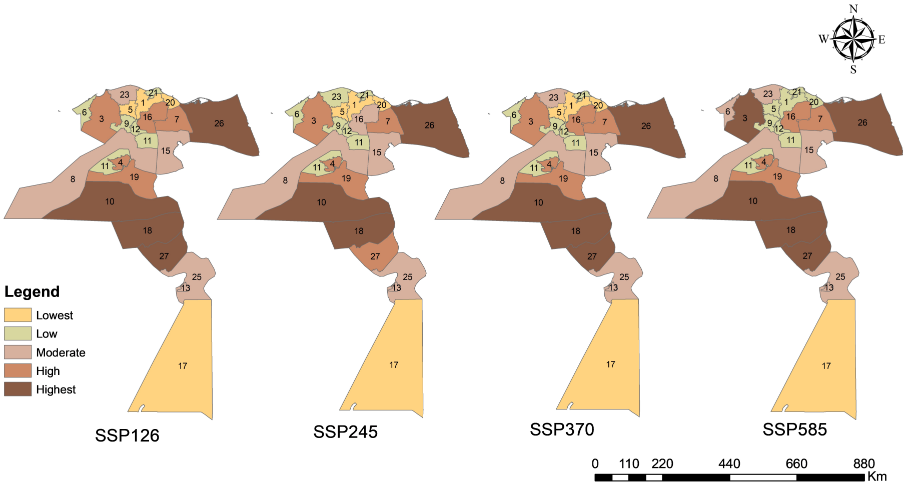

Fig. 6. The assessment of vulnerability across four different climate change scenarios.

proximity values of exposure factors, spanning from the lowest to the highest values.

The results indicate that nine governorates in Egypt, namely Asyut, Al Buhayrah, Al Fayyum, Al Isma'iliyah, Ash Sharqiyah, Al Minya, Bani Suwayf, Shamal Sina, and Suhaj, exhibit the highest and high degrees of vulnerability. Significantly, these governorates are mainly situated in the country's north and central regions. As previously discussed, the drivers behind the high vulnerability levels of these areas have been explicitly outlined, with each region facing at least two of the three factors of exposure, sensitivity, and adaptive capacity at a notably high degree.

Table 3 shows the results of the vulnerability assessment components for governorates with high and highest vulnerability degrees. The table indicates that the governorates with the highest vulnerability have a high degree in at least two of the vulnerability components. Under the climate change scenarios (SSP126, SSP245, and SSP370), the lowest vulnerability degree was observed in four governorates, namely Ad Daqahliyah, Al Gharbiyah, Aswan, and Bur Sa'id., Aswan exhibits the lowest vulnerability degree among these four governorates under the SSP585 scenario. The remaining governorates have moderate and low vulnerability degrees. In our research, we have utilized the assumption from previous studies [7, 54] that vulnerability can be expressed as a 50-50 ratio between potential impact (sensitivity and exposure) and adaptive capacity. However, it should be noted that if the vulnerability is driven primarily by factors such as human capital (adaptive capacity) rather than exposure to natural hazards or sensitivity to changes in climatic conditions, one possibility worth exploring is the allocation of a larger weight to adaptive capacity. Subsequent research efforts could focus on examining the effects of augmenting the weight of adaptive capacity on vulnerability. Additionally, in this study, we employed a deductive approach [55] to aggregate indicators within the three components of vulnerability. The study identified a number of indicators that are perceived to affect vulnerability, which were selected and given equal weight. Nevertheless, it is feasible to assign priority to specific indicator [56]. By considering their perceived significance, indicators can be prioritized. This prioritization can be accomplished through various methods, such as stakeholder meetings or expert consultations.

4. Conclusion

In conclusion, this study significantly contributes to climate change adaptation planning in Egypt by identifying the most vulnerable governorates at the sub-national level. This endeavor is of paramount importance, given the limited financial resources allocated to climate change adaptation. Our approach, in line with the IPCC 2014 report and standardized vulnerability assessment guidelines [24], considered seven key factors, offering a comprehensive analysis of vulnerability. The results pinpoint four governorates with the highest vulnerability and five with a high degree of vulnerability, serving as a crucial guide for targeted investments. While our study assigned equal weight to potential impact and adaptation capacity, it is noteworthy that, in certain contexts, adaptive capacity may warrant higher consideration, as suggested by [47]. In essence, this research equips decision-makers with valuable insights for formulating and fine-tuning adaptation plans tailored to the specific needs of the most vulnerable governorates in

Egypt.

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Conflict of interest:

There is no conflict of interest

Data availability statement:

The data supporting this study's findings are available on request from the corresponding Author.

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