



Irrigation Water Management in a Water-Scarce Environment in the Context of Climate Change

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Abstract Climate change has a considerable impact on irrigated agriculture, which is vital for food and fiber production. In this study, in the context of climate change, simulation model CROPWAT 8 was employed to compute the reference evapotranspiration, and net irrigation water requirement for wheat, barley, maize, sugar beet, potato, tomato, and date palm. In addition, the WaterGEMS model was utilized to design a new sprinkler irrigation system to run long-term simulations of hydraulic behavior within pressurized pipe networks to irrigate 43 acres for two arid sites (Siwa Oasis and West Elminya fields) inside the 1.5-million-acre groundwater irrigation project in the Egyptian western desert. Five scenarios for climate change were employed in the current (1991–2023), representative concentration path (RCP) 8.5 greenhouse gas emission scenarios for

the 2040s, 2060s, 2080s, and 2100s. Mean ET_0 values for the current scenario show 4.56 and 5.7 mm for the Siwa Oasis and West Elminya fields, respectively. The climate changes cause an increase of the reference evapotranspiration by 4.6, 5.9, 9.4, and 12.7% for RCP: 8.5 greenhouse gas emissions for the 2040s, 2060s, 2080s, and 2100s scenarios, respectively, for the Siwa Oasis field. On the other hand, an increased ratio for the reference evapotranspiration by 4.2, 5.4, 8.6, and 11.6% was observed for the scenarios in the West Elminya field, respectively. The designed sprinkler system indicated a capacity of $111.4 \text{ m}^3 \text{ h}^{-1}$ and $167 \text{ m}^3 \text{ h}^{-1}$ for Siwa and West Elminya fields, respectively. The study suggests using crop patterns for wheat, barley, potato, and sugar beet to save irrigation water.

Keywords Arid regions · CROPWAT 8 model · Sprinkler irrigation network · Water resource management

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1 Introduction

Groundwater is considered a crucial supply of irrigation water in arid and semi-arid areas such as the Middle East and North Africa, which confront water scarcity as a result of climate change and decreased surface water flow. However, demand for current water resources has increased due to population growth, climate change, and unsustainable depletion of water

resources, notably groundwater (Alotaibi et al., 2023; El-Rawy et al., 2023; Gabr, 2023a, b). In addition, Precipitation fluctuation and scarcity of surface water bodies are characteristics of arid and semi-arid regions, and water is the most valuable resource of the socioeconomic and political environment in these locations (Gabr, 2023b). Small dams and ponds are regularly utilized to collect runoff. Surface water reserving solutions, on the other hand, confront two major challenges: evaporation and siltation, which can significantly diminish effective storage capacity and efficiency (Yifru et al., 2021). In Egypt, irrigated agriculture is critical for the production of food, feed, and fiber (CAPMAS, 2022). Furthermore, the irrigation sector has historically been the largest water user in Egypt, accounting for 85% of total consumptive water usage (Gabr, 2022a, b). However, due to population growth, climate change, and unsustainable depletion of water resources, particularly groundwater, demand for existing water resources has intensified (NWRP, 2017). The Nubian Sandstone Aquifer System (NSAS) is the main Groundwater source for irrigation in the western desert of Egypt. It was utilized to produce shallow and deep groundwater wells in land reclamation operations and civilizations in the Western desert oases of Kharga, Dakhla, Bahariya, Siwa, and Farafra. Under present irrigation and cropping circumstances, producers are facing water supply issues in irrigating to meet the whole crop water requirement (Gabr, 2023a; Sharaky & Suad, 2022). Recently, the Egyptian government, in the Western Desert, implemented a massive land reclamation project with an area of 1.5 million acres, aiming to reduce the Delta's and Nile Valley's extremely high and ever-increasing population density by relocating people and widening urban space (Gabr, 2023a). The project creates modern, interconnected economies that are reliant on agriculture and opens up new horizons for long-term growth as primary and necessary support for integration with other economic sectors. It was planned based on groundwater capacity in the Western Desert Aquifer System (NSAS) (King-Okumu & Abdelkhalek, 2021). In addition, renewable energies wind and solar in the western desert are utilized to cover the energy needed to extract groundwater through the pumps. There is no doubt that irrigation management should be sustainable, given the importance of irrigated agriculture to the economy and food and fiber production in Egypt. Therefore,

selecting crop patterns, computation of irrigation requirements, and applying modern irrigation systems are all critical challenges for the project's long-term viability and sustainability. Simulation models are used to build irrigation networks, reconstruct or modernize them, and modify them (Msowoya et al., 2016). Irrigation systems in Egypt based on farm level are divided into two categories: traditional irrigation (flood irrigation) and modern irrigation (pressurized piped systems). According to the experience acquired from numerous nations in arid and semiarid locations, pressure-piped irrigation systems are successfully replacing outdated open canal surface technologies at the farm level (Phocaidis, 2007). In this study, a pressurized irrigation system, specifically sprinkler irrigation, will be used to irrigate selected fields in the study areas (1.5-million-acre project in Egypt's western desert) to improve irrigation effectiveness and assess system performance under various climatic and soil conditions. The construction of irrigation systems should aim to achieve efficiency, uniform water distribution, water conservation, and site demand satisfaction. Site-specific elements, as well as the deployment of water-saving measures and technology, should all be considered in the design. Sprinkler system design is divided into two stages: preliminary design steps, which involve gathering farm data to establish the parameters for the preliminary design, and final design procedures, which cover the process for establishing the performance parameters of irrigation equipment as well as human, physical, and financial elements (Waller & Yitayew, 2016). Therefore, in the context of climate change, the scarcity of surface water bodies is a feature of arid and semi-arid regions, rationale groundwater uses, and water is the most precious resource in these locales' socioeconomic, industrial, and political environments. As a result, addressing the impact of climate change on agricultural water requirements in arid and semi-arid regions is a critical issue for managing available water resources through crop pattern selection and minimizing irrigation water losses through the use of modern irrigation systems. Smart farming, recharging wells, advanced irrigation systems, and crop pattern selection are examples of adaption solutions to the consequences of climate change. Smart farming was established in response to the issues that agricultural production faces in terms of productivity, food safety, and sustainability

as a result of climate change (Francis et al., 2023). Pumping water into the aquifer might assist the growth of agricultural fields. As a result, artificial recharge can be regarded as one of the most essential methods for coping with the consequences of climate change and desertification (Hassan & Ghazi, 2023, Gabr et al., 2023). In this study, simulation models were applied in two phases for two specific sites (Siwa oasis and West Elminya arid regions) to compute net irrigation water requirement (NIWR) and irrigation scheduling and design a new sprinkler irrigation system for the sustainable exploitation of groundwater in the 1.5 million acres of land reclamation in Egypt's western desert: (i) the soil water characteristics were determinate by SPAW model and the CROPWAT 8 simulation model was used as a first phase to determine irrigation water requirements for the main crops (wheat, barley, maize, sugar beet, potato, tomato, and date palm), (ii) five climate change scenarios were employed to compute NIWR the current (1990–2022) 1st scenario, representative concentration path (RCP) 8.5 greenhouse gas emission for 2040s, 2060s, 2080s, and 2100s scenarios, corresponding to 1.6, 2.1, 3.3, and 4.4 °C expansion with respect to the current base line 1991–2022, (iii) the WaterGEMS simulation model was used as the second phase to perform hydraulic an extended period simulation of the sprinkler irrigation pipe network, and (iv) the study suggestions for the optimum application of modern irrigation systems and crop patterns to save irrigation water.

2 Materials and Methods

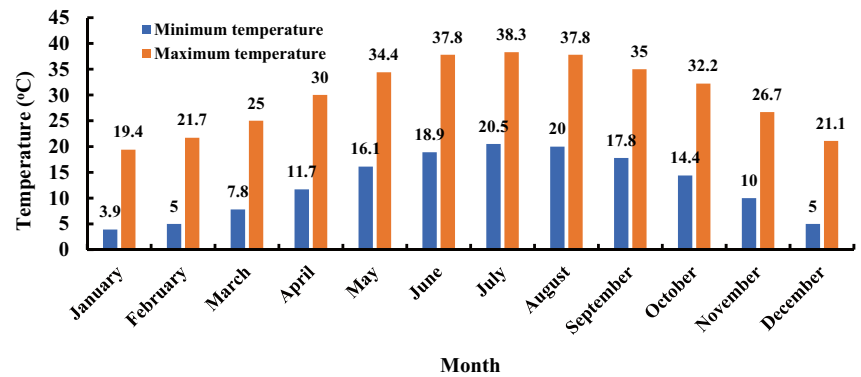
2.1 Study Area

The 1.5-million-acre land reclamation project was initiated for groundwater utilization in different locations in the western desert representing about 89.2% of the targeted area to utilize the groundwater in the NSAS in the Siwa, Farafra, Dakhla, and EL-Maghara Oases, West ELMinya, West Qena, Toshka, and Kom Ombo (King-Okumu & Abdelkhalek, 2021; Gabr, 2022a, b). In this study, two specific areas are considered as case studies, the Siwa Oasis field: a longitude of 25.51°, latitude of 29.25°, and altitude of 3 m; and the West ELMinya field with a longitude of 30.73°, a latitude of 28.08°, and altitude of 40 m were selected. Each field has an area of 600×300 m.

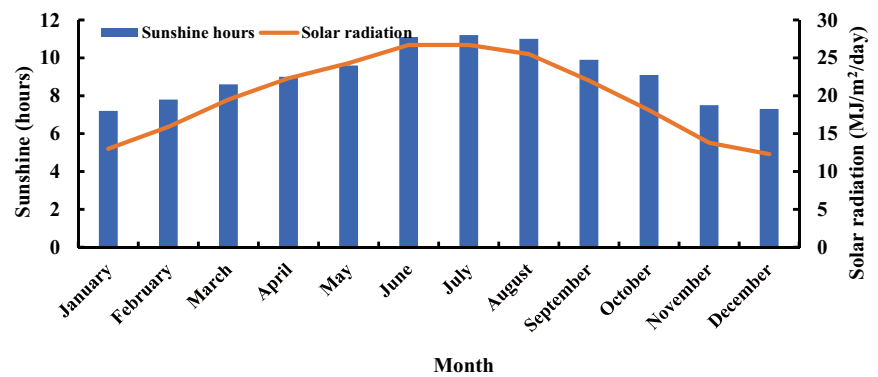
2.2 Meteorological, Soil, and Crop Data Collection

The The CMIP5 data collective, which produces the database for the global climate change predictions provided in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), is the primary data source for the Climate Change Knowledge Portal (CCKP) (IPCC, 2019). According to their total radiative forcing pathway and level by 2100, four representative concentration paths (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) were selected and categorized (a collective evaluation of greenhouse gas emissions from every source) around 2100, and the route and level. The RCP 2.6, for instance, implies a fairly strong mitigation scenario, in contrast to the RCP 8.5, which assumes business as usual. In this profile, the low (RCP 2.6), medium (RCP 4.5), and high (RCP 8.5) emission scenarios are referred to as such. For four alternative time horizons, according to the CMIP5 forecasts for key climate variables under a high emission scenario (RCP 8.5), ensemble projection precipitation anomaly in mm is 0.5, 1.9, 1.6, and 2.9 for 2040, 2060, 2080, and 2100, respectively. In addition, the temperature anomaly (°C) is 1.6, 2.1, 3.3, and 4.4 °C for 2040, 2060, 2080, and 2100, respectively. A crucial agroecological parameter for climatological and hydrological studies, as well as for irrigation planning and management, is reference evapotranspiration (ET_0) (Allen et al., 1998). According to Ouda et al., 2016, a rise in temperature of 1 °C may increase the ET_0 rate of 4–5%, while an increase of 3 °C may increase the ET_0 rate of 15%. Furthermore, Ibrahim et al., 2020 concluded that due to an increase in ET_0 in 2100, future climate change will likely result in higher potential irrigation demands. Meteorological data comprising average temperature (°C), relative humidity (RH) (%), wind speed ($m\ s^{-1}$), and sunshine hours (%) were collected from the Climatic Research Unit (CRU) product (Jones & Harris, 2008). Precipitation data were collected from the Global Precipitation Climatology Centre (GPCC) product (Schneider et al., 2018). The meteorological data are available in a gridded form in different spatial resolutions. The meteorological data for the period 1991 to 2022 were obtained for the two locations Siwa and West Elminya as shown in Figs. 1 and 2, respectively.

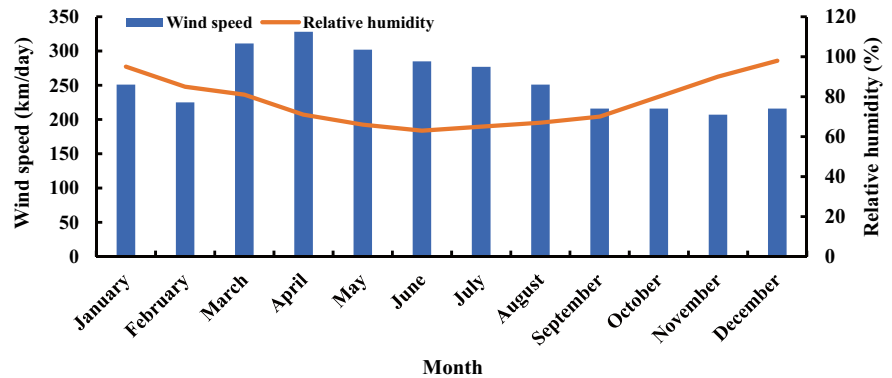
Fig. 1 Average monthly climate parameters for Siwa climate station



A Minimum and maximum temperatures



B Sunshine hours and solar radiation

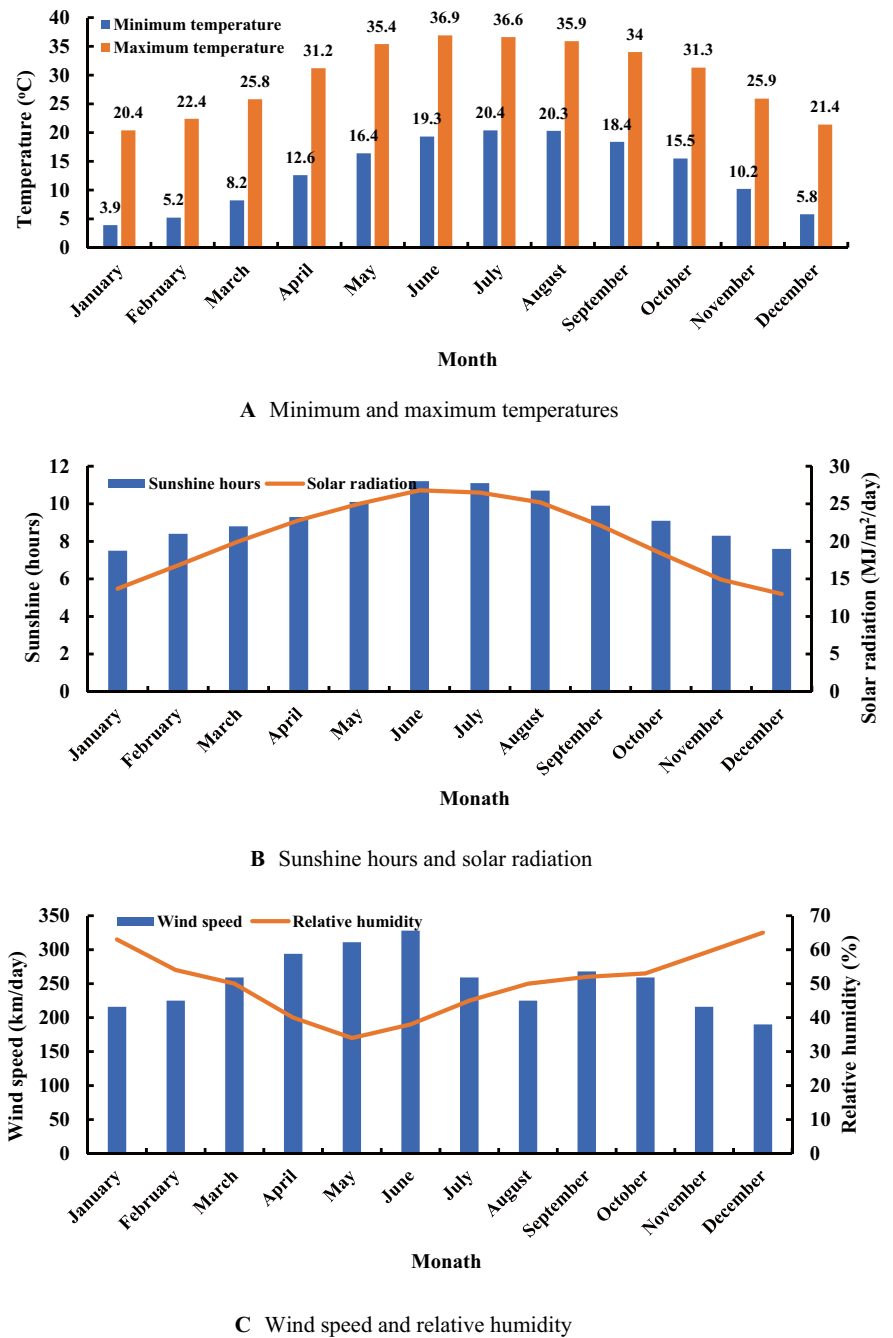


C Wind speed and relative humidity

The reference evapotranspiration (ET_0) was estimated using the FAO Penman–Monteith formula (Allen et al., 1998). The soil parameters and planting and harvesting crops (wheat, barley, maize, sugar beet, potato, tomato, and date palm) dates in

the two specific study sites used in the FAO-CROPWAT 8 model are summarized in Table 1 (Ministry of Agriculture and Land Reclamation (Moghazy, 2021). In this study on climate change, five scenarios were employed to compute the NIWR, the 1st

Fig. 2 Average monthly climate parameters for Elminya climate station



scenario (current (1990–2023)), and four scenarios due to the representative concentration path (RCP) 8.5 greenhouse gas emission for the 2040s, 2060s, 2080s, and 2100s, corresponding to 1.6, 2.1, 3.3, and 4.4 °C expansion concerning the current base-line 1991–2023.

2.3 Simulation Models Used in the Study

2.3.1 SPAW Model

SPAW (soil, plant, air, and water model) was produced by the United States Department of Agriculture

Table 1 Siwa Oasis and West Elminya fields soil parameters and planting and harvesting crop dates used in CROPWAT 8

Soil type		Soil parameter		Value	
Light soil (sandy)		Total available soil moisture (FC-WP)		60 mm m ⁻¹	
		Maximum rain infiltration rate		40 mm day ⁻¹	
		Maximum rooting depth		140 cm	
		Initial soil moisture depletion		0%	
		Initial available soil moisture		60 mm m ⁻¹	
Crop data (planting and harvest dates)					
Season	Crop	Planting date	Harvest date	Root zone depth (m)	Allow-able soil depletion
Winter	Wheat	01–Nov	10–Mar	0.9–1.8	0.5
	Barley	20–Nov	19–Mar	1.0–1.5	0.5
Summer	Maize	20–Apr	22–Aug	1.0–1.7	0.5
	Sugar Beet	01–Aug	07–Jan	0.7–1.2	0.5
	Potato	1-Sep	17-Jan	0.9–1.4	0.5
	Tomato	6-Jun	28-Oct	0.9–1.3	0.5
	Date palms	15-Feb	14-Feb	1–3.0	0.5

FC, field capacity; WP, wilting point

(USDA), Agricultural Research Service US Department of Agriculture (<https://ars.usda.gov/>). In this study, SPAW is used to model soil water tension, conductivity, and water holding capacity based on soil texture, with adjustments for gravel concentration, compaction, salinity, and organic matter. The studied fields represent light soil (sand), Table 1 summarizes the soil parameters and planting and harvesting crop dates used in CROPWAT 8.

2.3.2 CROPWAT 8.0 Model

The Food and Agriculture Organization (FAO) developed the CROPWAT 8.0 model as an empirical process-based tool that helps to propose proper irrigation strategies that result in better crop management and thus high agricultural productivity. The model uses rainfall, soil, crop, and climate data, and then integrates several modules that are necessary to calculate ET_o , crop evapotranspiration (ET_c), net irrigation water required, and irrigation scheduling. Among the literature, the model was applied by many researchers to estimate crop water requirements for several crops like potatoes (Banerjee et al., 2016), wheat and maize (Bal et al., 2022),

and soybean (Memon & Jamsa, 2018). In the present study, the CROPWAT 8.0 model was applied to estimate ET_c and irrigation water requirements for wheat, barley, maize, and sugar beet, which are grown inside the 1.5-million-acre reclamation project in the Egyptian western desert. The depth of water applied refers to how much water should be applied during irrigation to replace the water lost by the crop during evapotranspiration. Equation 1 defines the net depth of water application (Schneider et al., 1996),

$$d_{\text{net}} = (FC - WP) \times RZD \times PM \quad (1)$$

where d_{net} is the readily available moisture in mm, FC is the soil moisture content at the field capacity, WP is the soil's moisture content at the point where it permanently wilts (mm m⁻¹), RZD is the maximum depth of soil that the roots can efficiently utilize (m), and PM is the maximum amount of accessible moisture that the crop can deplete before the next irrigation. Rainfall was subtracted from the peak daily crop water requirements (ET_c) to arrive at the net irrigation requirement. The duration it takes for the crop to reach a specific soil moisture depletion level determines the frequency of irrigation. Equation (2) was

used to determine the irrigation frequency (IF) in days (Schneider et al., 1996):

$$\text{Irrigation frequency (IF)} = d_{\text{net}}/\text{ET}_c \quad (2)$$

where ET_c is the peak daily water use (mm day^{-1}) for the crops and d_{net} is the net depth of water per application (mm). The gross depth (d_g) was calculated by dividing the d_{net} by the field irrigation efficiency (η). The field irrigation efficiency includes any water lost due to pipe leakage; d_g was calculated from Eq. (3):

$$d_g = d_{\text{net}}/\eta \quad (3)$$

The efficacy of sprinkler system field irrigation varies depending on the climate. According to Phocaides, 2007, farm irrigation efficiency for sprinkler irrigation in hot temperature regions like the study regions in Egypt is 70%. Define effective rainfall computations independent method was utilized in this study; therefore, the total rainfalls are 10 and 5 mm/year for the Siwa Oasis and West Elminya fields, respectively, resulting in zero effective rainfall.

2.3.3 WaterGEMS Model

The WaterGEMS model is a friendly interface for users to examine, design, and optimize water distribution systems. WaterGEMS and WaterCAD were developed by the Bentley company. The software manages water network data and system variables (Sonaje & Mandar, 2015) such as pressure, velocity, and flow. WaterGEMS is a hydraulic application for water distribution and has the capabilities of building a network, computes friction head loss using the Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas, performing steady-state analysis, extended period simulations (EPS), pressure-dependent demand issuing from emitters (sprinkler heads) and provides robust results for hydraulic convergence. WaterGEMS Connect 2.00.10 includes a computation engine based on EPANET 2.00.10 with Bentley's enhancements and features. The WaterGEMS network nodes represent a sprinkler, with models acting as emitters according to Eq. (4).

$$Q = K_E \times P^n \quad (4)$$

where Q is the sprinkler discharge ($\text{m}^3 \text{h}^{-1}$), K_E is the emitter coefficient (0.05), P is the operating pressure

for the sprinklers in m, and n is the emitter exponent (0.5).

2.4 Sprinkler Irrigation Design Steps

Steps for designing sprinkler irrigation systems are classified into (i) the preliminary design, and (ii) the final sprinkler irrigation design. It is important to calculate the preliminary design variables using the net depth of water application, the frequency of irrigation during peak demand, and the gross depth of water application (Schneider et al., 1996). All of these design data are based on climate, water, soil, and the cultivated plant. The final sprinkler irrigation design steps are the selection of the sprinkler characteristics and spacing. Therefore, the following procedures may be followed to reconcile the preliminary design parameters: (i) the sprinkler selection and spacing are determined, (ii) it is determined the sprinkler system layout, (iii) is selected sprinkler system type specification, (iv) the allowable pressure variation is considered, and (v) final simulated sprinkler system layout (simulation result) is adopted.

2.4.1 Sprinkler System Layout and Specification

To leave as little land outside of the irrigated region as feasible, the system layout is created by matching the potentially allowable spacing to the field size. The sort of sprinkler system to use depends on the field dimensions and the set time (ST); this is the length of time each sprinkler unit needs to operate concurrently to provide the gross irrigation depth. To determine the type of sprinkler system, an irrigation scheme should be developed based on the crop watering schedule and the set time, which may be calculated using the following formula (Schneider et al., 1996):

$$S_T = d_{\text{gross}}/S_P \quad (5)$$

where S_P is the sprinkler precipitation rate (mm h^{-1}) and S_T is the set time (h).

When planning the system's layout, one crucial principle to remember is that the laterals should be located parallel to the prevailing wind direction to produce fairly consistent head losses. Equation (6) can be used to compute the capacity of such a system:

$$Q = N_S N_L Q_S \quad (6)$$

where Q is the system capacity ($\text{m}^3 \text{h}^{-1}$), N_s is the number of sprinklers per lateral while N_L represents the number of laterals operating per shift and Q_s is the sprinkler discharge (from the manufacturer's tables (Table 5 in the appendix).

Sprinklers and their spacing can be chosen using the manufacturer's tables (Table 5). In this paper, the recommendations of Phocaides, 2007 were used to determine the sprinklers and their spacing. Where (i) The term "nozzle size" refers to the size of the nozzle's aperture, (ii) pressure indicates the operating pressure of the sprinkler at the nozzle, (iii) discharge refers to the amount of water the nozzle provides per unit of time at a specific pressure, (iv) wetted diameter denotes the diameter of the circular area wetted by the sprinkler when operating at a given pressure and no wind, and (v) sprinklers are spaced at 12 m along the sprinkler lateral line and 18 m between sprinkler lines when they are spaced at a $12 \text{ m} \times 18 \text{ m}$ spacing. For both research situations, the sprinkler application should be less than 40 mm day^{-1} to avoid runoff, which is appropriate for the soil and crop. From design tables (Waller & Yitayew, 2016), we can choose from a variety of nozzle diameters, pressures, and sprinkler spacing options. However, additional factors such as the field dimensions, coefficient of uniformity, wind speed, and prevailing wind direction were taken into account while determining sprinkler spacing. The coefficient of uniformity (COU) is a metric indicating how uniformly water is applied. The selected sprinkler should have an average COU of at least 85%. When utilizing locally made sprinklers that do not test for COU values, it is advisable to avoid using low pressure because this is typically the pressure that corresponds to low COU values (Phocaides, 2007).

3 Results

3.1 ET_o , ET_c , and Irrigation Water Requirements

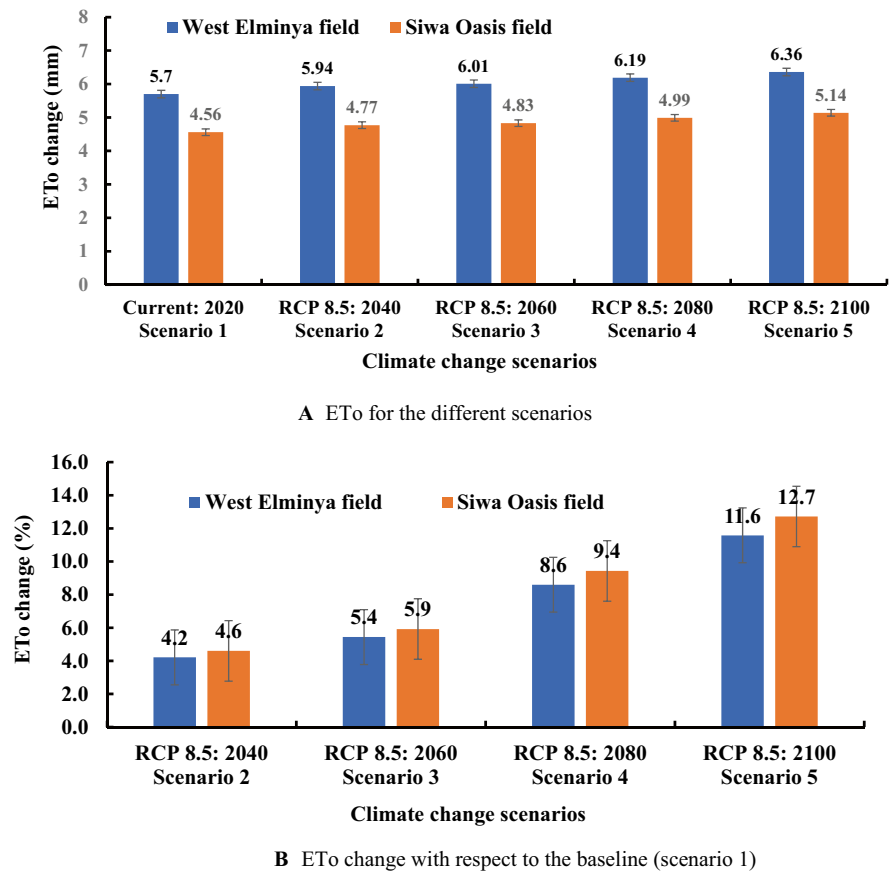
After the input of climate, crop, and soil data into the CROPWAT 8.0 model, estimated ET_o , and ET_c values. Therefore, ET_o average values for Siwa and West Elminya stations are 4.56 and 5.7 mm day^{-1} , respectively (Fig. 3A). For Siwa Oasis field, 1.6, 2.1, 3.3, and 4.4°C expansion concerning the current baseline

1991–2022, the climate changes cause an increased ratio for the ET_o by 4.6, 5.9, 9.4, and 12.7% for RCP: 8.5 greenhouse gas emissions for the 2040s, 2060s, 2080s, and 2100s scenarios, respectively (Fig. 3B). However, for the West Elminya field, the ET_o ratio increased by 4.2, 5.4, 8.6, and 11.6% in the 2040s, 2060s, 2080s, and 2100s scenarios, respectively. The results show zero effective rainfall values; then, the $ET_c = \text{NIWR}$. For climate change, RCP 8.5 for the 2040s, 2060s, 2080s, and 2100s corresponds to 1.6, 2.1, 3.3, and 4.4°C expansion, respectively. For the current scenario in the Siwa Oasis field, the ET_c values for wheat, barley, maize, sugar beet, potato, tomato, and date palm were found to be 203, 215.4, 785.1, 386.6, 360.6, 842.4, and 1607.2 mm, respectively (Fig. 4A). In addition, ET_c values for West Elminya field are 310.7, 327.4, 903, 542.1, 483.7, 955.6, and 2005.1 mm, respectively (Fig. 4B). Figure 5 shows the percentage increase in the ET_c for the crops for the RCP 8.5: 2040s, 2060s, 2080, and 2100 scenarios for A: the Siwa Oasis field, and B: The West Elminya fields. Therefore, for the Siwa field, ET_c for wheat increased by 5.7, 7.5, 12, 10.7, and 16.3% for the RCP 8.5: 2040s, 2060s, 2080, and 2100 emission scenarios, respectively, and for maize ET_c increased by 3.8, 5.1, 8.1, and 10.9% for the RCP 8.5: 2040s, 2060s, 2080, and 2100 emission scenarios, respectively. For date palm ET_c increased by 4.3, 5.7, 9.2, and 12.3% for the RCP 8.5: 2040s, 2060s, 2080, and 2100 emission scenarios, respectively (Fig. 5A). On the other hand, for the West Elminya field, ET_c for wheat is increased by 5.3, 7, 11, and 14.7% for the RCP 8.5: 2040s, 2060s, 2080, and 2100 emission scenarios, respectively (Fig. 5B). Also, ET_c for maize is increased by 3.5, 4.7, 7.4, and 9.9% for the RCP 8.5: 2040s, 2060s, 2080, and 2100 emission scenarios, respectively. In addition, date palm ET_c is increased by 3.7, 5, 8.1, and 10.9% for the RCP 8.5: 2040s, 2060s, 2080, and 2100 emission scenarios, respectively.

3.2 Sprinkler Irrigation System

The maximum d_{net} values for wheat and barley are 24.75 and 27.50 mm for Siwa Oasis field; and 27.00 and 30.00 mm for the West Elminya field. While in the summer season, the maximum computed d_{net} for maize and sugar beet is 39.33 and 28.89 mm for the Siwa Oasis field; and 42.90 and 31.52 mm

Fig. 3 ET_o values due to climate change **A** ET_o for the different scenarios and **B** ET_o change with respect to the baseline (scenario 1)



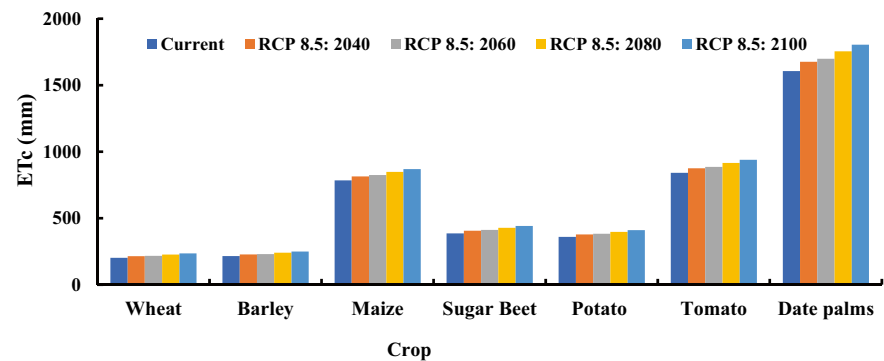
for the West Elminya field. The difference in net depths between the wheat and maize crops refers to the climatic conditions of the season while the convergence in d_{net} values refers to the similarity of soil parameters in both fields. The irrigation frequency for maize in the Siwa is 4.54 days. It was determined that the soil moisture depletion should not be higher than 55% during the time of highest water demand, which usually happens in the summer. Irrigation frequency was reduced to 4 days for practical purposes. The corresponding (d_{net}) for maize in Siwa is 34.68 mm. Soil moisture depletion was calculated for selected crops (Table 2). The corresponding soil moisture depletion (p) for maize in the West Elminya is 49.6%. The efficacy of sprinkler system field irrigation varies depending on the climate. According to Phocaidis, 2007, farm irrigation efficiency for sprinkler irrigation in hot temperature regions like the study regions in Egypt is 70%. As a result, for the Siwa field, d_g for the maize crop was estimated as 49.5 mm. The water

demand was estimated as the maximum value of gross depth requirements (d_g) for all crops in each field. The maximum water demand occurs during maize cultivation, this is reasoned by the increase in air temperature during summer. The gross depth requirements for maize are 49.5 mm and 59.5 mm in the Siwa and the West Elminya fields, respectively. These values were adopted in the design process of the sprinkler irrigation system for each field to account for the optimum crop water requirement. In this paper, the sprinkler system was designed for the Siwa Oasis field to fulfill the irrigation water demands of the maize crop. Table 2 summarizes the net and gross depth of irrigation required in the Siwa and the West Elminya fields, respectively.

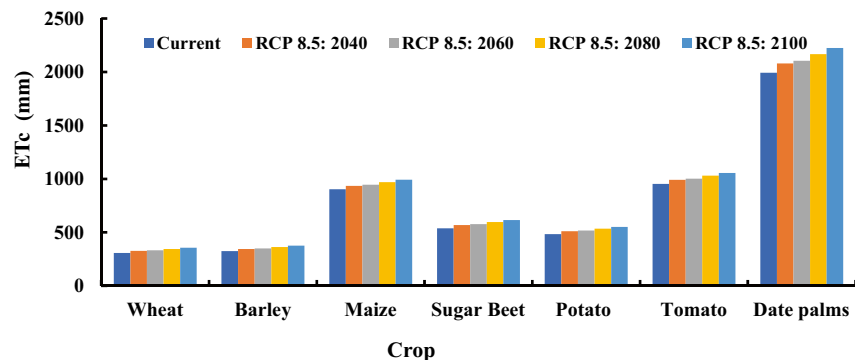
3.2.1 Sprinkler Selection and Spacing

Table 1 depicts the findings of a study on soil water characteristics that were influenced by the sandy soil features of the Siwa and the West Elminya fields. It

Fig. 4 NIWR for the crops during different scenarios for **A** Siwa Oasis field and **B** West Elminya fields



A Siwa Oasis field



B West Elminya field

should be noted that both study locations had a basic infiltration rate of soil of 40 mm day^{-1} . According to Fig. 1, the monthly average metrological statistics for the Siwa Station and West Elminya districts show that the average wind speed in each location is roughly 3.4 and 4.0 m/s in March, April, and June, respectively. Consequently, for a square pattern, sprinkler spacing should be 45% of the wetted Diameter (D), while for a rectangle pattern, sprinkler spacing should be 30% between sprinklers and 50% between laterals. The next step is to see if the possible spacings are sufficient to meet the wind requirements. The sprinkler spacing of $12 \text{ m} \times 12 \text{ m}$ satisfies the requirements regarding the discharge, pressure, as well as wind speed, and the nature of the soil in which the predominant sort of slow infiltration rate occurs in both research fields. Therefore, at a pressure of 350 kPa, the sprinkler precipitation rate is 8.06 mm h^{-1} , and the wetted diameter of the 4 mm nozzle size is 30.50 m. For a wind speed of 14.4 km h^{-1} , 45% for the $12 \times 12 \text{ m}$ spacing is 13.72 m (> than 12 m). The

prevailing wind direction in Egypt is from the north-west direction (Mortensen et al., 2006). Laterals are aligned normally to the prevailing wind direction. Furthermore, to reduce runoff on sloping land, an adjustment of the precipitation rate is needed. However, because the ground in this study is nearly flat, no precipitation reduction correction is required. Table 3 summarizes the number of pipes, lengths, total lengths, and diameters for the proposed sprinkler irrigation system.

3.2.2 Sprinkler System Layout and Specification

Substituting values for gross depth and sprinkler precipitation rate in Eq. (5), the set time for Siwa and Western Elminya fields was calculated (Table 4). The set time for the maize crops in the Siwa field is 6.15 h. The utilization of the sprinkler system was optimized by maximizing the number of working shifts per day using the set time of the highest demanding crop in Siwa (6.15 h for maize). Considering the

Fig. 5 Percentage increase in the ET_c for the crops for the RCP 8.5: 2040s, 2060s, 2060s, and 2100s scenarios for **A** the Siwa Oasis field and **B** The West Elminya fields

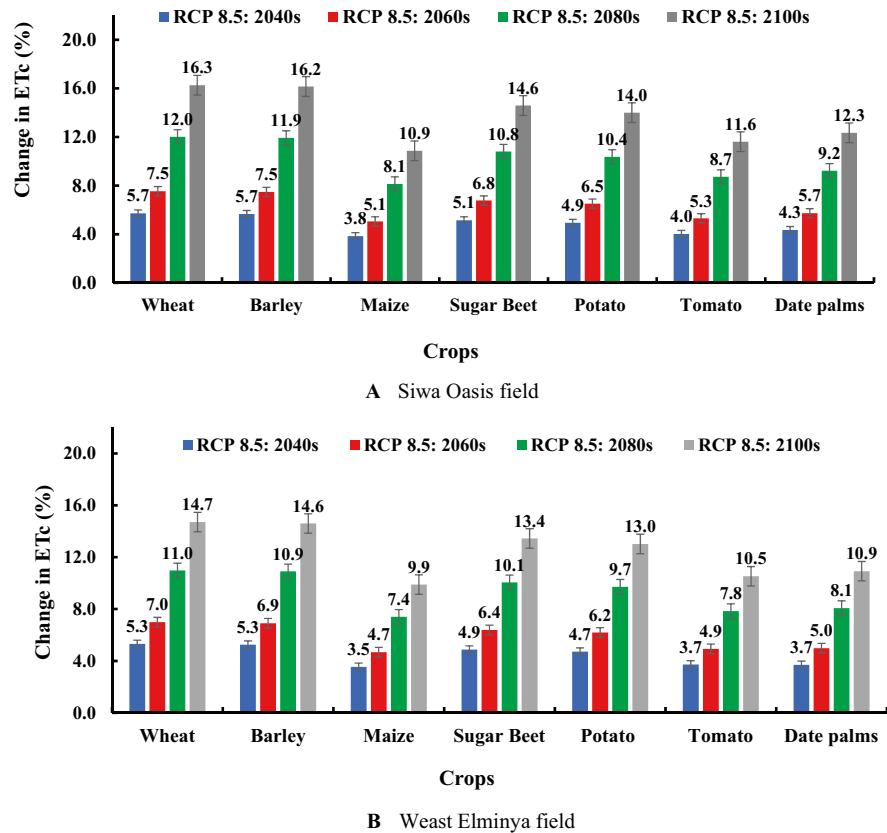


Table 2 Net and growth depth of irrigation required in Siwa and West Elminya fields

Siwa Oasis field				
	Wheat	Barley	Maize	Sugar beet
Irrigation frequency	6.97	7.18	4.54	4.99
Chosen irrigation frequency (days)	8	8	4	5
Net depth of irrigation required (mm per watering)	28.40	30.64	34.68	28.95
Moisture depletion (p) %	0.37	0.40	0.45	0.38
Gross depth of irrigation (mm per watering)	40.6	43.8	49.5	41.4
West Elminya field				
	Wheat	Barley	Maize	Sugar beet
Irrigation frequency	8.41	8.65	4.12	4.90
Chosen irrigation frequency (days)	8	8	4	4
Net depth of irrigation required (mm per watering)	25.68	27.76	41.64	25.72
Moisture depletion (p) %	0.31	0.33	0.50	0.31
Gross depth of irrigation (mm per watering)	36.7	39.7	59.5	36.7

maximum time of pump operation is 20 h, the number of shifts for the lateral pipe is rounded to 3 shifts day⁻¹ (3.25 h.). According to the indicated set time for maize, the semi-permanent irrigation system type was selected as the fit system for that operating time.

The semi-permanent system includes movable lateral lines, stationary water sources, permanent mainlines, sub-mains, and a pumping facility. Permanent pipes are buried deeply enough to allow crop harvesting and field preparation to take place without disturbing

Table 3 Number of pipes, lengths, total lengths, and diameters

Pipe network identity	Number of pipes	Length per subfield (m)	Length per field (m)	Pipe internal diameter (mm)
S1	8	132	1056	50
S2	8	15	120	63
S3	2	150	300	75
S4	2	129	258	110
S5	1	200	200	125
Total			1934	

Table 4 Working, non-working days, set time, and operation hours for Siwa and West Elminya fields

Siwa field				
	Wheat	Barley	Maize	Sugar beet
Irrigation frequency (days)	8	8	4	5
Working days	4	4	4	4
Non-working days	4	4	0	1
Number of shifts day ⁻¹	3	3	3	3
Set time (hours)	5.03	5.43	6.15	5.13
Operation time (h day ⁻¹)	15.10	16.29	18.44	15.39
West Elminya field				
	Wheat	Barley	Maize	Sugar Beet
Irrigation frequency (days)	8	8	4	4
Working days	4	4	4	4
Non-working days	4	4	0	0
Number of shifts per day	2	2	2	2
Set time (hours)	4.55	4.92	7.38	4.56
Operation time (h day ⁻¹)	9.10	9.84	14.76	9.12

the pipes. Given that the sprinkler and lateral spacing is 12×12 m, 50 lateral positions would be needed to cover half of the farm's total area. Around half of the farm, 6 m width for roadways, then 48 lateral places (The entire space may be covered with 96 laterals). The mainline can be positioned in the middle of the farm for a more beneficial arrangement from an operational perspective; this design will allow the laterals to rotate around the mainline, and irrigation will be completed in 4 days using 12 laterals (60 positions 4 day⁻¹). Each lateral will run in three shifts per day, with a discharge of 13.92 m³ h⁻¹ and 12 sprinklers per lateral functioning concurrently to finish the irrigation cycle. The buried mainline runs

the length of the farm, delivering water to the laterals from the buried supply pipe. Equation (6) can be used to determine the farm system capacity, which is 111.4 m³ h⁻¹.

3.2.3 Sprinkler System Layout Simulation Result

To test network performance and conformance of results (head, velocity, and irrigation demands) with hydraulic conditions and irrigation water application requirements, a final design result was selected and simulated using the WaterGEMS simulation model technique. Figure 6 depicts the simulation output structure and network setup for the 0.18 km² farm with dimensions of 600 m \times 300 m. This farm has a semi-permanent sprinkler irrigation system with a flow capacity of 111.4 m³ h⁻¹ for a 4 days irrigation cycle (during the peak watering season for maize, a fixed timing of 6.15 h). Pipes (supply mainlines, and laterals), flow control valves, sprinklers, and a pump station are all part of the system. The following is a brief description of the system capacity and pipe velocity.

3.2.4 Sprinkler Distribution

Sprinklers with a 12 \times 12 m spacing, 4.0 mm nozzle size, 350 kPa pressure, 30.5 m wetted diameter, and 1.16 m³ h⁻¹ precipitation rate were selected. As a result, there are 96 sprinklers in the farm system. A total of 48 lateral positions are placed every 12 m along the mainline, with 8 laterals functioning simultaneously to provide irrigation water over a 4-day irrigation cycle (Fig. 7). The mainline is connected to laterals that are installed on the ground using hydrants and UPVC pipes with a diameter of 50 to 125 mm (Hazen & Williams factor, $C=150$). The sizes and lengths of pipes are listed in Table 3 for one farm.

3.2.5 Simulated Pressure and Velocity Results of The System

Pressure variances should be kept within a certain range throughout the system, block, or subunit to provide a high degree of water application uniformity. As a result, lateral friction losses should be kept to a minimum, and the maximum permissible lateral friction loss in the lateral line should not exceed 10% of the sprinkler operating pressure whenever

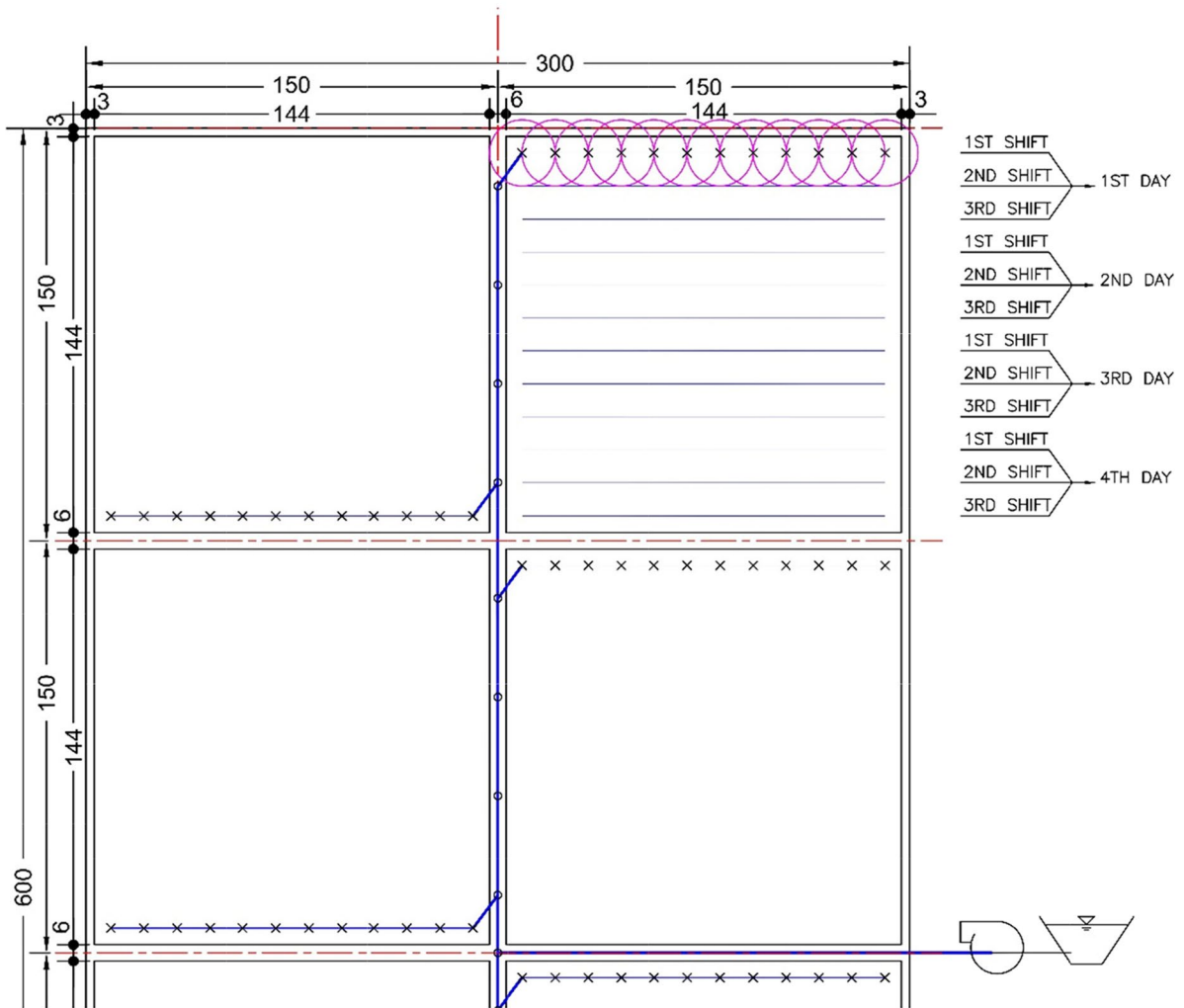


Fig. 6 Half plan of the sprinkler irrigation network

possible. For the provided spacing and nozzle size of 4 mm operating at a pressure of 350 kPa, the predicted pressure loss in the lateral line is 35 kPa, or 3.57 m. Figure 7 shows the pressure head along with the various nodes of the sprinkler irrigation network, the minimum pressure at the farthest lateral is 36.1 m at the farthest node on the line, while the maximum pressure on the same lateral line is 39.5 m, resulting in a pressure variation of 3.4 m (9.42%), as, it satisfies the constraint of sprinkler working pressure and falls within the minimum pressure requirement. The pressure head of the pumping station is 55 m. The most crucial restriction for pressurized network design is velocity

restrictions; the manifold pipe has the lowest velocity at 1.2 m s^{-1} which leads to fewer friction losses per unit length of the pipe while the highest velocity is 2.5 m s^{-1} in the main pipe, typically causes the pipe stretch's unit head losses to increase. The result of the design discharge simulation for the sprinkler irrigation system is $111.4 \text{ m}^3 \text{ h}^{-1}$.

3.2.6 Application of Designed Sprinkler System for Other Crops

The sprinkler system was developed to achieve the water needs of maize irrigation, which is one of the most water-intensive crops in both selected locations

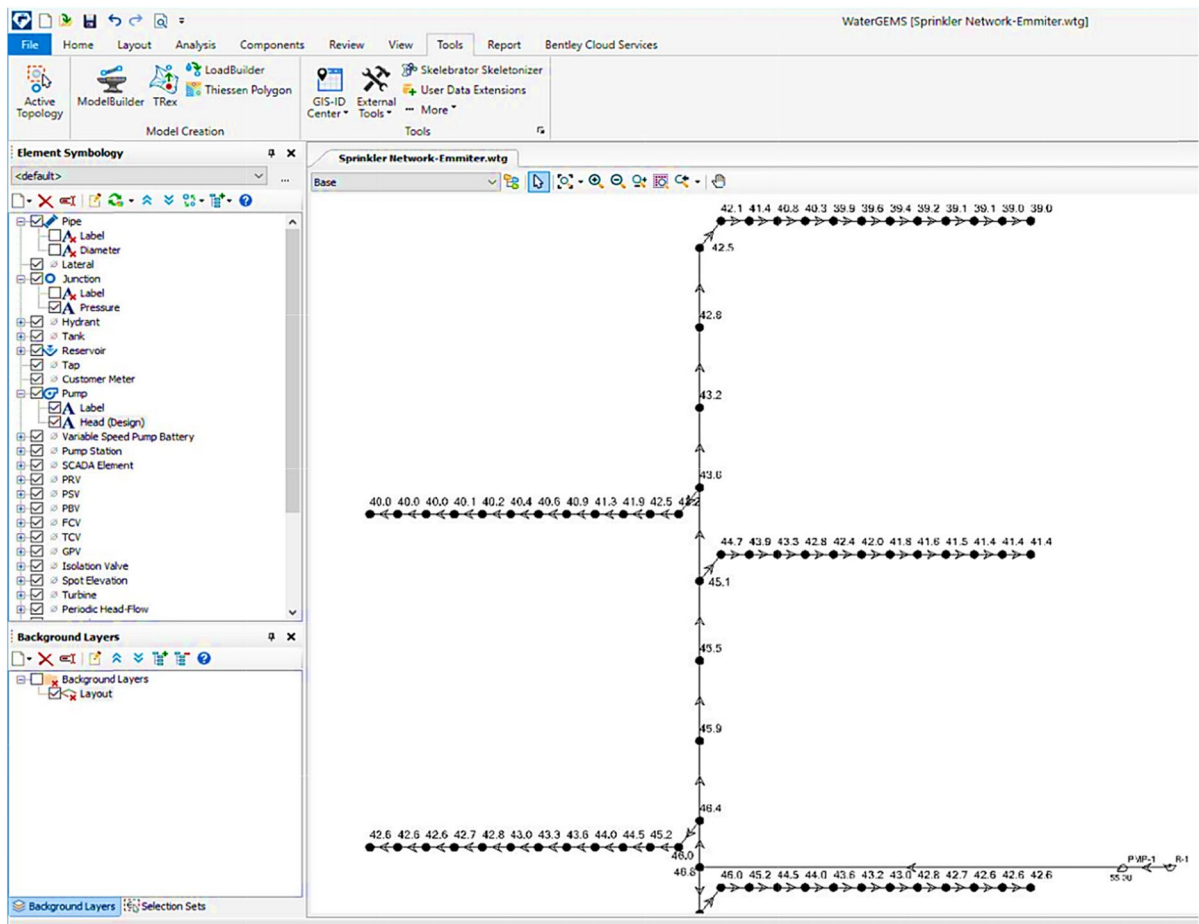


Fig. 7 Pressure head along the various nodes of the sprinkler irrigation network

throughout the summer, but it also can meet the needs of other crops. In this study, the proposed system was utilized to irrigate other crop kinds, including wheat, barley, and sugar beet, although at different periods. Considering the same number of working days for all crops (4 days), then the number of non-working days can be deduced for each crop. Irrigation frequency for wheat was calculated as 8 days; therefore, the number of non-working days is 4. Considering the same number of shifts (3 shifts) for all crops, then the operation time per day for each crop can be deduced. The set time for the wheat crop is 5.03 h; then, the daily operation time for wheat in the Siwa field is 15.1 h. The irrigation frequency, working days, non-working days, set time, and operation hours for various crops in Siwa are in Table 4. The set time for maize crops in the West Elminya field was estimated as 7.38 h.

The number of shifts for the lateral pipe in Western Elminya was rounded down to 2 shifts per day which made a different sprinkler distribution plan in Western Elminya than that in Siwa. Considering the irrigation frequency is 4 days, then one subfield can be covered by 8 lateral positions (4×2). Assuming the same sprinkler and lateral spacing (12×12 m), half of the farm would require 50 ($600/12$) lateral locations to cover half of the whole area. Allocating 4 m width for roads around half the farm, then 48 lateral positions (the entire space may be covered with 96 laterals.), when each subfield has 8 lateral positions, there are a total of 12 subfields, which allows for the simultaneous operation of 12 laterals. The farm system capacity will be $167 \text{ m}^3 \text{ h}^{-1}$ if Eq. (6) is applied as a consequence. The minimum pressure in the farthest lateral is 36.1 m located at the farthest node on

the lateral line, while the maximum pressure on the same lateral line is 39.5 m, resulting in a pressure variation of 3.4 m using the same Siwa field sprinkler specifications (350 kPa pressure, 30.5 m wetted diameter, $1.16 \text{ m}^3 \text{ s}^{-1}$, and an emitter coefficient with a 4.0 mm nozzle size (0.054)). The pressure head at the pump's station is 50 m. The lowest velocity is 1.2 m s^{-1} while the highest velocity is 2.5 m s^{-1} . The result of the design discharge simulation for the sprinkler irrigation system is $166.92 \text{ m}^3 \text{ h}^{-1}$.

4 Discussions

One of the areas most susceptible to climate change is the Middle East region. Increased aridity, heat waves, and sea-level rise are some of the effects. The area may become uninhabitable before the year 2100 if greenhouse gas emissions are not decreased (Das et al., 2018; Rosa et al., 2020). Even if warming is limited to 1.5°C , living in the Middle East and North Africa is going to become extremely difficult. The Middle East is already more vulnerable to climate change than most regions because of limited water supplies and long summers that are already very hot (Duran-Encalada et al., 2017). The study's findings are consistent with Moghazy & Kaluarachchi, 2021, who addressed the climate change-driven long-term problems of establishing an agricultural project in the Siwa Oases, where groundwater from the non-renewable Nubian Sandstone Aquifer System (NSAS) is the only supply of water. They used. Different climate models were used to simulate two representative concentration trajectories (RCPs): RCP 4.5 and RCP 8.5. Summer temperatures are projected to rise by $1.68 \pm 1.64^\circ\text{C}$ in 2060 and $4.65 \pm 1.82^\circ\text{C}$ in 2100 under RCP 4.5 and RCP 8.5, respectively. The increase in agricultural water requirements is anticipated to be 6–8.1% under RCP 4.5 and 9.7–18.2% under RCP 8.5. Maximum losses in strategic crop yields range from 2.9 to 12.8% in 2060 under RCP 4.5, and 10.4 to 27.4% in 2100 under RCP 8.5. Furthermore, the findings of this study are consistent with Mostafa et al., 2021 study on the impact of climate change on the water demands of wheat, one of Egypt's most important food crops in the Middle Egypt region. Their findings indicate that an increase in greenhouse gas emissions will cause the temperature in the study

area to rise by approximately 2.12°C in 2050 and 3.96°C by 2100. As a result, the irrigation water requirements for wheat production are expected to rise by 6.2 and 11.8% in 2050 and 2100, respectively. In addition, wheat productivity will fall by 8.6% in 2050 and 11.1% in 2100. The results of this study also agreed with Badr et al., 2023, they used a water evaluation and planning model to replicate the irrigation network systems of Egypt's Minia Governorate on the western bank of the Nile's narrow valley, and Nubariya in the West Nile Delta, the Nile's lower reaches. Using field data and experience, as well as other inputs, geographic information system (GIS) software digitized streams from satellite imagery. They concluded that for climate change from 2021 to 2050, increasing temperature in the areas leads to evapotranspiration increases of 5.42% and 5.13%, and (2) canal lining scenarios, which found flow savings in the areas, demonstrating that we can overcome the anticipated water shortage progress if canal lengths are rehabilitated by 10% and 25% in Minia and Nubariya, respectively. Crop combinations such as wheat and maize, wheat and sugar beet, wheat and potato, wheat and tomato, date palm, maize, and tomato are being investigated to preserve irrigation groundwater. Based on growth, the irrigation water needed per acre per year is 4000 m^3 (MWRI-allocated water), as are the NIWR and GIWR for the seven crop patterns. To determine the growth irrigation water requirements, irrigation efficiency for the proposed sprinkler system is assumed to be 70%. Figure 8 shows the net and growth irrigation water requirement for recommended crop patterns compared to allocated irrigation water provided by the MWRI for the different scenarios. The results show that crop pattern 1 (wheat or bearly in the winter season and sugar beet in the summer season) and crop pattern 2 (wheat or bearly in the winter season and potato in the summer season) satisfy the policies of the MWRI and climate change for sustainable water resource management.

5 Conclusions

In the context of climate change simulation models were utilized to calculate the ET_0 , net irrigation water requirement, and design a new sprinkler

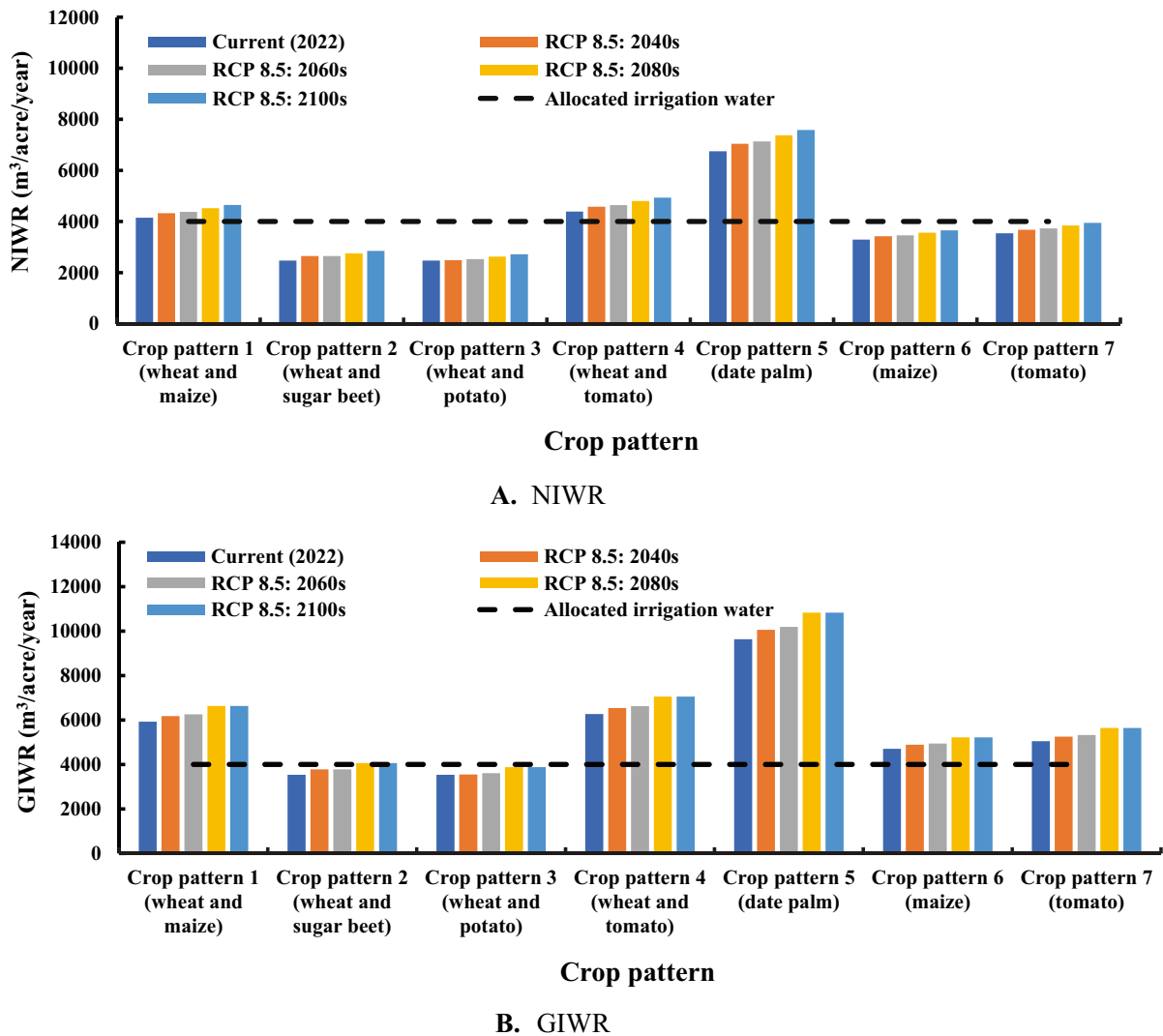


Fig. 8 A NIWR and B GIWR for recommended crop patterns compared to allocated irrigation water for the different scenarios

irrigation system for two arid sites (Siwa Oasis and West Elminya fields) inside the 1.5-million-acre reclamation project in the western desert of Egypt. CROPWAT 8 model was applied for the crops wheat, barley, maize, sugar beet, potato, tomato, and date palm. Five scenarios were used: the current (1991–2022) scenario, the representative concentration path (RCP) 8.5 greenhouse gas emission for the 2040s, 2060s, 2080s, and 2100s scenarios, which correspond to 1.6, 2.1, 3.3, and 4.4 °C expansion from the current baseline. In addition, the WaterGEMS model was utilized to run long-term simulations of hydraulic behavior within

pressurized pipe networks to irrigate 43 acres using deep groundwater wells. The findings indicate that the Siwa Oasis and West Elminya fields' ET_0 values for the current situation were 4.56 and 5.7 mm, respectively. For the Siwa Oasis field, the climate changes result in ET_0 increases of 4.6, 5.9, 9.4, and 12.7% for RCP: 8.5 greenhouse gas emissions for the 2040s, 2060s, 2080s, and 2100s scenarios, respectively. On the other hand, the West Elminya field's ET_0 ratio climbed by 4.2, 5.4, 8.6, and 11.6%, respectively. For the Siwa and West Elminya fields, the sprinkler system's intended capacity was 111.4 $m^3 h^{-1}$ and 167 $m^3 h^{-1}$, respectively. Furthermore,

rising temperatures in the studied regions led to increasing groundwater abstraction for irrigation purposes. Adopting sustainable methods and effectively managing resources becomes critical to ensuring the region's resilience and prosperity in the face of environmental difficulties. The study recommends using contemporary irrigation techniques and crop patterns for wheat, barley, potatoes, and sugar beet to conserve irrigation water. This study can be applied in a similar environment in the North Africa and Middle East regions for groundwater irrigation.

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Conflict of Interest The authors declare no competing inter-

Table 5 Sprinkler specifications and suggested spacing (Waller & Yitayew, 2016)

Sprinkler specifications				Sprinkler application rate (mm h^{-1})						
Nozzle size (mm)	Pressure (KPa)	Discharge ($\text{m}^3 \text{h}^{-1}$)	Wetted diameter (m)	Sprinkler spacing (m \times m)						
				9 \times 12	9 \times 15	12 \times 12	12 \times 15	12 \times 18	15 \times 15	18 \times 18
3.0	250	0.57	25.00	5.28	4.22	3.96				
3.0	300	0.63	25.60	5.83	4.67	4.38				
3.0	350	0.68	26.20	6.30	5.04	4.72				
3.5	250	0.75	26.85	6.94	5.56	5.21	4.17			
3.5	300	0.82	27.60	7.59	6.07	5.69	4.56			
3.5	350	0.89	28.35	8.24	6.59	6.18	4.94			
4.0	300	1.08	26.60		8.00	7.50	6.00	5.00	4.60	
4.0	350	1.16	30.50		8.59	8.06	6.44	5.37	5.16	
4.5	300	1.32	30.95			9.17	7.33	6.11	5.87	
4.5	350	1.42	32.00			9.86	7.89	6.57	6.31	
4.5	400	1.52	33.05			10.56	8.44	7.04	7.56	
5.0	300	1.7	33.00				9.44	7.87	8.18	5.25
5.0	350	1.84	34.30				10.22	8.52	8.18	5.68
5.0	400	1.96	35.60				10.89	9.07	8.71	6.05

Data Availability Data is available under a request from the corresponding author.

Declarations

Appendix

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