5-2021

Sustainable Agricultural Development in the Western Desert of Egypt Under Climate Change: A Case Study of the Siwa Region

Noha Hossam Moghazy
Utah State University

SUSTAINABLE AGRICULTURAL DEVELOPMENT IN THE WESTERN DESERT OF EGYPT UNDER CLIMATE CHANGE: A CASE STUDY OF THE SIWA REGION

by

Noha Hossam Moghazy

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

Approved:

Jagath J. Kaluarachchi, Ph.D. Major Professor	Mac McKee, Ph.D. Committee Member
Alaa El-Din Abdin, Ph.D. Committee Member	Richard Peralta, Ph.D. Committee Member
Arthur Caplan, Ph.D. Committee Member	D. Richard Cutler, Ph.D. Interim Vice Provost for Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2020

ABSTRACT

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Under Climate Change: A Case Study of the Siwa Region

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Noha Hossam Moghazy, Doctor of Philosophy

Utah State University, 2020

Major Professor: Dr. Jagath J. Kaluarachchi
Department: Civil and Environmental Engineering

Egypt is facing major challenges due to the increase in population, limited water resources, and insufficient agriculture production. To combat these stresses, the Egyptian government initiated a new development project in 2015 to reclaim 1.5 million acres mostly located in the Western Desert of Egypt. The goals of this project are to increase agricultural areas enabling rural development, population resettlement from dense regions, and increase strategic crop production. The primary source of water is the non-renewable Nubian Sandstone Aquifer System (NSAS) which is a transboundary aquifer shared between Egypt, Libya, Sudan, and Chad. NSAS in Egypt has two aquifers; the upper one is Post Nubian Aquifer (PNA) followed by Nubian Aquifer System (NAS). The Siwa region is one of the areas that will be reclaimed with an area of about 30,000 acres which is the focus of this research given the abundance of groundwater from NSAS. This research addressed the practical concerns of developing new and sustainable agriculture practices in Siwa under different climatic conditions. The first step is to assess the historical use of groundwater from the Nubian aquifer and the corresponding negative impacts from 1980 to 2012. Total water use is estimated then compared with the actual withdrawal to define the amount of excess water and water use efficiency. The impact of using high groundwater salinity from PNA on crop yield and revenue is analyzed. The second step is to investigate if government goals of the new project are achievable in Siwa for the next 20 years using high groundwater quality from NAS under current climatic conditions. Crop area and total water requirements for population and livestock are estimated by 2040. An optimization model is used to maximize crop production. The third step is to address the impact of climate change on agriculture productivity and crop water requirement in Siwa through this century. Regional climate models (RCMs) are used under two representative concentration pathways (RCPs); RCP 4.5 and RCP 8.5. Methodology provided in this research can be applied to similar regions in Egypt or elsewhere so management and adaptation options can be prepared for sustainable agricultural development.

(143 pages)

PUBLIC ABSTRACT

Sustainable Agricultural Development in the Western Desert of Egypt

Under Climate Change: A Case Study of the Siwa Region

Noha Hossam Moghazy

The Siwa region located in the Western Desert of Egypt is a natural depression and has a large volume of groundwater from the non-renewable Nubian Sandstone Aquifer System (NSAS). Recently the government initiated a development project to reclaim 1.5 million acres where most of the lands are located in the Western Desert to use available groundwater from NSAS. The primary goal of this project is to increase agricultural areas enabling rural development. Siwa is one of the areas that will be reclaimed in the desert by about 30,000 acres consisting of good soil quality. This dissertation aims to understand the historical groundwater use, its impact on the Siwa region, and ways to expand agricultural practices in the coming decades per government development initiative considering different climatic conditions. In this dissertation, three studies are addressed. The first one is to analyze and assess the historical use of the groundwater from NSAS and the corresponding impact on crop yield and revenue. The second study is to address the proposed development project in Siwa consisting of 30,000 acres under current climatic conditions and considering government policies in the next 20 years. In the third one, the effect of climate change on agricultural developments is studied. This research is a useful guide to analyze and assess the development potentials of other areas of the Western Desert under similar government policies considering different climatic conditions.

To my parents Hossam and Maryam,
my husband Mohamed,
and my lovely kids Ammar and Sofiya

ACKNOWLEDGMENTS

This Ph.D. thesis is the output of a challenging journey, upon which many people have contributed given their support. At the end of this journey, I am extremely grateful to all those people who made this thesis possible and an unforgettable experience for me.

I would like to express my deepest gratitude and sincere appreciation to my advisor Dr. Jagath Kaluarachchi for his continuous support in all stages of my Ph.D. journey, for his motivation and encouraging me all the time. His guidance has tremendously helped me develop a set of skills that will make me a better researcher. Special thanks to him for his patience with my slow progress during the sickness of my daughter.

Besides my advisor, I would like to thank my dissertation committee members: Dr. Mac McKee, Dr. Alaa El-Din Abdin, Dr. Richard Peralta, and Dr. Arthur Caplan for their insightful comments and valuable feedback. They all helped me and guided me through this Ph.D. journey. Many thanks to Dr. Alaa El-Din Abdin for providing me with the data needed about my study area.

I fully acknowledge the funding support from the Cultural Affairs and Missions Sector, Ministry of Higher Education, Egypt and Utah Water Research Laboratory, Utah State University. I am thankful for my colleagues Sonia Binte Murshed, Homin Kim, Hadia Akber, Ayman Alafifi and many others for their endless support.

My greatest appreciation and thanks to my family in Egypt; my father Dr. Hossam Moghazy for his endless support, encouragement, believing in me and providing me with needed data, and my mother for her prayers, support and love. Many thanks to my grandfather Mohamed Moghazy, my sister Nada and my brothers Ahmed and Kareem. Special thanks to my dear husband for his continuous love, encouragement, and endless support. Without the support of all of them, I could not have made it here. Many thanks and hugs to my kids Ammar and Sofiya for their patience and pure love.

Noha Hossam Moghazy

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The primary source of water in Egypt is the Nile River which provides 55.5 billion m^3 annually since the agreement between Egypt and Sudan in 1959 [1,2]. This amount represents 94% of all renewable water resources in Egypt [3]. Further, Egypt's population has experienced rapid growth; an increase of 66 million to 96 million between 2002 and 2018, respectively [4] with an average increase of 2.7% annually. The rapid increase in population has contributed to water stress by widening the gap between availability and demand. The total renewable water resources per capita in Egypt decreased to 570 m^3/year/capita in 2018 (https://www.egypttoday.com/Article/2/67788/Egypt-s-per-capita-share-of-pure-water-rises-by accessed in November 2018) from 1,000 m^3/year/capita in 1997 [5], heading towards serious water scarcity. Most strategic crops in Egypt are imported as food production is insufficient for population needs. In 2017, self-efficiency values of wheat, barley, broad bean, and maize were 34.5%, 86%, 30.7%, and 47%, respectively [6]. Therefore, for any socio-economic development in Egypt, water resources management is important to develop and protect these limited water resources [5].

Accordingly, the Egyptian government is constantly seeking ways to increase and better manage its water resources. In the early 1960s, the government commenced reclaiming the desert to increase agricultural production using groundwater from the non-renewable Nubian Sandstone Aquifer System (NSAS) which is a transboundary aquifer underlying Egypt, Libya, Sudan, and Chad. NSAS includes two aquifer systems; the most important is the Nubian Aquifer System (NAS) that has high water quality and underlies the highly saline Post Nubian Aquifer (PNA) [7]. Groundwater withdrawal was initiated at different locations in the Western Desert of Egypt including Siwa oasis which is the focus of this research because of its large volume of groundwater available for the future expansion of agricultural areas under proper management. Siwa has salty lakes that have formed due to the absence of a good drainage system, causing water logging problems [8,9].

In 2015, the Egyptian government initiated a new national project to reclaim 1.5 million acres where most of the lands are located in the Western Desert for new resettlements that will depend primarily on NSAS. The goals of this project are to increase agricultural areas, increase the production of strategic crops, decrease imported crops, population resettlement from the already over-populated Delta region, and increase investments and job opportunities. Due to the major expenses of this project, the project will be conducted in three phases with each phase consisting of 0.5 million acres. The Siwa region is planned to be in the second phase, to reclaim about 30,000 acres consisting of good soil quality and away from salty lakes and marshes. Ministry of Water Resources and Irrigation (MWRI) set restricted policies to avoid significant depletion of this non-renewable groundwater resource and to ensure the sustainability of this aquifer for future generations [10].

1.2 Research Objectives and Questions

The objective of this research is to address the practical concerns of developing new and sustainable agricultural practices in Siwa subject to available groundwater under current and future climatic conditions and considering government policies.

The research specific objectives and questions are given below:

1. Assessment of historical groundwater use efficiency from the Nubian aquifer and possible negative impacts on Siwa region.
    a. What is the estimated historical total water use in Siwa?
    b. What is the historical excess water due to unmanaged groundwater withdrawal from PNA?
    c. What is the correlation between areas of salty lakes in Siwa and the amount of excess water?
    d. How does groundwater salinity affect crop yield and revenue?
2. Assessment of strategies for sustainable agricultural development in Siwa in the next two decades under current climatic conditions and government policies.
    a. What is the available area for cultivation considering government policies and what are the appropriate crop types?
    b. What are the estimated crop area and total water requirements to satisfy population and livestock needs?
    c. Are government goals achievable?
    d. How to maximize agricultural production by 2040 from available land and groundwater?
    e. What is the expected future profit from the project and the corresponding uncertainty?
3. Study the possible impacts of climate change on agricultural development in Siwa during this century.

a. Which regional climate models (RCMs) are appropriate to project meteorological data for this century?

b. What are the projected values of reference evapotranspiration (ET_o) in years; 2020, 2040, 2060, 2080, and 2100?

c. Is there an impact of climate change on crop productivity and crop water requirement?

d. What are the crop areas and total water requirements that satisfy the population and livestock needs of this century?

e. Are the government goals achievable under potential climate change and if not, what are the possible recommendations to address deficits?

1.3 Dissertation Organization

This dissertation consists of five chapters. Chapter 2 assesses the efficiency of groundwater use from the Nubian aquifer and the corresponding impacts. This chapter also, discussed the changes in groundwater salinity, crop yields, and revenues to understand the potential linkage between these variables. Chapter 3 addresses the new development project in Siwa to reclaim 30,000 acres considering government policies in the next 20 years under current climatic conditions. This chapter also aims to explore other possible changes in the policies to further expand agriculture production, especially using groundwater available from NAS. Chapter 4 investigates the potential challenges faced in the presence of climate change and possible impacts on governmental goals in Siwa through this century. The impact of climate change on agriculture productivity and crop water requirement is considered under two representative concentration pathways (RCPs); RCP 4.5 and RCP 8.5. Finally, chapter 5 summarizes the results of the research and presents the recommendations and future works.

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CHAPTER 2

ASSESSMENT OF GROUNDWATER RESOURCES IN SIWA OASIS, WESTERN DESERT, EGYPT[1]

Abstract

One of the major challenges facing Egypt is limited water resources associated with rapid increase in population. In 1960s, Egyptian government started to use groundwater from the Nubian Sandstone Aquifer System (NSAS) in the Western Desert to expand agricultural sector. Siwa Oasis is the focus of this study to assess the efficiency of groundwater use and corresponding impacts from 1980 to 2012. Results show that from 1980 to 1998, withdrawal from poorly designed wells increased rapidly causing an increase in excess water about 336%. The increase of excess water with the usage of poor drainage produced lakes. Remote Sensing showed that in 2000, there were 21,348 acres of lakes with an increase of 89% since 1987 due to unmanaged withdrawal. After management intervention, excess water decreased about 94.7% from 1998 to 2012 causing a decrease in lakes area by 24%. Groundwater electrical conductivity (EC) increased from 4.5 to 10.5 ds/m in 1996 and 2013, respectively. Yields of olives and date palms decreased about 46% and 55%, respectively from 2000 to 2011 resulting in net revenue decrease of more than 60%. Results show that salinity has a strong negative correlation with yield and net revenue. Findings showed the importance of developing a meaningful groundwater resources management plan for Siwa region.

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2.1 Introduction

The primary source of water in Egypt is the Nile River which provides 55.5 billion m^3 annually since the agreement between Egypt and Sudan in 1959 [1,2]. This amount represents 94% of all renewable water resources in Egypt [3]. Egypt's climate is arid with an average annual rainfall of 18 mm [1]. Consequently, water resources are limited. Further, Egypt's population has experienced rapid growth; an increase of 66 million to 96 million between 2002 and 2018, respectively [4] with an average increase of 2.7% annually. The rapid increase in population has contributed to water stress by widening the gap between availability and demand. The total renewable water resources per capita decreased to 570 m^3/year/capita in 2018 (https://www.egypttoday.com/Article/2/67788/Egypt-s-per-capita-share-of-pure-water-rises-by accessed in November 2018) from 1000 m^3/year/capita in 1997 [5], indicating serious water scarcity. If this number decreases below 500 m^3/year/capita, inhabitants can face acute scarcity [6]. In essence, water resources management is important to develop and protect these limited water resources especially for sustainable socio-economic development in Egypt [5].

Although the Nile Valley and the Delta region cover about 5.5% of Egypt, this region contains 95% of the population. To satisfy the high food demand, the agricultural sector consumes about 80% of available water [2]. Therefore, the Egyptian government is constantly seeking ways to increase and better manage its water resources. For example, the government is reclaiming the desert using the groundwater to increase agricultural production and attract people from the already over-populated Delta region.

In the early 1960s, the government started to use groundwater from the non-renewable NSAS which is a transboundary aquifer occupying Egypt, Libya, Sudan, and

Chad as shown in Figure 2.1. It is one of the largest aquifers in the world with a total area of 2.2 million km^2 distributed as follows: 828,000 km^2 in Egypt (38%), 760,000 km^2 in Libya (34%), 376,000 km^2 in Sudan (17%), and 235,000 km^2 in Chad (11%) [7-9].

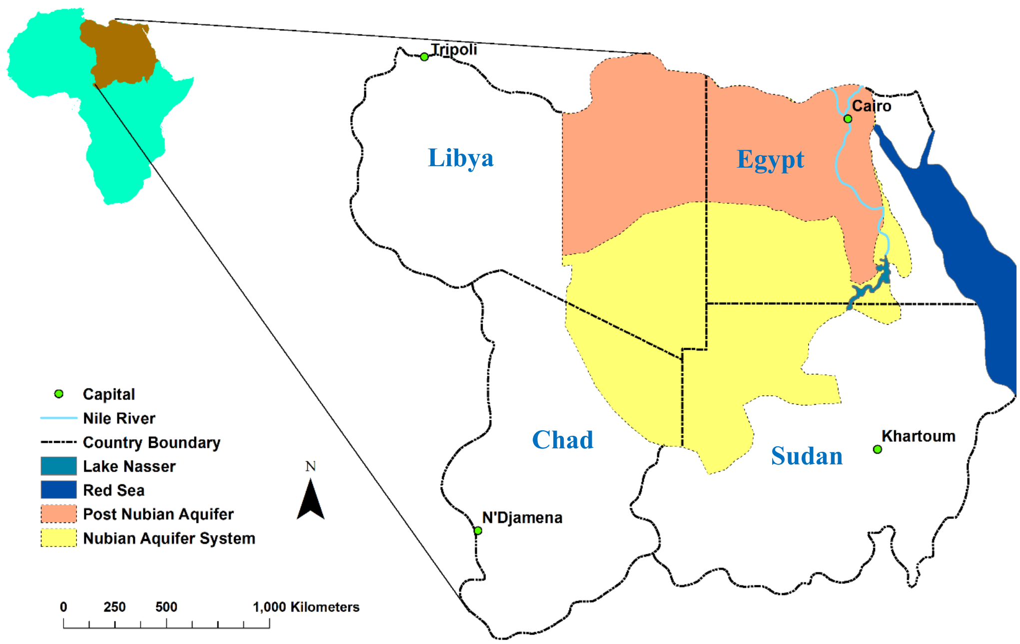


Figure 2.1 Distribution of NSAS transboundary aquifer between Egypt, Libya, Sudan, and Chad [8].

NSAS has two aquifers; the most important is the Nubian Aquifer System (NAS) which is located underneath the Post Nubian Aquifer (PNA) as shown in Figure 2.1. Low permeability layers are located between these two aquifers. PNA is an unconfined aquifer located only in the northern region of NSAS and is used by Egypt and Libya. NAS covers the whole area of NSAS and is used by all four countries. Although NAS is unconfined in the south of NSAS, it is confined in the northern region due to the presence of PNA. NSAS contains a large amount of groundwater amounting to about 475,753 km^3 assuming storativity values of the confined and unconfined aquifers to be 10^{-4} and $7x10^{-2}$, respectively. However, only a small portion of this volume can actually be developed due to deep depths to groundwater and the corresponding high pumping costs [9,10]. Bakhbakhi [9] calculated the total recoverable groundwater in each country assuming maximum water level declines in unconfined and confined aquifers are 100 m and 200 m, respectively. The result found that the total recoverable groundwater in Egypt to be 5,367 km^3 and the extraction at that time was only 0.506 km^3/year, indicating the availability of a large volume of unused water.

NSAS occupies almost all of Egypt. However, the largest volume of available groundwater is within the Western Desert region which covers approximately two-thirds of Egypt [8,1]. The use of NSAS in the Western Desert region started in 1960 in an effort to increase agricultural production. Groundwater withdrawal was initiated at five locations; Kharga, Dakhla, Farafra, Bahariya, and Siwa Oases, as shown in Figure 2.2, for both agricultural and domestic uses. In 1990, a new agricultural area was developed using groundwater from East Oweinat [7,8].

Siwa received great attention in previous studies given the abundance of groundwater that can be used for future development. It has salty lakes that had been formed due to the absence of good drainage [11,10]. Abou El-Magd [12] showed that lakes areas are increasing which were; 12,409, 14,702, and 18,414 acres in years 1986, 1992, and 2000 respectively. Abdallah and Khedr [13] used Remote Sensing (RS) and Geographic Information System (GIS) to estimate these areas and found total lakes area decreased to 11,476 in 2010.

Monitoring water and soil salinity is important because plants have difficulty absorbing and extracting water under high soil salinity. Two indicators can be used to evaluate salinity; total dissolved solids (TDS, ppm) and electrical conductivity (EC, ds/m).

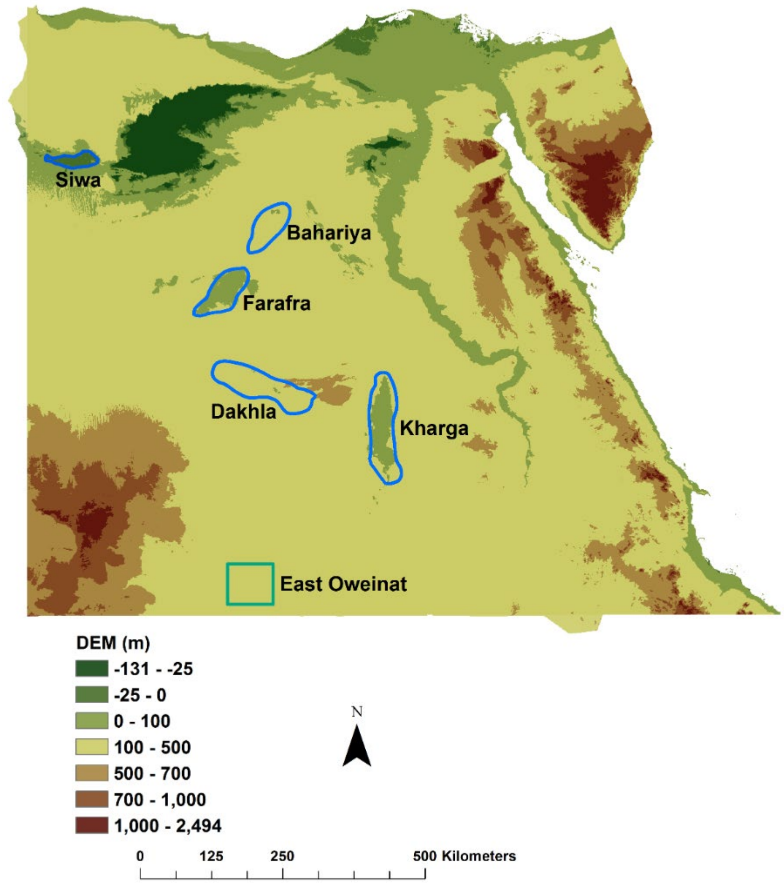


Figure 2.2 Locations of groundwater withdrawal in the Western Desert, Egypt [8].

A conversion factor of 650 is used to transfer salinity units from ppm to ds/m [14]. According to World Health Organization [15] and Egyptian Higher Committee for Water [16], maximum acceptable TDS for drinking water is 1,000 ppm (1.54 ds/m) and 1,200 ppm (1.85 ds/m), respectively. Acceptable groundwater for irrigation and soil salinity levels are developed by US Salinity Laboratory [17] and given in Table 2.1.

Aly et al. [18] monitored groundwater quality from PNA by measuring EC of 44 wells in Siwa from 1998 to 2008. The results are shown in Table 2.2 indicating from 1998 to 2008, groundwater salinity increased in the entire Siwa region from 5.7 to 7.8 ds/m, respectively with highest values in Zeitoun area. Abo El-Fadl et al. [19] collected 24

Table 2.1 Soil and water irrigation classification developed by US Salinity Laboratory [17].

Soil EC (ds/m)	Soil classification	Water EC (ds/m)	Water classification
0 - 2	Non-saline	0 - 0.25	Low salinity
2 - 4	Low salinity	0.25 - 0.75	Medium salinity
4 - 8	Mild salinity	0.75 - 2.25	High salinity
8 - 16	High salinity	> 2.25	Very high salinity
> 16	Severe salinity		

Table 2.2 Groundwater salinity in different locations of Siwa [18].

Location	EC (ds/m)	
	1998	2008
North and middle of Siwa	3.92	5.2
Western Siwa	4.09	5.6
Maraqi area	6.54	9.51
Zeitoun area	8.1	10.7
Mean	5.7	7.8

groundwater samples from different shallow and deep wells in 2014 and showed that TDS from shallow wells range from 1,794 to 7,473 ppm (2.8 to 11.5 ds/m). The highest values were found in Siwa, Aghurmi, and Zeitoun lakes. TDS from deep wells ranged from 169 to 325 ppm (0.26 to 0.5 ds/m). Aly [20] measured soil salinity in 2011 from 10 different locations in Siwa and the EC values range from 4.7 to 12.3 ds/m with the highest values were found around Aghurmi Lake, and the western region of Siwa Lake.

Although groundwater withdrawal from NSAS comes from six major locations, Siwa is the focus of this study because of its large volume of groundwater available for the future expansion of the agricultural area under proper management. Several studies analyzed groundwater withdrawal in Siwa [8,21] and others monitored the changes in lakes area [12,13]. However, none of the studies focused on the efficiency of groundwater use and the long-term management affecting salt lakes formation. Others have monitored groundwater and soil quality [18,19,20,22], but, the effects of salinity on agriculture productivity or income have not been studied as well.

Therefore, the primary purpose of this research is to assess the efficiency of groundwater use from the Nubian aquifer and the corresponding negative impacts on crop yields and income.

2.2 Study Area Description

Siwa is a region with a natural depression located in the Matrouh Governorate, northwest of the Western Desert (see Figure 2.2). It has an area of 1,200 km^2 (or 285,714 acres) with an elevation ranging from 0 to -25 m above mean sea level. It is located between longitudes 25° 16' and 26° 7' E and latitudes 29° 7' and 29° 21' N. Climate in this region is arid to semi-arid with monthly average maximum and minimum temperatures of 39.6°C in August and 7°C in January, respectively. Monthly average maximum and minimum relative humidity are 60% in December and 29% in May, respectively. Average annual rainfall is 13 mm and evaporation ranges from 5.2 mm/day in December to 17 mm/day in June [10,22].

RS and GIS were used in Siwa to define land uses in 2006. A Landsat Enhanced Thematic Mapper Plus (ETM+) image was downloaded from the United States Geological Survey (USGS), and Supervised Classification was used by GIS. Figure 2.3 shows the land use of Siwa which includes six saline lakes; Maraqi, Siwa, Aghurmi, Zeitoun, Tamera, and Massir. Around these lakes, there are wet and dry marshes which cover 40% of Siwa's land area, whereas cultivated areas only cover about 6%.

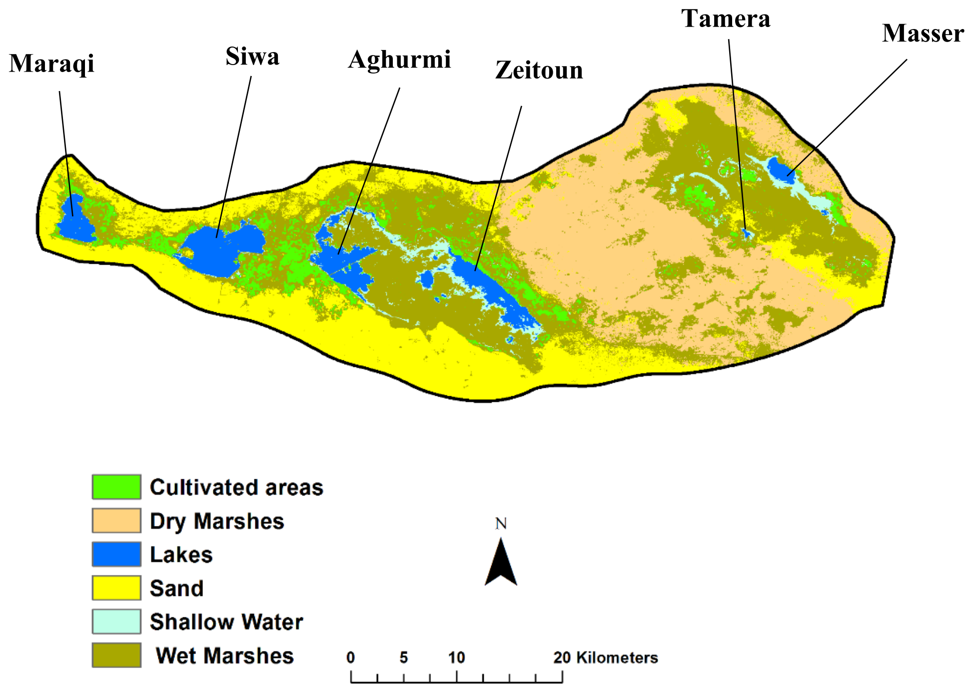


Figure 2.3 Land use of Siwa in 2006.

The region's primary economic activity is agriculture, which in turn depends on NSAS. The two major cash crops are olives and date palms, whereas the other crops are for local consumption. Groundwater is the only source of water in Siwa. PNA has high salinity ranging from less than 4.62 to 10.8 ds/m that can be used for irrigation with restrictions but not for domestic use. However, NAS contains high-quality groundwater with a lower salinity of 0.31 to 0.62 ds/m that can be used for all purposes [19,21].

2.2.1 Historical Use of the Nubian Aquifer

Siwa is a unique oasis given the natural depression and groundwater is under pressure. Groundwater pressure in PNA ranges from 0 to 10 m above mean sea level. However, in NAS groundwater pressure ranges from 80 m in the west of Siwa to 120 m in the east [23,21]. From 1960 to 1980, the only source of water was 200 flowing springs with a total discharge of 65.9 MCM/year which was used to irrigate 2,000 acres [7,8,21].

Groundwater from these springs is recharged from PNA. In the period from 1962 to 1977, the water table increased about 1.33 cm/year [24]. Since the discharges from these springs started to decrease in 1981, farmers built about 700 wells (±100 m) which freely discharge from PNA [7]. These hand-dug wells were poorly designed and operated without proper management. When the discharge from a well decreases, farmers tend to build a new well without government approval. In 1990, the total discharge from PNA was 235 MCM from 1350 shallow wells [7,21]. From 1977 to 1990 the water table increased about 4.6 cm/year [24]. In 1991, the government developed five deep wells of ±1,000 m depth for drinking purposes with an annual discharge of about 20 MCM using high water quality of NAS. By the end of 1998, there were 1500 shallow wells and the total annual discharge from both aquifers reached 308 MCM [7].

Starting in 1996, Research Institute for Groundwater (RIGW) monitored the wells used for groundwater withdrawal. They found that only 60% of groundwater withdrawal was used for irrigation and the rest found its way through the existing poor drainage system [21]. RIGW later developed new regulations on withdrawal from the Nubian aquifer. More than 300 shallow wells were closed and replaced with 180 legal wells [21]. In 2006, the total annual groundwater withdrawal reached 275 MCM [25] and continued to decrease to 172 MCM in 2012 [26].

2.3 Methodology

2.3.1 Water Use

The total water use in Siwa was estimated from 1980 to 2012. Total water use is the sum of irrigation water requirement (IWR), and domestic and industrial water uses. Industrial water demand is insignificant compared to crop water demand [27]. Therefore, it can be ignored and only IWR and domestic water use are considered.

Evapotranspiration (ET) was calculated to determine crop water demand. The FAO Penman-Monteith method was used to calculate reference evapotranspiration (ET_o) on a monthly basis [28]. The FAO Penman-Monteith equation is given as:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \quad (1)$$

where ET_o is monthly reference evapotranspiration (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean monthly air temperature at 2 m height (°C), u_2 is monthly average wind speed at 2 m height (m/sec), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is slope vapor pressure curve (kPa $°C^{-1}$), and γ is the psychrometric constant (kPa $°C^{-1}$).

$$G_{month,i} = 0.14(T_{month,i} - T_{month,i-1}) \quad (2)$$

where $T_{month,i}$ is mean air temperature of month i (°C), and $T_{month,i-1}$ is mean air temperature of the previous month (°C).

$$R_n = R_{ns} - R_{nl} \quad (3)$$

where R_{ns} is incoming net shortwave radiation (MJ m^{-2} day^{-1}), and R_{nl} is outgoing net longwave radiation (MJ m^{-2} day^{-1}).

$$R_{ns} = (1 - \alpha)\,R_s \quad (4)$$

where α is albedo (0.23), and R_s is incoming solar radiation (MJ m^{-2} day^{-1}).

$$R_{nl} = \sigma \left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2}\right] \left(0.34 - 0.14\sqrt{e_a}\right) \left(1.35\frac{R_s}{R_{so}}\right) \quad (5)$$

where σ is Stefan-Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}), $T_{max,K}$ is maximum absolute temperature in K, $T_{min,K}$ is minimum absolute temperature in K, and R_{so} is clear-sky radiation (MJ m^{-2} day^{-1}).

$$R_s = k_{Rs} \sqrt{(T_{max} - T_{min})}\ R_a \qquad (6)$$

where k_{Rs} is adjusted coefficient (0.16 °C$^{-0.5}$ for interior locations), T_{max} is maximum air temperature (°C), T_{min} is minimum air temperature (°C), and R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}).

$$R_{so} = (0.75 + 2*10^{-5}\ z)\ R_a \qquad (7)$$

where z is the elevation above sea level (m).

$$R_a = \frac{24\ (60)}{\pi} G_{sc}\ d_r\ [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad (8)$$

where G_{sc} is solar constant (0.0820 MJ m^{-2} min^{-1}), d_r is the inverse relative distance Earth-sun (dimensionless), ω_s is sunset hour angle (rad), φ is the latitude (rad), and δ is the solar declination (rad).

$$\omega_s = \arccos\ [-\tan(\varphi) \tan\ (\delta)] \qquad (9)$$

$$d_r = 1 + 0.033 \cos\ (\frac{2\ \pi}{365} J) \qquad (10)$$

$$\delta = 0.409 \sin\ (\frac{2\ \pi}{365} J - 1.39) \qquad (11)$$

where J is the number of the day in the year.

To calculate monthly ET_o, four meteorological data types are required; maximum temperature, minimum temperature, wind speed, and relative humidity. The available monthly data relevant to Siwa from 1980 to 2012 were downloaded from the National Centers for Environmental Prediction (https://globalweather.tamu.edu/).

Crop evapotranspiration ET_c (mm/day) represents crop water demand where monthly ET_c was calculated as [28]:

$$ET_c = K_c * ET_o \qquad (12)$$

where K_c is the crop coefficient (dimensionless).

Crop coefficient values should be used under standard climatic conditions with a minimum relative humidity of 45% and moderate wind speed with an average of 2 m/sec. If the actual climatic conditions differ from standard conditions, then crop factor values should be adjusted as described by Allen et al. [28].

Annual ET_c is computed as:

$$ET_c = \sum(K_c * ET_o) \tag{13}$$

After crop water demand was calculated, crop water requirement was estimated as follows [29]:

$$CWR = \frac{ET_c - R}{(1-LR)*E} * 4.2 \tag{14}$$

where CWR is crop water requirement (m^3/acre/day), R is effective rainfall (mm/day) which is almost negligible in Siwa [22], LR is leaching requirement, E is irrigation efficiency, and 4.2 is a conversion factor from mm/day to m^3/acre/day. Furrow irrigation is the domain irrigation system in Siwa [21]. The corresponding efficiency is 65% [30,31]. Elnashar [32] provided values of LR for crops in Egypt under different irrigation water salinity conditions and accumulated salts in soils. Due to the use of high groundwater salinity from PNA, we found that 20% is a good estimate as recommended by Abdrabbo et al. [33].

To estimate the total water use since 1980, data on crop types, areas, and population are needed. Crop areas from the years 2000 to 2011 are shown in Table 2.3 [27] where olives, date palms, and alfalfa are occupying the largest areas. The cultivated area was only 2,000 acres in 1980 and thereafter, increased to 10,000, 14,802, and 17,182 acres in 1995, 2000, and 2011, respectively [7,27].

Table 2.3 Areas of cultivated crops (in acres) in Siwa [27].

Year	Winter Vegetables	Summer Vegetables	Wheat	Barley	Broad Bean	Winter Onion	Alfalfa	Olive	Date Palm	Other	Total
2000	67	59	77	41	6	29	1,450	7,619	5,250	204	14,802
2001	47	93	15	50	6	10	1,450	7,646	5,250	209	14,776
2002	43	47	50	0	6	10	1,300	7,650	5,000	283	14,389
2003	43	72	30	0	5	12	1,300	7,650	5,000	156	14,268
2004	35	61	58	150	5	32	1,300	7,700	5,642	232	15,215
2005	67	62	140	0	5	32	2,000	7,700	5,642	232	15,880
2006	68	87	150	0	6	35	2,848	7,750	5,642	234	16,820
2007	32	110	70	40	0	0	2,830	8,000	5,800	233	17,115
2008	66	238	150	35	0	60	2,850	8,000	5,800	234	17,433
2009	39	90	200	20	0	0	2,850	8,000	5,800	234	17,233
2010	30	91	175	0	0	32	2,800	8,000	5,800	233	17,161
2011	59	79	200	0	0	0	2,800	8,000	5,800	244	17,182

As a consequence of missing data, the following assumptions were made; (a) before 2000, only three crops were cultivated; olives, date palms, and alfalfa with areas distributed at 53%, 37% and 10%, respectively, (b) cultivated areas gradually increased from 1980 to1995 and from 1995 to 2000, and (c) crop area distributions are the same in 2011 and 2012.

Table 2.3 provides the guide for assumption (a) to use the same crop pattern for olives, date palms, and alfalfa. Additionally, these three crops have been cultivated over larger areas compared with other crops. Assumption (b), regarding the gradual increase in agricultural areas, was made because groundwater withdrawal has been increasing since 1980. Assumptions (c) was made due to the unknown crops area distributions in 2012. Eq. (14) was used to calculate CWR, thereafter, annual IWR from 1980 to 2012 can be estimated which is the summation of water requirement of each crop multiplied by the area of each crop.

Population in Siwa increased from 7,200 in 1976 [34] to 26,610 in 2009 [27]. In 2016, population reached 32,741 (https://en.wikipedia.org/wiki/Siwa_Oasis accessed in June 2019). Average domestic water use is assumed to be 70 and 100 m^3/capita/year before and after 2000, respectively [1,3]. Therefore, annual domestic water use was calculated from 1980 to 2012.

2.3.2 Water Use Efficiency (WUE)

A rapid increase in population with limited water resources increases the risk of water scarcity. Therefore, improving WUE is vital, particularly in arid and semi-arid regions. Unfortunately, WUE has different definitions in literature. For example, Sinclair et al. [35] defined WUE as the ratio between crop yield to crop water use. Ali and Talukder [36] defined WUE as the amount of water used to produce a crop. Meanwhile, FAO [37] has a different definition, where WUE is the ratio between effective water use and actual water withdrawal. Given that the focus of this study is making comparisons between actual withdrawal in Siwa and the estimated water use, the FAO [37] definition was used.

2.3.3 Lake Areas

The changes in the areas of all Siwa lakes were monitored from 1987 to 2010 to study the effect of groundwater management on lakes areas. Due to the lack of field data, RS and GIS are used. There are different indices that extract water bodies using RS such as Normalized Difference Water Index [NDWI; 38], Modified Normalized Difference Water Index [MNDWI; 39], and Automated Water Extraction Index [AWEI; 40]. NDWI was calculated as [38]:

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \quad (15)$$

where Green is a green band and NIR is a near-infrared band which represent bands 2 and 4 respectively, in Landsat Thematic Mapper (TM). Positive values represent water bodies while zero and negative values represent vegetation and soil [38]. Satellite images from Landsat TM are used for years; 1987, 1993, 2000, 2005, and 2010. These images are with spatial resolution of 30 m and can be downloaded using USGS Global Visualization Viewer (GLOVIS) (https://glovis.usgs.gov/ accessed in May 2019).

2.3.4 Groundwater and Soil Salinity

The changes in groundwater and soil salinity in Siwa were analyzed. As PNA is commonly used for irrigation while it has high groundwater salinity. Groundwater salinity data about PNA are provided by RIGW. In 1996 more than 1200 groundwater samples were collected from different shallow wells to monitor groundwater quality [41]. Again in 2013, RIGW collected groundwater samples from 42 wells [21]. Due to the limited field data available on soil salinity, data and results from Aly [20] are also used.

2.3.5 Crop Yield

World Bank et al. [42] stated that calculating crop yield is one of the essential indicators of agricultural development. Crop yield is the amount of crop production harvested per unit of land area (tons/acre). Since olives and date palms have the largest crop areas in the region while being the cash crops, yields of these crops were calculated from 2000 to 2011. Data about production and area of these crops were collected from the Agriculture Directorate of Matrouh [43].

High groundwater and soil salinity may affect crop yield, especially for crops with lower tolerance to salinity. Maas and Hoffman [44], and Ayers and Westcot [45] provided tolerance values of crops, with regards to water and soil salinity as shown in Table 2.4. This table is used to study the effect of salinity on crop yields.

Table 2.4 Crop tolerance related to water and soil salinity [44,45].

Crop	EC (ds/m)	Maximum yield	Yield reduction by 10%	Yield reduction by 25%	Yield reduction by 50%	Can't be cultivated
Olives	Water	1.8	2.6	3.7	5.6	11
	Soil	2.7	3.8	5.5	8.4	14
Date Palms	Water	2.7	4.5	7.3	12	21
	Soil	4	6.8	11	18	32

2.3.6 Net Revenue

To understand the impact of high salinity on crop yield and therefore on the local economy, it is important to calculate net revenue. Net revenue is calculated as follows:

$$\text{Net revenue} = (\text{Price} * \text{Yield}) - \text{Cost} \qquad (16)$$

where units of net revenue and cost are in \$/acre, price in \$/ton, and yield in tons/acre. Through the period from 2000 to 2011, the average price of olives and date palms are \$569 and \$711 per ton, respectively [27] and the average cost per acre for both is \$747 [46] in 2010 dollars. This cost included labor, seeding, irrigation, pesticides, fertilizers, and maintenance.

2.3.7 Trend and Correlation Tests

Many statistical tests have been developed to detect the trends of variables over time. Linear regression is a parametric test that assumes a normal distribution of data.

However, Mann-Kendall [47,48] and Spearman's Rho [49,50] are non-parametric tests that applicable independent of existing distributions of the variables. In this study, Mann-Kendall and Spearman's Rho are applied to investigate the changes of groundwater salinity, yields of olives and date palms and their net revenue over time from 2000 to 2011. The null hypothesis (H_0) is that there is no trend over time, while the alternative hypothesis (H_1) is that there is a positive or negative trend. Correlation tests are used to measure the strength of relation between variables. Results are considered significant when two-sided p-value < 0.025. R software version 3.6.1 has been used for these tests (https://www.r-project.org/).

As groundwater salinity data is few and limited, the observed average salinity in 1996 and 2013 and the data from Aly et al. [18] in 1998 and 2008 are used in this analysis. Accordingly, EC values are assumed gradually increased during each period.

2.4 Results and Discussion

2.4.1 Water Use Efficiency

One goal of this work is to calculate water use efficiency in Siwa. Therefore, total water use is estimated, which is the sum of IWR and domestic water use. Monthly average ET_o in Siwa from 1980 to 2012 was calculated using Eq. (1). The results showed that maximum ET_o is 9.8 mm/day in June and the minimum is 2.7 mm/day in January. Figure 2.4 shows a comparison between the calculated monthly average ET_o values and the estimated values by Farrag et al. [51]. The results show that there are slight differences between both results which range from -0.47 to 0.76 mm/day with a mean value of 0.126 mm/day and standard deviation of 0.4 mm/day.

To calculate crop water demand, ET_c was calculated using Eq. (13). Average water

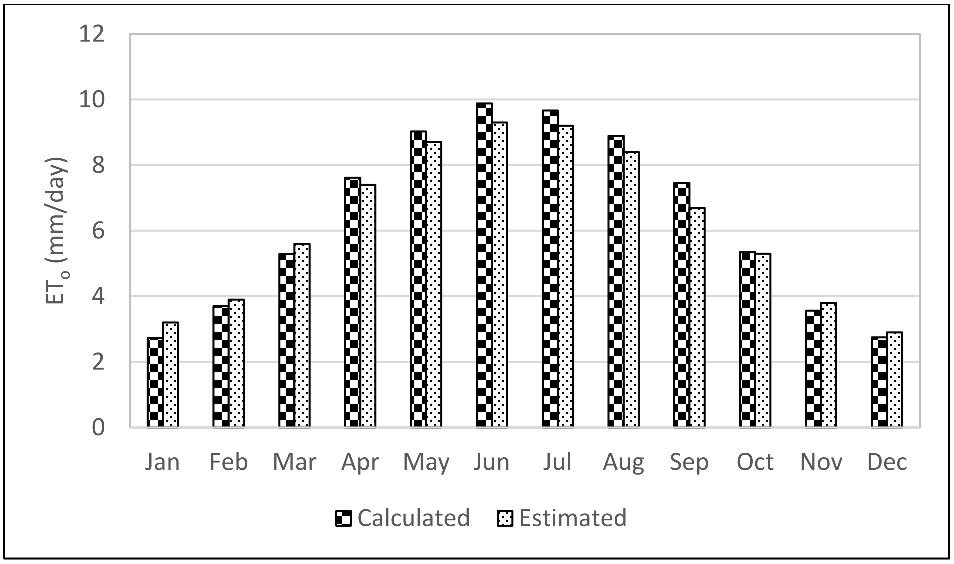


Figure 2.4 Comparison between calculated monthly average ET_o from 1980 to 2012 and estimated values by Farrag et al. [51].

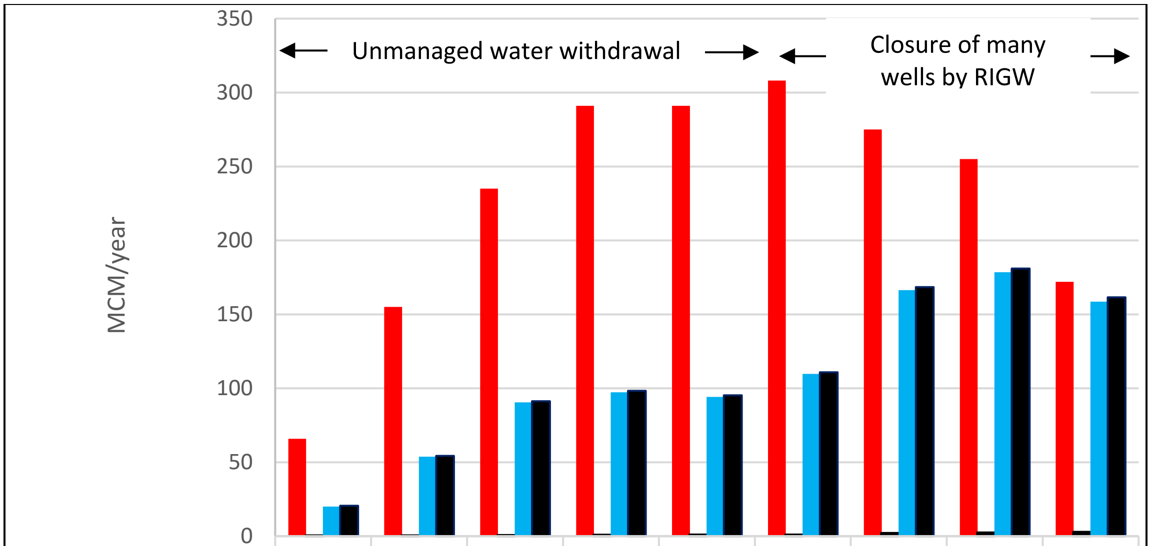
demands of cultivated crops were calculated for the period of 2000 to 2012 and compared with published literature as shown in Table 2.5. The comparison shows that water demand values are within the acceptable ranges.

IWR and domestic water use were calculated from 1980 to 2012. A comparison between estimated total water use and actual withdrawal in Siwa is shown in Figure 2.5.

Table 2.5 Comparison between calculated and estimated crop water demand.

Crop	Calculated crop water demand (2000-2012) (m^3/acre)	Estimated crop water demand (m^3/acre)
Wheat	2,142	1,890-2,730[1]
Barley	1,919	1,890[2]
Broad bean	1,839	1,260-2,100[1]
Onion	1,979	1,470-2,310[1]
Alfalfa	5,443	3,360-6,720[1]
Date palms	6,595	7,000[2]

[1](http://www.fao.org/land-water/databases-and-software/crop-information/en/ accessed in April 2019)
[2][46]



	1980	1985	1990	1995	1997	1998	2006	2008	2012
Actual Withdrawal	65.9[1]	155 [1]	235[1]	291[1]	291[1]	308[1]	275 [2]	255 [3]	172 [4]
Domestic Use	0.5	0.55	0.8	1.0	1.1	1.1	2.1	2.5	2.9
IWR	20.0	53.8	90.5	97.3	94.1	109.7	166.3	178.5	158.6
Total Water Use	20.5	54.3	91.2	98.2	95.2	110.9	168.5	181.0	161.5

Figure 2.5 Comparison between actual withdrawal and estimated total water use in Siwa.
[1][8]
[2][25]
[3][52]
[4][26]

It is clear that total water use is gradually increasing since 1980 due to the increase in population and cultivated areas. However, actual groundwater withdrawal has been increasing rapidly given the readily available groundwater present under pressure in shallow wells. The difference between actual withdrawal and estimated total water use is excess water and can be defined as wasted water. In the absence of an appropriate groundwater management plan, these excess water amounts were significant until 1998.

Table 2.6 shows the values of excess water and WUE. Excess water volume increased about 336% over 19 years (1980-1998). In this period WUE was low with an average of 35% due to the large volume of groundwater from uncontrolled shallow wells. After the closure of many wells by RIGW, this excess water volume decreased by about

94.7% from 1998 to 2012. The corresponding WUE increased gradually; 61%, 71%, and 94% in 2006, 2008, and 2012, respectively showing the importance of groundwater management to avoid the depletion of NSAS and to ensure sustainability for future generations.

Table 2.6 Excess water produced and WUE.

Year	1980	1985	1990	1995	1997	1998	2006	2008	2012
Excess water (MCM)	45.3	100.7	143.8	192.8	195.8	197.3	106.5	74	10.5
Water use efficiency %	31	35	39	34	33	36	61	71	94

2.4.2 Lake Areas

NDWI was used to estimate lake areas in Siwa through 1987 to 2010. The results showed that lake area was 11,295 acres in 1987 then continued to increase to 13,096 and 21,348 acres in 1993 and 2000, respectively. Thereafter, this area decreased to 16,852 acres in 2005. In 2010, lake area was 16,144 acres. These findings are similar to the work of Abou El-Magd [12], and Abdallah, and Khedr [13]. In the period from 1987 to 2010, the minimum and maximum areas of lakes were in 1987 and 2000, respectively. Figure 2.6 clearly shows that in 2000, there is a significant increase in the areas of lakes; Maraqi, Siwa, and Aghurmi.

Figure 2.7 shows the relationship between groundwater withdrawal and lake areas. These results show that from 1980 to 1990, groundwater withdrawal increased about 257%. As a consequence, lake areas covered 11,295 acres in 1987. From 1990 to 1995, groundwater withdrawal continued to increase by about 24%. This continuous withdrawal

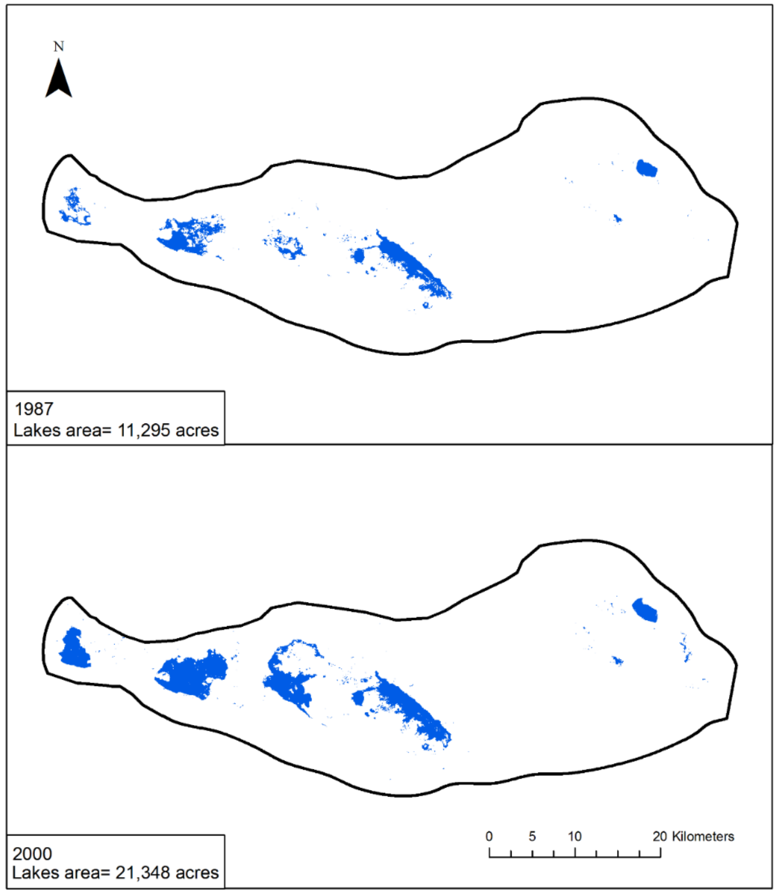


Figure 2.6 A comparison of salty lake areas between 1987 and 2000.

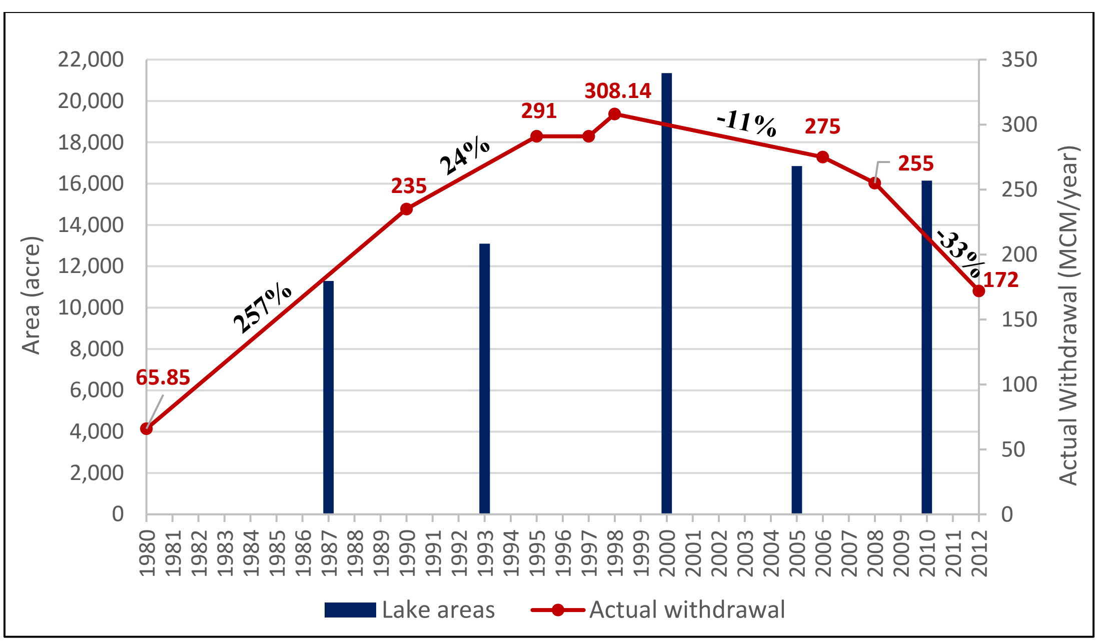


Figure 2.7 Relationship between groundwater withdrawal and lake areas (numbers in percentage are the changes in withdrawal through different periods).

without proper management increased lakes area by about 89% over fourteen years (1987-2000). After the closure of hand-dug wells, groundwater withdrawal decreased by about 11% (1998-2006). The replacement of old dug-wells with newly designed wells with proper management by the government, decreased groundwater withdrawal by about 33% from 2008 to 2012. As a consequence, lake area decreased by 24% over 10 years (2000-2010).

Comparing these two situations before and after 1998 confirms that there is a direct relationship between groundwater withdrawal and lake areas. As a large volume of unused excess water is accumulated in addition to an existing poor drainage system produced salty lakes causing waterlogging in Siwa. This shows the necessity of proper groundwater management. As good management practices help formulate effective and productive groundwater withdrawal, excess water production is decreased and as a consequence lakes areas have decreased. It is also important to improve the drainage system in Siwa to help reducing lakes areas further.

2.4.3 Groundwater and Soil Salinity

EC data from RIGW is used to analyze the changes in groundwater salinity in 1996 and 2013. The results show that groundwater EC values in Siwa increased from 1996 to 2013 with an average of 4.5 and 10.5 ds/m, respectively. According to US Salinity Laboratory [17] information shown in Table 2.1, groundwater is classified as *very high salinity* with an increase of 100% to 366% above the acceptable ranges in 1996 and 2013, respectively indicating severe restrictions using water for irrigation. In such instances, more water is required for leaching in addition to the choice of crops that can tolerate high salinity.

Figure 2.8 shows a comparison between groundwater salinity distribution in 1996 and 2013 in Siwa using inverse distance weighted interpolation. The results in Table 2.7 show that the Zeitoun area has the highest EC in 1996. However, in 2013, Aghurmi area and the western part of Siwa lake have the highest EC values. These results are in agreement with the findings of Aly et al. [18] who found that EC values in PNA increased from 1998 to 2008 as listed in Table 2.2. The increase in groundwater salinity is due to the excess usage of groundwater from PNA for irrigation in addition to the existence of poor drainage in the region.

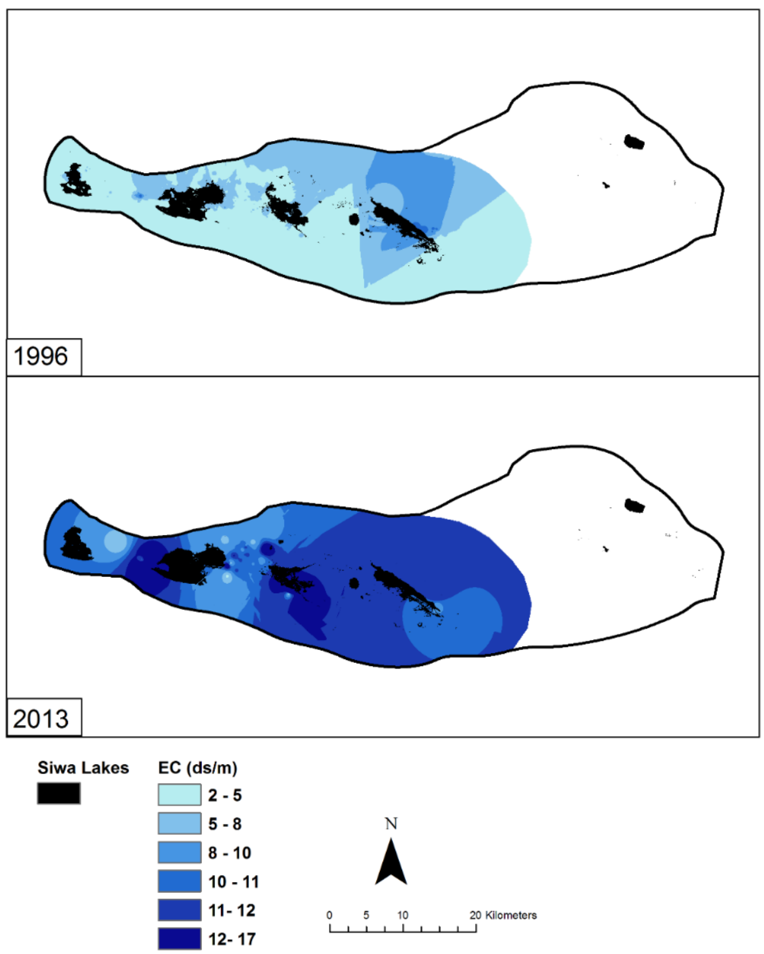


Figure 2.8 Comparison between groundwater salinity distribution in 1996 and 2013.

Table 2.7 Comparison between groundwater salinity in 1996 and 2013.

Location	EC (ds/m)	
	1996	2013
Maraqi area	2 - 5	8 -11
Siwa area	2 - 8	8 -17
Aghurmi area	2 - 8	12 -17
Zeitoun area	5 - 10	10 -12

The results from Aly [20] found that soil EC values of 4.7 to 12.3 ds/m in 2011. Using the soil classifications of Richards [17] shown in Table 2.1, mild (4 < EC < 8) to high (8 < EC < 16) soil salinity affects yields of many of crops. This finding is not surprising in existing salty lakes in Siwa given the accumulation of salts on the surface.

2.4.4 Crop Yield and Revenue Impact

Yields of olives and date palms are calculated from 2000 to 2011. Figure 2.9 shows that in 2000, the yield of olives was 4 tons/acre but decreased to 2.2 tons/acre in 2011, amounting to a 46% decrease. The same occurred with date palms, where the yield decreased from 10 tons/acre in 2000 to 4.5 tons/acre in 2011 with 55% decrease. The average yield of olives and date palms from 2000 to 2011 were 2.9 and 8.4 tons/acre, respectively (Figure 2.9), while the corresponding average values in Egypt were 3.63 and 14.6 tons/acre, respectively [53]. The comparison showed that in Siwa, there were a decrease of 20% and 42% in yields of olives and date palms, respectively. Therefore, it is important to analyze the factors causing this decrease in yields and the corresponding revenue impacts.

Figure 2.10 shows net revenues for olives and date palms from 2000 to 2011. Net revenue for olives changed from $1,564/acre in 2000 to $491/acre in 2011 with a decrease of 68%. Similarly, net revenue for date palms decreased from $6,418/acre in 2000 to $2,426/acre in 2011, with 62% decrease. This decrease in net revenue affects farmer income, and therefore, the local economy. For a region with limited economic activity, this type of decrease in agricultural income can be a devastating for the local population.

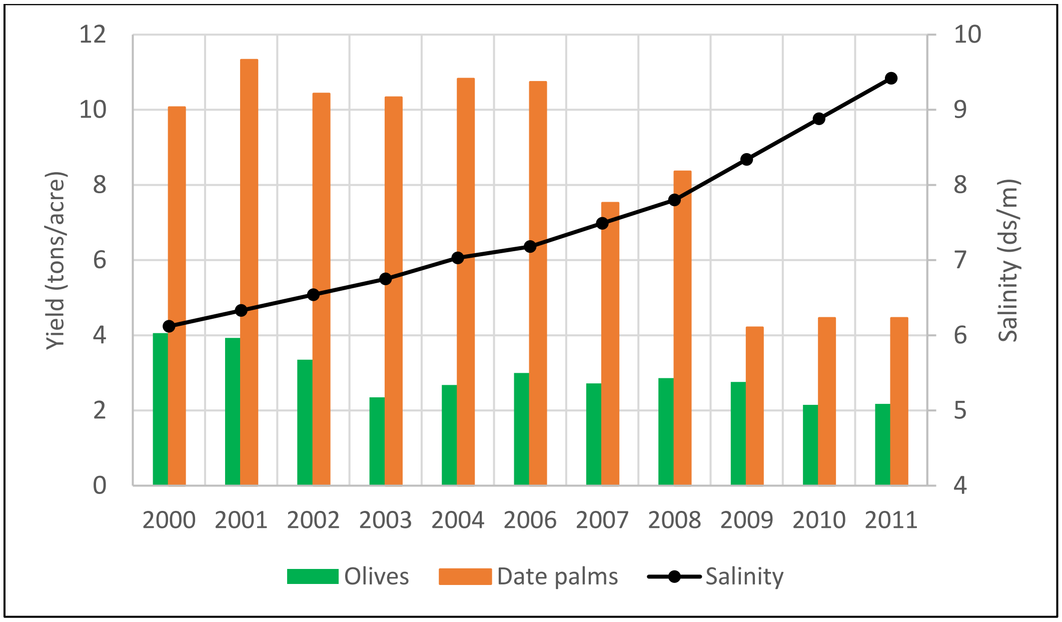


Figure 2.9 Groundwater salinity and yields of olives and date palms.

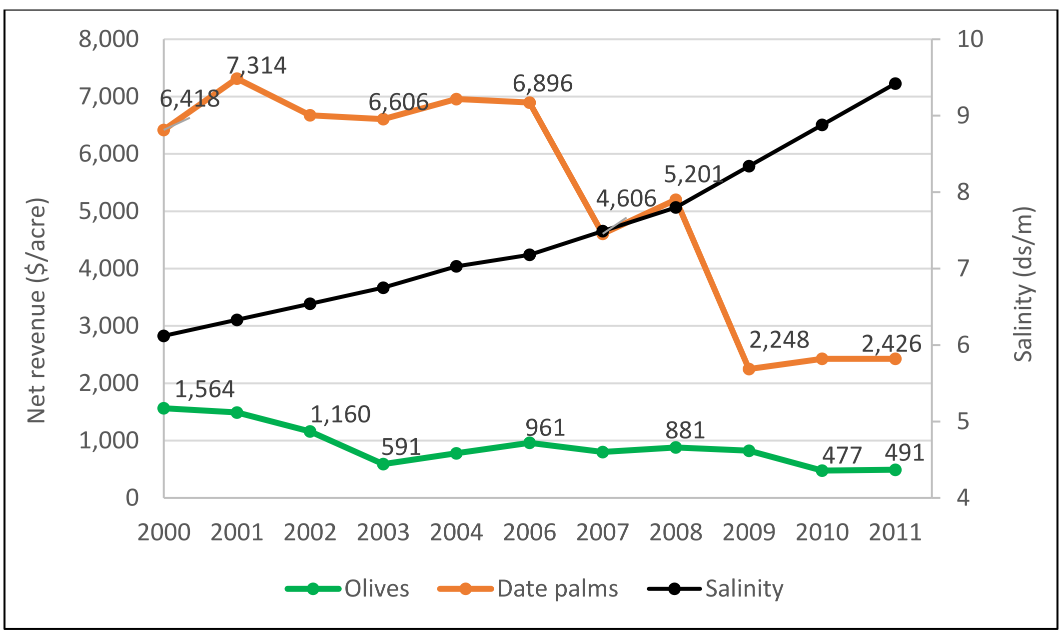


Figure 2.10 Groundwater salinity and net revenues of olives and date palms.

2.4.5 Effect of Salinity on Crop Yield and Revenue

Figures 2.9 and 2.10 show that the yields and net revenue of olives and date palms are decreasing with time from 2000 to 2011. However, groundwater EC values are increasing annually throughout this period. Mann-Kendall and Spearman's Rho tests are both applied to investigate the significance of trend for these variables over time. Table 2.8 shows the results of these two tests where the decrease of yields and net revenue for olives and date palms are significant throughout this period with 95% confidence interval. The increase of groundwater salinity is also significant at 95% level. To detect the correlation between these variables, Kendall and Spearman correlation tests are applied. Figures 2.11 and 2.12 show the correlation coefficients between groundwater salinity, yields and net revenues of olives and date palms, respectively using both tests. These results show that there is significant negative correlation between groundwater salinity and olives yield as the correlation coefficients are -0.56, -0.74 using Kendall and Spearman, respectively. The same for date palms that yield has a significant negative correlation with groundwater salinity where coefficient values are -0.55, -0.75 using Kendall and Spearman, respectively. Correlation between yield and net revenue for both crops is statistically significant with a coefficient value of 1 which is not surprising as net revenue depends on yield (Eq. 16). Therefore, the correlation tests show that the increase in groundwater salinity decreased yield and net revenue for both crops.

However, correlation does not necessarily produce information on causation. The observed data of groundwater and soil salinity are used to identify the sensitivity of crop yields to salinity in Siwa. According to work of Maas and Hoffman [44], and Ayers and Westcot [45] shown in Table 2.4, when the average EC values of groundwater are 4.5 and

Table 2.8 Mann-Kendall and Spearman's Rho trend results.

Parameter	Mann-Kendall		Spearman	
	τ	2 sided p-value	ρ	2 sided p-value
Olives yield	-0.564	0.019517*	-0.736	0.01338*
Olives revenue	-0.564	0.019517*	-0.736	0.01338*
Date palms yield	-0.55	0.023542*	-0.7517	0.0076*
Date palms revenue	-0.55	0.023542*	-0.7517	0.0076*
Groundwater salinity	1	2.62E-05*	1	< 2.2E-16*

*Statistically significant at $p < 0.025$

10.5 ds/m in 1996 and 2013, respectively, then the expected decrease for olives yield ranges from 36% to 95%, respectively. The same for date palms where the expected decrease in the yield ranges from 10% to 42% in 1996 and 2013, respectively. Meanwhile, soil EC values ranged from 4.7 to 12.3 ds/m in 2011 that corresponds to a decrease in olives yield in the ranges of 18% to 85% respectively. For date palms, the corresponding decreases are from 2.5% to 30% respectively.

These results confirm that groundwater and soil salinity are the major reasons for crop yield reduction in Siwa which is causing a detrimental impact on rural livelihood, especially in agriculture income indicating salinity management is a priority for this region.

2.5 Conclusions

The Siwa oasis was selected for this study to address groundwater development issues and associated impacts in the Western Desert of Egypt, given the abundance of groundwater. In this study, the historical water use from the Nubian aquifer, groundwater and soil salinity, agricultural crop yield, and agricultural income in Siwa oasis were

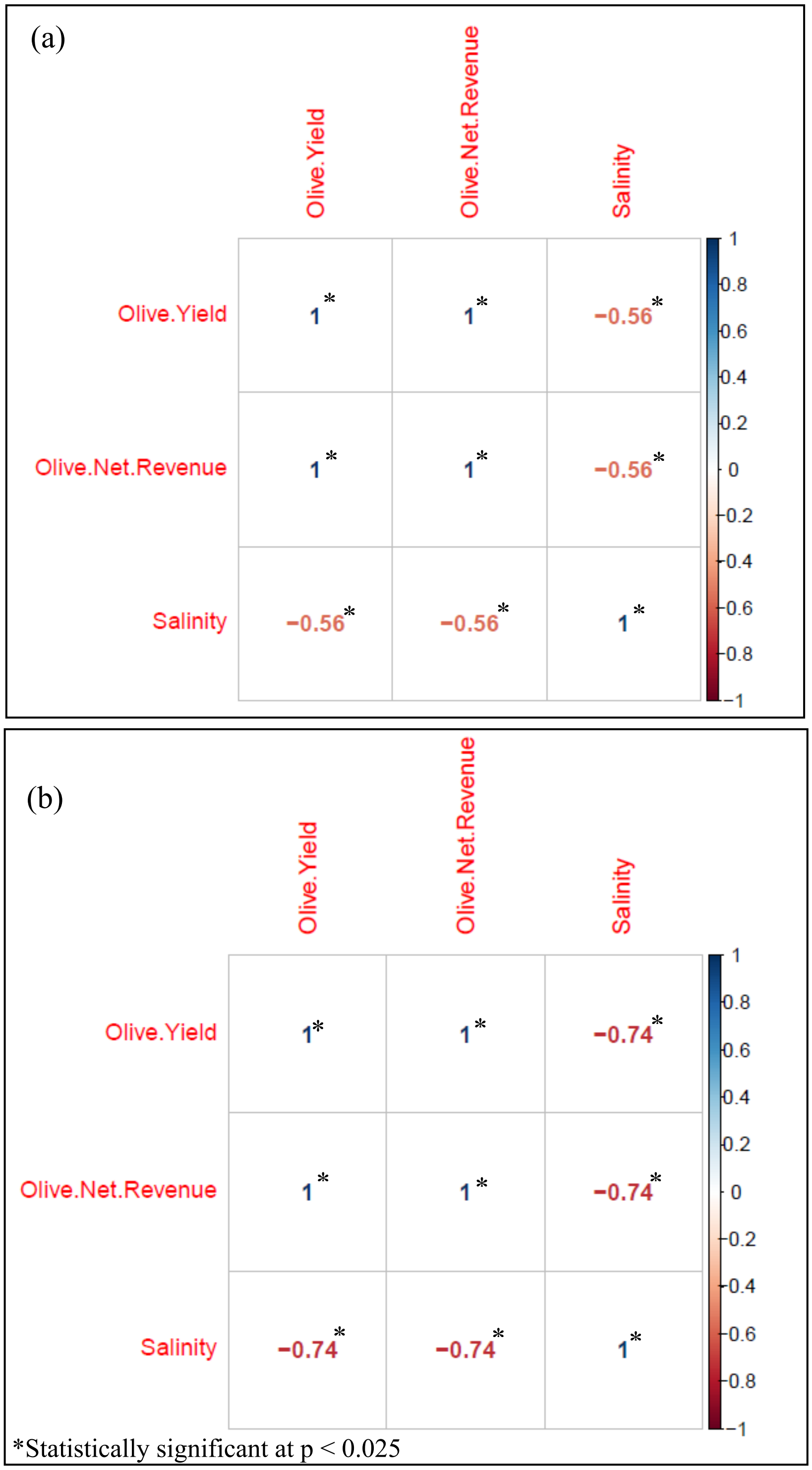


Figure 2.11 Correlation coefficients between groundwater salinity and olives using: (a) Kendall test, and (b) Spearman test.

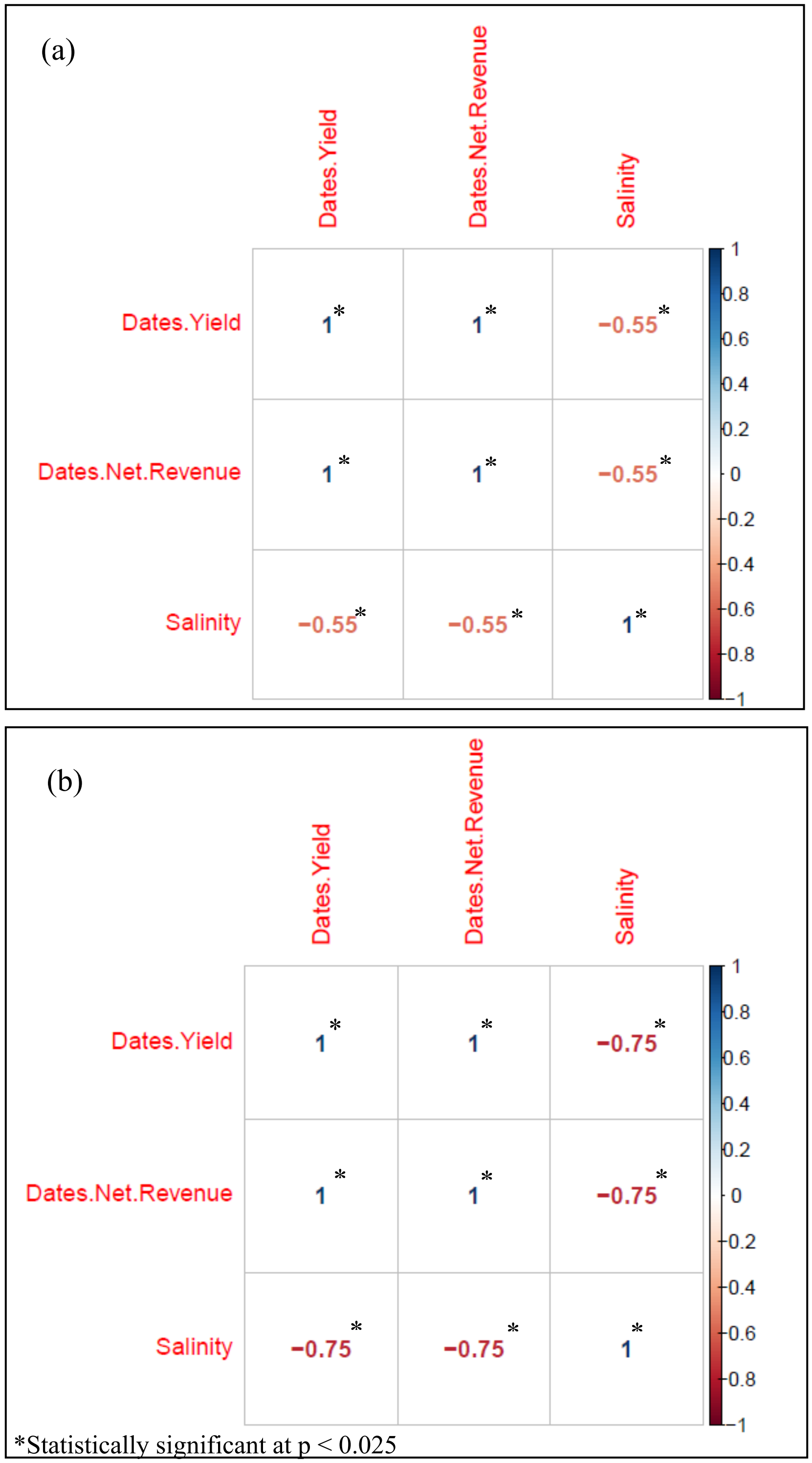


Figure 2.12 Correlation coefficients between groundwater salinity and date palms using: (a) Kendall test, and (b) Spearman test.

analyzed. Total water use was estimated as the sum of IWR and domestic water use. Thereafter, estimated water use was compared with actual withdrawal to define the amount of excess water and the corresponding water use efficiency from 1980 to 2012. NDWI was used to identify the total area of salty lakes in Siwa. The impact of salinity of groundwater and soil on crop yield and the corresponding income were analyzed.

The results showed the importance of groundwater management in the NSAS. The findings determined that two starkly different situations had taken place in Siwa. Until 1998, total annual groundwater withdrawal was 308 MCM from 1,500 shallow hand-dug wells. When this volume was compared with estimated total water use, it was found that a large amount of excess water amounting to 197.3 MCM was produced with only 35% WUE. Due to the increase in excess water since 1960, salty lakes were formed as a result of the existing poor drainage system prevailing in the region. The total area of these lakes reached 21,348 acres in 2000. In 1996, RIGW of Egypt developed policies and regulations to limit groundwater withdrawal from the Nubian aquifer. This was an important step and improved the conditions in Siwa by reducing annual groundwater withdrawal to 172 MCM in 2012. Therefore, excess water decreased to 10.5 MCM with an increase of WUE to 94%. As a consequence, the total area of salty lakes decreased to 16,144 acres in 2010.

Average groundwater EC values increased from 4.5 to 10.5 ds/m in 1996 and 2013, respectively. These values exceed the acceptable limit for irrigation water with an increase of 100% to 366%, respectively and classified as very high salinity. Therefore, severe restriction on water use needs to be considered. Soil EC ranged from 4.7 to 12.3 ds/m in 2011 which classified as mild and high salinity. Using PNA as the primary source of irrigation in addition to the existing salty lakes are the major reasons for high groundwater and soil salinity. From 2000 to 2011, the yields of olives and date palms decreased about 46% and 55%, respectively. As a result, net revenues of these crops decreased more than 60%. Mann-Kendall and Spearman trend tests showed that the increase in groundwater salinity and the decrease in crops yield and net revenue over time are significant. The results of this work showed a direct link between the increase in salinity and the corresponding decrease in crop yield affecting income.

In conclusion, the findings of this study clearly showed that groundwater management is a critical need in this region, especially to avoid significant depletion of this non-renewable water resource and to ensure the sustainability of this aquifer for future generations. Although recent groundwater management increased WUE and decreased the area of salty lakes, the concerns related to the poor drainage system in addition to high salinity are still present and require immediate attention. It is recommended to use efficient irrigation methods such as drip or sprinkler systems instead of furrow irrigation which is a good solution to decrease water waste. Replacing shallow wells with deep wells given the higher water quality in the deep aquifer with the usage of good drainage systems are important to decrease salinity in Siwa.

Acknowledgments

This work was funded by the Egyptian Ministry of Higher Education (Cultural Affairs and Missions Sector) and Utah Water Research Laboratory of Utah State University.

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CHAPTER 3

SUSTAINABLE AGRICULTURE DEVELOPMENT IN THE WESTERN DESERT OF EGYPT: A CASE STUDY ON CROP PRODUCTION, PROFIT, AND UNCERTAINTY IN THE SIWA REGION[2]

Abstract

The Egyptian government initiated a development project in 2015 to reclaim 1.5 million acres with the primary goal of increasing agricultural production. Siwa is one of these areas in the Western Desert of Egypt with 30,000 acres using groundwater from the Nubian Sandstone Aquifer System (NSAS). This study investigates if government goals are achievable in the next 20 years to secure the food and water needs of the Siwa region. Results show that total required crop areas are 7,154 and 6,629 acres in winter and summer, respectively. These areas are less than 17,010 acres of available area for cultivation (A_V). The estimated total water requirement is 40.6 million cubic meters (MCM) which is less than the 88 MCM that is considered available groundwater in the Nubian Aquifer System (NAS). Due to available capacity in Siwa, an optimization model is used to maximize crop production considering government policies. The Autoregressive Integrated Moving Average (ARIMA) model was applied to predict production costs and sell prices of cultivated crops. Analysis included different scenarios beyond government recommended approaches to identify ways to further expand agriculture production under sustainable conditions. Results provide valuable insights to the ability to achieve government goals

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[2]Moghazy, N. H., and Kaluarachchi, J. J. (2020). "Sustainable Agriculture Development in the Western Desert of Egypt: A Case Study on Crop Production, Profit, and Uncertainty in the Siwa Region." Sustainability, 12(16), 6568. https://doi.org/10.3390/su12166568.

from the project and changes that may be required to enhance production.

3.1 Introduction

The Nile River is the primary source of water in Egypt which represents 94% of all renewable water resources [1]. Egypt is facing water scarcity where the population was 97 million and total renewable water resources was 570 m^3/year/capita in 2018 [2] which is below the water scarcity level of 1000 m^3/capita/year [3]. Most essential food products are imported as production is insufficient to meet population needs. Self-sufficiency values of some strategic crops in Egypt from 2013 to 2017 are shown in Figure 3.1. These data show that self-sufficiency values of wheat, maize, broad bean, and barley are decreasing over time, where in 2017 these values are 34.5%, 47%, 30.7%, and 86%, respectively [4]. For sustainable socioeconomic developments in Egypt, water resources management is therefore important to protect limited water resources [5].

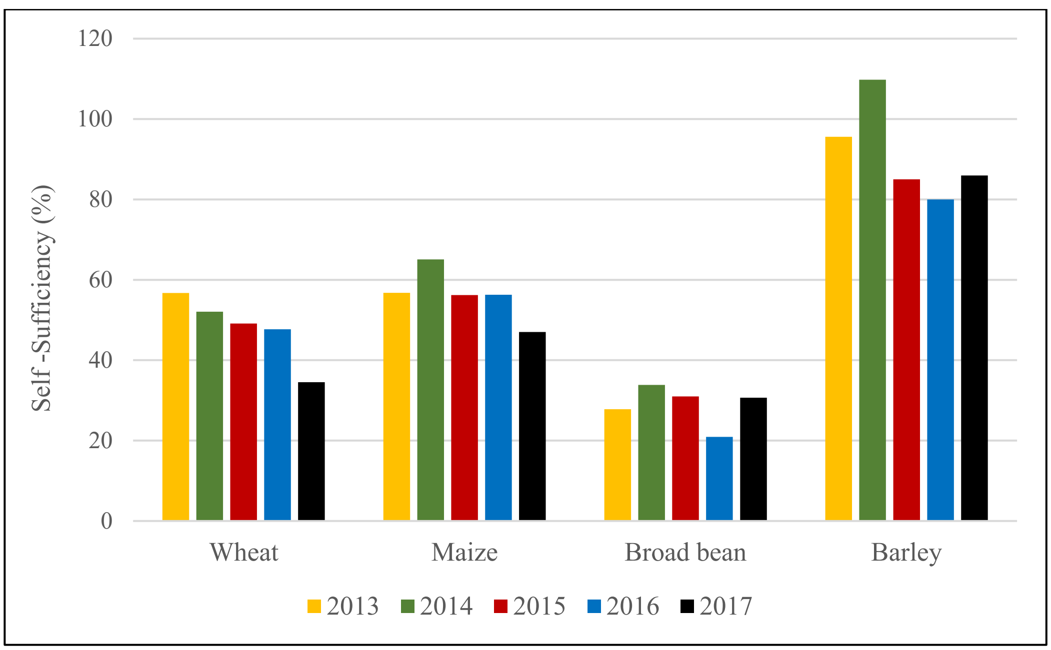

Figure 3.1 Self-sufficiency of selected strategic crops in Egypt [4].

The Egyptian government always seeks alternative water resources and agriculture expansion projects to address some of these needs. In the 1960s, the government initiated a project in the Western Desert (see Figure 3.2) to increase agricultural areas and attract people from over-populated regions. The primary source of water for this project was groundwater from the NSAS which is a non-renewable groundwater resource that is shared between Egypt, Libya, Sudan, and Chad. NSAS has two aquifers; the upper part is the Post Nubian Aquifer (PNA) followed by the Nubian Aquifer System (NAS) which has better groundwater quality [6,7]. NSAS in Egypt has a large volume of freshwater in storage which is 190,587 km^3 while total recoverable groundwater is 5,367 km^3 assuming maximum water decline of 100 m in the unconfined aquifer and 200 m in the confined aquifer [7]. Groundwater withdrawals in Egypt are from different locations in the Western Desert such as the Siwa region (see Figure 3.2) which is the focus of this study given the abundance of groundwater from NSAS.

The major economic activity in Siwa is agriculture while water-related issues have surfaced due to unmanaged groundwater withdrawal. Siwa has about 200 flowing springs, more than hundreds of poorly designed wells, in addition to six salty lakes [8]. Moghazy and Kaluarachchi [9] assessed the efficiency of groundwater use from the Nubian aquifer in Siwa and the corresponding negative impacts on crop yield and income from 1980 to 2012. The findings of this study showed that water use efficiency (WUE) was low at about 35% from 1980 to 1998. However, the Research Institute for Groundwater (RIGW) of Egypt developed regulations in 1996 to limit groundwater withdrawal from the Nubian aquifer by closing some of the shallow wells and replacing others. As a result, WUE increased gradually to 94% by 2012. These regulations were important to improve the conditions in Siwa, but, the salty lakes in Siwa are still present due to the poor drainage system. Also, the use of groundwater from the PNA which has high groundwater salinity around 3,000 to 7,000 ppm decreased yields of two major cash crops; olives and date palms by about 46% and 55%, respectively from 2000 to 2011. As a result, net revenue of both crops decreased more than 60%.

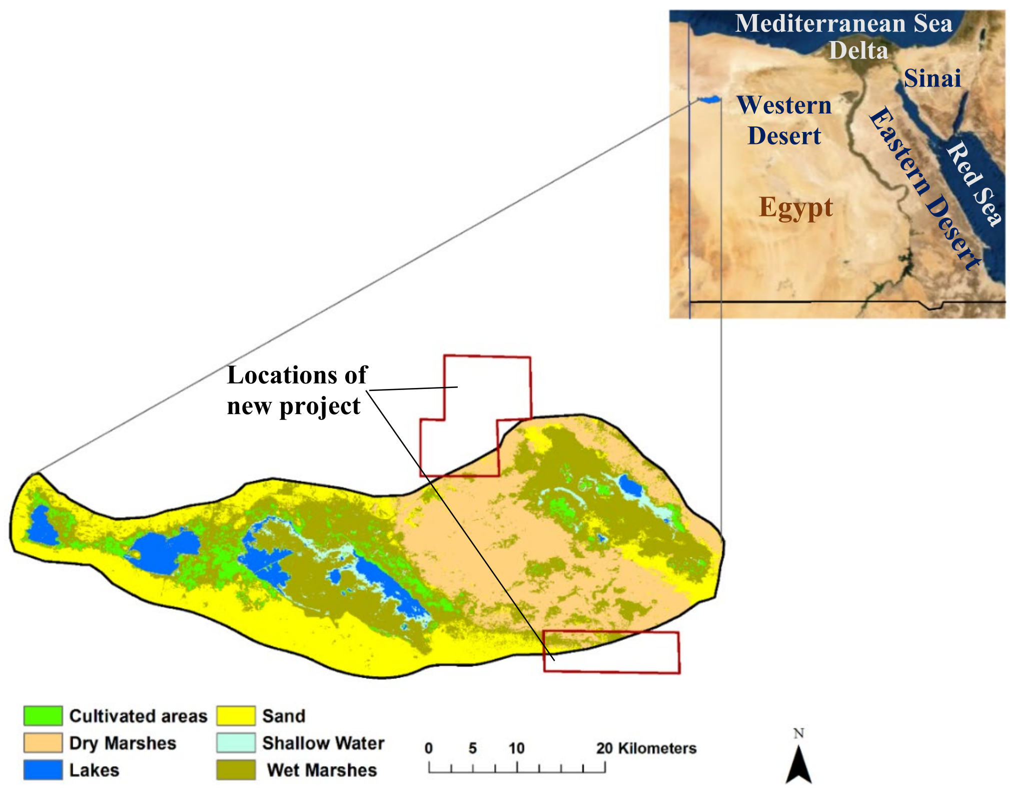

Figure 3.2 Physical description of the proposed reclamation project including the Western Desert and Siwa.

In 2015, the Egyptian government initiated a national project to reclaim 1.5 million acres in 16 different locations of Egypt where most of the lands are located in the Western Desert region due to the large volume of groundwater available from NSAS. Due to the cost of this project, the work is conducted in three phases with each phase consisting of 0.5 million acres. The Egyptian Countryside Development Company (ECDC) is responsible for managing this reclamation project (https://www.elreefelmasry.com). The goals of this project are to increase agricultural areas, increase crop production, decrease imported crops, population resettlement from the already over-populated Delta region, and increase investments and job opportunities. The Ministry of Water Resources and Irrigation (MWRI) has restricted policies to avoid significant depletion of this non-renewable groundwater resource and to ensure the sustainability of the aquifer for future generations. The Siwa region is planned for the second phase to reclaim about 30,000 acres consisting of good soil quality [10]. Groundwater from NAS is used for development of Siwa given high water quality with salinity around 200 to 400 ppm [11].

Groundwater is the primary source of potable water in some countries, but there are challenges that affect sustainability due to population growth, climate variability, and land development [12]. AbuZeid and Elrawady [13] estimated the sustainability of NSAS under three different scenarios starting from 2008. In the first scenario, they assumed that the annual increase of population in Egypt is 2%, total water available in Egypt which is 57 billion m^3 annually is the primary source of water, NSAS will be used to cover the shortage in water, and industrial and domestic water uses are 20% of total water available while agriculture will consume 80%. The second scenario assumed a 2% increase in population in the Western Desert, NSAS is the only source of water, and agriculture will be the primary economic activity. In the third scenario, the assumptions are the same as in the second except that industry is the primary activity. Results showed that, in the first scenario, NSAS can be used for 60 years and the expected area that can be cultivated is 39.3 million acres in 2068 with crop water use of 5,000 m^3/acre/year. In the second scenario, NSAS can be used for 67 years with a total cultivated area of 32.5 million acres in 2074. In the third scenario, NSAS is sustainable for 119 years and the total cultivated area will be 22.4 million acres in 2126. As a result, the third scenario showed the availability of water from NSAS for 119 years, but with the least agricultural benefits.

Usually, agriculture developments face a problem of finding the optimal cropping patterns to obtain selected goals such as maximizing profit, minimizing costs, or maximizing production. Optimization is a method used to determine the best possible solution for a problem based on an objective with specific constraints. Sharma et al. [14] used a dynamic nonlinear programming model to analyze profit and risk of optimum cropping patterns under alternate policy scenarios in Himachal Pradesh, India. They found that relaxing some constraints can help increase income.

Since this national project has not commenced in Siwa yet, very little research and information are available. Therefore, this study addressed the development project in Siwa to reclaim 30,000 acres considering government policies in the next 20 years assuming the project starts in 2020. Due to the available capacity of land and groundwater in Siwa, this study also explored additional strategies for sustainable agriculture developments by 2040 under current climatic conditions. One other goal of this work was to develop a suitable methodology and demonstrate its applicability in the Siwa region so that the methodology can be used in other regions of the Western Desert and other phases of this reclamation project.

3.2 Study Area Description

The Siwa region is located in the northwest area of the Western Desert in Egypt. It is a natural depression with an area of 0.28 million acres and an example of a closed basin where groundwater is the only source of water. Climate is arid to semiarid where average annual rainfall is 13 mm and evaporation ranges from 5.2 to 17 mm/day [8,15]. Figure 3.2 identifies locations of the new proposed project in Siwa which are away from the salty lakes and marshes.

RIGW [16] determined the groundwater potential from both aquifers in Siwa. It has been reported that to ensure the sustainability of NSAS for the next 100 years, annual groundwater withdrawal should not exceed 60 and 88 million cubic meters (MCM) from PNA and NAS, respectively where these values are small compared to the available groundwater in storage. Since this proposed new project in Siwa will use groundwater from NAS given high groundwater quality, a total of 88 MCM of groundwater is available annually for development.

3.2.1 Government Policies

Restricted policies of MWRI include prioritizing water consumption from the non-renewable NSAS to ensure aquifer sustainability. Some of these policies are as follows; the maximum discharge rate of each well is 150 m^3/hr with maximum daily working hours of 10. Well spacing is 1 km to avoid well interaction causing water table depressions, which means that each well covers an area of 1 km^2 or about 238 acres. The maximum allowable crop water use is 4,000 m^3/acre/year (based on consultation from water and agriculture experts in Egypt) to limit water consumption. Crops such as rice, banana, and alfalfa are prohibited due to high water demands. Modern irrigation technology such as drip and sprinkler should be used [17]. The Ministry of Agriculture and Land Reclamation (MALR) suggested the distribution of lands to be 70% and 30% for seasonal and permanent crops, respectively providing more area for strategic crops [18].

3.3 Methodology

3.3.1 Required Crops Area

One goal of this project is to ensure that local food production is adequate for the population and to sustain livestock farming. While there are 30,000 acres in Siwa for reclamation, it is important to determine A_v. Government policies are followed to identify the number of wells and maximum water available annually from which A_v can be calculated.

This study assumed that the project will commence in 2020 under current conditions and will not consider potential impacts due to climate change for the next 20 years. To decide if the government goals are achievable by 2040, crops area and total water requirements for population and livestock were estimated and then compared with the available capacity in Siwa. The first step was to predict the population and corresponding livestock and poultry. ECDC sells land to youth and investors where each land parcel contains a well with a surrounding area of about 238 acres. ECDC sets a condition that each land parcel will be sold to a group of people with a minimum of 10 to a maximum of 23 [19]. As a result, each participant is responsible for at least 10 acres. To estimate the total number of inhabitants at the beginning of the project, assumptions include: each family consists of an average of four members, about 200 personnel are required for community development, and 10 workers are associated with each groundwater well operation. Therefore, the total number of inhabitants in 2020 can be estimated. Future population forecasts will be calculated using an annual growth rate of 2.5% [2]. Average consumption of beef and poultry is 13 and 10.6 kg/capita/year, respectively [20]. While sheep and goats have the great ability to adjust harsh environmental conditions, they can be raised in arid and semiarid regions [21]. Therefore, due to the dry climate in Siwa, the suggested livestock types are sheep and goats where both are used to satisfy beef consumption, while chicken is the main source of poultry. Therefore, the total population and livestock can be predicted until 2040.

The second step was to define the area needed for each crop. This study used the land use distribution suggested by MALR where seasonal crops cover 70% of the land and consist of wheat, barley, and broad bean in the winter, and maize and soybean in the summer. Permanent crops occupy the remaining 30% of land with olives and date palm. Wheat, barley, broad bean, and maize are sources of strategic crops to cover the crop deficit in Egypt. Olives, date palm, and soybean are considered cash crops and used as a source of income. Equation (1) is used to calculate the annual area of strategic crops needed for the population:

$$\text{Crop area (acres)} = \frac{\text{N}*\text{Crop Consumption (kg/capita/year)}}{1000*\text{Crop Yield (tons/acre)}} \quad (1)$$

where N is population, and population average consumption for wheat, barley, broad bean, and maize are 143.2, 0.3, 7.8, 62 kg/capita/year, respectively [22]. Table 3.1 shows the average yields of the proposed crops [23].

Livestock feeds consist of two components: concentrate feeds and roughage feeds. Concentrate feeds correspond to wheat, barley, maize, oats, and broad bean and provide energy and protein for livestock. However, roughage feeds have two types: green fodder that represents alfalfa, sorghum, and silage, and dry fodder which are straws and stover that provide fiber. For sheep and goats, feed consumption ($Feed_{sheep}$ and $Feed_{goat}$) is as follows [24]:

$Feed_{sheep}$=0.6 kg/day concentrate feed + 0.6 kg/day dry fodder + 900 kg/year green fodder (2)

$Feed_{goat}$=0.25 kg/day concentrate feed + 0.4 kg/day dry fodder + 600 kg/year green fodder (3)

Table 3.1 Average yields of crops [23].

Crop		Yield (tons/acre)
Wheat	Cereal	2.78
	Straw	2.75
Barley	Cereal	1.65
	Straw	1.83
Broad bean	Bean	1.45
	Straw	1.61
Maize	Cereal	3.41
	Stover	2.54
Soybean	Bean	1.4
	Straw	4.72
Olives		4.15
Date Palm		14.5

In this study, livestock consumption of concentrate feeds will be divided equally among wheat, barley, and broad bean in winter, while maize will be the only source in summer. Straws from wheat, barley, broad bean in addition to stover from maize are the sources of dry fodder. The source of green fodder is silage from maize which has a yield of 20 tons/acre [25,26]. Thus, areas of wheat, barley, broad bean, and maize as concentrate feeds for livestock are calculated. As a result, the total area of strategic crops needed for the population and livestock can be calculated until 2040. For cash crops, soybean area is assumed to be the same area of maize, while olives and date palm are assumed to cover the area of permanent crops equally. Finally, the total crop areas in winter or summer is compared with A_V to assess land availability.

3.3.2 Total Water Requirement

To estimate the total water requirement in 2040, irrigation water requirement (IWR), population water requirement, and water requirement for livestock and poultry are identified. Domestic water requirement is 250 L/capita/day [27]. The water requirement for sheep and goats is 10 L/head/day [28], while 0.3 L/head/day for chicken [29]. For crop water demand, the United Nations Food and Agriculture Organization (FAO) Penman-Monteith equation was used [30] which requires four meteorological data types: maximum temperature, minimum temperature, wind speed, and relative humidity. Monthly data of Siwa in the past 10 years were downloaded from the National Centers for Environmental Prediction (https://globalweather.tamu.edu/). This study used the same steps applied by Moghazy and Kaluarachchi [9] to calculate reference evapotranspiration ET_o (mm/day) and annual crop evapotranspiration ET_c (mm/year) for different crops in Siwa. Eq. (4) is used to calculate crop water requirement [31]:

$$CWR = \frac{ET_c - R}{(1 - LR) * E} * 4.2 \qquad (4)$$

where CWR is crop water requirement (m^3/acre/year), R is effective rainfall (mm/year) which is almost negligible in Siwa [15], LR is leaching requirement, 4.2 is a conversion factor from mm/year to m^3/acre/year, and E is irrigation efficiency. A drip irrigation system has a distinct advantage over flood and sprinkler irrigation systems in arid regions [32]. Therefore, drip irrigation is assumed to be used in Siwa due to high evaporation and this assumption is consistent with efficient use of the non-renewable groundwater resource. The corresponding efficiency is 90% [33]. The usage of drip irrigation for wheat, barley, and soybean has been supported by earlier experiments [34–38]. Elnashar [39] provided values of LR for different crops in Egypt under different alternatives of irrigation water.

Due to the usage of high-quality groundwater from NAS, LR is assumed to be 10%.

IWR of all crops is the sum of CWR multiplied by the area of each crop. Therefore, total water requirement for crops, population, and livestock in 2040 can be estimated and compared with 88 MCM, which represents the available annual groundwater from NAS. The value of IWR is divided by Av so the value of IWR per acre can be compared with 4,000 m^3/acre/year to assess the government policy of maximum crop water use. If the estimated crop area and total water requirements are less than the available capacity of Siwa, then optimization is used to maximize the benefits as presented in the next section.

3.3.3 Optimization Analysis

Optimization is used in decision-making related to the efficient use of available resources. The common methods of optimization are linear programming (LP), nonlinear programming, dynamic programming, integer programming, binary programming, etc. [40]. LP is one of the best and most simple techniques [41] that helps decision-makers in water resources planning and management. In this work, LP is used to optimize the available capacity of groundwater and land areas by determining the best allocation of crops. The objective function is to maximize crop production by 2040 subject to stipulated government constraints and described as follows:

$$\text{Max } P = \sum_{i=1}^{n} Y_i * A_i \qquad (i = 1, 2, \ldots, n) \qquad (5)$$

where P is total crop production (tons), n is number of crops, Y_i is yield of crop i (tons/acre) (shown in Table 3.1), and A_i is area of crop i (acres).

As discussed earlier, the constraints can be represented as:

$$\sum_{i=1}^{w} A_i \leq 70\% \text{ Av} \qquad (6)$$

where w is number of seasonal crops in winter, which are wheat, barley, and broad bean.

$$\sum_{i=1}^{s} A_i \leq 70\% \text{ Av} \tag{7}$$

where s is number of seasonal crops in summer which are maize and soybean.

$$\sum_{i=1}^{m} A_i \leq 30\% \text{ Av} \tag{8}$$

where m is number of permanent crops which are olives and date palm.

For strategic crop production, the production of each strategic crop should be more than or equal to the total demand by population and livestock.

$$Y_j * A_j \geq CP_j * N + \sum_{k=1}^{2} CL_{jk} * L_k \tag{9}$$

where Y_j is yield of strategic crop j (tons/acre), j is number of strategic crops (wheat, barley, broad bean, and maize), A_j is area of strategic crop j needed for population and livestock (acres), CP_j is annual consumption of strategic crop j per capita (ton/capita/year), k is number of livestock categories (sheep and goats), CL_{jk} is consumption of strategic crop j as concentrate feeds for each k (ton/head/year), and L_k is number of heads in each k.

For groundwater availability constraint, the estimated total water requirement using the current climatic conditions should be less than or equal to available groundwater from NAS which is 88 MCM/year.

$$\sum_{i=1}^{n} (CWR_i * A_i) + \text{Population and livestock water requirement} \leq 88 \text{ MCM/year} \tag{10}$$

where CWR_i is water requirement for crop i (m^3/acre/year).

For crop water use constraint, the amount should be less than or equal to the maximum crop water use allowed which is 4,000 m^3/acre/year.

$$\frac{\sum_{i=1}^{n}(CWR_i * A_i)}{A_V} \leq 4{,}000 \text{ m}^3/\text{acre/year} \quad (11)$$

The LP model is applied using General Algebraic Modeling Systems (GAMS; http://www.gams. com/).

3.3.3.1 Optimization Scenarios

Optimization can be used to analyze possible variations of crop patterns to maximize the production in Siwa. Therefore, this work used scenarios beyond the government policies to explore other agricultural development practices by relaxing some of the government policies. The first scenario was to change land distribution (Eqs. 6–8) to be 80% for seasonal crops, while allowing the remaining 20% for permanent crops and keeping other constraints the same. The purpose of this scenario was to increase the area of strategic crops. The second scenario was to relax only the maximum crop water use (Eq. 11) to determine the increase in crop area and the corresponding IWR per acre. The third scenario was a combination of the two earlier scenarios.

In case of extra groundwater needed to expand the agricultural areas, more scenarios will be added to increase water for irrigation by mixing groundwater from NAS with a small volume from PNA that has high salinity. As a result, the corresponding salinity can be calculated using Eqs. (12) and (13) which depends on the portion of groundwater from each aquifer [42].

$$EC_w = \sum_{i=1}^{g} EC_{wi} * f_i \quad (12)$$

$$\sum_{i=1}^{g} f_i = 1 \quad (13)$$

where EC_w is electric conductivity after groundwater mix (ds/m), g is number of groundwater resources which are PNA and NAS, EC_{wi} is electric conductivity of groundwater resource i (ds/m), and f_i is fraction of source i in the mix. A conversion factor of 650 is used to transfer salinity units from ppm to ds/m [43]. To study the effect of groundwater salinity on crop yield, Table 3.2 is used which provides tolerance values of crops toward water salinity [44,45].

Table 3.2 Crop tolerance to water salinity [44,45].

Crop	Maximum Yield	Yield Reduction by 10%	Yield Reduction by 25%	Yield Reduction by 50%	Maximum Salinity Possible
	Water Salinity (ds/m)				
Wheat	4	4.9	6.3	8.7	13
Barley	5.3	6.7	8.7	12	19
Broad bean	1.1	1.8	2	4.5	8
Maize	1.1	1.7	2.5	3.9	6.7
Soybean	3.3	3.7	4.2	5	6.7
Olives	1.8	2.6	3.7	5.6	11
Date Palm	2.7	4.5	7.3	12	21

3.3.4 Expected Profit

Previous optimization scenarios described maximizing agricultural production for the proposed project in Siwa without considering profit generated from the project. However, in real-life development projects where investments are made both by the government and private sector, anticipated profit is equally important. Therefore, annual profit from each scenario can be calculated until 2030 as follows:

$$\text{Profit (\$)} = \text{Annual Crops Net revenue} - \text{Annual Cost of Project} \\ = \left(\sum_{i=1}^{n} S_i * Y_i - C_i\right) * A_i - \text{Annual Cost of Project} \tag{14}$$

where S_i is selling price of crop i (\$/ton), and C_i is production cost of crop i (\$/acre).

3.3.4.1 Annual Costs

In this section, all costs of the project in Siwa are identified. This project is still in the first phase of reclamation and has not started yet in Siwa. Therefore, land prices are assumed to be the same as in the first phase specifically for regions that have similar conditions as Siwa. These land prices are $2,500 per acre using 2017 dollars for youth, while $3,611 per acre for investors [19]. In this study, an average value of $3,055 per acre was used in Siwa. The cost of a single deep well is $194,444, while the cost of a solar-powered pump is $72,222. Costs of irrigation and drainage systems are $555 and $333 per acre, respectively. Land price includes the price of a well and a solar-powered pump, while maintenance and operation costs which represent 5% of the actual cost is the responsibility of the owner [17]. Capital costs include land price, irrigation, and drainage systems, while annual costs are the costs of maintenance and operation. To convert from capital cost to annual cost, capital recovery factor (CRF) is used as follows (https://en.wikipedia.org/wiki/Capital_recovery_factor accessed November 2019):

$$\text{CRF}=\frac{r(1+r)^{U}}{(1+r)^{U}-1} \tag{15}$$

where r is interest rate and U is number of years. All capital costs are assumed to be paid in 10 years with an interest rate of 12.25% stated by the Central Bank of Egypt (https://www.cbe.org.eg/ar/Pages/default.aspx accessed February 2020). ECDC sets the policy for cost of land where 15% of the cost should be paid in advance when the land is sold and the remaining 85% can be paid within nine years with an interest rate of 5% [19]. As a result, all costs are defined annually.

3.3.4.2 Net Revenue

To calculate net revenue, annual selling prices and production costs are predicted from 2020 to 2030. Cultivated crops such as wheat, barley, broad bean, maize, and soybean have two sell prices; the price of crop and the price of its straw ($/ton) where yield values are shown in Table 3.1. Production costs of these crops include land preparation, seeding and planting, irrigation, fertilization, pest control, harvesting, and labor ($/acre). However, for date palm which is a permanent crop, it costs about $582 per acre for establishment which is paid once at the beginning of cultivation and includes land preparation, seeding, and planting costs [46]. The remaining costs such as irrigation, harvesting, and labor are paid annually. The production of dates starts in the fifth year with a yield of 20 kg/palm and increases gradually to 125 kg/palm in the tenth year [47]. The average number of palms per acre is 115 [23].

The ARIMA model was used in this study to analyze the cost and price data from 2000 to 2017 for all crops, in addition to developing appropriate models that can predict these values for the next 10 years with a confidence level of 95% for prediction interval. As a result, net revenues can be calculated. The ARIMA (p, d, q) model is a combination of three parts: Autoregressive AR(p), Integrated I(d), and Moving Average MA(q). AR(p) refers to the use of past values in the regression equation. I(d) is the differencing between observations to achieve the stationary assumption where there is no trend or seasonality in the data. MA(q) represents the error of the model as a combination of previous errors. The equation of the ARIMA model is as follows:

$$Y_t = c + \varphi_1 y_{d\,t-1} + \ldots + \varphi_p y_{d\,t-p} + e_t - \theta_1 e_{t-1} - \theta_q e_{t-q} \tag{16}$$

where Y_t is variable at time t, c is constant, φ_1, φ_p, θ_1, and θ_q are parameters from the model, d is degree of differencing, p is number of lag observations, q is size of moving average window, and e_t is error at time t.

Autocorrelation function (ACF) and Partial autocorrelation function (PACF) are used to estimate the characteristics of time series. ACF plots display the correlation between a series and its lags which can help to estimate the order of MA(q). However, PACF plots display the direct relationship between a variable and its lag, so the order of AR(p) can be estimated. Annual historical data about the prices and costs of cultivated crops are collected from the Ministry of Agriculture and Land Reclamation [48] and the Central Agency for Public Mobilization and Statistics [49]. Data are divided into two sets: training set from 2000 to 2010, and test set for the remaining seven years' data from 2011 to 2017. These steps can help to test the accuracy of the ARIMA model for future predictions of prices and costs for each crop.

The selection of the ARIMA model that fitted the training set is based on goodness-of-fit criteria. In this work, we used mean absolute error (MAE), root-mean-squared error (RMSE), and mean absolute percentage error (MAPE). Models that have lower values of MAE, RMSE, and MAPE are used to predict data from 2011 to 2017 then compared with the test set to measure the performance of forecasting. As a result, production cost and sell price of each crop can be predicted with a confidence level of 95% for prediction intervals. MAE, RMSE, and MAPE are defined as follows:

$$\text{MAE}=\frac{1}{U}\sum_{t=1}^{U}(Y_t-\hat{Y}_t) \tag{17}$$

$$\text{RMSE}=\sqrt{\frac{1}{U}\sum_{t=1}^{U}(Y_t-\hat{Y}_t)^2} \tag{18}$$

$$\text{MAPE}= \frac{100}{U} \sum_{t=1}^{U} \left| \frac{Y_t - \hat{Y}_t}{Y_t} \right| \quad (19)$$

where Y_t and $\hat{Y}_t$ represent observed and predicted values in year t, respectively. The ARIMA model was applied using R software version 3.6.1 (https://www.r-project.org/). Finally, revenues from the cultivated crops are predicted annually from 2020 to 2030. As a result, profit is estimated for each scenario using Eq. (14).

3.3.5 Profit Uncertainty

In the previous section, selling prices and production costs of crops have uncertainty in the prediction intervals. Therefore, this uncertainty in profit is addressed using Monte Carlo simulations (MCS) which require the probability distribution of input variables to describe uncertainty. A common approach in financial forecasting is the triangular distribution where the minimum, maximum, and most likely values are known to occur [50,51]. Therefore, this work used triangular distribution for predicted prices and costs of crops in years 2025 and 2030. The number of simulations used was 10,000 to increase the accuracy as suggested by Khader [52]. R software is also used for the Monte Carlo simulations.

3.4 Results and Discussion

3.4.1 Available Area for Cultivation (Av)

Government policies are followed to ensure the sustainability of NSAS for future generations. Each well covers an area of 238 acres which indicates that 126 wells are needed to cultivate 30,000 acres. Using stipulated well discharge rate and working hours, the maximum water available annually is 68 MCM. By dividing this value by maximum crop water use of 4,000 m^3/acre, Av is computed as 17,010 acres which represents 56.7%

of the total area. As a result, each well can cultivate only 135 acres. The remaining areas can be used for stocks, fishing, and livestock farming. Using the land distribution of 30% for permanent crops and 70% for seasonal crops, there are 5,103 acres available for olives and date palm, while 11,907 acres are available for wheat, barley, and broad bean in winter, and maize, and soybean in the summer.

3.4.2 Crop Area and Total Water Requirements in 2040

The purpose of this section is to assess if government goals are achievable by 2040 where crop area and total water requirements for population and livestock are estimated and then compared with available capacity in Siwa. It is mentioned earlier that each participant is responsible for at least 10 acres, therefore, 30,000 acres in Siwa can be sold to approximately 3,000 persons. Using the assumptions made earlier, the number of inhabitants at the beginning of the project is 16,460 in 2020. The predicted population in 2040 will be 26,972 using an annual population growth rate of 2.5%. The corresponding estimated numbers of sheep, goats, and chickens in 2040 are 5,127, 7,969, and 204,987, respectively.

To calculate the area of strategic crops for population needs, Eq. (1) is used. For livestock feeds, Eqs. (2) and (3) are used where the total values of concentrate feeds, dry, and green fodders needed in 2040 are 1,850, 2,287, and 9,396 tons, respectively. As wheat, barley, broad bean, and maize are the sources for concentrate feeds, Table 3.3 shows the details to compute these areas. Thereafter, the total area of strategic crops needed for population and livestock concentrate feeds in 2040 are 1,501, 192, 358, and 763 acres for wheat, barley, broad bean, and maize, respectively as shown in Table 3.4. It is important to ensure that these areas are enough to meet dry and green fodders for livestock. Dry

Table 3.3 Strategic crops area for livestock concentrate feeds in 2040.

<table>
<tr><th></th><th>Consumption per Season</th><th>Crop</th><th>Consumption per Crop (tons)</th><th>Area (acres)</th></tr>
<tr><td rowspan="4">Concentrate feeds = 1,850 tons/year</td><td rowspan="3">Winter = 925 tons</td><td>Wheat</td><td>308.3</td><td>111</td></tr>
<tr><td>Barley</td><td>308.3</td><td>187</td></tr>
<tr><td>Broad bean</td><td>308.3</td><td>213</td></tr>
<tr><td>Summer = 925 tons</td><td>Maize</td><td>925</td><td>272</td></tr>
</table>

Table 3.4 Calculated required areas (in acres) for strategic crops in 2040.

Crop	Required area for Population	Required area for Livestock	Total Area
Wheat	1,390	111	1,501
Barley	5	187	192
Broad bean	145	213	358
Maize	491	272	763

fodder required in winter or summer is 1,143.5 tons. The production of wheat straw is 4,127 tons which can cover the consumption of dry fodder in winter. The production of maize stover is 1,938 tons which is enough to cover dry fodder in summer. For green fodder, the production of silage from maize is 15,260 tons where this quantity is enough for the whole year. For cash crops, areas of soybean, olives, and date palms are 763, 2,551, and 2,552, respectively, based on the assumptions made earlier. As a result, the total area required in winter is 7,154 acres which is the summation of area needed for wheat, barley, broad bean, olives, and date palm. Less area is needed in the summer which is about 6,629 acres. The comparison between crop areas required in winter or summer with Av of 17,010 acres indicates that there is still extra area available that can be cultivated in Siwa.

Population water requirement in addition to water requirements for livestock and poultry are 2.5 MCM in 2040. Water requirement for each crop is calculated using Eq. (4) and the results are shown in Table 3.5. As a result, IWR for all crops is 38.1 MCM in 2040, and the corresponding total water requirement is 40.6 MCM which is less than 88 MCM. When IWR is divided by 17,010, the result of 2,240 m^3/acre/year is less than 4,000 m^3/acre/year. These results indicate that government goals are achievable in 2040 where the available land and groundwater are adequate for the estimated population needs while allowing further expansion of agriculture.

Table 3.5 Calculated crop water requirement (CWR).

Crop	CWR (m^3/acre/year)
Wheat	2,504
Barley	2,281
Broad bean	2,184
Maize	4,046
Soybean	3,750
Olives	4,198
Date palm	6,449

3.4.3 Optimization

Since the earlier analysis showed that more capacity is available in the system, optimization is used to evaluate possible scenarios to increase production. Table 3.6 shows the results of LP optimization for all scenarios discussed earlier. It is clear that, in all scenarios, soybean and olives are not appropriate due to their lower yields compared to maize and date palm, respectively. For seasonal crops, the production of barley and broad bean satisfies only the required values for population and livestock, while extra areas can be cultivated with wheat in the winter and maize in the summer. Date palm is the only source of income and can always cover the entire area allocated to permanent crops.

For the base scenario where government policies are followed, the production of wheat and maize are 31,572.5 and 4,619.5 tons, respectively, indicating that production exceeds demand. Therefore, extra production can be used outside Siwa to cover the national deficit of strategic crops in Egypt. Total crop production which is the objective function is 111,021 tons while the total production of strategic crops is 37,027 tons. The sensitivity analysis showed that the binding constraints are permanent crop area, seasonal crops area in winter, and crop water use. Also, the areas of barley and broad bean are binding. Shadow prices of binding constraints are analyzed for the increase or decrease in the objective function per unit increase in the constraint. Results show that the shadow prices of permanent crop area and seasonal crop area in winter are 9.06 and 0.67 tons per acre, respectively indicating that to increase the production, it is best to increase the area of permanent crops such as date palm. If the goal however is to increase the production of strategic crops, then the land distribution needs to be changed as discussed in the first scenario. The shadow price of crop water use is 14.33 tons per unit increase which is relaxed in the second scenario to determine the increase in the production and the corresponding crop water use. The shadow price of barley and broad bean has negative values of -0.57 and -0.73 tons/acre, respectively as these crops have lower yields compared with wheat. For the first scenario where the land distribution changed to 80% for strategic crops and 20% for permanent crops, the results show that production of wheat and maize increased by 15% and 122.4%, respectively, compared with the base scenario. However, total production decreased by about 12.8% because of the decrease in date palm area by 33.3%. In the base case and first scenarios, there is still available groundwater and land in the summer, but, this land could not be cultivated due to the constraint of crop water use.

In the second scenario where maximum crop water use is relaxed, the only change is in the production of maize which increases by about 318.6% compared with the base

Table 3.6 Results from optimization analysis for different scenarios.

Crop	Population and Livestock Requirement		Scenarios to Maximize Production					
			Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Wheat	Area (acres)	1,501	11,357	13,058	11,357	13,058	11,318.7	13,019.7
	Production (tons)	4,172.8	31,572.5	36,301.2	31,572.5	36,301.2	31,466	36,194.8
Barley	Area (acres)	192	192	192	192	192	192	192
	Production (tons)	316.8	316.8	316.8	316.8	316.8	316.8	316.8
Broad bean	Area (acres)	358	358	358	358	358	396.3	396.3
	Production (tons)	519.1	519.1	519.1	519.1	519.1	519.1	519.1
Maize	Area (acres)	763	1,354.7	3,013.2	5,670.5	7,328.9	10,617	12,275.5
	Production (tons)	2,601.8	4,619.5	10,275	19,336.4	24,991.5	31,851	36,826.5
Date palm	Area (acres)		5,103	3,402	5,103	3,402	5,103	3,402
	Production (tons)		73,993.5	49,329	73,993.5	49,329	73,993.5	49,329
Total area in Winter (acres)			17,010	17,010	17,010	17,010	17,010	17,010
Total area in Summer (acres)			6,457.7	6,415.2	10,773.5	10,730.9	15,720	15,677.5
IWR per acre (m^3/acre/year)			4,000	4,000	5,026.5	5,026.5	6,202.2	6,202.2
Total water requirement (MCM/year)			70.5	70.5	88	88	108	108
Objective function (tons)			111,021.4	96,741.2	125,738.3	111,457.7	138,146.4	123,186.2
Strategic crop production (tons)			37,027.9	47,412.2	51,744.8	62,128.7	64,152.9	73,857.2

scenario. Thereafter, the total production increased by about 13.3%. For the third scenario, which is the combination of the first and second scenarios, the results show that the production of wheat and maize increased about 15% and 441%, respectively, while total production did not change much compared with the base scenario. In the second and third scenarios, IWR per acre is 5,026 m^3/acre/year and all available groundwater in NAS is needed. Therefore, to withdraw 88 MCM the discharge rate from each well needs to increase to about 194 m^3/hr instead of 150 m^3/hr, or increase the number of wells to 163 instead of 126. There is still an available area in the summer that can be cultivated, but, the constraint of groundwater availability is violated.

The comparison between these scenarios shows that the whole area of 17,010 acres can be cultivated in the winter but not in the summer due to the higher crop water demand. It is recommended that decision-makers should consider increasing the limit of crop water use, in addition to increasing the discharge rate of wells and the number of wells where possible.

Another solution is to increase the irrigation water supply by mixing PNA with NAS considering the effect of water salinity on crop yield. Average values of groundwater salinity are 5,000 (7.7 ds/m) and 300 ppm (0.46 ds/m) for PNA and NAS, respectively. Population and livestock water requirement of 2.5 MCM in 2040 can use high-quality groundwater from NAS. However, the remaining amount of 85.5 MCM from NAS can be mixed with 20 MCM from PNA. The corresponding salinity from this mix using Eqs. (12) and (13) is 1.83 ds/m. From Table 3.2, the only crops that will be affected by groundwater salinity are broad bean and maize where the decrease in yield is 10% and 12%, respectively. As a result, yield values of broad bean and maize can decrease to 1.31 and 3 tons/acre, respectively.

Scenarios 4 and 5 have the same conditions as 2 and 3, respectively, but with more groundwater available at 108 MCM. The results show that, although the yield of maize decreased by 12% in scenarios 4 and 5, the production of maize increased by 64.7% and 47.4% compared with scenarios 2 and 3, respectively. In addition, cultivated areas in the summer increased to cover about 92% of A_v. The comparison between all scenarios shows that scenario 4 has the maximum production of 138,146 tons from all crops, while the production from strategic crops is 64,153 tons. However, to maximize the production of strategic crops, scenario 5 is recommended which produces 73,857 tons of strategic crops and the corresponding total production is 123,186 tons. With either of these two scenarios, policy-makers may have to decide to increase the limit of crop water use to 6,202 m^3/acre/year, in addition to increase well discharge rate and the number of wells to withdraw 88 MCM from NAS, while for PNA, policy-makers can define a suitable discharge rate and working hours to withdraw 20 MCM.

3.4.4 Profits

To estimate profit until 2030, costs of the proposed project and revenues from crops are calculated annually. As mentioned earlier, costs of the project include capital and annual costs. Table 3.7 summarizes these costs, where CRF is used to convert from capital cost to annual cost.

Optimization results show that wheat, barley, broad bean, maize, and date palm are the only required crops. Therefore, the ARIMA model is applied to predict the annual sell prices and production costs of these crops from 2020 to 2030, such that net revenues can be estimated. Steps to choose the best ARIMA model to predict the price of wheat cereal are presented in this study. Figure 3.3 shows the time series for annual price of wheat from 2000 to 2010 which is the training set. The analysis indicates an increasing trend in prices such that differencing is applied to time-series data to make it stationary.

Table 3.7 Annual cost data.

Type of Cost	Description
15% of land price ($)	Paid once at the beginning of project
85% of land price ($/year)	Capital cost is paid annually with an interest rate of 5% for a life span of 9 years (CRF= 0.141)
Cost of irrigation system ($/year)	Capital cost is paid annually with an interest rate of 12.25% for a life span of 10 years (CRF= 0.178)
Cost of drainage system ($/year)	Capital cost is paid annually with an interest rate of 12.25% for a life span of 10 years (CRF= 0.178)
Maintenance of wells ($/year)	Paid annually for 126 wells
Maintenance of solar pumps ($/year)	Paid annually for 126 pumps
Maintenance of irrigation and drainage systems ($/year)	Paid annually

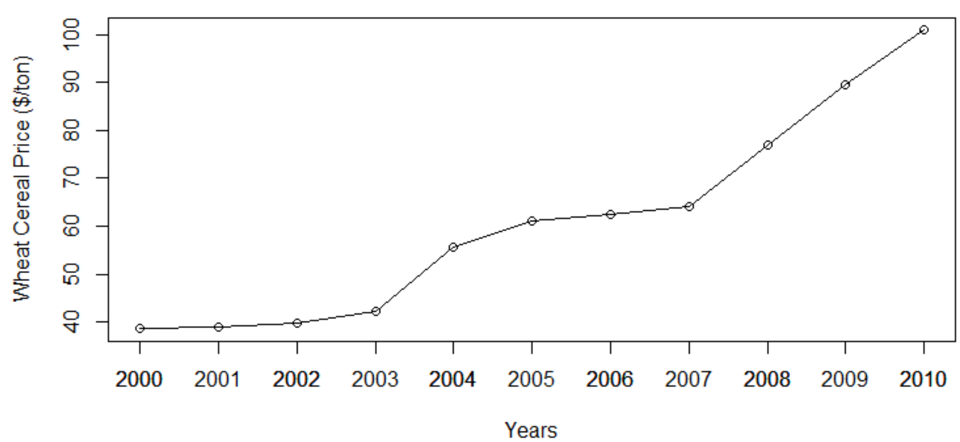

Figure 3.3 Time-series plot of annual price of wheat cereal from 2000 to 2010.

Figure 3.4 shows the plots of ACF and PACF that are used to estimate initial values of AR(p) and MA(q). This plot indicates that there is only one significant spike in ACF and the same for PACF. As a result, different ARIMA models are suggested and goodness-of-fit criteria are used to find better models that fit the training set as shown in Table 3.8.

The results show that ARIMA (2,2,2) and (2,3,2) have the lower error values and are chosen to predict the prices of wheat cereal through 2011 to 2017 with 95% confidence

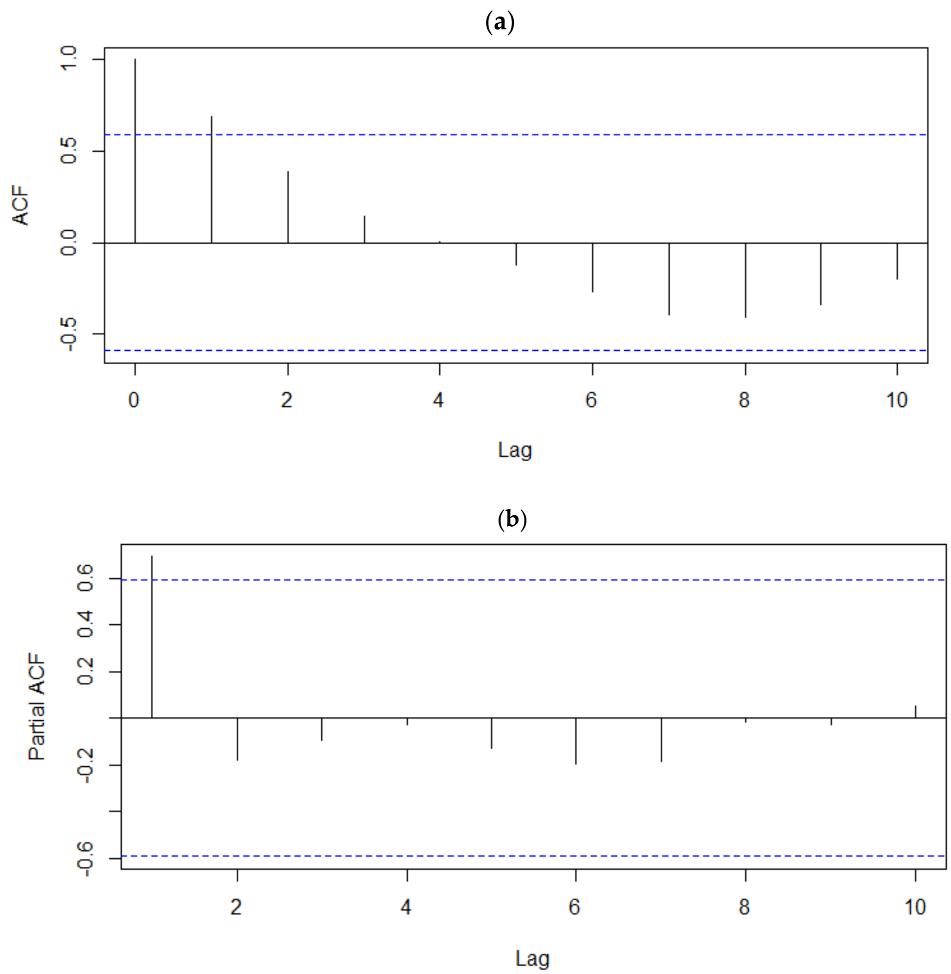

Figure 3.4 Plots for the price of wheat cereal; (a) ACF and (b) PACF.

Table 3.8 Goodness-of-fit criteria of ARIMA models for the price of wheat cereal.

ARIMA	(2,1,1)	(2,2,2)	(1,2,2)	(1,3,3)	(2,3,2)
MAE	3.5	2.13	3.3	2.8	2.53
RMSE	5.37	3.32	5	4.2	3.68
MAPE	5.4	3.3	5.13	4.44	3.93

level for prediction intervals. To identify the accuracy of these two models, the predicted data were compared with test sets using MAE, RMSE, and MAPE. The results show that values of MAE, RMSE, and MAPE for ARIMA (2,2,2) are 17.7, 21.5, and 11.3, respectively, while for ARIMA (2,3,2) these values are 13.4, 16.7, and 9.1, respectively. As a result, ARIMA (2,3,2) was selected to predict the price of wheat cereal with perdition intervals at 95% confidence level as shown in Figure 3.5. These steps are repeated to predict prices and production costs for all cultivated crops until 2030 and the corresponding ARIMA models are shown in Table 3.9. As a result, net revenues from these crops can be calculated.

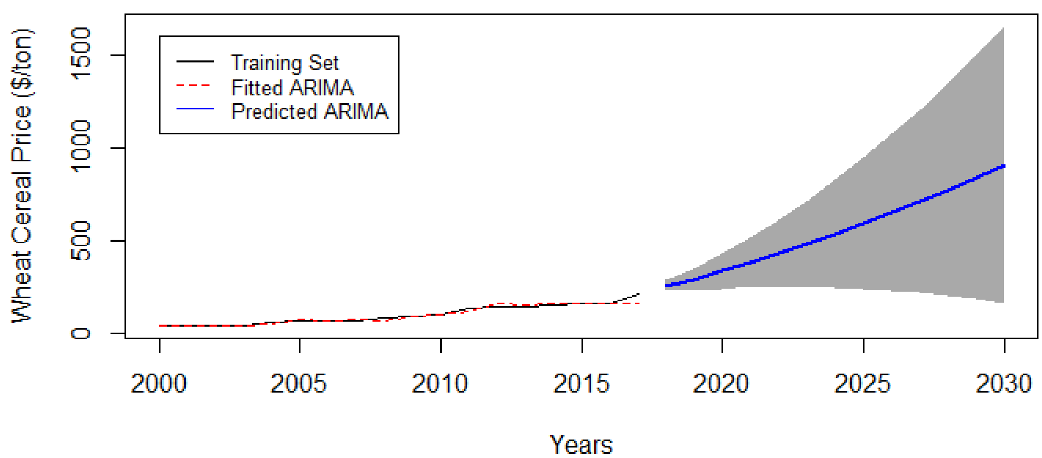

Figure 3.5 Predicted values using ARIMA (2,3,2). Note that shaded areas represent perdition intervals with a 95% confidence level.

Table 3.10 shows profits from each scenario from 2020 to 2030. Negative values of profit are present at the beginning of the project because of date palm where the production of this cash crop starts in year 5.

Figure 3.6 shows a comparison between the base scenario and the other five scenarios in crop production and cumulative profits from 2020 to 2030. This plot indicates

Table 3.9 Results of ARIMA model for all crops.

Crop		ARIMA
Wheat	Cereal price	(2,3,2)
	Straw price	(2,2,2)
	Production cost	(2,3,2)
Barley	Cereal price	(1,3,3)
	Straw price	(3,3,2)
	Production cost	(0,2,2)
Broad bean	Bean price	(2,2,1)
	Straw price	(0,2,2)
	Production cost	(1,2,1)
Maize	Cereal price	(1,2,3)
	Straw price	(2,2,2)
	Production cost	(2,2,1)
Date Palm	Price	(2,2,2)
	Annual cost	(2,3,1)

Table 3.10 Estimated profit for each scenario.

Profits ($ million)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Base Scenario	-29.8	-12.4	-12	-11.4	22.3	40.6	59.7	97.5	136.8	188.8	243.6
Scenario 1	-25.2	-8.3	-7.5	-6.4	16.8	29.7	43.2	69.2	96.2	135.4	173.8
Scenario 2	-28.3	-10.9	-10.4	-9.7	24.1	42.4	61.6	99.5	138.9	190.9	245.9
Scenario 3	-23.6	-6.7	-5.8	-4.7	18.6	31.6	45.2	71.2	98.3	137.5	176.0
Scenario 4	-27.4	-10.0	-9.5	-8.8	25.1	43.4	62.7	100.5	140.0	192.1	247.0
Scenario 5	-22.9	-6.0	-5.0	-3.9	19.4	32.4	46.1	72.1	99.2	138.5	177.0

that the cumulative profits in scenarios 1, 3, and 5 decreased by 28.5%, 25.7%, and 24.4%, respectively, compared to the base scenario because of the decrease in date palm area which is the source of income, however, there is an extra production in strategic crops. For instance, in scenario 5, extra production of wheat and maize can feed around 33,000 and 519,467 people, respectively. For scenarios 2 and 4, there is an increase in cumulative profits of about 2.8% and 4.4%, respectively compared with the base scenario as date palm area covers the entire 30% area of permanent crops. Scenario 4 has more profit than scenario 2 because of more groundwater availability. As a result, the highest cumulative profit is $755.2 million in scenario 4 given the maximum production while scenario 1 has the lowest value of $517 million.

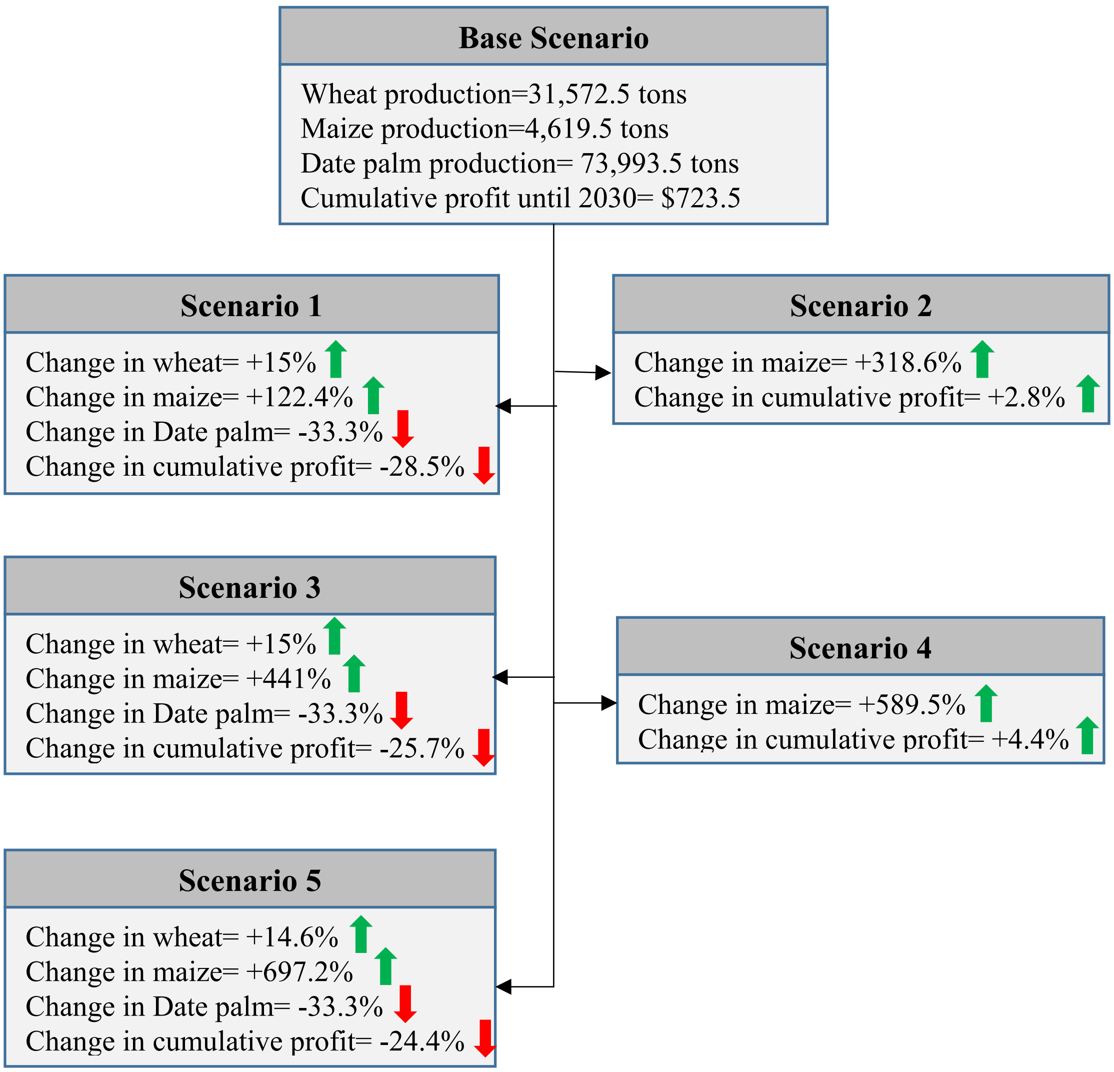

Figure 3.6 Comparison between different scenarios for crop production and profit.

3.4.5 Uncertainty Analysis

Due to the uncertainty and risks in estimating future profit, Monte Carlo simulations (MCS) were applied in years 2025 and 2030. The probability distributions of prices and production costs of cultivated crops are triangular distributions and the number of simulations is 10,000. Figure 3.7 shows box plots of profit from all scenarios in 2025 and 2030. The comparison between all scenarios shows that the median of profit for the base scenario, and scenarios 2 and 4, are around \$42 million and \$245 million in 2025 and 2030, respectively. However, for the remaining scenarios, these values are \$31 million and \$175 million in 2025 and 2030, respectively. These values are close to the estimated profit shown in Table 3.10. The higher profits are present in the base scenario, and scenarios 2 and 4 because the land distribution allocated 30% for cash crops.

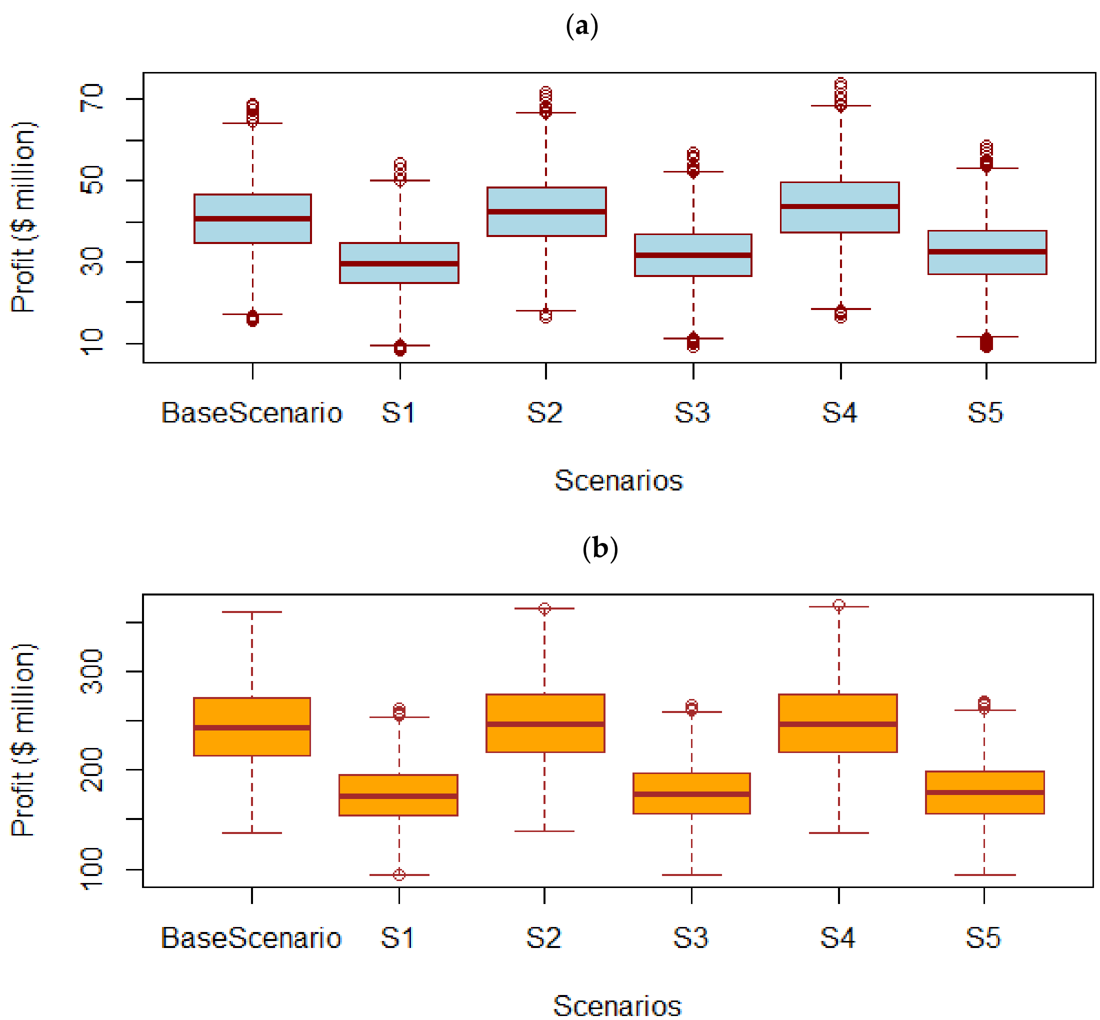

Figure 3.7 Box plot of profit from uncertainty analysis for all scenarios; (a) 2025 and (b) 2030.

To evaluate the risk to profit, histograms are used and shown for the base scenario and scenario 5. These two scenarios are chosen as these represent two situations where the base scenario follows the government policy while scenario 5 allows advancing beyond these policies to increase crops production. Figure 3.8 shows the cumulative probability distribution of profits for the base scenario in years 2025 and 2030. The results indicate that there is 95% probability that profits can be \$56.9 million and \$323.3 million in 2025 and 2030, respectively. However, the profits for scenario 5 at same probability can be \$47.4 million and \$239.5 million in 2025 and 2030, respectively, as shown in Figure 3.8. Comparing these values with Table 3.10 shows that expected profits with uncertainty considered can exceed the estimated values by about 1.3%. As a result, there is a low risk of not achieving the estimated profit subjected to the conditions selected here.

Results from this study prove that government goals are achievable by 2040 under current climatic conditions. Of course, this work did not consider external stresses due to natural disasters and global and regional political and economic impacts. The proposed crop types and land distribution may be changed in the future based on the population consumption and their needs. Also, leaching requirement may be increased to address any increase in groundwater salinity.

Different strategies are proposed for enhancing both crops area distribution and profit under sustainable agriculture development in Siwa. The methodology proposed in this study can be a significant contribution to understand and assess the development potentials of other areas of the reclamation project in the Western Desert region under similar government policies. In future work, the effect of climate change on agriculture developments needs to be studied.

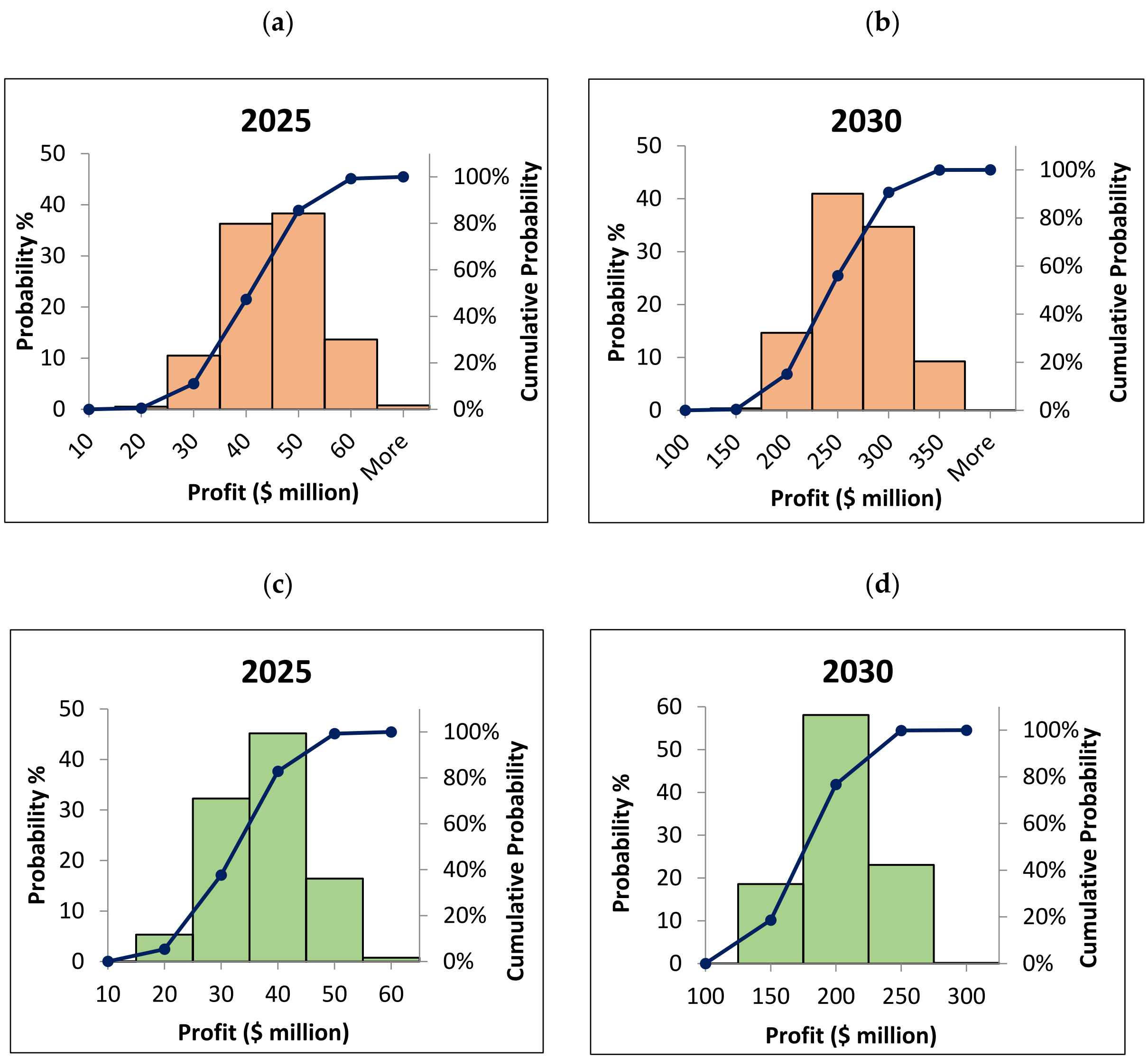

Figure 3.8 Histograms of profit with uncertainty; (a) and (b) base scenario for years 2025 and 2030, respectively, (c) and (d) scenario 5 for years 2025 and 2030, respectively.

3.5 Conclusions

The Egyptian government initiated a project in 2015 to reclaim 1.5 million acres to increase agriculture production and rural resettlement from the Delta region that has high population density. This study focused on the 30,000 acres in the Siwa region within the proposed project area to identify if the government goals can be achieved under stipulated policies. It also aimed to explore possible other changes in the policy to further expand agriculture production under sustainable conditions especially using groundwater available in NAS. This study determined the crop area and the estimated total water requirements for both population and livestock under current climatic conditions by 2040. An optimization model was used to maximize crops production. An ARIMA model was applied to predict sell prices and production costs of cultivated crops such that profit from the project can be estimated.

The results show that only 17,010 acres can be cultivated in Siwa under the proposed government policies which represents 56.7% of the planned area. Required crop areas in winter and summer are 7,154 and 6,629 acres, respectively. The estimated total water requirement is 40.6 MCM which is a summation of IWR, and population and livestock water requirement. Crop area and total water requirements were compared with available land of 17,010 acres and available groundwater from NAS which is 88 MCM, respectively. The comparison shows that there is available capacity of land and groundwater in Siwa. As a result, optimization analysis was used to maximize crop production under stipulated government policies. Different scenarios were also proposed by relaxing some of the government policies to further increase agriculture production. The results from these scenarios show that the available land area can be cultivated in the winter but not in the summer due to high crop water demand for summer crops.

The ARIMA model was used to develop models that can predict crop sell prices and production costs for the next 10 years. The results indicate that to maximize production, scenario 4 is recommended which has a total production of 138,146 tons, while the corresponding production from strategic crops is 64,153 tons. This scenario has the highest cumulative profit from 2020 to 2030 which is $755.2 million. However, to maximize production from strategic crops regardless of profit compared with the base scenario, scenario 5 is recommended where the production of strategic crops is 73,857 tons and the corresponding cumulative profit is $547 million. Scenario 4 represents the condition of relaxing crop water use and mixing water from NAS with water from PNA. Scenario 5 is the same as 4 except the change of land distribution to be 80% for strategic crops and 20% for cash crops.

The uncertainty analysis considering sell prices and production costs of cultivated crops shows that the profits are about 1.3% higher than the estimated values without uncertainty. This result indicates a low risk in the estimated profits.

In conclusion, the findings from this study show that there is available capacity in Siwa that can be used for future expansion to cover the national deficit in the strategic crop production of Egypt. Optimization analysis is a good tool to understand the true potential of the region with selected uncertainty analysis to address price and cost uncertainty. One distinct advantage of this study is that the results highlight a methodology that can be easily used in other parts of the Western Desert as the project expands with time to ensure the full potential of investment is realized.

Acknowledgments

This work was funded by Cultural Affairs and Missions Sector, Ministry of Higher Education, Egypt and Utah Water Research Laboratory, Utah State University.

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CHAPTER 4

CLIMATE CHANGE IMPACTS ON AGRICULTURE DEVELOPMENT IN THE WESTERN DESERT OF EGYPT: A CASE STUDY OF THE SIWA REGION

Abstract

The Siwa region located in the Western Desert of Egypt has 30,000 acres available for reclamation as a part of a national project to increase agricultural production and encourage population resettlement in Egypt. This study addressed the climate change-driven long-term concerns of developing an agricultural project in this region using groundwater from the Nubian Sandstone Aquifer System (NSAS). This study used two regional climate models (RCMs) under two representative concentration pathways (RCPs); RCP 4.5 and RCP 8.5. Results show that the increase in water requirement of crops is estimated around 6% to 8.1% under RCP 4.5 while around 9.7% to 18.2% under RCP 8.5 in this century. Projected seasonal temperatures are compared with observed data showing that the maximum increase in summer is 1.68 ± 1.64°C in 2060 and 4.65 ± 1.82°C in 2100 under RCP 4.5 and RCP 8.5, respectively. In winter, these values are 0.66 ± 0.74°C in 2060 and 2.51 ± 0.47°C in 2100, respectively. Maximum reductions of strategic crop yields vary from 2.9% to 12.8% in 2060 under RCP 4.5, while from 10.4% to 27.4% at the end of this century under RCP 8.5. While there is uncertainty in the results, this study shows there is a significant impact of climate change on the proposed development project in Siwa. Results from this study indicate that government goals are achievable with proper land area adjustments. The proposed methodology can be used to project the impact of climate change on similar regions in Egypt or elsewhere such that management and

adaptation options can be proposed for sustainable agricultural development.

4.1 Introduction

Egypt has been facing major challenges due to the increase in population, limited water resources, and insufficient agriculture production. At the beginning of 2020, population in Egypt exceeded the 100 million (https://www.worldometers.info/world-population/egypt-population/ accessed August 2020) with an increase of 60% since the early 2000s [1]. The Nile River represents 94% of all renewable water resources in Egypt which provides 55.5 billion m^3 annually since the agreement between Egypt and Sudan in 1959 [2]. However, there are concerns about the future availability of this resource with the commencement of the Grand Ethiopian Renaissance Dam (GERD) that may reduce the water share of Egypt during the filling period. Crop production in Egypt is insufficient for population needs, where self-sufficiency values of some strategic crops such as wheat, maize, broad bean, and barley are 34.5%, 47%, 30.7%, and 86%, respectively in 2017 [3]. As a result, these concerns are the major threats to the long-run food security in Egypt.

Accordingly, the Egyptian government initiated a new development project in 2015 to reclaim 1.5 million acres mostly lands located in the Western Desert of Egypt. The goals of this project are to increase agricultural areas enabling rural development, population resettlement from dense regions such as the Delta region, increase strategic crop production, and increase investments. The primary source of water is the non-renewable NSAS which is a transboundary aquifer shared between Egypt, Libya, Sudan, and Chad. In Egypt, NSAS has two aquifers; the upper aquifer is Post Nubian Aquifer (PNA) which has high groundwater salinity around 3,000 to 7,000 ppm, and the lower aquifer is Nubian Aquifer System (NAS) which has high groundwater quality with salinity around 200 to

400 ppm [4]. The Siwa region is one of the areas that will be reclaimed with an area of about 30,000 acres (see Figure 4.1) which is the focus of this study.

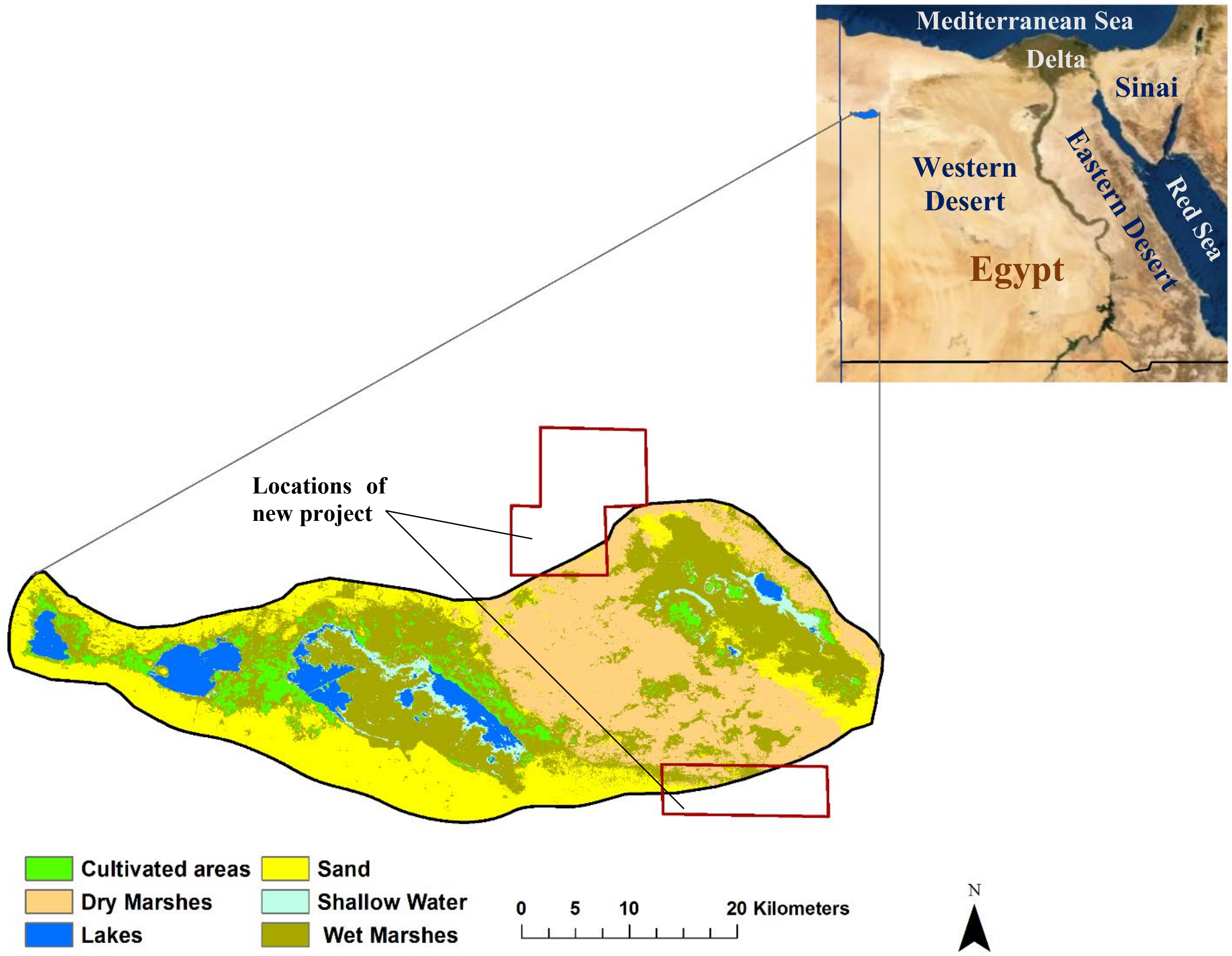


Figure 4.1 Physical description of the proposed reclamation project in Siwa.

To ensure sustainability of any future agriculture development, the possible impacts of climate change should be considered. Climate change considers the increase in temperature, increase of carbon dioxide (CO_2), sea-level rise, and precipitation variability that can have a significant effect on crop production [5]. Rising CO_2 might increase crop yield due to enhancing the photosynthesis process and water use efficiency [6], however, the effect of CO_2 varies due to the uncertainty in many complex interaction mechanisms

[7,8]. Therefore, this study considers the effect of rising temperature only while the impact of CO_2 is neglected. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) predicted an increase in global temperature of 0.3–4.8°C by the end of the 21st century under different greenhouse gas (GHG) emission scenarios [9,10]. Zhao et al. [11] investigated the impacts of global mean temperature increase on different crops and showed that the reduction of global yields of wheat and maize are $6 \pm 2.9\%$ and $7.4 \pm 4.5\%$, respectively per degree Celsius increase in temperature. In Africa, temperature is projected to exceed 2°C by mid-21st century and 4°C by the end of the 21st century [12] where crop yields are expected to decrease by 10% to 20% in 2050 [13].

To simulate the response of the global climate system due to the increase of GHG emissions, global climate models (GCMs) are typically used, but, the spatial resolutions of GCMs are coarse (>100 km). Therefore downscaling techniques are used to obtain local and regional climate information through RCMs with resolution (≤ 50km) [14]. Coordinated Regional Downscaling Experiment (CORDEX) is a project established by the World Climate Research Programme (WCRP) which produced a large number of RCM scenarios. CORDEX covered the globe through 14 spatial domains that provide historical data from 1951 to 2005, and projection data from 2006 to 2100 through different RCPs; RCP 2.6, RCP 4.5, and RCP 8.5. For RCP 4.5, global GHG emissions are stable at 4.5 W/m^2 before 2100 by using technology and different strategies. While RCP 8.5 assumes continuous increases of GHG emissions over time until 8.5 W/m^2 in 2100 (https://sos.noaa.gov/datasets/climate-model-temperature-change-rcp-45-2006-2100/ accessed in January 2020). In this study, RCMs are used due to the higher resolution under two emission scenarios; RCP 4.5 and RCP 8.5 where these represent two situations of moderate and high GHG emissions, respectively that may happen in the future.

It is expected that Egypt may be affected by climate change which may produce a decrease in the agricultural economy of Egypt [15]. Abdrabbo et al. [16] studied reference evapotranspiration (ET_o) over time in Egypt using different RCPs; RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5 for three time periods; 2011-2040, 2041-2070, and 2071-2100. The comparison between the results and observed data from 1971 to 2000 showed that ET_o can increase in the Delta region by about 5% to 20.1%, while 4.7% to 19.6% in the Middle of Egypt. The increase of ET_o in the South of Egypt can be between 11% and 26.8%.

While this development project has not commenced in Siwa yet, this study assumes a start of 2020. This study addressed the practical concerns of developing new and sustainable agricultural practices in Siwa considering the impact of climate change on agriculture productivity and crop water requirement in this century. An optimization analysis was conducted to maximize crop production using the available capacity in Siwa. The methodology developed in this study is a useful guide to analyze and assess the development potentials of other areas of the Western Desert in Egypt.

4.2 Study Area Description and Data

The Siwa region is a natural depression located in the northwest of the Western Desert in Egypt as shown in Figure 4.1. It has an area of 0.28 million acres and groundwater is the only source of water. Climate is semiarid where rainfall is almost negligible [17]. The development project in Siwa of 30,000 acres will depend on groundwater from NAS due to high groundwater quality.

This study followed the proposed government policies to avoid significant depletion of NSAS and to ensure sustainability of the aquifer for future generations. The

Ministry of Water Resources and Irrigation (MWRI) has restricted policies about prioritizing water consumption, where some of these policies are related to the maximum discharge rate of each well, maximum daily working hours per pump, spacing between wells, and maximum allowable crop water use which is estimated to be 4,000 m^3/acre/year [18]. The Research Institute for Groundwater (RIGW) of Egypt provided recommendations to ensure sustainability of NSAS in this century. Accordingly, the government policies on maximum annual groundwater withdrawal from PNA and NAS are 60 and 88 million cubic meters (MCM), respectively [19]. The Ministry of Agriculture and Land Reclamation (MALR) suggested the land distribution to be 70% for seasonal crops and the remaining for permanent crops [20].

4.2.1 Collected Data

Recent studies predicted a negative impact of increase in temperatures on crop yield as shown in Table 4.1. Kheir et al. [21] studied the impacts on wheat in the North coast of Egypt while Hassanein and Medany [22] predicted maize yield under different climatic conditions in Egypt. EL-Mansoury and Saleh [23] assessed the impact of climate change on broad bean in the North Nile Delta. Calzadilla et al. [24] provided data about the response of crop yield to changes in temperature of 2°C and 4°C using crop types C3 and C4, and the location. As barley is considered a C3 crop which is a type that is highly affected by temperature, results related to North Africa are used. Eid et al. [25] found that an increase in temperature of 2°C can decrease barely yield by 20% in Egypt which is in agreement with Calzadilla et al. [24]. Knezević et al. [26] investigated the possible impact of climate change on olives production through nine stations in Montenegro, Europe. Results related to the northern stations are shown in Table 4.1 given their similar climatic conditions as in Egypt. Ponti et al. [27] studied the effect of climate change on olives in different sub-regions of the Mediterranean basin. Their results showed that with an increase in temperature of 1.8°C from 2041 to 2050, the yield of olives in Egypt can decrease by 9.4% which is compatible with the results of Knezević et al. [27]. Due to the limited data about date palm, it is assumed that the reduction in date palm yield due to the increase in temperature is the same as oil palm. As a result, the study made by Sarkar et al. [28] is used where they assessed the relationship between climate change and oil palm production using multiple regression in Malaysia. Finally, the results provided in Table 4.1 are used here to define the linear relationship between the increase in temperature and crop yield over time.

Table 4.1 Impact of temperature on crop yield from prior studies.

Crop	Change in crop yield (%) at different increases in temperature				Reference
	1°C	**2°C**	**3°C**	**4°C**	
Wheat	-5.08	-9.35	-13.11	-17.65	Kheir et al. [21]
Date Palm	-10.17	-20.38	-30.55	-40.75	Sarkar et al. [28]
Olives	-6		-14	-18	Knezević et al. [26]
Maize		-14.4		-24.2	Hassanein and Medany [22]
Barley		-17.29		-29.32	Calzadilla et al. [24]
Broad Bean	**1.9°C**	**2.1°C**	**2.3°C**	**2.5°C**	EL-Mansoury and Saleh, [23]
	-11.43	-14.15	-18.15	-23.14	

4.2.2 Climate Change Models

This study used two RCMs; Rossby Centre regional climate model (RCA4) and Regional Atmospheric Climate Model (RACMO22T). RCA4 is developed at the Swedish Meteorological and Hydrological Institute (SHMI) and considered three downscaled GCMs; Centre National de Recherches Météorologiques (CNRM-CM5), EC-EARTH consortium (EC-EARTH), and Max Planck Institute for Meteorology (MPI-ESM-LR).

RACMO22T is developed at the Koninklijk Netherlands Meteorological Institute (KNWI) and linked to the downscaled EC-EARTH model. Table 4.2 shows the combinations of these four climate models. The selection of these combinations depends on the availability of four meteorological data; maximum temperature (T_{max}), minimum temperature (T_{min}), relative humidity (RH), and wind speed (U) for the historical climate condition and future climate projection under RCP 4.5 and RCP 8.5. Daily meteorological data is downloaded using CORDEX-Africa domain (AFR-44) with a spatial resolution of 0.44° by 0.44° (approximately 50 km by 50 km) (http://www.cordex.org/domains/region-5-africa/ accessed January 2020) for years; 2020, 2040, 2060, 2080, and 2100. Data were downloaded in NetCDF format and Grid Analysis and Display System (GrADS) software (http://opengrads.org/) was used in the analysis.

Table 4.2 Description of RCMs used and the corresponding GCMs.

Developer	RCM		GCM		Model Identifier
	Model	Resolution	Model	Resolution[1]	
SMHI	RCA4	0.44°x0.44°	CNRM-CM5	1.4°x1.4°	M1
KNMI	RACMO22T	0.44°x0.44°	EC-EARTH	1.125°x1.125°	M2
SMHI	RCA4	0.44°x0.44°	EC-EARTH	1.125°x1.125°	M3
SMHI	RCA4	0.44°x0.44°	MPI-ESM-LR	1.875°x1.875°	M4

[1]https://portal.enes.org/data/enes-model-data/cmip5/resolution accessed July 2020.

4.3 Methodology

4.3.1 Reference Evapotranspiration (ET_o)

The United Nations Food and Agriculture Organization (FAO) Penman-Monteith equation is applied to project ET_o (mm/day) using the four meteorological data mentioned earlier. As a result, crop evapotranspiration (ET_c) (mm/day) can be calculated [29]. Details about ET_o and ET_c calculations for different cultivated crops in Siwa are provided by

Moghazy and Kaluarachchi [30]. Thereafter, crop water requirement (CWR) (m^3/acre/year) can be calculated which is a function of the projected ET_c, irrigation efficiency, and leaching requirements [31].

After downloading the daily meteorological data using the four climate models, a bootstrap technique is applied for monthly data for resampling with replacement of 10,000 runs. Thereafter, the new values of daily meteorological data are used to estimate ET_o for each model. However, different climate models produce uncertainty, therefore, to evaluate the performance of these models, long-term average monthly historical ET_o values from 1981 to 2005 are compared with observed values using root mean squared error (RMSE) as follows:

$$\mathrm{RMSE}=\sqrt{\frac{1}{U}\sum_{i=1}^{U}(E_i - \widehat{E}_i)^2} \qquad (1)$$

where E_i and $\widehat{E}_i$ represent historical and observed ET_o values, respectively for the long-term average of month i, and U is the number of months. The observed data in Siwa were downloaded from the National Centers for Environmental Prediction (https://globalweather.tamu.edu/).

To estimate ET_o using the accuracy of each climate model, a weighted model is developed and used. ET_o is a function of T_{max}, T_{min}, RH, and U, therefore, the uncertainty of ET_o is a combination of errors from these variables. Monthly uncertainty of ET_o for each model ($\delta ET_o(M)$) is computed using an error propagation method as shown in Equation (2) using the work of Askari et al. [32].

$$\delta ET_o(M) = \sqrt{\left[\frac{\partial ET_o}{\partial T_{max}}\,\delta T_{max}(M)\right]^2 + \left[\frac{\partial ET_o}{\partial T_{min}}\,\delta T_{min}(M)\right]^2 + \left[\frac{\partial ET_o}{\partial RH}\,\delta RH(M)\right]^2 + \left[\frac{\partial ET_o}{\partial W}\,\delta W(M)\right]^2} \qquad (2)$$

where $\frac{\partial ET_o}{\partial T_{max}}$, $\frac{\partial ET_o}{\partial T_{min}}$, $\frac{\partial ET_o}{\partial RH}$, and $\frac{\partial ET_o}{\partial W}$ are partial derivative of ET_o with respect to T_{max}, T_{min}, RH, and W, respectively, M is order of the climate model (see Table 4.2), and $\delta T_{max}(M)$, $\delta T_{min}(M)$, $\delta RH(M)$, and $\delta W(M)$ are monthly errors of these variables when comparing historical data of each model (M) with observed data from 1981 to 2005. $\delta ET_o(M)$ values are inversely weighted to determine the accuracy of each model. Therefore, a monthly weighted ET_o model (ET_o(weighted)) is calculated as follows:

$$ET_o(\text{weighted}) = \sum_1^M \left[ET_o(M) * \frac{W(M)}{100}\right] \quad (3)$$

where $ET_o(M)$ is monthly predicted ET_o of model M (mm/day), and W is weight of model M (%). As a result, the corresponding water requirement of cultivated crops is projected until 2100 and compared with the current requirements from 2000 to 2017 to explore the need for adaptation actions due to climate change.

4.3.2 Projection of Temperature and Crop Yield

The resampled values of T_{max} and T_{min} are used to project the trend of future temperature. To study the impact of temperature on crop yield, seasonal average temperature (T_{avg}) of the primary growing seasons of summer and winter is used. The winter season is from October to April for wheat, barley, and broad bean while the summer season is from May to September for soybean, maize, and cotton, etc., [33].

Seasonal T_{avg} is compared with observed values from 2000 to 2017 to determine the changes in temperatures for each season ($\triangle T$) using the four climate models for years; 2020, 2040, 2060, 2080, and 2100. To account for uncertainty, the mean of $\triangle T$ values is used with 95% confidence intervals (CI).

To identify the relationship between increase in temperature and crop yield, the following linear regression equation is used with data presented earlier:

$$CY = a + b * \triangle T + e \quad (4)$$

where CY is change in crop yield (%), a and b are constants, and *e* is error. As a result, crop yields until 2100 can be projected under different emission scenarios. Results are considered significant when two-sided p-value < 0.025. R software version 3.6.1 was used (https://www.r-project.org/).

4.3.3 Projected Crop Area and Water Requirements

The goal of this study is to investigate if government goals of increasing agricultural areas and population resettlements from the already over-populated Delta region are achievable this century. Therefore, crop area and total water requirements for population and livestock are estimated then compared with available land and groundwater in Siwa. The assumptions made by Moghazy and Kaluarachchi [31] on population and livestock at the beginning of the proposed project in 2020 are used in this study where the annual growth rate of population is 2.5% [1].

Although there are 30,000 acres available in Siwa, stipulated government policies are considered in the estimation of actual available land for cultivation (Av) per details of Moghazy and Kaluarachchi [31]. This study used the land distribution suggested by Moghazy and Kaluarachchi [31] to maximize the production of strategic crops in Siwa where seasonal crops cover 80% of Av and consist of wheat, barley, and broad bean in the winter, and maize in the summer as sources of strategic crops to cover crop deficit in Egypt. The remaining 20% of Av is for permanent crops such as olives and date palm which are the sources of rural income. To calculate the area of strategic crops needed to satisfy population consumption annually, Eq. (5) is used.

$$\text{Crop area (acres)} = \frac{\text{N}*\text{Crop Consumption (kg/capita/year)}}{1{,}000*\text{Crop Yield (tons/acre)}} \quad (5)$$

where N is population, and crop consumptions are 143.2, 0.3, 7.8, and 62 kg/capita/year for wheat, barley, broad bean, and maize, respectively [34]. It is assumed these values to remain same for the future. Crop yield depends on the projected temperature under each emission scenario. The area of strategic crops required for livestock feeds as concentrate feeds and roughage feeds is calculated per Moghazy and Kaluarachchi [31]. For permeant crops, olives and date palm are assumed to cover the area equally. As a result, the total required crop area in winter or summer season can be estimated then compared with A_V to assess land availability.

Total water requirement is the summation of irrigation water requirement (IWR), industrial water requirement, and water requirement for population and livestock. Industrial water requirement is neglected because this project is primarily focused on reclamation and rural development. Current domestic water requirement is 250 L/capita/day [35], and water requirement for sheep, goats, and chicken is 10, 10, 0.3 L/head/day, respectively [36,37]. Both domestic and livestock water requirements are assumed to remain constant. IWR of crops is the summation of CWR multiplied by the area of each crop. As a result, total water requirement can be estimated over time and compared with 88 MCM of allowable annual groundwater extraction from NAS. When IWR is divided by A_v, the value of IWR per acre can be compared with the allowable crop water use of 4,000 m^3/acre/year to determine if government policy is satisfied.

4.3.4 Optimization Analysis

Optimization is a method used for optimal allocation of available resources based on an objective with specific constraints. In this work, linear programming (LP) is used to find opportunities to maximize strategic crop production through the most appropriate cropping pattern subject to a given set of constraints. Moghazy and Kaluarachchi [31] suggested different scenarios to maximize crop production in Siwa. This study used one scenario from this earlier study to maximize the production of strategic crops as a part of government goals. This scenario increases the area of strategic crops to 80% of Av instead of 70% while relaxing the crop water use constraint. Therefore, the objective function and constraints are as follows:

$$\text{Max } P = \sum_{i=1}^{n} Y_i * A_i \qquad (i= 1, 2, \ldots, n) \qquad (6)$$

where P is total crop production (tons), n is number of crops, Y_i is yield of crop i (tons/acre), and A_i is area of crop i (acres).

For land availability, an additional constraint is added where olives and date palm cover the area of permanent crops equally to control date palm cultivation given high water requirement.

$$\sum_{i=1}^{w} A_i \leq 80\% \text{ Av} \qquad (7a)$$

where w is number of seasonal crops in winter which are wheat, barley, and broad bean.

$$\sum_{i=1}^{s} A_i \leq 80\% \text{ Av} \qquad (7b)$$

where s is number of seasonal crops in summer which is maize.

$$A_o \leq 10\% \text{ Av} \qquad (7c)$$
$$A_d \leq 10\% \text{ Av} \qquad (7d)$$

where A_o, and A_d are the areas of olives and date palm (acres), respectively.

For crop production, the total production of strategic crops should satisfy the total requirement of population and livestock.

$$Y_j * A_j \geq CP_j * N + \sum_{k=1}^{2} CL_{jk} * L_k \qquad (8)$$

where Y_j is yield of strategic crop j (tons/acre), j is number of strategic crops (wheat, barley, broad bean, and maize), A_j is area of strategic crop j needed for population and livestock (acres), CP_j is annual consumption of strategic crop j per capita (ton/capita/year), k is number of livestock categories (sheep and goats), CL_{jk} is consumption of strategic crop j for each category k (ton/head/year), and L_k is number of heads in each category k.

Also total water requirement should be less than the available groundwater from NAS.

$$\sum_{i=1}^{n}(CWR_i * A_i) + \text{Population and livestock water requirement} \leq 88 \text{ MCM/year} \quad (9)$$

where CWR_i is water requirement of crop i (m^3/acre/year).

In this work, optimization is used in year 2100 as it represents the worst period of this century and analysis is conducted for each emission scenario. The reason is to assess whether crop and water requirements are sustainable across all years as sought by the government. The LP model was applied using General Algebraic Modeling Systems (GAMS; http://www.gams. com/).

4.4 Results and Discussion

4.4.1 Predicted ET_o

ET_o is predicted using the resampled daily meteorological data for each climate model (see Table 4.2). Figure 4.2 shows the comparison between the current ET_o values and the median values for each month using Model 1 in 2100 under different emission scenarios. Results show that a minimum of 2.79 mm/day and a maximum of 10.53 mm/day can happen in January and June, respectively under RCP 4.5 which are higher than the current values of 2.73 and 9.25 mm/day, respectively. With RCP 8.5, these values are 3.05 mm/day and 11.17 mm/day, respectively with an increase of more than 6% compared to RCP 4.5. Similar comparisons were conducted with other models in different years. As expected, ET_o is showing uncertainty among the four climate models as shown in Figure 4.3 for monthly ET_o in 2100 under RCP 4.5. To evaluate the performance of these models given this uncertainty, RMSE is calculated using Eq. (1) and the results are shown in Table 4.3 demonstrating that Model 1 is the best to use while model 2 is the worst. Table 4.4 shows the accuracy of each model to determine monthly ET_o using an error propagation method described in Eq. (2). Results indicate that Model 1 is not always the best model, as Models 3 and 4 have also better accuracy in some months.

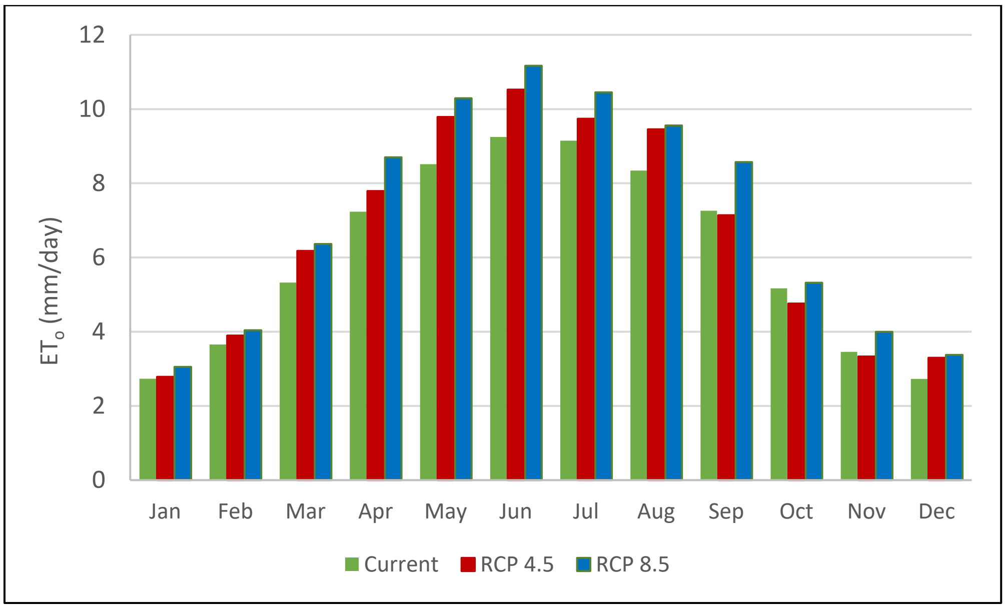


Figure 4.2 Comparison between current ET_o and monthly projected ET_o using Model 1 in 2100 under RCP 4.5 and RCP 8.5.

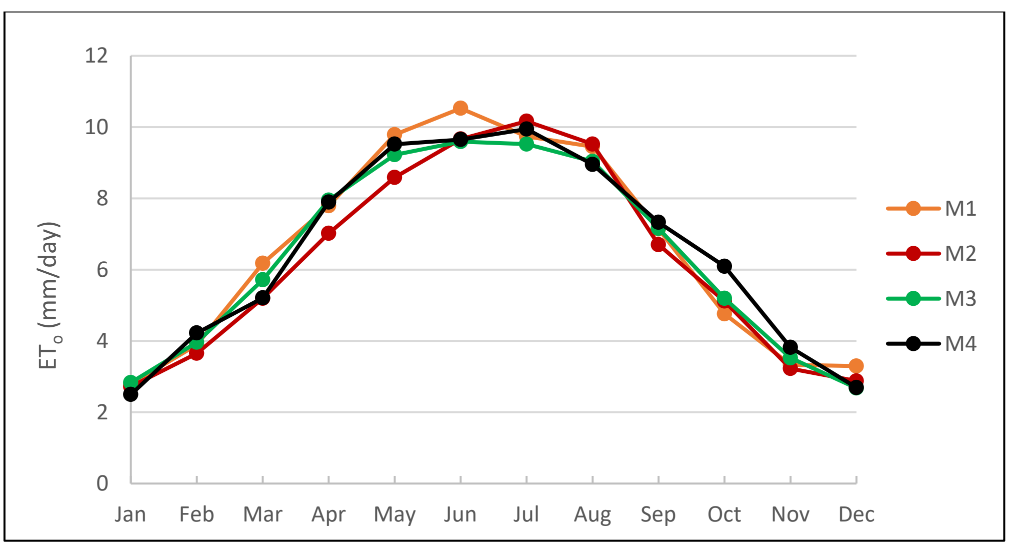


Figure 4.3 Uncertainty of monthly ET_o between models in 2100 under RCP 4.5.

Table 4.3 RMSE produced by different climate models.

Model Identifier	RMSE
M1	0.278
M2	0.726
M3	0.419
M4	0.327

The advantage of using multiple climate models is that uncertainty produced by each model can be used to develop an appropriate weighted model for future use. As a result, a monthly weighted model is used to calculate ET_o(weighted) using Eq. (3). RMSE for this weighted model is 0.259 which is better than 0.278 produced by Model 1. Thereafter, ET_o(weighted) can be calculated in the future using the accuracy of each model (see Table 4.4). Figure 4.4 shows ET_o(weighted) in 2100 under RCP 4.5 and RCP 8.5 where the highest values are in June of 9.97 and 10.72 mm/day, respectively.

Table 4.4 Accuracy of each climate model (%). Numbers in bold represent the highest accuracy value in each month.

Month	Model 1	Model 2	Model 3	Model 4
January	24.85	16.32	**32.53**	26.30
February	**41.64**	11.82	31.66	14.88
March	18.60	18.56	**31.45**	31.39
April	26.06	9.43	**38.58**	25.94
May	22.01	12.18	23.97	**41.84**
June	**37.33**	15.07	20.71	26.89
July	**37.81**	15.44	22.16	24.59
August	**36.91**	14.75	20.14	28.19
September	**36.47**	13.70	18.23	31.60
October	27.60	13.40	21.00	**37.99**
November	25.31	17.70	24.50	**32.49**
December	19.80	10.36	19.41	**50.43**

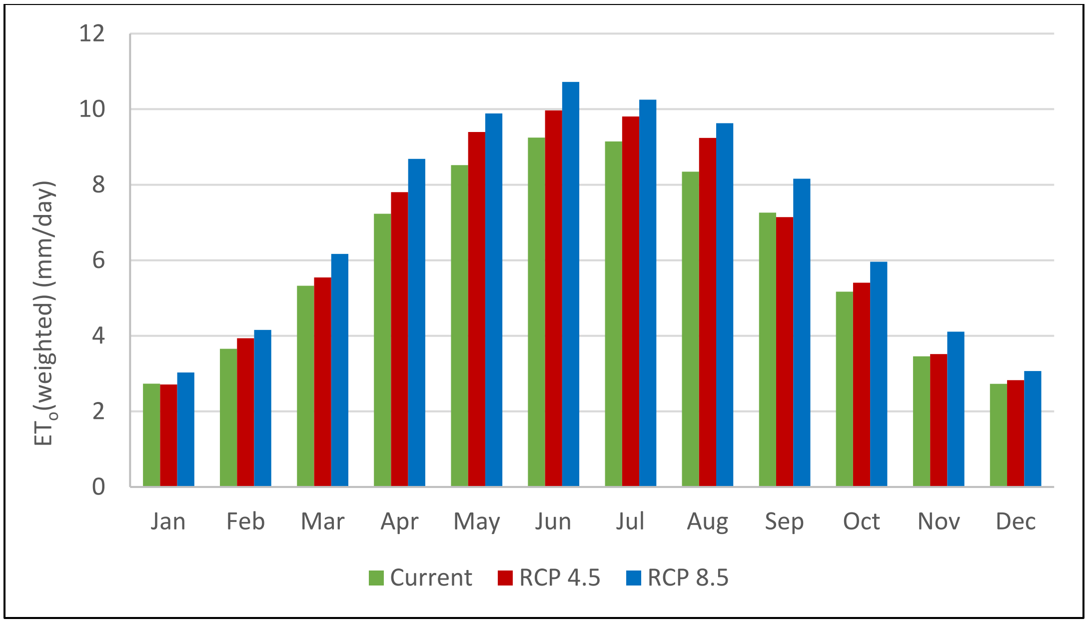


Figure 4.4 ET_o(weighted) under RCP 4.5 and RCP 8.5 in 2100.

Using the calculated values of ET_o(weighted), CWR in this century can be projected as shown in Table 4.5. Results show that the maximum water requirement of crops is 26,786 m^3/acre in 2040 under RCP 4.5 while it is 29,279 m^3/acre in 2100 under RCP 8.5. Annual water requirement of crops is compared with the current requirement of 24,771 m^3/acre and the results show that the increase over time ranges from 6% to 8.1% under RCP 4.5, while it is 9.7% to 18.2% under RCP 8.5 as shown in Table 4.5.

4.4.2 Projected Temperature

Figure 4.5 shows box plots of projected annual T_{max} using the four climate models under different emission scenarios. Results show the fluctuations of T_{max} over time under RCP 4.5 where median is the highest at 30°C in 2060 then decreased to 29.5°C in 2100. This is compatible with the expectations of RCP 4.5 where greenhouse gas emissions are expected to be controlled before 2100. However, median values are increasing gradually until 2100 under RCP 8.5 with a maximum value of 32°C. These increases in temperatures

Table 4.5 Change in projected CWR with different emission scenarios.

RCP	Water requirement	2020	2040	2060	2080	2100
RCP 4.5	Cultivated crops (m^3/acre/year)	26,247	26,786	26,626	26,677	26,554
	Changes to current requirment (m^3/acre/year)	1,475	2,014	1,855	1,906	1,783
	Changes (%)	6.0	8.1	7.5	7.7	7.2
RCP 8.5	Cultivated crops (m^3/acre/year)	27,169	28,072	28,346	29,075	29,279
	Changes to current requirment (m^3/acre/year)	2,398	3,301	3,574	4,304	4,508
	Change (%)	9.7	13.3	14.4	17.4	18.2

are expected due to the continuous increase of GHG. The same is observed with projected T_{min} where median has a maximum of 15°C in 2080 and 18°C in 2100 under RCP 4.5 and RCP 8.5, respectively.

Predicted T_{avg} in summer using the four models under RCP 4.5 is compared with observed values and the corresponding ΔT values are shown in Figure 4.6. It shows that Model 1 and 4 have positive values of ΔT until 2100 while the other models show a decrease in temperature in some years. The same comparison was done for winter, and under RCP 8.5. Results show that at the end of this century, ΔT values in summer range from 0.03 to 3.49°C and 2.4 to 6.9°C under RCP 4.5 and RCP 8.5, respectively. In the winter, these values range from -0.2 to 1.5°C and 1.9 to 3.1°C, respectively.

Due to the uncertainty in seasonal △T values, the mean is used to study the impact of climate change on crop yield which is discussed later. Table 4.6 shows the mean of △T with 95% CI for each season over time under both emission scenarios. Results show that the maximum increase in temperature in summer is 1.68 $\pm$ 1.64°C in 2060 and 4.65 $\pm$ 1.82°C in 2100 under RCP 4.5 and RCP 8.5, respectively. In winter, these values are 0.66

± 0.74°C in 2060 and 2.51 ± 0.47°C in 2100, respectively.

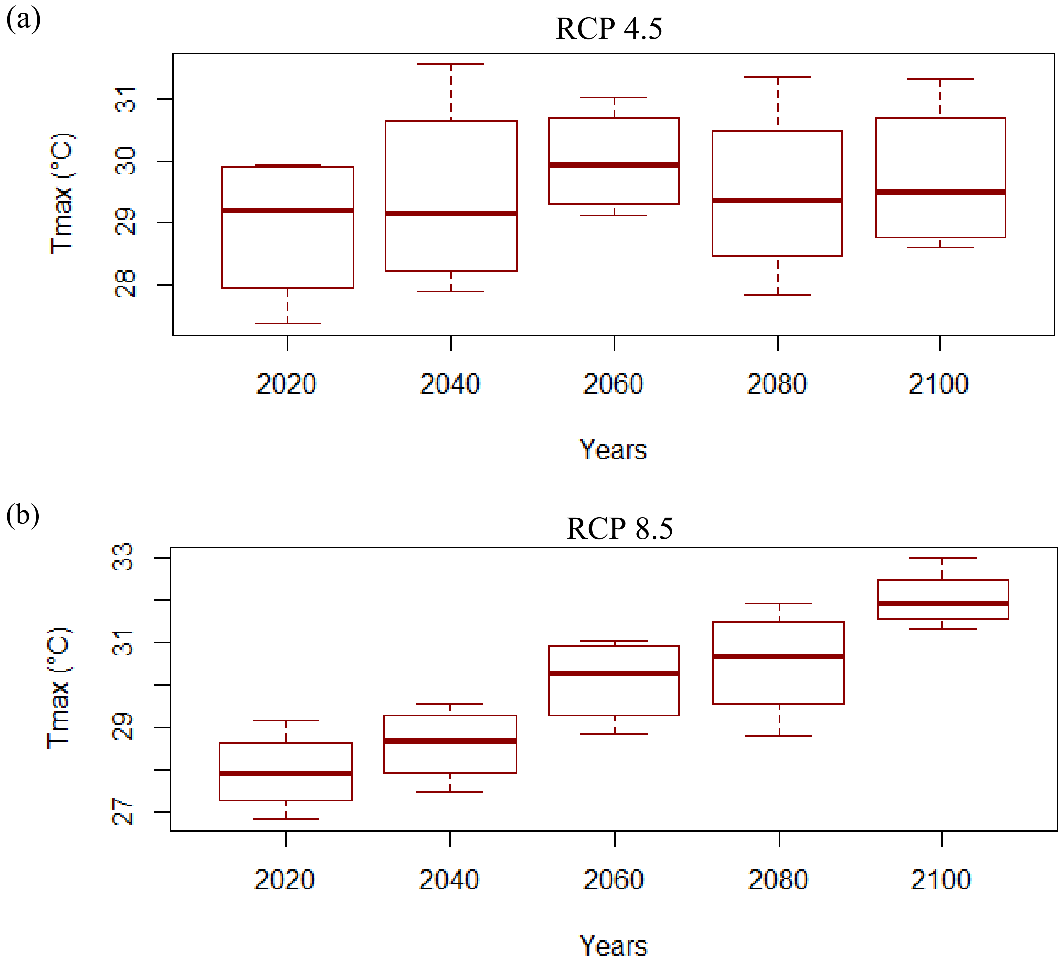


Figure 4.5 Box plots of annual T_{max} under; (a) RCP 4.5 and (b) RCP 8.5.

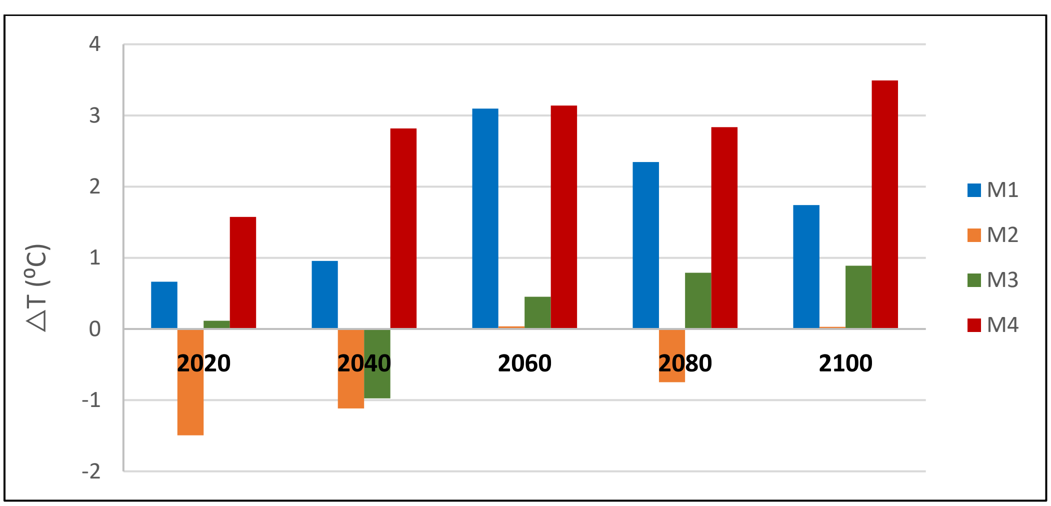


Figure 4.6 ΔT values in the summer using four climate models under RCP 4.5.

Table 4.6 Projected ΔT with 95% CI over time.

RCP	Season	ΔT (°C)	2020	2040	2060	2080	2100
RCP 4.5	Summer	Mean	0.22	0.42	1.68	1.31	1.54
		Lower Limit	-1.05	-1.40	0.05	0.29	0.09
		Upper Limit	1.48	2.24	3.32	2.90	2.99
	Winter	Mean	0.47	-0.16	0.66	0.31	0.60
		Lower Limit	-0.91	-1.49	-0.07	-1.47	-0.14
		Upper Limit	1.85	1.16	1.40	2.09	1.34
RCP 8.5	Summer	Mean	0.12	0.73	2.40	2.90	4.65
		Lower Limit	1.80	1.09	1.78	1.62	1.86
		Upper Limit	-1.64	-0.34	0.65	1.31	2.82
	Winter	Mean	-0.76	-0.75	0.84	1.61	2.51
		Lower Limit	0.73	1.17	1.77	1.10	0.48
		Upper Limit	-1.47	-1.90	-0.90	0.53	2.04

4.4.2.1 Impact of Temperature on Crop Yield

A linear distribution between increase in temperature and change in crop yield is developed and presented in Table 4.7. Results show that the intercept values for all crops are significant except for wheat and date palm where p-values are more than 0.025. Slope values for all crops are significant. As a result, the projected values of crop yields can be calculated as shown in Table 4.8. Results show that the maximum reduction in yields of wheat, barley, broad bean, and maize are 2.9%, 9.2%, zero, and 12.8%, respectively in 2060 under RCP 4.5, while these values under RCP 8.5 are 10.4%, 20.4%, 22.6%, and 27.4%, respectively at the end of this century. It is clear that the most affected strategic crop is maize due to the high increase of temperatures in summer.

4.4.3 Estimated Crop Area and Total Water Requirements

Population and livestock data are calculated to estimate future requirements of crop area and water. Accordingly, population in 2020 of 16,460 is projected to be 118,669 by 2100. Similarly for livestock of sheep, goat, and chicken are expected to increase from

Table 4.7 Relationship between ΔT (°C) and change in crop yield (%).

Crop	Linear regression equation			
	Intercept	p-value	Slope	p-value
Wheat	-0.93	0.0778	-4.147	0.000589
Barley	-5.26	0.0000	-6.015	0.0000
Broad bean	26.32	0.0221	-19.56	0.0083
Maize	-4.6	0.0000	-4.9	0.0000
Olive	-1.95	0.0048	-4.01	0.00079
Date palm	0.015	0.4020	-10.19	2.6E-07

3,129, 4,864, and 125,096, respectively in 2020 to be 22,555, 35,062, and 901,889, respectively in 2100. Av is determined by Moghazy and Kaluarachchi [31] which is 17,010 acres and consistent with government policies. Population and livestock consumption of strategic crops over time is calculated and Tables 4.9 and 4.10 show crop area for years 2020, 2040, 2060, 2080, and 2100 under both emission scenarios. Results show that the

Table 4.8 Predicted crop yield under two emission scenario RCP 4.5 and RCP 8.5.

Crop	Crop yield (tons/acre)				
	RCP 4.5				
	2020	2040	2060	2080	2100
Wheat	2.73	2.78	2.7	2.74	2.71
Barley	1.52	1.65	1.50	1.53	1.50
Broad bean	1.45	1.45	1.45	1.45	1.45
Maize	3.22	3.18	2.97	3.03	3.00
Olive	4.00	4.04	3.87	3.93	3.88
Date palm	14.00	14.31	12.77	13.30	12.92
	RCP 8.5				
Wheat	2.78	2.78	2.68	2.59	2.49
Barley	1.65	1.65	1.48	1.40	1.31
Broad bean	1.45	1.45	1.45	1.36	1.12
Maize	3.23	3.13	2.85	2.77	2.48
Olive	4.14	4.14	3.79	3.69	3.47
Date palm	14.50	14.50	12.11	11.18	9.21

Table 4.9 Projected crop area and water requirements under RCP 4.5.

Crop	2020	2040	2060	2080	2100
Wheat (acres)	943	1,500	2,550	4,117	6,846
Barley (acres)	128	192	346	556	928
Broad bean (acres)	218	357	585	958	1,570
Maize (acres)	493	817	1,433	2,302	3,809
Olives (acres)	1,701	1,701	1,701	1,701	1,701
Date Palm (acres)	1,701	1,701	1,701	1,701	1,701
Total area in Winter (acres)	4,691	5,451	6,883	9,033	12,746
Total area in Summer (acres)	3,895	4,219	4,835	5,704	7,211
Estimated total water requirement (MCM/year)	29.9	35.3	44.1	57.4	80.1

Table 4.10 Projected crop area and water requirements under RCP 8.5.

Crop	2020	2040	2060	2080	2100
Wheat (acres)	916	1,500	2,569	4,357	7,458
Barley (acres)	117	192	351	607	1,063
Broad bean (acres)	218	357	585	1,022	2,033
Maize (acres)	491	830	1,494	2,518	4,608
Olives (acres)	1,701	1,701	1,701	1,701	1,701
Date Palm (acres)	1,701	1,701	1,701	1,701	1,701
Total area in Winter (acres)	4,653	5,451	6,907	9,388	13,956
Total area in Summer (acres)	3,893	4,232	4,896	5,920	8,010
Estimated total water requirement (MCM/year)	30.8	37	47	64.6	**94.5**

required areas of wheat, barley, broad bean, and maize in 2100 under RCP 4.5 are 6,846, 928, 1,570, and 3,809 acres, respectively. However, these areas increased by 8.9%, 14.5%, 29.5%, and 21%, respectively under RCP 8.5 due to the impact of temperature increase on crop yield. Results also show that the total cultivated areas in winter or summer are less than A_V of 17,010 acres through all years. Total water requirement (m^3/year) is estimated over time as shown in Tables 4.9 and 4.10 where the projected values are 80.1 and 94.5 MCM in 2100 under RCP 4.5 and RCP 8.5, respectively. Figure 4.7 shows the corresponding IWR per acre of 4,000 and 4,900 m^3/acre under RCP 4.5 and RCP 8.5, respectively in 2100 where 4,900 m^3/acre is more than the government limit of 4,000 m^3/acre/year. Results show that under RCP 4.5 government goals of this project are achievable until the end of this century where adequate land and groundwater are available in Siwa. On the other hand, government goals under RCP 8.5 are satisfied until the 2080s only, while total water requirement exceeds available groundwater in NAS of 88 MCM by 2100. As a result, changes to crop area distribution are required, for example decreases the areas of olives or date palm, to satisfy population needs and be consistent with government policies. Figure 4.7 also shows the values of IWR per acre when neglecting the impact of climate change. These values are the lowest compared with RCP 4.5 and RCP 8.5 due to the higher crop water requiremnt under climate change and the impact of temperature increase on crop yield.

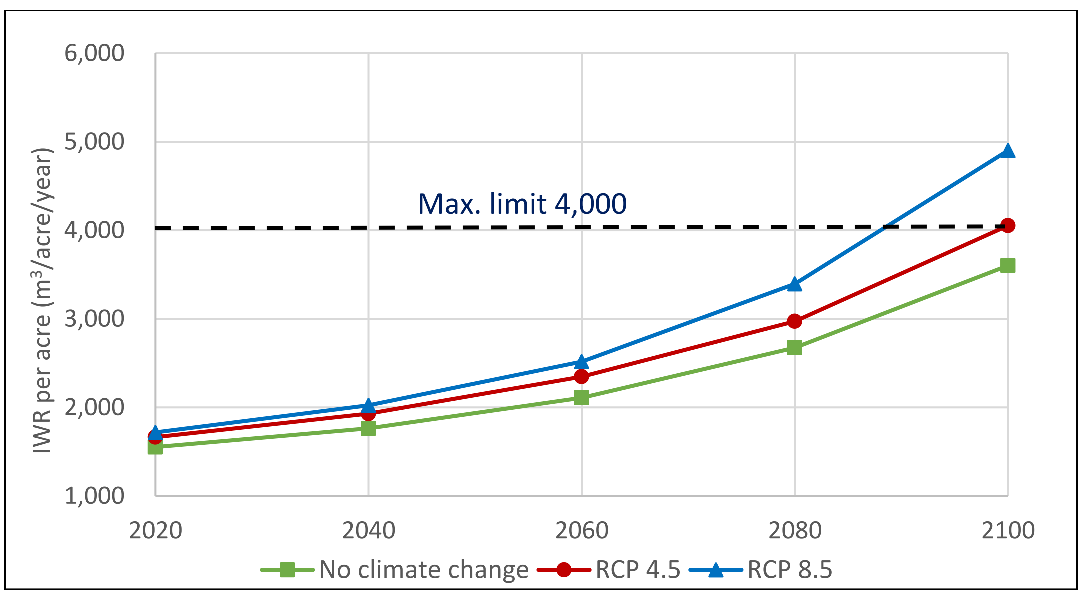


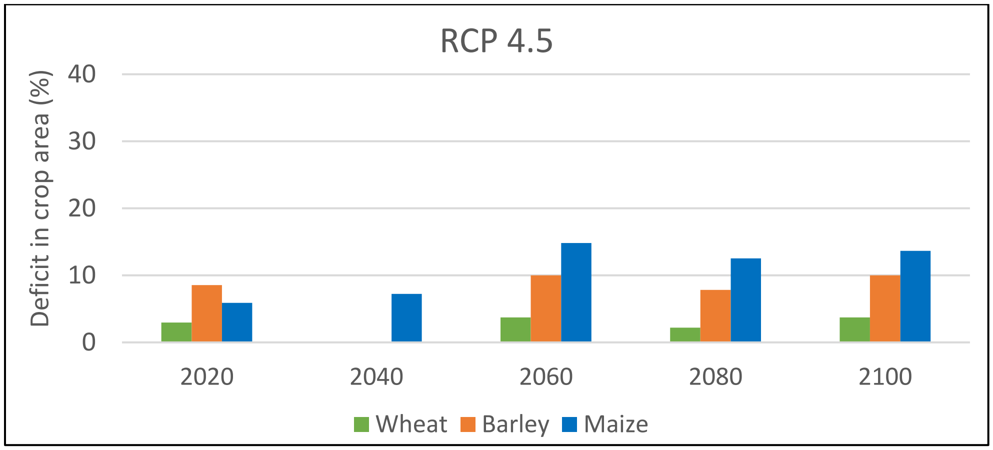
Figure 4.7 Irrigation water requirement per acre over time under both emission scenarios and in case of neglecting the impact of climate change.

Required area of strategic crops is calculated disregarding the impact of climate change on crop yield then compared with values presented in Tables 4.9 and 4.10. Figure 4.8 shows the possible future deficits to these areas where the deficit in maize is the largest compared to other crops due to the highest impact by temperature. Broad bean is not affected by climate change until 2080 under RCP 8.5. Figure 4.8 also shows that the maximum deficits in the areas of wheat, barley, broad bean, and maize are 3.7%, 10%, zero, and 14.8%, respectively in 2060 under RCP 4.5. A more significant deficits are exhibited in 2100 under RCP 8.5 with values of 13%, 26%, 29.5%, and 37.5%, respectively. These results clearly show while climate models have inherent uncertainty among their projections, there is a definite impact of climate change on agriculture productivity in Siwa. Therefore, climate change plays an important role in the decision-making of agriculture planning and management.

4.4.4 Optimization

As mentioned earlier, LP is used to identify the opportunities to maximize strategic crop production considering climate change impacts under both emission scenarios. Previous results showed that the development project in Siwa is achievable through this century under RCP 4.5 and not possible in 2100 under RCP 8.5 due to the proposed groundwater constraint of the government. As a result, LP is applied in 2100 under RCP 4.5. Since RCP 8.5 showed unsustainable development from 2080 through 2100, optimization is applied in 2080. Table 4.11 shows crop area that can be cultivated using the available land and groundwater under different emission scenarios. Results show that under RCP 4.5, the areas of strategic crops for wheat, barley, broad bean, and maize are 11,111, 928, 1,570, and 3,809 acres which are adequate for population and livestock needs

(a)



(b)

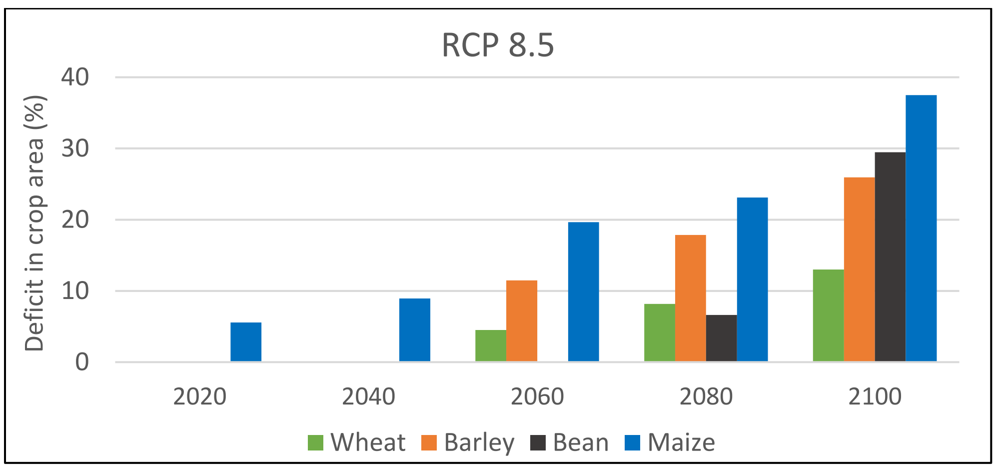


Figure 4.8 Percent Deficit in strategic crop areas produced when climate change is disregarded; (a) RCP 4.5, and (b) RCP 8.5.

until 2100. However, these areas under RCP 8.5 are 11,980, 607, 1,022, and 2,518 acres, respectively until 2080. It is noticed that the area of olives does not occupy the 10% of A_V to increase the area of strategic crops. LP shows that the total cultivated area in winter and summer can be increased to cover around 96% and 34% of A_v, respectively given the summer season has higher crop water requirement.

The cultivated areas for barley, broad bean, and maize under RCP 8.5 are not sufficient for population needs in 2100 per results shown in Table 4.10. Therefore it was decided to use optimization to identify if land allocations can be modified to achieve some

Table 4.11 Crop area and water requirements predicted from optimization analysis.

Crop	**2020-2100 (RCP 4.5)**	**2020-2080 (RCP 8.5)**	**2100 (RCP 8.5)**
Wheat (acres)	11,111	11,980	8,445
Barley (acres)	928	607	1,063
Broad bean (acres)	1,570	1,022	2,033
Maize (acres)	3,809	2,518	4,608
Olives (acres)	768	1,318	0
Date Palm (acres)	1,701	1,701	1,701
Total area in Winter (acres)	16,078	16,628	13,242
Total area in Summer (acres)	6,278	5,537	6,309
Estimated total water requirement (MCM/year)	≤ 88	≤ 88	88

of the development targets. The results of this optimization using LP for 2100 under RCP 8.5 are presented in Table 4.11. Results show that olives cannot be cultivated to satisfy the population needs of strategic crops causing some loss of profit, but, development targets are achievable with improved land and groundwater management. The corresponding values of IWR per acre are presented in Figure 4.9 where these values range from 4,470 to 4,554 m^3/acre/year and from 4,420 to 4,774 m^3/acre/year under RCP 4.5 and RCP 8.5, respectively. It is therefore recommended to increase the limit of crop water use to be 4,774 m^3/acre/year instead of 4,000 m^3/acre/year.

This analysis also calculated the production of strategic crops before and after optimization and the results are presented in Figure 4.10. It shows the increase in production for all years demonstrating the contribution of optimization to increase agriculture areas while maintaining sustainability. For example, the extra production in 2020 is 891% and 847% under RCP 4.5 and RCP 8.5, respectively showing that extra production of strategic crops may be used to cover the shortfalls in other parts of Egypt.

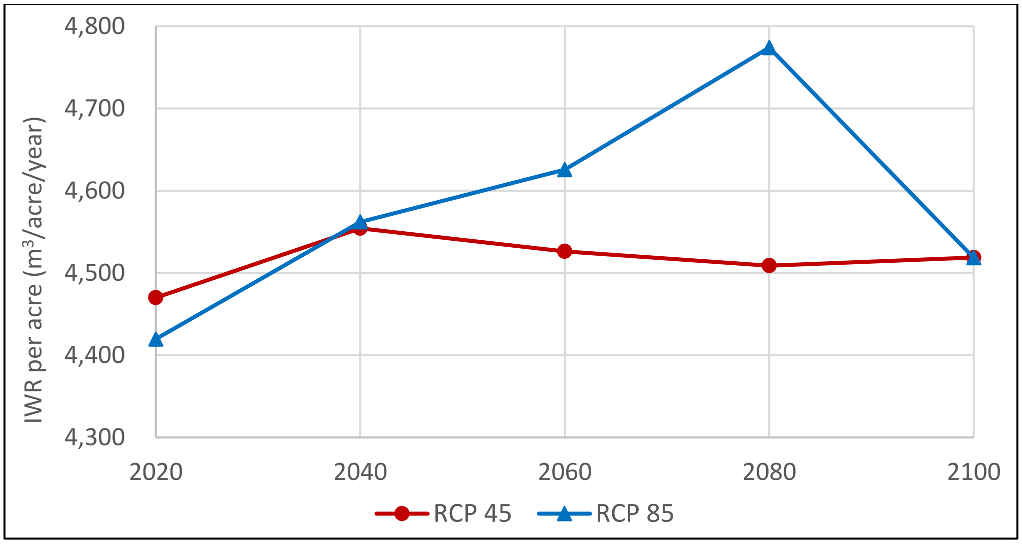


Figure 4.9 Irrigation water requirement per acre after optimization for both emission scenarios.

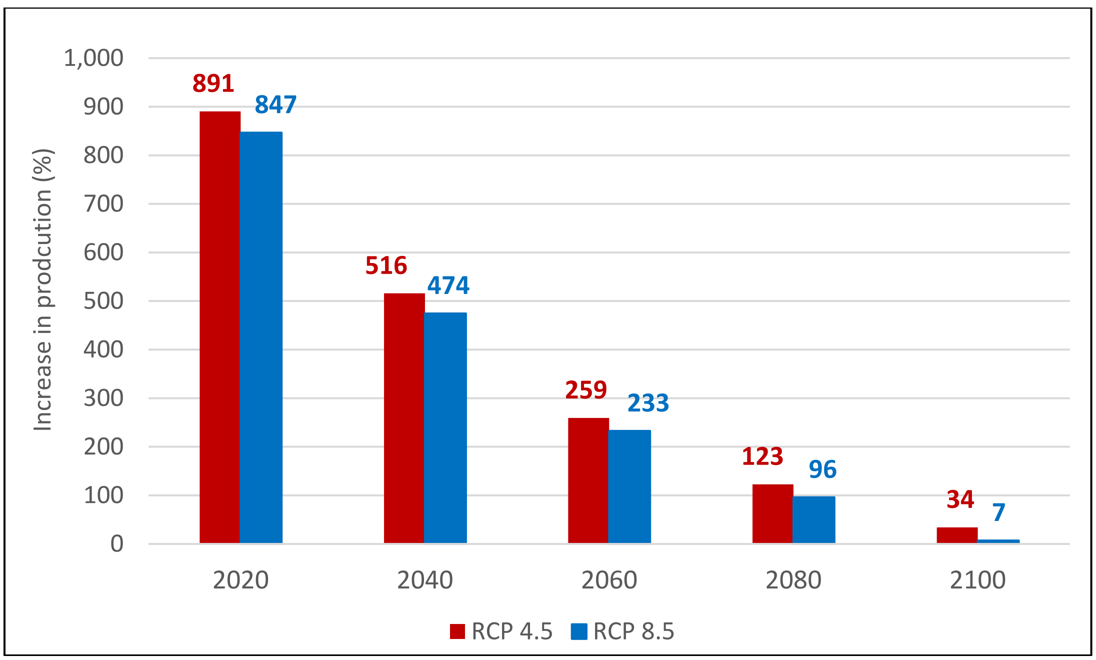


Figure 4.10 Increase in strategic crop production with optimization under RCP 4.5 and RCP 8.5.

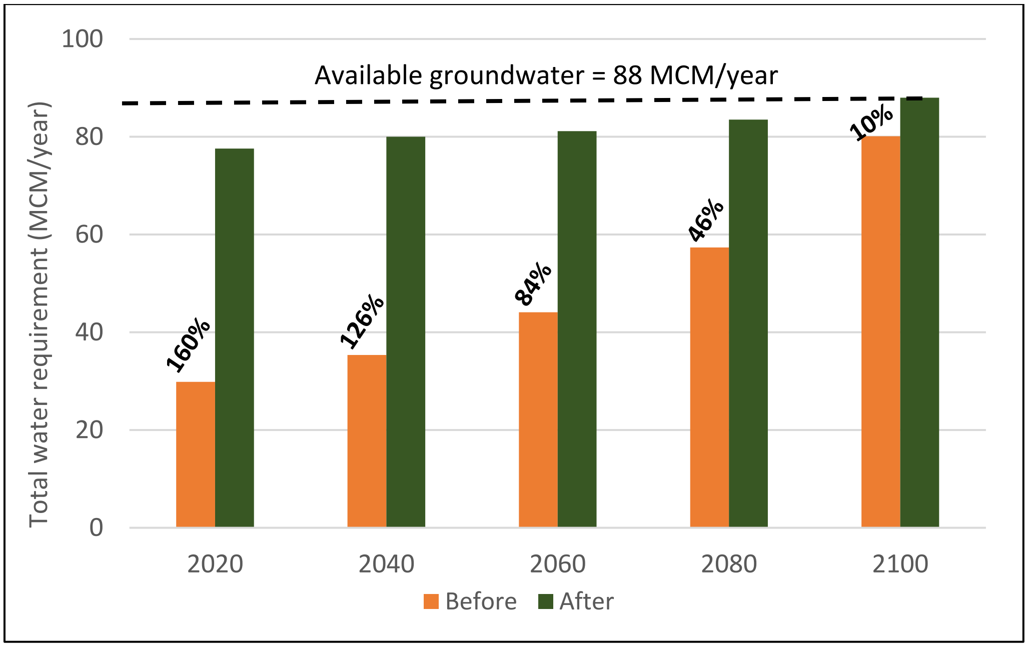
The projected total water requirement is also compared before and after optimization under both emission scenarios as shown in Figure 4.11. The results display the increase in water requirement over time due to the increase in agriculture areas predicted through optimization. In 2020, water requirement increases by 160% and 149% under RCP 4.5 and RCP 8.5, respectively after optimization using the available groundwater in NAS. It is noticed that under RCP 8.5 water requirement decreases by 7% in 2100, therefore, this development project is achievable without the depletion of the Nubian aquifer. Figure 4.11 also shows that there is still extra groundwater available for possible system expansion; for example, in 2020 total water requirement is estimated to be 29.86 MCM under RCP 4.5 while optimization showed that this requirement can increase to 77.58 MCM which is still less than 88 MCM.

Finally, this work projected the future changes in temperature in the Siwa region under two emission scenarios and assessed the impacts on crop water requirement and crop productivity. Results show that the proposed development in Siwa is possible until 2100 under the moderate emission scenario RCP 4.5 using the available land and groundwater. However, in the more aggressive emission scenario RCP 8.5, changes are needed in the land distribution to satisfy the required crop area for population and livestock farming needs until 2100. These results based on assumptions such as using current population and livestock water requirement, current crop consumption, and population growth rate of 2.5%. Also, there is a possibility that more water is needed in the future to address any increase in groundwater and soil salinity.

4.5 Conclusions

The proposed development project in Siwa is to reclaim 30,000 acres which is a part of a national project to reclaim 1.5 million acres mostly in the Western Desert of Egypt. The goals of this project are to increase agricultural areas enabling rural development and increase agriculture production to cover crop production needs in Egypt. This study investigated if stipulated government goals are possible under climate change during this century. As a part of this study, the estimated population and livestock data are used with projected temperatures to calculate land area needed, water requirement, and crop

(a)



(b)

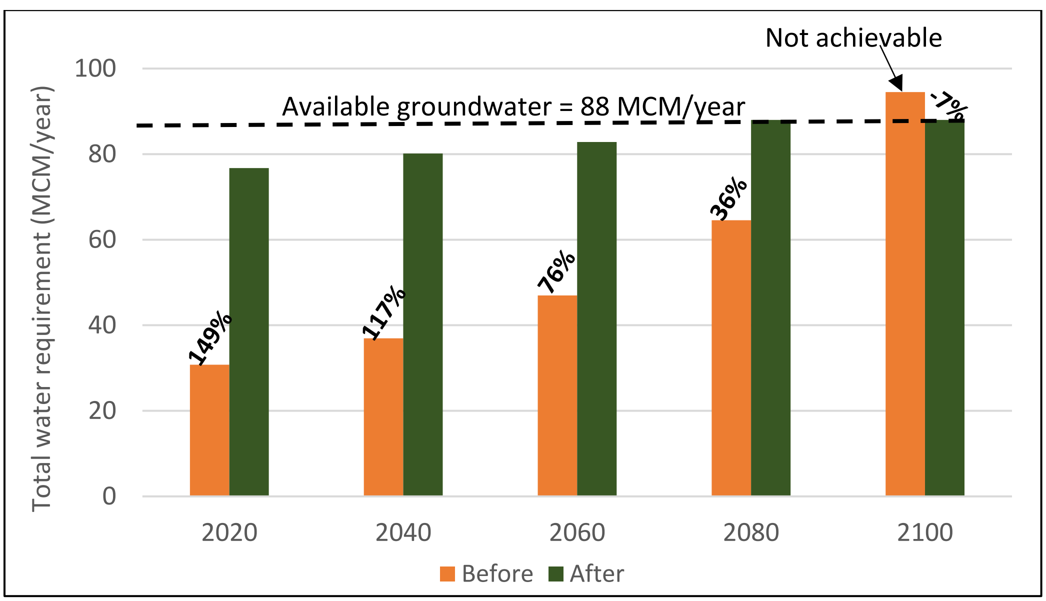


Figure 4.11 Estimated total water requirement before and after optimization; (a) RCP 4.5, and (b) RCP 8.5. Numbers in bold represent percent change in water requirement after optimization.

production. To maximize the benefits of this project, LP-based optimization analysis was conducted to explore the possibility of maximizing crop production subject to government policies.

Different meteorological data are downloaded using CORDEX-Africa under four climate models with two emission scenarios; RCP 4.5 and RCP 8.5. Results show that the maximum increase in temperature in summer is 1.68 ± 1.64°C in 2060 and 4.65 ± 1.82°C in 2100 under RCP 4.5 and RCP 8.5, respectively. In winter, these values are 0.66 ± 0.74°C in 2060 and 2.51 ± 0.47°C in 2100, respectively. The impact of temperature increase on crop yield is addressed and results show that the maximum reduction in yields of wheat, barley, broad bean, and maize are 2.9%, 9.2%, zero, and 12.8%, respectively in 2060 under RCP 4.5, while 10.4%, 20.4%, 22.6%, and 27.4%, respectively under RCP 8.5 at the end of this century. Maize is the most affected crop due to climate change with higher temperatures in the summer. The increase in water requirement of crops over time ranges from 6% to 8.1% under RCP 4.5 and from 9.7% to 18.2% under RCP 8.5.

The required area of strategic and permanent crops is determined then compared with the limit of 17,010 acres to assess land availability in Siwa. Future water requirement is also estimated until 2100 then compared with 88 MCM of available groundwater from NAS. Results show that this development project is possible in Siwa under the moderate emission scenario RCP 4.5 in this century. While under RCP 8.5, some of the proposed agricultural practices may need to be changed especially after 2080 such as olives crop that will not be cultivated in 2100.

The optimization analysis showed the possible increase in strategic crop production over time where the extra production is 891% and 847% in 2020 under RCP 4.5 and RCP

8.5, respectively. Also, water requirement increases over time due to the increase in agriculture areas through optimization. In 2020, water requirement increases by 160% and 149% under RCP 4.5 and RCP 8.5, respectively using the available groundwater in NAS.

In conclusion, the findings from this study show that the proposed agriculture development in Siwa under the national project to reclaim 1.5 million acres is possible. Although climate models produced uncertainty in their projections, one can agree that there is a definite impact of climate change on temperature, crop water requirement, and agriculture productivity. While this work is a case study demonstrating the viability of the proposed national project in the Siwa region, the key benefit is that the proposed methodology can be readily applied elsewhere in the Western Desert to assess the potential agriculture development projects under climate change.

Acknowledgments

This work was funded by Cultural Affairs and Missions Sector, Ministry of Higher Education, Egypt, and Utah Water Research Laboratory, Utah State University.

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CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary and Conclusions

In 2015, the Egyptian government initiated a development project to reclaim 1.5 million acres in different locations of Egypt. The goals of this project are to increase agriculture areas, increase crop production, decrease imported crops, population resettlement from the already over-populated Delta region, and increase investments and job opportunities. The Siwa region is one of the areas that will be reclaimed in the desert with 30,000 acres which is the focus of this study due to the abundance of groundwater from NSAS. The results of this dissertation can help the policymakers to find possible options for sustainable agricultural development in the Siwa region with or without the influence of climate change.

Chapter 2 addressed the historical behavior of groundwater withdrawal from PNA and the corresponding negative impact in Siwa Oasis from 1980 to 2012. This chapter analyzed historical water use, groundwater salinity, crop yield, and agricultural revenue. Total water use was estimated then compared with actual withdrawal to define the amount of excess water and the corresponding water use efficiency. Normalized Difference Water Index (NDWI) was used to identify the changes in the area of salty lakes in Siwa. The impact of groundwater salinity on crop yield and the corresponding income were analyzed. Findings from this chapter help to better understand and develop agricultural practices to ensure the sustainability of this aquifer for future generations.

Chapter 3 investigated if government goals of the development project in Siwa are achievable in the next 20 years to secure food and water requirements of population and livestock under current climatic conditions and ensuring government policies are followed. It also aimed to explore other possible changes in these policies to further expand agriculture production under sustainable conditions using available water and land capacity in Siwa. This chapter estimated crop area and total water requirements for both population and livestock under current climatic conditions by 2040. An optimization model was used to maximize crops production. An Autoregressive Integrated Moving Average (ARIMA) model was applied to predict selling prices and production costs of cultivated crops, such that profit from the project can be estimated considering the uncertainty.

Chapter 4 addressed the impact of climate change on agriculture productivity and crop water requirement for the development project in Siwa in this century. Different meteorological data were projected using the Coordinated Regional Downscaling Experiment (CORDEX) through the Africa domain. Two regional climate models (RCMs) were used under two representative concentration pathways (RCPs); RCP 4.5 and RCP 8.5. This chapter used population and livestock data with projected temperatures to calculate crop area and total water requirements to compare them with available capacity in Siwa.

The contributions from this dissertation are listed below:

- Identify the concerns in Siwa since 1980 related to unmanaged groundwater withdrawal and the usage of high salinity groundwater from PNA.
- Use the knowledge from this work to mitigate future concerns and better develop agricultural practices.
- Provide valuable insights to the ability to achieve government goals of the development project under current climatic conditions and the changes that may be

required to enhance production.

- Exploration of different scenarios above and beyond government goals to provide decision-makers with possible options for sustainable agriculture development.
- Predict annual profits of the project in Siwa until 2030 using ARIMA model considering uncertainty and risk involved.
- Investigate challenges faced in the presence of climate change and possible impacts on government development goals.
- Demonstrate that the proposed development project in Siwa is achievable under climate change with appropriate adjustments in crop areas.
- Development and demonstration of a comprehensive methodology that is readily exportable to other parts of the region that is able to address water-related concerns in sustainable agriculture development with and without the impacts of climate change and allowing decision-makers to explore various adaptation strategies.

5.2 Recommendations

- For the current activities in the Siwa region, groundwater management is a critical need to avoid the depletion of the Nubian Aquifer. To preserve groundwater resources while satisfying the needs of the region, proper irrigation management is essential. This includes the use of efficient irrigation methods such as drip or sprinkler systems instead of furrow irrigation which is a good solution to decrease water waste. Additionally, good drainage system in Siwa is critical to minimize the formation of salt lakes that can ruin water quality and soil fertility.
- For the development proposed project in Siwa, it is recommended to increase the discharge rate of wells and the number of wells considering the maximum

withdrawal of 88 MCM from the Nubian Aquifer System (NAS).

- Continuous use of optimization with improved and better data is an important step to use the available capacity of land and groundwater in the Siwa region to maximize production.
- It is recommended to mix groundwater from NAS with appropriate amounts from PNA, change land distribution to be 80% for strategic crops and 20% for cash crops, and increase the limit of crop water use to maximize the production of strategic crops under current climatic conditions.
- It is encouraged to apply the proposed methodology elsewhere in the region to assess the development potentials of similar reclamation project in the Western Desert region.

5.3 Future Works

- Explore possible mitigation options to reduce existing salty lake areas that are affecting the groundwater and soil quality.

- Continue collecting essential data related to meteorological information, water requirement, crop production, production costs, available groundwater in NSAS, etc. such that the proposed methodology can be used to improve prediction capability of the models and thereby improve development strategies.
- Given the uncertainty present in the climate change analysis, more work is needed to improve the uncertainty analysis of this work so the projections are more reliable.

- Improve and strengthen institution control of resource management through local and government policies to ensure adequate and equitable use of water and other resources across all stakeholder groups.
- Improve supply-demand network and other water relevant economic opportunities across the region such that economic conditions of the rural population can be improved beyond addressing food demand only.

APPENDIX

Appendix: CURRICULUM VITAE

Noha Hossam El Din Mohamed Mourad Moghazy

PhD candidate, November 2020
Department of Civil and Environmental Engineering
Utah State University
4100 Old Main Hill, Logan, UT 84322-4100, USA
Email: noha.moghazy@aggiemail.usu.edu, nonihoss2004@hotmail.com

EDUCATION

PhD in Water Resources Engineering, Utah State University, Logan, Utah. (November/2020). Grad GPA: 3.87 (A=4.0). Dissertation: Sustainable Agricultural Development in the Western Desert of Egypt Under Climate Change: A Case Study of the Siwa Region. Advisor: Dr. Jagath Kaluarachchi.

MSc in Irrigation Engineering and Hydraulics, Alexandria University, Alexandria, Egypt. GPA: 4.0. Thesis: Hydrodynamic Behavior of the Estuaries and Lake Inlets under the Effect of Tide and Waves. Advisors: Dr. Rawya Kansoh, and Dr. Mohamed Abd El-Mooty.

BSc in Civil Engineering, Alexandria University, Alexandria, Egypt. Total Graduation Grade: Distinction with Degree of Honor 92.46%.

PROFESSIONAL EXPERIENCE

Graduate Assistant (January, 2015-December, 2020), Department of Civil and Environmental Engineering, Utah State University, Logan, Utah, USA

Assistant Lecturer (June, 2013 to present, on study leave from December 2015 for pursuing Ph.D.), Irrigation Engineering and Hydraulics Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

Demonstrator (September, 2009 to June, 2013), Irrigation Engineering and Hydraulics Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

AWARDS

- 2016 to 2020: Full academic scholarship for Ph.D. degree funded by the Egyptian Ministry of Higher Education (Cultural Affairs and Missions Sector)

- 2009 to 2013: Full teaching assistantship with a stipend by Alexandria University, Egypt.

- 2006 to 2009: Excellent Award for Top Academic Performance

- 2007: Scientific prize of Prof. Dr. Mounir Kansoh
  (Certificate of Excellence in Hydraulics)

TEACHING EXPERIENCE

Teaching the following courses:

• Hydraulics I (Introduction to Hydraulics – Flow through pressurized pipelines - Pumps).

• Hydraulics II (Open Channels Hydraulics, Dimensional Analysis - Modeling).

• Water Resources Engineering (Descriptive & Quantitative Hydrology – Ground Water – Reservoirs – Flood Damage Mitigation).

• Design of Pressurized Pipe Lines and Pipe Line Networks.

• Applied Hydraulics (Scour Around piers – Sediment transport).

• Computer Application on Hydraulic Structures.

• Design of Irrigation Structures I (Crossing structures – Weirs – Spillways).

Hydraulics Laboratory Instructor.

PUBLICATION

- Moghazy, N. H., and Kaluarachchi, J. J. (2020). 'Sustainable Agriculture Development in the Western Desert of Egypt: A Case Study on Crop Production, Profit, and Uncertainty in the Siwa Region'. Sustainability, 12(16), 6568. https://doi.org/10.3390/su12166568.

- Moghazy, N. H., and Kaluarachchi, J. J. (2020). 'Assessment of groundwater resources in Siwa Oasis, Western Desert, Egypt'. Alexandria Engineering Journal, 59(1): 149-163. https://doi.org/10.1016/j.aej.2019.12.018.

- Moghazy, N. (2013), 'Hydrodynamic Behavior of the Estuaries and Lake Inlets under the Effect of Tide and Waves'. M.SC. Thesis, Alexandria University, Egypt.

Presentations:

- Moghazy, N. H., and Kaluarachchi, J. J. (2020). ‘Sustainable Agricultural Development Under Climate Change in the Siwa Region, Western Desert of Egypt’. AWRA 2020 Virtual Annual Water Resources Conference, November 9-11, 2020.

- Moghazy, N., Kansoh, R., and Abd EL-Mooty, M. (2012), ‘Environmental Study of the Egyptian Lakes’. RETBE'12, 9th International Conference, Alexandria, December 2012.

- Moghazy, N., Abd EL-Mooty, and M., Kansoh, R. (2012), ‘Hydrodynamic Behavior of the Estuaries under the effect of Tides and Waves’. RETBE'12, 9th International Conference, Alexandria,
December 2012.