



**PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)**

Master Dissertation

Submitted in partial fulfilment of the requirements for the Master degree in

WATER ENGINEERING

Presented by

Ahmed Bashir Mahmoud Alghali

**ASSESSING THE ADEQUACY OF WATER SUPPLY FOR MEETING
IRRIGATION NEEDS. “A CASE STUDY OF THE GEZIRA SCHEME”**

Defended on 00/04/2024 Before the Following Committee:

Chair

Supervisor

Prof. Abdelkrim Khaldi

External Examiner

Internal Examiner

**PAN AFRICAN UNIVERSITY FOR WATER AND ENERGY SCIENCES
(INCLUDING CLIMATE CHANGE)**

Assessing The Adequacy of Water Supply for Meeting Irrigation Needs.
“A Case Study of The Gezira Scheme”

A master's thesis submitted to the Pan African University Institute for Water and Energy Sciences (Including Climate Change) in partial fulfilment of the requirements for the award of Masters of Science degree in water sciences (Engineering option).

Presented By

Ahmed Bashir Mahmoud Alghali

B.Sc. (Honours). in Water Resources Engineering

Supervisor: Prof. Abdelkrim Khaldi

April, 2024

Tlemcen, Algeria

DISSERTATION APPROVAL PAGE


Assessing The Adequacy of Water Supply for Meeting Irrigation Needs.
“A Case Study of The Gezira Scheme”

Submitted by

Ahmed Bashir Mahmoud Alghali.....April, 2024

Name of Student

Signature:



Approved by Examining Board

Date: April, 2024

Thesis Supervisor

Prof. Abdelkrim Khaldi.....April,2024

Name of Supervisor

Signature:



DEDICATION

With heartfelt gratitude, this master's thesis is dedicated to my loving father, mother, and cherished family, along with my supportive friends and esteemed professors.

STATEMENT OF THE AUTHOR

By my signature below, I declare that this thesis/dissertation is my work. I have followed all ethical principles of scholarship in the preparation, data collection, data analysis, and completion of this thesis or dissertation. I have given all scholarly matter recognition through accurate citations and references. I affirm that I have cited and referenced all sources used in this document. I have made every effort to avoid plagiarism.

I submit this document in partial fulfilment of the requirement for a degree from Pan African University. This document is available from the PAU Library to borrowers under the rules of the library. I declare that I have not submitted this document to any other institution for the award of an academic degree, diploma, or certificate.

Scholars may use brief quotations from this thesis or dissertation without special permission if they make an accurate and complete acknowledgment of the source. The dean of the academic unit may grant permission for extended quotations or reproduction of this document. In all other instances, however, the author must grant permission.

Name: Ahmed Bashir Mahmoud Alghali

Signature:



Date: April, 2024

Academic Unit:

PAU Institute:

ACKNOWLEDGEMENT

I am profoundly grateful to the Pan African University and the African Union Commission for awarding me the invaluable scholarship that enabled my academic pursuits. Your backing has been a cornerstone in my educational and research progress.

I must express my deep appreciation to my supervisor, Professor Abdelkrim Khaldi, for his unwavering support, guidance, insightful feedback, and thorough revisions, which have significantly enhanced the quality of my thesis. His understanding, patience, and tolerance of any shortcomings throughout this project have been extraordinary.

My thanks also go to Prof. Dr. Abdellatif Zerga, PAUWES Director, and the entire PAUWES team for their kindness in offering the essential support and fostering an encouraging learning atmosphere. Your assistance has been critical on this educational path.

I am grateful to all my PAUWES professors, undergraduate lecturers, and teachers who have been instrumental in my academic and personal development. Your commitment to teaching has played a crucial role in shaping the individual I have become.

I extend my sincere gratitude to Dr. Karim SEBAA, Engineer Ibrahim, and all the staff and management of SOGEHRWIT Company for providing me with the opportunity to undergo training with them. Their cooperation and hospitality made me feel truly welcomed and at ease, akin to being in my own home.

Lastly, to all mentioned above and those who have played a part in my academic journey, whether in significant or minor ways, I offer my sincere thanks. Your support and guidance have been key in achieving this significant milestone, and I am truly blessed to have had your support throughout this journey.

List of Symbols, Acronyms, Abbreviations

%:	Percentage
GDP:	Gross Domestic Product
BCM:	Billion Cubic Meters
FAO:	Food And Agriculture Organization
NGOs:	Non-Governmental Organizations
IWRM:	Integrated Water Resources Management
JICA:	The Japan International Cooperation Agency
ET ₀	Reference Crop Evapotranspiration
K _c :	Crop Coefficient
CWR:	Crop Water Requirements
MoIWR:	Ministry Of Irrigation and Water Resources
WUAs:	Water Users' Associations
IOD:	Irrigation Operations Directorate
EMC:	Earth Moving Cooperation
NCWR:	National Council for Water Resources
GDP:	Gross Domestic Product
m/s:	Meters Per Second
NIR:	Net Irrigation Requirement
IWR:	Irrigation Water Requirements
Pe _{ff} :	Effective Dependable Rainfall
ha:	Hector
TAM:	Total Available Soil Moisture
θ_{FC} :	Water Content at Field Capacity
θ_{pwp} :	Water Content at Wilting Point
FC:	Field Capacity
ET _c :	Water Needs of Crops
Irr. Req:	Irrigation Requirements
Gr Irr:	Total Gross Irrigation
WP:	Wilting Point

Table of Contents

CHAPTER ONE.....	1
1. INTRODUCTION.....	1
1.1. Background of the Study.....	1
1.2. Problem Statement.....	3
1.3. Objectives.....	4
1.3.1. Main Objective.....	4
1.3.2. Specific Objectives.....	4
1.4. Research Questions and The Working Hypothesis.....	4
1.4.1. Questions.....	4
1.4.2. Working Hypothesis.....	4
1.5. Significance of this Study.....	5
1.6. Scope of research.....	5
1.7. Organization of Thesis.....	6
CHAPTER TWO.....	7
2. LITERATURE REVIEW.....	7
2.1. Introduction.....	7
2.2. Profile of Sudan.....	7
2.3. Overview of Sudan’s Water Resources.....	8
2.3.1. Surface Water.....	9
2.3.2. Rainfall.....	10
2.3.3. The Nile.....	11
2.3.4. Seasonal streams.....	11
2.3.5. Wetlands.....	12
2.3.6. Lakes.....	12
2.4. Groundwater Resources.....	12
2.5. Alternative water sources.....	14
2.6. Water Management in Sudan.....	16

2.7. Irrigation Definition	16
2.8. Overview of Diverse Irrigation Methods and Their Environmental Impact	16
2.9. Overview of Irrigation in Sudan.....	17
2.10. Overview of Irrigation in the Gezira Scheme	18
2.11. Overview of Sudan Arable Land.....	19
2.12. Climate of Sudan.....	20
2.12. Overview of Water Uses in Agriculture in Sudan.....	21
2.15. Overview of Irrigated Water Management in Sudan	22
2.16. Water Consumptive Uses and Future Demand in Sudan	22
2.17. Integrated Water Resources Management.....	24
2.18. Integrated Water Resource Management in Sudan	24
2.19. Critical Issues Affecting the Global Outlook for Water and Food Security	25
2.19.1. Growing Demand	25
2.20. The Role of Irrigation for Food Security.....	28
2.21. Overview on The Gezira Irrigation Scheme	29
2.22. Evapotranspiration (ET ₀).....	30
2.23. Crop Coefficient (K _c).....	31
2.24. Crop Water Requirements	32
2.25. Irrigation Scheduling.....	32
2.26. Overview of Water Policies in Sudan	33
2.26.1. The Irrigation and Drainage Act.....	33
2.26.2. The 2005 Gezira Scheme Act (GSA)	34
2.26.3. The 1995 Water Law	35
2.26.4. The 2007 Water Policy	35
2.27. Previous Studies	35
CHAPTER THREE	39
3. METHODOLOGY	39
3.1. Introduction	39

3.2. Case Study Presentation	39
3.2.2. Climate of the Study Area	40
3.2.3. Irrigation Management	40
3.3. Research Design	41
3.3.1. Description of the Research Approach	41
3.3.2. Rationale for the Chosen Approach	42
3.4. Data Collection	43
3.4.1. Climatic Data	43
3.4.2. Rainfall Data	44
3.4.3. Crop Data	44
3.4.4. Soil Data	44
3.5. Overview on CROPWAT 8.0	45
3.6. Limitation of Cropwat8.0 Software	46
3.7. Input Soil Information	47
3.8. Input Rainfall Information: Determining Effective Rainfall on the Study Area.....	48
3.9. Input Climate Information: Determine Reference Evapotranspiration (ET _o) of the Study Area	49
3.10. Input Crop Information	51
3.10.1. Summer Season	51
3.10.1.1. Cotton	51
3.10.2. Winter Season	52
CHAPTER FOUR.....	54
4. ANALYSIS OF RESULTS AND DISCUSSIONS	54
4.1. Introduction	54
4.2. Summer season.....	54
4.2.1. Cotton	54
4.3. Winter season	60
4.3.1. Sunflower.....	60

4.3.2. Tomato.....	63
4.4. Summary of results.....	66
4.4.1. The first Scenario: Current Utilization Area from The Gezira Irrigation Scheme (169,563 ha).....	66
4.4.2. The Second Scenario: The Cultivated Landmass of The Gezira Irrigation Scheme Spanning 882,000 Hectares	68
4.5. The Water Supply in The Gezira Irrigation Scheme.....	71
4.6. Assessing Water Adequacy	71
4.7. Annual Supply versus Irrigation Demand.....	71
4.7.1. The first Scenario.....	71
4.6.1.2. The Second Scenario	72
CHAPTER FIVE	74
5. CONCLUSION AND RECOMMENDATIONS	74
5.1. Conclusions	74
5.2. Recommendations	75
References	76

List of Tables

Table 2-1. Groundwater Capacity and Quality of sDifferent Basins of Sudan.[21].....	14
Table 2-2. Summary of the available water in Sudan.[24]	14
Table 2-3.Storage facilities in Sudan.[24]	15
Table 2-4. Projected Water Demand until 2027 (bcm).[24]	15
Table 2-5. Irrigated Schemes in Sudan.[16]	18
Table 3-1. Some important features of The Gezira Scheme.....	41
Table 3-2. Wad Medani Monthly average for long term Rainfall and Effective Rainfall Data.	48
Table 3-3. Reference Evapotranspiration (ETo) for long term monthly average climatic data of the study Area.	49
Table 4-1. Crop Water Requirement, and Irrigation Requirement for Cotton.....	54
Table 4-2. Irrigation Schedule for Cotton: Simulated Results of Irrigation Timing Based on 100% Critical Depletion and Replenishment to Field Capacity.	55
Table 4-3. Crop Water Requirement, and Irrigation Requirement for Sorghum.....	57
Table 4-4. Irrigation Schedule for Sorghum.	58
Table 4-5. Crop Water Requirement, and Irrigation Requirement for Sunflower.....	60
Table 4-6. Irrigation Schedule for Sunflower	61
Table 4-7. Crop Water Requirement, and Irrigation Requirement for Tomato.	63
Table 4-8. Irrigation Schedule for Tomato	64
Table 4-9. Cotton and Sorghum Water Requirements and Cultivation Area in Summer Season	66
Table 4-10. Sunflower and Tomato Water Requirements and Cultivation Area in Winter Season	66
Table 4-11. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Cotton and Sorghum During the Summer Season.	66
Table 4-12. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Sunflower and During the Winter Season.....	66
Table 4-13. Seasonal Actual and Net Irrigation Requirements Compared to Total Gross Irrigation.	67
Table 4-14. Seasonal and Total Volumes of Actual, Net, and Gross Irrigation Water Requirements	67
Table 4-15. Cotton and Sorghum Water Requirements and Cultivation Area in Summer Season.	

.....	68
Table 4-16. Sunflower and Tomato Water Requirements and Cultivation Area in Winter Season.	69
Table 4-17. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Cotton and Sorghum During the Summer Season.	69
Table 4-18. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Sunflower and During the Winter Season.	69
Table 4-19. Seasonal Actual and Net Irrigation Requirements Compared to Total Gross Irrigation.	69
Table 4-20. Seasonal and Total Volumes of Actual, Net, and Gross Irrigation Water Requirements.	70

Table of Figures

Figure 2-1. Map of Sudan.[15]	8
Figure 2-2. The relative size of each basin compared to the total geographic area of Sudan.[16]	9
Figure 2-3. Water basins in Sudan and South Sudan.[17]	9
Figure 2-4. The mean annual precipitation in Sudan and South Sudan.[16]	10
Figure 2-5. Surface Water in Sudan and South Sudan.[17]	11
Figure 2-6. Mayaas in Dinder National Park.[17]	12
Figure 2-7. Aquifers in Sudan.[22]	13
Figure 2-8. Utilisation of water resources across various sectors in Sudan.[24]	15
Figure 2-9. The cultivable land of Sudan.[16]	19
Figure 2-10. Sudan's climatic regions. [16]	21
Figure 2-11. Sector Wise Water Consumption from Different Resources in Sudan. [22]	23
Figure 2-12. Estimate of the yearly water usage by 2030 in Sudan. [22]	23
Figure 2-13. Relationships between the natural, administrative, and socioeconomic aspects of water resources, as well as their interactions with the environment.[35]	24
Figure 2-14. Agricultural Output by Region. [39]	26
Figure 2-15 . Worldwide water scarcity by significant river basin.[39]	27
Figure 2-16. Farm in The Gezira Irrigation Scheme.[46]	29
Figure 2-17. Sennar Dam.[47]	30
Figure 2-18. Crop coefficient (Kc).[54]	31
Figure 3-1. Map depicting the study area. [65]	39
Figure 3-2. The irrigation system of The Gezira Irrigation Scheme. [65]	41
Figure 3-3. Process flow of the CROPWAT model for the methodology	46
Figure 3-4. Soil data	47
Figure 3-5. Graphical representation of the climatic parameters ETo and Peff. in the study. [17]	50
Figure 3-7. Crop Data for Cotton	51
Figure 3-8. Crop Data for Sorghum	51
Figure 3-9. Crop Data for Sunflower	52
Figure 3-10. Crop Data for Tomato.	53
Figure 4-1. Crop water requirements graph for Cotton.	55
Figure 4-2. Irrigation scheduling graph for Cotton	56

Figure 4-3. Cotton Crop Irrigation Schedule and Water Usage Summary.	57
Figure 4-4. Crop water requirements graph for Sorghum.....	58
Figure 4-5. Irrigation scheduling graph for Sorghum.....	59
Figure 4-6. Sorghum Crop Irrigation Schedule and Water Usage Summary.	59
Figure 4-7. Crop water requirements graph for Sunflower.....	60
Figure 4-8. Irrigation scheduling graph for Sunflower.....	61
Figure 4-9. Sunflower Crop Irrigation Schedule and Water Usage Summary.	62
Figure 4-10. Crop water requirements graph for Tomato.....	63
Figure 4-11. Irrigation scheduling graph for Tomato.....	65
Figure 4-12. Tomato Crop Irrigation Schedule and Water Usage Summary.	65
Figure 4-13. Bar chart of Annual Water Supply Versus Demand in The Gezira Irrigation Scheme for the first Scenario.....	71
Figure 4-14. Bar chart of Annual Water Supply Versus Demand in The Gezira Irrigation Scheme for the second scenario.....	72

Résumé

Face aux défis croissants posés par la pénurie d'eau, en particulier dans les régions arides et semi-arides, l'impératif de comprendre et de gérer efficacement les besoins en irrigation pour l'agriculture durable ne peut être surestimé. Cette étude se concentre sur l'investigation de l'adéquation de l'approvisionnement en eau pour répondre aux besoins en irrigation dans le cadre du Schéma de la Gezira au Soudan, une région agricole cruciale confrontée à des demandes agricoles croissantes, aux impacts du changement climatique et à l'expansion urbaine. En utilisant les capacités analytiques du modèle Cropwat8.0, cette recherche évalue méticuleusement les besoins en eau des cultures (CWR) et les demandes en eau d'irrigation (IWR) pour les principales cultures - coton, sorgho, tournesol et tomate - à la fois en été et en hiver. Les résultats soulignent des besoins en irrigation significatifs, tels que 1141,9 mm pour le coton et 715,6 mm pour le sorgho en été, et 854,9 mm pour le tournesol et 1083,5 mm pour la tomate en hiver. En supposant une efficacité du système d'irrigation de 50 %, des calendriers d'irrigation sont élaborés pour répondre à ces demandes. Malgré un approvisionnement annuel en eau de 11,16 milliards de mètres cubes dans le cadre du Schéma de la Gezira, deux scénarios mettent en évidence des niveaux variables de demandes en irrigation. Dans la superficie actuelle de 169 563 hectares, les besoins d'irrigation réels s'élèvent à 2,28 milliards de m³, avec une irrigation nette totale de 3,22 milliards de m³ et une demande brute totale en irrigation de 6,43 milliards de m³. En s'étendant pour englober toute la superficie de 882 000 hectares, ces chiffres augmentent notablement pour atteindre des besoins d'irrigation réels de 17,52 milliards de m³, une irrigation nette totale de 16,73 milliards de m³ et une demande brute totale en irrigation de 33,46 milliards de m³. L'étude souligne que si l'approvisionnement actuel en eau satisfait adéquatement la superficie actuellement cultivée, il ne répond pas aux besoins de l'ensemble de la zone du projet. Pour combler cette disparité, il est nécessaire d'améliorer les stratégies de gestion de l'eau, d'adopter des techniques d'irrigation modernes et de mettre en œuvre des mesures robustes de conservation. Ces efforts garantissent non seulement la durabilité du projet, mais ouvrent également la voie à la culture de zones de projet plus vastes tout en optimisant l'utilisation de l'eau. En fin de compte, ces stratégies visent à promouvoir des pratiques agricoles durables et à renforcer la sécurité alimentaire au Soudan. Elles fournissent des perspectives inestimables aux parties prenantes impliquées dans la gestion des ressources en eau et le développement agricole, orientant les efforts vers un paysage agricole plus résilient et prospère.

Abstract

In light of the escalating challenges posed by water scarcity, particularly in arid and semi-arid regions, the imperative of understanding and effectively managing irrigation needs for the sake of sustainable agriculture cannot be overstated. This study is centred on investigating the adequacy of water supply for meeting irrigation needs within Sudan's Gezira Scheme, a crucial agricultural region grappling with mounting agricultural demands, the impacts of climate change, and urban expansion. Utilising the analytical capabilities of the Cropwat8.0 model, this research meticulously evaluates the crop water requirements (CWR) and irrigation water demands (IWR) for major crops—cotton, sorghum, sunflower, and tomato—across both summer and winter seasons. The findings underscore significant irrigation needs, such as 1141.9 mm for cotton and 715.6 mm for sorghum during summer, and 854.9 mm for sunflower and 1083.5 mm for tomato in winter. Assuming an irrigation system efficiency of 50%, irrigation schedules are devised to meet these demands. Despite an annual water supply of 11.16 billion cubic meters within the Gezira Scheme, two scenarios highlight varying levels of irrigation demands. In the current area of 169,563 hectares, actual irrigation requirements amount to 2.28 billion m³, with a total net irrigation of 3.22 billion m³ and a total gross irrigation demand of 6.43 billion m³. Expanding to encompass the entire area of 882,000 hectares, these figures notably escalate to actual irrigation requirements of 17.52 billion m³, total net irrigation of 16.73 billion m³, and total gross irrigation demand of 33.46 billion m³. The study underscores that while the current water supply adequately caters to the presently cultivated area, it falls short of meeting the needs of the entire project area. Addressing this disparity necessitates the enhancement of water management strategies, adoption of modern irrigation techniques, and implementation of robust conservation measures. These endeavours not only ensure the sustainability of the project but also pave the way for cultivating larger project areas whilst optimising water usage. Ultimately, these strategies aspire to promote sustainable agricultural practices and fortify food security in Sudan. They furnish invaluable insights for stakeholders engaged in water resource management and agricultural development, directing efforts towards a more resilient and prosperous agricultural landscape.

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

Water is a fundamental resource for agricultural productivity and plays a pivotal role in global food security.[1] Irrigated agriculture, which occupies 20 percent of the world's arable land, contributes 40 percent of total food production. This method is notably more efficient than rainfed agriculture, allowing for enhanced crop intensification and diversification. The growing global population, alongside urbanization and climate change impacts, intensifies the competition for water resources, particularly affecting agriculture. With the population expected to exceed 10 billion by 2050, there is an urgent need to increase food and fibre production. The rising incomes in developing countries, leading to greater calorie intake and diverse diets, mean that agricultural production must increase by about 70% by 2050.[2]

Future water demands across various sectors will likely necessitate reallocating 25 to 40% of water from lower to higher productivity uses, especially in water-scarce regions. Agriculture, currently responsible for 70 percent of global freshwater withdrawals and a higher proportion of consumptive use, is anticipated to be the primary source for this reallocation.[3] This reallocation will involve both physical redistribution of surface and groundwater resources from agricultural to urban, environmental, and industrial users, as well as virtual water movement. The latter refers to the production of water-intensive commodities in water-rich areas and their trade to water-deficient regions. Improvements in water use efficiency and delivery systems are crucial to support this transition. Elevating efficiency in agricultural water use will depend on aligning improvements in the main system (off-farm) with incentives for on-farm investments in soil and water management. Advanced technologies, like soil moisture sensors and satellite evapotranspiration measurements, are key to increasing water efficiency and productivity in agriculture.[4]

Addressing these challenges necessitates a comprehensive reevaluation of water management within agriculture, integrating it within the overall context of water resource management and water security. Furthermore, irrigation and drainage systems, significant as rural public works, present opportunities for employment in local communities.[5] Despite the crucial role of irrigation in meeting increasing food demands, the anticipated 50% rise in global food demand by 2050 (doubling in developing countries) makes the current use of water resources for agriculture unsustainable. This situation is attributed to factors like aquifer depletion, reduced river flows, ecological degradation, and soil salinization due to irrigation. Sustainable

agricultural practices and efficient resource use are essential to prevent future hunger and malnutrition, minimizing adverse effects like environmental damage and soil erosion. [6] Although significant investments in irrigation infrastructure were made in the past, challenges persist. Governments and international donors have recognized the need for better management of irrigation schemes, leading to the promotion of Irrigation Management Transfers (IMTs), which shift responsibility to entities like Water User Associations and the private sector. In Sudan, the primary use of fresh water is for irrigated farming, which accounts for approximately 94% of all freshwater usage, predominantly for food cultivation. This sector is experiencing increasing competition for water resources from other areas like industry and household use. Factors such as population growth, urban expansion, and climate change are expected to intensify this competition. Sudan's population is projected to reach 66.8 million by 2050, which will lead to a heightened demand for food in the coming years. Consequently, the agricultural sector is faced with the task of enhancing its water productivity in crop production, aiming to grow more food using less water.[7] The Gezira Scheme, a major focus of research and international attention, has undergone numerous studies to understand its development and the reasons for its underperformance.[8]

For many years, the Gezira Scheme has been a crucial pillar of Sudan's economy and continues to play a vital role. Around 4 million people in Gezira state are deeply affected by its socioeconomic influence. The existence and well-being of approximately 110,000 tenant farmers and their families are closely tied to this Scheme. It provides essential water and fodder for around 2 million livestock, including 500,000 cattle, 2.5 million sheep, and 3 million goats. In the 1984 drought, a significant number of animals from the regions east of the Blue Nile (Butana) and west of the White Nile sought refuge in the Scheme for sustenance and hydration. The Scheme played a key role in compensating for shortages in sorghum production, which is a primary food source for local residents, particularly during dry periods. In terms of water management, the Scheme utilizes about one-third of Sudan's allocation of Nile water, amounting to 6 to 7 billion cubic meters annually. The Gezira Irrigation Scheme in Sudan, a prime example of an area where effective water management is crucial for agriculture, faces challenges like water scarcity, inefficient water use, and sustainability issues. These problems are exacerbated by the region's arid climate, unpredictable rainfall, and increasing upstream demand. Traditional irrigation methods, aging infrastructure, and insufficient maintenance result in water losses, suboptimal use, and reduced productivity. Additionally, waterlogging and soil salinity due to inefficient irrigation reduce agricultural potential and degrade soil quality over time. Strategies and interventions to modernize irrigation infrastructure, introduce water-saving

technologies, and reform water governance have been implemented, but challenges remain. This research aims to critically analyse water resource management in the Gezira Scheme, focusing on evaluating the adequacy of water resources for irrigating its key crops. Utilizing tools like Cropwat8.0 and Climatewat2.0, the study will examine current water usage, model irrigation requirements, assess climate change impacts, and develop sustainable water management strategies. The outcomes are expected to guide policymakers, practitioners, and academics in water resource management and agricultural development. [9]

1.2.Problem Statement

At the core of Sudan's agricultural economy lies The Gezira Scheme, a crucial irrigation-dependent system that significantly contributes to the country's food production and economic stability. However, this essential agricultural hub faces numerous challenges that compromise its ability to efficiently utilize irrigation water. A key concern is the inefficient use of water, primarily due to outdated irrigation techniques. This inefficiency results in considerable water wastage, and the transition to more water-efficient technologies is advancing too slowly to address these issues effectively. Furthermore, the scheme's rapid expansion has outpaced the maintenance of its irrigation infrastructure, putting additional pressure on its limited water resources. The situation is compounded by deteriorating infrastructure and lack of proper maintenance, leading to significant water losses, suboptimal water application, and reduced agricultural yields. Complications such as waterlogging and increased soil salinity, arising from poor irrigation practices, further diminish the scheme's agricultural productivity and soil health, aggravating the existing problems. A particularly pressing issue is the uneven distribution of irrigation water, with certain areas experiencing acute water shortages. This imbalance not only affects crop production in these areas but also underscores the disparities in water resource distribution and accessibility throughout the scheme.

Moreover, the absence of comprehensive data collection and regular monitoring exacerbates these challenges. This deficiency impedes informed decision-making regarding water allocation and use, making it difficult to accurately assess the water requirements of different crops. The lack of reliable data and consistent oversight poses a major obstacle to improving irrigation efficiency and effectively managing water resources in the region. Addressing these multifaceted challenges, including the specific problem of water scarcity in certain areas, is vital for the Gezira Scheme to maintain its essential role in Sudanese agriculture. This study aims to use analytical tools, such as the Cropwat8.0 model, to evaluate the adequacy of irrigation water supplies and develop strategies to enhance water use efficiency. By tackling

the complex issues surrounding water resource management, including optimizing water usage, maintaining infrastructure, and adopting modern agricultural practices amid the scheme's growth, this research endeavours to promote sustainable agricultural development in one of Sudan's most critical agricultural zones.

1.3. Objectives

1.3.1. Main Objective

To assess the adequacy of water supply for meeting the irrigation needs within the Gezira scheme.

1.3.2. Specific Objectives

- To determine the crop water requirement (CWR).
- To estimate the irrigation requirements (Irr.Req) under varying conditions.
- To devise an efficient irrigation schedule.

1.4. Research Questions and The Working Hypothesis

1.4.1. Questions

- How sufficient are the water supply in the scheme for irrigation purposes?
- What are crop water requirement (CWR)?
- What are the irrigation water requirements (IWR) under different conditions, including both the summer and winter seasons?
- How can an effective irrigation schedule be established to optimize water usage?

1.4.2. Working Hypothesis

This study's foundational assumption suggests that the prevailing strategies for managing water and the irrigation systems in place at the Gezira Scheme fall short of adequately addressing both the present and anticipated water requirements for agriculture in the area, leading to less-than-optimal farm output and long-term viability. The root of this water utilization inefficiency is traced back to the reliance on antiquated farming and irrigation techniques, the neglect of necessary upkeep for the infrastructure, and the failure to effectively marry cutting-edge water conservation technologies with age-old agricultural methods. The hypothesis further proposes that a thorough investigation into whether the water supply is sufficient, coupled with an analysis of the water needs for crops under different weather patterns, could pave the way for crafting more effective watering schedules. Such advancements are expected to fine-tune water consumption, boost crop production, and secure the future of water supplies. Moreover, the study anticipates that by taking decisive steps towards updating the irrigation framework, embracing technologies that conserve water, and overhauling the management of water

resources, the existing difficulties confronting The Gezira Scheme could be substantially alleviated. This hypothesis highlights the transformative potential such measures could have in elevating the scheme's efficiency in water use, agricultural productivity, and its pivotal role in enhancing food security and economic stability in Sudan.

1.5. Significance of this Study

This study tackles a pivotal issue within Sudan's The Gezira region: the effective and long-term management of irrigation water. Considering the critical importance of agriculture in Sudan, where a significant majority of the populace, ranging from 60% to 80%, depend on subsistence farming for their daily sustenance, the impact of this research extends widely. Central to Sudan's agricultural output and the assurance of food security is The Gezira irrigation system. Agriculture stands as the linchpin for the livelihood of most Sudanese, contributing substantially to the economy by supplying essential raw materials, food products, and earning foreign exchange. It's the foremost source of employment and plays a crucial role in diversifying the national economy. The insights provided by this study into the betterment of water utilization within the irrigation framework aim to boost crop production and food security, all the while preserving water resources. By centering on the judicious management of irrigation water, the research not only tackles the pressing issues of enhancing agricultural productivity but also feeds into the wider narrative on environmental preservation and the pursuit of sustainable development within Sudan. Given these points, the outcomes of this study are poised to be an essential resource for the Gezira Irrigation Scheme Administration and the Ministry of Irrigation and Water Resources. The application of its recommendations promises substantial gains in water usage efficiency, bolstering the resilience of the agricultural sector, improving food security, and fostering the sustainable stewardship of crucial water supplies in the area.

1.6. Scope of research

This investigation aims to thoroughly assess the capacity of water supply to fulfil the irrigation requirements of The Gezira Scheme in Sudan, highlighting its crucial role in the agricultural sector and the overall economic health of the country. It includes a detailed examination of the water needs for key crops grown in the area, with a special focus on the varied climatic conditions of the summer and winter seasons and their impact on irrigation. A pivotal element of this study is its examination of a diverse range of crops to offer a comprehensive view on the irrigation needs across various types of agricultural produce. This strategy not only deepens the understanding of the specific water requirements of each crop but also supports the

objectives of achieving food security and sustainable agriculture amidst the challenges posed by increasing population and climate change.

To achieve these goals, the research will utilize advanced analytical tool like Cropwat8.0 to model irrigation needs, evaluate the effects of climate change, and formulate strategies for water management that are both effective and sustainable. These methodologies will play a critical role in reviewing current water usage, evaluating the sufficiency of water supplies, and suggesting enhancements to boost water efficiency and conservation. The study will also explore the factors leading to water shortage and inefficiency, such as outdated irrigation techniques, deteriorating infrastructure, and the necessity for modernization along with the adoption of technologies that conserve water. Additionally, it will investigate water resource management, assessing how well current policies and practices manage water distribution and use in agriculture. Furthermore, the research will consider potential strategies and reforms to improve water use within The Gezira Scheme, including the potential for water resource reallocation, better management practices both on and off the farm, and the introduction of innovative farming techniques to counter water scarcity and increase agricultural output. The outcomes of this research aim to provide policymakers, practitioners, and scholars with insights into water resource management and agricultural advancement. By delivering an in-depth evaluation of the present and future status of water resources in one of Sudan's key agricultural regions, this study seeks to offer valuable recommendations for the sustainable management of agricultural water resources, thus contributing to the nation's food security and economic progress.

1.7. Organization of Thesis

Chapter 1: Introduction (Problem Statement, Objectives, Research Questions, scope, etc.).

Chapter 2: Literature review (Theoretical framework and Empirical Literature).

Chapter 3: Methodology (Data presentation, Mathematical and Technical details, Simulation using CROPWAT 8.0).

Chapter 4: Result Presentation.

Chapter 5: Conclusion and recommendations.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

This chapter presents a literature review on Sudan's water resources, focusing on their role in the country's agricultural sector, particularly within the Gezira Scheme. It aims to offer a comprehensive understanding of Sudan's hydrological profile, the challenges in water management, and the impact of climate change on these resources. This review sets the context for assessing the adequacy of water supply for meeting the irrigation needs in the Gezira Scheme, a vital component of Sudan's agricultural framework.

2.2. Profile of Sudan

Sudan, encompassing an approximate area of 1.9 million square kilometres, ranks as the third-largest nation on the African continent and the 16th largest globally. This vast landmass is bordered by several countries: Egypt to the north, Libya to the northwest, Chad to the west, the Central African Republic to the southwest, South Sudan to the south, Ethiopia to the southeast, and Eritrea to the east. Additionally, Sudan boasts a significant coastline along the Red Sea, enhancing its geographical prominence.^[10] As of 2023, the population of Sudan is estimated at approximately 47.9 million, exhibiting an annual growth rate near 2 percent. A notable majority of this population, approximately 70%, resides in rural areas. The distribution of inhabitants is predominantly aligned along the Nile River, a pivotal geographical feature of the country. This river flows from south to north, culminating in the capital city of Khartoum, where the confluence of the White Nile and Blue Nile occurs. This junction represents not only a geographical milestone but also a cultural symbol of significant importance.^[11]

The Sudanese economy is multifaceted, primarily dependent on sectors such as oil production, agriculture, gold mining, and remittances from overseas. Post the secession of South Sudan in 2011, there has been a noted decline in oil production. Agriculture remains a cornerstone of the economy, employing 80% of the workforce and contributing to 40% of the Gross Domestic Product (GDP). Sudan is notably recognized for being a leading producer of gum Arabic. The gold mining sector has grown in importance, significantly impacting income and foreign exchange.^[12] Additionally, remittances from Sudanese working primarily in Gulf countries constitute a substantial part of the economy. Despite these resources, the economy is grappling with challenges such as inflation, unemployment, poverty, and corruption.^[13]



Figure 2-1. Map of Sudan.[15]

Geographically, Sudan’s landscape is diverse, encompassing deserts, savannas, and rainforests. The Nile River, central to the country’s water and irrigation systems, contributes to the formation of lakes such as Lake Nubia and Lake Merowe. The topography includes mountain ranges like the Marrah Mountains, with the highest point being Deriba Caldera, standing at 3,042 meters.[14]

2.3. Overview of Sudan’s Water Resources

Sudan relies on diverse water sources including rainfall, multiple rivers, temporary streams (wadis and khors), lakes, and wetlands. Groundwater also contributes significantly to the country's water resources, along with unconventional approaches such as wastewater recycling and desalination.[16]

Regarding hydrological divisions, Sudan is divided into seven main basins, as illustrated in Figure 2-2. Additionally, Figure 2-3 offers a comprehensive view of the relative size of each basin compared to Sudan's total geographical area.

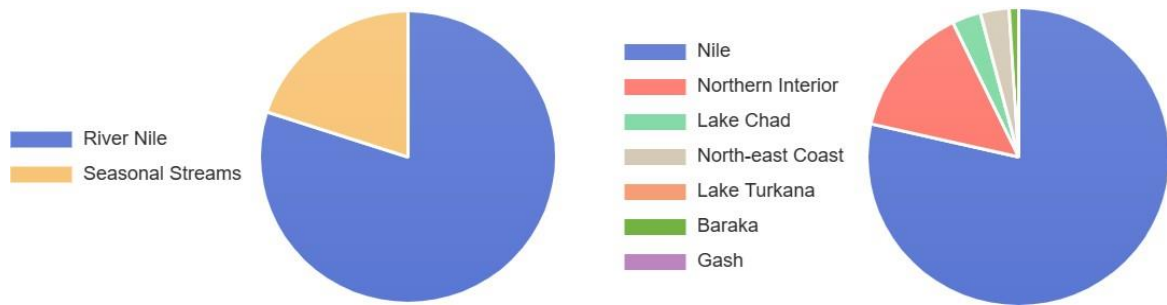


Figure 2-2. The relative size of each basin compared to the total geographic area of Sudan.[16]

2.3.1. Surface Water

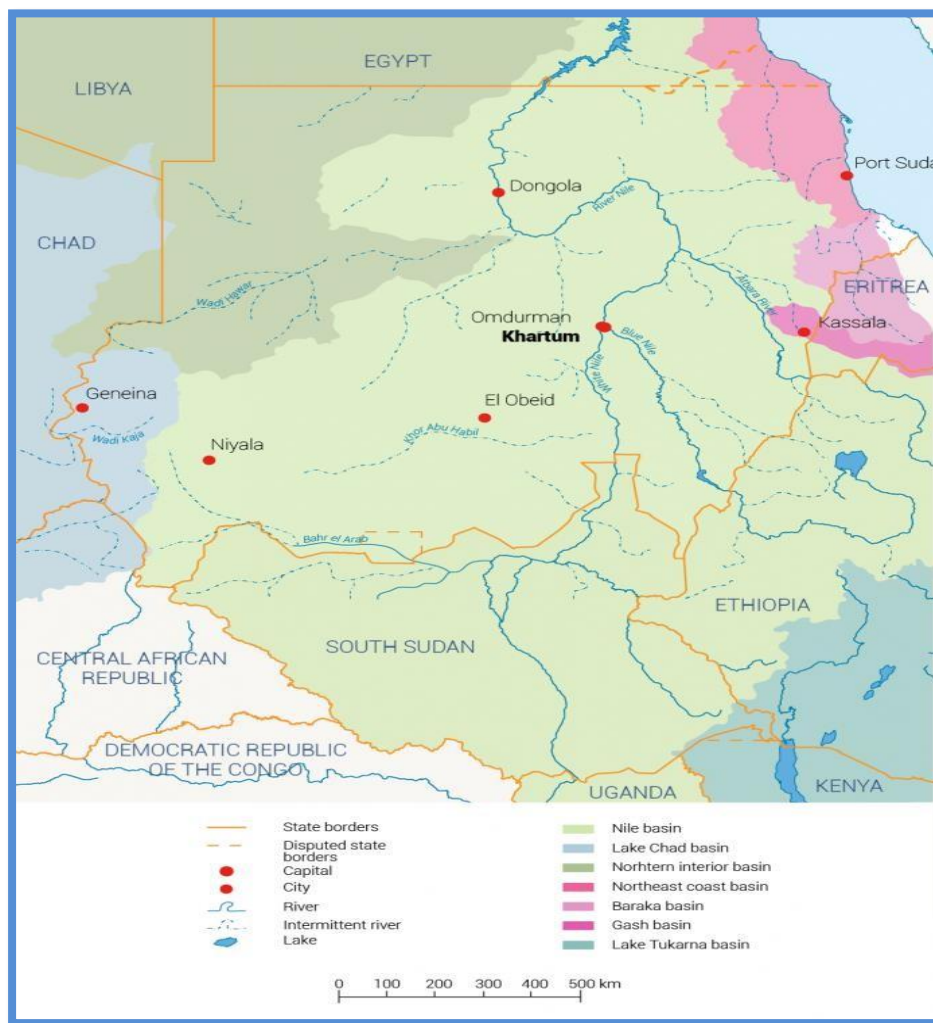


Figure 2-3. Water basins in Sudan and South Sudan.[17]

Sudan possesses around one million hectares of surface water, its distinguishing characteristic is a 2,000-kilometre expanse of the Nile River and its affluents, encompassing nearly half of the Nile River Basin. Wetlands cover about 10% of Sudan's land area, while forested areas make up 4%. The country also features numerous seasonal watercourses known as khors, which mainly flow during the short rainy season. However, systematic measurements of discharge volumes, flow durations, and water quality of these khors are lacking. Outside the Nile basin,

the total annual discharge from more enduring rivers is approximately 7.0 billion cubic meters (BCM). These include significant rivers such as the Gash, Baraka, and Khor Arbaat in the eastern regions, Wadi Azoom and Galol in Darfur, and Khor Abu Habil, which drains the Nuba Mountains in Southern Kordofan. [12]

2.3.2. Rainfall

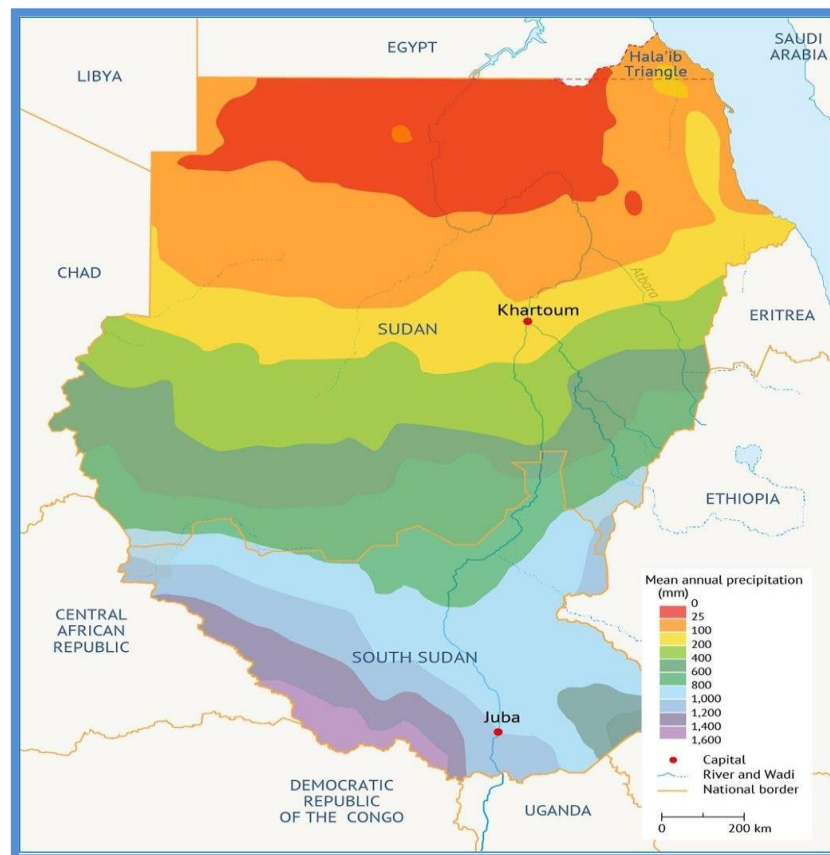


Figure 2-4. The mean annual precipitation in Sudan and South Sudan.[16]

Sudan receives an estimated annual rainfall of about 440 billion cubic meters. The southern regions encounter the highest precipitation, reaching up to 800 millimetres per year. As one moves towards the north, rainfall decreases, with areas around Khartoum receiving approximately 120 millimetres annually, and areas close to the Egyptian border experiencing minimal rainfall. The Sudanese northward territory. typically witnesses short rainy periods and Intermittent precipitation.

Across the country, there is a prevalent scarcity of rainfall for most of the year, as evapotranspiration consistently exceeds precipitation levels. Exceptions occur during August, September, and portions of October when runoff is adequate to activate seasonal watercourses and recharge groundwater reservoirs. Nevertheless, this drainage frequently carries sediment

and debris, leading to erosion in catchment areas. Deforestation exacerbates this issue, contributing to the accelerated erosion rate. [17]

2.3.3. The Nile

In Sudan, the Nile River and its tributaries provide 73% of the annual freshwater supply. Managed under the Nile Water Agreement established in 1959, Sudan receives 18.5 billion cubic meters of water from the river's total annual output of 80 billion cubic meters. This allocation encompasses water from the Blue Nile, which originates in Ethiopia, passes through Sudan, and reaches Egypt. The Nile system in Sudan consists of the Blue Nile, its tributaries - the Dinder and Rahad rivers, the White Nile, the Atbara River, and temporary streams. [18]

2.3.4. Seasonal streams

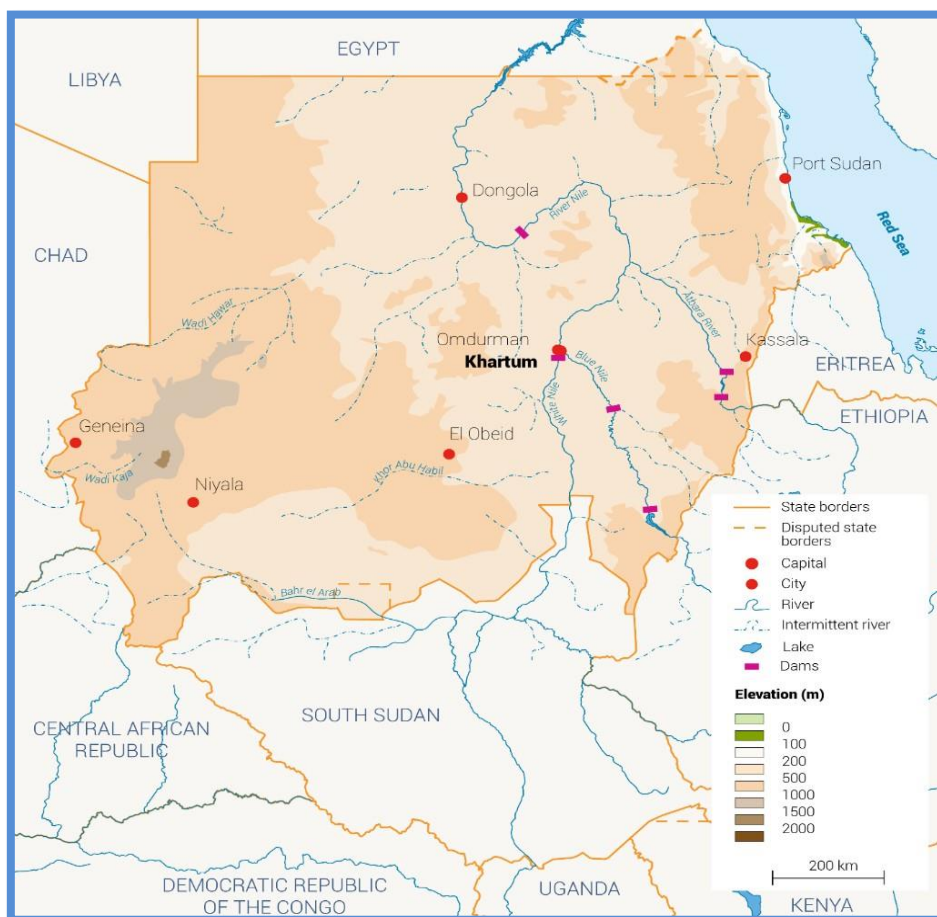


Figure 2-5. Surface Water in Sudan and South Sudan.[17]

Sudan boasts numerous seasonal waterways, locally referred to as wadis or khors. These channels typically run from July to October, with brief durations, often lasting only a few days or hours, before drying up for the rest of the year. Among them, the four largest are shared with neighbouring nations: the Gash and Baraka with Eritrea, and the Azum and Hawar with Chad, alongside others bordering South Sudan and the Central African Republic. Additional

intermittent streams found in Sudan encompass Khor Abu Habil, Wadi El Mugaddam, Wadi Kaja, Wadi Nyala, Alawataib, and Alhawad. The flow of these watercourses primarily relies on rainfall patterns, with most lacking continuous monitoring. On average, these seasonal streams contribute an estimated 5.5 billion cubic meters (BCM) of water annually. [19]

2.3.5. Wetlands

In Sudan, there are 30 distinct types of wetlands. Three of these have been designated as Ramsar sites, indicating their international importance. An example is the mayas, or oxbow lakes, situated in Dinder National Park.[16]

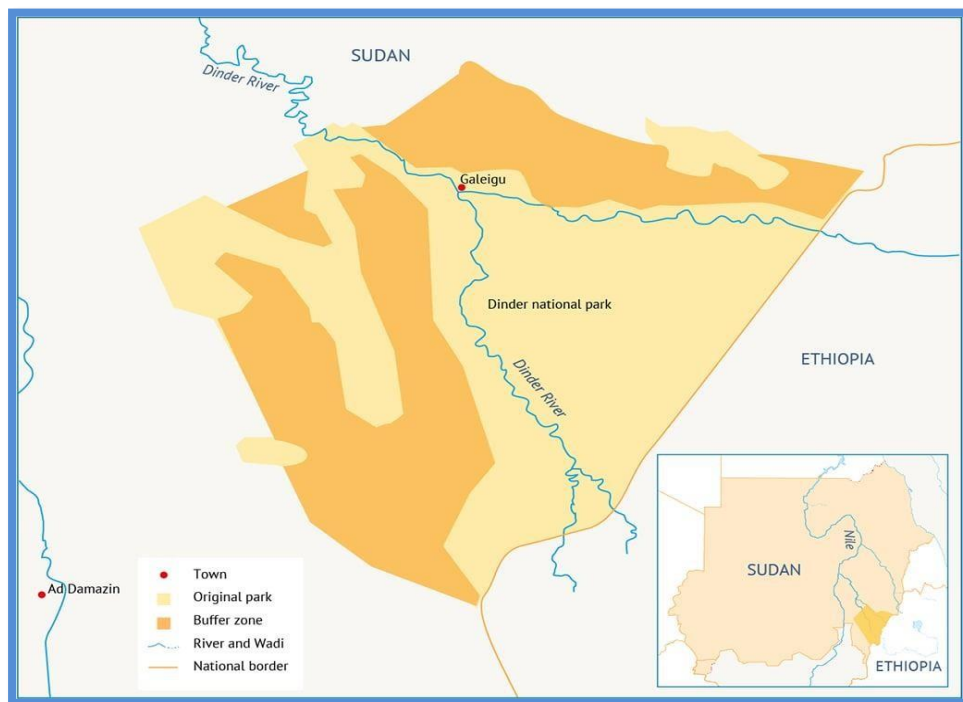


Figure 2-6. Mayaas in Dinder National Park.[17]

2.3.6. Lakes

Sudan boasts a variety of natural features, including freshwater lakes like Kundi, Abyad, and Turdat el-Rahad, along with saline lakes such as Dariba crater and Malha. Oases like Nikheila, Natroon, and Saleema are also found in the northern regions. Additionally, the country has artificial reservoirs created by dams like Sennar, Roseires, Jebel Aulia, Khashm El-Girba, and the Upper Atbara and Setit Complex. Notable among these is the Merowe Dam and Lake Nubia, which forms part of the Egyptian High Aswan Dam's reservoir.[16]

2.4. Groundwater Resources

Approximately half of Sudan's territory contains groundwater, with varying depths of 40 to 400 meters. The primary sources of this groundwater are the Nubian sandstone, the Umm

Rawaba formation, the Nubian/Basalt, and the Alluvial Basin. Notably, the Nubian basin, spanning 28.15% of Sudan and shared with Libya and Egypt, is known for its quality water. It boasts a storage capacity of 12,600 billion cubic meters (BCM) and recharges annually at a rate of 1,008 million cubic meters (MCM).[20] The Umm Rwaba basin, significantly recharged by the White Nile, has a storage capacity of 3,150 BCM and an annual recharge of 300 MCM. Covering an area of 29,016 square kilometres, the Nubian/Basalt basin has a Capacity for storage of 715 BCM and an annual recharge of 325 BCM. These basins are of historical importance, having been centres for early civilizations and agricultural development.[21]

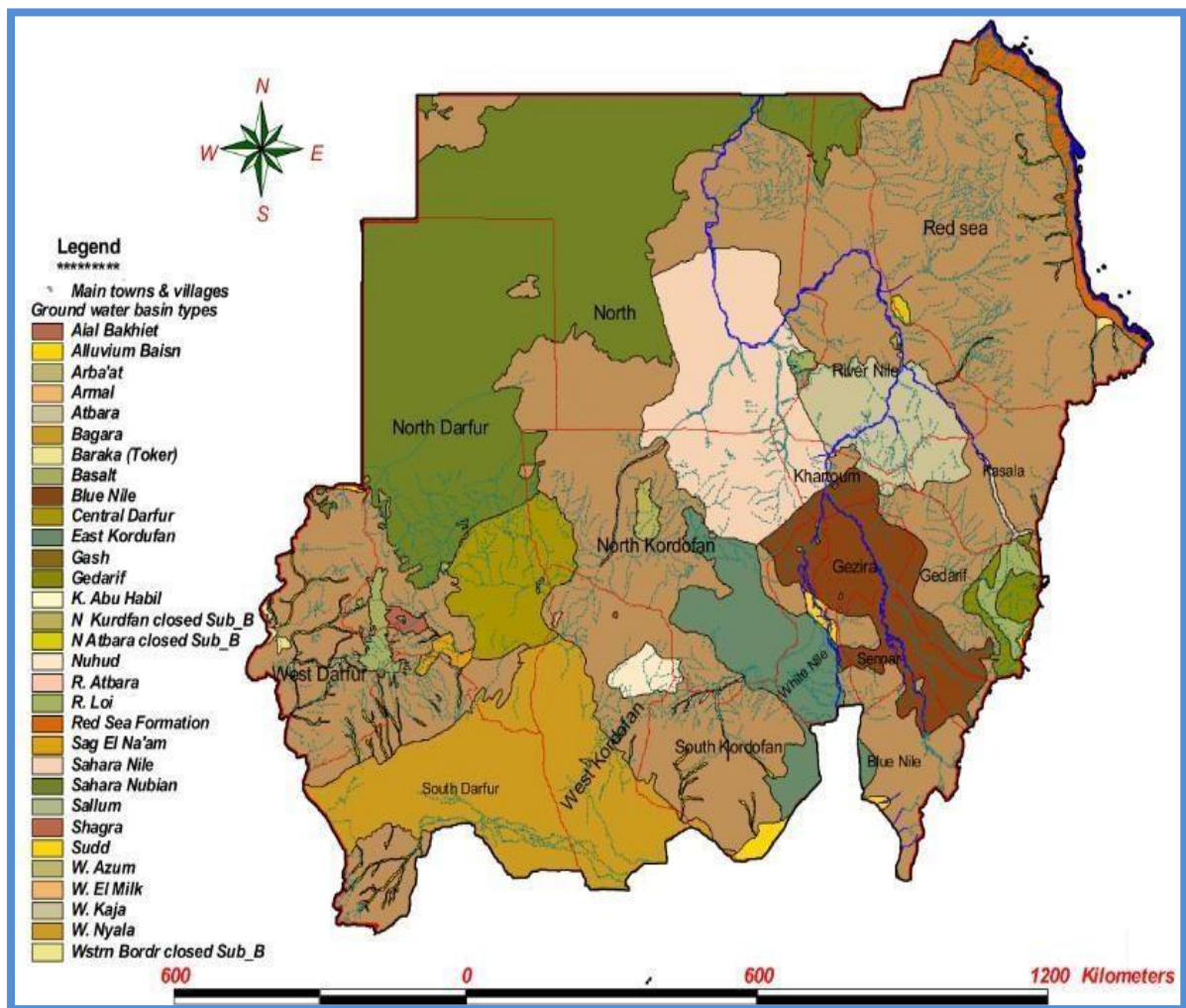


Figure 2-7. Aquifers in Sudan.[22]

Table 2-1. Groundwater Capacity and Quality of Different Basins of Sudan.[21]

Groundwater Basin	Area (km ²)	Quantity of Water (BCM)	Water Quality (dissolved solids ppm)	Annual Average Recharge (MCM)
Nubian Basin	637073	12600	100-800	1008
Umm Rwaba Basin	400,957	3150	500-600	300
Nubian Basalt Basin	29,016	715	400-500	325
The Alluvial Basin	-	2.5	-	1800
Total		16502.2		3433

2.5. Alternative water sources

Sudan ran five desalination plants in Port Sudan in 2020. These facilities produced a total of 20,000 cubic meters of water daily. While the reuse of wastewater is limited, it's mainly employed for irrigation near Khartoum. In the past, communities in western Sudan stored water in baobab trees until hand pumps were introduced by UNICEF. Rainwater collection in haffirs is common in Darfur and Kordofan for various needs. Sudan's water sources include Nile water, non-Nile rivers, and groundwater. According to the FAO, Sudan's per capita water usage is estimated at 1,020 cubic meters annually. [24]

Table 2-2. Summary of the available water in Sudan.[24]

Water resources	Quantity BCM	Constraints
Sudan present share from the Nile water agreement (at central Sudan)	20.5	Periodic nature, restricted storage capacities, anticipated sharing with neighbouring riparian states.
Water from seasonal streams	5.0 to 7.0	Significant fluctuations in quantities, brief flow durations, challenging to monitor or harness, some shared with neighbouring regions.
Sustainable groundwater	4.0	Deepwater, expensive abstraction, remote locations, and inadequate infrastructure.
Current sum	30.0	
Anticipated from the reclamation of marshes	6.0	High capital investment social and environment problems expected.
Total	36	

Table 2-3. Storage facilities in Sudan.[24]

Dam Reservoir	Location (River)	Construction Year	Design Capacity BCM	Present Capacity BCM
Sinnar	Blue Nile	1925	0.93	0.40
Jabel Awlia	White Nile	1937	3.5	3.5
Roseries	Blue Nile	1966	7.4	7.4
Khashm Elgerba	Atbara Rivers	1966	1.3	0.65
Total			13.3	11.5

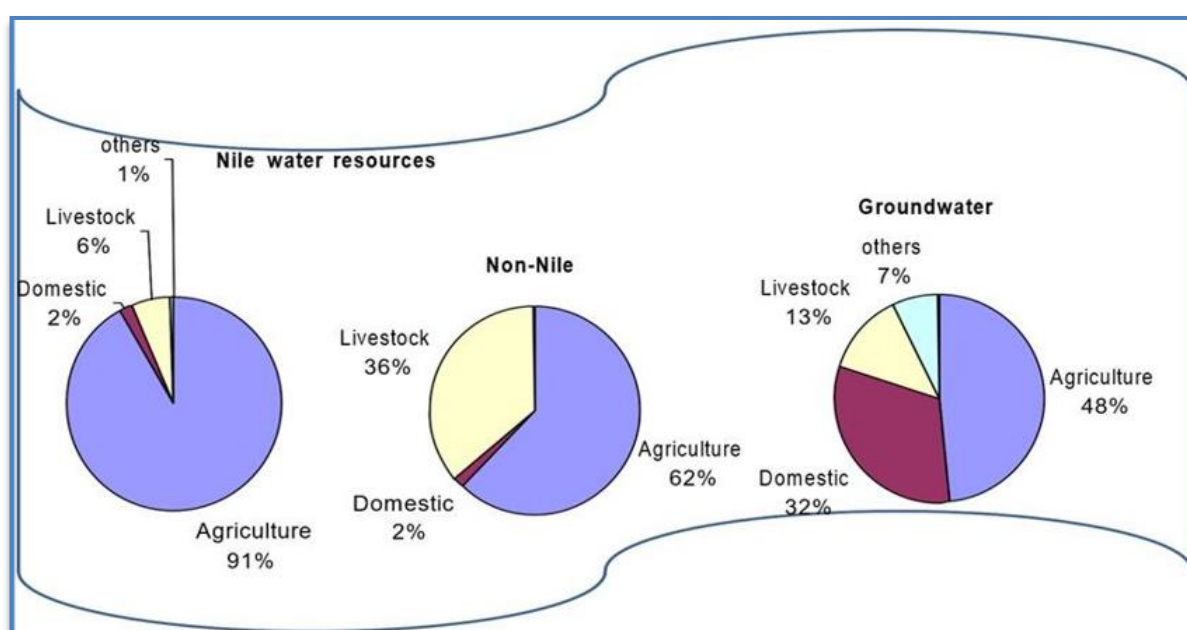


Figure 2 -8.. Utilization of water resources across various sectors in Sudan.[24]

Table 2-4. Projected Water Demand until 2027 (bcm).[24]

Year	Irrigation	Animals & others	Domestic Supply	Total
2010	27.1	3.9	1.1	32.1
2020	32.6	5.1	1.9	39.6
2025	40.3	5.3	2.5	48.0
2027	42.5	7.3	2.8	52.6

2.6. Water Management in Sudan

The Federal Ministry of Water Resources and Irrigation in Sudan is responsible for establishing national water resource policies and overseeing related projects. However, state-level institutions often face challenges in managing water resources, primarily due to insufficient funding and unclear delineation of responsibilities. Other governmental departments involved in water administration include the Ministry of Agriculture and the Ministry of Environment, Natural Resources, and Physical Development. In 2018, the latter was replaced by the National Council for Environment. Furthermore, in 2020, the Higher Council for Environment and Natural Resources was established. The Water Resources Act was passed in 1995, with certain regulations related to water resources being revised in 2016. These revisions included updates to regulations governing the exploitation of groundwater, irrigation and drainage licensing, as well as regulations concerning surface water.[23] At the community level, Village Development Committees are tasked with land allocation for agricultural and grazing purposes, as well as the supply and development of water, which includes the operation and maintenance of water yards in rural areas. Local non-governmental organizations (NGOs), such as the Sudanese Environment Conservation Society, along with international NGOs like the Environmental Network of the Horn of Africa, play a crucial role in local community development. Water serves as a key entry point for all of their development initiatives.[16]

2.7. Irrigation Definition

Irrigation refers to the deliberate distribution of water to cultivated fields to fulfil the hydration needs of crops that aren't met by natural rainfall, particularly in arid environments. It's essential for producing sufficient food and fibre, as it mitigates the risks of reduced harvests and crop failure linked to erratic rainfall. In semi-arid areas, where low rainfall and elevated temperatures prevail, irrigation is almost always necessary. Additionally, in humid and sub-humid areas, it serves as a safeguard against the potential loss of crops.[25]

2.8. Overview of Diverse Irrigation Methods and Their Environmental Impact

Various irrigation techniques exist, each differing in their water delivery methods to plants. The most traditional method, surface or gravity irrigation, dates back several millennia. Sprinkler irrigation involves distributing water via high-pressure overhead devices, connected through pipes to central points in the field. In contrast, micro-irrigation, a low-pressure system, delivers water through a piped network, directly discharging small amounts near each plant. This method is more efficient in terms of water and pressure usage compared to sprinkler systems. Drip irrigation targets water delivery directly to plant root zones. In regions with high water

tables, subirrigation has been utilized for field crops for many years, working by artificially elevating the water table to dampen the soil beneath the plant roots. of irrigation water include groundwater (obtained from springs or wells), surface water (collected from rivers, lakes, or reservoirs), or unconventional sources like recycled wastewater, desalinated water, drainage water, or collected fog. Depending on the region, irrigation may supplement natural rainfall, typical in rainfed agriculture, or constitute the primary source of water for crops, particularly in arid areas with minimal rainfall or in semi-arid regions during non-rainy seasons. Irrigation's environmental impact involves alterations in the quantity and quality of soil and after, affecting both natural and societal aspects in and around irrigation areas. These changes result from the setup and operation of irrigation systems. One significant issue is the depletion of underground water reserves due to excessive extraction. Inefficient water distribution or management can lead to over-irrigation, wasting water and chemicals and potentially causing water pollution. Excessive irrigation can also raise water tables, leading to saline soil conditions and necessitating the control of water tables through some form of underground drainage system.[26]

2.9. Overview of Irrigation in Sudan

In Sudan, the total area encompassed by irrigation within the agricultural sub-sector is around 1.89 million hectares. The largest of these is the Gezira-managil Scheme, covering 0.882 million hectares. This is followed by other significant public sector initiatives such as New Halfa, Rahad, and the Blue and White Nile Schemes. Additionally, there are five sugarcane schemes and various smaller public schemes like El Suki, Abu Nama, and the Northern Agricultural Production Scheme. Outside the Nile system, the Gash and Tokar schemes are also notable. The private sector, mainly comprising pump schemes in the north, irrigates approximately 0.19 million hectares.[27]

Sudan's potential for arable land is about 7.6 million hectares, with 7% dedicated to cultivated land, 3% to permanent crops, and the rest to annual crops. Sudanese agriculture is categorized into three sub-sectors: irrigated, mechanized rainfed, and traditional rainfed. The irrigated sector, which contributes more than 10% to the cultivated area, is crucial to the Sudanese economy, accounting for over half of the agricultural output. Covering about 4.4 million feddans, this sector is essential for cash, food, and fodder crops, predominantly in Sub-Saharan Africa. Water for agriculture primarily comes from surface water, with groundwater being used only in limited areas, mainly for domestic purposes. Irrigation, employing various surface irrigation techniques, markedly increases productivity compared to rainfed conditions. In pump-irrigated

schemes, water is lifted to the surface and then distributed to fields either through gravity or flooding.

Table 2-5. Irrigated Schemes in Sudan.[16]

Scheme	Area (ha)	Irrigation method	Crops	Water source
Gezira	882000	Surface (short furrow)	Cotton, wheat, Sorghum	The Blue Nile River
El Rahed	243000	Surface (short furrow)	Cotton, wheat, Sorghum	The Blue Nile River
New Halfa	133650	Surface (short furrow)	Cotton, wheat, Sorghum	Atbara River
Sugar cane company	68000	Surface (short furrow)	Sugar cane + forage	White, blue, Atbara Rivers
Kenana	36000	Surface (short furrow)	Sugar cane	The White Nile River
White Nile	52000	Surface (short furrow)	Sugar cane + forage	The White Nile River
Marowe Dam schemes	61000	Surface + center pivot	Wheat, vegetable, fruit	The Nile River

2.10. Overview of Irrigation in the Gezira Scheme

The Gezira Scheme, situated in central Sudan southeast of Khartoum where the Blue and White Nile rivers meet, stands as one of the world's largest irrigation endeavours. Initiated by the British during their governance of Sudan, this scheme facilitates the distribution of water from the Blue Nile across its farmlands, situated amidst the Blue and White Nile rivers, through a network of canals and ditches.[28] The area's topography, gently sloping away from the Blue Nile, naturally aids the gravity-driven flow of water through these irrigation channels. The high clay content in the Gezira's soil minimizes water loss due to drainage.[29] The soil type in this region is classified as Vertosols, characterized by their tendency to form cracks. These cracks are critical in influencing the soil's hydraulic conductivity, a factor previously underestimated when only considering the fraction of small pores. The expansion and contraction of Vertosols play a significant role in determining or representing soil-water interactions. Such cracking leads to increased soil moisture loss at deeper levels through evaporation when the soil is dry, although this loss can be substantially mitigated under well-established crops. Furthermore, these cracks contribute to a heightened need for irrigation water during the initial irrigation post-dry season. They also pose risks of tunnel erosion in semi-arid areas, particularly under

heavy irrigation or intense rainfall conditions, and can cause physical damage to crop roots. This phenomenon and its implications were detailed in the study by Gilbert and Charles in 1987.[28]

2.11. Overview of Sudan Arable Land

Historically, the primary sector in Sudan has been agriculture and pastoralism, engaging nearly half of the workforce and constituting a third of the national GDP. The country possesses approximately 68.2 million hectares of arable land, equivalent to about 183.3 million feddans, constituting roughly 36.2% of the country's total land area. However, only about 29% of this land, or 20.0 million hectares, is currently under cultivation. The majority of this arable land is located in the Kordofan (covering 35.6% of the country's arable area) and Darfur (32.4%) regions. Other significant areas of arable land are found in the states of Gedaref (6%), Sennar (4.3%), Blue Nile (4.1%), and White Nile (4%). This sector employs about 60% of the rural workforce and is responsible for producing a similar percentage of the country's food grains.[12] The primary staple crops in Sudan are sorghum, which is typically cultivated on clay soils, and millet, grown on sandy soils. The country also produces a variety of cash crops, including sesame, groundnut, sunflower, kerkade (roselle), watermelon, and sugarcane.[16]

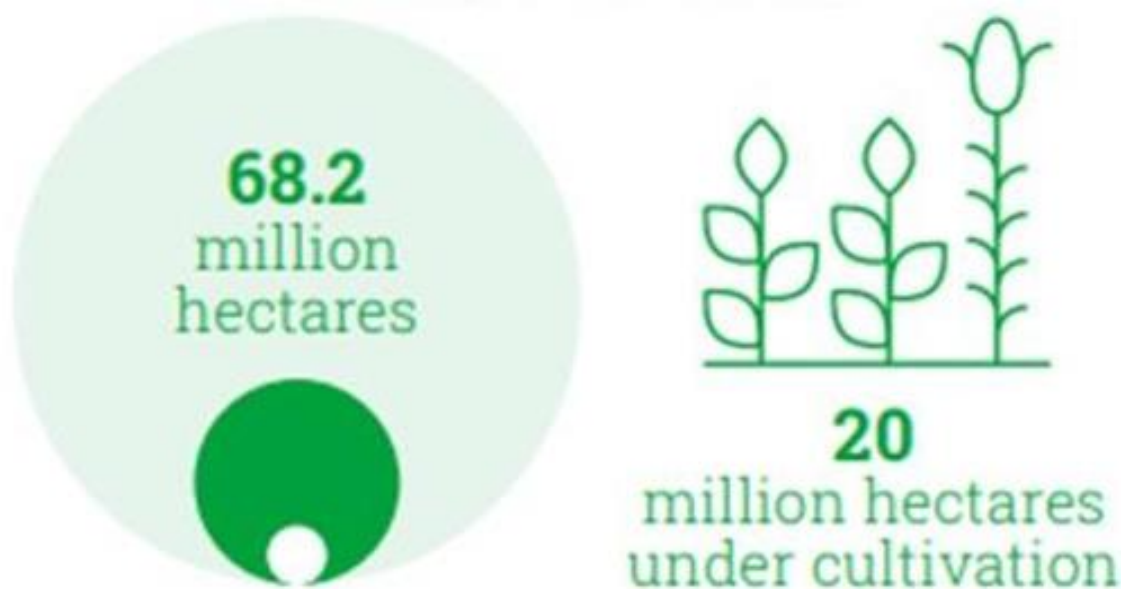


Figure 2-9. The cultivable land of Sudan.[16]

Agriculture in Sudan is confronted with several significant obstacles, key among them being the lack of comprehensive macroeconomic policies. Despite the country's extensive

agricultural activities, domestic production still falls short of meeting the annual demands. There's a noticeable trend of increasing production in high-value export crops, which contrasts with the production levels of crops meant for local consumption, including those from rain-fed agriculture. Additionally, there is a notable lack of supportive policies for small-scale agricultural projects. Issues with funding and financial support are frequent, adding to the challenges faced by small producers. Another critical concern is the unavailability of production inputs and sustainable agricultural technologies. In contrast, the use of chemical fertilizers and pesticides is prevalent, posing potential risks to sustainable agricultural practices. [16]

2.12. Climate of Sudan

Sudan's climate varies widely across the country, ranging from arid conditions in the north and southwest to relatively wet conditions in the south. The central and northern desert regions experience extreme dryness and abundant sunshine, with some areas enduring long periods without rainfall. Summers are extremely hot, with temperatures often exceeding 40°C and occasionally reaching 45°C. [30]

Temperature changes between seasons are minimal, especially in the far south where temperatures remain consistently high. Rainfall and the length of the dry season are influenced by prevailing winds, with dry northeasterly winds bringing little rain from January to March and moist south-westerly winds bringing rain from May onwards.[31] Droughts can occur if these winds fail to bring rain, as seen in the 1970s and 1980s, severely impacting both the people and economy of Sudan. EL Damazine in the east experiences an eight-month rainy season, while Khartoum in the north has a three-month rainy season. Delayed or absent rains due to droughts can have significant consequences for Sudanese society and the economy.[32]

2.13. Climatic Zones

Figure 2-10, as presented in the Sudan National REDD+ Programme (2017), illustrates the various climatic zones of Sudan, ranging from desert to semi-humid conditions. Notably, the majority of Sudan's irrigation schemes are situated in the dry zones of the country. Conversely, the bulk of rain-fed agriculture is predominantly located in the semi-humid zone.[16]

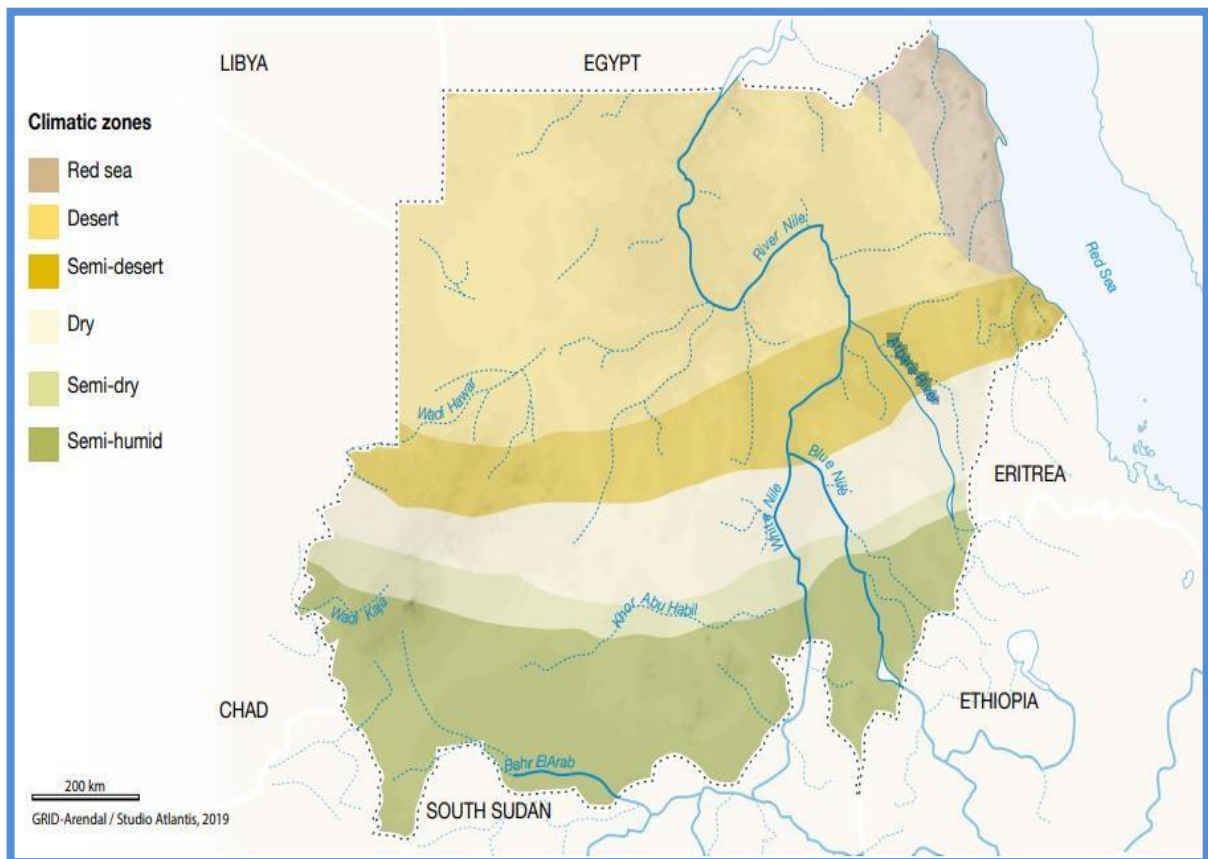


Figure 2-10. Sudan's climatic regions. [16]

2.12. Overview of Water Uses in Agriculture in Sudan

Sudan stands out for possessing the second-largest irrigated area in Africa, next only to Egypt. This irrigation plays a vital role in the nation's agricultural output and overall economic stability, especially given the escalating occurrences of droughts and increased susceptibility to rainfall variations in recent times. As per the 1959 Nile Water Agreement, irrigation constitutes approximately 96.2% of Sudan's Nile water allocation, equating to 18.55 billion cubic meters. [33] Sudan boasts nearly 292 million feddans (equivalent to 122.6 million hectares) of agriculturally suitable land, covering almost half of its total land area. Of this, 29.5 million feddans (about 12.4 million hectares) are employed for rainfed agriculture, comprising 96.1% of the land used for cereal cultivation nationwide. Additionally, 15 million feddans (around 6.7 million hectares) are designated for semi-mechanized rainfed agriculture, forming a band across various states including Kassala, Gedaref, Blue Nile, Sennar, White Nile, and South Kordofan. Sorghum is the predominant crop on 80% of these lands, with other cultivated produce including sesame, sunflowers, millet, and cotton. While agricultural mechanization in Sudan offers certain benefits, it has also led to adverse environmental consequences such as deforestation, soil erosion, and land degradation. Moreover, an additional 8.3 million feddans

(approximately 3.5 million hectares) are allocated for irrigation, where major crops like millet, wheat, cotton, groundnuts, sesame, sugarcane, and various vegetables such as potatoes, onions, okra, and tomatoes are cultivated.[34]

2.15. Overview of Irrigated Water Management in Sudan

The primary application of Nile water in Sudan is for irrigation, consuming an average of 15.9 billion cubic meters (BCM) annually over the past decade. This irrigation supports the production of key crops, including the entirety of Sudan's sugar and the majority of its cotton, along with significant portions of sorghum, groundnuts, fruits, and vegetables. Despite this, water use efficiency for crops like cotton, sorghum, groundnut, and wheat is below 0.2 kilograms per cubic meter (kg/m^3), which is lower than the global average. There's a recognized potential to enhance this efficiency to reach around $1 \text{ kg}/\text{m}^3$. [35] Sugar cane, a major water-consuming crop, occupies about 10% of Sudan's cultivated land but accounts for 30% of its Nile water usage. Sugar beet, on the other hand, has shown promise in Gezira state's agroclimatic conditions, yielding high sugar content. Comparatively, sugar beet requires significantly less water than sugar cane for irrigation and produces a higher yield of pure sugar per hectare. There is a pressing need for extensive research to develop and implement high-efficiency irrigation techniques and management practices to minimize water losses and improve water use efficiency. This includes cultivating drought-resistant crops or varieties and optimizing irrigation schedules. [33] In the Gezira Scheme, which is central to Sudan's irrigated agriculture, simple but effective water management practices are essential, especially in heavy-cracking clay soils. These soils, prone to waterlogging due to their texture, can adversely affect crop growth if not managed properly. Over-irrigation leads to surface water accumulation and anaerobic soil conditions, which can inhibit plant growth and reduce crop yields. Therefore, careful management of irrigation intervals is crucial to avoid water stress and maintain optimal growing conditions for crops. [21]

2.16. Water Consumptive Uses and Future Demand in Sudan

In the Nile River basin, there has been a significant and rapid increase in water consumption over the past half-century, a trend expected to continue. This growth in water use is primarily driven by a combination of factors including population expansion, expansion of irrigation and urban areas, environmental challenges, seasonal water flow variations, inefficiencies in water usage, and suboptimal management of water infrastructure. These elements have exerted considerable strain on the limited water resources in the Nile basin. Irrigation accounts for the lion's share of water consumption, using up to 80% of the resources. In Sudan, the demand for

water in agriculture is amplified due to the inefficient irrigation systems and the high water needs of the crops grown. In contrast, the combined water uses for domestic, livestock, and industrial purposes constitutes less than 20% of the total consumption. Regarding agricultural land, approximately 1.85 million hectares have been developed for agricultural schemes, with the actual cultivated area exceeding 1.35 million hectares. This figure is anticipated to increase to about 2.31 million hectares shortly. This figure is anticipated to increase to about 2.31 million hectares shortly. [22]

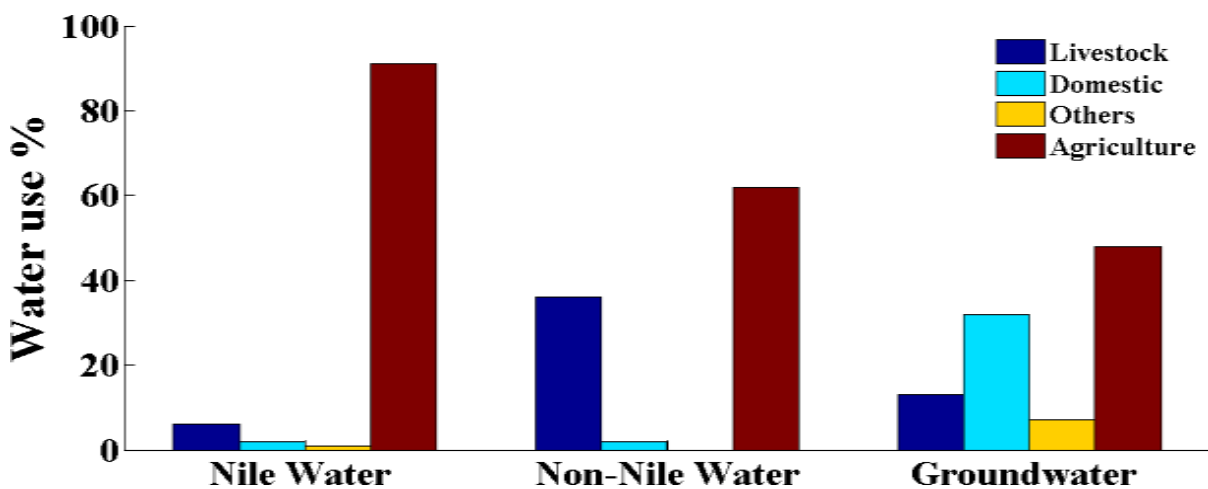


Figure 2-11. Sector Wise Water Consumption from Different Resources in Sudan. [22]

In Sudan, the efficiency of irrigation systems is considered high. The Gezira scheme, which utilizes 40% of the current water withdrawals, boasts an impressive water use efficiency of about 85%. Nevertheless, this system faces significant challenges, including the siltation of canals, the proliferation of aquatic weeds, and the deterioration of its irrigation infrastructure. Additionally, water loss due to evapotranspiration is notably high in the region. [22]

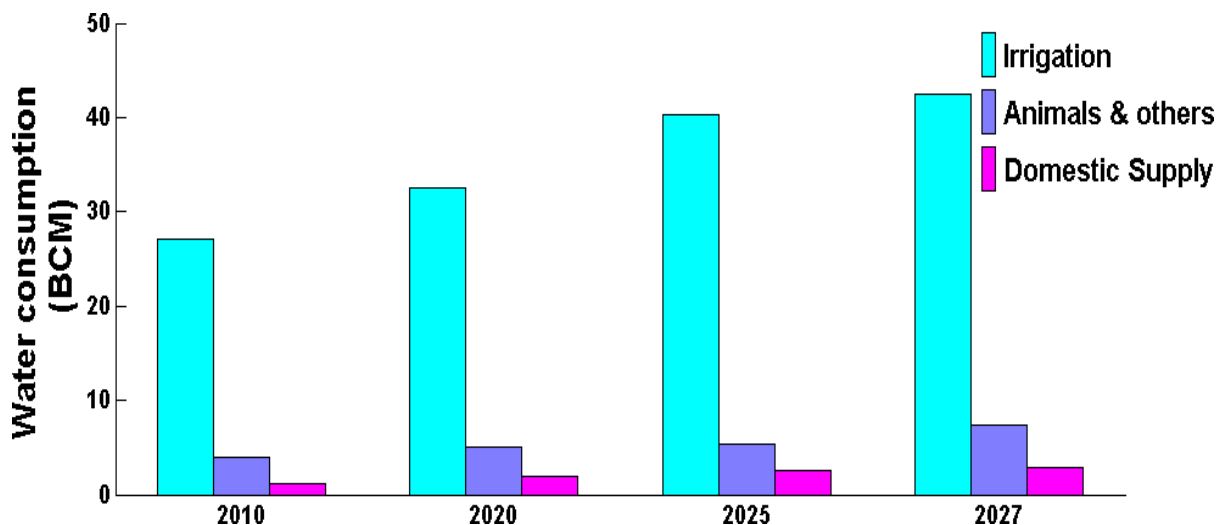


Figure 2-12. Estimate of the yearly water usage by 2030 in Sudan. [22]

2.17. Integrated Water Resources Management

The concept of Integrated Water Resources Management (IWRM) has evolved over recent decades as a response to the increasing strain on water resource systems due to burgeoning populations and socioeconomic developments. Globally, the challenges of water shortages and deteriorating water quality have compelled many countries to re-evaluate their development policies in relation to the management of water resources. Consequently, Water Resources Management (WRM) has been witnessing a global shift, transitioning from a predominantly supply-oriented, engineering-focused approach to a demand-oriented, multisectoral approach, commonly referred to as integrated water resources management.[33] IWRM represents a departure from the traditional top-down approach of "water master planning," which typically concentrates on water availability and development. Instead, it advocates for "comprehensive water policy planning," focusing on the interplay between various subsectors. This approach is encapsulated in Figure 2-13, highlighting the holistic and interconnected nature of water resource management under the IWRM framework.[35]

2.18. Integrated Water Resource Management in Sudan

Since 2005, Sudan has committed to adopting Integrated Water Resources Management (IWRM) to ensure the sustainable and fair management of its water resources. The Japan International Cooperation Agency (JICA) has been engaged in Sudan, partnering with the Ministry of Irrigation and Water Resources, on a project aimed at improving the implementation of IWRM. This initiative has resulted in two notable achievements: conducting a water balance analysis and pinpointing critical concerns in water resource management.[36] Sudan has been the site of numerous successful practices and case studies in IWRM. The United Nations Environment Programme (UNEP) has examined and assessed more than 30 case

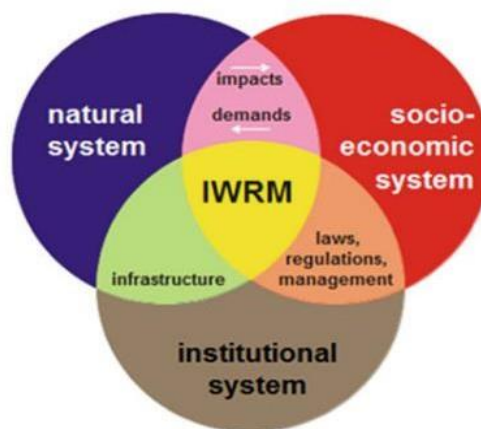


Figure 2-13. Relationships between the natural, administrative, and socioeconomic aspects of water resources, as well as their interactions with the environment.[35]

studies of this nature. Among them, six case studies, originating from various regions of Sudan, were specifically chosen for presentation. These case studies cover a wide array of geographic areas, encompassing different ecological zones, and involve a variety of water utilisation practices. Some notable examples include the Wadi El Ku Catchment Management Project in Darfur, the National Adaptation Programme for Action focusing on Climate Change Adaptation, the Butana Integrated Rural Development Project, and the Rural Water for Sudan project. Each of these endeavours demonstrates the diverse applications and advantages of IWRM in Sudan, underscoring its significance in effectively managing water resources across varying regions and circumstances.[37]

2.19. Critical Issues Affecting the Global Outlook for Water and Food Security

2.19.1. Growing Demand

The United Nations Department of Economic and Social Affairs forecasts that by 2030, the global population could reach 8.4 to 8.6 billion and may increase to between 9.5 and 13.3 billion by 2100. After reaching this peak, a stabilization and potential decline in population numbers is anticipated. The Food and Agriculture Organization (FAO) notes a concerning trend: over the last century, global water withdrawal has increased 1.7 times faster than the population growth, raising sustainability concerns for water usage in agriculture, industry, and domestic sectors. By 2050, agricultural production must grow by 60% from 2005/2007 levels to meet escalating demands. Economic growth and higher incomes are shifting food preferences towards more water-intensive products like meat, fish, and dairy. This shift also increases demand for animal feed, particularly coarse grains and protein meals, which impacts water resources due to the higher water requirements for meat and dairy production compared to cereals.[38]

Around 90% of the necessary increase in global food production by 2050 is expected in developing countries, where their contribution to global food production is projected to rise from 67% in 2007 to 74%. Livestock production in these countries will also grow significantly, increasing their share of global production from 55% in 2005/2007 to 68% by 2050. Regions like South Asia and sub-Saharan Africa are anticipated to see substantial increases in agricultural production. The majority of global population growth between 2015 and 2050 is projected to occur in urban areas of low-income countries. Given that a substantial amount of global food is produced locally (with only around 19% traded internationally), improving productivity in developing nations is vital for ensuring food security. However, issues of poverty and hunger will likely persist in many areas, especially in poor households in lower-income countries and regions with depleted or degraded natural resources. Persistent poverty,

hindering households' ability to purchase enough food, particularly during scarcities or high price periods, is expected to remain the primary cause of food insecurity.[39]

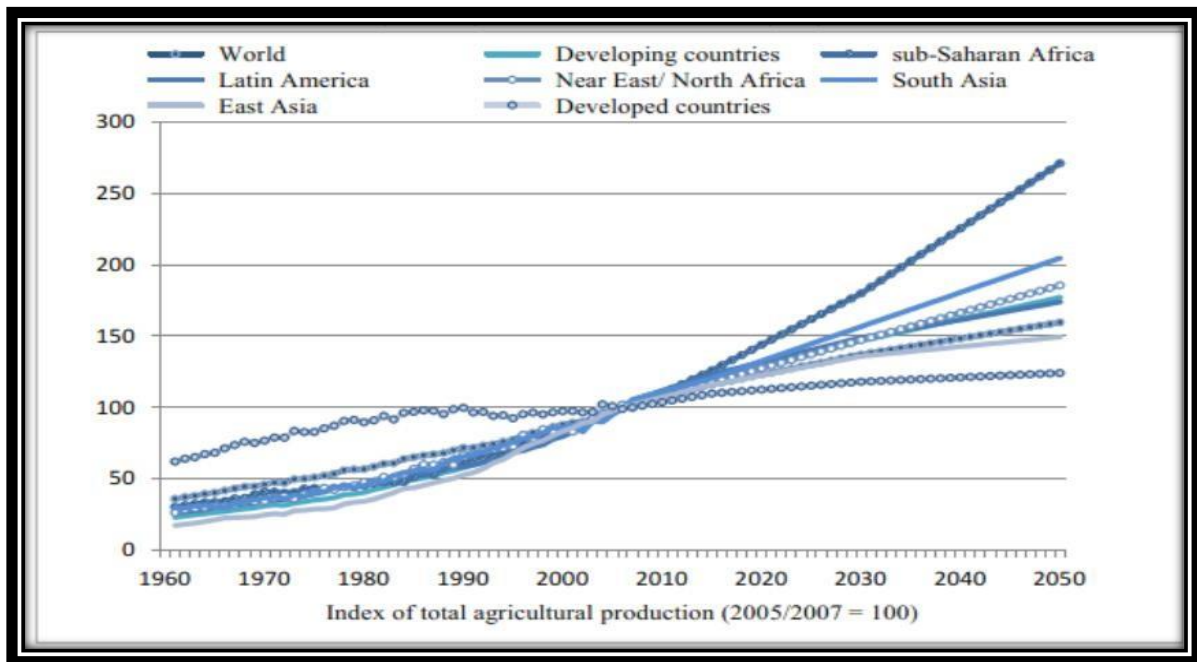


Figure 2-14. Agricultural Output by Region. [39]

2.19.2. Water Scarcity

Water scarcity occurs when the demand for water exceeds the available supply, often due to high usage across sectors like agriculture, industry, and domestic consumption, coupled with limitations in institutional frameworks and infrastructure.[40] Despite projections indicating that global freshwater resources should be sufficient for agriculture's needs by 2050 with appropriate technologies and investments, there will likely be significant variations in water availability both between and within countries. Regions like the Near East, North Africa, South Asia, and others are anticipated to persistently encounter significant water scarcity. As urban areas and industries increasingly compete with agriculture for water resources, many countries or regions are experiencing critical levels of water stress and pollution. This situation is particularly concerning in some river basins which are also major cereal-producing areas, indicating a direct impact on food production. A global overview of current water scarcity levels shows that regions with critical water shortages often coincide with key agricultural zones, presenting significant challenges for sustainable water management and food production in these areas.[39]

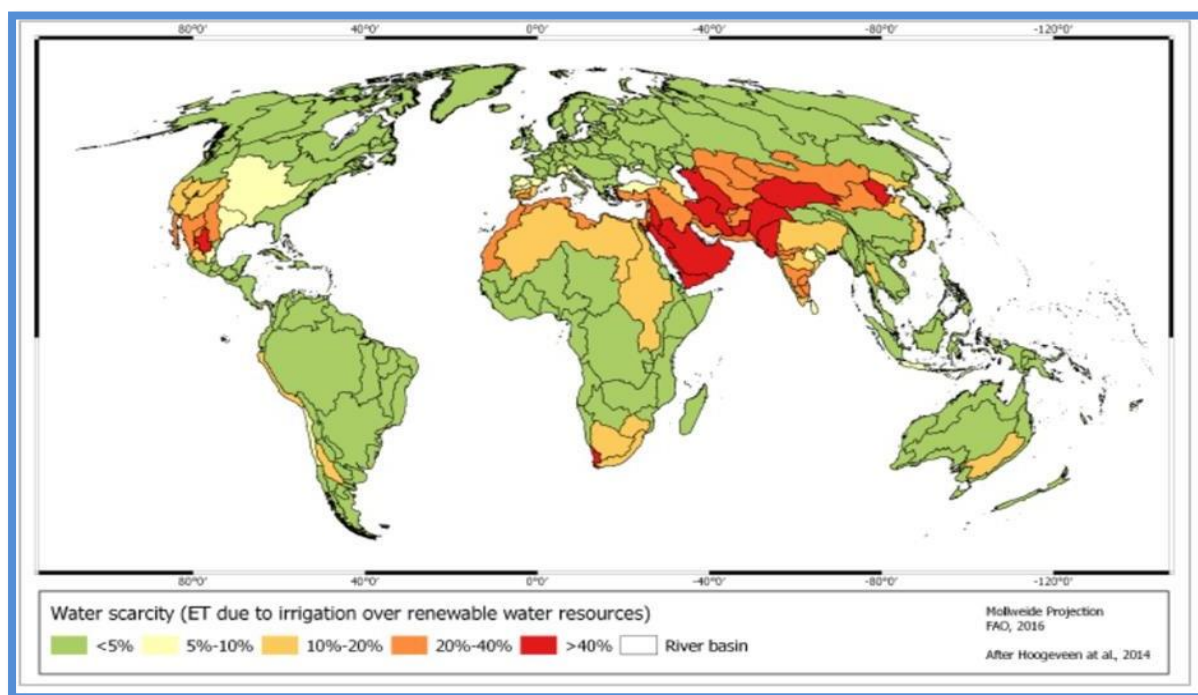


Figure 2-15 . Worldwide water scarcity by significant river basin.[39]

2.19.3. Climate Change

Climate change significantly complicates the existing challenges of water scarcity, impacting agriculture and ecosystems. This is anticipated to disrupt the water cycle, leading to changes in rainfall patterns and impacting both the availability and quality of surface and groundwater. This change will influence agricultural production and ecosystems, especially through the variability of rainfall, impacting surface water flow and aquifer recharge rates. Sea-level rise, a direct consequence of climate change, threatens agricultural land through inundation or saline intrusion into aquifers, necessitating the development of new food-producing areas. Rainfed agriculture, which represents a significant portion of global cropland and food output, is particularly vulnerable, especially in arid and semi-arid regions.[41]

More research is necessary to fully grasp the potential effects of climate change on ecosystems dependent on groundwater. The impacts are anticipated to be more severe in arid areas, shallow aquifers, and already stressed ecosystems. Some regions may benefit from warmer temperatures and longer growing seasons, leading to altered cropping patterns and increased yields. However, overall, the negative impacts on agriculture are likely to outweigh the positives. In large countries such as China and India, the impacts of climate change and the effectiveness of policy responses and investments may vary significantly across different regions.[42] Elevated temperatures can also negatively affect the health and productivity of livestock. Smallholder farmers, who have limited resources and capacity for adaptation, are especially vulnerable to these impacts. This situation highlights the urgent need for targeted

strategies and investments to help these vulnerable groups adapt to changing climates, protecting their livelihoods and food security.[41]

2.20. The Role of Irrigation for Food Security

Irrigation is vital for ensuring food security, which encompasses both the availability and accessibility of food. Here's a paraphrased explanation of its importance:

- **Enhancing Crop Production:** Irrigation boosts the number of crops grown per area, leading to a substantial increase in overall food production, especially in areas with unreliable rainfall.
- **Consistent Agricultural Output:** It lessens reliance on rainfall, providing a steady output of crops regardless of weather changes, thus maintaining a regular food supply.
- **Diversity of Crops:** Irrigation enables the cultivation of a broader range of crops, including nutrient-rich fruits and vegetables, enhancing dietary diversity and farmers' economic resilience.
- **Longer Growing Periods:** By providing water throughout the year, irrigation allows for more planting cycles annually, boosting total food production.
- **Counteracting Droughts:** In drought-prone areas, irrigation is crucial for sustaining crop growth during dry spells, ensuring uninterrupted food supply.
- **Quality and Nutritional Improvement:** A regular water supply can lead to better quality and more nutritious produce. **Economic Advancement and Poverty Alleviation:** Increased yields and diverse crops can elevate farmers' incomes and contribute to poverty reduction, thereby improving access to food.
- **Expanding Arable Land:** Irrigation can transform unproductive lands into fertile fields, increasing the land available for growing food.
- **Innovative and Efficient Water Use:** Modern irrigation techniques promote water efficiency and sustainability, supporting long-term food security goals.

Adapting to Climate Change: As global weather patterns shift due to climate change; irrigation becomes crucial for adjusting farming practices to new environmental conditions.

While irrigation significantly boosts food security, it's essential to employ sustainable practices to avoid issues such as water scarcity, soil degradation, and environmental damage. Responsible water management is key to sustaining the benefits of irrigation for long-term food security.[43]

2.21. Overview on The Gezira Irrigation Scheme

The Gezira Scheme, one of the world's most extensive irrigation projects, is situated in the Sudanese state of Gezira, just southeast of where the Blue and White Nile rivers converge at Khartoum. Initiated by the British during the era of Anglo-Egyptian Sudan, the project leverages water from the Blue Nile, distributing it through a network of canals and ditches to tenant farms nestled between the Blue and White Nile.[44] The region, known as "Gezira" (meaning "island"), is particularly well-suited for irrigation, benefiting from a natural slope away from the Blue Nile which facilitates gravity-driven water flow through the canals. The soil's high clay content minimizes water loss due to seepage.

Initially, Reginald Wingate, the British governor-general of Sudan, had envisioned wheat cultivation, but this idea was later revised in Favor of a more lucrative cash crop. The discovery that Egyptian-type long staple cotton thrived in the region aligned well with the needs of the British textile industry. Cotton cultivation in the area dates back to 1904, with 24 squares kilometres beingcultivated by 1914 following several irrigation experiments.[45]



Figure 2-16. Farm in The Gezira Irrigation Scheme.[46]

The construction of the Sennar Dam on the Blue Nile, which was finished in 1925, was a reaction to the lowest Nile flood in 200 years. The dam, approximately 3 kilometres long, created a reservoir to ensure water availability. Initially financed by the Sudan Plantations Syndicate in London, the project later received backing from the British government. In 1950, management transitioned to the Sudan Gezira Board, headed by Arthur Gaitskell, replacing private enterprise.[47]



Figure 2-17. Sennar Dam.[47]

Farmers in the region collaborated with the Sudanese government and the Gezira Board. The irrigation infrastructure, which included a canal and ditch network extending 4,300 kilometres, expanded with the completion of the Manaqil Extension in the early 1960. By 2008, the irrigated area encompassed 8,800 square kilometres, representing about half of Sudan's total irrigated land. Despite diversification attempts, cotton remained the primary crop in this region.

2.22. Evapotranspiration (ET₀)

Reference crop evapotranspiration (ET₀) is characterized as the rate of evapotranspiration from a hypothetical, extensive grass surface. This surface is uniformly covered with actively growing green grass, approximately 8 to 15 cm in height, which completely shades the ground, assuming no water limitation.[55] The calculation of reference crop evapotranspiration, ET₀, is commonly conducted using the Penman-Monteith formula. This formula represents a well-established method in the field of agricultural sciences for estimating the evapotranspiration rate from a reference surface. The Penman-Monteith equation takes into account various

climatic factors, including temperature, humidity, solar radiation, and wind speed, to provide a comprehensive and accurate estimation of ET_0 . This measure serves as a standard benchmark for understanding and comparing evapotranspiration rates under different climatic conditions and is crucial in the effective planning and management of irrigation systems in agriculture.[56]

2.23. Crop Coefficient (K_c)

The crop coefficient is a crucial ratio that signifies the relationship between crop evapotranspiration (ET_c) and reference evapotranspiration (ET_0). This ratio is fundamental in irrigation planning and design, as it provides an accurate estimation of evapotranspiration essential for sustainable agricultural practices. The FAO 56 method combines the concepts of reference evapotranspiration and crop coefficients (K_c), offering a comprehensive framework for this estimation.[52]

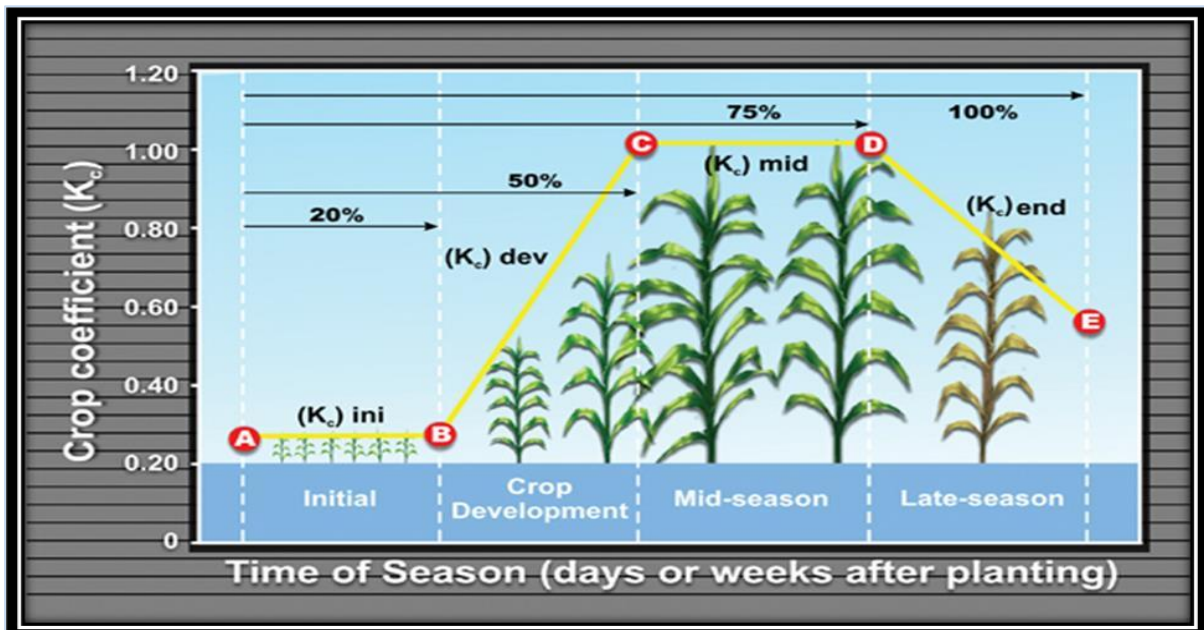


Figure 2-18. Crop coefficient (K_c).[54]

There are two main methodologies for estimating crop evapotranspiration: the single and dual crop coefficient approaches. The single crop coefficient (K_c) approach amalgamates the impacts of both crop transpiration and soil evaporation into a singular coefficient. In contrast, the dual crop coefficient method utilizes two distinct coefficients: the basal crop coefficient (K_c), which pertains to crop transpiration, and the soil evaporation coefficient (K_e). To accurately calculate ET_c for specific crops, it is essential to empirically determine crop coefficients (K_c) based on the local climatic conditions. The K_c value for any particular crop growth stage is regarded as constant and equal to the K_c of the current growth stage throughout both the initial and mid-season stages. However, during the crop development and late-season stages, the K_c

value is subject to linear variation.[50] It transitions between the K_c at the conclusion of the preceding stage and the K_c at the commencement of the subsequent stage, with the final stage K_c value being particularly pertinent during the late-season stage. This methodical approach in determining K_c values facilitates precise irrigation scheduling, optimizing water use efficiency and contributing to sustainable crop production.[53]

2.24. Crop Water Requirements

Crop Water Requirements (CWR) refer to the amount of water necessary to compensate for the evapotranspiration losses from a cultivated field, essentially matching the water needed for a crop's evapotranspiration. The determination of CWR is influenced by several factors, including climate, soil type, crop species, and the stage of crop growth. Typically, CWR is quantified in units such as mm/day, mm/month, or mm/season. It is intrinsically connected to crop evapotranspiration and signifies the amount of irrigation water required to attain optimal crop yield.[48] CWR can be calculated on a daily basis, provided that daily reference evapotranspiration data are available. It is important to understand that CWR for a specific crop variety may vary across different locations, influenced by climatic variations. These variations include differences in reference evapotranspiration rates, planting dates, lengths of growing seasons, and crop coefficient (K_c) values. In the Gezira region, empirical CWR values for various crops have been established by management at 100 mm per hectare every two weeks. The total water usage is computed by multiplying the actual number of irrigations by 100 mm per hectare, while excluding rainfall contributions. The crop water requirements (referred to as crop evapotranspiration under standard conditions, ET_c .) are calculated by determining the evapotranspiration of a reference crop (ET_0) using relevant meteorological data (as per Allen et al., 1998) and applying a specific crop coefficient (K_c). This approach allows for a more precise and localized assessment of the water needs for optimal crop cultivation in the Gezira region.[49]

2.25. Irrigation Scheduling

Irrigation scheduling represents a methodical approach to managing soil water reserves, ensuring the availability of water precisely when crops require it. This process involves the integration of soil moisture and weather monitoring to determine the optimal timing for irrigation, while considering factors such as the soil's water-holding capacity and the specific needs of the crop type, the appropriate amount of water to be applied is determined. Accurate irrigation scheduling is fundamental to the design and operation of an efficient irrigation system and is a critical component in water management strategies, often resulting in significant water

conservation when properly implemented.[21] The quantity and frequency of irrigation are dictated by a variety of factors, including the characteristics of the soil, plant water needs, prevailing meteorological conditions, and economic considerations. Irrigation schedules can be classified into three categories: full, medium, or deficit irrigation. These categories reflect the varying needs and conditions of different plants, soils, and climatic scenarios. Diverse irrigation strategies, soil types, and systems may necessitate different water volumes to achieve optimal crop yields. Effective irrigation scheduling requires a comprehensive understanding of several key factors: the soil's water-holding capacity, the crop's water consumption patterns, and the crop's sensitivity to moisture stress at different stages of growth. This understanding must account for both effective rainfall and the available irrigation water. [51] The methodologies employed for irrigation scheduling typically revolve around two principal approaches: soil measurements and crop monitoring. Both approaches aim to optimize water use efficiency, ensuring that crops receive the right amount of water at the right time, thereby enhancing agricultural productivity while conserving water resources.[57]

2.26. Overview of Water Policies in Sudan

Over the past decades, Sudan has formulated numerous water acts and regulations, with the 1990 Irrigation and Drainage Act and the 2005 Gezira Scheme Act being particularly influential. These legislations have significantly impacted the agricultural sector's current underperformance. Despite these efforts, Sudan has yet to finalize and endorse a contemporary water policy. The 1995 Water Law, which is frequently referenced, along with the draft 2007 Water Policy, are analysed for their relevance. Several shortcomings identified in these legislative frameworks can be linked to the decline in the agriculture sector witnessed over the past thirty years. These gaps highlight the necessity for updated and effective water management policies that can address the evolving challenges faced by Sudan's agricultural sector and contribute to its revival and sustainability.[19]

2.26.1. The Irrigation and Drainage Act

The 1990 Irrigation Drainage Act of Sudan is characterized by its regulatory nature. One of its key provisions mandates that any irrigation or drainage-related activities require a permit from the Ministry of Irrigation and Water Resources (MoIWR). Additionally, the Act stipulates that licensees must notify the Ministry when drawing water for irrigation, whether it be from the Nile River, its tributaries, or any other rivers or public canals. However, the Act largely overlooks facilitative and enabling aspects of water management. It does not adequately address issues such as improving living conditions, creating career pathways, and providing

capacity development opportunities for irrigation and water professionals. Nor does it focus on mechanisms to enhance irrigation and related farming services for farmers and other beneficiary groups. This omission has contributed to poor operation and maintenance, as well as low crop and water productivity, particularly within the four national large-scale irrigation schemes that span nearly 2 million hectares. The necessity to fortify the facilitative roles of Acts and Policies was acknowledged during the 2016 international conference focused on the revitalization of the Gezira irrigation scheme. Among the top priority areas for improvement identified at the conference was Human Resources and Services. This includes enhancing training, housing, office, and communication facilities for those working in the irrigation and water sector. Emphasizing these areas is crucial for elevating the effectiveness and efficiency of irrigation practices and, by extension, improving the agricultural productivity and water management in Sudan.[19]

2.26.2. The 2005 Gezira Scheme Act (GSA)

The 2005 Gezira Scheme Act (GSA) in Sudan was designed with the intention of shifting significant irrigation water management and farming responsibilities from engineers and agricultural officers to the farmers themselves. The Act aimed to empower farmers to participate in the planning and execution of projects affecting their livelihoods, oversee irrigation at the field canal level through water users' associations (WUAs), and have independence in their production and economic activities with technological assistance. However, the Act did not fully achieve these goals. A substantial number of irrigation and agricultural experts were prematurely let go, based on the assumption that WUAs would be able to assume their roles. Despite the establishment of nearly 1,500 WUAs, they struggled due to a lack of essential technical and financial support, leading to many becoming non-functional. This resulted in poor coordination between the farmers and the staff of the Gezira scheme. Consequently, farmers began to independently make decisions about crop types, cultivation timing, and areas. This disconnection in coordination and planning led to improper irrigation and cropping schedules. Farmers often cultivated areas larger than what the canal capacity could support, particularly in the tail-end areas of the scheme, causing delays and inadequacies in irrigation.[44]

Another significant aspect of the GSA was its provision for substantial private sector involvement in irrigation management. However, this move was hindered by the absence of regulatory guidance from the Irrigation Operations Directorate (IOD) and specific standards for private sector engagement. The machinery used by the private sector and the Earth Moving

Cooperation (EMC) was found to be inefficient, and the administrative system was lacking, with no effective integration of workflow. Maintenance activities were poorly overseen by the IOD, which operated with outdated facilities. Furthermore, private companies were often compensated based on the distance of land cleared rather than the quality of work, leading to inconsistent excavation efforts and subpar water delivery.[58]

2.26.3. The 1995 Water Law

The 1995 Water Law in Sudan is significantly flawed, lacking in integrated water resource management principles, clear guidelines for water utilization, and comprehensive coverage of key issues such as management, productivity, gender inclusion, and pollution control. It suffers from ambiguous jurisdictional roles between federal and state levels, resulting in ineffective implementation by the National Council for Water Resources (NCWR). The absence of a National Water Resources Allocation Plan hampers strategic water investment, crucial for addressing agriculture, food security, and climate change challenges. Overall, these deficiencies highlight Sudan's vulnerability to climate change and the urgent need for legislative reform and enhanced water management.[19]

2.26.4. The 2007 Water Policy

The 2007 draft Water Policy in Sudan, though acknowledging the need for integrated water resource management, fails to clearly define roles and responsibilities across sectors and regions, mirroring issues in the 1995 Water Law. This ambiguity hinders effective use and maintenance of water resources, particularly in irrigation and drinking water facilities. As a result, many irrigation schemes, especially medium-sized pump systems utilizing Nile water, have deteriorated. Approximately 60% of these systems, crucial for supporting a significant portion of the nation's agriculture and livelihoods, have ceased production due to poor operation and maintenance, reflecting a broader issue of inadequate resource allocation and strategic planning in the water sector.[19]

2.27. Previous Studies

Agriculture remains a cornerstone of global sustenance and economic vitality, particularly in regions where it forms a significant part of the Gross Domestic Product (GDP). A critical aspect of agricultural success is efficient water management, especially in the face of varying climatic conditions and the growing challenges posed by climate change. Over the years, numerous studies have been conducted to understand and optimize crop water requirements (CWRs) under different environmental and hydrological scenarios. These studies utilize advanced tools like the FAO's CROPWAT model and various methodologies to estimate irrigation needs, analyse

climate data, and propose sustainable agricultural practices. This collection of research provides invaluable insights into the evolving landscape of agricultural water management, highlighting the significance of precision irrigation and effective resource utilization in ensuring crop productivity and sustainability. The following is a summary of key studies that have significantly contributed to this domain, offering a comprehensive perspective on the nuances of crop water management across diverse geographical and climatic conditions.

In the 2017 publication "Crop Water Requirement for Different Hydrological Scenarios Using CROPWAT" by Shakuntala an assessment was conducted on the water necessities for various crops within the Ghataprabha command area, Karnataka, India. This evaluation was based on three decades of climatic data, employing the FAO Penman Monteith method within the CROPWAT framework. The study aimed to ascertain the irrigation requirements under different hydrological conditions such as dry (P80), wet (P20), and typical rainfall (P50) scenarios. The results indicated a higher irrigation demand in dry conditions, with a noticeable decrease in wet scenarios. The study observed that Kharif crops required less irrigation compared to Rabi and dual-season crops. This research underlined the criticality of efficient agricultural water resource management, particularly in Asia's agricultural sectors where it contributes significantly to GDP. The study highlighted the need for adept water management strategies, exacerbated by the challenges of limited arable land and unpredictable rainfall patterns due to climate change. The research utilized the CROPWAT tool, developed by the FAO, for calculating crop evapotranspiration, water needs, and irrigation scheduling. The conclusion emphasized the variable irrigation needs of crops under different climatic conditions, underscoring the importance of selecting optimal scenarios for effective water resource management and crop yield maximization.[48]

Edy Suryadi et al., in their 2018 study "A Study of Crop Water Needs and Land Suitability in the Monoculture System and Plant Intercropping in Arjasari," focused on the arid region of Arjasari, developed for cultivating palawija (secondary food) crops. The study aimed to determine the water requirements of the crops and the land's suitability for efficient water usage. Employing descriptive analysis for climate data and the Blaney Criddle method for water needs estimation, the study concluded that appropriate water allocation could enhance crop productivity. This research is vital in understanding the impact of efficient water use in arid regions and developing strategies for sustainable agriculture.[59]

In 2019, Salam Hussein Ewaid, Salwan Ali Abed, and Nadhir Al-Ansari conducted a study titled "Crop Water Requirements and Irrigation Schedules for Some Major Crops in Southern Iraq," which focused on the semi-arid climate of Iraq. They highlighted the importance of

accurately estimating crop water requirements (CWRs) and irrigation scheduling given Iraq's evolving climate and water resource conditions. The study utilised the FAO CROPWAT 8.0 simulation software and the CLIMWAT 2.0 tool, demonstrating the effectiveness of these tools in managing water resources efficiently.[60]

Maie Kabbashi Alla Jabow's 2020 study "Irrigation Schedule of Chickpea (*Cicer arietinum* L.) Using CROPWAT Model under Gezira Conditions Sudan" provided an in-depth analysis of chickpea water requirements and optimal irrigation scheduling under Sudan's Gezira conditions. The study utilized climatic data and field experiments to employ the CROPWAT 8.0 Model, exploring various irrigation scheduling criteria. This research highlighted the significance of precision in irrigation scheduling for water use efficiency in Sudan's agricultural sector.[7]

In 2021, Yemane Mebrahtu Hagos, Mehari Yetagesu, and Nurga Habtamu Tamiru's paper "Estimation of Crop Water Requirement using CROPWAT Model for Maize: A Case Study of Raya Azebo District, Ethiopia" examined the essential role of water in crop production and the necessity for effective irrigation management for maize cultivation in Raya Azebo, Ethiopia. Utilizing the FAO Cropwat 8.0 model, the study aimed to estimate maize's water requirements, revealing distinct variations between off-season and main season needs due to climatic differences and rainfall availability. This research provides valuable insights for water resource management and optimization of maize production, underlining the influence of climatic conditions on irrigation needs.[61]

The 2022 study by Randa S. Makar and colleagues, titled "Evaluating the Impacts of Climate Change on Irrigation Water Requirements," explored the implications of climate change on agriculture and water resources, focusing on Egypt's El-Beheira governorate. The research projected future climate scenarios using atmospheric analysis, remote sensing, GIS, and the CROPWAT 8 model. It highlighted an expected increase in irrigation water requirements for key crops in response to climate changes over the next three decades. This study emphasizes the urgency of adopting efficient irrigation management strategies to adapt to climate change and water availability fluctuations.[62]

In 2023, Abhishek Agrawala and his team conducted a study "Future Projections of Crop Water and Irrigation Water Requirements Using a Bias-Corrected Regional Climate Model Coupled with CROPWAT." This research aimed to assess the impact of climate change on rice Crop Water Requirement (CWR) and Net Irrigation Requirement (NIR) using the NASA Earth Exchange Global Daily Downscaled Projection (NEX-GDDP) combined with the CROPWAT 8.0 model. The study's findings indicated a significant increase in both maximum and minimum

temperatures by 2040, leading to heightened NIR. This work underscores the criticality of adapting agricultural practices to anticipated climatic shifts to ensure efficient water management and sustainable crop production. These studies collectively contribute to a comprehensive understanding of crop water requirements under varying climatic and hydrological conditions. They underscore the importance of precision in water resource management for sustainable agriculture, particularly in the face of climate change and its associated impacts on water availability and crop productivity.[63]

2.27. Theoretical Concerns

This study seeks to push the frontiers of existing research by meticulously identifying the water requirements for irrigation under varying climatic conditions, including periods of both rain and drought. It delves deeply into understanding the specific water needs throughout the diverse climates of the summer and winter months. The scope of this research is further broadened to include an extensive variety of crops, aiming for a comprehensive analysis of their irrigation needs. A pivotal aspect of this investigation is the evaluation of the current water supply's adequacy in meeting the irrigation demands of principal crops in The Gezira scheme, a critical factor often overlooked in previous studies. This evaluation is crucial for devising efficient and sustainable strategies for water management. To enrich the study further, attention will be paid to both the presently utilized area and the overall extent of the Gezira irrigation scheme. Integrating these spatial considerations allows for a deeper insight into the scheme's operational capacity and usage patterns, leading to a more precise evaluation of its water management practices. Through this inclusive approach, the study aims to make a significant contribution towards advancing knowledge and enhancing the practices of water resource management in the field of agriculture.

CHAPTER THREE

3. METHODOLOGY

3.1. Introduction

In this section, we explore the investigative methods used to evaluate the adequacy of irrigation water supply within the Gezira scheme, utilizing a comprehensive quantitative analysis. This process involves collecting and scrutinizing data concerning weather patterns, crop water requirements, and soil characteristics. Notably, emphasis is placed on the utilization of CROPWAT 8.0 software, which is crucial for accurately determining irrigation needs and devising plans accordingly. The pivotal role of this tool in providing precise and actionable insights for water resource management is highlighted. Additionally, a brief overview is provided regarding the study area, encompassing its climate and the irrigation system employed within the Gezira irrigation scheme.

3.2. Case Study Presentation

3.2.1. Study area

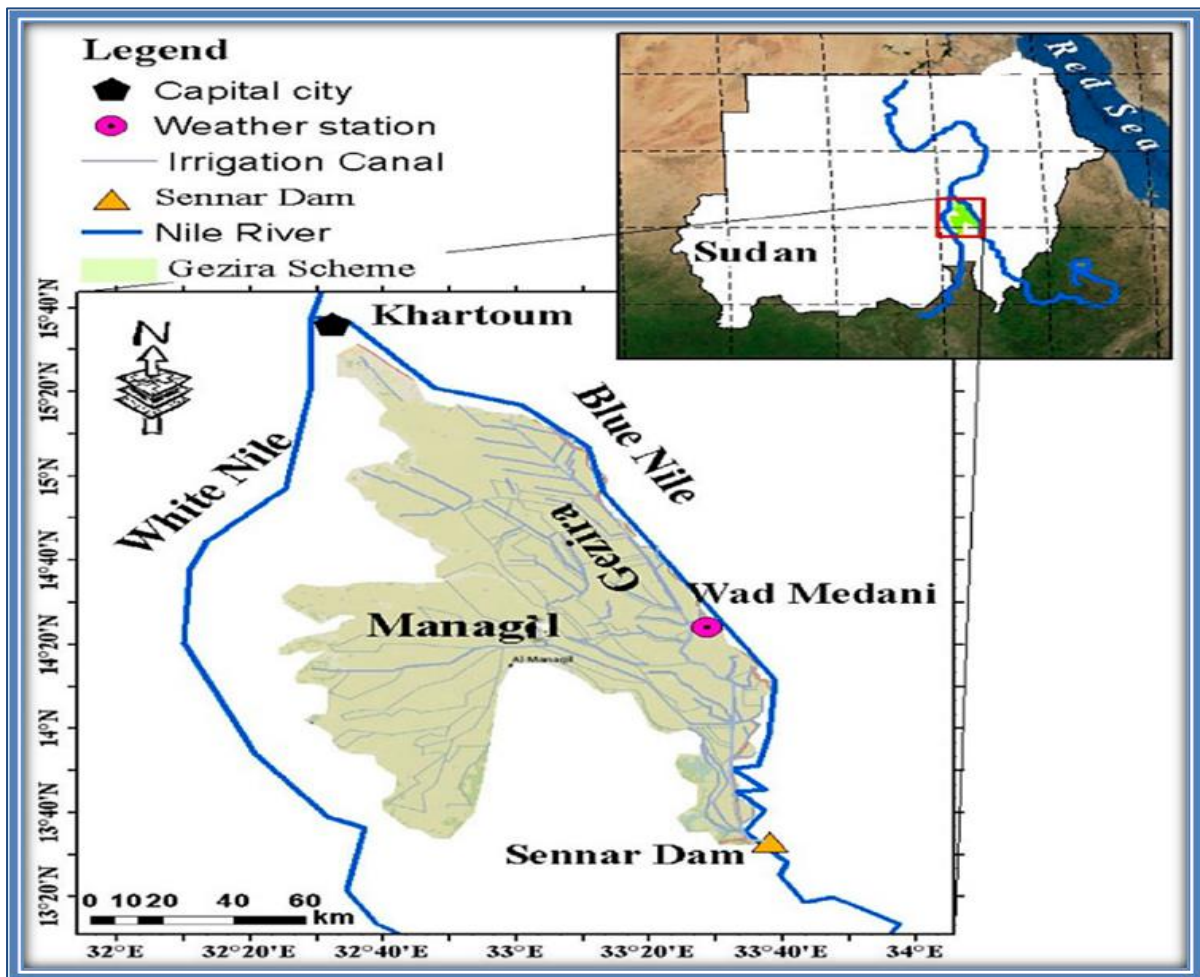


Figure 3-1. Map depicting the study area. [65]

The Gezira Irrigation Scheme, located between the Blue and White Nile rivers to the south of Khartoum, covers an area of approximately 882,000 hectares. Divided into the Gezira main and Managil Extension, it relies on gravity-fed irrigation from the Sennar Dam. This scheme, managed by a single entity, is the world's largest irrigated scheme. It constitutes about a quarter of Sudan's total irrigation area and consumes 35% of the country's Nile water allotment. Originally focused on cotton production, it now cultivates food and high-value export crops. Social development within the scheme area is a key objective, including improvements in education, healthcare, employment, and settlement security. Crop diversity includes cotton, groundnut, wheat, sorghum, and vegetables, with significant contributions to national 1 output. Livestock husbandry is also prevalent within the scheme's domain.[64]

3.2.2. Climate of the Study Area

The Gezira Irrigation Scheme is situated within a hot and semi-arid climatic zone characterised by three distinct seasons: winter (November to February), summer (April and May), and autumn (July to September), with transitional months of March, June, and October. Rainfall intensity exhibits a gradient from north to south. The yearly average rainfall over the long term is 156 mm in Khartoum, 354 mm in Wad Medani, and 472 mm in Sennar (as shown in Figure. 3-1). At Wad Medani, the daily mean temperatures fluctuate, registering at 25°C, 29.4°C, and 31°C during winter, autumn, and summer, respectively.[65]

3.2.3. Irrigation Management

The administration of irrigation involves the operation and supervision of the irrigation system, which consists of two principal canals originating from the Sennar Dam: the Gezira canal, with a capacity of 168 m³/s, and the Managil canal, with a capacity of 186 m³/s. Figure 3-2 depicts the primary canal responsible for delivering water to the major canals. Subsequently, water is directed to minor canals at predetermined and fixed levels to ensure equitable distribution among field canals (Abu Ishreen). Farmers utilise internal canals (Abu Sitta) to irrigate their farms.

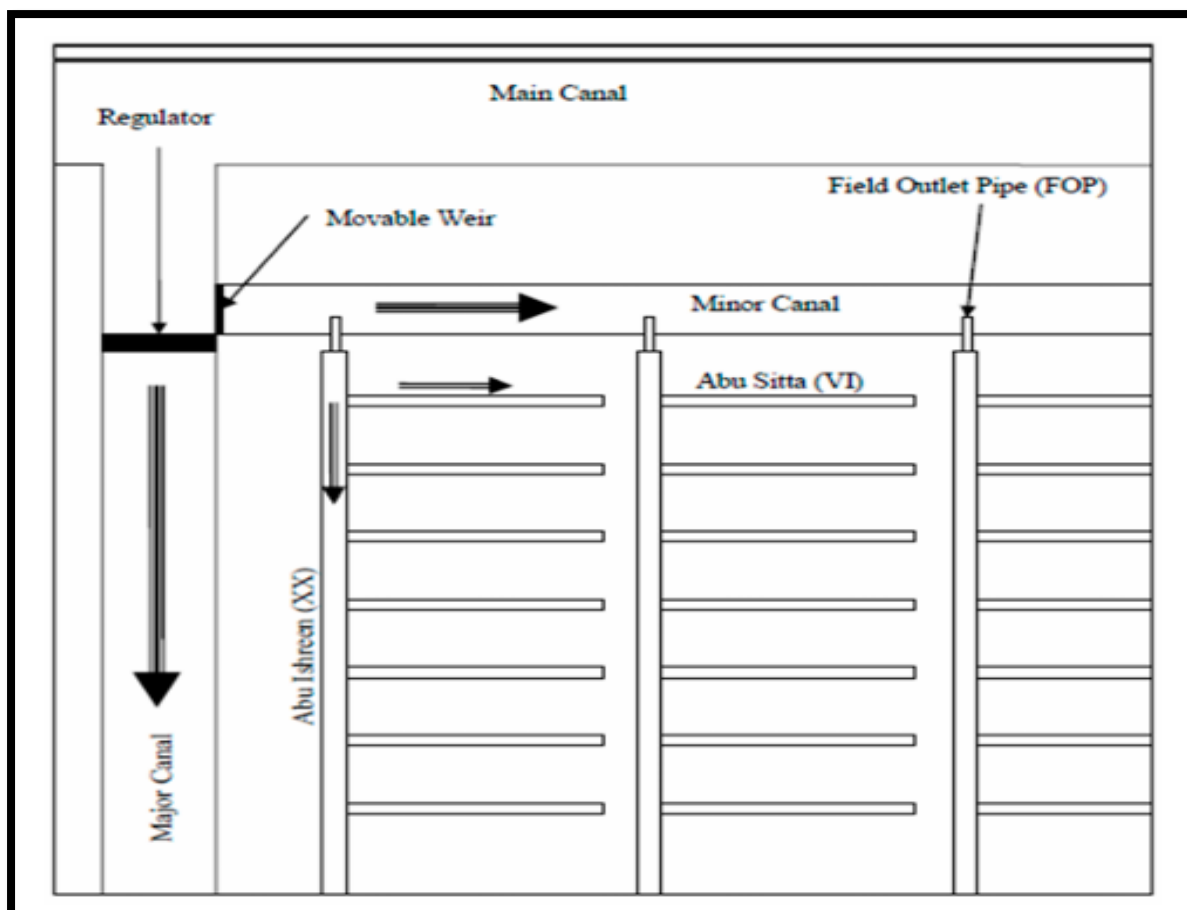


Figure 3-2. The irrigation system of The Gezira Irrigation Scheme. [65]

Table 3-1. Some important features of The Gezira Scheme.

No.	Feature	Length (km)	Capacity (m ³ /s)
2	Main canals	261	Max. 186 & 168
11	Branch canals	651	25 to 120
107	Major canals	1652	1.5 to 15
1,498	Minor canals	8,119	0.5 to 1.5
29,000	Water courses	40,000	0.116
350,000	Field channels	100,000	0.05
Total irrigated Area			882,000 ha
Total number of Tenants			110,000
Average farm size			8.4 ha

3.3. Research Design

3.3.1. Description of the Research Approach

This research employs a quantitative methodology to assess the sufficiency of water provision for meeting the irrigation demands within the Gezira Scheme. The selection of a quantitative

approach stems from the research's objectives and inquiries, which necessitate numerical data for analysing crop water requirements (CWR), irrigation water requirements (IWR) under varying precipitation conditions, and for devising an effective irrigation schedule. This methodology entails the gathering and statistical analysis of data pertaining to climatic factors, rainfall patterns, crop attributes, and soil characteristics. These data are utilised in computational models, such as the CROPWAT model, to determine specific water requirements and evaluate the Gezira Scheme's capacity to meet these demands.

3.3.2. Rationale for the Chosen Approach

The rationale for adopting a quantitative approach lies in its capacity to yield precise, objective, and generalisable findings essential for informed decision-making concerning irrigation water management within the Gezira Scheme. This methodology permits the application of mathematical and statistical techniques to compute crop water requirements (CWR) and irrigation water requirements (IWR), assess the influence of rainfall on irrigation demands, and devise an efficient irrigation timetable. Through quantitative analysis, relationships between climatic variables and irrigation needs can be scrutinised, facilitating the evaluation of water supply adequacy across diverse scenarios. Furthermore, it enables the assessment of various irrigation strategies to enhance water use efficiency and sustainability. By employing a quantitative methodology, this study seeks to contribute empirical evidence to the discourse on agricultural water resource management, particularly within the context of the Gezira irrigation scheme.

Furthermore, the quantitative approach aligns with the study's specific objectives and research inquiries by furnishing a structured framework to:

- Quantify crop water requirements (CWR) utilising climatic data, crop characteristics, and soil attributes.
- Determine irrigation water requirements (IWR) under varying seasonal conditions, thus evaluating the impact of effective rainfall on irrigation tactics.
- Develop and implement a coherent irrigation schedule to optimise water utilisation while ensuring adequate water provision for crop growth throughout their respective growing periods.

The utilisation of quantitative data sourced from the Wad Medani weather station and other pertinent references ensures a robust analysis of water requirements and the sufficiency of water supply within the Gezira Scheme. This approach underscores the significance of meticulous data collection and statistical analysis in addressing the pivotal challenges

associated with water management in agriculture.

3.4. Data Collection

The data collection process for this research was designed to comprehensively gather essential information required for evaluating the adequacy of water supply to meet the irrigation water requirements within the Gezira scheme. This section details the sources and types of data collected, which include climatic data, rainfall data, crop data, and soil data.

3.4.1. Climatic Data

The climatic data used in this study were obtained from the Wad Medani Meteorological Station, spanning a decade from 2007 to 2022. This dataset comprises essential meteorological variables, including maximum and minimum temperatures, humidity levels, wind speed, and solar radiation. These parameters are pivotal for computing the reference evapotranspiration (ET₀) through the CROPWAT model, as referenced in Table 3-3, which utilises the Penman-Monteith equation:[66]

$$ET_0 = \frac{0.408(Rn-G) + \gamma \left(\frac{900}{T+273} \right) u_2 (e_s - e)}{\Delta + \gamma(1+0.34u_2)} \quad \dots \quad (1)$$

Δ = Slope vapor pressure curve (kPa /°C).

Rn = Net Radiation at the crop surface (MJ/m²/d).

G = Soil heat flux density (MJ/m²/d).

T = mean daily air temperature at 2 m height (°C).

u₂ = wind speed at 2 m height (m/s).

e = Actual vapor pressure (kPa).

e_s = Saturation vapor pressure (kPa).

γ = Psychrometric constant (kPa/°C).

The model determines the Crop Water Requirements (ET_c) throughout the growing season by utilizing ET₀ and crop coefficients (k_c) according to the specified equation:[67]

$$ET_c = K_c \times ET_0 \quad \dots \quad (2)$$

The model computes the irrigation water requirement (IR), which is identified as the amount of water needed to be provided via the irrigation system to guarantee the crop meets its complete crop water requirement, using the designated equation: [67]

$$IR = ET_c \times P_{eff} \quad \dots \quad (3)$$

IR = Irrigation water requirement. ET_c = Crop water requirements (mm).

P_{eff} = Effective dependable rainfall (mm).

3.4.2. Rainfall Data

Rainfall data, sourced from the Wad Medani weather station, are crucial for calculating effective rainfall, as demonstrated in Table 3-2. This information is essential for assessing the role of rainfall in fulfilling the water needs of crops, which in turn influences the determination of irrigation water needs.

3.4.3. Crop Data

Comprehensive data on the analysed crops was collected, encompassing essential details for both summer crops like cotton and sorghum, and winter crops such as tomato and sunflower. This compiled information included crop names, crop coefficients (K_c), root depths, growth stage durations, critical depletion fractions (p), and yield response factors (K_y). This dataset forms the basis for accurately calculating the crop water requirements (CWR) using specified equations and models. Sourced from Cimatewat2.0, this data is referenced in figures 3-6,3-7,3-8 and 3-9.

3.4.4. Soil Data

The area under study was characterised by clay soil. In order for the software to operate effectively, it necessitates fundamental soil data, including the Total Available Soil Moisture (TAM), as illustrated in Figure 3-4. This data was obtained from the Gezira Research Station. TAM represents the difference in water content between field capacity and the wilting point, and it is calculated using a designated equation: [7]

$$TAM = 1000(\theta_{fc} - \theta_{pwp})Z_r \quad \dots (4)$$

Where:

TAM = total available soil water in the root zone (mm). θ_{FC} = water content at field capacity (m^3/m^3) θ_{pwp} = water content at wilting point (m^3/m^3). Z_r = rooting depth (m).

Total Available Soil Moisture (TAM) represents the entire volume of water within the crop's root zone that crops can utilize. The water level in the root zone diminishes due to crop absorption. As soil moisture lessens, water binds more tightly to the soil particles, making it harder to extract. When soil moisture falls below a certain level, the soil cannot transport water quickly enough to the roots to meet the crop's transpiration needs, leading to stress in the crop. The portion of TAM that a crop can use from the root zone without undergoing water stress is termed as Readily Available Soil Water (RAM), and it can be determined using a specific equation: [7]

$$RAM = p \times TAM \quad \dots (5)$$

Where:

p represents the average portion of the Total Available Soil Water (TAM) that can be used up from the root zone before moisture stress (leading to a decrease in evapotranspiration, or ET) begins. Water uptake halts once the wilting point is reached. The document also covers:

- The maximum rate at which rainwater can infiltrate the soil.
- The deepest extent of root growth.
- default value of 0% signifies a soil profile that is fully saturated at field capacity (FC), while 100% indicates soil at the Wilting Point (WP). This information, which is displayed in Figure 3-4, is derived from a soil water budget to schedule calculations. It involves daily assessments of soil moisture status by considering both incoming and outgoing water within the root zone.

3.5. Overview on CROPWAT 8.0

CROPWAT is a software tool designed for the purpose of irrigation planning and management, created by the land and water development division. It employs CROPWAT 8.0, leveraging meteorological data to make use of the FAO Penman Monteith formula for the estimation of the crop reference evapotranspiration (ET_0), the water needs of crops (ET_c), and the planning of irrigation considering different management approaches and water availability scenarios. The software determines the requirements for water and irrigation by processing data on climate, crops, and soil, along with information on irrigation practices and precipitation.[\[68\]](#) It utilizes various crop-specific parameters to estimate evapotranspiration, perform water balance analyses, and assess the impact of water scarcity on crop yields. These parameters include the crop coefficient (K_c), the duration of the crop's growth period, the critical level of water depletion, and the yield response factor (K_y). Soil data inputs consist of the total soil water capacity, and the initial moisture content at the beginning of the growing period. The software produces tables that summarize the potential yield losses at different stages of crop growth and the effectiveness of water utilization.[\[69\]](#)

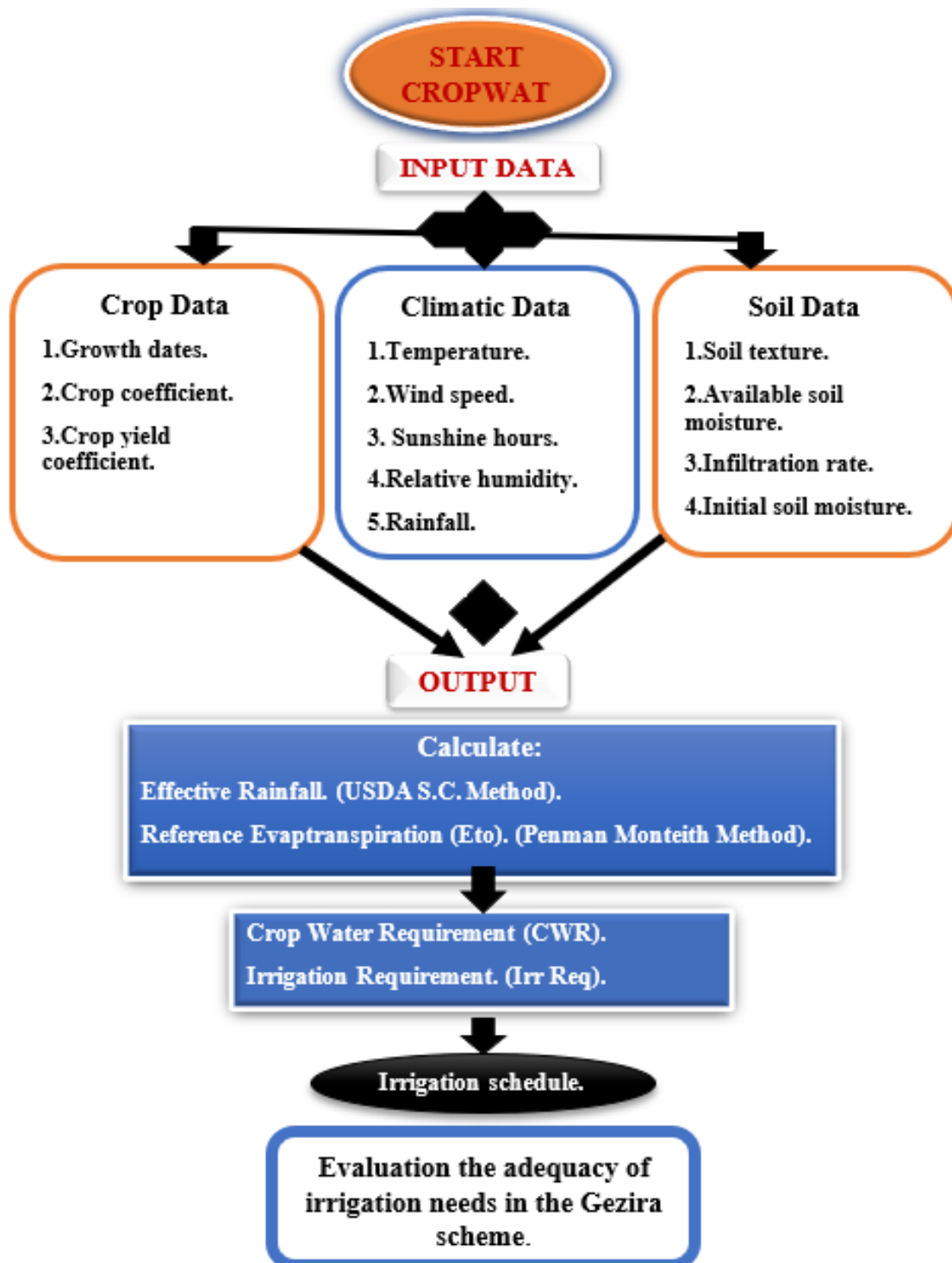


Figure 3-3. Process flow of the CROPWAT model for the methodology.

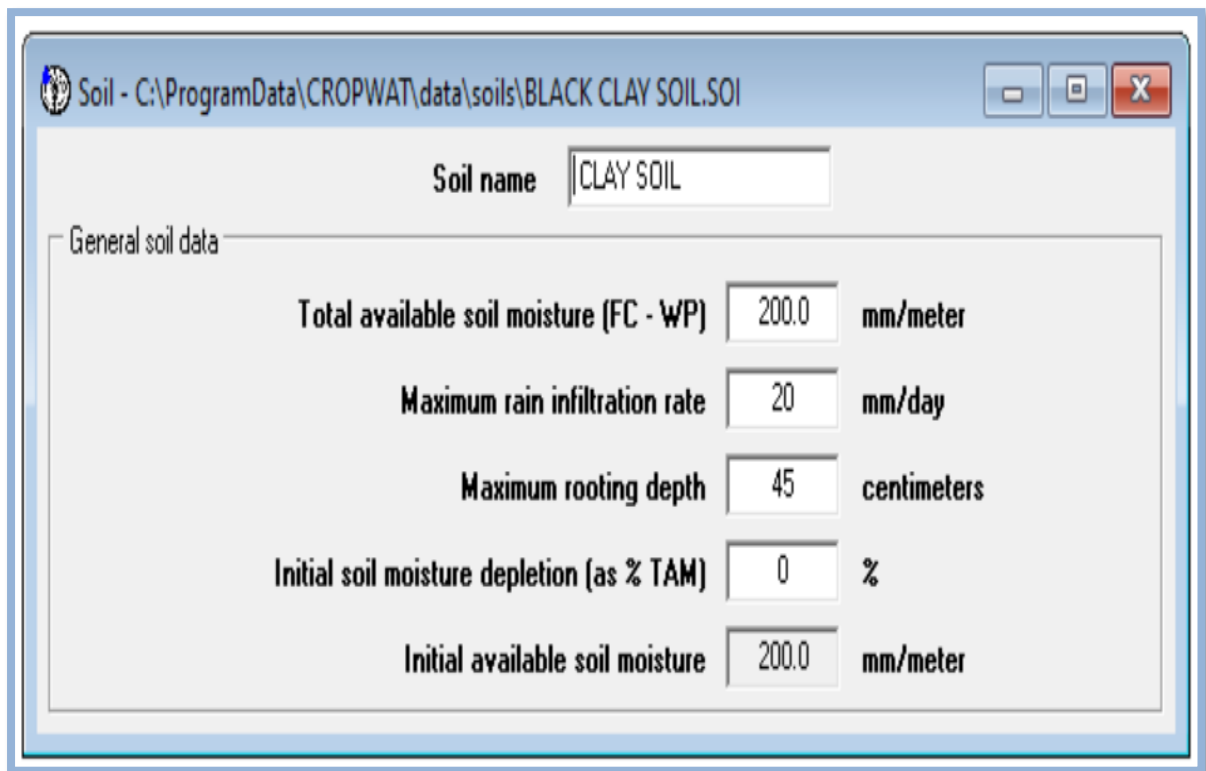
3.6. Limitation of Cropwat8.0 Software

- **Data Quality Dependence:** The accuracy of CROPWAT is contingent upon the availability of high-quality, comprehensive data pertaining to weather, crops, and soil. Discrepancies in this data may lead to erroneous calculations of water requirements.
- **Inadequate for Varied Landscapes:** The tool lacks mechanisms to account for the diverse

array of environmental factors present in large or complex areas, potentially compromising the precision of its estimations.

- **Rainfall Prediction Limitations:** CROPWAT may not adequately capture the variability and impact of rainfall on irrigation needs, particularly in regions characterized by fluctuating rainfall patterns.
- **Climate Change Projection Constraints:** Primarily reliant on historical climate data, CROPWAT's ability to predict water requirements in the face of climate change may be limited, as it may not reflect future climatic variations accurately.
- **Limited Consideration for Soil Salinity:** While CROPWAT does incorporate basic soil types into its calculations, it offers limited tools for managing soils with high levels of salinity, which can significantly influence crop water use efficiency and yield.
- **Expertise-Driven Usage:** Efficient utilisation of CROPWAT necessitates a profound understanding of irrigation management principles and local conditions, posing challenges for inexperienced users.

3.7. Input Soil Information



The screenshot shows a software window titled "Soil - C:\ProgramData\CROPWAT\data\soils\BLACK CLAY SOIL.SOI". The window contains a "Soil name" field with the text "CLAY SOIL". Below this is a section titled "General soil data" containing five input fields with their respective units:

Parameter	Value	Unit
Total available soil moisture (FC - WP)	200.0	mm/meter
Maximum rain infiltration rate	20	mm/day
Maximum rooting depth	45	centimeters
Initial soil moisture depletion (as % TAM)	0	%
Initial available soil moisture	200.0	mm/meter

Figure 3-4. Soil data.

3.8. Input Rainfall Information: Determining Effective Rainfall on the Study Area

Table3-2. Wad Medani Monthly average for long term Rainfall and Effective Rainfall Data.

	Rain	Eff rain
	mm	mm
January	0.0	0.0
February	0.0	0.0
March	0.0	0.0
April	1.2	1.2
May	17.9	17.4
June	28.2	26.9
July	88.0	75.6
August	123.9	99.3
September	45.9	42.5
October	19.2	18.6
November	1.7	1.7
December	0.0	0.0
Total	326.0	283.3

Based on the data provided, there is no recorded rainfall between January and March. April experiences minimal rainfall. The onset of the rainy season appears to commence in May, with the highest rainfall occurring in August at 123.9 mm. Effective rainfall generally mirrors the actual rainfall pattern but registers slightly lower each month, implying that the USDA Soil Conservation Method incorporates factors such as evaporation, runoff, or other variables that reduce water available for agricultural purposes. The total annual rainfall is recorded as 326.0 mm, whereas the total effective rainfall is calculated to be 283.3 mm. The emphasis on the effective rainfall column suggests its significance for agricultural planning, water resource management, or environmental studies.

3.9. Input Climate Information: Determine Reference Evapotranspiration (ET_o) of the Study Area

Table 3-3. Reference Evapotranspiration (ET_o) for long term monthly average climatic data of the study Area.

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun hours	Rad MJ/m ² /day	ETo mm/day
January	14.2	37.4	34	268	9.1	19.5	7.13
February	15.9	34.8	24	311	10.0	22.4	8.11
March	19.1	38.2	20	268	9.9	24.0	8.55
April	22.6	40.1	18	268	10.0	24.9	9.26
May	24.5	41.6	23	311	9.6	24.2	9.94
June	39.1	39.8	39	423	9.2	23.2	11.24
July	23.7	37.3	57	423	8.1	21.7	8.15
August	22.5	34.7	73	311	8.2	22.0	5.88
September	22.2	35.9	63	268	9.1	22.9	6.44
October	22.1	38.2	47	190	9.2	21.7	6.44
November	18.4	36.2	37	268	9.6	20.5	7.08
December	17.1	33.5	37	268	9.7	19.7	6.42
Average	21.8	37.3	39	298	9.3	22.2	7.89

This table presents climate data for a specific location identified as Location 32, situated at the WAD-MEDANI weather station.

- Month: Lists each month of the year.
- Min Temp (°C): Indicates the average minimum temperature recorded for each month in degrees Celsius.
- Max Temp (°C): Specifies the average maximum temperature recorded for each month in degrees Celsius.
- Humidity (%): Illustrates the average relative humidity percentage for each month.
- Wind (km/day): Provides the average daily wind speed in kilometres.
- Sun (hours): Displays the average number of sunlight hours per day for each month.
- Rad (MJ/m²/day): Presents the average daily solar radiation received per square meter in

Megajoules.

- ETo (mm/day): Shows the average daily reference evapotranspiration in millimetres, calculated using the Penman-Monteith equation.

The table also includes average values at the bottom for all listed parameters, presenting an overall climate profile for the location. The data suggests a warm climate with notable temperature variations throughout the year, coupled with moderate to high solar radiation levels and a broad spectrum of humidity levels. Notably, the ETo values, crucial for agricultural and water management purposes, indicate heightened water demand for crops during warmer months, particularly June, owing to increased temperatures and potential evapotranspiration rates.

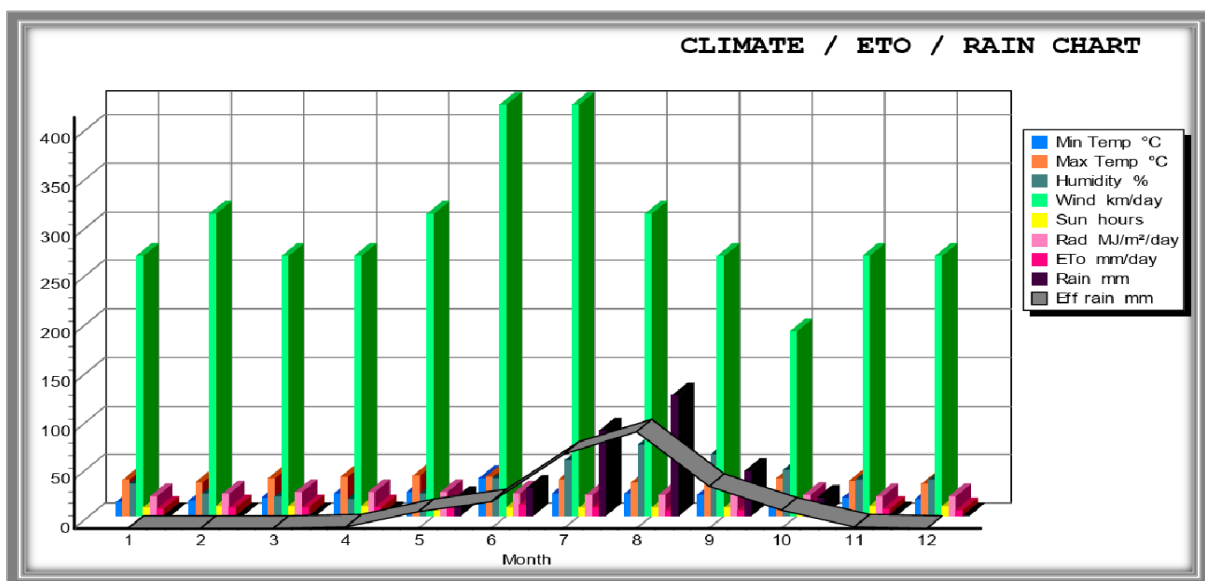


Figure 3.5. Graphical representation of the climatic parameters ETo and Peff. in the study. [17]

This graph depicts the monthly climate patterns and rainfall in the Gezira region. The green bars represent humidity levels, indicating fluctuations in atmospheric moisture throughout the year, with some months experiencing higher humidity than others. The blue and red bars denote minimum and maximum temperatures, respectively, showcasing the temperature range that could impact various activities, particularly agriculture. Variations in wind speed (purple bars) and sunshine hours (pink bars) are evident, potentially influencing activities such as wind power generation and solar energy harvesting. The dark green bars illustrate ETo (reference evapotranspiration), highlighting water loss from soil and plant surfaces, which is pivotal for irrigation planning. Rainfall is represented by the black line, delineating the timing and quantity of rainfall, crucial for water resource management. Additionally, the grey line for effective rain likely signifies the actual contribution to usable water, essential for assessing water availability for crops.

3.10. Input Crop Information

3.10.1. Summer Season

3.10.1.1. Cotton

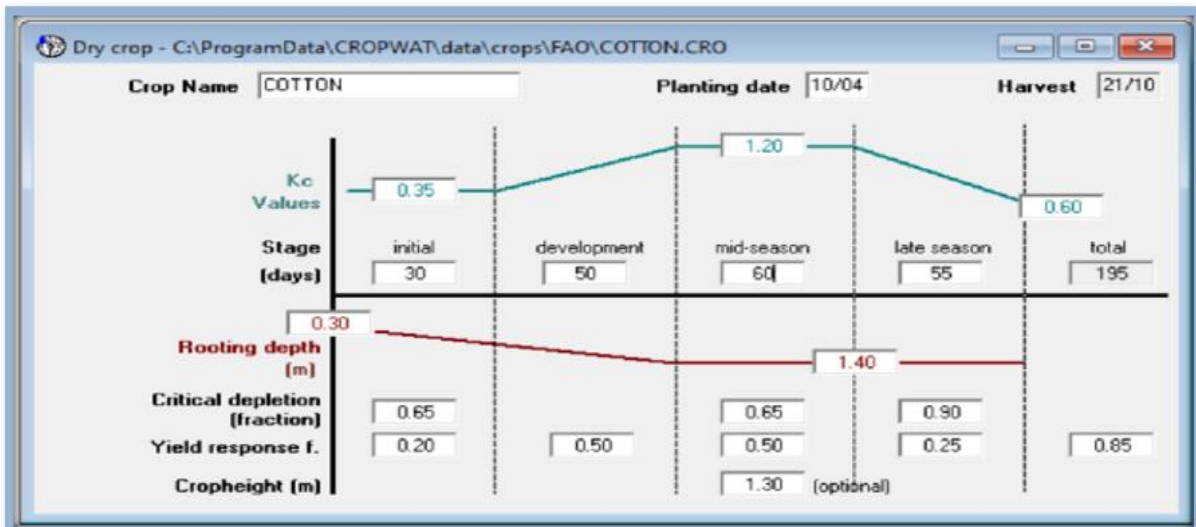


Figure 3-6. Crop Data for Cotton.

Figure 3-6. outlines the growth trajectory of cotton and its corresponding water requirements throughout its growing season, spanning from planting on April 10th to harvest on October 21st. The depiction illustrates a gradual escalation in water demands from the early to mid-season stages, followed by a decline as the season advances. Additionally, the root depth begins shallow and progressively deepens, reflecting the plant's heightened capacity for water absorption. Variations in water stress tolerance and yield impact are observed across different growth stages. This tool proves indispensable for irrigation management aimed at maximising cotton production efficiency.

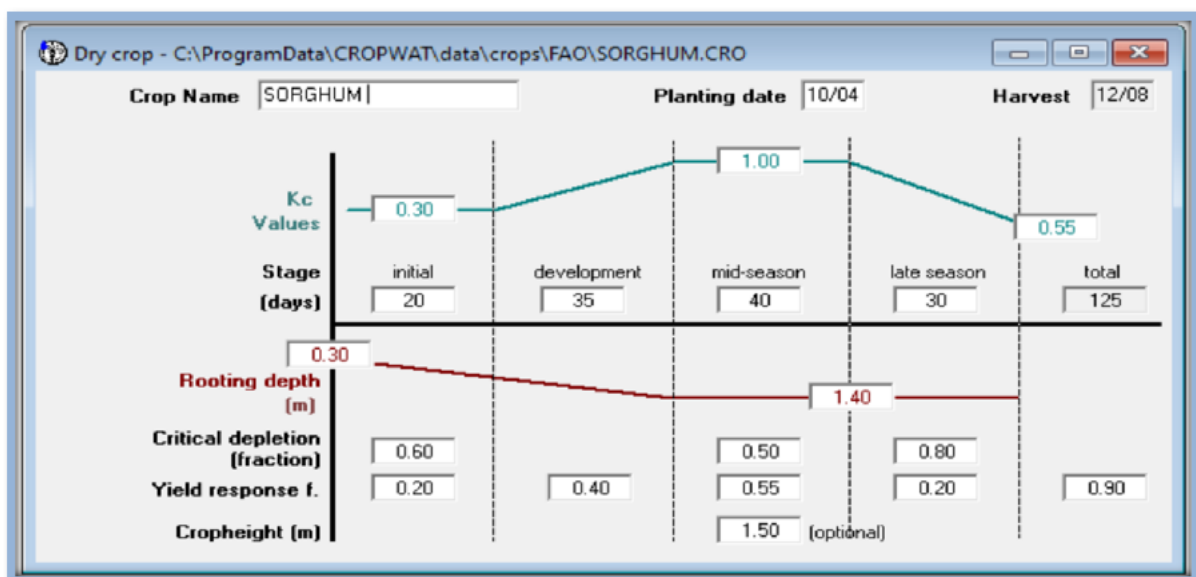


Figure 3.7. Crop Data for Sorghum.

This figure presents data on the cultivation of sorghum, indicating that it is planted on April 10th and harvested on August 12th. The crop's water requirement, as measured by Kc values, begins at a low level, gradually increases to its peak during mid-season, and subsequently decreases towards the end of the growth cycle. Concurrently, the rooting depth of the plant deepens significantly as it matures. The crop exhibits its highest tolerance to water depletion at the initial stage, which diminishes as it progresses through development, highlighting varying levels of water stress sensitivity across different growth stages. Additionally, a potential maximum crop height is provided, illustrating the physical growth of the crop alongside its water requirements. This information is instrumental in irrigation management, facilitating the optimisation of sorghum yield.

3.10.2. Winter Season

3.10.2.1. Sunflower

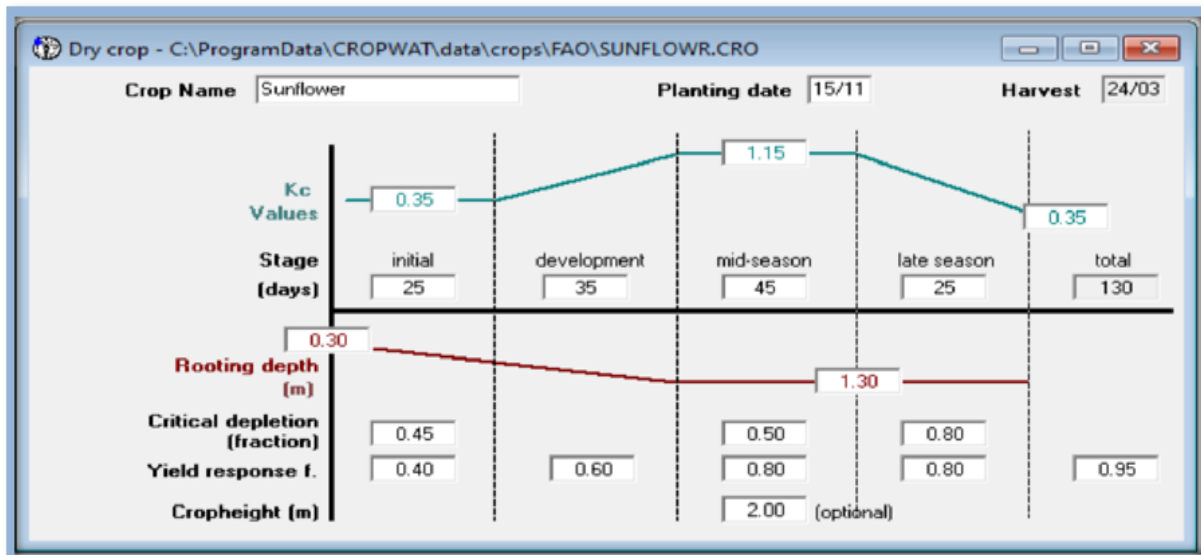


Figure 3-8. Crop Data for Sunflower.

This figure pertains to sunflower cultivation, with a planting date of November 15th and a harvest date of March 24th. The depicted Kc values indicate that water requirements commence and conclude at lower levels, reaching a peak during mid-season. The increase in root depth to 1.30 meters signifies the plant's maturation over time. The crop displays varying levels of tolerance for water depletion, suggesting distinct irrigation needs at different growth stages. Throughout its lifecycle, sunflower yield demonstrates moderate sensitivity to water stress. Additionally, a maximum crop height of 2.00 meters is provided, although this field is optional. This data plays a pivotal role in effective irrigation management, ensuring robust sunflower growth and yield.

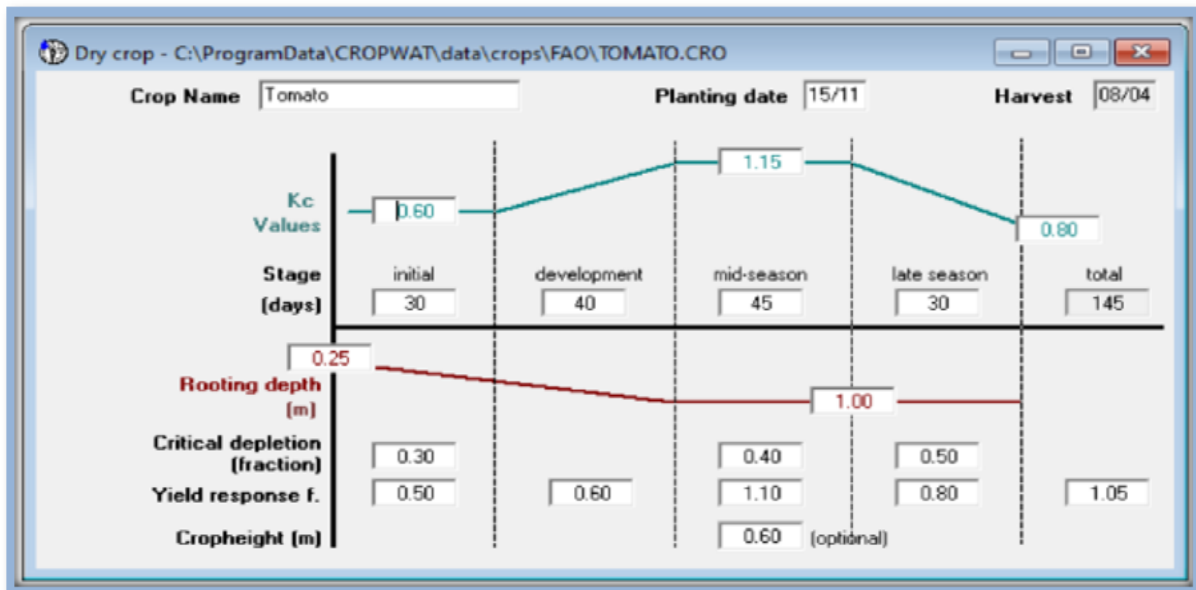


Figure 3-9. Crop Data for Tomato.

The figure delineates the irrigation requirements for tomato crops, which are planted on November 15th and harvested on April 8th. Water demand, as indicated by Kc values, begins at a high level, reaches its peak during mid-season, and gradually decreases towards the end of the growth cycle. The rooting depth initially starts shallow but extends to 1 meter, implying an augmented water uptake as the plants progress. The crop exhibits its lowest tolerance to water shortage during the development stage, underscoring the critical necessity for consistent water supply during this period. Furthermore, the sensitivity of yield to water stress is most pronounced during the development and mid-season stages, underscoring the imperative of adequate irrigation to ensure optimal tomato yields.

CHAPTER FOUR

4. ANALYSIS OF RESULTS AND DISCUSSIONS

4.1. Introduction

This chapter focuses on evaluating results and discussions regarding the irrigation requirements of various crops throughout different seasons. It starts with an in-depth analysis of cotton's water needs during the summer, covering irrigation timing and the role environmental factors play in determining water demand. The study further explores the irrigation necessities for crops like sorghum, sunflower, and tomato, considering their unique growth periods. Utilizing information from CROPWAT 8.0, the chapter thoroughly investigates irrigation planning, the water needs of crops, and how rainfall contributes to irrigation requirements. The objective is to shed light on effective water management techniques, emphasizing the essential equilibrium between water supply and demand in farm irrigation.

4.2. Summer season

4.2.1. Cotton

Table 4-1. Crop Water Requirement, and Irrigation Requirement for Cotton.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	1	Deve	0.35	3.42	34.2	4.2	30.0
May	2	Deve	0.47	4.66	46.6	6.1	40.5
May	3	Deve	0.66	6.84	75.2	7.1	68.2
Jun	1	Deve	0.85	9.47	94.7	6.7	88.0
Jun	2	Deve	1.03	12.12	121.2	7.2	114.0
Jun	3	Mid	1.21	12.74	127.4	13.2	114.2
Jul	1	Mid	1.26	11.56	115.6	20.6	95.0
Jul	2	Mid	1.26	10.26	102.6	26.4	76.3
Jul	3	Mid	1.26	9.31	102.4	28.6	73.8
Aug	1	Mid	1.26	8.11	81.1	33.0	48.1
Aug	2	Mid	1.26	7.03	70.3	36.9	33.4
Aug	3	Late	1.25	7.33	80.6	29.3	51.3
Sep	1	Late	1.15	7.20	72.0	19.5	52.5
Sep	2	Late	1.04	6.67	66.7	12.6	54.1
Sep	3	Late	0.92	5.94	59.4	10.5	48.9
Oct	1	Late	0.81	5.20	52.0	8.7	43.3
Oct	2	Late	0.69	4.46	44.6	5.9	38.7
Oct	3	Late	0.63	4.19	4.2	0.4	4.2
					1419.5	278.0	1141.9

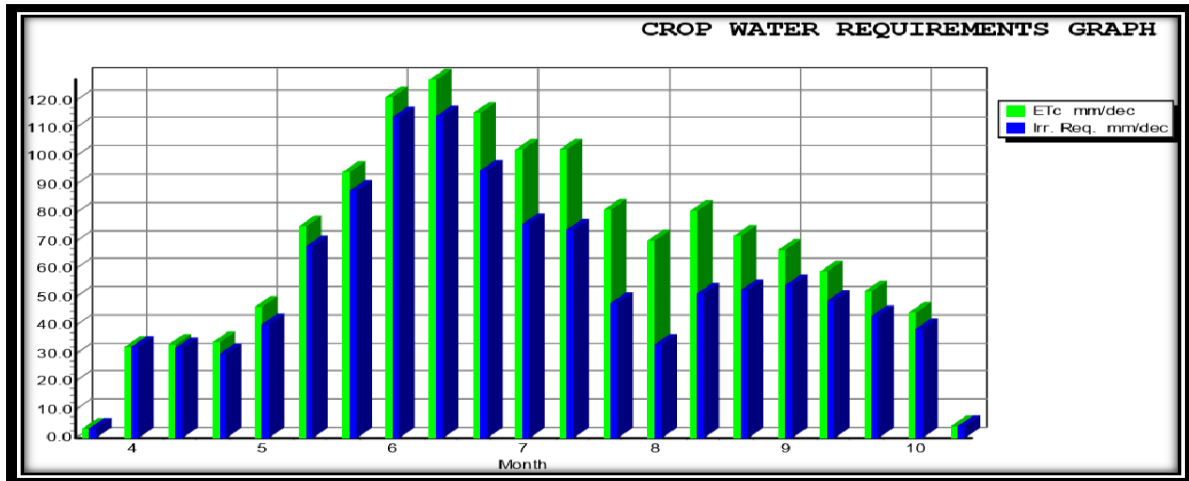


Figure 4-1. Crop water requirements graph for Cotton.

The graph shows the water needs of cotton from April to October, with the highest demand occurring in July. Both crop evapotranspiration (ETc) and irrigation requirements (Irr. Req.) increase until July before gradually decreasing towards October. It's important to note that irrigation needs consistently remain lower than evapotranspiration levels, suggesting that additional water sources like rainfall are crucial for meeting the crop's water requirements.

Table 4-2. Irrigation Schedule for Cotton: Simulated Results of Irrigation Timing Based on 100% Critical Depletion and Replenishment to Field Capacity.

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract	%	%	mm	mm	mm	mm	l/s/ha
22-Apr	13	Init	0	1	100	65	42.2	0	0	84.5	0.75
8-May	29	Init	0	1	100	69	49	0	0	97.9	0.71
21-May	42	Dev	0	1	100	71	54	0	0	108	0.96
30-May	51	Dev	0	1	100	69	54.3	0	0	108.5	1.4
6-Jun	58	Dev	0	1	100	74	60.3	0	0	120.6	1.99
12-Jun	64	Dev	0	1	100	74	62.1	0	0	124.2	2.4
17-Jun	79	Dev	3.5	1	100	66	57	0	0	114.1	2.64
22-Jun	74	Dev	0	1	100	70	61.8	0	0	123.7	2.86
28-Jun	80	Dev	0	1	100	77	69.2	0	0	138.4	2.67
4-Jul	86	Mid	0	1	100	67	60	0	0	120	2.32
11-Jul	93	Mid	0	1	100	75	67.9	0	0	135.8	2.25
20-Jul	102	Mid	0	1	100	74	66.9	0	0	133.8	1.72
30-Jul	112	Mid	0	1	100	66	59.1	0	0	118.1	1.37
12-Aug	125	Mid	0	1	100	72	64.4	0	0	128.9	1.15
26-Aug	139	Mid	0	1	100	69	62.1	0	0	124.2	1.03
6-Sep	150	End	0	1	100	76	68.6	0	0	137.3	1.44
18-Sep	162	End	0	1	100	77	69.3	0	0	138.5	1.34
4-Oct	178	End	0	1	100	87	78.2	0	0	156.4	1.13
21-Oct	End	End	0	0	0	73					

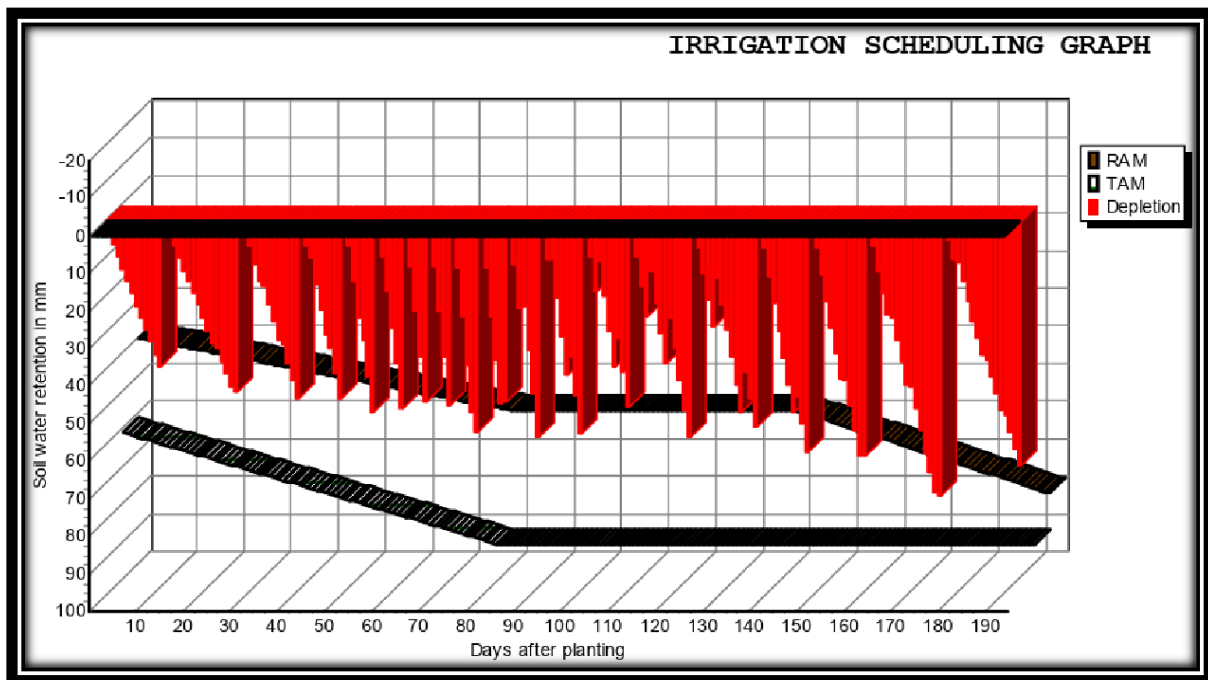


Figure 4-2. Irrigation scheduling graph for Cotton.

This irrigation schedule graph illustrates the soil moisture levels for cotton cultivation over approximately 190 days following planting. Key information is as follows:

- Days after Planting (x-axis): This axis denotes the timeline commencing from the day of cotton planting, covering nearly six months.
- Soil Water Retention (y-axis): Measured in millimetres, this axis signifies the quantity of water present in the soil. The scale extends below zero, indicating the deficit of water in the soil concerning crop water requirements.
- RAM (Readily Available Moisture): The black hashed area denotes the level of soil moisture readily accessible for cotton plants' utilization without encountering water stress.
- Depletion (Red Bars): These red bars represent the shortfall of moisture in the soil below the RAM threshold at various intervals during the growth period. The length of each red bar reflects the extent of moisture deficit, indicating the necessity for irrigation.
- Irrigation Timing: When the red bars extend beneath the black hashed line, it signifies that soil moisture has dropped below the level readily utilizable by the cotton crop, necessitating irrigation. Conversely, the absence of red bars above the black hashed line indicates adequate soil moisture.

This graph provides insights into the timing and frequency of irrigation required for cotton cultivation. The objective is to sustain soil moisture levels above the black hashed line, thereby averting water stress that could impede crop growth and yield.

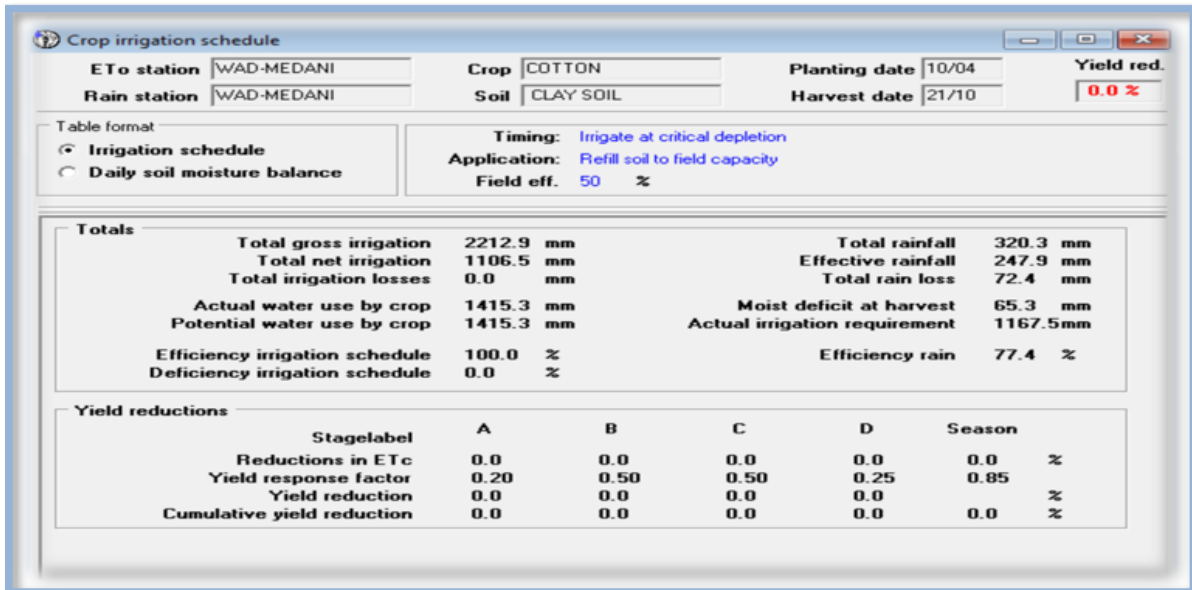


Figure 4-3. Cotton Crop Irrigation Schedule and Water Usage Summary.

4.2.2. Sorghum

Table 4-3. Crop Water Requirement, and Irrigation Requirement for Sorghum.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	1	Init	0.30	2.71	2.7	0.0	2.7
Apr	2	Init	0.30	2.78	27.8	0.0	27.8
Apr	3	Deve	0.30	2.87	28.7	1.3	27.3
May	1	Deve	0.43	4.14	41.4	4.2	37.2
May	2	Deve	0.62	6.17	61.7	6.1	55.6
May	3	Deve	0.83	8.56	94.2	7.1	87.1
Jun	1	Mid	0.97	10.86	108.6	6.7	101.9
Jun	2	Mid	0.98	11.51	115.1	7.2	108.0
Jun	3	Mid	0.98	10.34	103.4	13.2	90.2
Jul	1	Mid	0.98	9.00	90.0	20.6	69.5
Jul	2	Late	0.95	7.72	77.2	26.4	50.8
Jul	3	Late	0.82	6.10	67.0	28.6	38.4
Aug	1	Late	0.70	4.49	44.9	33.0	11.9
Aug	2	Late	0.63	3.49	7.0	7.4	7.0
					869.8	161.7	715.6

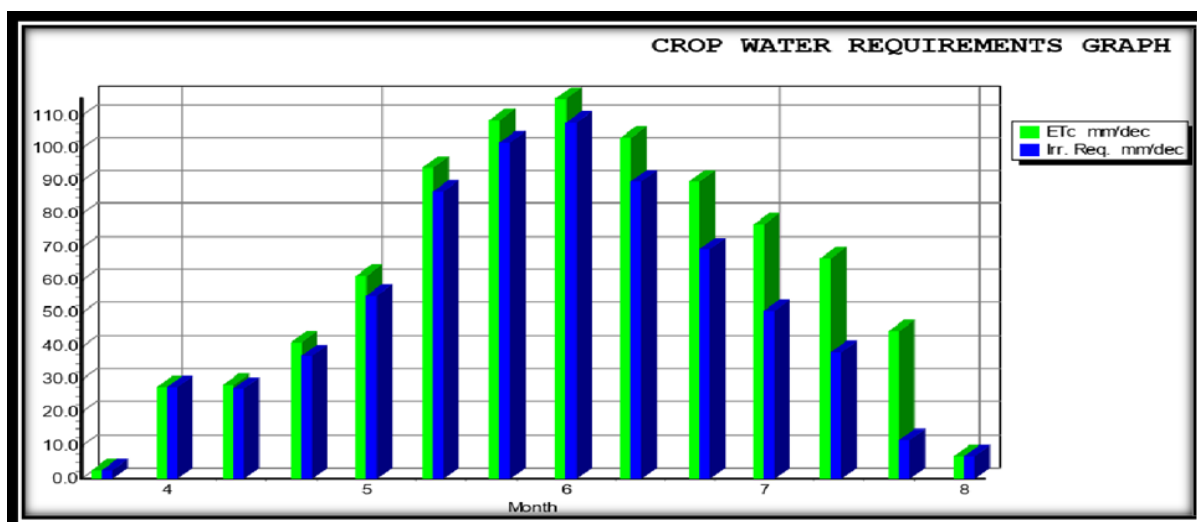


Figure 4-4. Crop water requirements graph for Sorghum.

The depicted graph presents the crop water requirements for Sorghum spanning from April to August. Notably, the peak water demand for Sorghum occurs in July. Both the values for crop evapotranspiration (ETc) and irrigation requirements (Irr. Req.) demonstrate an upward trajectory from April onwards, reaching their zenith in July, followed by a downward trend in August. The notable decrease in both ETc and Irr. Req. from July to August signifies a substantial reduction in Sorghum's water demand as the growing season progresses towards its conclusion.

Table 4-4. Irrigation Schedule for Sorghum.

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract	%	%	mm	mm	mm	mm	l/s/ha
24-Apr	15	Init	0	1	100	61	41.3	0	0	82.6	0.64
8-May	29	Dev	0	1	100	60	45.4	0	0	90.8	0.75
17-May	38	Dev	3.1	1	100	56	45.3	0	0	90.6	1.16
24-May	45	Dev	0	1	100	58	49.1	0	0	98.2	1.62
30-May	51	Dev	0	1	100	54	47.7	0	0	95.5	1.84
4-Jun	56	Mid	0	1	100	54	48.6	0	0	97.3	2.25
9-Jun	61	Mid	0	1	100	57	50.9	0	0	101.9	2.36
14-Jun	66	Mid	0	1	100	59	53.4	0	0	106.7	2.47
19-Jun	71	Mid	0	1	100	60	54	0	0	108	2.5
24-Jun	76	Mid	0	1	100	51	45.6	0	0	91.2	2.11
30-Jun	82	Mid	0	1	100	61	54.8	0	0	109.6	2.11
8-Jul	90	Mid	0	1	100	54	48.6	0	0	97.2	1.41
16-Jul	98	End	0	1	100	55	49.1	0	0	98.2	1.42
31-Jul	113	End	0	1	100	71	63.9	0	0	127.7	0.99
12-Aug	End	End	0	1	100	24					

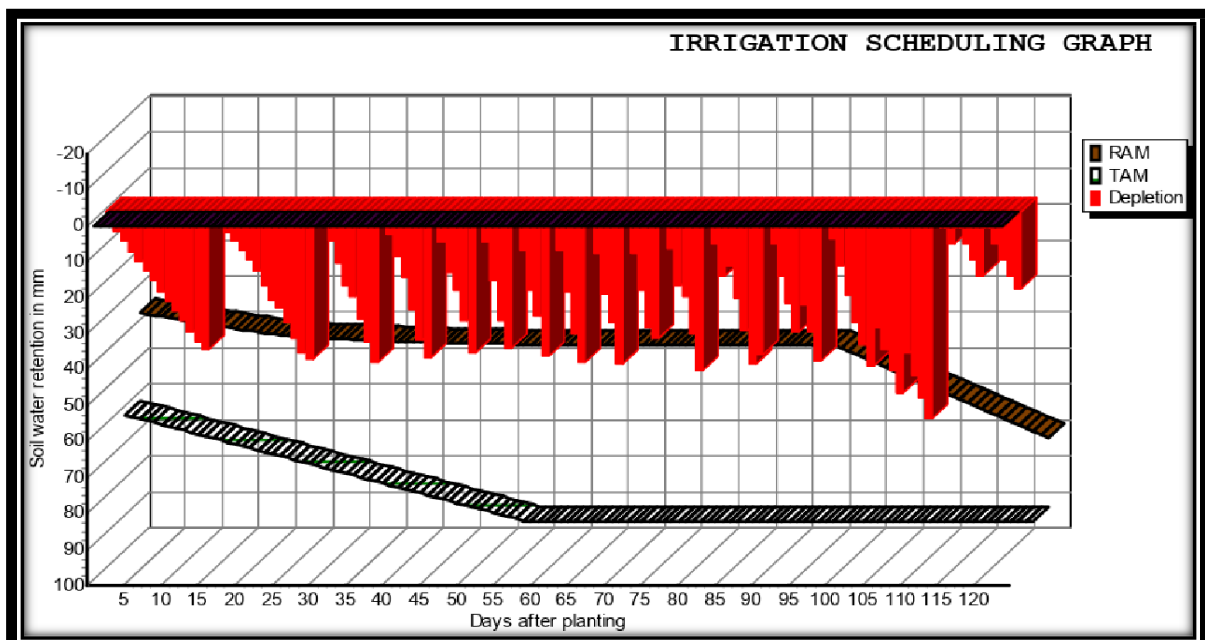


Figure 4-5. Irrigation scheduling graph for Sorghum.

This irrigation schedule for sorghum indicates the timing for watering (depicted by red bars) across a period of 120 days following planting. Watering is advised when the red bars dip below the black line to maintain soil moisture at a level sufficient for the crop's requirements.

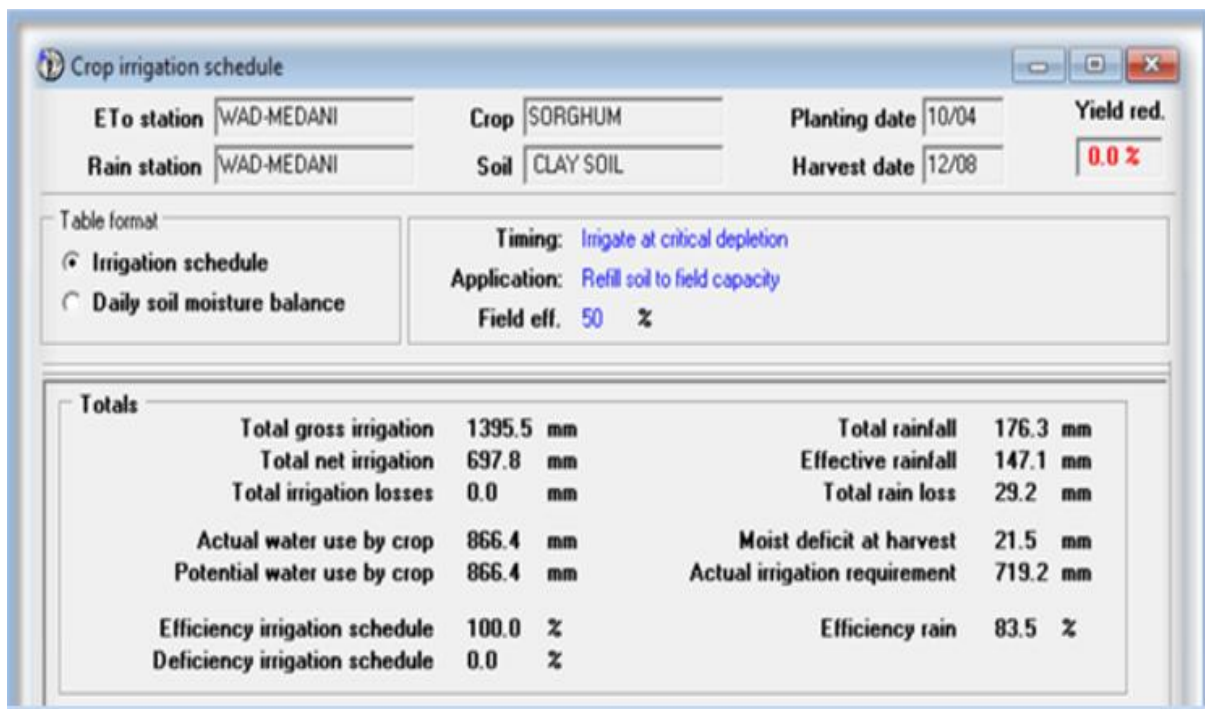


Figure 3-6. Sorghum Crop Irrigation Schedule and Water Usage Summary.

4.3. Winter season

4.3.1. Sunflower

4.5. Crop Water Requirement, and Irrigation Requirement for Sunflower.

Crop Water Requirements							
ETo station		WAD-MEDANI		Crop		Sunflower	
Rain station		WAD-MEDANI		Planting date		15/11	
Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	2	Init	0.35	2.51	15.1	0.0	15.1
Nov	3	Init	0.35	2.42	24.2	0.0	24.2
Dec	1	Deve	0.35	2.32	23.2	0.1	23.0
Dec	2	Deve	0.52	3.27	32.7	0.0	32.7
Dec	3	Deve	0.79	5.20	57.2	0.0	57.2
Jan	1	Deve	1.06	7.31	73.1	0.0	73.1
Jan	2	Mid	1.25	8.89	88.9	0.0	88.9
Jan	3	Mid	1.25	9.35	102.9	0.0	102.9
Feb	1	Mid	1.25	9.76	97.6	0.0	97.6
Feb	2	Mid	1.25	10.17	101.7	0.0	101.7
Feb	3	Late	1.25	10.32	82.5	0.0	82.5
Mar	1	Late	1.02	8.56	85.6	0.0	85.6
Mar	2	Late	0.66	5.62	56.2	0.0	56.2
Mar	3	Late	0.40	3.55	14.2	0.0	14.1
					855.1	0.2	854.9

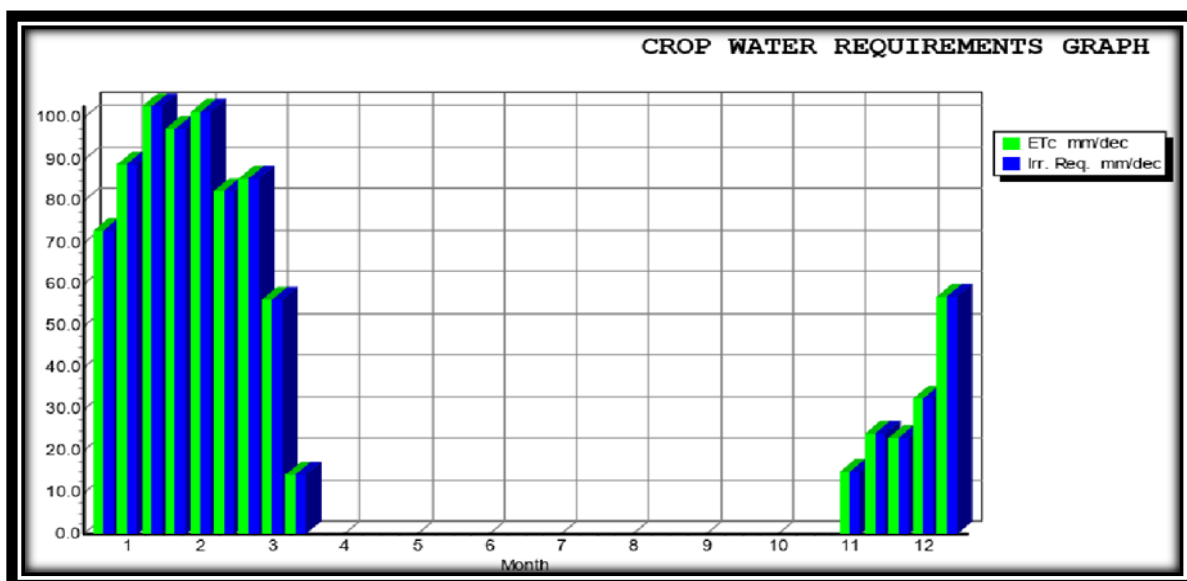


Figure 4-7. Crop water requirements graph for Sunflower.

The graph water requirements during the winter growing season. The demand rises starting in

November, peaks in February and March, During the active growing months, this pattern suggests that Sunflower crops have the highest water needs in January and February. This information is essential for efficient water management specific to winter-cultivated Sunflower.

Table 4-6. Irrigation Schedule for Sunflower.

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Defi cit	Loss	Gr. Irr	Flow
			mm	frac t	%	%	mm	mm	mm	mm	l/s/h a
27-Nov	13	Init	0	1	100	48	32	0	0	64.1	0.57
11-Dec	27	Dev	0	1	100	46	33.6	0	0	67.2	0.56
22-Dec	28	Dev	0	1	100	50	39.8	0	0	79.7	0.84
30-Dec	29	Dev	0	1	100	50	41.6	0	0	83.2	1.2
6-Jan	30	Dev	0	1	100	57	49.1	0	0	98.1	1.62
12-Jan	31	Dev	0	1	100	53	47	0	0	94	1.81
18-Jan	32	Mid	0	1	100	59	53.3	0	0	106.7	2.06
23-Jan	33	Mid	0	1	100	51	45.8	0	0	91.7	2.12
28-Jan	34	Mid	0	1	100	52	46.8	0	0	93.5	2.16
2-Feb	35	Mid	0	1	100	53	47.6	0	0	95.1	2.2
7-Feb	36	Mid	0	1	100	54	48.8	0	0	97.6	2.26
12-Feb	37	Mid	0	1	100	55	49.6	0	0	99.2	2.3
17-Feb	38	Mid	0	1	100	56	50.8	0	0	101.7	2.35
22-Feb	39	Mid	0	1	100	57	51.6	0	0	102.3	2.37
27-Feb	40	Mid	0	1	100	57	51.6	0	0	103.2	2.39
5-Mar	41	End	0	1	100	59	53.1	0	0	106.3	2.05
14-Mar	42	End	0	1	100	73	65.3	0	0	130.6	1.68
24-Mar	43	End	0	1	100	49					

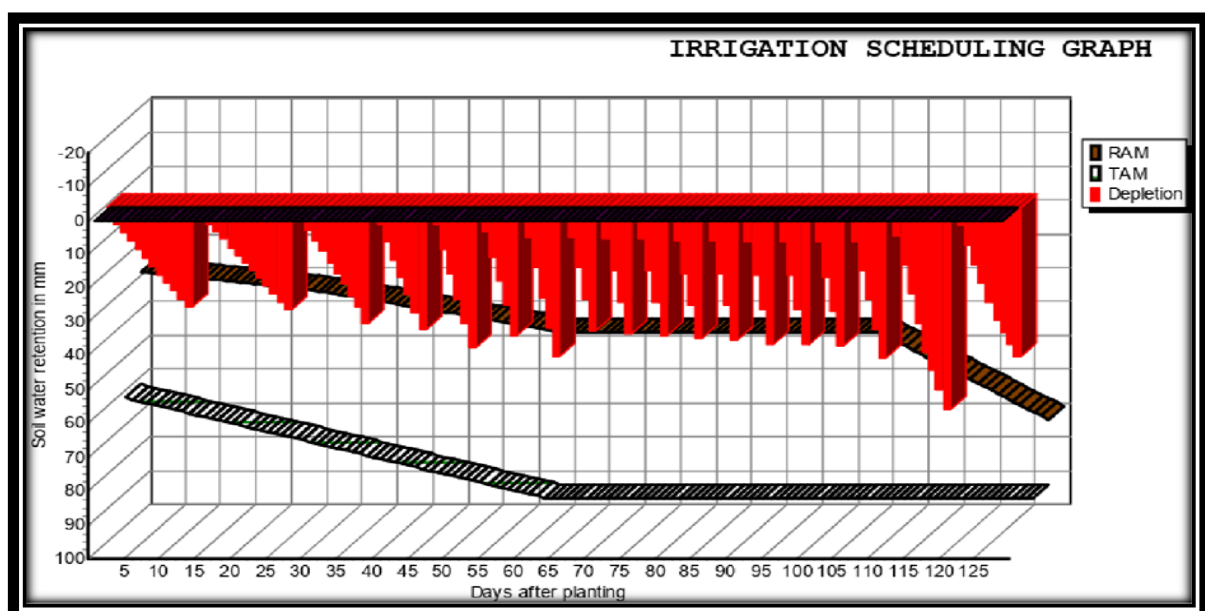


Figure 4-8. Irrigation scheduling graph for Sunflower.

This irrigation schedule for sunflower shows the watering requirements (red bars) for about 125 days after planting. When red bars drop below the black line, it's a signal to irrigate to meet the crop's moisture needs.

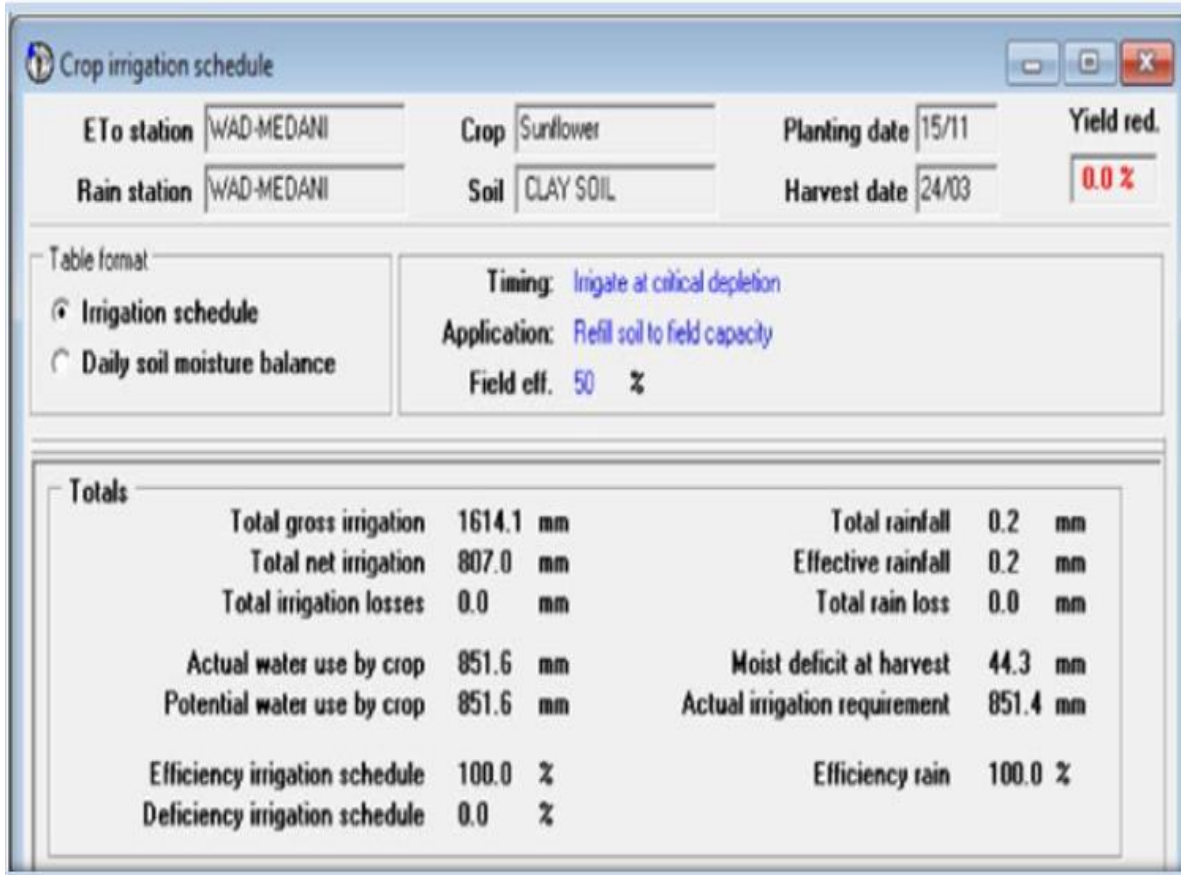


Figure 4-9. Sunflower Crop Irrigation Schedule and Water Usage Summary.

4.3.2. Tomato

Table 4-7. Crop Water Requirement, and Irrigation Requirement for Tomato.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	2	Init	0.60	4.31	25.9	0.0	25.9
Nov	3	Init	0.60	4.16	41.6	0.0	41.6
Dec	1	Init	0.60	3.94	39.4	0.1	39.3
Dec	2	Deve	0.63	4.00	40.0	0.0	40.0
Dec	3	Deve	0.79	5.18	56.9	0.0	56.9
Jan	1	Deve	0.95	6.53	65.3	0.0	65.3
Jan	2	Deve	1.10	7.86	78.6	0.0	78.6
Jan	3	Mid	1.21	9.05	99.6	0.0	99.6
Feb	1	Mid	1.22	9.48	94.8	0.0	94.8
Feb	2	Mid	1.22	9.88	98.8	0.0	98.8
Feb	3	Mid	1.22	10.06	80.5	0.0	80.5
Mar	1	Late	1.22	10.23	102.3	0.0	102.3
Mar	2	Late	1.14	9.75	97.5	0.0	97.5
Mar	3	Late	1.01	8.90	97.9	0.1	97.7
Apr	1	Late	0.90	8.09	64.8	0.0	64.7
					1083.8	0.3	1083.5

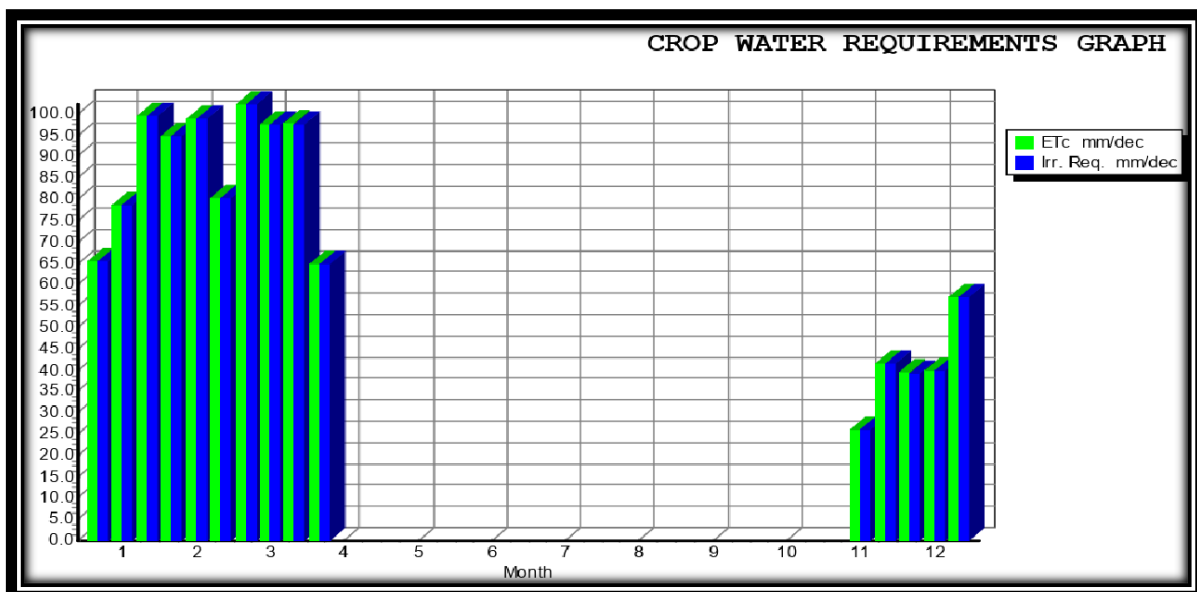


Figure 4-10. Crop water requirements graph for Tomato

Figure 4-10 portrays a graph demonstrating the water needs of tomato crops starting from their planting in November until the harvesting phase. It is evident that initially, the water requirement for the crops is low, while the highest demand for irrigation is observed during February and March.

Table 4-8. Irrigation Schedule for Tomato.

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract	%	%	mm	mm	mm	mm	l/s/ha
18-Nov	4	Init	0	1	100	33	17.2	0	0	34.5	1
22-Nov	8	Init	0	1	100	31	16.9	0	0	33.9	0.98
27-Nov	13	Init	0	1	100	36	20.8	0	0	41.6	0.96
2-Dec	18	Init	0	1	100	34	20.4	0	0	40.7	0.94
7-Dec	23	Init	0.1	1	100	31	19.6	0	0	39.3	0.91
12-Dec	28	Init	0	1	100	30	19.8	0	0	39.6	0.92
18-Dec	34	Dev	0	1	100	35	24	0	0	47.9	0.92
23-Dec	39	Dev	0	1	100	33	23.5	0	0	47	1.09
28-Dec	44	Dev	0	1	100	34	25.9	0	0	51.8	1.2
2-Jan	49	Dev	0	1	100	37	28.6	0	0	57.2	1.32
7-Jan	54	Dev	0	1	100	40	32.7	0	0	65.3	1.51
12-Jan	59	Dev	0	1	100	42	35.3	0	0	70.7	1.64
17-Jan	64	Dev	0	1	100	45	39.3	0	0	78.6	1.82
22-Jan	69	Dev	0	1	100	47	41.7	0	0	83.4	1.93
26-Jan	73	Mid	0	1	100	40	36.2	0	0	72.4	2.1
30-Jan	77	Mid	0	1	100	40	36.2	0	0	72.4	2.1
3-Feb	81	Mid	0	1	100	42	37.5	0	0	75	2.17
7-Feb	85	Mid	0	1	100	42	37.9	0	0	75.9	2.2
11-Feb	89	Mid	0	1	100	43	38.3	0	0	76.7	2.22
15-Feb	93	Mid	0	1	100	44	39.5	0	0	79	2.29
19-Feb	97	Mid	0	1	100	44	39.5	0	0	79	2.29
23-Feb	101	Mid	0	1	100	45	40.1	0	0	80.1	2.32
27-Feb	105	Mid	0	1	100	45	40.2	0	0	80.5	2.33
3-Mar	109	Mid	0	1	100	45	40.8	0	0	81.5	2.36
7-Mar	113	Mid	0	1	100	45	40.9	0	0	81.9	2.37
11-Mar	117	End	0	1	100	45	40.4	0	0	80.9	2.34
15-Mar	121	End	0	1	100	43	39	0	0	78	2.26
20-Mar	126	End	0	1	100	54	48.7	0	0	97.5	2.26
25-Mar	131	End	0	1	100	49	44.4	0	0	88.8	2.06
30-Mar	136	End	0	1	100	49	44.4	0	0	88.8	2.06
5-Apr	142	End	0	1	100	55	49.4	0	0	98.7	1.9
8-Apr	End	End	0	1	100	18					

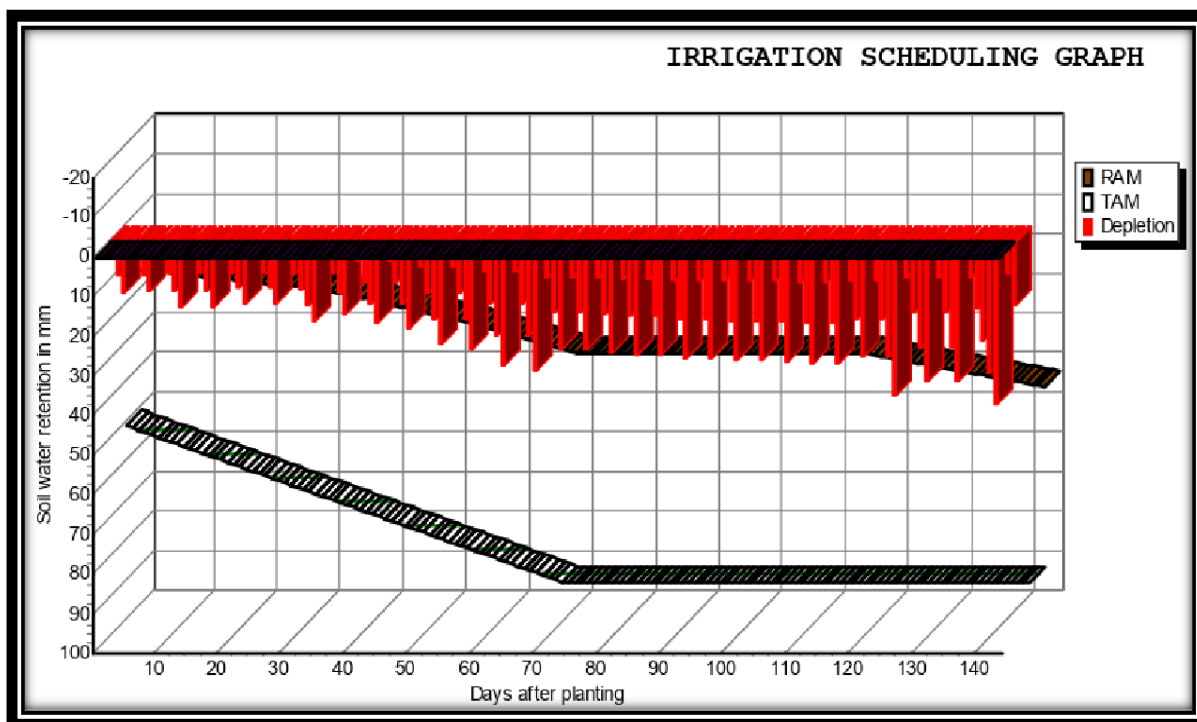


Figure 4-11. Irrigation scheduling graph for Tomato.

This irrigation schedule for tomato indicates watering needs (red bars) over the growth period. Irrigate whenever the red bars go below the black line to maintain proper soil moisture. The peak irrigation needs are seen at end of February.

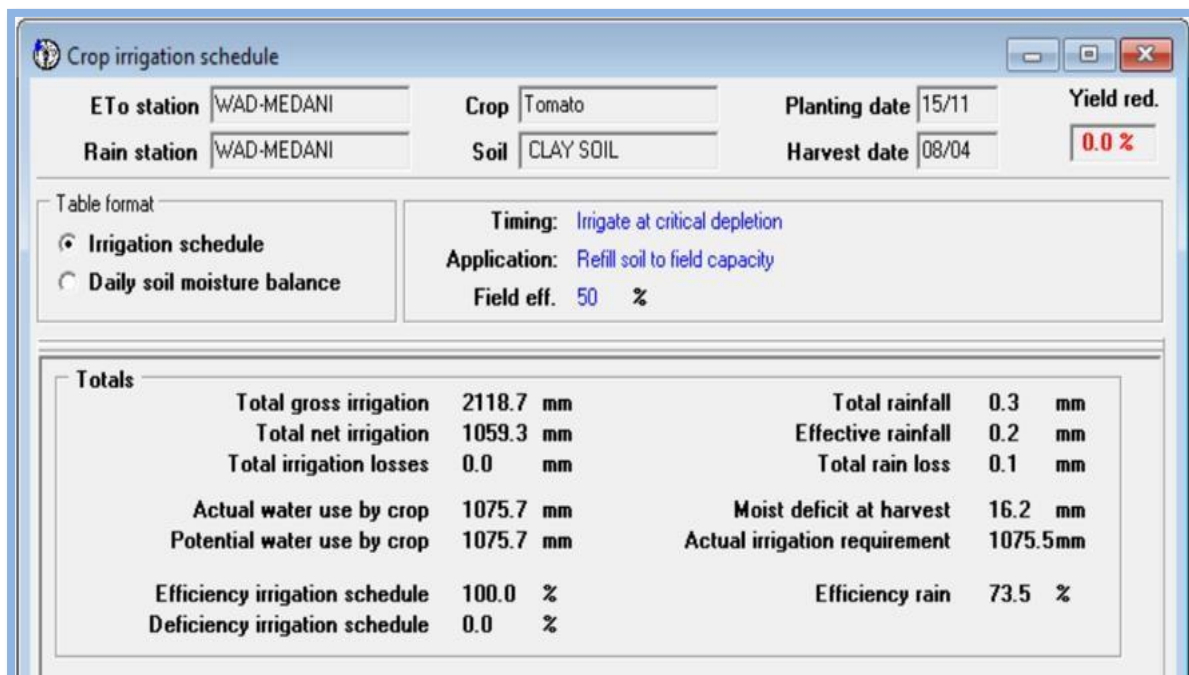


Figure 4-12. Tomato Crop Irrigation Schedule and Water Usage Summary.

4.4. Summary of results

4.4.1. The first Scenario: Current Utilization Area from The Gezira Irrigation Scheme (169,563 ha)

This scenario focus on the area presently utilized within the Gezira scheme, providing a closer look at irrigation demands within a more limited operational scope.

Table 4-9. Cotton and Sorghum Water Requirements and Cultivation Area in Summer Season.

Crop	CRW (mm)	Eff rain (mm)	Irr.Req (mm)	Crop area (ha)
1.Cotton	1419.5	278.0	1141.9	56,521
2.Sorghum	869.8	161.7	715.6	56,521
Total	2289.3	439.7	1857.5	113,042

Table 4-10. Sunflower and Tomato Water Requirements and Cultivation Area in Winter Season.

Crop	CRW (mm)	Eff rain (mm)	Irr.Req (mm)	Crop area (ha)
1.Sunflower	855.1	0.2	854.9	42,390.75
2.Tomato	1083.8	0.3	1083.5	14,130.25
Total	1938.9	0.5	1938.4	56,521

Table 4-11. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Cotton and Sorghum During the Summer Season.

Crop	Actual Irr.Req mm	Total Net Irr mm	Total gross irrigation (m ³)
1.Cotton	1167.5	1106.5	2212.9
2.Sorghum	851.4	807.0	1614.1
Total	2018.91	1913.5	3827

Table 4-12. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Sunflower and During the Winter Season.

Crop	Actual Irr.Req (mm)	Total Net Irr mm	Total gross irrigation
1. Sunflower	851.4	807.0	1614.1
2.Tomato	1075.5	1059.3	2118.7
Total	1926.9	1866.3	3732.8

Table 4-13. Seasonal Actual and Net Irrigation Requirements Compared to Total Gross Irrigation.

Seasons	Actual Irr.Req mm	Total Net Irr mm	Total gross irrigation	Crop area (ha)
Summer	2018.9	1913.5	3827	113,042
Winter	1926.9	1866.3	3732.8	56,521
Total	3945.8	3779.8	7559.8	169,563

Table 4-15. Seasonal and Total Volumes of Actual, Net, and Gross Irrigation Water Requirements.

Seasons	Actual Irr.Req (m ³)	Total Net Irr (m ³)	Total gross irrigation (m ³)
Summer	2,281,966,798	2,162,447,470	4,324,939,740
Winter	1,089,493,839	1,054,819,333	2,110,217,728
Total	3,371,460,637	3,217,266,803	6,435,157,468

This table presents the water amounts necessary for irrigation during two distinct periods – summer and winter – and summarizes the total usage for the area currently used in The Gezira Irrigation Scheme.

Actual Irrigation Requirement (Actual Irr.Req)

- The Actual Irrigation Requirement during the summer months reaches an impressive 2.28 billion cubic meters. This estimate is based on a constant land area and irrigation needs, suggesting that water consumption for agriculture in the summer is notably elevated, possibly a result of increased heat and evaporation.
- During winter, the water requirement decreases to around 1.1 billion cubic meters. The adjusted figure of 1926.9 mm for irrigation points to the impact of winter's milder temperatures and decrease in the area planted during this season, which could reduce the dependency on irrigation in comparison to summer demands.
- Combining the requirements for both seasons, the Actual Irrigation Requirement amasses to over 3.37 billion cubic meters, highlighting the significant amount of water agriculture consumes annually. This combined metric also reflects how changing seasonal climates affect irrigation over a large swath of farmland.

Total Net Irrigation (Total Net Irr)

- The summer's Total Net Irrigation need is 2.16 billion cubic meters, slightly below the Actual Irrigation Requirement. This difference because it does not include rainwater.
- For winter, the Total Net Irrigation necessity dips to 1.05 billion cubic meters. This reduction suggests that the cooler weather could lead to a natural decline in water loss and the decrease of the planted area in this winter to the third of the total area (56,521ha).
- When looking at the entire year, the Total Net Irrigation adds up to nearly 3.22 billion cubic meters with a collective irrigation requirement of 3779.8 mm. This total indicates the ongoing necessity for meticulous water management to maintain year-round agricultural production.

Total Gross Irrigation

- The summertime Total Gross Irrigation requirement tops the charts at nearly 4.32 billion cubic meters. This highest demand due to the efficiency of the irrigation system in The Gezira Irrigation Scheme, which reaches 50% or less.
- In the winter, the Total Gross Irrigation demand remains substantial at over 2.11 billion cubic meters and a Total Gross Irrigation of 3732.8 mm.
- The overall Total Gross Irrigation demand for both summer and winter hits an impressive 6.43 billion cubic meters, with a gross irrigation of 7559.8 mm.

4.4.2. The Second Scenario: The Cultivated Landmass of The Gezira Irrigation Scheme Spanning 882,000 Hectares

This scenario now turns towards analysing the Gezira irrigation scheme, which covers a total area of 882,000 hectares. This analysis aims to understand its ability to fulfil the varying water needs of different crops throughout both summer and winter seasons. Through thorough examination, the study uncovers significant insights regarding the adequacy of water supply.

Table 4-16. Cotton and Sorghum Water Requirements and Cultivation Area in Summer Season.

Crop	CRW (mm)	Eff rain (mm)	Irr Req (mm)	Crop area (ha)
1.Cotton	1419.5	278.0	1141.9	294000
2.Sorghum	869.8	161.7	715.6	294000
Total	2289.3	439.7	1857.5	588,000

Table 4-17. Sunflower and Tomato Water Requirements and Cultivation Area in Winter Season.

Crop	CRW (mm)	Eff rain (mm)	Irr.Req (mm)	Crop area (ha)
1.Sunflower	855.1	0.2	854.9	220500
2.Tomato	1083.8	0.3	1083.5	73500
Total	1938.9	0.5	1938.4	294000

Table 4-18. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Cotton and Sorghum During the Summer Season.

Crop	Actual Irr.Req mm	Total Net Irr mm	Total gross irrigation
1.Cotton	1167.5	1106.5	2212.9
2.Sorghum	851.4	807.0	1614.1
Total	2018.91	1913.5	3827

Table 4-19. Comparison of Actual and Net Irrigation Requirements with Total Gross Irrigation for Sunflower and During the Winter Season.

Crop	Actual Irr.Req (mm)	Total Net Irr mm	Total gross irrigation
1. Sunflower	851.4	807.0	1614.1
2.Tomato	1075.5	1059.3	2118.7
Total	1926.9	1866.3	3732.8

Table 4-20. Seasonal Actual and Net Irrigation Requirements Compared to Total Gross Irrigation.

Seasons	Actual Irr.Req mm	Total Net Irr mm	Total gross irrigation	Crop area (ha)
Summer	2018.9	1913.5	3827	588,000
Winter	1926.9	1866.3	3732.8	294000
Total	3945.8	3779.8	7559.8	882000

Table 4-21. Seasonal and Total Volumes of Actual, Net, and Gross Irrigation Water Requirements.

Seasons	Actual Irr.Req (m ³)	Total Net Irr (m ³)	Total gross irrigation (m ³)
Summer	11,861,199,200	11,251,280,000	22,485,960,000
Winter	5,660,796,000	5,480,002,200	10,972,032,000
Total	17,521,995,200	16,731,282,200	33,457,992,000

This table presents the water amounts necessary for irrigation during two distinct periods – summer and winter – and summarizes the total usage.

Actual Irrigation Needs (Actual Irr.Req)

In the summer, the required irrigation water volume is measured at 11.86 billion cubic meters (m³), based on the depth of water needed and the total area for irrigation.

- The winter season sees a reduction in water needs, with a requirement of about 5.66 billion m³. This reflects the seasonal changes in weather and the water requirements of crops as well in the area cultivated during this season.
- The yearly actual irrigation needs, combining both seasons, is roughly 17.52 billion m³. This amount represents the total water demand for irrigation over the year being studied.

Net Irrigation Needs (Total Net Irr)

- The summer requires a net irrigation water volume of approximately 11.25 billion m³, which is slightly less than the actual need.
- The winter need is around 5.48 billion m³.
- The annual combined net irrigation needs totals about 16.73 billion m³. This figure is essential for water resource planning and management, ensuring enough water is allocated for agriculture without excessive waste.

Gross Irrigation Needs (Total Gross Irrigation)

- The required gross irrigation water volume for summer is estimated at 22.49 billion m³. Gross irrigation includes all water supplied to the farm, covering both crop-utilized water and any wastage.
- The winter season's gross requirement is around 10.98 billion m³.
- The total yearly gross irrigation needs, summing up both seasons, is approximately 33.46 billion m³. This total is vital for managing water resources as it accounts for all water

delivered to the field, including usage and surplus.

These statistics are crucial for the strategic management of water resources, promoting sustainable irrigation methods, and upholding agricultural productivity. Understanding the differences between actual, net, and gross requirements provides insight into water use efficiency and opportunities for conservation.

4.5. The Water Supply in The Gezira Irrigation Scheme

The annual flow based on a capacity of 354 m³/s is 11,163,744,000 m³.

4.6. Assessing Water Adequacy

4.7. Annual Supply versus Irrigation Demand

4.7.1. The first Scenario

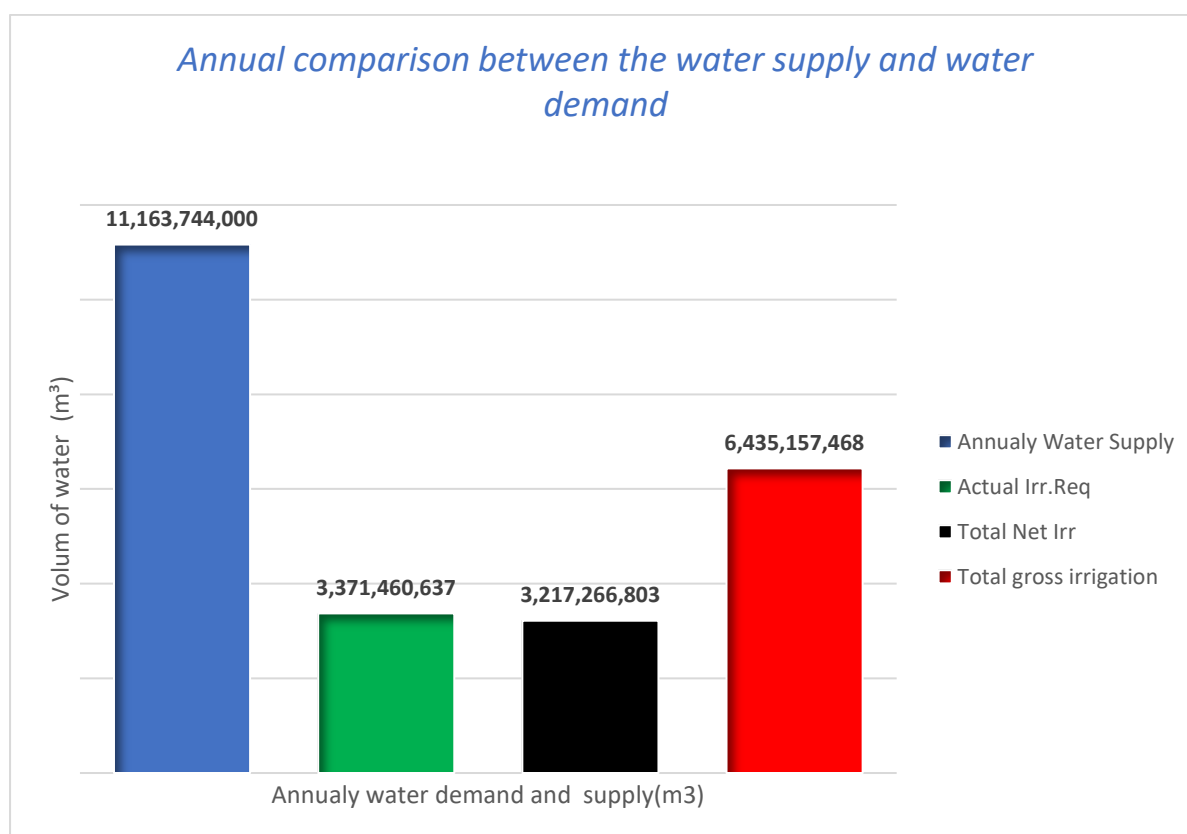


Figure 4-13. Bar chart of Annual Water Supply Versus Demand in The Gezira Irrigation Scheme for the first Scenario.

This bar chart illustrates the equilibrium between water supply and irrigation requirements. Here are the main points:

- Annual Water Supply: The blue bar represents the annual water supply, which totals 11,163,744,000 cubic meters.
- Actual Irrigation Requirement (Green): Approximately 3.4 billion cubic meters.

- Total Net Irrigation (Black): Comparable to the actual requirement, at around 3.2 billion cubic meters.
- Total Gross Irrigation (Red): This demand is higher, reaching approximately 6.4 billion cubic meters.

Overall, the supply significantly surpasses the total irrigation demand, indicating ample water supply for irrigation purposes in this scenario.

4.6.1.2. The Second Scenario

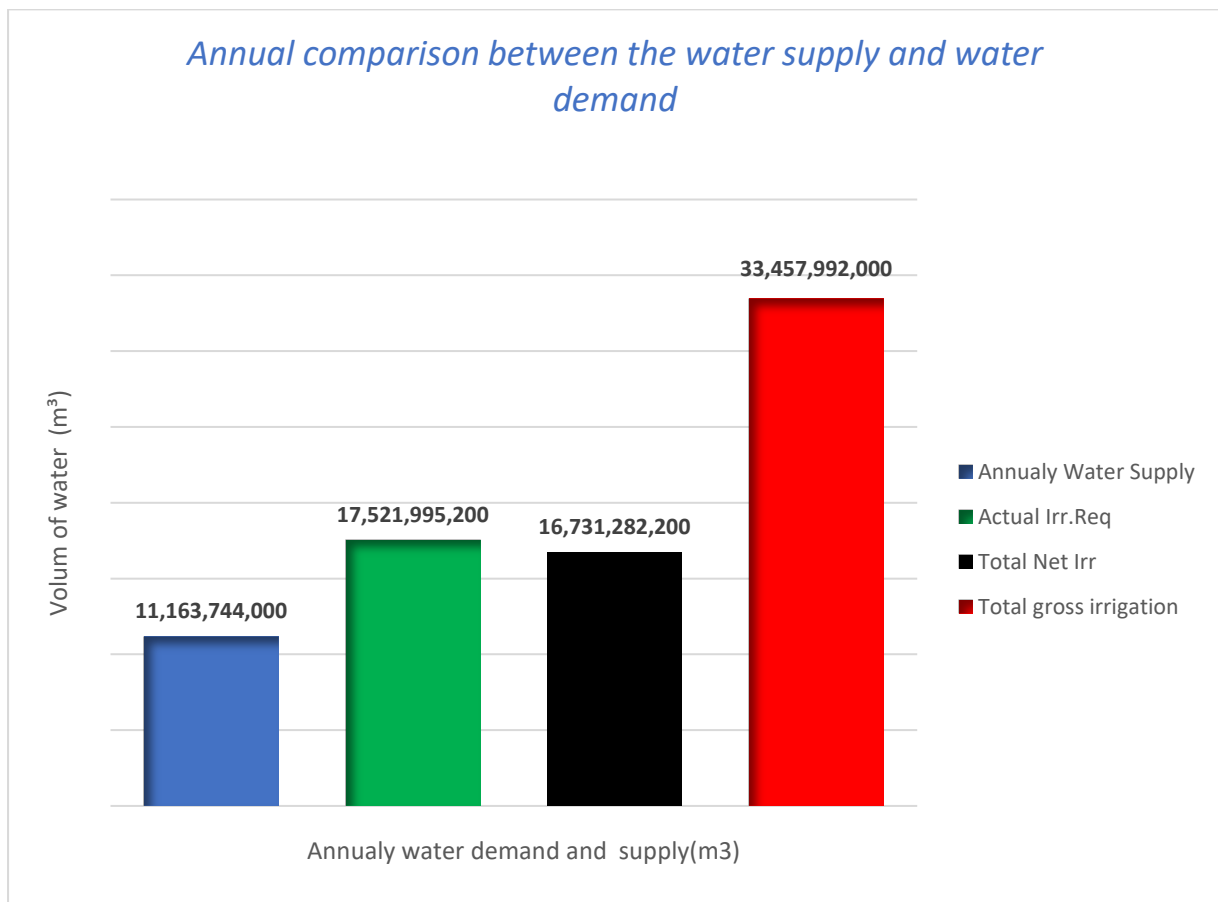


Figure 4-14. Bar chart of Annual Water Supply Versus Demand in The Gezira Irrigation Scheme for the second scenario.

This bar chart shows how much water is available and how much is needed for crops in the Gezira Irrigation Scheme.

- The blue bar represents the amount of water available each year, which is 11,163,744,000 cubic meters.
- The green bar shows how much water is actually needed for irrigation, which is 17,521,995,200 cubic meters.

- The black bar displays the net amount of water used for irrigation after considering losses, which is 16,731,282,200 cubic meters.
- The red bar indicates the total amount of water used for irrigation, including losses and additional water due to inefficiencies, which is 33,457,992,000 cubic meters.

Overall, the amount of water needed for irrigation is much more than what's available each year, which suggests there may be a water shortage. To balance things out, it's important to increase the water supply in the Gezira scheme and make the irrigation system more efficient.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

- In conclusion, this research has undertaken a comprehensive examination of the adequacy of water supply for meeting irrigation needs within The Gezira Irrigation Scheme, utilizing CROPWAT 8.0 software and it has delved into the scheme's ability to meet agricultural demands amidst the challenges posed by climate change and evolving irrigation needs. Through meticulous analysis across two distinct scenarios, covering both the scheme's total area and its current utilization, significant disparities between water supply and demand have been illuminated, emphasising the urgent need for efficient water management.
- In the first scenario, focused on the existing area of the Gezira irrigation scheme (169,567 hectares), the annual water supply (1,116,744,000 cubic meters) exceeds the annual irrigation water demand. This suggests an underutilization of water resources, which could significantly enhance agricultural activities. Expanding this area presents an opportunity to maximise agricultural productivity and optimise water usage.
- In the second scenario, assuming full cultivation of The Gezira Scheme's total area (882,000 ha), a notable gap emerges between the annual water supply and the total annual irrigation water requirement. This gap could potentially double the current water supply if the irrigation system operates at 50% efficiency. Addressing this challenge requires increasing both the water supply volume and improving irrigation efficiency, crucial steps towards sustaining the project's expansion.
- The insights gleaned from this study hold significant implications for the future of sustainable agriculture and water management within the Gezira Scheme and similar irrigation systems worldwide. Enhanced water management strategies, incorporating advanced irrigation technologies and optimised crop water usage, are imperative to tackle water scarcity challenges and ensure agricultural sustainability, thereby supporting livelihoods dependent on such systems.
- This study lays the groundwork for future research endeavours aimed at delving deeper into sustainable water management practices and irrigation efficiencies. Subsequent studies could explore innovative irrigation techniques, assess alternative water sources, and investigate climate-resilient cropping patterns. Such research is indispensable for

advancing our comprehension of sustainable agriculture amidst global environmental challenges.

- The Gezira Irrigation Scheme, pivotal to Sudanese agriculture, stands at a critical juncture. The challenges outlined in this study, including significant water supply and demand gaps, low irrigation efficiency, and implications for sustainable agriculture, call for immediate and strategic interventions. By embracing efficient water management practices and sustainable agricultural techniques, there is the potential to rejuvenate the Gezira Scheme and set a precedent for similar irrigation schemes worldwide. This study contributes a vital perspective to the discourse on water management and sustainable agriculture, offering actionable insights to guide policy, practice, and future research in the field

5.2. Recommendations

- Sudan's government should prioritize the development of agriculture, capitalizing on the strategic location, extensive land, fertile soil, and ample water resources of the Gezira project. Expanding agricultural activities within this project area is essential for bolstering food security and fostering economic prosperity.
- **Modernizing Irrigation Systems:** Implementing advanced irrigation technologies such as drip and sprinkler systems is imperative to minimize water wastage and maximize agricultural productivity.
- **Farmer Education Initiatives:** It is crucial to roll out educational programs aimed at instructing farmers on water conservation techniques and modern agricultural practices, ensuring the sustainability of the irrigation system in the long run.
- **Policy Reforms and Legislative Updates:** Authorities and relevant stakeholders should revise water management policies to facilitate equitable distribution, promote efficient utilization, and enforce practices that support sustainable agriculture.
- **Climate Change Adaptation:** Developing and implementing comprehensive strategies to mitigate the adverse impacts of climate change on water resources and agricultural production is paramount.

References

- [1] C. Ringler, N. Perez, and H. Xie, “The Role of Water in Supporting Food Security: Where We Are and We Need to Go,” *Agric. Dev. New Perspect. a Chang. World*, pp. 661–680, 2021.
- [2] A. Goelnitz and M. Al-Saidi, “Too big to handle, too important to abandon: Reforming Sudan’s Gezira scheme,” *Agric. Water Manag.*, vol. 241, no. July, p. 106396, 2020, doi: 10.1016/j.agwat.2020.106396.
- [3] Y. He, Y. Zheng, X. Chen, B. Liu, and Q. Tan, “Water resources allocation considering water supply and demand uncertainties using newsvendor model-based framework,” *Sci. Rep.*, vol. 13, no. 1, pp. 1–14, 2023, doi: 10.1038/s41598-023-40692-7.
- [4] H. Shemer, S. Wald, and R. Semiat, “Challenges and Solutions for Global Water Scarcity,” *Membranes (Basel)*, vol. 13, no. 6, 2023, doi: 10.3390/membranes13060612.
- [5] M. M. Altayib and M. M. Abdulwahab, “Design of Irrigation Management System in Gezira Scheme Using Geographic Information System,” *J. Telecommun. ...*, vol. 12, no. 2, pp. 69–73, 2020, [Online]. Available: <https://jtec.utem.edu.my/jtec/article/view/5527>
- [6] F. Dizon, S. Imtiaz, and J. Yu, “Water Constraints to Agricultural Productivity in Bhutan,” no. April, 2023, [Online]. Available: <http://www.worldbank.org/prwp>.
- [7] M. Kabbashi and A. Jabow, “Irrigation Schedule of Chickpea (*Cicer arietinum* L.) Using CROPWAT Model under Gezira Conditions, Sudan,” *J. Agric. Sci*, vol. 28, no. January 2020, pp. 82–104, 2020.
- [8] A. Kishore and F. Dizon, “An Assessment of Community-Led Lift Irrigation Systems in Jharkhand, India,” no. May, 2023.
- [9] Y. A. Ibrahim, “Complex adaptive system approach for improved irrigation management: The case of the Gezira scheme in Sudan*,” *Irrig. Drain.*, vol. 69, no. 5, pp. 1072–1081, 2020, doi:10.1002/ird.2516.
- [10] S. Muhammad and A. Hassan, “The Physical Geography of Sudan: A State’s Power and Threats International Journal of Research Publication and Reviews The Physical Geography of Sudan: A State’s Power and Threats,” no. January, 2024.
- [11] C. Overview, “SUDAN Impact of the current conflict on WASH needs,” no. September, 2023.
- [12] T. Disintegrazione and J. Capaldo, “Working Paper No. 14-03,” 2014. P. Reconstruction and G. Agenda, “Post-Conflict Reconstruction, Stabilization and Growth Agenda for Sudan,” no. 1662, 2023.
- [13] A. Sonia, K. Richard, and G. Hani, “Modelling land suitability to evaluate the potential for

- irrigated agriculture in the Nile region in Sudan,” *Sustain. Water Resour. Manag.*, vol. 9, no. 1, pp.1–17, 2023, doi: 10.1007/s40899-022-00773-3.
- [14] “World,” 2019, [Online]. Available: <https://www.mapsofworld.com/answers/geography/what-are-the-key-facts-of-sudan/#>
- [15] S. Development, *Sudan First State of Environment and Outlook Report 2020*. 2020.
- [16] “Water Resources in Sudan.” [Online]. Available: <https://water.fanack.com/sudan/water-resources-in-sudan/>
- [17] “Nile.” [Online]. Available: <https://en.wikipedia.org/wiki/Nile>
- [18] E. Mulder and F. van Steenberghe, “Sudan Water Policy Review and Analysis,” no. November, 2021.
- [19] D. Wadi, W. Wu, I. Malik, A. Fuad, and M. M. Thaw, “Assessment and feasibility of the potential artificial groundwater recharge in semi-arid crystalline rocks context, Biteira district, Sudan,” *Sci. African*, vol. 17, p. e01298, 2022, doi: 10.1016/j.sciaf. 2022.e01298.
- [20] S. Soomro et al., “Estimation of irrigation water requirement and irrigation scheduling for major crops using the CROPWAT model and climatic data,” *Water Pract. Technol.*, vol. 18, no. 3, pp. 685–700, 2023, doi: 10.2166/wpt.2023.024.
- [21] A. K. Basheer, A. B. Ali, N. A. Elshaikh, and G. H. Agbna, “Sustainable Utilization of Water Resources in Agriculture Sector of Sudan , After The Secession of South Sudan,” vol. 25, pp. 51–65, 2023.
- [22] A. M. Omer, “Water resources management and sustainable development in Sudan,” *Int. J. Water Resour. Environ. Eng.*, vol. 2, no. 2, pp. 190–207, 2010.
- [23] A. W. M. Elamin, “Water Resources in Sudan International Agricultural Research and Training Center Water Resources in Sudan Dr Ali W M Elamin University of Khartoum- Sudan,” *Univ. Khartoum*, no. May 2013, 2015.
- [24] B.A.Jones, “irrigation agriculture.” [Online]. Available: <https://www.britannica.com/technology/irrigation>.
- [25] “irrigation for agriculture and landscapes.” [Online]. Available: <https://en.wikipedia.org/wiki/Irrigation>
- [26] M. A. Hussein, M. B. Elgali, and R. H. Mustafa, “Sudan agricultural markets performance under climate change,” *J. Posit. Sch. Psychol.*, vol. 4, pp. 9955 – 9968, 2022, [Online]. Available: <http://www.fao.org/3/a-bu259e.pdf>
- [27] A. Elgilany, S. Jamalludin, and M. Saidatulakmal, “Assessment of socioeconomic aspects in

- irrigation water use inefficiency in Sudan,” *Desalin. Water Treat.*, vol. 52, no. 28–30, pp. 5295–5305, 2014, doi: 10.1080/19443994.2013.808785.
- [28] O. A. Mirghani, A. H. Ibrahim, A. A. Hashim, and A. E. S. O. Khalifa, “Determinants of Food Security in Gezira Scheme of Sudan,” vol. 6, no. 11, pp. 279–289, 2016.
- [29] I. M. Oroud, “The Impacts of Climate Change on Water Resources in Jordan,” *Environ. Sci. Eng.*, no. 2, pp. 110–123, 2008, doi: 10.1007/978-3-540-85047-2_10.
- [30] K. Siddig, D. Stepanyan, M. Wiebelt, H. Grethe, and T. Zhu, “Climate change and agriculture in the Sudan: Impact pathways beyond changes in mean rainfall and temperature,” *Ecol. Econ.*, vol. 169, no. October 2018, p. 106566, 2020, doi: 10.1016/j.ecolecon.2019.106566.
- [31] S. Mohammad and A. Hassan, “THE IMPACTS OF UTILIZATION OF NATURAL RESOURCES AND CLIMATE CHANGE IN SUDAN,” no. January, pp. 1–10, 2024, doi: 10.36713/epra1213.
- [32] OECD/FAO, Please cite this publication as: OECD/FAO (2017), OECD-FAO Agricultural Outlook 2017-2026, OECD Publishing, Paris. http://dx.doi.org/10.1787/agr_outlook-2017-en. 2017. [Online]. Available: http://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2017-2026_agr_outlook-2017-en
- [33] S. M. Ahmed, “Impacts of drought, food security policy and climate change on performance of irrigation schemes in Sub-saharan Africa: The case of Sudan,” *Agric. Water Manag.*, vol. 232, no. January, p. 106064, 2020, doi: 10.1016/j.agwat.2020.106064.
- [34] P. W. France, *Water resource systems planning and analysis*, vol. 4, no. 3. 1981. doi: 10.1016/0309-1708(81)90046-4.
- [35] United Nations Environment Programme (UNEP), “ADAPT FOR ENVIRONMENT AND CLIMATE RESILIENCE IN SUDAN (ADAPT!): Integrated Water Resources Management GoodPractices in Sudan,” 2020, [Online]. Available: <http://www.unep.org>
- [36] F. Jaspers, “Towards Integrated Water Resources Management: International experience in development of river basin organisations,” no. April, p. 32, 2014.
- [37] P. Steduto et al., “Food Security by Optimal Use of Water: Synthesis of the 6th and 7th World Water Forums and Developments since Then,” *Irrig. Drain.*, vol. 67, no. 3, pp. 327–344, 2018, doi: 10.1002/ird.2215.
- [38] Food and Agriculture Organisation, *Water for Sustainable Food and Agriculture Water for Sustainable Food and Agriculture*. 2017. [Online]. Available: <https://bit.ly/3GJtCtP>
- [39] A. Wästerström, “Global Water Stress Indices : An example of their industrial usage,” *VATTEN –J. Water Manag. Res.*, no. 72, pp. 23–30, 2016.

- [40] S. K. Balasundram, R. R. Shamshiri, S. Sridhara, and N. Rizan, “The Role of Digital Agriculture in Mitigating Climate Change and Ensuring Food Security: An Overview,” *Sustainability*, vol. 15, no. 6, p. 5325, 2023, doi: 10.3390/su15065325.
- [41] B. K. Singh et al., “Climate change impacts on plant pathogens, food security and paths forward,” *Nat. Rev. Microbiol.*, vol. 21, no. 10, pp. 640–656, 2023, doi: 10.1038/s41579-023-00900-7.
- [42] A. Aldababseh, M. Temimi, P. Maghelal, O. Branch, and V. Wulfmeyer, “Multi-criteria evaluation of irrigated agriculture suitability to achieve food security in an arid environment,” *Sustain.*, vol. 10, no. 3, 2018, doi: 10.3390/su10030803.
- [43] World Bank, “The World Bank and the Gezira Scheme in the Sudan Political Economy of Irrigation Reforms,” no. 69873, 2010.
- [44] O. A. Mirghani, A. H. Ibrahim, A. A. Hashim, and A. E. S. O. Khalifa, “Determinants of Food Security in Gezira Scheme of Sudan,” *Int. J. Sci. Res. Publ.*, vol. 6, no. 11, pp. 279–289, 2016, [Online]. Available: www.ijsrp.org
- [45] “No Title,” 2021, [Online]. Available: <https://kushnews.net/2021/07/295113>
- [46] “Sennar Dam.” [Online]. Available: https://en.wikipedia.org/wiki/Sennar_Dam
- [47] V. SHAKUNTALA G., S. R., and H. CHANDRASHEKARAYYA G., “Cropwater Requirement for Different Hydrological Scenarios Using Cropwat,” *i-manager’s J. Civ. Eng.*, vol. 7, no. 4, p. 27, 2017, doi: 10.26634/jce.7.4.13800.
- [48] A. E. Elhag and A. A. Abdelkarim, “Analysis of Irrigation Water Requirements in Gezira Scheme Using Geographic Information Systems: Case Study Block Number 26 (Dolga),” *J. Eng. Comput. Sci.*, vol. 22, no. 1, pp. 81–91, 2021.
- [49] J. Feng, W. Wang, F. Xu, and S. Wang, “Evaluating the ability of deep learning on actual daily evapotranspiration estimation over the heterogeneous surfaces,” *Agric. Water Manag.*, vol. 291, no. November 2023, p. 108627, 2024, doi: 10.1016/j.agwat.2023.108627.
- [50] G. Nikolaou, D. Neocleous, E. Kitta, and N. Katsoulas, “Assessment of the Priestley-Taylor coefficient and a modified potential evapotranspiration model,” *Smart Agric. Technol.*, vol. 3, no. May 2022, p. 100075, 2023, doi: 10.1016/j.atech.2022.100075.
- [51] S. Issue, “Journal of Agrometeorology,” *J. Agrometeorol.*, vol. 6, no. 1, pp. 5–9, 2004.
- [52] L. E. Olivera-Guerra et al., “Modeling actual water use under different irrigation regimes at district scale: Application to the FAO-56 dual crop coefficient method,” *Agric. Water Manag.*, vol. 278, no. August 2022, 2023, doi: 10.1016/j.agwat.2022.108119.
- [53] J. C. Henggeler, S. Extension, I. Specialist, P. Guinan, S. Climatologist, and J. Travlos, “Simple

- Charts for Modifying Crop Coefficients to Local Conditions,” vol. 63873, pp.1–20.
- [54] G. S. Solangi et al., “Investigation of Irrigation Water Requirements for Major Crops Using CROPWAT Model Based on Climate Data,” *Water (Switzerland)*, vol. 14, no. 16, 2022, doi: 10.3390/w14162578.
- [55] H. Salahudin et al., “Using Ensembles of Machine Learning Techniques to Predict Reference Evapotranspiration (ET₀) Using Limited Meteorological Data,” *Hydrology*, vol. 10, no. 8, pp. 1–20, 2023, doi: 10.3390/hydrology10080169.
- [56] A. H. Halimi and A. H. Tefera, “Application of Cropwat Model for Estimation of Irrigation Scheduling of Tomato in Changing Climate of Eastern Europe: the Case Study of Godollo, Hungary,” *Int. J. Agric. Environ. Sci.*, vol. 6, no. 1, pp. 1–11, 2019, doi: 10.14445/23942568/ijaes-v6i1p101.
- [57] A. K. Abdalla, “An Integrated Value-Based Framework for Modeling Strategic Decision Analysis and Planning in Public Agricultural Corporations in Sudan: The case of the ...,” *Gezira J. Econ. Soc. Sci.*, no. May, 2018, [Online]. Available: https://www.researchgate.net/profile/Abdalla-Abdalla7/publication/333164324_An_Integrated_Based_Framework_for_Modeling_Strategic_Decision_Analysis_and_Planning_in_Public_Agricultural_Corporations_in_Sudan_The_case_of_the_Gezira_Scheme/links/5cde9e3
- [58] E. Suryadi, D. R. Kendarto, B. A. Sistanto, D. Ruswandi, and S. Dwiratna, “A study of crop waterneeds and land suitability in the monoculture system and plant intercropping in Arjasari,” *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 8, no. 2, pp. 554–560, 2018, doi:10.18517/ijaseit.8.2.4943.
- [60] S. H. Ewaid, S. A. Abed, and N. Al Ansari, “نظير الزنصري,” *Water*, vol. 11, no. 4, pp. 1–12, 2019.
- [61] Y. Mebrahtu, “Estimation of Crop Water Requirement using CROPWAT Model for Maize, A Case Study of Raya Azebo District, Ethiopia,” *J. Resour. Dev. Manag.*, vol. 74, pp. 18–22, 2021, doi: 10.7176/jrdm/74-03.
- [62] R. S. Makar, S. A. Shahin, M. El-Nazer, A. Wheida, and M. Abd El-Hady, “Evaluating the Impacts of Climate Change on Irrigation Water Requirements,” *Sustain.*, vol. 14, no. 22, 2022, doi: 10.3390/su142214833.
- [63] A. Agrawal, P. K. Srivastava, V. K. Tripathi, D. J. Shrinivasa, S. Maurya, and R. Sharma, “Future projections of crop water and irrigation water requirements using a bias-corrected regional climate model coupled with CROPWAT,” *J. Water Clim. Chang.*, vol. 14, no. 4, pp. 1147–1161, 2023, doi: 10.2166/wcc.2023.349.

- [64] O. A. Mirghani, A. H. Ibrahim, A. A. Hashim, and A. E. S. O. Khalifa, “Determinants of Food Security in Gezira Scheme of Sudan,” *Int. J. Sci. Res. Publ.*, vol. 6, no. 11, pp. 279–289, 2016, [Online]. Available: www.ijsrp.org
- [65] A. Goelnitz and M. Al-Saidi, “Too big to handle, too important to abandon: Reforming Sudan’s Gezira scheme,” *Agric. Water Manag.*, vol. 241, no. July, p. 106396, 2020, doi: 10.1016/j.agwat.2020.106396.
- [66] M. Bidabadi, H. Babazadeh, J. Shiri, and A. Saremi, “Estimation reference crop evapotranspiration (ET₀) using artificial intelligence model in an arid climate with external data,” *Appl. Water Sci.*, vol. 14, no. 1, pp. 1–10, 2024, doi: 10.1007/s13201-023-02058-2.
- [67] J. C. Henggeler, S. Extension, I. Specialist, P. Guinan, S. Climatologist, and J. Travlos, “Simple Charts for Modifying Crop Coefficients to Local Conditions,” vol. 63873, pp. 1–20.
- [68] E. Science, “Estimating irrigation requirement and scheduling for major crops: Case study 9n Kampong Thom, Estimating irrigation requirement and scheduling for major crops : Case study in Kampong Thom , Cambodia”, doi: 10.1088/1755-1315/1297/1/012051.
- [69] W. A. Case, S. Karmaker, S. Bandyopadhyay, and S. Bauer, “Geospatial Approaches to Improve Water Availability through Demand Assessment in Agriculture Based on Treated,” 2024.