THESIS

Elsadig Bashir Mohammed Omer

Agricultural Water Management Engineering

Gödöllő

2023

`

HUNGARIAN UNIVERSITY OF
AGRICULTURE AND LIFE SCIENCES

Hungarian University of Agricultural and life science- Szent István Campus, Gödöllő

Agricultural Water Management Engineering

Master Degree

Evaluation of Water Productivity and Wheat Yield Using Remote Sensing WaPOR database and AquaCrop model for Gezira Scheme in Sudan

Primary Thesis Adviser: **Dr. Istvan Waltner**
Associate professor

Author: **Elsadig Bashir Mohammed Omer**
JINON8

Institute of Environmental Sciences, Department of Water Management and Climate Adaptation

Gödöllő

2023

Table of Contents

Contents

1. Introduction 1
1.1 General Objective 2
1.2 Research Objectives 2
1.3 Research Questions 2
2. Literature review 3
2.1 Agricultural Water Productivity 3
2.2 Water Use Efficiency 4
2.2 Irrigation 4
2.4 Irrigation Development in Sudan 5
2.5 Irrigation water management 6
2.6 Irrigation Scheduling 6
2.7 Irrigation Application 7
2.8 Application of WaPOR Database in Irrigation 7
2.9 WaPOR Data Coverage 8
2.10 WaPOR data components per level 10
2.11 Relationship Between WaPOR Data Components 11
2.12 Crop Models 11
2.13 AquaCrop 12
2.13.1 Evaluation of AquaCrop 14
2.13.2 Soil-Crop-Atmosphere continuum: 15
2.13.3 Evaporation, Transpiration, and Interception 15
2.13.4 Moisture Content of Yield (MC) 15
2.13.5 Harvest Index (HI) 16
3. Materials and Methods 17
3.1 Site Description: 17
3.2 Climate 18
3.3 Description AquaCrop Model 19
3.3.1 Data collection 19
III. Weather data 21

IV. Soil data 21
3.3.2 Irrigation scheduling 21
3.4 Field management practices 22
3.5 WaPOR data components: extraction, analysis, and evaluation: 23
3.6 Methodological framework 25
4. Results 27
4.1 Assessment of data collected: 27
4.2 Wheat Farms 28
4.2 Sensitivity analyses of AquaCrop Model 29
4.3 Sensitivity analyses: 29
4.3 Overall Evaluation of AquaCrop Results 31
4.4 AquaCrop Calibration and validation 33
4.5 Aboveground biomass 35
4.6 Water Productivity 37
4.7 WaPOR and AquaCrop Comparison 38
5. Discussion 42
6. Conclusions and Recommendation 44
7. Summary 45
List of References 48
Appendices 54

LIST OF TABLES

Table 1 Overview of the WaPOR data components, per Level, with temporal and spatial resolutions specified. 10
Table 2 Main input parameters used for the calibration and the validation of the AquaCrop model for table dates during 2020 and 2021 growing seasons: 20
Table 3 Overview of WaPOR data components used for this study: 24
Table 4 Simulation input for wheat farms 29
Table 5 lists the outputs of the simulation for aeras selected. (*Observed canopy data were cleaned; see simulation assessment.) 32
Table 6 Statistical result of AquaCrop model calibration for dry wheat yield: 33
Table 7 Shown the statistical analysis between simulate and observed data. 35

Table of figures

Figure 1 WaPOR data coverage at continental level 8
Figure 2 WaPOR data coverage at national level 9
Figure 3 WaPOR data coverage at third level (Sub-national) 9
Figure 4 Data component flow chart. 11
Figure 5 Flowchart of AquaCrop indicating the main components of the soil-plant-atmosphere continuum, (Steduto et al. 2009). 13
Figure 6 Monthly climatology of T- Min, T-mean, T-max and Precipitation Gezira, Sudan. 18
Figure 7 WaPOR methodology 23
Figure 8 Flowchart of the work process methodology. (REF Source) Modified by (Omer. E) 26
Figure 9 : average monthly precipitation and ETo of Gezira Scheme. 27
Figure 10. Average daily temperature in a month of weather station 28
Figure 11; The AquaCrop model SA with yield output for the minimum, mean and maximum value for the selected parameters (fc, hi and rtx), indicated with blue for the minimum value, orange for the mean value and grey for the maximum value. 30
Figure 12; The AquaCrop model SA with ETa output for the minimum, mean and maximum value for the selected parameters (fc, hi and rtx), indicated with blue for the minimum value, orange for the mean value and grey for the maximum value. 31
Figure 13 shows coloration simulated and measured yield at farms wheat producers in the selected blocks. 34
Figure 14 shows coloration simulated and measured yield at farms wheat producers for the selected blocks. 35
Figure 15 shows the simulated biomass after planting days for all selected blocks. 36
Figure 16 shows simulated biomass yield and measured yield at farms wheat producers in the selected plots. 36
Figure 17shows coloration simulated and measured biomass at farms wheat producers in the selected blocks. 37
Figure 18 showed simulated WP yield and measured WP at farms wheat producers in the selected plots. 38
Figure 19 showed simulated WP yield and measured WP at farms wheat producers in the selected plots. 38
Figure 20 WaPOR ETIa cell values for the study area and presented with blue columns for the seasons 2019/2020, AquaCrop ETa outputs form the seasons 2019/2020, and AquaCrop ET0 outputs for season2019/2020 presented with yellow and orange and gray columns/ 39
Figure 21 : Correlation between WaPOR ETa and AquCrop ETa for all selected block 40
Figure 22 WaPOR, AquaCrop and observed fresh dry yield for all selected blocks. 40
Figure 23 Shows correlation between WaPOR Y and observed AquaCrop WP for the selected blocks. 41
Figure 24 Shows correlation between WaPOR Y and observed WP for the selected blocks. 41

LIST OF ABBREVIATIONS

FAO	*Food and Agriculture Organization of the United Nations*
WaPOR	*FAO portal to monitor Water Productivity through Open access of Remotely sensed.*
HI	*Harvest Index*
NDVI	*Normalized Difference Vegetation Index*
NPP	*Net Primary Productivity.*
ET	*Evapotranspiration*
WP	*water productivity*
CCo	*initial canopy cover*
AET	*Actual evapotranspiration*
AGB	*Above ground biomass*
DMP	Dry Matter Production
RS	*Remate sensing*
Tr	*Transpiration*
RMSE	*Root Mean square Error*

1. Introduction

Background and problem definition

The primary goal for systems of crop production has always been to achieve maximum productivity in order to produce the highest crop yield (output) while using the best and least affordable management techniques. However, not only is water scarcity a challenge to meeting such a target in locations where crop water used a significant economic value. (Exposito, A., & Berblel J 2017). Water shortages have become one of the world's most pressing challenges because of global changing climte and rapid socioeconomic growth (Naimi Ait-Aoudia and Berezowska-Azzag, 2016, Wang and Zhang 2011). The agricultural sector, the single largest consumer of the planet's accessible fresh water with 65–75% of freshwater being currently used for (Wu, B., et al. 2022, Panhwar, A., et al. 2022). Moreover, the agriculture sector is under great pressure due to rising food demand, competition from other sectors, and uncertainty from climate change. As a result, it is unlikely to receive more water allocation in the future, according to research by (Zwart et al. 2010). To meet the food requirements of future generations, it is necessary to improve agricultural water productivity, which is a crucial parameter for evaluating the management of agricultural water (Lascano, R. J et al. 2006), This involves producing more food with less water. According to (Molden et al. 2007), the definition of agricultural water productivity is the ratio between the yield of crops and the amount of water used through evapotranspiration. To increase the efficiency of agricultural water use, it is crucial to understand water productivity, which can be assessed at the plot or field level by analyzing crop yield and water usage data. However, this approach may not provide an accurate assessment due to unknown evapotranspiration rates and spatial variation. Advanced technologies and monitoring systems are required to ensure sustainable water use in agriculture (Bastiaanssen, W. G., & Steduto, P 2017). To ensure future food security, there is a need for the development of new technologies that improve water productivity (Taddeo, S 2022). Using remote sensing to evaluate water productivity enables us to identify areas with varying levels of water productivity, investigate the factors contributing to the differences, and evaluate the potential for enhancement through scientific research. The FAO's WaPOR portal provides open access to 11 years of continuous observation data over Africa and the Near East, which can help estimate water and land productivity gaps in both irrigated and rain-fed agriculture (FAO 2020). This information could be useful for water managers, agronomists, farmers, and other stakeholders in making informed decisions on practical management practices and enhancing agricultural production sustainability. However, uncertainties and mistakes in the derived datasets still exist due to the algorithms used to derive key variables like biomass and actual evapotranspiration (AET), critical to water productivity (WP) estimation. Therefore, it's crucial to assess the accuracy level of these datasets.

The aim of this study is to evaluate the accuracy of WaPOR data by comparing it to data obtained from fieldwork and modeled using AquaCrop 6.1 for specific farms in Sudan's Gezira scheme. The FAO developed AquaCrop, a crop growth model, to evaluate the impact of environmental factors and management techniques on crop production and food security. This model utilizes a water-driven approach to simulate plant growth and root development. By examining the results of this comparison, the study aims to gain a better understanding of the dependability of remote sensing data, specifically for the purpose of evaluating water productivity using WaPOR.

1.1 General Objective

The overall goal of the study is to evaluate crop yield by analyzing crop productivity in the Gezira irrigation scheme, using freely available remotely sensed data (RS) for research from the WaPOR database, and primary collected field data validated using the crop water model AquaCrop.

1.2 Research Objectives

The following specific objectives are adopted, to achieve the general objective of the study:

1- Facilitate a comparison between the results of AquaCrop and from WaPOR database.
2- Analyze possible causes of discrepancies between AquaCrop and WaPOR output.
3- To evaluate the applicability of WaPOR database for Water Productivity Analysis for the case of Gezira irrigation scheme.

1.3 Research Questions

- How does the crop water productivity, and yield estimate from remote sensing-based measurements compare with field and model estimates?
- How well WaPOR database-based WP data components are correlated with observed field data and AquaCrop model estimate?

2. Literature review

2.1 Agricultural Water Productivity

The concept of water productivity (WP) in agricultural production systems is based on "more crop per drop," a key phrase in assessing agricultural water use and, in a wider sense, defined as the value or benefit derived from the use of water (Kijne et al. 2009; Molden et al. 2010). The ratio of net benefits from agricultural systems such as crops, forests, fisheries, livestock, and mixed farming to the amount of water used to generate those benefits is known as water productivity (D.Molden et al. 2010). Moreover, water productivity indicates which plots are very efficient and inefficient with water while also having a high or low food production (Bastiaanssen & Stedut, 2017). Biomass or yield can be used to calculate food production. Water productivity using biomass will be referred to as 'Gross/Net Biomass Water Productivity', while water productivity using yield will be referred to as 'Crop Water Productivity'. The plant's evapotranspiration can be used to calculate water consumption (FAO 2019). It is a useful technique for contrasting water productivity across various basin regions and between agriculture and other productive sectors (Zwart & Bastiaanssen, 2004). According to equation 2-1 from this study, it is measured in kilograms of yield (or dry biomass) produced per cubic meter of water lost through evapotranspiration.

$$\boldsymbol{WP} = \frac{\mathrm{Y}}{\mathrm{AET}} \ (\mathrm{Kg/m^3}) \ \ldots\ldots\ldots\ldots\ldots\ldots \ \mathrm{Eq}\ [2.1]$$

Where AET is the total water lost through soil evaporation and crop transpiration over the course of a crop cycle (m^3/ha) and Y is the actual crop yield (kg/ha).

Some of the factors that could affect water productivity include the availability of water, crop cultivar type, soil features, climate, and management practices (Ali & Talukder 2008). Because of the rising demand for grain production, agricultural water productivity will continue to improve. (Steduto et al. 2012), The recent FAO drainage document 66 WP values for various crops are based on a review of the results of field measurement experiments presented in the global literature. According to reports, most crops now have WP values that are higher than they had in the 1970s. This was assigned to improved crop types that yield larger yields, crops are resistant to (pest - disease, and drought), improved soil fertility, and water management strategies for land.

2.2 Water Use Efficiency

A crucial agricultural metric for crop simulations is water use efficiency (WUE), which has numerous meanings (Steduto and Albrizio 2005). There is some difficulty in distinguishing between efficient water usage (EWU) and water use efficiency (WUE). According to (Steduto 1996), EWU is exclusively concerned with agricultural water transport and is the ratio of water output by transpiration to water imported via rain or irrigation. According to (Langhorn, C.M. 2016), EWU is only concerned with crop water transport and is the ratio of water output through transpiration to water imported by rain or irrigation. WUE differs in that it is computed by dividing the amount of carbon acquired from photosynthesis by the amount of water lost through transpiration. Water plays a critical role in various processes, and if there are significant changes in plant-water interactions caused by climate change, it could impact both of these processes. Additionally, the transpiration process from leaf surfaces requires a significant amount of energy due to the latent heat of vaporization, which helps cool the foliage by up to 5°C below the air temperature. Any modifications in water usage or availability by plants could have a considerable impact on nitrogen absorption and cause an increase in tissue temperatures (Brouder, S.M. and Volenec, J.J 2008). WUE can be defined in different ways, but when it comes to modeling crops, the assessment of yield-WUE is commonly used (Todorovic et al. 2009). This evaluation helps to establish the correlation between crop yield and total evapotranspiration. WUE, also referred to as (WP), is a phrase used in agricultural modeling research to indicate the amount of crop yield or biomass produced for each unit of water utilized (Hsiao, T.C et al. 2009; Andarzian et al 2011, Steduto et al. 2009; Todorovic et al. 2009; VanVan Halsema, G.E. and Vincent, L 2012).

2.2 Irrigation

The term irrigation refers to the process of supplying water to the soil artificially with the aim of ensuring that the plant roots receive sufficient moisture, which helps to avoid stress that can cause reduced crop yields and/or poor crop quality (Scherer et al. 2017). Additionally, it helps to cool the soil and atmosphere and to offer insurance against droughts. High-yield seed varieties can be grown affordably by using irrigation, which also supplies adequate nutrients to plants and helps pest prevention (Singh, S.P et al. 2013).

This agricultural practice is used to allow plants to grow when there is low rain, particularly in arid region. Additionally, it is used in less arid areas to provide plants with the water they require for seed germination. In areas where the given crop is generally cultivated using rain-fed agriculture, irrigation is considered to be supplemental when it is utilized because rainfall is insufficient to allow the crop to grow (Shand and & Basson 2003). Supplemental irrigation is the technique of delivering more water to the crop with the goal of stabilizing and improving yield. Irrigation is a critical component of agricultural management when increased food and fiber production is required despite severe water resource restrictions. Effective irrigation water utilization is a critical problem for agricultural growth in areas where water is limiting factor for crop production (Todorovic, M., et al. 2011).

2.4 Irrigation Development in Sudan

Sudan has the largest amount of irrigated land in Sub-Saharan Africa and the second most in Africa overall, after Egypt. During the era of British colonialism between 1898 and 1956, the implementation of large-scale gravity irrigation was initiated, and the agricultural strategy in the Nile basin was centered around encouraging the growth of cotton. Pumping water irrigation was developed in the early twentieth century to replace traditional flood irrigation and water wheel methods.

The oldest and largest gravity irrigation system in Sudan is known as the Gezira Scheme, and it lies between the Blue Nile and the White Nile. Began in 1925 and gradually expanded after that, especially with its Managil expansion. It is one of the world's largest continuous irrigation systems, covering around 870 000 ha, and is divided into roughly 138 000 tenancies, with an average size of about 8 ha (NBI 2008). It receives water from the Sennar Dam on the Blue Nile and withdraws over a third of Sudan's share of Nile water under the 1959 Agreement (UNEP 2007)–from 2 km3 in 1958 to 7.1 km3 in 1998 (NBI 2008). The scheme has contributed significantly to Sudan's economic growth by providing a significant portion of the government's income and foreign exchange earnings. Additionally, it has aided in ensuring the nation's food security and providing a means of livelihood for the estimated 2.7 million residents of the scheme's command area.

Despite covering only about 11% of the total cultivated land, the irrigated sub-sector contributes over 50% of the total agricultural production. This sector has gained significance in recent decades due to the unpredictability and variability of rainfall and drought. Notably, the irrigated sector accounts for most of the high-quality cotton (95%) and all sugar production, as well as a significant portion of sorghum (36%) and groundnuts (32%). Additional crops grown through irrigation include fodder, wheat, and vegetables, while maize, sunflower, potatoes, roots and tubers, and rice are also produced in smaller amounts.

2.5 Irrigation water management

Irrigation water management (IWM) involves regulating the timing and amount of irrigation water used to meet crop water needs efficiently, while minimizing water wastage, preserving soil and plant nutrients, and avoiding soil degradation. It involves using water based on crop needs, in amounts that can be kept in the soil while remaining available to crops, and at rates that are consistent with the soil's intake characteristics and the site's erosion danger. Water savings from enhanced irrigation supply management are regarded as critical to fulfilling future water needs (D. Molden et al. 2010). Calculating the amount and time of irrigation depends on the crop type and development stage because different crops have different water requirements at different phases of growth. Numerous advantages of enhanced irrigation management of water include conserving scarce water resources, reducing the impact of irrigation on quality, and increasing producer net profit. Plant water requirements fluctuate depending on weather conditions, crop type, development stage, and environmental factors, therefore determining the volume and timing of irrigation is important. Irrigation management therefore aims to keep the water level in the root zone within a range where crop production and quality are not affected by either insufficient or excessive water. Irrigation scheduling approaches may increase irrigation water management, which is crucial for agricultural and water productivity (Werner, 1992). A primary goal in the field of irrigation water management is to provide irrigation decisionmakers with an understanding of conservation irrigation principles by demonstrating how they can judge the effectiveness of their own irrigation practices, make good water management decisions, recognize the need to make minor adjustments in existing systems, and recognize the need to make major improvements in existing systems or install new systems (Kelly J. Klausmeyer et al. 2004).

2.6 Irrigation Scheduling

Irrigation scheduling is the technique of determining how much water and when the given volume is applied into an irrigated area. Determining when and how much water is required for a crop involves knowledge of soil properties, particularly moisture-holding ability, weather conditions, crop type, and growth stage (Ali, M.H. 2010; Scherer, T.F, et al, 1996; Verma, S.B. and Jha, J. 2014). Irrigation scheduling calculations are based on estimates of crop water requirements

(CWR), which represent the quantity of water lost by plants through evapotranspiration. The optimal use of water, energy, and other production inputs like fertilizer depends on proper timing. It enables irrigation to be coordinated with other farming practices, like cultivation and chemical applications. Maximizing net profits will need a more price approach than simply increasing agricultural yields. This is significantly more complex and challenging, needing water to be delivered with includes determining, precision, and accuracy as the margin for error narrows (English, M.J., et al. 2002). Among the benefits of proper irrigation scheduling is improved crop yield and/or quality, water and energy conservation, and lower production costs (Fernández García, et al. 2020). It is clear from the above overview that carrying out an optimal irrigation scheduling is essential for improving water and energy use in irrigated agriculture.

2.7 Irrigation Application

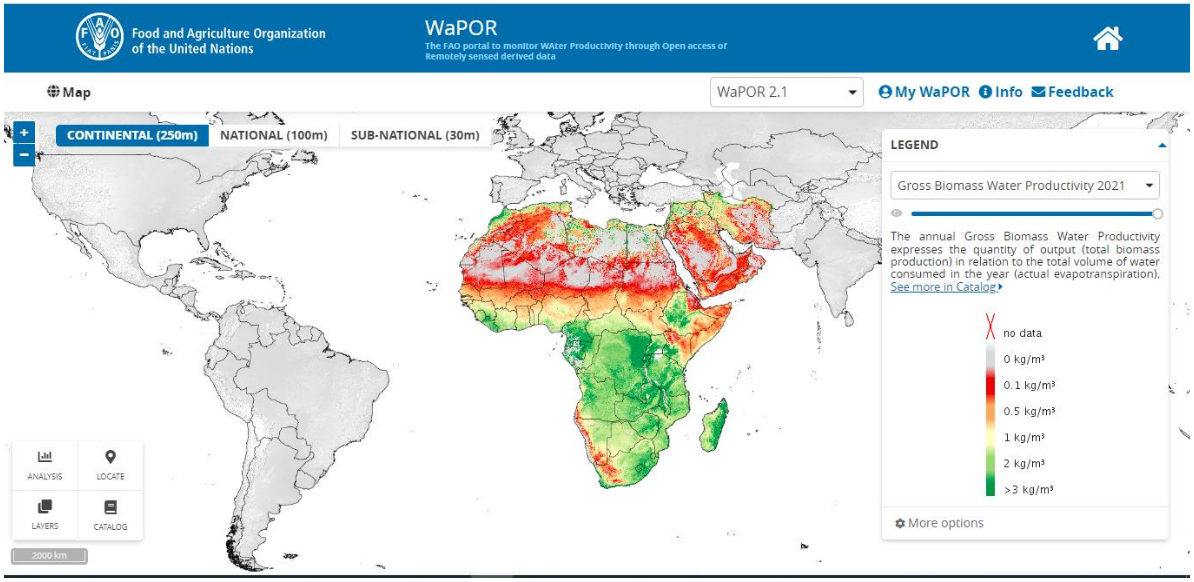
The irrigation application method, or how water is applied, has some direct effect on the efficiency of irrigation water. Different methods have been attempted to conserve water and use it efficiently. Irrigation methods have different application efficiencies, e.g., efficiency of sprinkler is 60% -80%, furrow 40% -60% and drip 75% - 90% (Knox et al. 2012). Compared to other application methods, furrow irrigation has a lower initial cost, whereas drip irrigation requires skilled labor, high maintenance costs, and is relatively high - priced despite having the highest efficiency. Farmers typically over-irrigate when irrigation water supply is not a concern, but they switch to increasing irrigation intervals when water supply is limited, which causes crop stress and leads to low- and poor-quality yields (Goldhamer & Fereres, 2004).

2.8 Application of WaPOR Database in Irrigation

For both present and future generations, achieving food security while utilizing water resources responsibly will be a significant task. Population growth, economic expansion, and climatic change all result in higher demand for the available resources. (Abiyu, G.A., 2021). Since agriculture consumes a large amount of water, it is important to carefully monitor the agricultural use of water and look for ways to improve it. The most crucial way to deal with the rising water demand in agriculture is frequently to increase water productivity. Remote sensing techniques can help identify water productivity gaps and evaluate suitable strategies to address these gaps through systematic monitoring of water productivity. (FAO, 2017). Access to 10 years of continuous observations over Africa and the Middle East is available through the FAO portal for monitoring water production through open access to remotely sensed derived data (WaPOR) (FAO 2020a). For Africa and the Near East from January 1, 2009, to the present, the WaPOR database is a comprehensive database that offers close to real-time data on biomass (for food production) and evapotranspiration (for water consumption). (FAO 2020a).

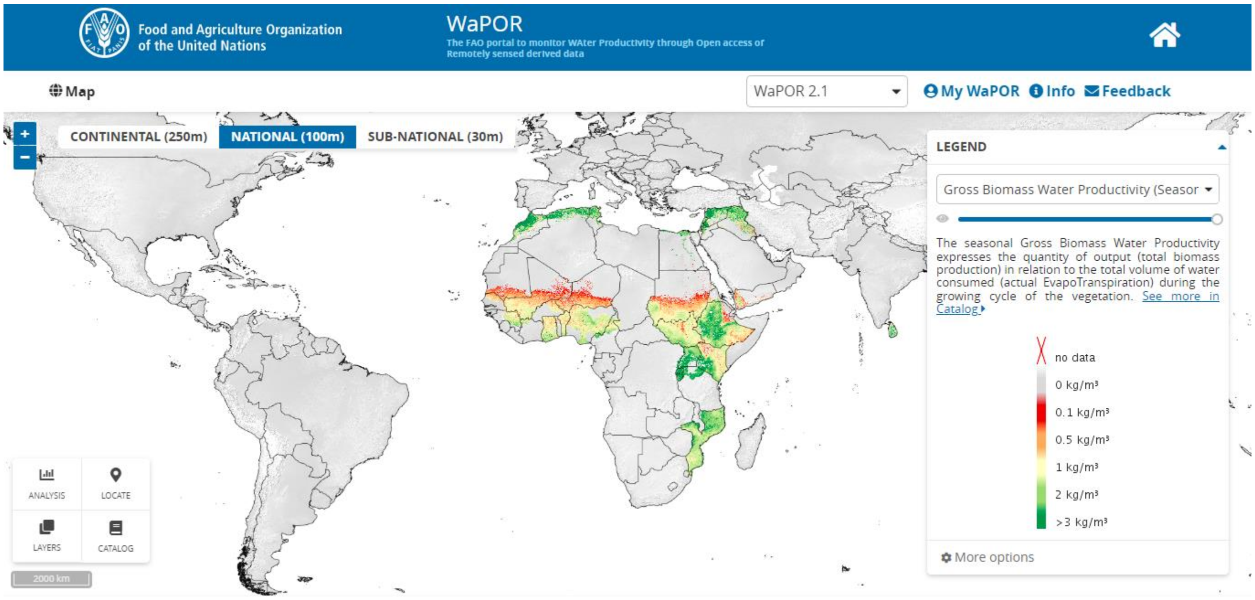
2.9 WaPOR Data Coverage

On April 20, 2017, WaPOR beta version was released, and version1 was released in Jun 2018, followed by WaPOR version2 in June 2019, which covers the entire Africa and Near East region. Extensive internal and external validation and quality assessment were used to improve each data version. Most of Africa and a considerable chunk of the Middle East (L1) are covered by the continental-level data (250mFor 21 different countries and four river basins (L2), national-level data (100m) are accessible. Eight irrigation zones are located on the third level (30 m) (FAO, 2020a). The method used for building the database at Level 3 (30 m), as given available through the WaPOR database version-2, which will be launched in June 2019 by the WaPOR consortium partners (http://www.fao.org/in-action/remote-sensing-for-water-productivity/en/n).



The annual Gross Biomass Water Productivity expresses the quantity of output (total biomass production) in relation to the total volume of water consumed in the year (actual evapotranspiration).

Figure 1 *WaPOR data coverage at continental level*



The seasonal Gross Biomass Water Productivity expresses the quantity of output (total biomass production) in relation to the total volume of water consumed (actual EvapoTranspiration) during the growing cycle of the vegetation. See more in Catalog

Figure 2 *Continental level for WaPOR database coverage*

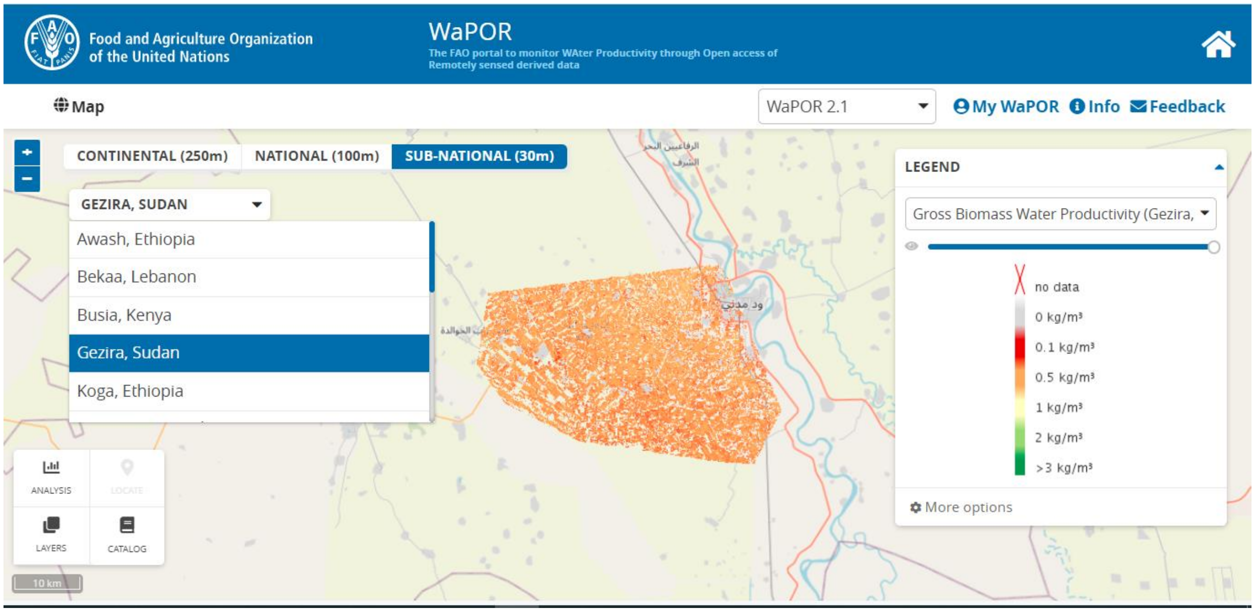


Figure 3 *WaPOR data coverage at third level (Sub-national)*

2.10 WaPOR data components per level

WaPOR data components that can be extracted from the WaPOR database are listed in (Table 1) below. which includes Water Productivity, Evaporation, Transpiration, Interception, Net Primary Productivity, Above Ground Biomass Production, and Land Cover Classifications at all three levels. Precipitation and Reference Evapotranspiration are the only Level 1 data components produced, and they have a lower spatial resolution than the other Level 1 data components. These two data elements are also produced every day. While HI is only available at Level 3, phenology is available at Levels 2 and 3. This allows for the computation of agricultural yield. (FAO 2019).

Table 1 *A summary of the WaPOR data components, per Level, with defined temporal and spatial resolutions.*

Data components	**Level^1** (~250m)	**Level^2** (~100m)	**Level^3** (~30m)	**Remarks**
Water Productivity (WP)	Annual^2	Dekadal^3/ Seasonal^4	Dekadal/ Seasonal	Level specific calculations
Evaporation (E)	Dekadal/ Annual	Dekadal/ Annual	Dekadal/ Annual	
Transpiration (T)	Dekadal/ Annual	Dekadal/ Annual	Dekadal/ Annual	
Interception (I)	Dekadal/ Annual	Dekadal/ Annual	Dekadal/ Annual	
Actual evapotranspiration and interception (ETIa)	Dekadal/ Annual	Dekadal/ Annual	Dekadal/ Annual	
Net primary production (NPP)	Dekadal	Dekadal	Dekadal	
Total biomass production (TBP)	Annual	Seasonal	Seasonal	
Phenology		Seasonal	Seasonal	
Harvest Index (HI)			Seasonal	
Reference Evapotranspiration (RET)	Daily/ Dekadal/ Annual			Different resolution: 20km
Precipitation	Daily/ Dekadal/ Annual			Different resolution: 5km
Land cover classification	Annual	Annual	Dekadal	Level specific classes

Source :-(FAO, 2020)

1- Level ^{1}: Continental, level^{2}: country/river basin, level ^{3}: Irrigation scheme/sub-basin.

2-Annual as standard product, with the possibility of calculating on user-defined intervals.

3-Dekadal is a term used to describe a time frame of about 10 days. It divides the month into three sections, with the first and second dekads each having ten days, and the final dekad having between eight and eleven days.

4-Seasonal is referring to the growing season. The length and number of growing seasons can vary, with a maximum of two each year.

2.11 Relationship Between WaPOR Data Components

The link between the data components is depicted in Figure 2.4 below. The gray boxes stand for intermediary data components that convert outside data into standardized input. Data components with green outlines are exclusively derivations of other data components. Data components that need outside data sources that aren't depicted in the flow chart are represented by boxes with orange outlines. WaPOR-distributed data variables are shown by blue boxes. (FAO 2020)

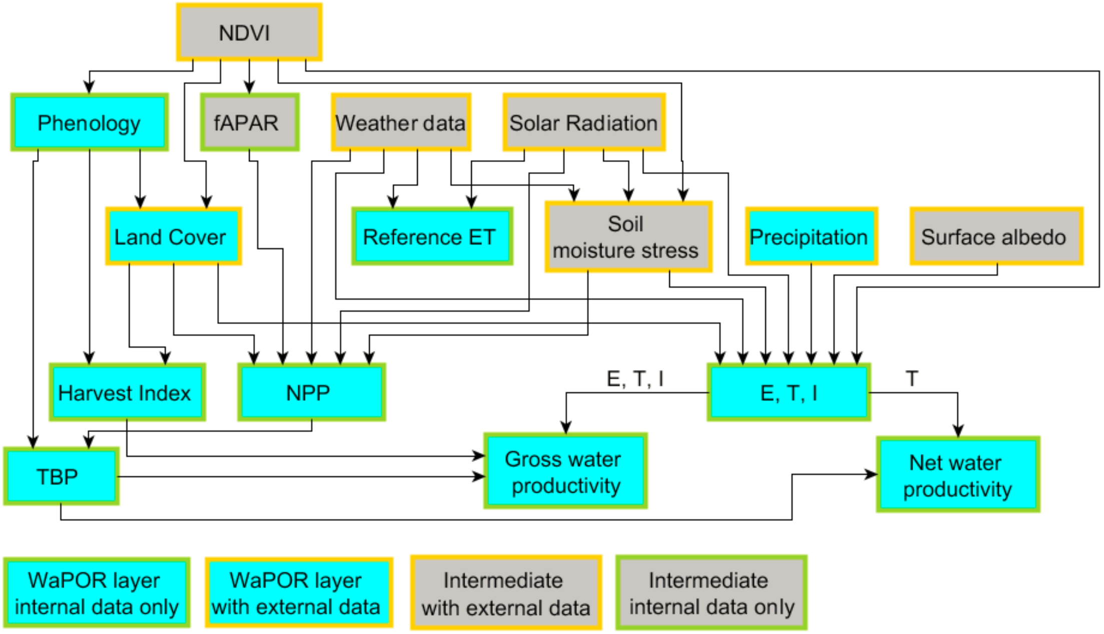


Figure 4 *Data component flow chart. Source: (FAO 2020)*

2.12 Crop Models

Crop models have been generated over the last few decades for various purposes, such as analyzing yield gaps, decision guidance, and reducing time-consuming and expensive field experiments (Holzworth, et al. 2015). Also Crop models are well-suited to conduct integrated evaluations including interactions between management, environment, and genotype.

(Boonwichai, S., et al 2018). Crop models, in general, are based on the concept of crop physiological ecology (Graves, et al. 2002). This includes the dynamic in terms of application, mechanism, and comprehensiveness, which may be used to model the impact of soil, weather, genetics and management on crop growth and development (Montesino-San Martín, et al. 2014). These processes are represented in the models as algorithms, which express the relationship between plant processes such as partitioning, biomass growth, respiration, plant water uptake, and photosynthesis, and environmental variables such as daily temperature, photoperiod, or soil water availability (Boote, K.J., et al 2018). There are several crop models in use across the world. For simulating crop growth, each model has a unique structure, technique, inputs, and algorithms (Todorovic et al. 2009). The following section will provide a review of the AquaCrop model, used in this study.

2.13 AquaCrop

The AquaCrop model is defined by (Steduto et al. 2009) as "canopy-level and engineering type of model, mainly focusing on simulating the attainable crop biomass and harvestable yield in response to the water available". The model was developed to represent how plant crops respond to water in terms of yield, and it is especially well adapted to situations where water is a major production-limiting aspect. Accuracy, simplicity of use, and durability are all matched by AquaCrop. For AquaCrop to simulate yield production, water is the main driving factor. It has long been known that one of the main variables reducing crop growth is water, which is crucial for crop production (S Fahad, et al. 2017). Crops utilize water to move nutrients, sugar, and hormones around the plant. Water is also vital to the chemical process of photosynthesis (Mansour, H.A., et al 2020). Water-limiting factors will cause lower yields at the end of the season, so it is an important factor for crop modelling. The main concepts of connecting the soil-crop-atmosphere continuum in AquaCrop are illustrated in (Fig 5).

Like other models, AquaCrop includes more than simply the continuum of soil, plants, and atmosphere. It consists of three primary components: the soil's water balance, the plant's growth, development, and yield processes, as well as the climate's temperature, precipitation, evaporative requirement, and carbon dioxide concentration. Additionally, different management factors (such as irrigation, fertilization, etc.) will influence crop development, soil water balance, and ultimately yield. Weeds, pests, and diseases are not included (Steduto, et al 2009). Figure 5 shows the interaction of several variables used by AquaCrop to simulate yield output. For agricultural yield modeling, Climate data, crop characteristics, management (irrigation and field), soil (soil qualities and groundwater), and simulation time are each used as separate inputs to the model.

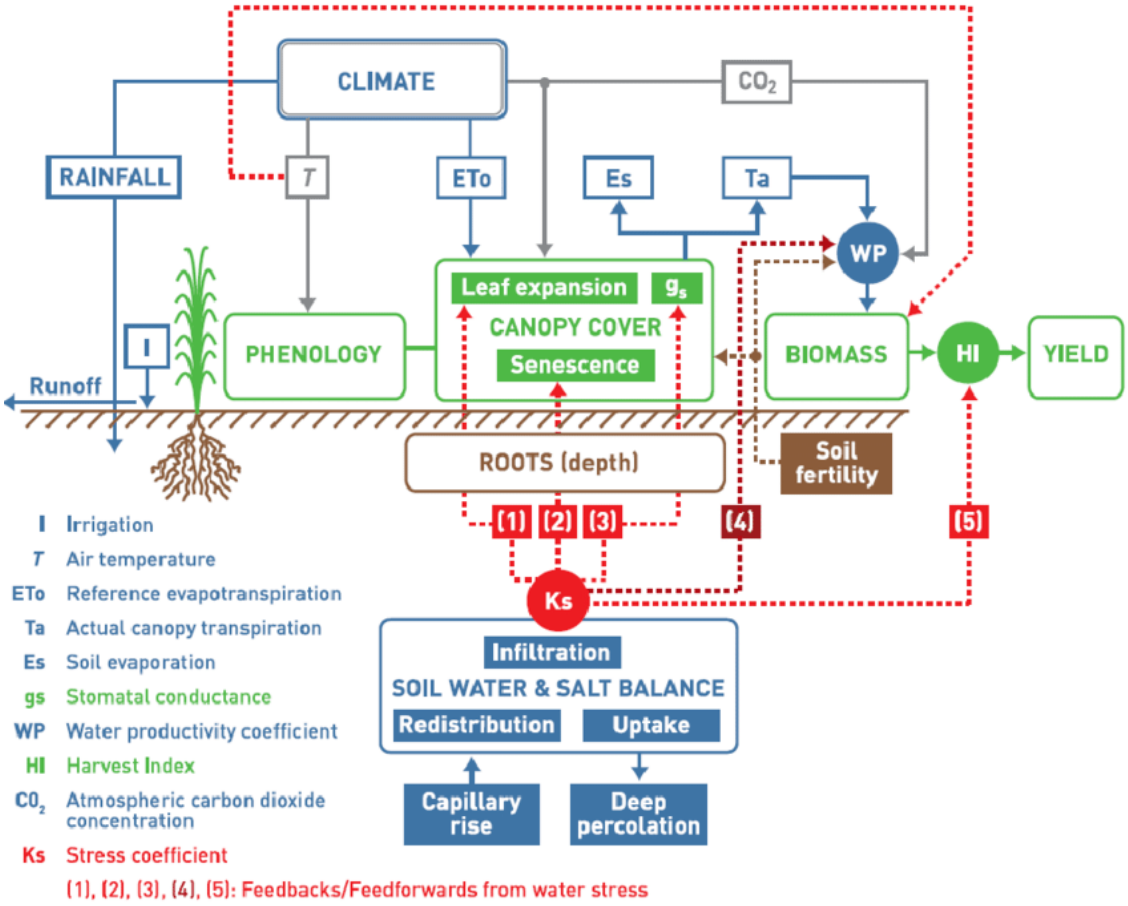


***Figure 5** AquaCrop flowchart showing the main components of the soil-plant-atmosphere continuum (Steduto et al. 2009).*

The AquaCrop model's yield response to water is based on equation (Eq. 2) as a starting point. By separating evapotranspiration into crop transpiration and soil evaporation, AquaCrop builds on this approach (Eq. 3) and generates a final yield as a function of crop biomass (Eq. 4). This division makes it possible to separate the impacts of soil evaporation and non-productive water consumption to more accurately model crop growth. For a particular set of climatic conditions, the water productivity (WP, biomass produced per unit of cumulative transpiration) is considered as a conservative parameter and constant. (Steduto et al. 2009).

$$\frac{\mathbf{(Yx - Ya)}}{\mathbf{Yx}} = \mathbf{Ky(} \frac{\mathbf{(ETx - ETa)}}{\mathbf{ETx}} \text{ …………… Equation 1}$$

where Yx and Ya represent maximum and actual yield, ETx and ETa represent maximum and actual evapotranspiration, and Ky represents the proportionality factor between relative yield loss and relative evapotranspiration reduction..

$$B=WP* \Sigma Tr \qquad \textit{Equation 2}$$

where WP refers to water production (biomass per unit of cumulative transpiration) and Tr stands for crop transpiration.

In order to predict future climatic conditions and be flexible to a variety of places, the WP factor is based on atmospheric evaporative demand and CO2 concentration. Equation [2.4] explains how to calculate the normalized WP using changes in annual CO2 concentrations. The WP response was thus addressed by including a crop sink strength parameter, which led to a better yield (Vanuytrecht, Eline, Dirk Raes, and Patrick Willems, 2014). However, there are still a lot of unknowns, and more research is required to understand how crops will behave as CO2 levels rise.

$$\text{WP} = \left(\frac{B}{\Sigma\left(\frac{Tr}{ET0}\right)} \right) Co2 \qquad \textit{Equation 1}$$

where ETo represents the atmospheric evaporative demand, and CO2 is the mean annual CO2 concentration. The CO2 outside the bracket is the normalization concentration for that year.

Once the final biomass is calculated after harvest, the final yield output is a function of the final biomass (B) and the Harvest Index (HI). HI is the proportion of harvested biomass to total aboveground biomass (Unkovich et al., 2010).

2.13.1 Evaluation of AquaCrop

According to studies (Araya et al., 2010; Andarzian et al., 2011; Stricevic et al., 2011; Hamidreza, S. et al., 2011; Abedinpour et al., 2012; A Mkhabela and Bullock, 2012; Iqbal et al., 2014), crop yields were simulated using the AquaCrop model, and the results were reasonable. For simulating agricultural yields under full irrigation conditions in Serbia (Stricevic et al. 2011) and India (Abedinpour et al. 2012), AquaCrop has generated remarkably accurate results. However, both studies discovered that AquaCrop's biggest mistake is trying to replicate crops that are fed by rain, especially during a rainy year. Several investigations, on the other hand, revealed that the

AquaCrop model overestimated water usage and production for certain crops exposed to severe water stress in various climate settings (ELSHEIKH, E., and SCHULTZ, B.,). Cotton water productivity was overstated in simulated values rather than measured ones, according to the model.

2.13.2 Soil-Crop-Atmosphere continuum:

Crop models have evolved to the point where they can be utilized for various purposes, as they simulate how crops react dynamically to their surroundings, including the techniques that modify them. Annual crops, with their one-year life cycle from seedling to harvest, offer an advantage for simulation purposes. (Jeuffroy, M.H. et al. 2014). This feature allows for multiple validations of crop developmental stages. Location is critical, as local climates and soils play a crucial role in determining crop growth, as emphasized by (Bechini, L., et al. 2006). (Ordoñez, et al. 2009). Water transport across the soil-crop-atmosphere continuum is a crucial function of this integrated system. A modification in any element of the system dynamically affects the entire system, influencing crop growth and yield (Bwalya 2013)

2.13.3 Evaporation, Transpiration, and Interception

Evapotranspiration is the sum of transpiration from the canopy (T), interception (I), and soil evaporation (E). It is referred to as "interception" when rains are captured by plant leaves and directly evaporate off their surface. Evaporation, transpiration, and interception (soil moisture content) are all influenced by the weather (wind speed, radiation, and air temperature) and the state of the soil. The total of all three variables, or Actual Evapotranspiration and Interception (ETIa), can be used to determine how much water is used for agriculture. Combining biomass production or yield with agricultural water productivity can be determined (Blatchford et al., 2020The ETLook model provided by (Bastiaanssen et al. 2012) provides a framework for the method used to calculate E and T. It employs the Penman-Monteith (P-M) equation, which has been modified for input data from remote sensing.

2.13.4 Moisture Content of Yield (MC)

One of the most crucial factors influencing evapotranspiration and biomass production is the availability of soil moisture. The growth of biomass can be severely hampered by dry soil since less vegetation will transpire. Through evaporation from the topsoil and transpiration from the vegetation cover, soil moisture is immediately transferred to the atmosphere. Grain moisture will eventually reach an equilibrium with the environment for a given air temperature and RH. This grain characteristic is known as equilibrium moisture content (EMC). The grain MC level is thus affected by the temperature and RH properties of the drying air. If the same RH (75%) and temperature (75°F) are forced through soybean, rice, and wheat for an extended period of time, these grains will eventually reach EMCs of 15.2%, 15.2%, and 14.6%, respectively (Bautista & Rice 2014). The majority of seed crops are harvested when the seed reaches "harvest maturity." Most grain crops have a moisture content of 12-14%; oily seeds, such as soybean, groundnut, or cotton, have a moisture content of 8-10%. (Adam's 2005) extensive measurements of soil moisture of bare soil in June, July, August, and November, he found that in general an average value of 800 m^3 fed-1 for the first water during June and up to 10 July. Between 11to20 July 600 m^3 fed-1 is to be used. From 21 July to the end of August the first water is only 400 m^3 fed-1 after the rains,in November, the first water is taken as 600 m^3 fed-1.

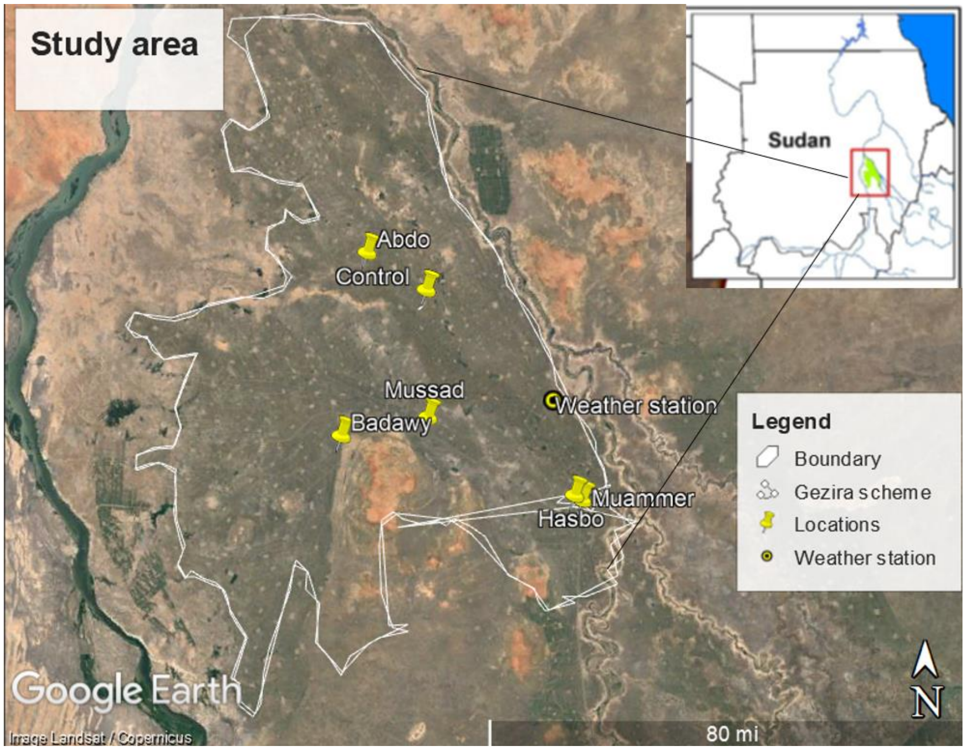
2.13.5 Harvest Index (HI)

The harvest index is utilized to differentiate between biomass production that can be harvested and that which cannot. By using the harvest index, crop yield, and water productivity can be computed. This index serves to evaluate the effectiveness of a particular plant variety by indicating how much of the biomass produced contributes to the harvestable portion of a crop. It is determined by dividing the weight of dry grains by the total dry matter. The harvest index is available on a seasonal basis and indicates the index at the conclusion of the growing season. It starts at 0 when all above-ground biomass production is harvested and gradually increases to a theoretical maximum of 1. For Level 3 crops, including wheat, maize, potatoes, fruit trees, olives, grapes, rice, and sugarcane, the harvest index is provided. According to the (FAO's AquaCrop model 2017), the harvest index can only be correctly interpreted when land cover and crop phenology information is available. The former links the harvest index to a specific crop, while the latter is associated with a specific growing season. For Level 3 crops, rice, wheat, maize, and sugarcane have typical reference harvest index values of 0.43, 0.48, 0.48, and 0.35, respectively (FAO 2019).

3. Materials and Methods

3.1 Site Description:

The research topic focuses on the Gezira irrigation scheme in East Africa's Sudan, which comprises a vast expanse of irrigated land measuring 0.9 million hectares. This irrigation scheme is unique in that it is one of the world's largest under single management, not just in Sudan but also globally. The Gezira Irrigation Scheme is situated in the region between latitudes 1330N and 1530N and longitudes 3215E and 3345E, with an elevation of 405 meters above sea level. It is located south of Khartoum, Sudan's capital, in a flat area between the Blue and White Niles, as illustrated in (figure 5). Water from the blue Nile is stored by the Sennar Dam and supplied to the field through an extensive network of canals that includes two main canals (194 km), major canals (2300 km), minor canals (8000 km) that feed tertiary canals (locally known as Abu XX) that delivers irrigation water to the field (Abu VI) (Goelnitz, A. and Al-Saidi, M. 2020). The environment of Gezira is classified as very hot and dry for wheat production. The whole Gezira scheme lies within the dry zone, which has a short rainy season (July-September) and an average annual rainfall of 200 to 300 mm (Ahmed, B. M., et, al 2010). Monitoring and assessment of the activities based on field observations and interviews were done for each farmer in coordination and collaboration with the concerned stakeholders.



(Figure 5) *Location of the study area in Gezira Irrigation Scheme - Sudan*

From the above map, we have the sampling locations at Hosh section 2 sample, Mokashfi section 2 sample, Huda1 sample, and at Mansi 1 sample respectively. All locations share the same weather station Wad Medani weather station from where we have used the meteorological data for modeling the AquaCrop model.

3.2 Climate

Sudan's climate is sub-continental and tropical, with summer temperatures ranging from 30℃ to 40℃, and winter temperatures between 10℃ to 25℃. The country's climate varies from desert in the north to summer-rain in the center and semi-dry in the south. There are two distinct rainfall zones in Sudan, with annual rainfall ranging from 25 mm at the border with Egypt to 200 mm in the center of the country. In the north, rainfall is limited to two to three months, and occurs in isolated showers of varying duration and location. In the south, rainfall is concentrated from July to October, with annual rainfall reaching up to 700 mm and averaging between 300 to 500 mm. Rainfed agriculture is mainly practiced in this region, but productivity varies significantly due to the high variability in rainfall from year to year (FAO, 2015). The climate in the Gezira Scheme ranges from arid to semi-arid. Also, the maximum temperature varies from 34 to 36 degrees. Minimum temperatures range from 14 degrees Celsius in January to 42 degrees Celsius in April and May, with maximum temperatures ranging from 42 degrees Celsius in April and May.

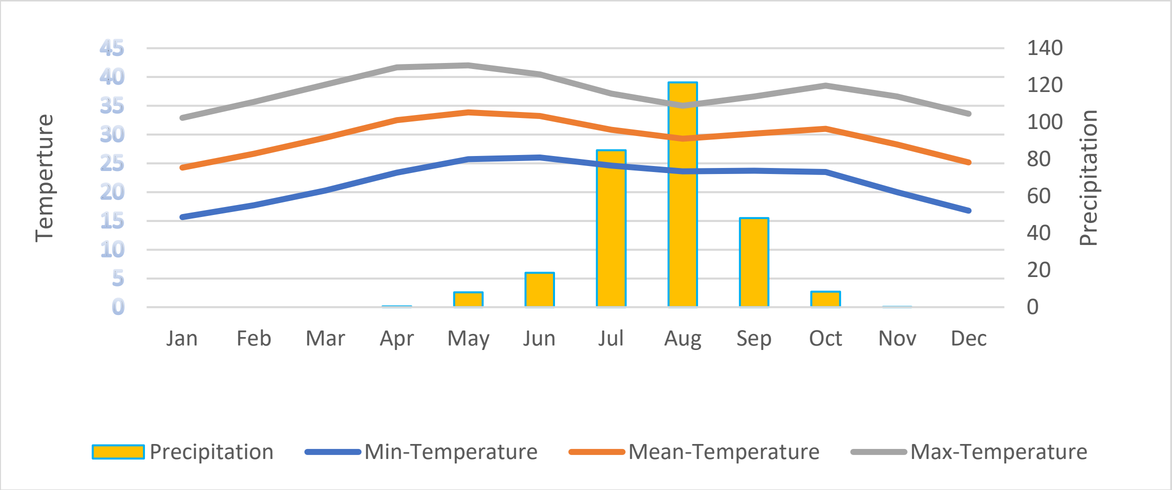


Figure 6 *Monthly climatology of T- Min, T-mean, T-max and Precipitation Gezira, Sudan.*

3.3 Description AquaCrop Model

The need for modeling of water use efficiency set up the need for software model which FAO developed the AquaCrop model. A crop growth model, to address food security and evaluate how the environment and management affect crop productivity (www.fao.org/aquacrop/en/). This water-driven model was created to simulate the formation of the green canopy and roots in a controlled setting (Steduto et al., 2009). AquaCrop simulates daily water balances in the root zones and crop growth using a limited number of input needs (rainfall, reference evapotranspiration (ETo), air temperature, and CO2 concentration). AquaCrop separates evapotranspiration into soil evaporation (E) and crop transpiration (C) to determine crop biomass and yield output (T). This division ensures that the estimates for yield and biomass production do not account for non-productive (soil evaporation) water consumption.

3.3.1 Data collection

I. Field Data Input

The AquaCrop model requires input data on the climate, crops, soil, and field management parameters to accurately predict outputs. The closest weather station, Wad-Madani meteorological station, which is located at latitude 14°21'22.62"N, longitude 33°28'52.50"E, and elevation of 681 m.a.s,l, provided the climatic data used as input in the model. The weather data consisted of data time series on daily maximum and minimum temperature, daily maximum and minimum relative humidity, monthly solar radiation, and monthly wind speed, including daily precipitation data collected from the same station. Using the P-M equation, the daily ET0 was determined from the climatic data. Daily precipitation data was also collected from the closest rain station, in Wad-Madani meteorological station.

In 2019-2020, while visiting the field, data was collected for the application of the AquaCrop model. This data included information on weather, crops, soil, irrigation, and field management. Six plots were chosen for analysis and their locations were recorded using a handheld GPS device. Using Google Earth, the shape files of each plot were created. A summary of the data collected for our research is provided below.

II. Crop data

The crop module of Aqua Crop comprises five significant elements, namely phenology, canopy development, root depth, biomass production, and harvestable yield. These components can be assessed periodically in the field throughout the crop's growth season. Nevertheless, due to time constraints and the lengthy growth cycle of the crop being studied, the crop data regarding the start of the season (planting date, SOS), end of the season (harvesting date, EOS), planting density, specific crop variety (wheat), and yield production were obtained by interviewing farmers for this study. Information was collected about general practices related to crop management such as the initial state of the field, types of crop varieties, application of fertilizers and pesticides, as well as seeding and harvesting methods. In (Table 2) the mean value from the conducted field survey (Appendix B) answered by the farmers and irrigation managers can be seen. The field survey was conducted during the (TAAT) project period and the data was exclusively used as input for the AquaCrop model. Technologies for African Agricultural Transformation (TAAT) it is a project between the (ARC) and the (IWWI) under the title WEC in the Gezira scheme.

Table 2 *Main input parameters used for the calibration and the validation of the AquaCrop model for table dates during 2020 and 2021 growing seasons:*

Phenology	
Transplanting	Not occurring
Sowing date	(12 to 24) of November
Flowering start data	Middle of January
Full canopy cover	February
Harvest date	End of march
Irrigation management	
Irrigation type	Basin/ furrow
Irrigation frequency	Every 15 days
Irrigation depth	75 mm per irrigation
Height of soil bunds [m]	0.43
Fertilizer management	
Fertilizer	Inorganic fertilizers (urea, NPK, DAP)
Frequency of application	Beginning + development stage
Application amount [kg/ha]	60/fed……convert
General recommendations of	2N + NPK
application for fertilizers [kg/ha]	Doe/fed
Field control	
Weed control	Chemicals
Tillage	Mechanical (with tractor)
Frequent pest/disease	Insects
Frequent soil problem	No problem/sedimentation
Crop rotation	Occurring

III. Weather data

The climate module of AquaCrop explains the atmospheric conditions necessary for crop growth and uses various meteorological factors as inputs. Daily weather data including rainfall, temperature, humidity, sunshine hours, and wind speed were obtained from a weather station for the years 2010-2020. The reference evapotranspiration was calculated using an ETo calculator program integrated into AquaCrop and based on the FAO Penman Monteith equation (Eq.2) described by (Allen et al. 1998). The method for estimating missing climatic parameters is also provided by the program. The model also requires annual CO2 concentrations in the atmosphere. In this study, the default CO2 concentration of study area provided by the AquaCrop model was used.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Equation 2}$$

Where: T mean daily air temperature at 2 m height [°C], u2 wind speed at 2 m height [m s^{-1}], ETo reference evapotranspiration [mm day^{-1}], Rn net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}], g psychrometric constant [kPa °C^{-1}], es saturation vapour pressure [kPa], ea actual vapour pressure [kPa], es - ea saturation vapour pressure deficit [kPa], D slope vapour pressure curve [kPa °C^{-1}].

IV. Soil data

The study area had Vertosols as its soil type, which expands when wet and contracts when dry. At a depth of 25 cm from the surface, the clay content on average was approximately 58%. To use the AquaCrop model in the study, it was necessary to know the number of soil horizons present and the specific physical properties of each horizon, such as the water content at field capacity, saturation, permanent wilting point, and saturated hydraulic conductivity. To determine these characteristics, soil data were obtained from the Sudan soil information system,. For AquaCrop modeling purposes, a single soil horizon was assumed.

3.3.2 Irrigation scheduling

A wide-ranging system of canals and drains is utilized to distribute water across the field. Depending on the slope of the farm furrows with a width of 80 to145cm and varying lengths of 32m, 48m, and 64m are utilized. The timing of irrigation is adjusted based on the soil type and growth stage of the plants, as explained in (Annex 2). Irrigation periods are highly dependent on the stages of crop growth, soil quality and the prevailing temperatures during the season. Therefore, the farmer used to monitor his field on an almost daily basis to know the actual need for irrigation without being restricted to the periods mentioned below. The crop is irrigated every 12 - 14 days before the expulsion of the spikes, and every 10 days after the emergence of the spikes. As for the high temperatures, the irrigations increase (light irrigations with frequent periods). In general, the wheat crop needs 8-9 irrigation during the season. The negative effects of high temperatures can be mitigated by light irrigation at frequent intervals (every 10 days) because evaporation from the leaves leads to a decrease in the vegetation cover temperature.

3.4 Field management practices

This description outlines the management practice that farmers employ when cultivating cereal crops, specifically wheat. The information was gathered during a field visit and discussions with agricultural operation managers and farmers. The practices that are most closely tied to the success of crop production include managing the field, applying irrigation, fertilizers, pesticides, and weed control. To achieve a profitable and sustainable production of the wheat crop under conditions of heat stress in Sudan, it is always recommended to follow the Integrated Crop Management (ICM) system. Integrated Crop Management considers the entire value chain including proper crop rotation, appropriate crop variety, appropriate and timely application of various agricultural practices (such as soil and water management, crop nutrition, pest management, etc), and socio-economic factors. and environmental factors that can mitigate the negative impact of heat stress on crop yield and quality for end users.

Nitrogen fertilizer (urea) at a rate of 33.6 kg/ha for wheat and 7.5 kg/ha phosphorous oxide and {9.6 kg of tri-phosphorus (TSP or DAP) or 13.65 kg of mono ammonium phosphate (MAP) is applied for providing nutrients for the plant to providing a higher yield per unit area. Approved herbicides were used according to the recommended dose, such as: 2-4-D compounds to control broadleaf weeds, and there are many of them. The dose of the pesticide varies according to the concentration and ranges between 370 cc/ha for pesticides with a concentration of 60% and 240 cc/ha for pesticides with a concentration of 72%. Pesticides to control hydra, oats, and other grassy weeds, such as Puma, Topic, Traxos, Terdoc, Top Noor, and others. The dose for most of these pesticides is 176 cc/ha.

When considering field management practices that are assumed to be optimal, it is important to keep in mind that even though the management practices currently used in the estate are described as good or best, it is difficult to determine if they are being uniformly and efficiently applied throughout the plantation field. Crop production data from 6 plots in the Gezira scheme shows that the average seasonal production of wheat crop varies between fields with a coefficient of variation of 20%. Irrigation scheduling was a major challenge in this study when developing the model input. Although the information collected on irrigation and other management practices in the field is standard, it is not clear how efficiently the estate is managing the plantation. Therefore, the irrigation scheduling criteria were established based on these factors.

3.5 WaPOR data components: extraction, analysis, and evaluation:

Since 2009, the WaPOR portal has been providing information on important land and water usage parameters for agricultural production in Africa and the Near East (as shown in Figure 7). This data can be utilized to determine agricultural land and water productivity.

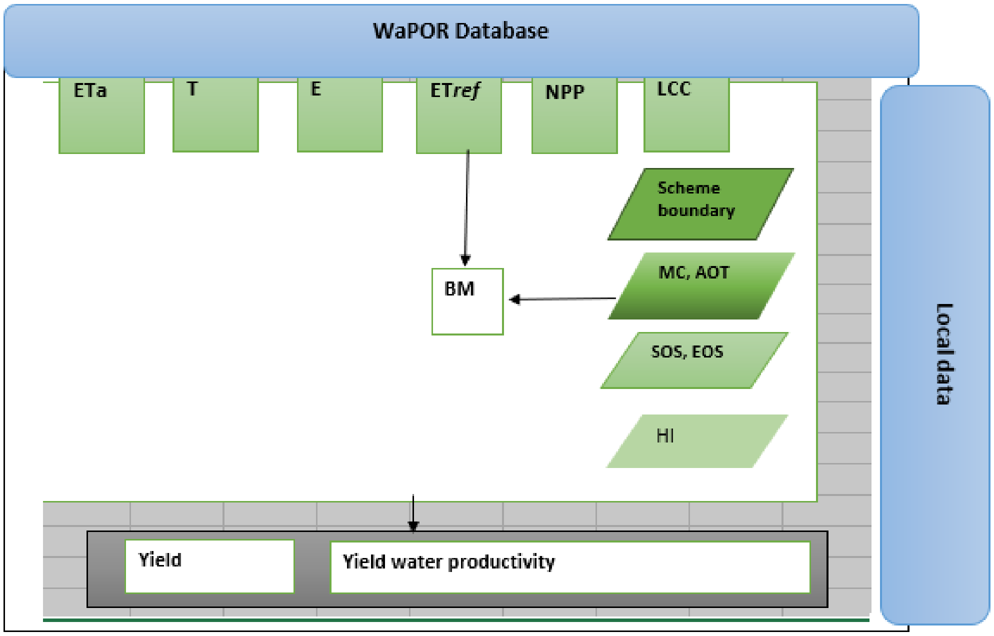


Figure 7 WaPOR database process methodology

The WaPOR platform provides information on several parameters related to land and water usage for agricultural production, including actual evapotranspiration and interception (AEa), transpiration (T), precipitation (P), reference evapotranspiration (ETref), land cover classification

(LCC), and net primary production (NPP). Table 3 displays the resolution of satellite images used to capture data for these parameters. The temporal resolution for the data components is decadel. The duration of one month can be divided into three parts, namely the first two parts consisting of 10 days each, and the third part containing between 8 to 11 days. The process of obtaining each element of the data is explained in the WaPOR database methodology. (FAO, 2017).

Table 3 *Overview of WaPOR data components used for this study:*

level	**Data component**	**Temporal Resolution**	**Temporal extent**	**Spatial resolution**	**Coordinate system**	**Conversion Factor**	**The unit**
L3	NPP	Dekad	2019-2020	30 m	WGS 84	multiplied by 0.001	gC/m2/day
L3	AET	Dekad	2019-2020	30 m	WGS 84	multiplied by 0.1	mm/day
L3	T frac	Dekad	2019-2020	30 m	WGS 84	None	%

This study only gathered field data during the 2019-2020 season, so the WaPOR was utilized to conduct seasonal analysis for the same year. To achieve this, Equation 4 was used to aggregate the above-mentioned parameters obtained from WaPOR and estimate seasonal evapotranspiration):

To determine Crop Water Productivity (CWP), monthly Net Primary Production (NPP) data from WaPOR database was used and then combined in QGIS software to obtain seasonal values. The data was further converted to Total Biomass Production (TBP) using (Equation 3.2), and then Yield was calculated using (Equation 4). Additionally, monthly Evapotranspiration (ETIa) values were also obtained from WaPOR database and aggregated into seasonal values using QGIS. Finally, CWP was obtained by dividing Yield by ETIa, as shown in (Equation 6).

$$TBP = AOT \times LUE \times \frac{NPP \times 22.222}{1 - MCbiomass} \quad \text{E.q. (4)}$$

Where TBP is the total biomass production [kgDM/ha], AOT is above ground over total biomass ratio, LUE is the light use efficiency correction factor, NPP is the net primary production [gC/m2], 22.222 is a conversion factor for dry matter (DM) converting gC/m2 to kgDM/ha (FAO 2020b) and MCbiomass is the moisture content in fresh biomass. Assuming paddy is the dominant crop, AOT is set to 0.75, LUE is set to 1 and MCbiomass is set to 0.15 (FAO n.d.d).

$$Yield = TBP \times HI \qquad \text{E.q. (5)}$$

Where yield is dry matter grain yield [kgDM/ha], HI is the harvest index. Assuming wheat is the main crop cultivated in the area, the HI value is set to 0.48 (details can be seen in section 2.8)

$$CWP = \frac{Yeild}{ETIa} \qquad Eq\ (6)$$

> *Where CWP is the crop water productivity [kgDM/m^3], yield is dry matter grain yield [kgDM/ha] and ETIa is the actual evapotranspiration and interception converted from [mm] to volume of water per unit area [m^3/ha].*

The AquaCrop model provides simulations for time steps of daily, 10-day, and monthly. The model was conducted in this study using a 10-daily time step to match WaPOR's temporal resolution. It is important to ensure that the output for the simulations of transpiration, evaporation, actual evapotranspiration, and biomass is a 10-day total. Data components in WaPOR are provided as the daily average for that dekad. By dividing the 10-day totals of T, E, and AET by the number of days in that dekad, the totals are then converted to the average. The model output may be directly compared to the biomass of WaPOR data converted to dekad. The seasonal biomass can be calculated by cumulative of dekadal simulated biomass overgrowth period of the crop. Statistical analysis and graphical methodologies were used to compare WaPOR extracted values with AquaCrop model output and in-situ data. The details of the analysis and evaluation are described in the next chapter.

3.6 Methodological framework

This study assessed RS level 3 data (spatial resolution of 30 m) from the WaPOR portal to estimate agricultural water use in the Gezira scheme in Sudan. Using web-portal, the decadal and monthly data were combined to create seasonal data. The AquaCrop model outputs (verified using primary field data collected) and historical yield data from the Gezira scheme were summarized and imported into AquaCrop model, modelling the crop growth of wheat fields. The AquaCrop results (where the field study was conducted) were compared with the WaPOR data. Moreover, using indicators collected from the WaPOR site, spatio-temporal variability in agricultural water usage was assessed using QGIS 3.28v (QGIS Development Team. 2020).

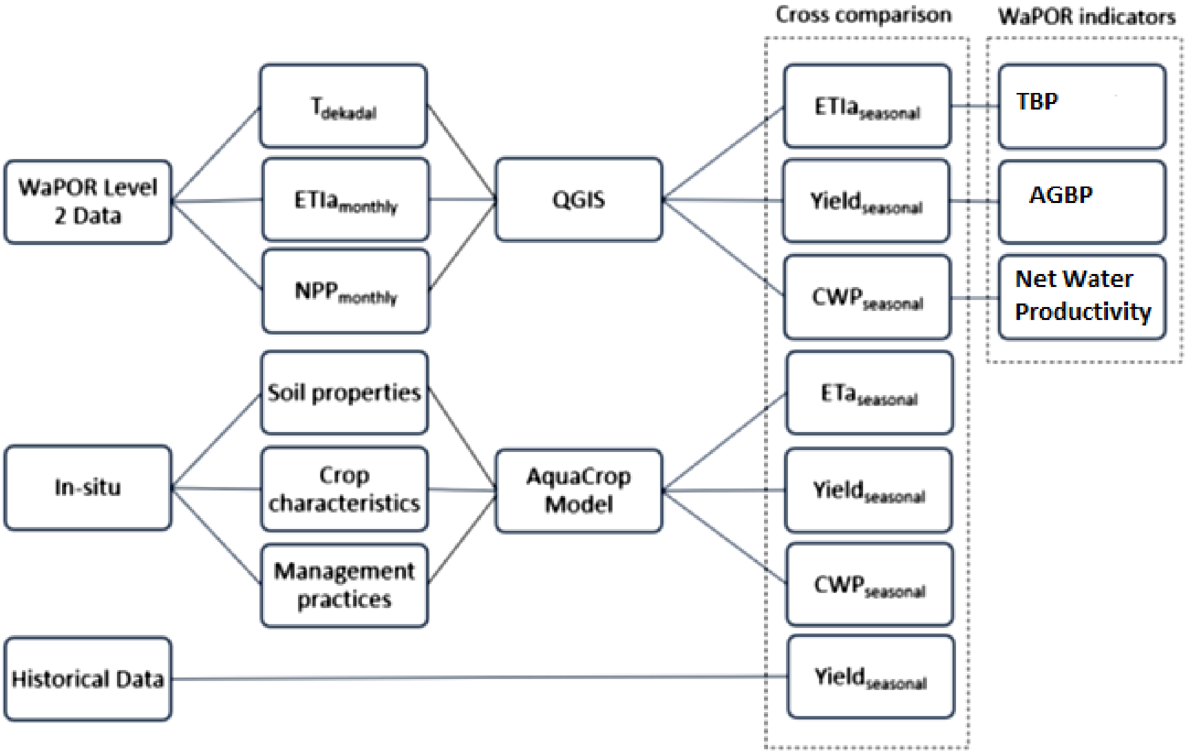


Figure 8 *Flowchart of the work process methodology (Widengren, V. 2022) Modified by (Omer. E)*

4. Results

4.1 Assessment of data collected:

Crop production is significantly impacted by the weather conditions of the surrounding environment, as it determines the available energy for evaporation. Therefore, when utilizing simulation models to assess crop production, it is crucial to consider the quality of weather data. The Gezira Metrological station was used to gather key meteorological parameters required for calculating ETo. However, the data point gap for wind speed due to the lack of records from surrounding stations. Nonetheless, the AquaCrop model can still estimate ETo even when solar radiation, wind speed, or air humidity data is missing by following the calculation procedures outlined in FAO Irrigation and Drainage paper Nr. 56.

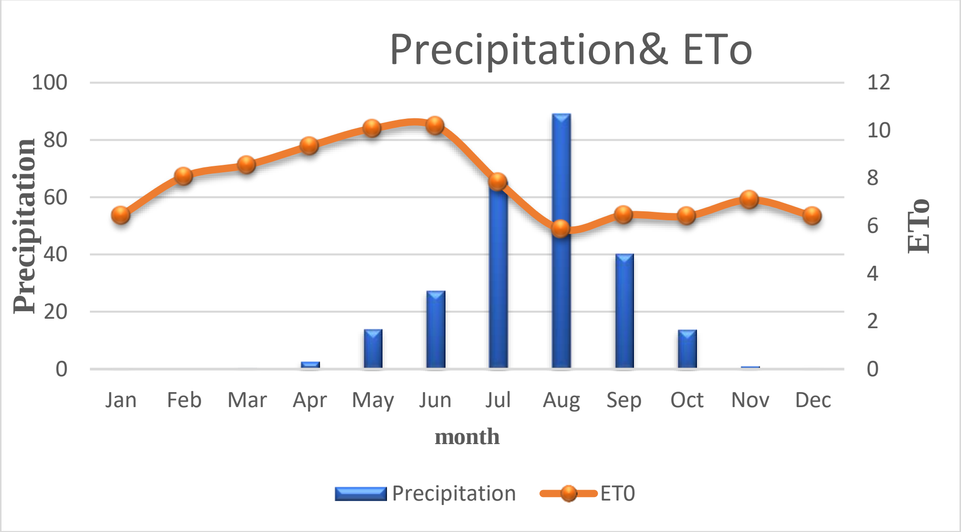


***Figure 9** : Average monthly precipitation and ETo of Gezira Scheme.*

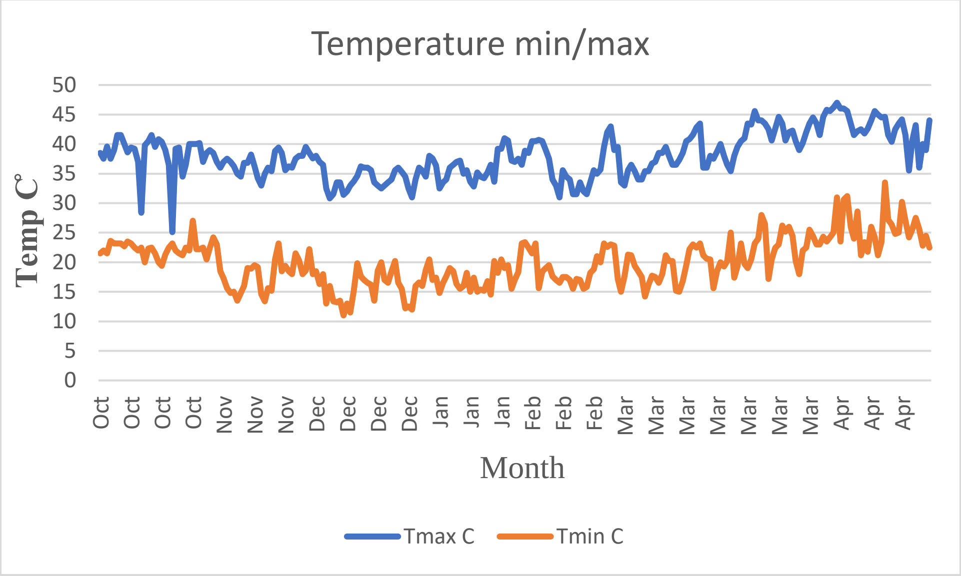


Figure 10. *Average daily temperature during season 2019/2020of weather station*

Wheat growing season (November–March) average daily maximum (TMAX) and minimum temperatures (TMIN) during the season 2019 - 2020 at the Wad Medani, meteorological station in Sudan. During the growing season the highest daily Tmax was above 40 °C and Tmin was above 26 °C from November to February. All records were higher than the thresholds (35 °C for hot days and 20 °C for hot nights).

4.2 Wheat Farms

The research area was analyzed for the season 2018/2019 and 2019/2020 wheat crop. During our field visits, we have seen similar cultivation patterns even in the surrounding fields. Crops were planted with extensive cultivation techniques and were applied fertilizers during the growth period on that year. All the selected wheat farms are in the same scheme (Figure - 5). The climate data used in the analysis were obtained from a single weather station, and all the farms under consideration cultivate the same variety of wheat (Imam). As a result, the crop's growth stages are consistent across all farms. Nonetheless, (Table 4) presents a comprehensive list of input parameters for the wheat fields, including planting and harvesting dates. Plant density was determined using sowing rate data from the field, expressed as kilograms of seed per hectare. The initial canopy cover (CCo) was estimated using the plant density information, while the rooting depth was set to 1 meter based on the FAO's recommended rooting depths[3].

Table 4 *Simulation input for wheat farms*

General information	**Farms**					
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Crop type	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
Variety	Imam	Imam	Imam	Imam	Imam	Imam
Root Depth (m)	0.6m	0.6m	0.6	0.6	0.6	0.6
Plant density (plants/ha)	350p/m	450p/m	380p/m	350p/m	300p/m	400p/m
Cropped Area (ha)	37.8 ha	38.4ha	34 ha	25ha	12.6ha	37.8 ha
CCo (%)	10%	15%	12%	10%	10%	15%
Max Canopy Cover (%)	90%	95%	90%	85%	75%	90%
Field Capacity (%)	50	54	59	45	53	45
Dry yield production (reported) (ton/ha)	4.6ton/ha	6 ton/ha	5.6 ton/ha	4 ton/ha	2.5 ton /ha	3.4 ton/ha
Planting date	12.11.2019	20.11.2019	22.11.2019	18.11.2019	12.11.2019	24.11.2019
Harvest date	29.3.2020	15.4.2020	12.4.2020	30.3.2020	29.3.2020	27.3.2020

4.2 Sensitivity analyses of AquaCrop Model

4.3 **Sensitivity analyses**:

Sensitivity analysis was used to examine how different parameters affected the results of the model. There are more than 40 parameters in AquaCrop's most recent version (version 6.1), which was employed for this investigation. In (figure 11, and figure12) the sensitivity analysis for the yield and the Eta AquaCrop model outputs are presented for the three selected parameters: field capacity (FC), reference harvest index (HI) and maximum effective rooting depth (rtx). Where a larger range for the min, mean and max value respectively indicates a higher sensitivity to that particular value, while a larger difference between the min, mean and max value indicates a higher sensitivity to changes in that parameter value. For the AquaCrop model yield output (figure 11), there was shown to be a variation in the range for each min, mean and max value, with lowest range being 3.5 kgDM/ha and highest being 6.5 kgDM/ha. There was also a difference between the values, lying between 4.0–6.0 kgDM/ha for the mean values. This indicates that there is a sensitivity for the yield output for the fc, hi and rtx input parameters.

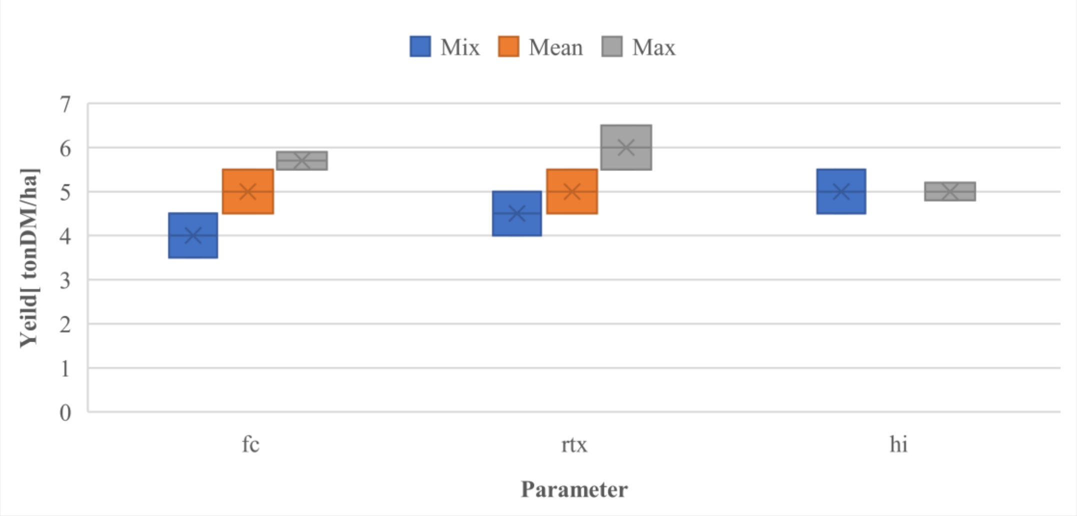


Figure 11; *The AquaCrop model SA with yield output for the minimum, mean and maximum value for the selected parameters (fc, hi and rtx), indicated with blue for the minimum value, orange for the mean value and grey for the maximum value.*

Rooting depth and biomass production have a positive relationship, as shown in (figure 12). The reason for the connection between crop transpiration and biomass production lies in the fact that water availability in the root zone greatly affects crop transpiration. When the roots of crops are able to extract more water due to an increase in root depth, this results in a higher rate of transpiration and ultimately leads to a greater accumulation of biomass. It is important to exercise caution when calibrating the rooting depth parameter, as a deeper root system may lead to increased water extraction and transpiration, ultimately affecting biomass accumulation, as noted by (Steduto et al 2009). It was found that the time to senescence had a greater impact on biomass production than the time to reach full canopy cover. As predicted, when crops experience a shorter period until they reach senescence, they will start to deteriorate and die earlier, leading to a decrease in biomass and yield compared to crops that take longer to reach senescence. On the other hand, the time it takes for crops to achieve maximum canopy cover has the opposite effect. The variation in the range for each min, mean, and max value for the AquaCrop model's ETa output (figure 12) was low, with the lowest range being 27 mm and the maximum range being 64 mm. This indicates that the value of each parameter has no effect on the ETa output. There is a variation in the values for the fc parameters min, mean, and max, with the mean values ranging between 413 and 471 mm. This indicates that the ETa output is sensitive to the fc input parameter. The ETa model result shows no sensitivity for the hi and rtx input parameters, which have the same mean value of 448 mm.

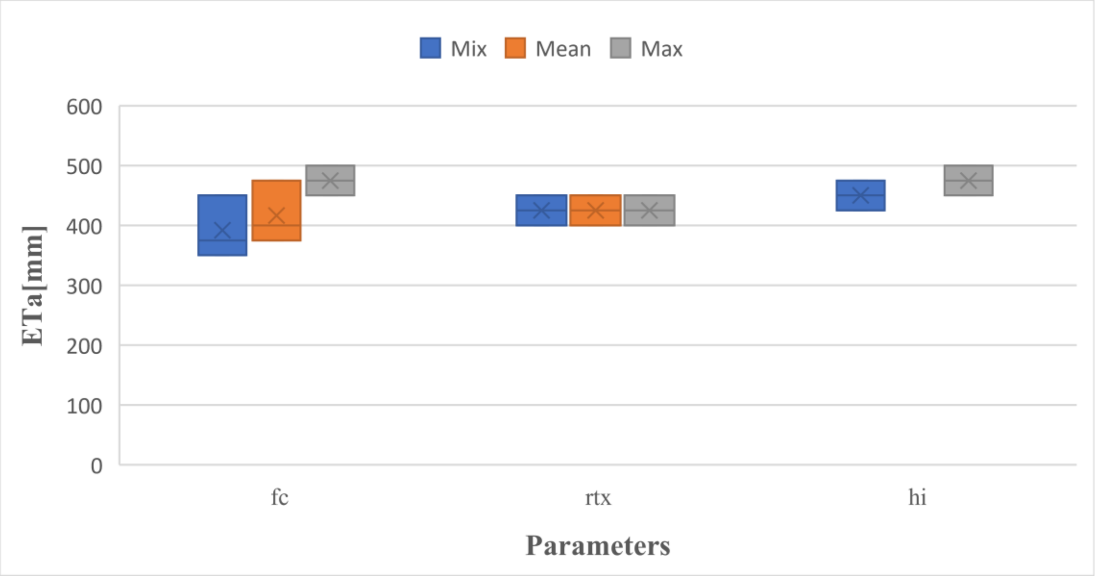


Figure 12; *The AquaCrop model SA with ETa output for the minimum, mean and maximum value for the selected parameters (fc, hi and rtx), indicated with blue for the minimum value, orange for the mean value and grey for the maximum value.*

4.3 Overall Evaluation of AquaCrop Results

Although the crop file was calibrated based on the data of the observation data, the model outputs were also compared with the real data of farmers in the region. The yield of the simulated crop in every single scenario was compared with the yield of wheat producers in the region. Wheat yields recorded by these farmers are 2.5, 3.1, 4, 4.6, 5.6, and 6 tons/ha respectively, in all selected plots area. The results of the simulations of all six farms are presented in Table 4-2. For all farms, ETo was calculated by the in-build ETo calculator in AquaCrop based on the FAO Penman-Monteith equation and the climatic data.

Table 5 *lists the outputs of the simulation for aeras selected. (*Observed canopy data were cleaned; see simulation assessment.)*

RESULTS

	Block 1	Bolck2	Block 3	Block 4	Block5	Block 6
*Correlation (r)	0.71	0.88	0.75	0.79	0.99	0.94
*Root mean square error (rmse) y ton/ha)	0.3	0.31	0.27	0.048	0.0511	0.71
*Average observed cc (%)	68.25	55.9	60	75	61.5	64
*Average simulated cc (%)	52.97	55.2	39.2	57.6	51.5	40.9
Evaporation (mm)	81	117	81	131	82	165
Transpiration (mm)	327	303	327	238	256	207
Evapotranspiration (eta) (mm)	645	774	645	632	600	660
Reference evapotranspiration (eto) (mm)	645	775	645	632	600	660
Irrigation applied	0	0	350	270	390	310
Dry yield production (simulated) (ton/ha)	4.867	5.056	6.4	4.43	3.83	3.2
Dry yield production (reported) (ton/ha)	4.6	5.6	6	4	2.5	3.1
Harvest index (adjusted) (%)	36.8	38.1	42.1	38.8	30	38.1
Potential biomass (ton/ha)	15.3	13.3	18.5	15.5	15.6	14.6
Actual biomass (ton/ha)	13.24	16.87	15.28	10.4	10.1	8.3
Wp (kg yield/m3 et)	1.2	1.22	1.5	1.1	1.4	0.9
Temperature (transpiration) stress (%)	1	1	1	1	-	-
Canopy expansion stress (%)	None	None	-	5	-	13
Stomata closure stress (%)	11	22	18	28	18	29
Weed infestation stress (%)	10	1	1	8	6	6
Soil fertility stress (%)	None	-	None	-	25	80

For all wheat farms, AquaCrop's default settings produced relatively good results on the research area. With relatively low root mean square errors (RMSE, Table 5), the fitting of the simulated and reported yield and canopy cover is satisfactory. All farmers were using the same wheat variety, which corresponded well to the modified crop default settings applied in AquaCrop. Additionally, wheat farms are all commercial farms. The AquaCrop simulation indicates growing conditions in the wheat farms were similar. The validation results showed RMSE (ton/ha) ranging from 1.67 to

23, with R^2 ranging from 0.70 to 0.95 for the entire validation plots. Although strong calibration agreement, good model validation performance could not be obtained in all plots, but it performs quite well in the majority of plots. The validation results show that the model overestimates wheat yield in most plots. Table 5 summarizes the model's overall performance. Overall, the results indicate that RMSE and R^2 are acceptable, however a good correlation could not be obtained.

4.4 AquaCrop Calibration and validation

The AquaCrop model's calibration and validation were carried out by comparing the simulated and observed yields of dry wheat. The observed wheat yield of each plot was analyzed in order to choose which plots to calibrate. The average observed wheat yield on a dry basis varied from 5.61 ton/ha in field number 1 to 3.1 ton/ ha in field number 3 which indicates the large difference in production of wheat yield. Therefore, to balance between high and low yield, some plots with average wheat yield around 4.5 – 5.5 ton/ha are selected as representatives for calibration. Based on these 6 plots (2 from the southern part of the scheme and 3 from the central part, and lastly 2 from the northern part of the scheme) selected sites are examples to present or to cover all the parts of the scheme. Where fine-tuned until a good agreement between observed and simulated is obtained. The calibration performance of the model is given respectively, RMSE (ton/ha) ranging from 0.31 to 0.07 and R2 is 0.94. Based on statistical metrics calculated in table 6, there is a good agreement between model and observed data for all soil classes.

Table 6 *Statistical result of AquaCrop model calibration for dry wheat yield:*

Location	Observed	Simulated		Field data VS	Model
#	Yield ton/ha	Yield ton/ha	RMSE ton/ha	Error	R^2
Block 1	4.6	4.867	0.305784	-0.267	0.95
Block 2	6	6.432	0.312964	-0.432	0.99
Block 3	5.2	5.9	0.275277	0.544	0.96
Block 4	4	4.4	0.048898	-0.044	0.91
Block 5	2.5	3.514	0.051171	-0.014	0.79
Block 6	3.1	4.171	0.071	-0.071	0.94

The following crop growth parameters were analyzed: GY, harvestable Biomass, and WP, indicating the ratio between GY at harvest and the water requirement. According to the research statistical results, R^2 values were 0.90, 0.85, and 0.96 for the AquaCrop model compared to the observed data.

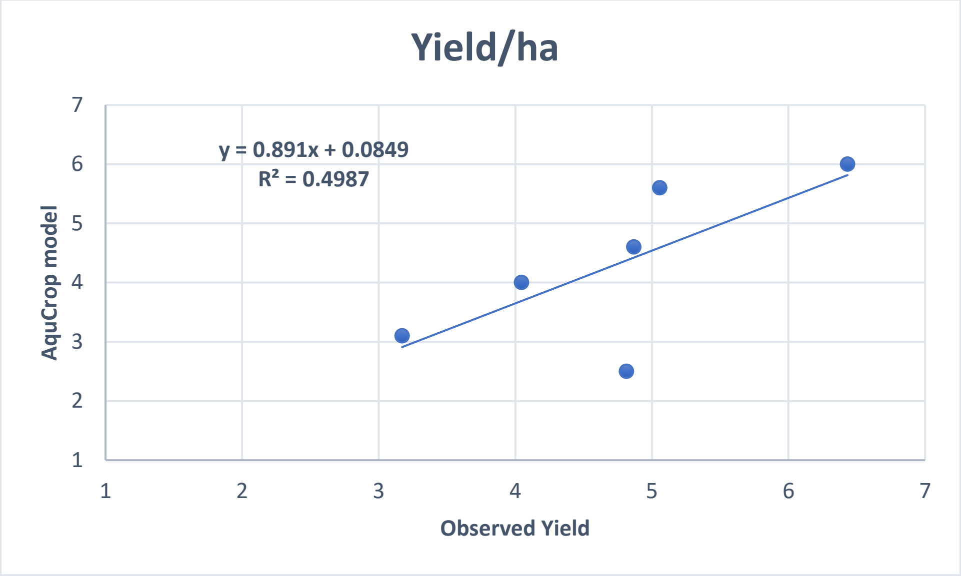


Figure 13 *Coloration between simulated and measured yield at wheat farms in the selected blocks.*

The reported yield in block 5 is exceptionally low, given the biomass simulated in AquaCrop. The reason that selected block in the Gezira scheme is not in line with the agricultural methods and wheat cultivation practices suggested by the scheme administration and agricultural research corporation is because of its non-compliance. Thus, a decrease in yield may affect the correlation with the AquaCrop simulated value. However, in the absence of additional supporting data, we cannot verifying this and it can be excluded from final analysis.

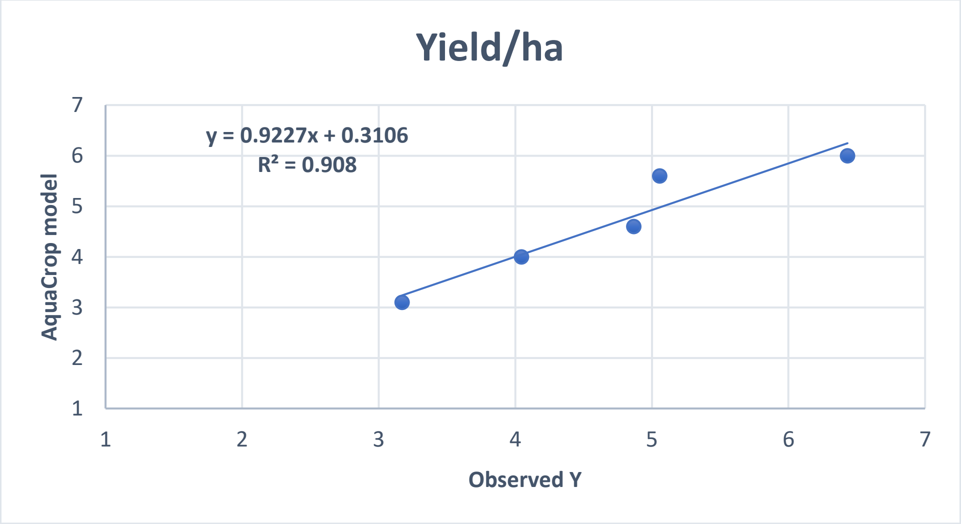


Figure 14 *Coloration between simulated and measured yield at wheat farm selected blocks* *<u>without block 5.</u>*

4.5 Aboveground biomass

In general, the model predictions and the observed biomass values were in good agreement (Table 7; Fig. 14). The model performed well at predicting harvest biomass values. Statistics indices, RMSE, normalized RMSE, D-index, and R^2 were calculated values of 0.6 t ha1, 4.4%, 0.95, and 0.99, respectively. The regression model showed that the variable Sim Biomass kg/ha explained 91.24% of the variance from the variable Obs Biomass kg/ha. An ANOVA was used to test whether this value was significantly different from zero. Using the present sample, it was found that the effect was significantly different from zero, F=41.67, p = .001, R2 = 0.91.

Table 7 *Shown the statistical analysis between simulate and observed data.*

	Obs Biomass kg/ha	Sim Biomass kg/ha
Mean	11.77	11.48
Std. Deviation	3.61	2.84
Minimum	8	8.3
Maximum	17	15.2
Quartile 3	14.25	13.28
Skew	0.55	0.03
Kurtosis	-1.43	-2
95% Confidence interval of Mean	8.88; 14.66	9.21; 13.75

(Figure 15, and 16) shows the simulated and observed sequential aboveground biomass in selected farm areas. In all the treatments, the simulated above-ground dry biomass agrees well with observed values, notwithstanding a slight overestimation by the model. This discrepancy could have been caused by an error in the observed data and/or the way the model simulates crop development. Aboveground biomass in the AquaCrop model is obtained from crop transpiration via crop water productivity, WP* normalized for ET0 and CO2 (Steduto et al., 2009).

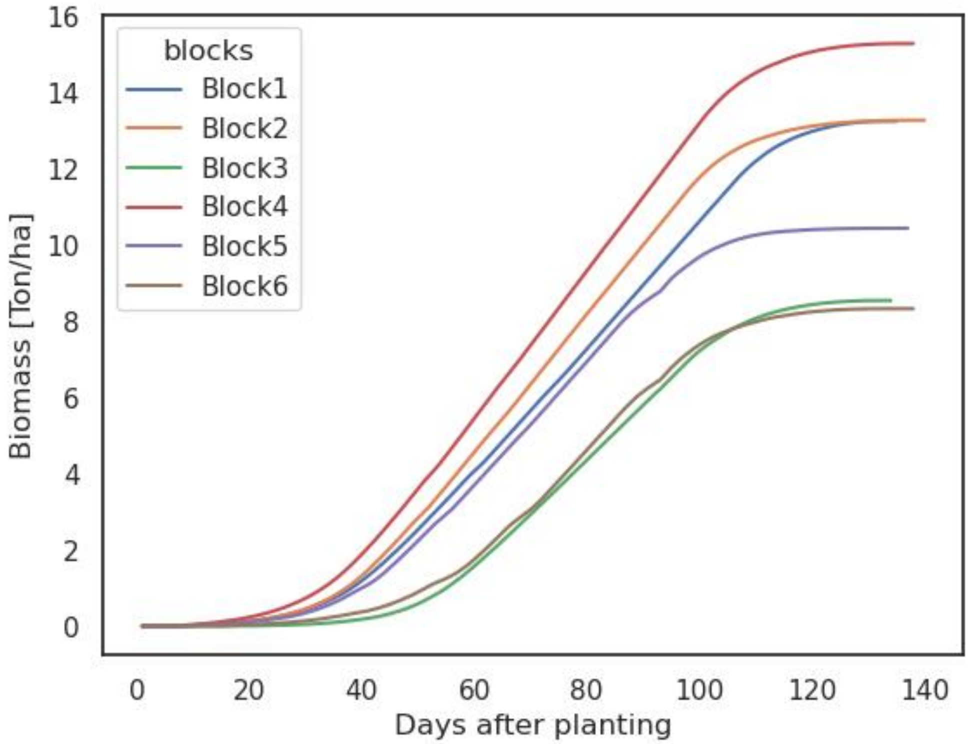


Figure 15 *Shows the simulated biomass after planting days for all selected blocks.*

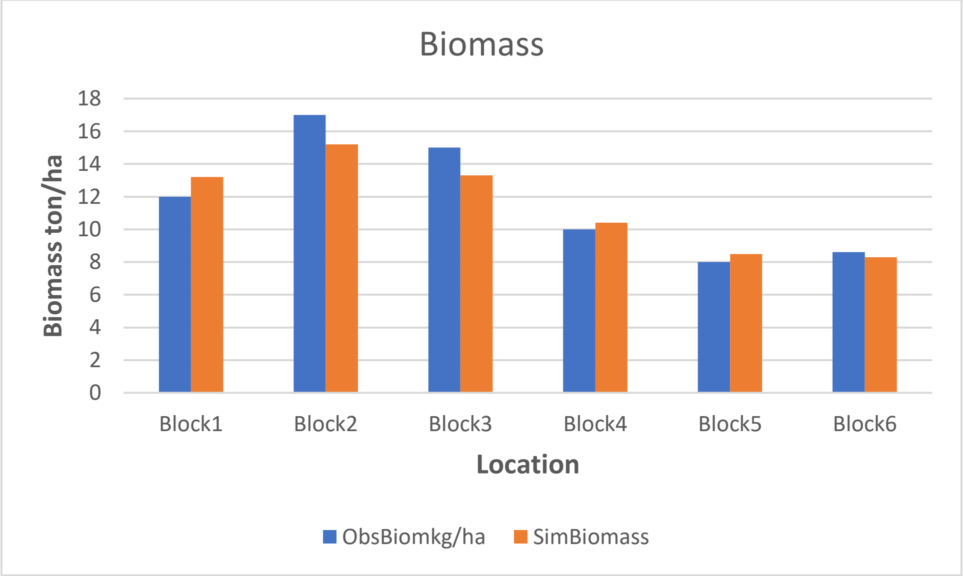


Figure 16 *Shows simulated biomass yield and measured yield at farms wheat producers in the selected plots.*

The simulated aboveground biomass agreed well with the observed biomass (figure. 17). The simulated aboveground biomass was also adjusted using the stress coefficient (such as Pupper for stomata) to reproduce the observed biomass. There was strong relationship between the observed and simulated biomass ($R^2 > 0.85$).

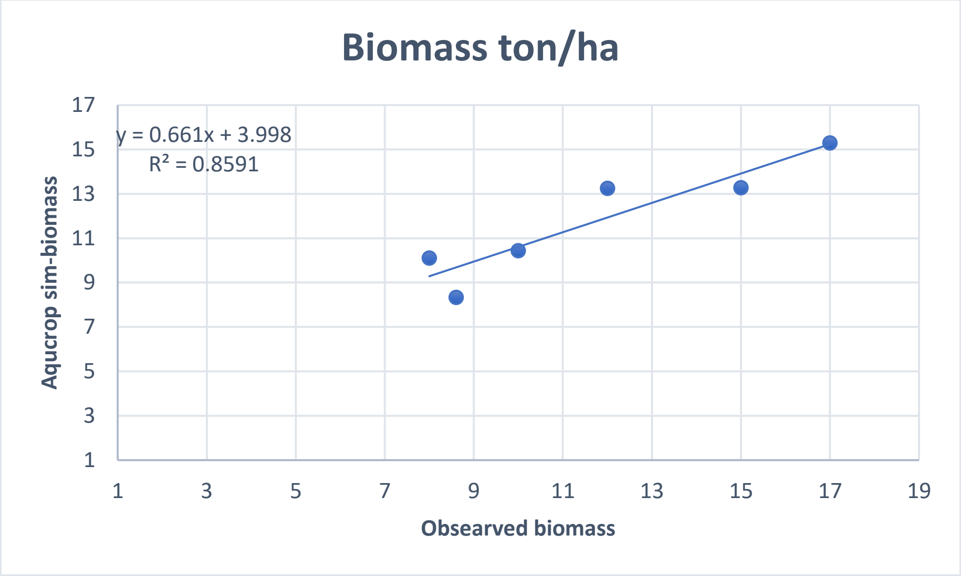


Figure 17 *Coloration between simulated and measured biomass at wheat farms in the selected blocks.*

4.6 Water Productivity

The AquaCrop simulations of wheat farms provide information on crop growth and water balance, which can help identify specific physiological stresses that affect production and water productivity during the growing season. The default crop settings of AquaCrop model performed well in all farms, allowing for adjustments to management parameters to obtain a good fit between observed and simulated canopies and yields. However, the simulations showed that all wheat crops were limited in their production and productivity due to various physiological stresses.

The data assimilation and measured yield and ET were used to calculate WP. The results indicated a good linear relationship between the data assimilation and measured WP over the selected block (Figure 18). The R2 value of simulated and measured WP was 0.85. The calibrated results are quite agreed with the validated results for WP in most wheat farms (Figure19). The results indicated that the AquaCrop model can be used to estimate WP for wheat crop in Gezira scheme.

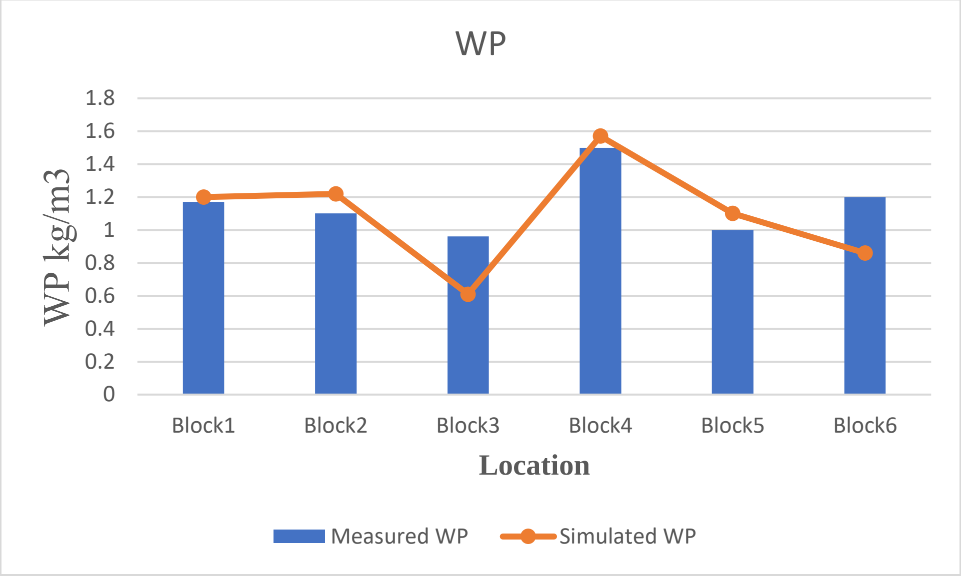


Figure 18 *Showed simulated WP yield and measured WP at farms wheat producers in the selected plots.*

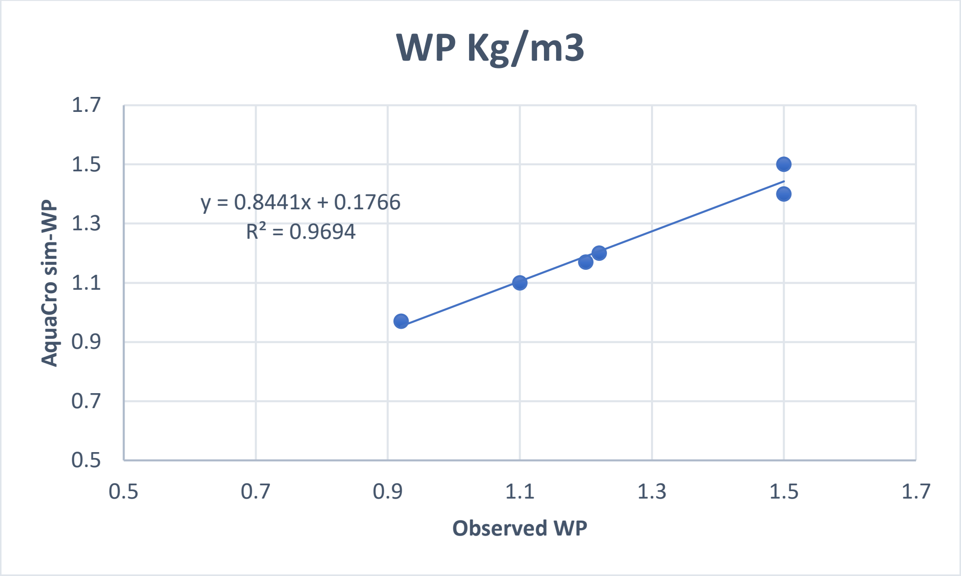


Figure 19 *Correlation between simulated WP yield and measured WP at wheat farms in the selected plots.*

4.7 WaPOR and AquaCrop Comparison

The precision of WaPOR data products was evaluated by using both the AquaCrop model output and wheat yield data obtained from the field. To compare WaPOR, model, and field data for biomass, intercomparisons were conducted, while for actual evapotranspiration, the WaPOR estimate was compared with the model output since there was no measured evapotranspiration.

Lastly, the water productivity calculated from WaPOR data components was compared to the model estimate. The subsequent sections present the statistical metrics and discussions of the outcomes.

Figure 20 displays the outputs of WaPOR ETIa, AquaCrop ETa, and AquaCrop ET0. The AquaCrop ETa results exhibit relatively consistent values, ranging from 370-420 mm during the entire study period, which is lower than the ET0 value ranging from 600-775 mm. Meanwhile, the WaPOR ETIa mean values show more variability, varying between 312-537 mm throughout the study period. The majority of blocks show that the WaPOR values lie in the upper part of the AquaCrop ETIa value range. This can be explained by the fact that AquaCrop calculates WP using ETa values at the plant's physiological maturity, whereas WaPOR calculates WP using ETa values till harvest., which resulted in higher actual evapotranspiration values for WaPOR.

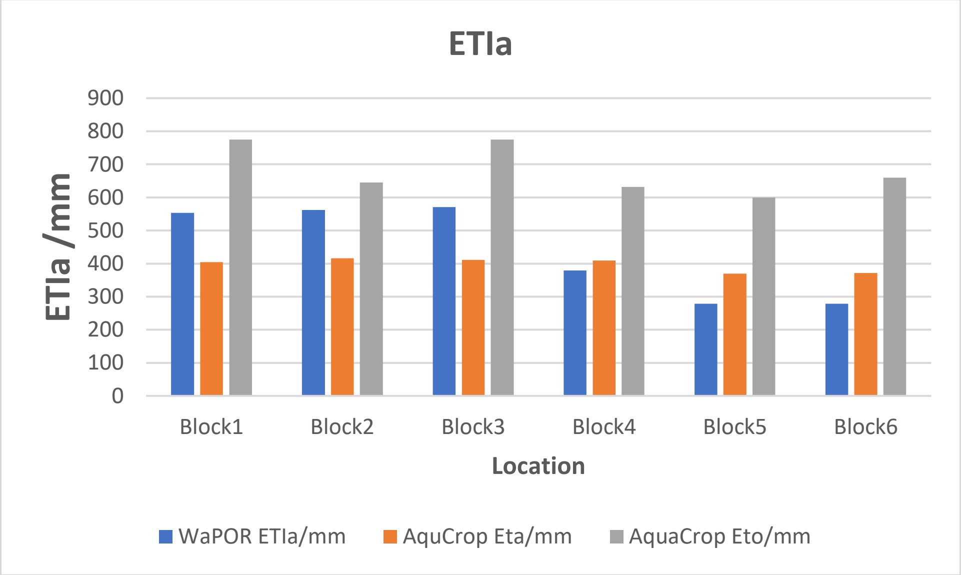


Figure 20 *WaPOR ETIa cell values for the study area and presented with blue columns for the seasons 2019/2020, AquaCrop ETa outputs form the seasons 2019/2020, and AquaCrop ET0 outputs for season2019/2020 presented with yellow and orange and gray columns/*

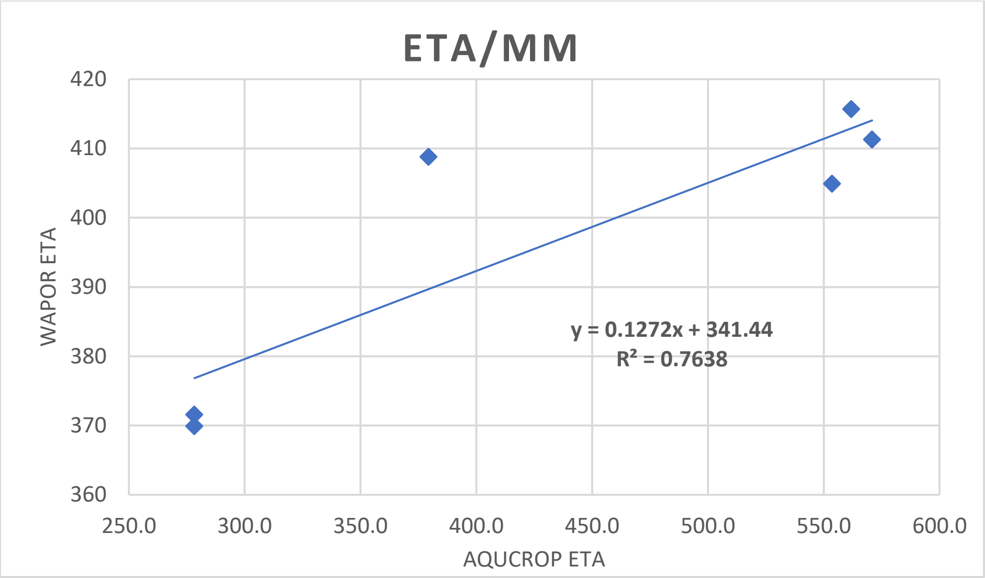


Figure 21 *: Correlation between WaPOR ETa and AquaCrop ETa for all selected blocks.*

In (Figure; 20), the WaPOR, AquaCrop, and observed yield values are shown. The AquaCrop yield output is around at 3.17–6.43 ton/ha for the observed period, corresponding well, both by trend and value, with the historical yield data lying at 2.5–5.6 ton/ha. WaPOR shows consistently lower yield values, with the mean values lying between 0.28–1.9 ton/ha per season for the study period, relative to observed data, with correlation R^2 0.76 as is shown in (Figure; 21).

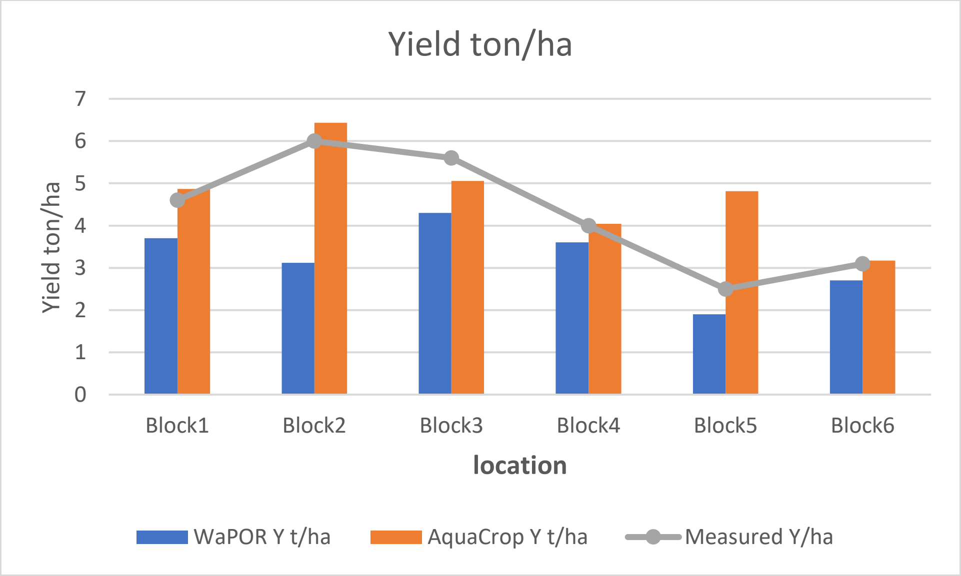


Figure 22 Shows *WaPOR, AquaCrop and observed fresh dry yield for all selected blocks.*

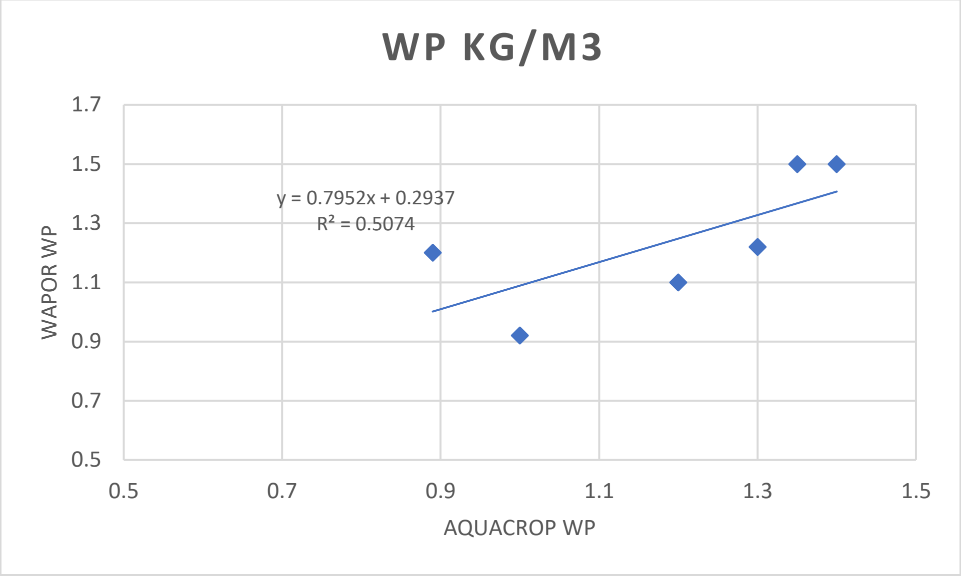


Figure 23 *Correlation between WaPOR Y and Simulated AquaCrop WP for the selected blocks.*

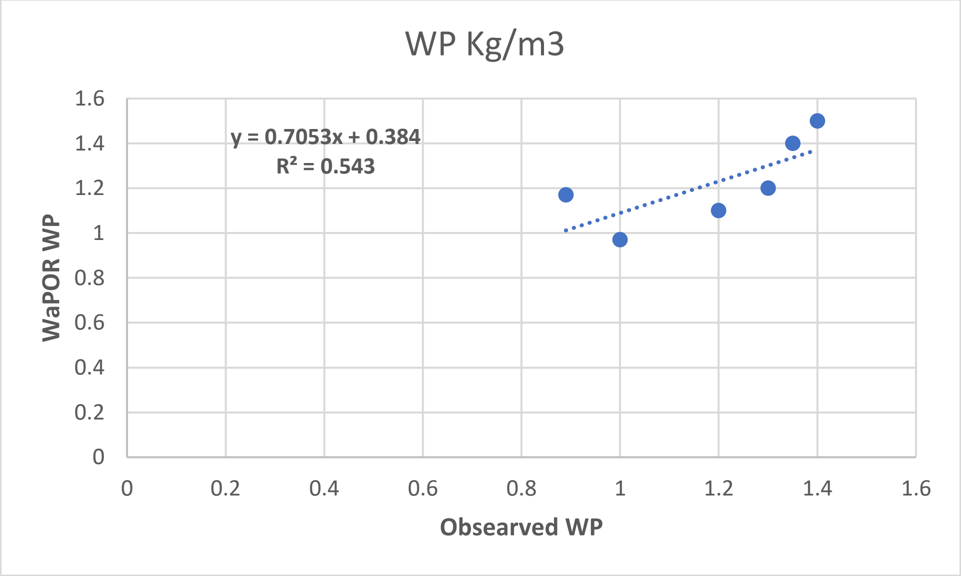


Figure 24 *Correlation between WaPOR Y and observed WP for the selected blocks.*

.

In (Fig-22), the WaPOR and AquaCrop crop water productivity (CWP) outputs are shown. The AquaCrop CWP output shows values of 0.92–1.5 kg /m^3, whereas WaPOR CWP show lower values, between 0.89–1.4 kg /m3 for the mean values. As the CWP values are calculated by taking the ratio of yield over ETa, the lower WaPOR CWP values are results of the lower WaPOR yield values noted in (figure 23).

5. Discussion

The study's section 5, Figure 20 shows the ETa values obtained from AquaCrop and WaPOR, which are quite similar to a previous study conducted by Widengren, V. (2022).) in Siri Lanka and Abiyu, G. A. (2021).in Ethiopia for wheat, showing values ranging from 312 - 537 mm and 370 - 420 mm, respectively. AquaCrop's ETa values were consistently higher than WaPOR's, but both models use the Penman Monteith equation to calculate ETa. WaPOR utilizes global meteorological stations and remote sensing data influenced by different parameters, while AquaCrop has more consistent values throughout the study period.

However, during the drought year, WaPOR displayed higher ETa values than AquaCrop, likely because of increased water loss from soil evaporation due to hot and dry weather conditions. AquaCrop uses point data from meteorological stations and primarily collected field data. A possible explanation to AquaCrop ETa outputs being at the upper range of the WaPOR ETIa values could be because of unlimited water conditions in the model environment. The frequency of the water application in the model was determined from survey answers (Annex B) and the irrigation amount was determined by the irrigation management administration in the Gezira scheme - Sudan. With these model settings, the water access in the model was non-limiting, leading to higher and more consistent ETa values. The value of AETI was also noted to be almost non-existent or zero in several areas of the scheme. For example, in the eastern and northeastern sides, the value of AETI is very low in the first and second seasons but equal to zero in the third, fourth, and fifth seasons. The decrease in AETI or absence of AETI in certain areas suggests that water productivity is non-existent, indicating that there is a major problem with water distribution.

The AquaCrop yield output values were shown to be in good agreement with the historical yield data values (3.17 - 6.43 and 2.5 - 5.6 ton/ha, respectively) in section 4. (Figure 13). WaPOR values were low (1.9 – 4.3 ton/ha), indicating a potential underestimating of WaPOR production. This could be explained by the difference in calculation approach between AquaCrop and WaPOR when calculating seasonal yield. The WaPOR database uses satellite data to determine yield from total biomass production with the help of global crop parameters (FAO 2020b).

Previous studies comparing remote sensed and in-situ data, which included a comprehensive literature review, indicated that there is a significant difference in reported accuracy of crop yield remote sensing. Previous knowledge and accurate allocation of crop type and factors such as HI, LUE, and moisture content (MC) were found to have a significant influence (Blatchford et al. 2019). Lower WaPOR yield values could thus be due to causes of error in these conversion calculations.

The principal collected field data inputs are used by the AquaCrop model. However, it does not take insects and diseases into account. According to survey responses in section 3.2.1, there were issues with insects and diseases. Therefore, it is possible that AquaCrop is simulating better growing conditions, resulting in higher yields than what is achieved. Moreover, the model only allows for a minimum maximum rooting depth of 1 m, whereas the actual maximum rooting depth measured in the field was 0.60 m.

In section 5, Figure 22, crop water productivity (CWP) values for the WaPOR output (0.89- 1.4 kg/m^3) were revealed to be lower than for the AquaCrop output (0.92-1.5 kg/m^3). The CWP values are determined by dividing the yield over the ETIa ratio, and since the ETIa and yield deviations differ, the compound of CWP seems to reduce divergence between the two techniques, creating an artifact of opposite trends for the ETIa and yield. Lower CWP values were a result of the low yield values from WaPOR.

6. Conclusions and Recommendation

The goal of the present study was to evaluate remote sensing derived water productivity data components by using the AquaCrop model together with primary collected field data. Three data components; NPP, AET, and TBP WaPOR database for the year 2019 - 2020 were extracted for each plot and used for the analysis. To answer the research questions from the result the WaPOR and AquaCrop ETa values were found to be in reasonable agreement (370 - 420 and 312-537 mm respectively). However, AquaCrop had more consistent values, which could be explained by the model environment's non-limiting water conditions, that resulted in a decreased sensitivity to meteorological data. WaPOR and AquaCrop ETa values were also found to be similar to those found in past studies on Africa and the Near East (560. - 563. mm) (Wanjala, H. V. K. (2020). As a result, it is possible to conclude that WaPOR is a useful technique for estimating ETIa.

Our results have indicated that model calibration could be more efficient by using not only final biomass/crop yield values, but multiple calibration points during the crop growing season. As a result, more continuous assessments of canopy cover, soil moisture, and biomass are required. Remote sensing data can also be utilized to obtain such local data during different stages of crop development. The study also found that irrigation scheduling has a significant impact on simulated AET and thus final AGB and crop yield, indicating that correct local irrigation information at the plot (field) level is required. To address this issue, it is suggested that the AquaCrop model be used in rain-fed agriculture involving cereal crops.

The study found that the WaPOR database often underestimates the AGB when compared to observed field data and simulated model output. This is further supported by the model's simulation of low transpiration and high AGB, while the WaPOR database estimate went in the opposite direction. Water productivity derived using the WaPOR database seems lower than the simulated AquaCrop model result, as expected. Due to the limitations and poor confidence in model output, assessing the final accuracy of the WaPOR database is difficult. Therefore, further research needs to be undertaken for a more detailed and accurate in-situ evaluation of WaPOR. This can be done through in-situ AET measurements with flux towers, derivations of WP data components using algorithms and satellite images not used by the WaPOR database, and comparisons and further evaluation of the WaPOR database in rain-fed agriculture.

7. Summary

Thesis title: Assessment of Water Productivity and Wheat Yield Using Remote Sensing WaPOR database and AquaCrop model for Gezira Scheme in Sudan.

Author: Elsadig Bashir Mohammed Omer

Course: MSc Agricultural water management

Institute/Department: Water management

Primary Adviser: Dr. Waltner Istvan, Assistant Professor, Department of Water Management

Water productivity (WP) is an essential performance measure for managing and evaluating agricultural land on a continental scale. Increasing food demand due to rapid population increase, combined with severe competition from other sectors and concerns about climate change, has put enormous pressure on agricultural water. To satisfy upcoming food demands, the agriculture sector must use its water resources more effectively. The aim of this study is to evaluate WaPOR data, by comparing it with data collected from the field and AquaCrop model, in specific for using WaPOR to evaluate water productivity for selected farms in the Gezira scheme in Sudan. The comparison was conducted for selected farms in Sudan's Gezira irrigation scheme. AquaCrop is a crop growth model developed by the FAO to assess the impact of environmental factors and management practices on crop production and food security. The FAO has developed a free database called WaPOR that uses satellite data to monitor agricultural water productivity at different scales ($level^1$: 250m, $level^2$: 100m, and $level^3$: 30m) to improve sustainable agricultural production. Based on a case study of the study area, $level^3$ (30m) water productivity data components of the WaPOR database were evaluated and compared with AquaCrop model output, and observed field data was applied to the AquaCrop model using 6 plots selected from the study area. Based on a case study of the Gezira irrigation scheme, the study evaluated the level 3 (30m) water productivity data components of the WaPOR database and compared them to AquaCrop model output and observed field data for six plots. The results showed that WaPOR's values were consistently underestimated in comparison to measured data and model output. The actual evapotranspiration (ETa) values for WaPOR and AquaCrop were found to be significantly in good agreement. However, the yield values for WaPOR were lower than the simulated and measured yield. WaPOR is compared plot-by-plot to AquaCrop values for wheat crop yield, above-ground biomass (AGB), and Crop water productivity. The analysis revealed that WaPOR’s values estimates have consistently been

underestimated in comparison to measured data and model output. The actual evapotranspiration ETa values for WaPOR and AquaCrop were found to be significantly in good agreement (278–553 and 369–415 mm respectively). However, the yield values for WaPOR (1.9-4.3 ton/ha) were lower than the simulated and measured yield (4.6-5.7 and 4.4-5.6 ton/ha, respectively). The results revealed that there is a strong correlation between AquaCrop model simulated values and the observed field data in terms of wheat yield, biomass production, and CWP with R2 range 0.90, 0.84, and 0.96 respectively. We also found that the model simulated ETa well, with a correlation coefficient of 0.76. Analysis of WaPOR database and AquaCrop model did not give a significant correlation for both CWP and AGB. is lower than the model estimate. To have a better understanding of potential limitations, it is recommended that future studies involve a sensitivity analysis for WaPOR and ground truth with yield data. It is also recommended to ground truth AquaCrop with yield and soil data to achieve precise site descriptions. In addition, this study does not take into account the range of crops. Therefore, for future researchers, I suggest creating a Python or R program that can be linked with the AquaCrop model to obtain more precise and accurate results.

Acknowledgement

I would like to express my deepest gratitude to my thesis supervisor, Professor "**Istvan Waltner**", for his invaluable guidance, support, and patience throughout the entire thesis process. His constructive feedback and insightful suggestions were instrumental in shaping and improving the quality of this work.

In addition, I would also like to thank my family for their unwavering love, encouragement, and support. Their sacrifices and belief in me have been a source of strength and motivation, and I could not have accomplished this without their constant support.

Also, I would like to acknowledge Hungary, Szent Istvan University staff, lecturers, the international coordinator, and all the campus staff for their warm welcome and for making my stay in Hungary easier.

Above all, I would like to give my special thanks to Stipendium Hungaricum Scholarship together with Tumpus Foundation, who give me the opportunity to do this MSc, in agricultural water management, and invested in me throughout those 22 months.

Finally, I would like to extend my appreciation to my dear friends and colleagues, especially **Florent Demelezi,** for their understanding, encouragement, and moral support during this challenging journey. Their presence has been a constant reminder that I am not alone in this pursuit, and their unwavering support has made all the difference.

List of References

Abedinpour, M., Sarangi, A., Rajput, T., Singh, M., Pathak, H., Ahmad, T., 2012. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. Agricultural Water Management 110, 55-66.

Abiyu, G. A. (2021). *CROP WATER PRODUCTIVITY ANALYSIS USING FAO-BASED (WaPOR) DATABASE, THE CASE OF KOGA IRRIGATION SCHEME, ETHIOPIA* (Doctoral dissertation).

Adam, H.S., 2005. Agroclimatology, crop water requirement and water management. *Gezira University Publication Company. Wadmedani, Sudan*.

Ait-Aoudia, M. N., & Berezowska-Azzag, E. (2016). Water resources carrying capacity assessment: the case of Algeria's capital city. *Habitat International*, *58*, 51-58.

Ali, M. H., & Talukder, M. S. U. (2008). Increasing water productivity in crop production—A synthesis. *Agricultural water management*, *95*(11), 1201-1213.

Ali, M.H., 2010. Crop water requirement and irrigation scheduling. In *Fundamentals of Irrigation and On-farm Water Management: Volume 1* (pp. 399-452). Springer, New York, NY.

Andarzian, ., Bannayan, M., Steduto, P., Mazraeh, H., Barati, M.E., Barati, M.A. and Rahnama, A., 2011. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. *Agricultural Water Management*, *100*(1), pp.1-8.

AO. 2020. WaPOR V2 quality assessment – Technical Report on the Data Quality of the WaPOR FAO Database version 2. Rome. https://doi.org/10.4060/cb2208en.

Araya, A., Habtu, S., Hadgu, K.M., Kebede, A., Dejene, T., 2010. Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (Hordeum vulgare). Agricultural Water Management 97, 1838-1846.

AREI Ch. 2.2 Irrigation Water Management - USDA ERS https://www.ers.usda.gov/webdocs/publications/41964/30287_irrigationwater.pdf?v=0

Bastiaanssen, W. G., & Steduto, P. (2017). The water productivity score (WPS) at global and regional level: Methodology and first results from remote sensing measurements of wheat, rice and maize. *Science of the Total Environment*, *575*, 595-611.

Bastiaanssen, W.G.M., Cheema, M.J.M., Immerzeel, W.W., Miltenburg, I.J. and Pelgrum, H., 2012. Surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model. *Water Resources Research*, *48*(11).

Bautista, R., & Rice, R. (2014). DIVISION OF AGRICULTURE Agriculture and Natural

Bechini, L., Bocchi, S., Maggiore, T. and Confalonieri, R., 2006. Parameterization of a crop growth and development simulation model at sub-model components level. An example for winter wheat (Triticum aestivum L.). Environmental modelling & software, 21(7), pp.1042-1054

Wu, B., Tian, F., Zhang, M., Piao, S., Zeng, H., Zhu, W., ... & Lu, Y. (2022). Quantifying global agricultural water appropriation with data derived from earth observations. *Journal of Cleaner Production*, *358*, 131891.

Blatchford, M.L., Mannaerts, C.M., Njuki, S.M., Nouri, H., Zeng, Y., Pelgrum, H., Wonink, S. and Karimi, P., 2020. Evaluation of WaPOR V2 evapotranspiration products across Africa. *Hydrological processes*, *34*(15), pp.3200-3221.

Boonwichai, S., Shrestha, S., Babel, M.S., Weesakul, S. a nd Datta, A., 2018. Climate change impacts on irrigation water requirement, crop water productivity and rice yield in the Songkhram River Basin, Thailand. *Journal of Cleaner Production*, *198*, pp.1157-1164.

Boote, K.J., Jones, J.W. and Hoogenboom, G., 2018. Simulation of crop growth: CROPGRO model. In *Agricultural Systems modeting and Simulation* (pp. 651-692). CRC Press.

Brouder, S.M. and Volenec, J.J., 2008. Impact of climate change on crop nutrient and water use efficiencies. Physiologia Plantarum, 133(4), pp.705-724.

Bwalya, A., 2013. *Validation of the aquacrop model for the irrigated african eggplant (solanum macrocarpon) at the UNZA field station* (Doctoral dissertation).

Charts. *University of Arkansas, US Department of Agriculture and County Governments Cooperating.*

Daryanto, S., Wang, L. and Jacinthe, P.A., 2017. Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agricultural Water Management*, *179*, pp.18-33.

English, M.J., Solomon, K.H. and Hoffman, G.J., 2002. A paradigm shift in irrigation management. *Journal of irrigation and drainage engineering*, *128*(5), pp.267-277.

Expósito, A., & Berbel, J. (2017). Why is water pricing ineffective for deficit irrigation schemes? A case study in southern Spain. *Water resources management*, *31*, 1047-1059.

Fahad, S., Bajwa, A.A., Nazir, U., Anjum, S.A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S. and Ihsan, M.Z., 2017. Crop production under drought and heat stress: plant responses and management options. *Frontiers in plant science*, p.1147.

FAO. (2019). DATABASE METHODOLOGY : LEVEL 3 DATA-Using remote sensing in support of solutions to reduce agricultural water productivity gaps.

FAO. (2020). WaPOR Database Methodology: Version 2 Release, April 2020.

Fernández García, I., Lecina, S., Ruiz-Sánchez, M.C., Vera, J., Conejero, W., Conesa, M.R., Domínguez, A., Pardo, J.J., Léllis, B.C. and Montesinos, P., 2020. Trends and challenges in irrigation scheduling in the semi-arid area of Spain. *Water*, *12*(3), p.785.

Geerts, S., Raes, D., Garcia, M., Miranda, R., Cusicanqui, J. A., Taboada, C., ... & Steduto, P. (2009). Simulating yield response of quinoa to water availability with AquaCrop. *Agronomy Journal*, *101*(3), 499-508.

Goldhamer, D.A. and Fereres, E., 2004. Irrigation scheduling of almond trees with trunk diameter sensors. *Irrigation Science*, *23*(1), pp.11-19.

Graves, A.R., Hess, T., Matthews, R.B., Stephens, W. and Middleton, T., 2002. Crop simulation models as tools in computer laboratory and classroom-based education. *Journal of Natural Resources and Life Sciences Education*, *31*(1), pp.48-54.

Hamidreza, S., Mohd, A.M.S., Teang, S.L., Sayed, F.M., Arman, G. and Mohd, K.Y., 2011. Application of AquaCrop model in deficit irrigation management of Winter wheat in arid region. *African Journal of Agricultural Research*, *6*(10), pp.2204-2215.

Hilaire, R.S., Arnold, M.A., Wilkerson, D.C., Devitt, D.A., Hurd, B.H., Lesikar, B.J., Lohr, V.I., Martin, C.A., McDonald, G.V., Morris, R.L. and Pittenger, D.R., 2008. Efficient water use in residential urban landscapes. *HortScience*, *43*(7), pp.2081-2092.

Holzworth, D.P., Snow, V., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J.W. and Thorburn, P., 2015. Agricultural production systems modelling and software: current status and future prospects. *Environmental Modelling & Software*, *72*, pp.276-286.

Hsiao, T.C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D. and Fereres, E., 2009. AquaCrop—the FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agronomy Journal*, *101*(3), pp.448-459.

Iqbal, M.A., Shen, Y., Stricevic, R., Pei, H., Sun, H., Amiri, E., Penas, A., del Rio, S., 2014. Evaluation of the FAO AquaCrop model for winter wheat on the North China Plain under deficit irrigation from field experiment to regional yield simulation. Agricultural Water Management 135, 61-72.

Jeuffroy, M.H., Casadebaig, P., Debaeke, P., Loyce, C. and Meynard, J.M., 2014. Agronomic model uses to predict cultivar performance in various environments and cropping systems. A review. Agronomy for Sustainable Development, 34(1), pp.121-137

Kijne, J. W., Barker, R., & Molden, D. (2003). Improving water productivity in agriculture: editors' overview. *Water productivity in agriculture: Limits and opportunities for improvement*, xi-xix.

Kijne, J., Barron, J., Hoff, H., Rockstroma, J., Karlberg, L., Growing, J., ... & Wichelns, D. (2009). Opportunities to increase water productivity in agriculture with special reference to Africa and South Asia. Stockholm Environment Institute, Project Report-2009.

Langhorn, C.M., 2016. Simulation of climate change impacts on selected crop yields in southern Alberta. University of Lethbridge (Canada).

Lascano, R. J., Payton, P., Mahan, J. R., Goebel, T. S., & Gitz III, D. C. (2022). Annual Rainfall and Dryland Cotton Lint Yield—Southern High Plains of Texas. *Agricultural Sciences*, *13*(2), 177-200.

Mansour, H.A., El-Hady, M.A., Eldardiry, E.I., Essa, S.F. and Eldwainy, C., 2020. Sustainable agriculture and food-Challenges and solutions: A review. *Plant Archives*, *20*(1), pp.3218-3223.

Mkhabela, M.S., Bullock, P.R., 2012. Performance of the FAO AquaCrop model for wheat grain yield and soil moisture simulation in Western Canada. Agricultural Water Management 110, 16-24

Molden, D., Oweis, T. Y., Pasquale, S., Kijne, J. W., Hanjra, M. A., Bindraban, P. S., ... & Upadhyaya, A. (2007). Pathways for increasing agricultural water productivity.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural water management*, *97*(4), 528-535.

Montesino-San Martín, M., Olesen, J.E. and Porter, J.R., 2014. A genotype, environment and management (GxExM) analysis of adaptation in winter wheat to climate change in Denmark. *Agricultural and Forest Meteorology*, *187*, pp.1-13.

Moore, T. S., Churnside, J. H., Sullivan, J. M., Twardowski, M. S., Nayak, A. R., McFarland, M. N., ... & Ruberg, S. A. (2019). Vertical distributions of blooming cyanobacteria populations in a freshwater lake from LIDAR observations. *Remote Sensing of Environment*, *225*, 347-367.

Ordoñez, Jenny C., Peter M. Van Bodegom, Jan-Philip M. Witte, Ian J. Wright, Peter B. Reich, and Rien Aerts. "A global study of relationships between leaf traits, climate and soil measures of nutrient fertility." Global Ecology and Biogeography 18, no. 2 (2009): 137-149.

Panhwar, A., Abro, R., Kandhro, A., Khaskheli, A. R., Jalbani, N., Gishkori, K. A., ... & Qaisar, S. (2022). Global Water Mapping, Requirements, and Concerns over Water Quality Shortages.

QGIS Development team (2020. QGIS Geographic Information system.Opensource Geospatial Foundation project. http:qgis.osqeo.org.Qgis.february.

Resources Grain Drying Tools: Equilibrium Moisture Content Tables and Psychrometric

Salemi, H., Soom, M. A. M., Lee, T. S., Mousavi, S. F., Ganji, A., & Yusoff, M. K. (2011). Application of AquaCrop model in deficit irrigation management of winter wheat in arid region. *African Journal of Agricultural Research*, *610*, 2204-2215.

Scherer, T.F., Seelig, B. and Franzen, D., 1996. Soil, water and plant characteristics important to irrigation.

Scherer, T.F., Seelig, B. and Franzen, D., 1996. Soil, water, and plant characteristics important to irrigation.

Shand, M.J. and Basson, M.S., 2003, March. South African water resources, availability, demands and strategic issues. In *Proceedings of a joint RSA-Australian workshop on water resources management* (Vol. 31, pp. 29-41).

Singh, S.P., Singh, B. and Kumar, U., 2013. Water management strategies for achieving food security. *APCBEE procedia*, *5*, pp.423-428.

Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E., 2009. AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal*, *101*(3), pp.426-437.

Stricevic, R., Cosic, M., Djurovic, N., Pejic, B., Maksimovic, L., 2011. Assessment of the FAO AquaCrop model in the simulation of rainfed and supplementally irrigated maize, sugar beet and sunflower. Agricultural Water Management 98, 1615-1621.

Taddeo, S. (2022). Leveraging time series of satellite and aerial images to promote the long-term monitoring of restored plant communities. *Applied Vegetation Science*, *25*(2), e12664.

Todorovic, M., Albrizio, R., Zivotic, L., Saab, M.T.A., Stöckle, C. and Steduto, P., 2009. Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agronomy journal*, *101*(3), pp.509-521.

Todorovic, M., Lamaddalena, N., Jovanovic, N. and Pereira, L.S., 2014. Agricultural water management: Priorities and challenges (Preface).

Unkovich, M., Baldock, J., & Forbes, M. (2010). Variability in harvest index of grain crops and potential significance for carbon accounting: examples from Australian agriculture. *Advances in agronomy*, *105*, 173-219.

Van Halsema, G.E. and Vincent, L., 2012. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. *Agricultural Water Management*, *108*, pp.9-15.

Vanuytrecht, Eline, Dirk Raes, and Patrick Willems. "Considering sink strength to model crop production under elevated atmospheric CO2." *Agricultural and Forest Meteorology* 151, no. 12 (2011): 1753-1762.

Verma, S.B. and Jha, J., 2014. Crop Water Requirements and Irrigation. *Irrigation Resources*, p.58.

Wang, S., & Zhang, Z. (2011). Effects of climate change on water resources in China. *Climate Research*, *47*(1-2), 77-82.

Wanjala, H. V. K. (2020). *Comparison of WaPOR RS-based to SWAT+ model water productivity estimates in Lake Naivasha Basin, Kenya* (Master's thesis, University of Twente).

Werner, H., 1992. *Measuring soil moisture for irrigation water management*. Cooperative Extension Service, South Dakota State University, US Department of Agriculture.

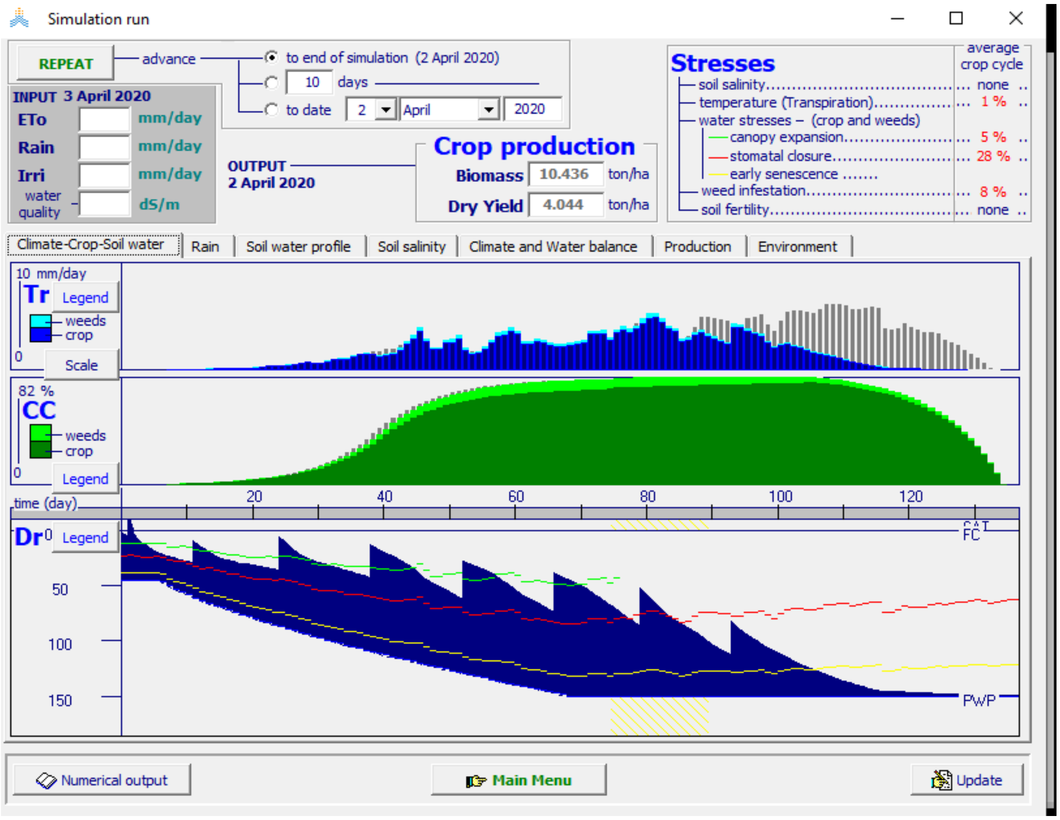
Widengren, V. (2022). Evaluation of Crop Water Use and Rice Yield Using Remote Sensing and AquaCrop Model for Three Irrigation Schemes in Sri Lanka.

Zwart, S. J., & Bastiaanssen, W. G. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural water management*, *69*(2), 115-133.

.Zwart, S. J., Bastiaanssen, W. G., de Fraiture, C., & Molden, D. J. (2010). WATPRO: A remote sensing based model for mapping water productivity of wheat. *Agricultural water management*, *97*(10), 1628-1636.

Appendices

AquaCrop run simulation.



advance ● to end of simulation (2 April 2020)

○ 10 days

○ to date 2 April 2020

INPUT 3 April 2020

ETo mm/day

Rain mm/day

Irri mm/day

water quality dS/m

OUTPUT 2 April 2020

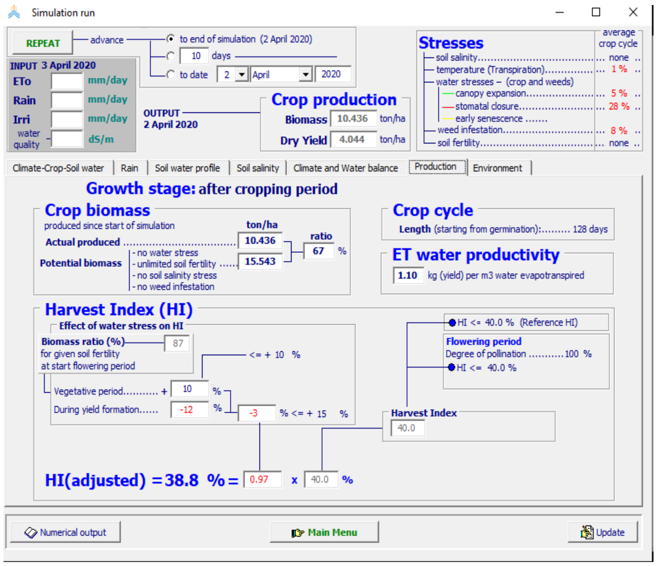
Crop production

Biomass 10.436 ton/ha

Dry Yield 4.044 ton/ha

Stresses (average crop cycle)

- soil salinity........ none
- temperature (Transpiration)........ 1 %
- water stresses – (crop and weeds)
  - canopy expansion........ 5 %
  - stomatal closure........ 28 %
  - early senescence ....
- weed infestation........ 8 %
- soil fertility........ none



advance ● to end of simulation (2 April 2020)

○ 10 days

○ to date 2 April 2020

INPUT 3 April 2020

ETo mm/day

Rain mm/day

Irri mm/day

water quality dS/m

OUTPUT 2 April 2020

Crop production

Biomass 10.436 ton/ha

Dry Yield 4.044 ton/ha

Stresses (average crop cycle)

- soil salinity........ none
- temperature (Transpiration)........ 1 %
- water stresses – (crop and weeds)
  - canopy expansion........ 5 %
  - stomatal closure........ 28 %
  - early senescence ....
- weed infestation........ 8 %
- soil fertility........ none

Growth stage: after cropping period

Crop biomass

produced since start of simulation (ton/ha)

Actual produced 10.436

Potential biomass (- no water stress - unlimited soil fertility - no soil salinity stress - no weed infestation) 15.543

ratio 67 %

Crop cycle

Length (starting from germination):......... 128 days

ET water productivity

1.10 kg (yield) per m3 water evapotranspired

Harvest Index (HI)

Effect of water stress on HI

Biomass ratio (%) for given soil fertility at start flowering period 87

<= + 10 %

Vegetative period.......... + 10 %

During yield formation...... -12 %

-3 % <= + 15 %

● HI <= 40.0 % (Reference HI)

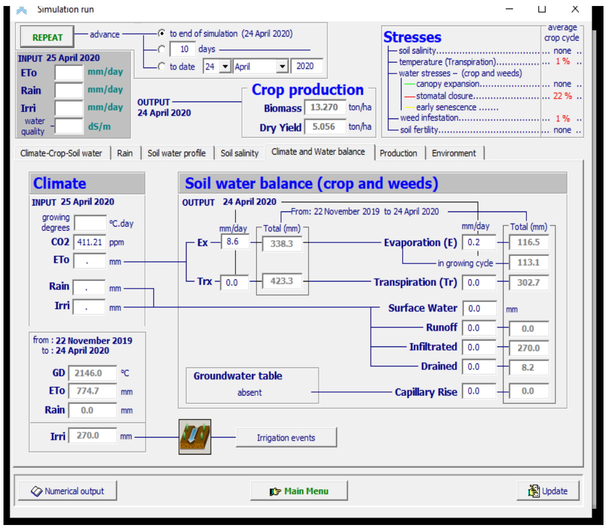
Flowering period

Degree of pollination .... 100 %

● HI <= 40.0 %

Harvest Index 40.0

HI(adjusted) = 38.8 % = 0.97 x 40.0 %



advance ● to end of simulation (24 April 2020)

○ 10 days

○ to date 24 April 2020

INPUT 25 April 2020

ETo mm/day

Rain mm/day

Irri mm/day

water quality dS/m

OUTPUT 24 April 2020

Crop production

Biomass 13.270 ton/ha

Dry Yield 5.056 ton/ha

Stresses (average crop cycle)

- soil salinity........ none
- temperature (Transpiration)........ 1 %
- water stresses – (crop and weeds)
  - canopy expansion........ none
  - stomatal closure........ 22 %
  - early senescence ....
- weed infestation........ 1 %
- soil fertility........ none

Climate

INPUT 25 April 2020

growing degrees °C.day

CO2 411.21 ppm

ETo . mm

Rain . mm

Irri . mm

from : 22 November 2019 to : 24 April 2020

GD 2146.0 °C

ETo 774.7 mm

Rain 0.0 mm

Irri 270.0 mm

Soil water balance (crop and weeds)

OUTPUT 24 April 2020

From: 22 November 2019 to 24 April 2020

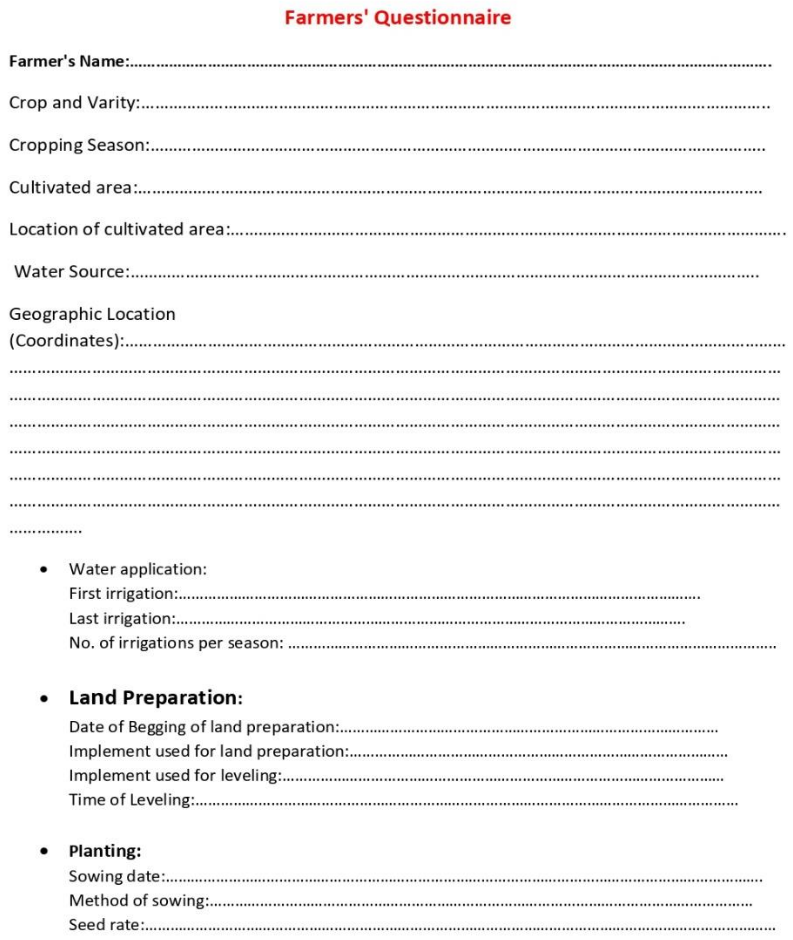
	mm/day	Total (mm)
Ex	8.6	338.3
Trx	0.0	423.3

	mm/day	Total (mm)
Evaporation (E)	0.2	116.5
in growing cycle		113.1
Transpiration (Tr)	0.0	302.7
Surface Water	0.0	mm
Runoff	0.0	0.0
Infiltrated	0.0	270.0
Drained	0.0	8.2
Capillary Rise	0.0	0.0

Groundwater table absent

Annex B

Field Survey:



Farmers' Questionnaire

Farmer's Name:…………………………………………………………………………………………………

Crop and Varity:……………………………………………………………………………………………

Cropping Season:…………………………………………………………………………………………

Cultivated area:……………………………………………………………………………………………

Location of cultivated area:………………………………………………………………………………

Water Source:………………………………………………………………………………………………

Geographic Location
(Coordinates):………………………………………………………………………………………………
……
……
……
……
……
……
……………

- Water application:
  First irrigation:……………………………………………………………………………………
  Last irrigation:……………………………………………………………………………………
  No. of irrigations per season: ……………………………………………………………………

- **Land Preparation:**
  Date of Begging of land preparation:………………………………………………………………
  Implement used for land preparation:………………………………………………………………
  Implement used for leveling:………………………………………………………………………
  Time of Leveling:……………………………………………………………………………………

- **Planting:**
  Sowing date:…………………………………………………………………………………………
  Method of sowing:……………………………………………………………………………………
  Seed rate:……………………………………………………………………………………………

- **Fertilizer application:**

  Type of Fertilizer used:……

  How much of fertilizer did you apply?

Date of Fertizer	Application (1)	Application(2)	Applicaion(3)
Which type of Ferti			
How Much of(F) did apply			
F/ application method			

- **Pest and disease:**

  Did you affected by any pest and disease during the cropping season?

  Yes…………………………….( )
  No…………………………….( )

  If yes, specify the level of infestation:

  High…………………………..( )
  Moderate…………………..( )
  Low……………………………( )

- **Harvesting:**

  Date of harvesting:…………………………………………………………………………………………………
  Method of harvesting:…………………………………………………………………………………………..
  Grain yield:……..

Data Collection:

DECLARATION

on authenticity and public assess of final essay/thesis/master's thesis/portfolio[1]

Student's name: __Elsadig Bashir Mohammed Omer

Student's Neptun ID: __JINON8

Title of the document: __Master's Thesis

Year of publication: __2023

Department: __Water Management and Climate adaptation

I declare that the submitted final master's thesis is my own, original individual creation. Any parts taken from another author's work are clearly marked and listed in the table of contents.

If the statements above are not true, I acknowledge that the Final examination board excludes me from participation in the final exam, and I am only allowed to take final exam if I submit another final essay/thesis/master's thesis/portfolio.

Viewing and printing my submitted work in a PDF format is permitted. However, the modification of my submitted work shall not be permitted.

I acknowledge that the rules on Intellectual Property Management of Hungarian University of Agriculture and Life Sciences shall apply to my work as an intellectual property.

I acknowledge that the electric version of my work is uploaded to the repository system of the Hungarian University of Agriculture and Life Sciences.

Place and date: Gödöllő; 2023.04.

Student's signature

---

[1] Please select the one that applies, and delete the other types.

STATEMENT ON CONSULTATION PRACTICES

As a supervisor of Elsadig Bashir Mohammed Omer (Student's name) JINON8 (Student's NEPTUN ID), I here declare that the master's thesis has been reviewed by me, the student was informed about the requirements of literary sources management and its legal and ethical rules.

I recommend/don't recommend[1] the final essay/thesis/master's thesis/portfolio to be defended in a final exam.

The document contains state secrets or professional secrets: yes no*[2]

Place and date: 2023 year 05 month 02 day

Internal supervisor