THE ANALYSIS OF THE AGRICULTURAL CROP WATER PRODUCTIVITY BEHAVIOURS IN SEMI-ARID AND HUMID REGIONS FOR IRRIGATED AND RAINFED AREAS, CASE STUDIES SUDAN AND RWANDA

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ABSTRACT

The agricultural water demand is increasing in semi-arid and humid regions. Agricultural water use efficiency is key to monitor and improve crop water productivity in changing climate. The arid or semi-arid regions face water scarcity problems. The objective of this research is to analyse crop water productivity behaviour in semi-arid and humid climates using the Gezira irrigation scheme of Sudan and Nasho irrigation scheme of Rwanda as semi-arid and humid regions, respectively. The research aim was achieved by quantifying, analysing, and comparing the crop water use indicators such as transpiration, evapotranspiration, biomass production, and gross crop water productivity in both semi-arid and humid climates for a period of three years from 2018 to 2020.

For the Gezira irrigation scheme, the results show the average seasonal transpiration values of 402, 322, and 713 mm/season for groundnut, sorghum, and cotton (both summer and winter) for the summer season and 395, 415, and 434 mm/season for onion, pigeon pea and wheat, respectively for the winter season. While average seasonal evapotranspiration of 564, 496, and 965 mm/season are obtained for groundnut, sorghum, and cotton (summer and winter), respectively for the summer season and 491, 517, and 540 mm/season for onion, pigeon pea, and wheat, respectively for the winter season. The overall average seasonal TBP are 2991, 2148 and 6359 kgDM/ha/season for groundnut, sorghum, and cotton, summer crops and 3225, 3246, and 3094 kgDM/ha/season for onion, pigeon pea and wheat as winter crops. While average seasonal gross crop water productivity values are 0.56, 0.43 and 1.96 kg/m^3 for groundnut, sorghum, and cotton, summer crops and 0.73, 0.77, and 0.76 kg/m^3 for onion, pigeon pea and wheat, respectively as winter crops.

For Nasho irrigation scheme, the results show the average seasonal transpiration values of 306 and 323 mm/season for beans and maize for the summer season and 364 and 420 mm/season for beans and maize, respectively for the winter season. While average seasonal evapotranspiration of 399 and 415 mm/season for beans and maize are obtained for the summer season and 493 and 538 mm/season for beans and maize, respectively for the winter season. The average seasonal TBP of 10534 and 11169 kgDM/ha/season for beans and maize as summer crops and 12440 and 13349 kgDM/ha/season for beans and maize as winter crops. Also, gross crop water productivity of 2.67 and 2.70 kg/m^3 for beans and maize, summer crops and 2.50 and 2.43 kg/m^3 for beans and maize as winter crops are obtained.

Comparative analysis of crop water consumption between semi-arid and humid climates finds the higher values of evapotranspiration for semi-arid climate compared to the humid climate in the summer season but both climates have almost the same values in the winter season.

Climate normalisation of crop water productivity approach was tested for groundnut, pigeon pea, sorghum, and wheat for semi-arid climate and for irrigated beans and maize of humid climate during summer and winter seasons. For semi-arid climate, the average values of CWP and CWPc are 0.57, 0.4 and 0.99, 0.62 kg/m^3 for groundnut and sorghum, respectively and 0.77, 0.6 and 1.42, 1.46 kg/m^3 for pigeon pea and wheat, respectively were obtained. For humid climate, the 2.5 and 3,2 kg/m^3 of CWP and CWPc for winter beans and 3.0 and 3.0 kg/m^3 of CWP and CWPc for summer beans were found. Also 2.7 and 2.0 kg/m^3 of CWP and CWPc for summer maize and 2.4 and 2.4 kg/m^3 of CWP and CWPc for winter maize. The study concludes that semi-arid climate crops are more affected by climate constraints than humid climate crops, especially for winter seasons. In both climates, the C3 crops are more affected than the C4 crops. This study also concludes that the Climate normalisation of the CWP approach can help at regional scale to evaluate the spatial variability of crop water productivity gaps within the irrigation

schemes, especially in arid and semi-arid climates where the agricultural crops are highly affected by the climate constraints.

Keywords: WaPOR, Crop Water Productivity, Climate normalisation of crop water productivity, Semi-arid climate, Sudan, humid climate, and Rwanda.

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LIST OF ABBREVIATIONS

ACWP	Agricultural Crop Water Productivity
CM	Crop Mask
CWP	Crop Water Productivity
CWPc	Climatically normalised Crop Water Productivity
DMP	Dry Matter Production
ET	Evapotranspiration
ETIa	Actual Evapotranspiration and Interception
ECMWF_ERA5	European Centre for Medium-Range Weather Forecasts 5th edition
FAO	Food and Agriculture Organization
FRAME	Consortium consisting of eLEAF, VITO, ITC, and the Waterwatch Foundation
GBWP	Gross Biomass Water Productivity
I	Interception
LAI	Leaf Area Index
NBWP	Net Biomass Water Productivity
NPP	Net Primary Products
R^2	Coefficient of Determination
RET	Reference Evapotranspiration
RMSE	Root Mean Square Error
STD	Standard deviation
TBP	Total Biomass Production
T	Transpiration
WaPOR	FAO portal to monitor Land and Water Productivity through Open access Remotely sensed derived data

1. INTRODUCTION

1.1. Background

The world population is rapidly growing; water usage is also increasing due to this population growth. Agriculture, industries, hydropower, domestic activities are the main water use domains. Agricultural activities are the most water consumables(Sharma et al., 2018). Several years ago, the agriculture domain relied on rainfed systems. But nowadays, the integration of irrigation technology causes the water use to be higher(Vladimirova et al. 2018). This increases the freshwater demand and limitation. The monitoring of agricultural crop water productivity is vital for water resources management to reduce water scarcity, ensure food security and water sustainability in the future (Zwart & Bastiaanssen, 2004).

According to Li et al. (2008), the agriculture sector is challenged by the production of more food from less water usage. This can be achieved by monitoring crop water productivity to improve the efficiency of water resources usage and management. The term water productivity is used in agriculture as an indicator of water use efficiency to evaluate agricultural water use and sustainability. Food Agriculture Organisation categorised crop water productivity into two components, gross and net biomass water productivity.

Evapotranspiration is an essential indicator of agricultural crop water consumption this means that it is very important to quantify seasonal evapotranspiration of agricultural crop fields to monitor agriculture water use. In 2015, Yang et al. (2015) were estimated the actual evapotranspiration using plot scale experiments for monitoring of crop water productivity. However, the actual evapotranspiration differs from global to region, the differences (water productivity gaps) can be caused by different factors such as applied irrigation practices, farming systems, water use management, and cropping techniques(Cai et al., 2011). Furthermore, the differences are not only relied on the above-mentioned factors but also the climatic conditions that may affect the actual evapotranspiration of a region and cause the water productivity gaps.

The climate constraints have also an implication to food security even though there were other factors such as soil nutrients, applied methods, and so on which might cause these water productivity gaps. Majumder et al. (2014) indicated that the irrigated areas are more productive than rainfed areas in both semi-arid (higher evaporative demand) and humid (lower evaporative demand) climates.

Globally, the water usage demands are increasing especially in the agriculture sector which is the most water consumable sector due to high demands for water to grow more food to feed the rapidly growing population while the cropland is remaining the same or decrease throughout the world. In this regard, Shiklomanov, (2000) concluded that the proportion improvement of water productivity will make the world feed the additional population in the future generation to ensure water sustainability and food security. The improved water productivity efficiency is also helpful to sustain the already stressed environment while the climate is changing(Kang, Khan, & Ma, 2009).
Not only the agriculture sector is affected by the higher water demands and climate conditions but also the other human development activities such as hydropower, industries, and drinking water and are significantly affected (Kang et al., 2009). Globally, the spatial variability of water productivity was poorly analysed and was limited by available technology and skills (Zwart & Bastiaanssen, 2004). Using the GIS-based environmental policy integrated climate (GEPIC) model is a first attempt to simulate the water productivity of wheat and seasonal evapotranspiration of their fields (Zwart et al., 2010a).

Kang et al. (2009) conclude that the variabilities of climatic conditions significantly change the water productivity behaviours year to year. The other different kinds of literature indicated that there are spatial and temporal variabilities of the crop water productivity under different climates (Bastiaanssen & Steduto, 2017).

Low crop water productivity has an impact on food security and social-economic developments. It is essential to monitor water productivity indicators under semi-arid and humid climates to analyse and compare its behaviours for rainfed and irrigated areas to recommend strategic measures on possible solutions concerning water productivity improvement in both climates(Kukal & Irmak, 2018). Therefore, there are two case studies which are Sudan and Rwanda. Sudan was used as a semi-arid (higher evaporative demand) climate and Rwanda was selected as a humid (lower evaporative demand) climate.

1.2. Problem Statement

Food insecurity became a global issue due to climate change and the demand for population growth; it is the most crucial problem in the 21st century. Food is not only the affected sector, but water resources are also stressed especially for African countries due to the water management problems in agricultural domain(Sharma et al., 2018). Address the problems of food insecurity and water scarcity, requires growing enough food to feed the population and improving water use efficiency especially in the agricultural sector and sustaining the disturbed environment(Kang et al., 2009).

Crop water productivity is influenced by climate change and its effects are predicted to be different in different areas as they will increase and decrease in some areas depending on the latitude and applied irrigation systems. The modelling outputs show that when there is an increase in precipitation increases the water productivity too, this means that the crop yields will also increase. Water productivity is more sensitive to rainfall than temperature(Zwart & Bastiaanssen, 2004). When water availability is decreasing, the crop production will also be reduced, and the soil with the high field capacity will maintain the crop production and reduce the impact of the water limitation.

Due to the rainfall variations and variability of soil moisture content, the crop yields will decline in the future and will have a negative impact on food security (Jin et al., 2018). It is crucial to analyse the influence of climate constraints on water productivity and crop yields to develop possible solutions. Besides this, the agricultural sector must produce more food and improve crop water productivity (Zwart & Bastiaanssen, 2004). The above-mentioned water scarcity, climate change, stressed environment and food insecurity are not only global problems but occur in Rwanda and Sudan which are the research case studies.

The major problem for future generations in both countries is to provide enough food for the rapidly increasing population under stressed environments. To solve the problem, modern agriculture should consider the monitoring of land and water productivity to improve the usability of water resources.

In this study, the crop water productivity, NPP, Actual Evapotranspiration and Interception, and biomass production were quantified under semi-arid and humid climates using the WaPOR Data, level 2. Then, the analyses of this transpiration, actual evapotranspiration, total biomass production and crop water productivity (gross biomass WP, and net biomass WP) behaviour under two climates was also done. The crop water productivity gaps can occur in form of yield gaps which are the gaps between potential and actual yields. The variability of evapotranspiration driven by climatic conditions has a negative impact on crop water productivity. These can be reduced by irrigation and other land management practices (Sadras et al., 2015).

The quantified CWP values in both Sudan and Rwanda were analysed and compared for each crop type but the study cannot compare CWP values of two different climates without performing the climate normalisation(Karimi et al., 2019). In this regard, the climate normalisation of crop water productivity (CWPc) was performed to analyse the impact of climate variability on crop water productivity. The Climate-normalised crop water productivity values were compared with the crop water productivity values in both dry and humid climates. Through this comparison, the effects of climate on crop water productivity were analysed. To solve this research problem, the study needs to fulfil following objectives.

1.3. Objective

The main objective of this study is to analyse and compare the behaviour of the agricultural crop water productivity indicator under semi-arid and humid regions on various crop types in both rainfed and irrigated areas using dekadal time series from 2018 to 2020.

1.3.1. Specific Objectives

- To quantify the agricultural crop water productivity using FAO WaPOR data portal, level II data for irrigated and rainfed areas such as Gezira and Nasho irrigation schemes respectively for 2018, 2019 and 2020 dekadal based time series.
- To analyse the spatial and temporal variability of the quantified Actual Evaporation, Transpiration, Interception, Net Primary Productivity, and Crop Water Production in both regions from 2018 to 2020.
- To perform climate normalisation of crop water productivity in both semi-arid and humid climates for comparison of CWP values.

1.4. Research Questions

- How to quantify the agricultural crop water productivity using FAO WaPOR data portal, level II data for the selected study areas and period?
- How do T, AETI, NPP, and crop water production vary between semi-arid and humid regions under irrigated and rainfed areas?
- How can Normalised CWP be applied in comparison to crop water productivity between semi-arid and humid regions?

1.5. The novelty of the study

There is a sudden increase in water demands and scarcity nowadays due to the rapidly growing population and climate change (Vladimirova et al. 2018). The agricultural sector is among the most freshwater consumable domains, and it is responsible to deal with how can produce more food to feed the growing population by using less water to sustain water resources in the future. The global data and models were used to perform climate normalisation of crop water productivity at global scales such as the WATPRO model, GEPIC water balance model, etc (Bastiaanssen & Steduto, 2017). The Food Agriculture Organisation (FAO) developed an open online remote sensing database portal (WaPOR) to monitor land and water productivity to improve and reduce water productivity gaps to ensure and sustain food security in the future. This study is using WaPOR data level 2 and ILWIS Software in the quantification and analysis of agricultural crop water productivity indicators in both semi-arid and humid climates and testing the applications of climate normalisation of CWP approach at the regional scale and evaluating the performance of irrigation schemes (mapping crop water productivity gaps) using WaPOR based methods.

2. LITERATURE REVIEW

2.1. Agricultural crop water productivity (ACWP)

The crop water productivity (Kg/m3) as a water use efficiency indicator, is used to evaluate the agricultural land and water productivity to grow more food with the same amount of water and land resources. It is also used to define gaps for water resources management and sustainability (Megan L. B et al., 2018). the crop water productivity (CWP) is defined as the developed biomass production per unit of accumulated transpired (T) and evaporated (E) water during the crop cycle of a given period(FAO, 2018a). Since the main goal of the agriculture sector is to grow more food without increasing water consumption, the improvement of the crop water productivity approach is essential to overcome water use efficiency limitations and ensure its sustainability in the future. To achieve high water use efficiency and sustainability, RS based methods, algorithms and field experiments were developed to monitor and evaluate crop water productivity performance and suggest measures for improvement.

2.2. Remote Sensing of crop water productivity

Nowadays, remote sensing technology is becoming popular for geospatial problems handling where it is used in many fields such agriculture, water resources management, environment, health-sciences, etc.

Regarding to agriculture sector, remote sensing is used for different purposes including monitoring of land and water productivity and RS techniques also can be used to assess the performance of irrigation system water uses(Karimi et al., 2019). Sharma et al. (2018) indicated that the physical water productivity (PWP) is 0.5 kg/m^3 and 0.4 kg/m^3 in Punjab and Haryana respectively while the irrigation water productivity in these regions is relatively low at 0.22 kg/m^3 which is indicating the inefficient irrigation water use in these states.
Thenkabail, (2009) using remote sensing products estimated crop cotton water productivity in central Asian study area, the results showed that about 11 % area had water productivity > 0.4 kg/m^3 34% area had moderate water productivity of 0.3 to 0.4 kg/m^{3}and 55% area had the water productivity of less than 0.3 kg/m^3. They also said that for the other crops the trends were similar with the cotton. Teshite, (2018) using FAO WaPOR estimated the water productivity in the upper Awash River basin (Ethiopia) for sugarcane in terms of AGB which was about 1.43 -3.46 kg/m^3 while the AquaCrop model estimates gave 2.49 – 5.39 kg/ m^3. The author concluded that the FRAME Water Productivity estimates were lower than the model estimates due to the insufficient data calibration of the model.
Choudhury and Bhattacharya, (2018) reported that in India, average WP of rice was 0.72 kg/m^3 and 0.61, 1.27, 8.04 and 1.05 kg/m^3 for different crops such as paddy, maize, cotton, sugarcane, and sunflower, respectively. They concluded that the WP of a certain crop can vary depending on different factors such as soil moisture content in the root zone, field management, and the crop water consumption for growth. Zwart et al. (2010a) simulated crop water productivity for wheat using WATPRO model and reported the highest wheat water productivity average values which are 1.52 Kg/m^3, 1.4 kg/m^3, and 1.39 kg/m^3 for Egypt's Nile delta, Kings County in USA, and The Netherlands, respectively.

2.3. Crop growth and Productivity models

The crop growth models are advanced algorithms developed to monitor crop development and production. Several crop models used to monitor crop water productivity are WATPRO(Zwart et al., 2010b), CROPWAT(Onyancha & Gachene, 2017), AquaCrop(Steduto et al., 2009), DSSAT(Jones et al., 2003), and SCOPE(Van Der Tol et al., 2009). But also

surface energy balance-based models can help. Using the ecohydrological soil-water-atmosphere-plant (SWAP) model, remote sensing, GIS and field experiments; Singh, (2002) computed WP values for crops such as wheat, rice, and cotton in Sirsa district, northwest India and the average WP was 1.39, 0.9, and 0.23 kg/ m^3 respectively.
Bastiaanssen and Steduto, (2017) estimated the values of 2.45, 2.4, and 4.9 kg/m3 for wheat, rice and maize respectively for the 99^{th} percentile of climatic normalised crop water productivity. They said that there was a significant scope to generate the same quantities or more using less water, by executing best practices. At the global scale, they recommended governments use the global water productivity score (GWPS) to define national water and food policies and agriculture planning to meet the sustainable development goals. At local scale levels, the water productivity score helps to improve farmers water management practices and rise the crop yields for both irrigated and rainfed crops.

2.4. Climate Normalisation of crop water productivity

Recently the natural environment and human-made activities have a significant contribution to climate change due to the economic development by emitting a lot of greenhouse gases into the atmosphere resulting in droughts and global warming that affect crop water productivity(Kingra & Singh, 2016). Not only climate change which influences crop water productivity but also rapid population growth causes high-water demand especially in the agriculture sector due to the high water usage in irrigation to grow more food to feed the population (Vladimirova et al., 2018). The water resources organisations, planners, users and other stakeholders may think about how to deal with the impact of climate change on crop production and water productivity in the future (Kingra & Singh, 2016). Improving the agricultural water use efficiency is one of the solutions that may reduce the water scarcity problem. As reported by Zwart et al. (2010a), crop water productivity is linearly regressed with evapotranspiration after normalised for climate effects. In this regard, the concept of climate normalisation of crop water productivity for crop types was developed to allow significant comparison between CWP values of two different climates from which the possible improvements can be advised accordingly (Kingra & Singh, 2016).
Bastiaanssen and Steduto, (2017) defined climatically normalised crop water productivity (CWP_c) as the ratio between actual crop yield and sum of actual evapotranspiration multiplied by the ratio between the sum of reference evapotranspiration of the area and worldwide climatic average reference evapotranspiration (ΣETo(c)).

$$\mathrm{CWPc} = \frac{\mathrm{Y}}{\Sigma ET} \times \frac{\Sigma \mathrm{ETo(a)}}{\Sigma \mathrm{ETo(c)}} \text{ (kg m}^{-3}\text{)(Bastiaanssen \& Steduto, 2017)}$$

Where ΣET is total actual ET for a growing season, ΣETo is seasonal reference evapotranspiration (estimated using the Penman-Monteith Equation), ΣETo(c) is the climatically normalised total ETo worldwide for a given crop, ΣETo(a) is total ETo in a given area. The ΣETo(c) is taken from literature and its values vary depending on the crop types and the values of 690, 545, and 555 mm/season are for Maize, Wheat and Rice, respectively (Bastiaanssen & Steduto, 2017). The climate normalisation of CWP helps in comparison of crop water productivity values under different climates to get significant differences that can be used to analyse the impact of climate constraints on crop production and water productivity.
Blatchford et al. (2018) used the SEBAL model to estimate CWP and normalised it for the climate in the West Bank, Palestine, estimated distribution of winter rotation crop water productivity (CWP) and winter tuber normalised Crop Water Productivity (CWPc) with 13.0 kg/m^3 and 13.4 kg/m^3, respectively. They concluded that the winter tuber normalised Crop Water Productivity has a higher standard deviation compared to the winter rotation Crop Water Productivity.
Bastiaanssen and Steduto, (2017) also simulated crop water productivity of wheat using the WATPRO (WATer PROductivity) model and normalised it for the climate. They reported that Egypt, Uruguay, and Mexico are the countries with the highest average normalised crop water productivity values of 2.65, 2.40, and 2.18 Kg/m3 respectively at a national scale.

In this study, WaPOR based methods were used to quantify crop water productivity for cotton, wheat, onion, pigeon pea, sorghum, and groundnuts in Sudan, Gezira irrigation scheme as semi-arid climate region and for maize, beans, banana, and sorghum in Rwanda, Nasho irrigation scheme and surrounding rainfed areas as humid climate region. More information about the study area, data and applied methods are described in chapter three.

2.5. Agricultural crop water productivity in Rwanda

In Rwanda, most agricultural activities rely on rainfall. Rwanda has three seasons, season A (long rainy season with sufficient precipitation starting from September to February), season B (short rainy season starting from February to May with insufficient precipitation) and season C (dry season starting from June to August (Magruder & Ndahimana, 2020). The agriculture sector plays an important role in Rwanda economic development where it contributes 33% of gross domestic production(GDP)(Lamek et al., 2016). The overall irrigated cropland is 4% of the total cultivated cropland (Rwanda Agriculture Board, 2017). The irrigation systems are usually suitable for the eastern part which is the warmest region of the country where precipitation is scarce.

2.6. Agricultural crop water productivity in Sudan

The agriculture of Sudan as arid and semi-arid country usually relies on watering technology for winter season where there is no rainfall during the entire season but for summer season the agriculture relies on both rainfall and irrigation. From 2000 to 2014, four surface energy balance based models such as mapping evapotranspiration with high resolution internalized calibration (METRIC™), surface energy balance algorithm for land (SEBAL) developed by Sebastian and MOD16ET were applied in Gezira irrigation scheme to estimate summer and winter crop ETa and a simplified surface energy balance (SSEB) model was considered as the best performing crop ETa estimate model(Al Zayed, 2015). The purpose of this study was to evaluate the performance of Gezira irrigation scheme through an assessment of crop water productivity in both summer and winter growing seasons. Ahmed et al. (2010) used remote sensing to estimate wheat water requirements, yield and water productivity in Gezira scheme as well. Also Al Zayed et al. (2016) indicated that the monitoring of agricultural crop water productivity can help in the management of water use efficiency throughout Gezira irrigation scheme as applied in many other places.

The estimation of water requirement and water productivity of Sesame crop in dryland areas of Sennar State, in Sudan, indicated that the average values of water productivity was 0.18 kg/m^3 and 0.29 kg/m^3 in semi-arid site and semi-humid site, respectively (Mohamoud et al., 2019).
In this study, WaPOR based method was used to quantity crop water productivity as an indicator of water use efficiency (WUE) for a selected area within the Gezira irrigation scheme (designed by FAO for a WaPOR level 3 validation study) and it was normalised for climate to compare its values with the humid climate (Rwanda) values.

3. METHODOLOGY

3.1. Study Areas Description

Two case studies with different climatic conditions were selected based on the research objectives. Rwanda as a humid climate and Sudan as a semi-arid climate country are used to carry out this research. Nasho and Gezira are selected specific study areas of the research as humid and semi-arid climatic regions of Rwanda and Sudan, respectively.

3.1.1. Rwanda

Rwanda, a country of a thousand hills with an area of 2,634,000 ha, situated in East Africa, is a land locked country with a population of more than 12.3 million (NISR, 2019). Rwanda has a topographic elevation of 1500 to 2500 meters and has coordinates of -2 latitudes and 30 longitudes. In Rwanda, land use is classified into six classes such as natural vegetation, build-up area, water, irrigated area, rainfed area and bare soil (Lamek et al., 2016). In this study, Rwanda is considered as a humid climate region to compare their crop water productivity behaviours with a semi-arid country which is Sudan.

3.1.1.1. Climate

The climate is an essential element to consider when we are dealing with agricultural crop water productivity and food security. In this study, Rwanda climate is described by the precipitation and temperature variabilities. The precipitation of Rwanda is bimodal, Rwanda has two rainy seasons, the long rainy which starts from September to January and the short rainy starts from February to May. The annual mean precipitation varies between 750 mm and 1,128 mm for low and highlands, respectively. The dry season runs from late May to early September(Ministry of Environment, 2017). Nasho irrigation scheme and surrounding rainfed areas are the specific study area of this study, they are in the eastern province which is the warmest region of the country. The figure3-1,2 show the long-term daily rainfall and average monthly rainfall for the eastern part. The data were taken at Kirehe station for 38 years from 1981 to 2018. Figure3-1 shows the long-term daily precipitation of the study area. While figure3-2 shows two rainy seasons per year of the study area, winter season starts in September and ends in February and summer starts in March and ends in July.

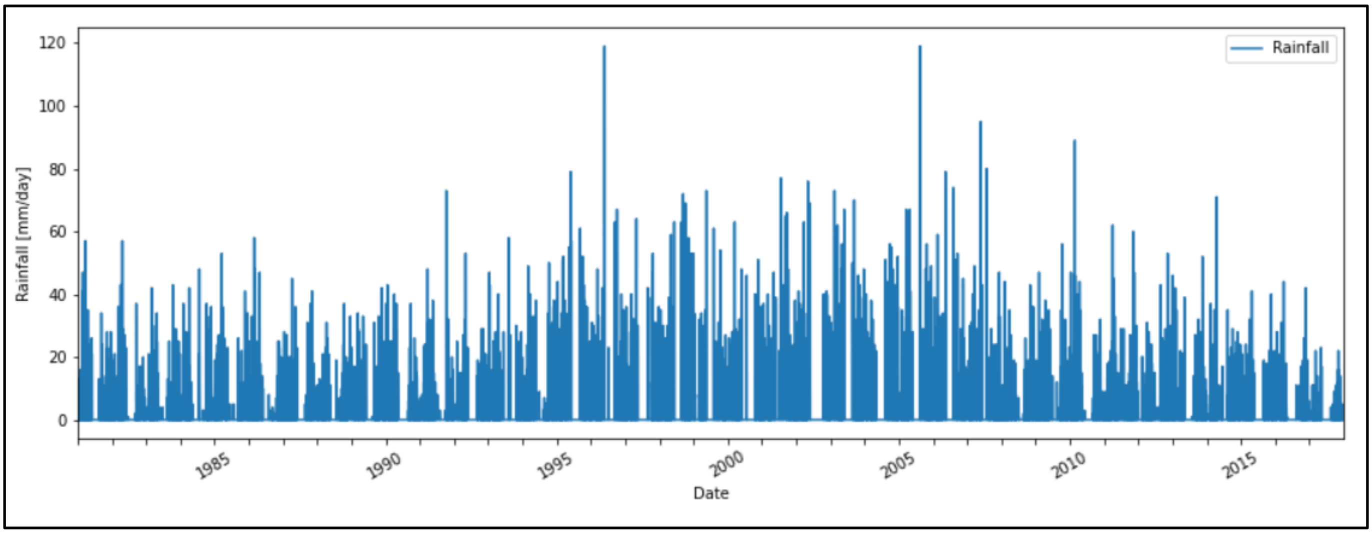

Figure 3-1 Long term daily precipitation from January 1981 to December 2017

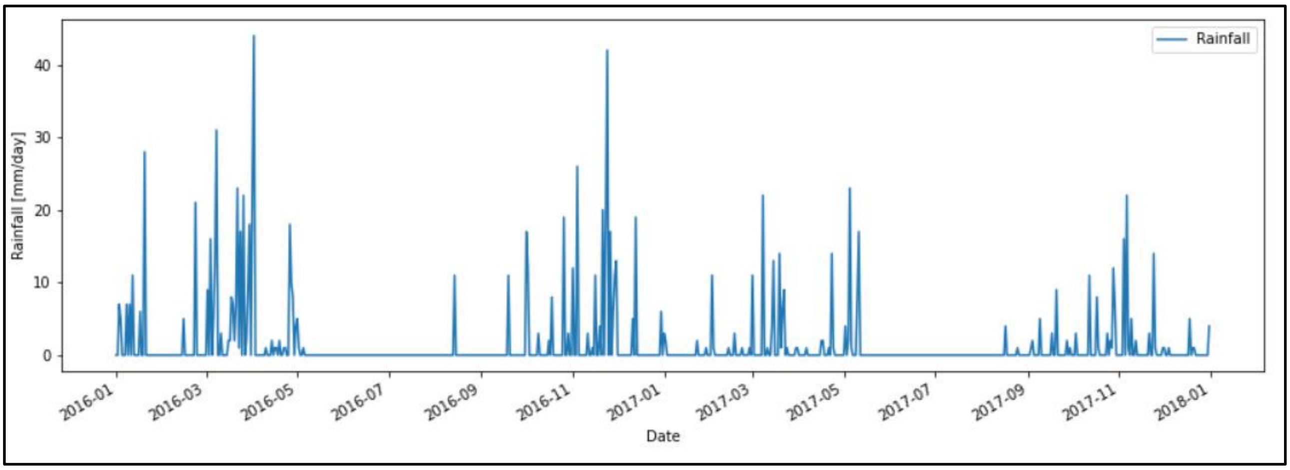

Figure 3-2: Two years daily precipitation from January 2016 to December 2017

Rwanda is located in the tropical belt, which causes Rwanda annual average climate temperature to vary between 15^{o} C and 20^{o} C but also varies depending on the topography. The warmest temperature is found in the eastern part of Rwanda(Ministry of Environment, 2017). Nasho sector which is the research study area is located in this warmest region of Rwanda. Using the daily air temperature of the study Nasho area taken at Kirehe station, which is located near the study area, the results are presented in the following figures as a daily average, minimum, and maximum air temperature of the area for 35 years from January 1983 to December 2017. These climatic data were provided by Rwanda Meteorological Agency.

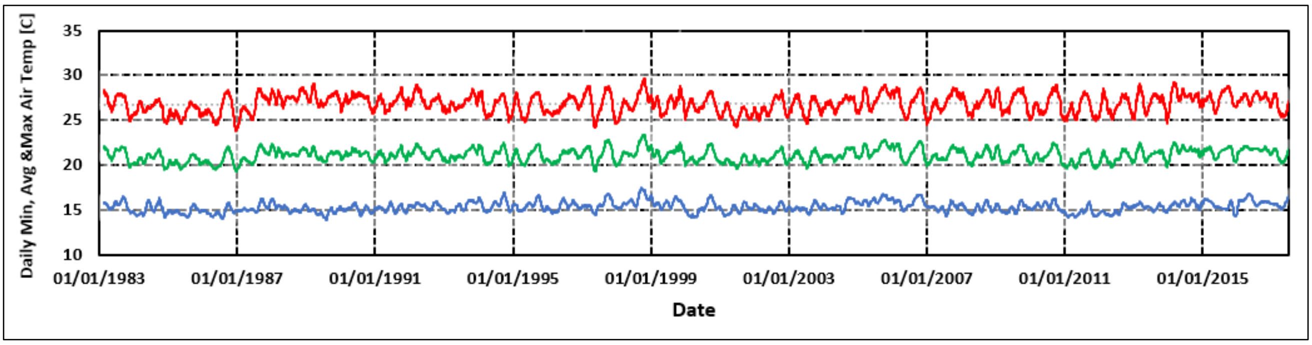

Figure 3-3 long term daily Minimum, Maximum and Average temperature from January 1983 to December 2017

3.1.1.2. Irrigation and cropping systems

The Nasho irrigation scheme was selected as a specific study area in Rwanda, located in the eastern province, Kirehe district, Nasho sector along the Lake Cyambwe from which the irrigation water is pumped. It has an area of 1,206 ha irrigated using a centre pivot irrigation system to improve water productivity and water use efficiency. The scheme has two main separate growing seasons per year:

- Season (a): is starting from September to February.
- Season (b): is starting from March to July.

The main crop types cultivated in the scheme are maize, French bean, and soybeans. The system of one crop type per pivot and the crop rotations are applied in each growing season.

3.1.1.3. The rainfed agriculture

The surrounding non-irrigated crop land areas were used as a rainfed area of the study. The main cultivated crops are sorghum, banana, and beans which are considered in this study. The other crop types such as cassava, peas, and potatoes are cultivated on small fields and have mixed one another. The map below shows the Nasho irrigation scheme and rainfed study areas.

Location Map of Nasho Study Area

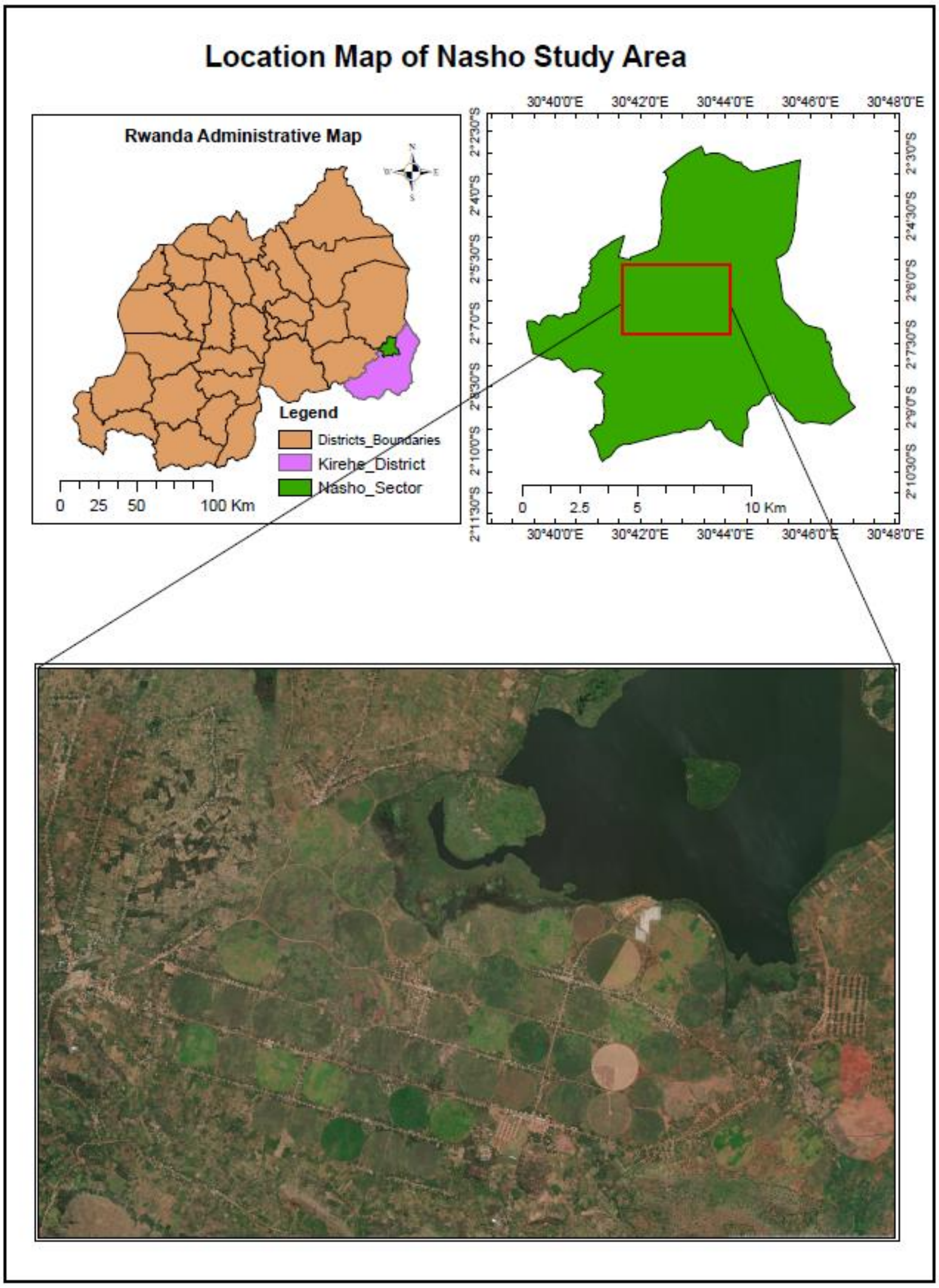

Figure 3-4 Nasho pivot irrigation scheme and surrounding rainfed areas

3.1.2. Sudan

Sudan is among the largest countries in Africa with an area of 250,581,000 ha, is in the northern part of Africa, south of Egypt. In this study, Sudan was considered a semi-arid climate region to be compared with the humid climate of Rwanda.

The Gezira irrigation area selected by FAO for validation of WaPOR level 3 with 104,000 ha is considered as the specific study area of this case study.

3.1.2.1. Climate

The climate is an essential element to consider when we are dealing with agricultural crop water productivity and food security. In this study, Sudan climate is described by temperature and precipitation variabilities.

Gezira scheme is in a semi-arid climate, the mean daily temperatures at Wad Wedani meteorological station is 31°C, 29°C, and 25°C in summer, Autumn, and winter seasons, respectively. Precipitation variability is also an important element to consider when describing climate. As a semi-arid climate, the Gezira scheme receives low rainfall where the annual average rainfall is 300 mm /year(Al Zayed, 2015). All rainfall is found in the summer season (July-November), less precipitation in Autumn (April-June) but no rainfall during the entire winter season from December to March (Al Zayed, 2015). The following figures show the daily minimum, and maximum air temperature and precipitation of the Gezira scheme for the last 38 years from 1981 to 2018 as taken at Wad Wedani meteorological station. The Climate data were provided by the Meteorological Authority of Sudan.

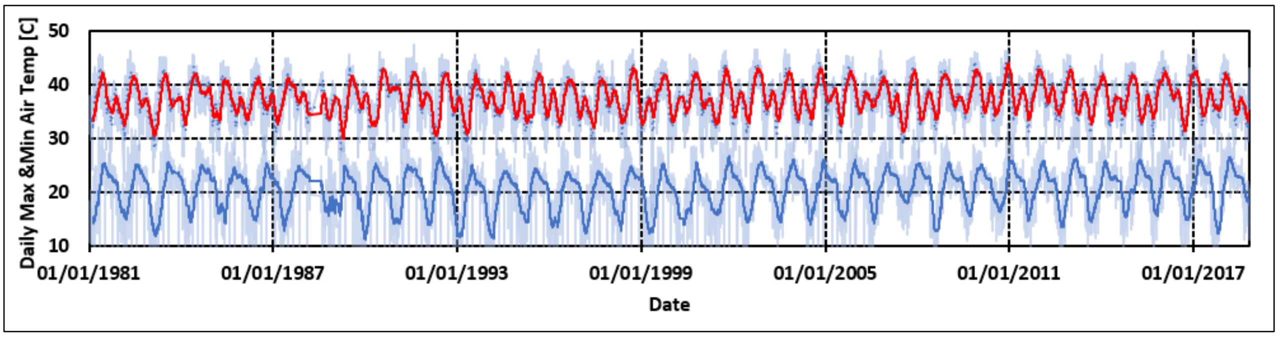

Figure 3-5 Daily maximum and minimum air temperature from January 1981 to October 2018

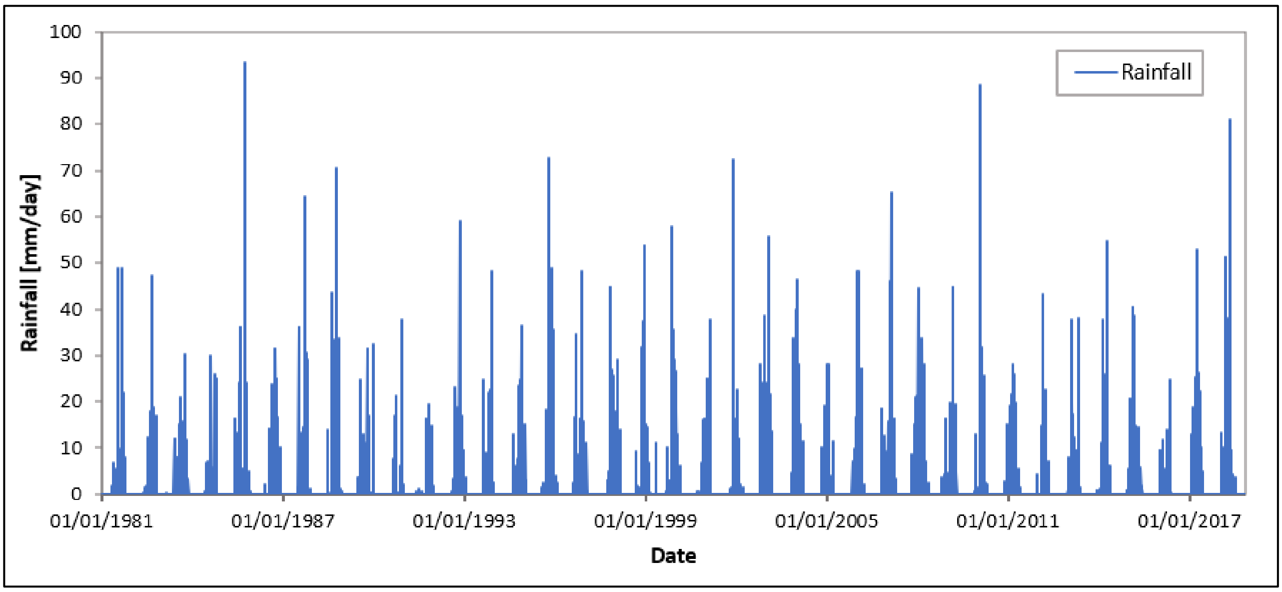

Figure 3-6 Long term daily precipitation for 38 years from January 1981 to December 2018

Figure3-7 shows precipitation events of two consecutive years of 2017 and 2018 for the Gezira irrigation scheme. There is a single rainy season throughout the year which starts from May to November and there is no rainfall during the entire period which starts from December to April every year. These show the availability of summer rainfall and lack of rainfall during winter season.

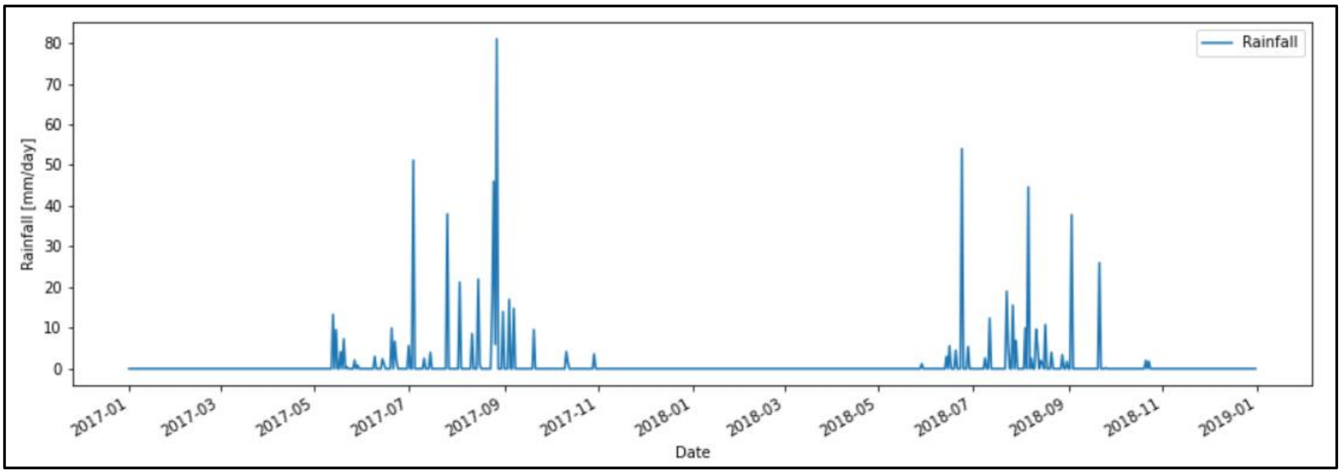

Figure 3-7 Two years daily precipitation from January 2017 to December 2018

3.1.2.2. Irrigation and cropping systems

The Level 3 Gezira irrigation area, a selected study area is either irrigated during the winter season or both irrigated and rainfed areas during the summer season. The area was designated by FAO as the WaPOR Level 3 study area, is about 200km south of Khartoum, is located (Figure 2) in the west of the city of Wad Medani on the Blue Nile. The L3 Gezira area is approximately 104,400 Ha (red boundary on Figure 8). It is part of the very large Gezira irrigation scheme with approximately 1,000,000 Ha, located between the White and Blue Nile, before their confluence near Khartoum. The water used for irrigation is taken from the Sennar dam which is constructed at the Blue Nile, and is distributed throughout the scheme using two main earth canals, Managel and Gezira with the discharge of 16 and 14.5 million m^3/day, respectively (Al Zayed, 2015). In this study, the WaPOR level 2 data with 100 m of spatial resolution and 10 days of the temporal resolution were used to quantify the crop water productivity of the study area. The area has non irrigated crop land during the summer season only. The agricultural activities in the Gezira scheme fully rely on the irrigation for the winter season.

The Gezira irrigation scheme has two separate growing seasons as above-named. The summer season starts from July to November. The cultivated summer crops are sorghum, cotton, groundnuts, and cotton, wheat, onion, and pigeon pea for the winter season which starts from December to March, and the crop rotation system is applied. Cotton is both summer and winter crop. The following map shows the location of the selected Gezira irrigation study area.

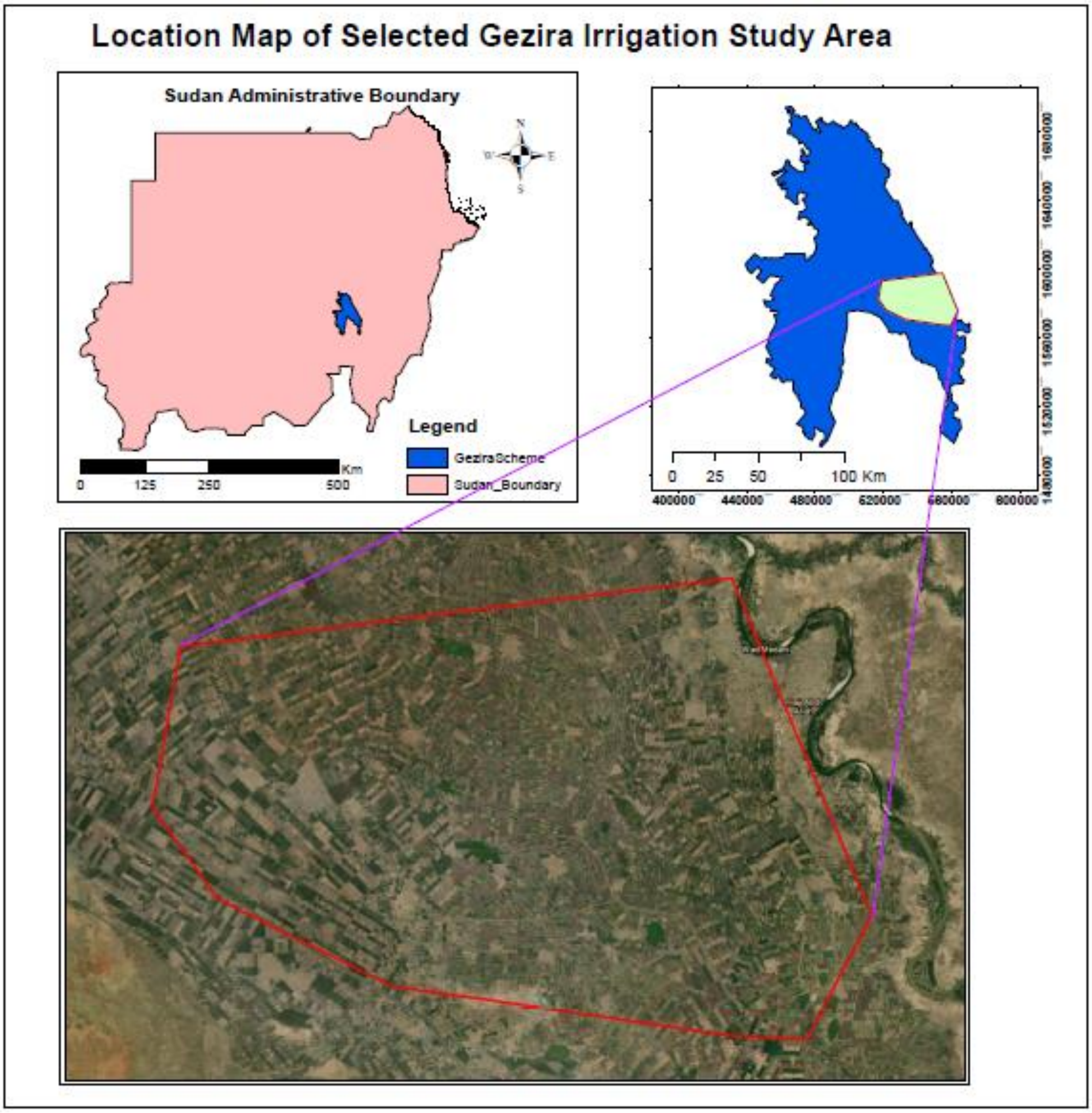

Figure 3-8 Selected study area as part of Gezira irrigation scheme

3.2. Methodological framework

The main activities of this study are shown in the following methodological flowchart.

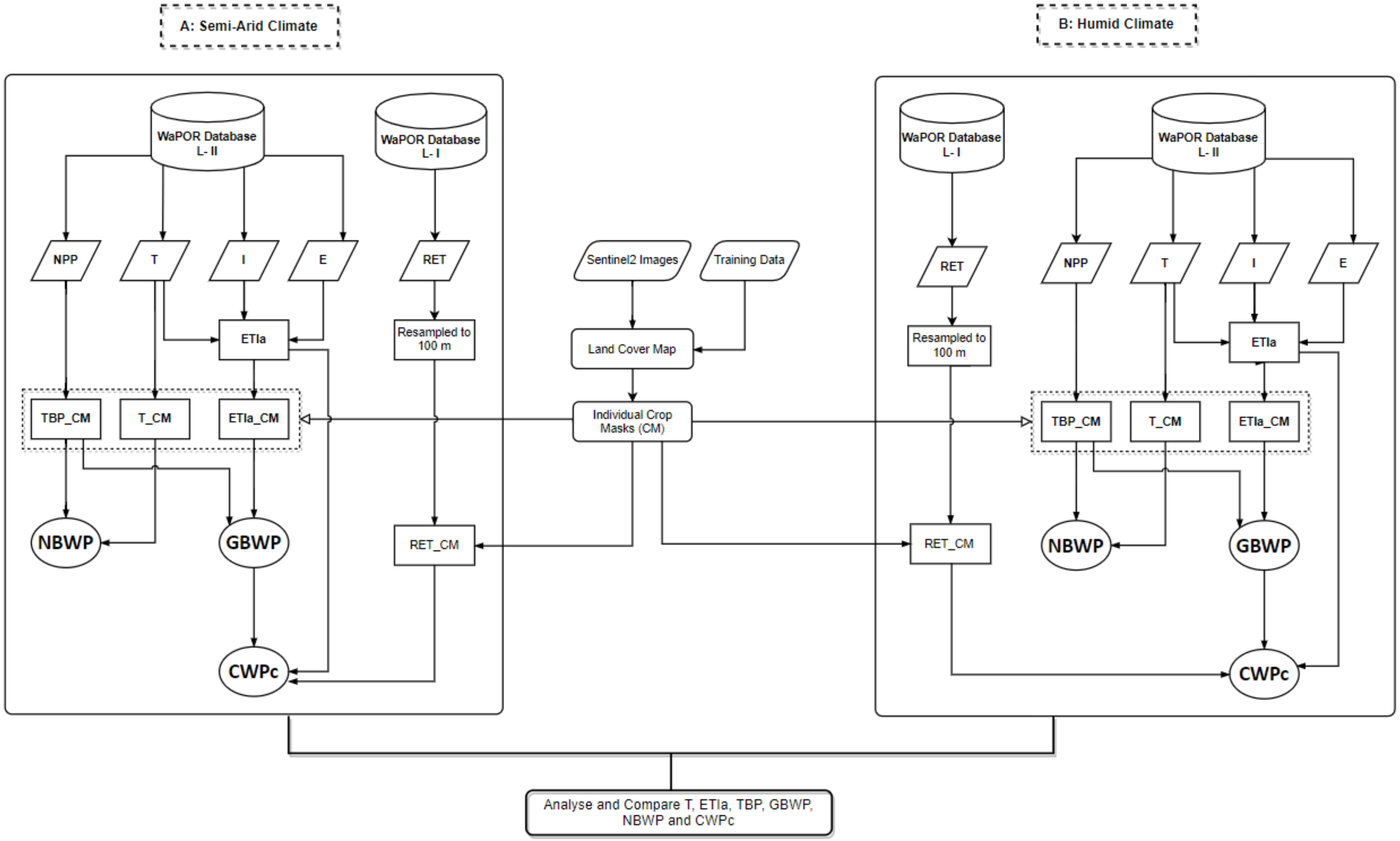

Figure 3-9 Methodological framework of the study

3.2.1. Main activities of the study

The above-mentioned methodological framework explains the main steps implemented for achieving the objectives of this research and the main activities are explained below.

3.2.1.1. Application of WaPOR based methods

In this study, the WAPOR based methods were used to quantify the crop water use indicators for the main cultivated crops for two agricultural growing seasons, summer, and winter from 2018 to 2020 in both Rwanda and Sudan. In the quantification process, the main applied steps are listed below.

- Calculation of dekadal Transpiration, Actual Evapotranspiration and Interception (ETIa) and Total Biomass Production (TBP).
- Calculation of seasonal ETIa and TBP.
- The quantified TBP, ETIa, and T were used to derive crop water productivity as Gross Biomass Water Productivity (GBWP) and Net Biomass Water Productivity (NBWP).
- Calculation of seasonal Reference Evapotranspiration (RET)
- Perform climate normalisation of Crop Water Productivity (CWPc). More details are explained in section 3.6.

3.2.1.2. land cover classification

The land cover classification was done to distinguish land use and land cover in the agricultural crop land of the selected study areas which are Rwanda and Sudan for summer and winter growing seasons. The classification was done for both irrigated and rainfed areas. For Nasho irrigation scheme, the main cultivated crops are maize, soybean, and bean. But for rainfed agriculture, the main crop types such as banana, sorghum, beans, soybean, and maize are mixed in the same crop field. The rainfed area is only considered for the Rwanda site which has two rainy seasons (Season A and Season B) a year. Season A starts in September and ends in February while season B starts in March and ends in July.

Regarding agricultural seasons for the Sudan site, Gezira irrigation scheme relies only on an irrigation system and has two growing seasons, the summer season starts in July to November with main crops such as cotton (both summer and winter seasons), groundnut, and sorghum and the winter season starts in December and ends in March with cultivated crop types such as wheat, cotton, onion and pigeon pea without rainfall during the entire season, e.g. fully dependent on irrigation.

3.2.1.3. Analysis of quantified agricultural crop water use indicators

Thirdly, the analysis of the quantified Actual Evapotranspiration and Interception and Net Primary Productivity and crop water productivity was done in both regions from 2018 to 2020 time series. The calculated Transpiration, ETIa, TBP and crop water productivity were seasonally analysed.

3.2.1.4. Climate normalisation of crop water productivity

Lastly, the climate normalisation of crop water productivity was done using reference evapotranspiration of the study area, worldwide averaged reference evapotranspiration and WaPOR derived gross biomass water productivity (GBWP) in both climates and the comparison of climatically normalised crop water productivity between semi-arid and humid climates for irrigated areas was done as well. The reference evapotranspiration is defined as evapotranspiration from the reference surface, e.g well-watered grass, of the study areas. To perform climate normalisation, the climate normalised factor was calculated as a ratio between seasonal reference ET of the study area and worldwide climatic average reference ET, both have the unit of mm/season. Climatically normalised CWP helps in the analysis of the climate impacts on crop water productivity in both regions by providing a meaningful comparison of CWP values between semi-arid and humid regions. All required data to fulfil the aims of this study are described in the following sections.

3.3. Data Description

In this study, Satellite and in-Situ datasets were used to achieve the objectives of the study by solving the research questions of the study. The following are the main used datasets:

3.3.1. Satellite Remote Sensing Data

3.3.1.1. WAPOR Data

The WaPOR data are the remote sensing data delivered from an online open remotely sensed data portal, which is the WaPOR database, it has different data components at three levels with different spatial and temporal resolutions.

The FAO launched the WaPOR database portal to monitor land and water productivity to reduce the water productivity gaps. In this study, the FAO WaPOR level II data portal with spatial and temporal resolutions of 100 m and 10 days, respectively was used because it provides all required data for two selected study areas. The WAPOR data level 2 provides the dekadal, seasonal, and annual pre-processed data such as actual Evapotranspiration, and Interception, Net Primary Productivity, land cover classification, above-ground biomass, and total biomass which are available freely on FAO web https://wapor.apps.fao.org/home/WAPOR_2/1. The WaPOR dekadal data were used as inputs data to quantify crop water productivity for our study areas.

Table 3-1 WaPOR data components used for this study

Data levels	Dataset	Spatial resolution	Temporal resolution
Level II	Net Primary production	100 m	10 days
Level II	Transpiration	100 m	10 days
Level II	Interception	100 m	10 days
Level II	Evaporation	100 m	10 days
Level I	Reference ET	20 km	10 days

Net Primary Production

The Net Primary Production is defined as the difference between carbon uptake by the biomass ecosystem (GPP) and autotrophic respiration. NPP is a fundamental characteristic of an ecosystem driven by photosynthesis (FAO, 2018b). WaPOR portal derived NPP from satellite imagery and meteorological data for specific dekad in a unit of gC/m²/day. The following formula was adopted by FAO to calculate NPP of a given ecosystem (FAO, 2020a).

$$NPP = Sc\ Rs\varepsilon p\ fAPAR\ SM\ \varepsilon lue\ \varepsilon T\ \varepsilon CO2\ \varepsilon AR\ [\varepsilon RES] \quad (1)$$

Where:

NPP Net Primary Production
Sc Scaling factor from DMP to NPP [-]
Rs Total shortwave incoming radiation [GJT/ha/day]
εp Fraction of PAR (0.4 – 0.7 μm) in total shortwave 0.48 [JP/JT]
$fAPAR$ PAR-fraction absorbed (PA)by green vegetation [JPA/JP]

SM	Soil moisture stress reduction factor [-]
εlue	Light use efficiency (DM=Dry Matter) at optimum [kg DM/GJPA]
εT	Normalised temperature effect [-]
$\varepsilon CO2$	Normalised C02 fertilization effect [-]
εAR	Fraction kept after autotrophic respiration [-]
εRES	Fraction kept after residual effects (including soil moisture stress) [-]

The value range of NPP of a region can vary between 0 and 5.4 gC m^2/day or between 0 and 120 kgDM/ha/day with a conversion factor of 22.222 but not limited to these values it may be higher up to 320 kgDM/ha/day (FAO, 2020a).

Evaporation, Transpiration, and Interception

The evapotranspiration and interception (ETIa) are a sum of the soil evaporation, canopy transpiration and intercepted rainfall at plant canopy level. Evaporation, transpiration, and interception are limited by the climate and the soil conditions (FAO, 2018a, 2020a).

The Evaporation and transpiration can be calculated using the Penman-Monteith Equation:

$$\lambda ET = \frac{\Delta(\mathrm{Rn} - \mathrm{G})\rho\mathrm{a}\,\mathrm{cp}\frac{(\mathrm{es} - \mathrm{ea})}{\mathrm{ra}}}{\Delta + \gamma(1 + \frac{\mathrm{rs}}{\mathrm{ra}})} \qquad (2)$$

Where:

λ is the latent heat of evaporation [Jkg^{-1}], E is evaporation [kg m^{-2} s^{-1}], T is transpiration [kg m^{-2} s^{-1}], Rn is net radiation [W m^{-2}], G is soil heat flux [W m^{-2}], ρa is air density [kg m^{-3}], cp is the specific heat of dry air [J kg^{-1} K^{-1}], ea is the actual vapour pressure of the air [Pa], es is saturated vapour pressure [Pa] which is a function of the air temperature. And Δ is the slope of the saturation vapour pressure vs temperature curve [Pa K^{-1}], γ is psychrometric constant [Pa K^{-1}], ra aerodynamic resistance [s m^{-1}] and rs is bulk surface resistance [s m^{-1}].

The rainfall interception was estimated using the following formula as suggested by FAO:

$$Interception\ (I_{mm}) = 0.2I_{lai}\left(1 - \frac{1}{1 + \frac{Cveg^P}{0.2I_{lai}}}\right) \qquad (3)$$

Where:

I_{lai} is Leaf Area Index [m^2m^{-2}], Cveg is Vegetation Cover [m^2], and P is Precipitation [mm].

The vegetation cover is calculated by using the following formula:

$$Cveg = 1 - \left(\frac{0.8 - I_{ndvi}}{0.8 - 0.125}\right)^{0.7} \qquad 0.125 < I_{ndvi} < 0.8 \qquad (4)$$

Where:

I_{ndvi} Normalised Difference Vegetation Index, and its range is $0.125 < I_{ndvi} < 0.8$

The conversion of vegetation cover into Leaf Area Index (I_{lai}) is required to calculate the rainfall interception, this is done through the formula below(FAO, 2018a).

$$I_{lai} = \frac{\ln\left(-(Cveg - 1)\right)}{-0.45} \qquad 0.125 < I_{ndvi} \leq 0.795 \qquad (5)$$

Reference Evapotranspiration

Reference evapotranspiration (RET) is defined as evapotranspiration from a hypothetical reference crop. It indicates a well-watered grass surface and can be used to derive potential ET for different crop types by applying predefined crop coefficients(FAO, 2018a). The crop coefficients were derived as the ratio between evaporation, transpiration and interception (ETIa) and reference RET(Ferreira et al., 2016). The equatorial rainforests have low reference evapotranspiration compared to the desert area due to their high relative humidity. In the equatorial area, the reference ET ranges from 1 to 5 mm/day, Reference ET is not affected by a land cover (FAO, 2018a). Reference ET can be calculated similarly using the Penman-Monteith Equation as evaporation and transpiration which are explained in equation (2), but the difference is predefined of some variables in RET equation.

Predefined variables are:

G: The soil heat flux which is null 0 for the whole day and r_a: The aerodynamic resistance of the reference crop with a defined height of 0.12 m is considered.

$$r_a = \frac{208}{u_{obs}} \tag{6}$$

Where u_{obs} is wind speed [m/s] at observation height of 10 m, r_s: The bulk surface resistance which is the resistance to vapour flow from the transpiring reference crop is set to 0.7 s/m where Δ, γ, and ρ_a are a function of air temperature and elevation. R_n: The net solar radiation is solved used radiation balance:

$$R_n = (1 - \alpha_0)R_s - L^* - I \tag{7}$$

Where α_0 is the surface albedo [-], a fixed albedo of 0.23 is used for reference crop, I is the energy needed to evaporate intercepted rainfall which is set at 0 for reference ET. Other parameters are like the ones in the Penman Monteith equation for calculating evaporation and transpiration. Rs is incoming solar radiation [w m^{-2}], L^* is net long wave radiation [w m^{-2}].

The following are examples of WaPOR level 2 data used in this study for both climates.

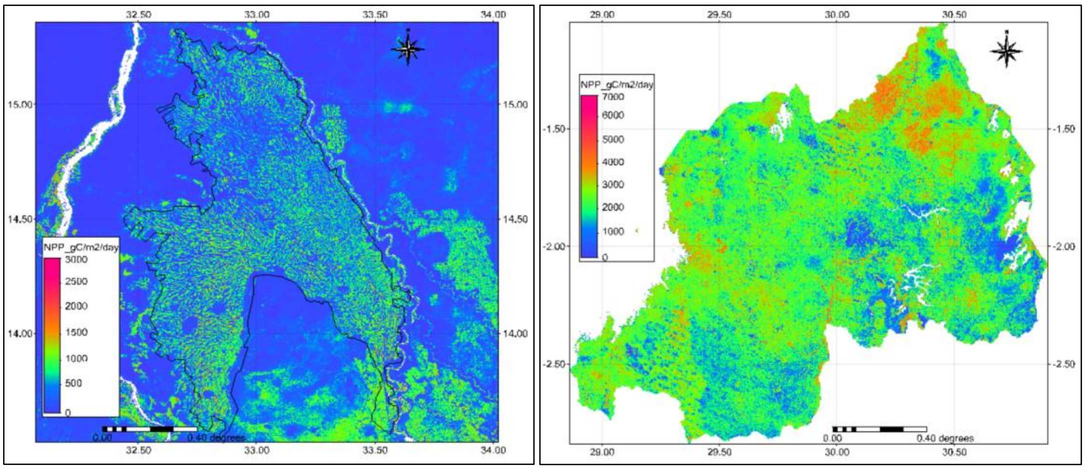

Figure 3-10 The 30th dekad of October 2020 of NPP for Gezira irrigation scheme (Left) and Rwanda (Right)

3.3.1.2. Sentinel 2 data

The Sentinel-2A images were used to classify the crop types for both Gezira and Nasho irrigation study areas. Sentinel-2 MSI satellite provides information on the Bottom of the Atmosphere. It has a spatial resolution of 10 m, 20 m, and 60 m and 5 days of revisit time and are freely available on the Copernicus website https://scihub.copernicus.eu/dhus/#/home. Their images are good for land use and land cover classification (Segarra, Buchaillot, & Araus, 2020). In this study, two images taken on 14th November 2019 and 12th February 2020 are used for land cover classification for summer and winter growing seasons, respectively. The spectral channels were resampled to 10m resolution to work with homogeneous size of pixels throughout the images, four visible and Near Infrared bands were used.

3.3.1.3. ECMWF ERA5 data

The surface model forecasting uses numerical algorithms and assimilation techniques to re-analyse the weather and climate to provide high-quality global data. The European Centre for Medium-range Weather Forecasts (ERA5-Land) provides the six main meteorological variables which are precipitation, solar radiation, air temperature, atmospheric pressure, wind speed, and relative humidity. The ERA5-Land are open access data, available from the Copernicus website https://cds.climate.copernicus.eu/#!/home. The ERA5 hourly data are available in both GRIB and NETCDF formats with a spatial resolution of 0.1 ° to 0.1 °, approximately 9 km (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5-land). The model generated data were used as alternative data when the in-situ data were not available, especially for the Gezira irrigation scheme. ERA5 data were tested for quality by comparing them with meteorological station data from Nasho study area in Rwanda.

3.3.2. In Situ Data

3.3.2.1. Meteorological Data

For Rwanda site, meteorological station data: Kazo station's daily data are available in CSV files (rainfall, wind speed, atmospheric pressure, temperature (min, mean and Max), humidity, and solar radiation) for 1981 to October 2017.

For Sudan, meteorological station data: T, P Wad Medani station daily data are available in CSV files for 1981 to 2019 (the data were provided to ITC in another research).

3.3.2.2. Field Data

In this study, some field data such as training samples, field reconnaissance information, etc used are explained below.

- The irrigation management information (Irrigation Method, watering time, quantity supply, and intervals)
- Field Management information (fertilizers, weeds, and pesticides) was collected to compare irrigation systems for two regions. The data were collected for the Sudan site.
- The soil (moisture content and types) and other agricultural data were used. Some data were collected for the Sudan site.
- The Irrigation systems applied in both schemes:
  - In the Gezira irrigation scheme, surface irrigation is applied where the water is distributed over and across the land with gravity.
  - In Nasho 2 irrigation scheme, the centre pivot irrigation is applied where the water is distributed through the pipes with a pressurized mechanism and the irrigation water is pumped from the lake Cyambwe.

- The growing season information like Start Of Season (SOS) and End Of Season (EOS), harvest period dates in both study areas were collected. The examples of field photos from Gezira and Nasho study areas are given in appendix 1 and 2.

3.4. Land Cover Classification

The land cover classification is an essential element in agriculture, it provides the land use and land cover information of a given study area in a period for different purposes. In this study, land cover classification was done to distinguish crops of the study areas. The SNAP toolbox, ILWIS, Sentinel 2 images, and training samples were used to classify the study areas, the performed activities are detailed in the following steps.

- Land cover classification of selected study areas was done from the processed Sentinel 2 images for 2018,2019,2020. In this study, three Sentinel-2 (atmospherically corrected/with less cloud) images of middle seasons for two main seasons (Summer and Winter) in both regions; time series of three years were considered (2018 to 2020) and the classified images were considered to be similar for the identical seasons.
- The Sentinel -2A images were processed using the SNAP toolbox. The images have different bands with different spatial resolutions, such as 10, 20 and 60 m. All the bands were resampled to the same resolution of 10 m and then subsetting the areas of interest in both regions.
- Importing the vector data shapefiles of training samples was also done to train the classification, adding the additional training data for open water, rivers, bare land, and urban areas. After adding these training data, the image was reprojected to lat/long WGS 84 to match its projection with the vectors.
- After getting the orthomosaic maps for the study areas at given study periods they were used in the land cover classification using the random forest classifier applied using 100 trees and 4 selected spectral channels bands(blue, green, red and near infra-red) for all training samples (Breiman, 2001 and Reza et al., 2016).
- The classification results obtained were verified and improved until they reached better results.
- The classified images were imported into ILWIS for further processing such as slicing and filtering to create individual crop masks.
- For land cover classification of rainfed areas, the irrigation surrounding cropland of non-irrigated areas was used as rainfed areas. The distinction of different crop types cultivated in one crop field was done.
  The google earth engine images and high-resolution Sentinel-2A images were used for the visualization of crops, training samples retrieval to distinguish maize, soybeans, and beans from one another. The dominant crop type was estimated based on its density within the crop field, the 30 per cent of the crop type was considered as a dominant crop.

3.5. Quantification of agricultural crop water productivity

The WaPOR data portal level 2 was used in this study because it contains the required data for both study areas, Gezira and Nasho irrigation schemes. The dekadal data was aggregated to distinguish two crop cycles (seasons) per year. The two main seasons are distinguished for Nasho irrigation scheme: season A starts in September and ended in February and season B starts in February and ended in July. For Gezira irrigation scheme there exist two growing seasons such as summer season which starts in July and ended in November and Winter season which starts in December and ended in March.
The time series Agricultural Crop Water Productivity (ACWP) from 2018 to 2020 in Sudan and Rwanda were quantified using WaPOR based data such as evaporation, transpiration and interception and net primary productivity. The ILWIS software through FAO Toolbox was used to derive seasonal ETIa, total Biomass Production, and crop water production for two seasons a year in dry and humid regions for both rainfed and irrigated areas. More details on used formulas are given in the following sections.

3.5.1. Actual Evapotranspiration and Interception (ETIa)

The evapotranspiration and interception (ETIa) are a sum of the soil evaporation, canopy transpiration and intercepted rainfall at plant canopy level. Evaporation, transpiration, and interception are limited by the climate and soil conditions.

$$ETIa\ (mm/day) = E + T + I \quad (8)$$

Where E is soil evaporation [mm/day], T is canopy transpiration [mm/day], and I is canopy transpiration [mm/day]

3.5.2. Total Biomass Production

The total and above biomass are production indicators that are used to monitor land and water productivity. The following formulas are used to estimate them from net primary production as used by FAO, (2020a).

$$TBP\ (\ kg\ DM/ha) = NPP\ \times 22.222 \quad (9)$$

Where TBP is Total Biomass Production [kg DM/ha]

3.5.3. Gross Biomass Water Productivity (GB_WP)

The gross biomass water productivity is divided into two depends on the parameters used to estimate it, one is calculated from the total biomass as indicated by the formulas below (FAO, 2020a).

$$GBWP\_TBP = \frac{TBP}{E + T + I} \quad (10)$$

Where TBP is total biomass production [kg DM /ha], E is actual evaporation [m^3/ha], T is transpiration [m^3/ha], and I is interception [m^3/ha].

3.5.4. Net Biomass Water Productivity (NB_WP)

The net biomass water productivity is divided into two depends on the parameters used to estimate it, one is calculated from the total biomass as indicated by the formulas below.

$$NBWP\_TBP\ = \frac{TBP}{T} \quad (11)$$

Where, TBP is Total biomass production [kg DM /ha] and T is canopy transpiration [m^3/ha].
The above-calculated GBWP requires climate normalisation to compare the water productivity values in both semi-arid and humid climates. The details on performed climate normalisation of CWP are described below.

3.6. Performing Climate Normalisation of Crop Water Productivty

Climatic conditions, soil moisture, and leaf area index cause the variability of ET. In this regard, a semi-arid climate has a higher sum of ET values due to the high evaporative demand, higher ΣET values have negative impacts on crop water productivity (Bastiaanssen & Steduto, 2017). The reference evapotranspiration (ETo) was downloaded from WaPOR database level 1. Therefore, for the third objective, the climatic normalisation was carried out for the analysis of CWP to make a reasonable comparison of CWP values in both semi-arid (high evaporative demand) and humid (less or moderate evaporative demand) climates.

3.6.1. The normalisation of crop water productivity

The climatically normalised crop WP was calculated using equation 12, analysed, and compared with CWP values between dry and humid climates to analyse crop water productivity variations between semi-arid to humid climates. It was also compared with the other literature in both semi-arid and humid regions.
To explain the variability of crop water productivity from one region to another, we need to know the water production levels or targets (Globally or Locally) we want to achieve. Water productivity scores targets vary from climate to climate. Crop water productivity(CWP) is defined as crop yield per unit of consumed water volume and was calculated using the following formula as established by Bastiaanssen and Steduto, (2017). The climatically normalised crop water productivity (CWP_c) is the ratio between seasonal crop yield and sum of actual evapotranspiration multiplied by the ratio between the sum of reference evapotranspiration of the area and worldwide climatic average evapotranspiration (ΣETo (c)). The ΣETo(c) values vary depending on the crop types and there are some examples like 690, 545, and 555 mm/season for maize, wheat and rice, respectively are adopted here (Bastiaanssen & Steduto, 2017).

In this study, the climate normalisation of CWP was calculated using the formula below:

$$\text{CWPc} = \frac{\Sigma\text{TBP}}{\Sigma ETIa} \times \frac{\Sigma\text{ETo(a)}}{\Sigma\text{ETo(c)}} \qquad (12)$$

Where, ΣETo (a) and ΣETo (c) are the sum of reference ET of a given area and worldwide averaged climatic reference ET, respectively (Bastiaanssen & Steduto, 2017). The following are main procedures used to get CWPc results.

- Dekadal reference evapotranspiration was downloaded from WaPOR database level 1 with a spatial resolution of 20 km.
- Importing reference evapotranspiration into ILWIS for further processing.
- Resampling reference ET: It was resampled to 100 m resolution. The nearest neighbourhood resampling method was applied to march it with a spatial resolution of quantified crop water productivity which have the spatial resolution of 100 m.
- Extraction of the study areas using Gezira irrigation selected study area and Nasho study area masks.
- Extraction of crop types using crop masks
- Calculation of seasonal reference ET by summing up the dekadal reference ET of each crop type.
- Maplist calculations were done to calculate normalised CWP (CWPc) by applying the formula explained in equation 12.
- The worldwide averaged climatic normalised reference ET of sorghum and pigeon pea are assumed to be 690 and 545 mm/season as of maize and wheat, respectively. The sorghum is considered to have the same value as maize and pigeon pea have the same value as wheat, both sorghum and pigeon pea are C4 and C3 crops, respectively.
- The calculated CWPc were obtained and are presented in chapter 4, section 4.5.

3.6.2. Comparison of crop water productivity and normalised CWP values between semi-arid and humid climates

In this study, normalised crop water productivity for selected crops in both climates was done and used to make a significant comparison between both climates. Comparing CWP and normalised CWP values of individual crops, the most affected areas were determined in both irrigated areas. Furthermore, the impact of climate on crop water productivity was analysed and the results are presented in chapter 4 of this study.

4. RESULT AND DISCUSSIONS

4.1. Land Cover Classification of Study Areas

The land cover classification is helpful to observe time-series changes over time for a given area of interest especially for agricultural cropland for monitoring water productivity and water budgeting. The land cover classification performed on Gezira irrigation scheme, FAO selected area for validation of WaPOR data level 3 located in Sudan and on Nasho irrigation scheme and surrounding rainfed area located in Rwanda. The performed activities were detailed in methodology, provided in chapter three. The random forest classifier was applied to both regions of interest and shows the high quality of the classification results. The obtained results for both study areas are explained below.

4.1.1. Semi-arid Climate- Gezira Irrigation Scheme, FAO selected area for validation study of WaPOR Level 3 data

Land cover classification of Gezira irrigation scheme study area was done for the summer and winter seasons of 2019 and 2020, respectively. Classified images are considered to be the same for the remaining growing seasons with the assumption of crop rotation between summer and winter seasons. Sentinel 2A images of 29/09/2019, and 12/02/2020, were used and classified images were evaluated for accuracy and reported as the correct predictions, RMSE, and Bias for the summer season of 2019 with the value of 96.34, 0.52, and -0.020, respectively with total samples of 10000. The winter season of 2020 has total samples of 10000 with 97.98, 0.34, and 0.006 of correct predictions, RMSE, and Bias, respectively. Table 4-1 shows the details on accuracy assessment report for summer and winter main crops.

Table 4-1 Accuracy assessment report of classified images for summer and winter seasons for Gezira study area

Seasons	**Summer Season**			**Winter Season**		
Crop type	Groundnut	Sorghum	Cotton	Onion	Pigeon pea	Wheat
Accuracy	0.99	0.99	0.99	0.98	0.98	0.99
Precision	0.94	0.96	0.96	0.94	0.91	0.99
Correlation	0.95	0.97	0.96	0.92	0.92	0.99

Cotton: Full year growing season (both summer and winter) and have the same parameters for winter season as the above-mentioned summer season.
After land cover classification using SNAP Toolbox, the classified images were imported into ILWIS software for reclassification processes to create crop masks for individual crop types.

4.1.2. Humid Climate: Rwanda- Nasho Irrigation Scheme and Rainfed area

Land cover classification was also performed for Nasho irrigation and rainfed areas using Sentinel 2A images of 19/06/2019 and 15/12/2020 for summer and winter of 2019 and 2020 growing seasons. Classified images were evaluated for accuracy and reported as the correct predictions, RMSE, and Bias for the summer season of 2020 with the value of 97.81, 0.73, and 9.59, respectively with total samples of 8335. The winter season of 2019 has total samples of 8033 with 97.95, 0.598, and -0.036 of correct predictions, RMSE, and Bias, respectively. Classified images are considered to be the same for the remaining growing seasons with the assumption of crop rotation between summer and winter seasons. Table 4-2 shows the details of accuracy assessment reports on main crops.

Table 4-2 Accuracy assessment report of classified images for summer and winter seasons for Nasho study area

Seasons	**Winter Season**				**Summer Season**			
Crop type	Banana	Beans	Maize	Sorghum	Banana	Beans	Maize	Sorghum
Accuracy	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.98
Precision	0.93	0.97	0.98	0.93	0.93	0.98	0.97	0.93
Correlation	0.95	0.98	0.97	0.96	0.95	0.97	0.98	0.93

Banana: Full-year plus growing season (both summer and winter) and have the same parameters as the winter season

After land cover classification using SNAP Toolbox, the classified images were imported into ILWIS for reclassification processes to create crop masks for individual crop types. Figure 4-1 and 4-2 show reclassified images for summer and winter growing seasons and the examples of crop masks for Gezira and Nasho study areas, respectively.

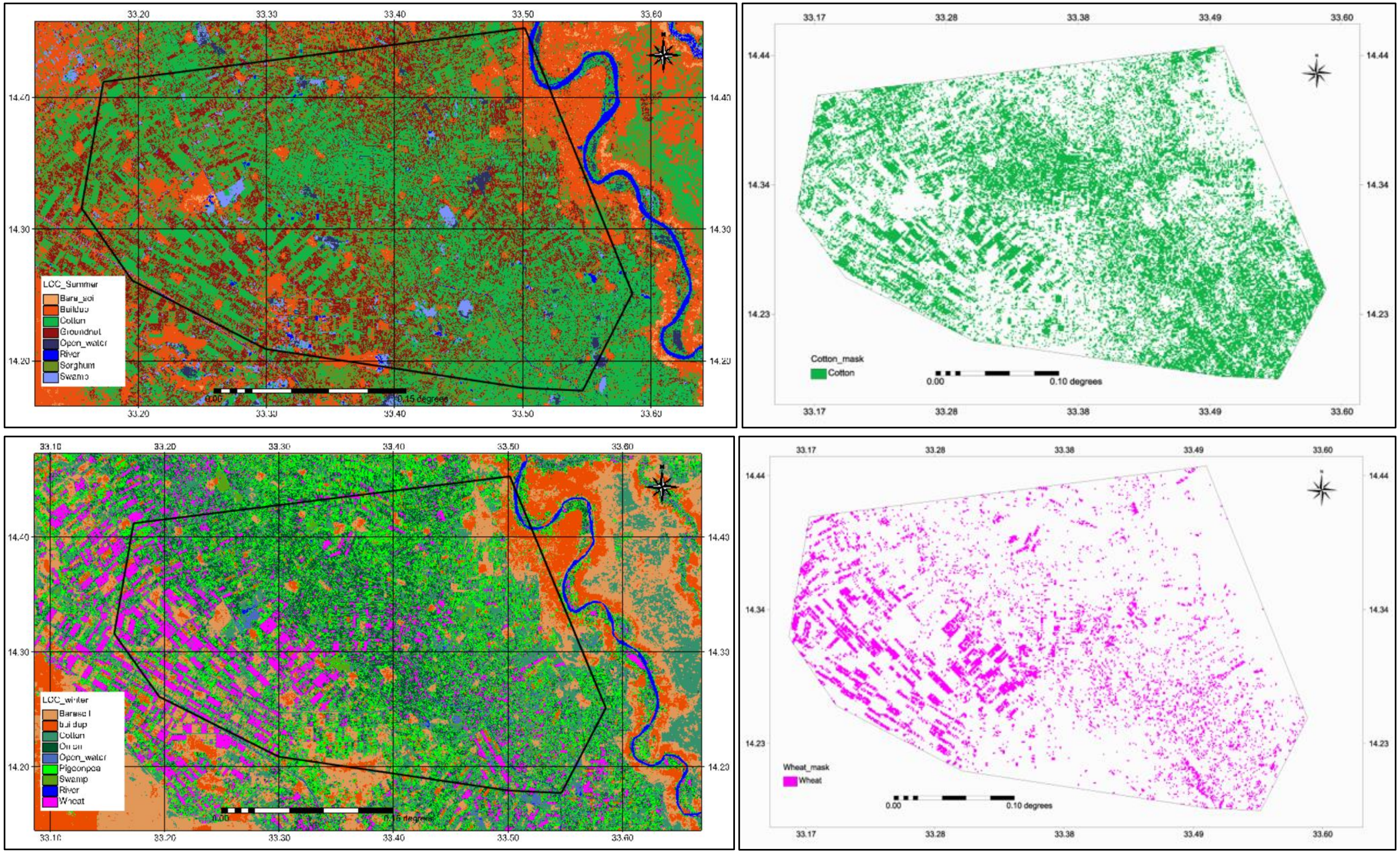

Figure 4-1 Land cover classification of Gezira study area summer and winter seasons (Left) and cotton and wheat masks (Right).

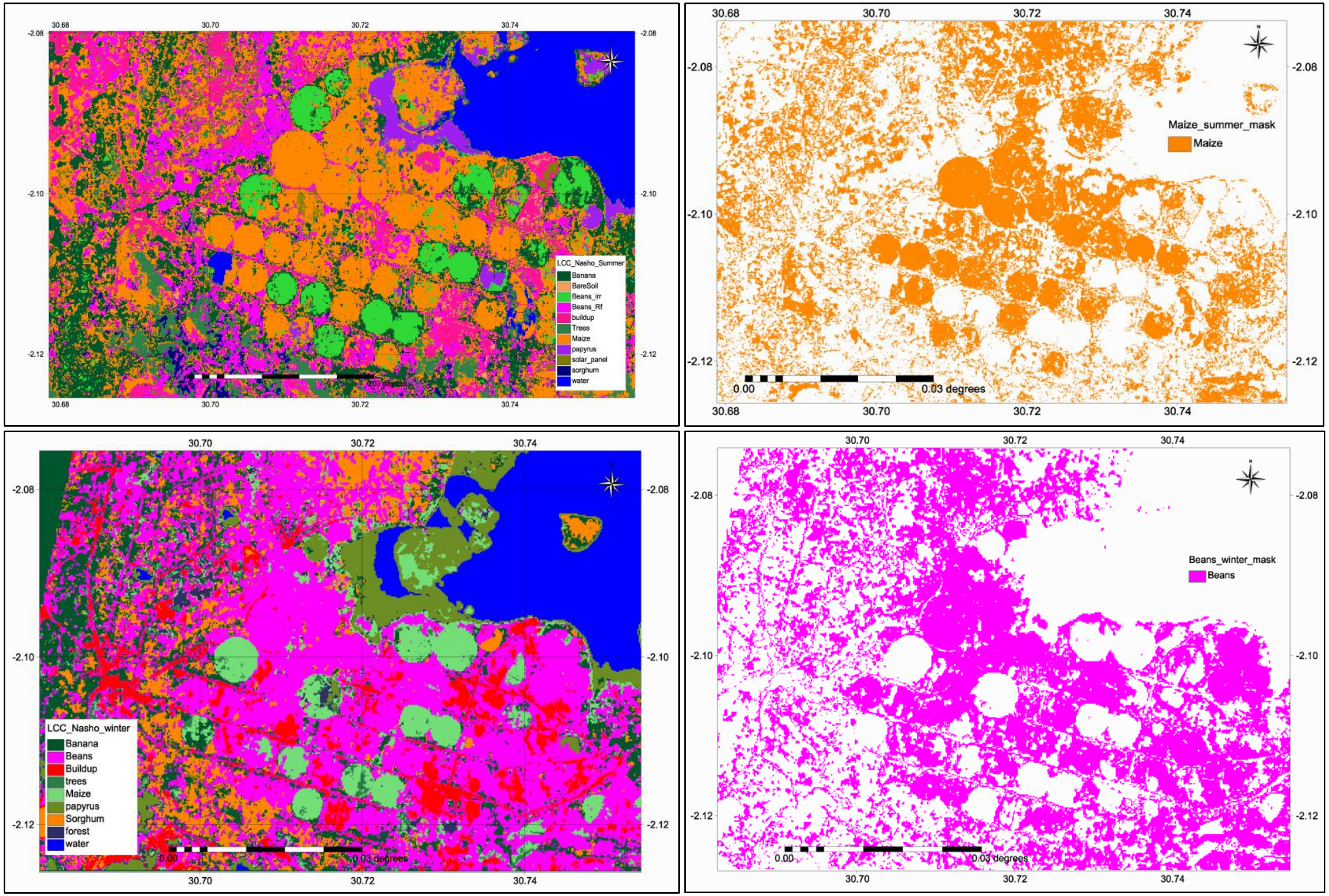

Figure 4-2 Land cover classification of Nasho study area summer and winter seasons (Left) and maize and bean masks (Right).

4.2. RESULT AND ANALYSIS FOR GEZIRA IRRIGATION SELECTED AREA

In this study, the FAO selected study area for WaPOR level3 data validation mask is used as study area and crop water use indicators like crop transpiration, evapotranspiration, biomass production, and crop water productivity of main crops were calculated and seasonally analysed for two agricultural growing seasons, summer (July to November), and winter (December to March). More details are described in the following sections. Note that the time series graphs presented below are based on the averaged five (5) selected sample pixels.

4.2.1. TRANSPIRATION (T)

The dekadal transpiration was downloaded from WaPOR database level 2 and imported into ILWIS as raster format and used to calculate the seasonal transpiration by using FAO-FRAME Toolbox which is available in ILWIS software. Also using the crop masks from classified Sentinel 2A images, the dekadal and seasonal transpiration of sorghum, groundnut, and cotton for summer and onion, pigeon pea and wheat for the winter season were extracted. The results and analysis are presented in the following sections.

Figure4-6 shows the transpiration time-series behaviours of sample pixels for summer and winter seasons of 2018, 2019 and 2020 for cotton, groundnut, sorghum, onion, pigeon pea and wheat. The observations made show the gradual increase of transpiration to reach the peak and gradually decrease from the peak for all the crops in summer and winter. The sorghum has very low peak point in 2020 season which may be caused by the change of land cover type or other causes. A sudden decrease of groundnut transpiration is occurred at the end of 2018 and 2019 summer seasons, this can be caused by the early harvesting activity at the moment. The cotton has a gradual increase to the peak and decreasing from peak point in all seasons. There are also fluctuation occured in November 2020 and in February 2021 for all crops that may be caused by the water deficits at the moments. In these time series graphs, there is a change of behaviours of trends for all crops occurred in summer season of 2019 (July to November) which shows a lot of fluctuates during the entire season. This may be caused by the high variation of climatic conditions of the season or special cases (problems) occurred in irrigation management. The wheat has the highest peak point among the other crops occurred in 2020 winter season with the value of almost 100 mm/dekad and the sorghum has the lowest peak point which is occurred in 2020 summer season with the value of 18 mm/dekad. More details on transpiration statistics of each crop for each growing season are summarised in the following sections.

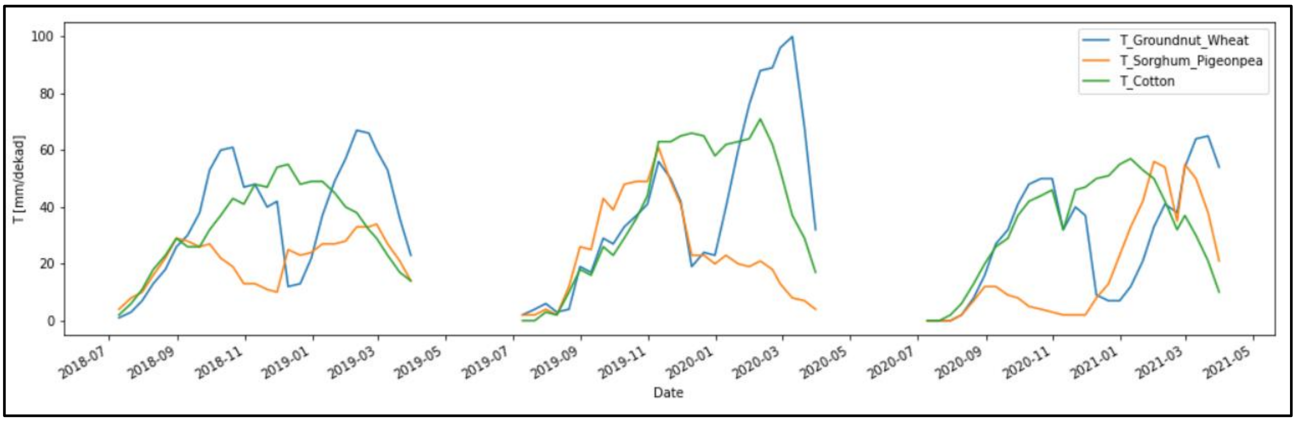

Figure 4-3 Dekadal transpiration of Cotton, Groundnut, Wheat, Pigeon pea and Sorghum from July 2018 to March 2021

4.2.1.1. Transpiration for Summer Season

Table 4-1 summarizes the statistics of transpiration of the entire selected area of Gezira scheme where averaged seasonal transpiration values of groundnut were 415.32, 378.55 and 412.33 mm/season with a standard deviation of 180.39, 173.07, 174.32 for 2018, 2019 and 2020, respectively. For Sorghum, the average seasonal transpiration values were 382.84, 339.42 and 243.05 mm/season with a standard deviation of 153.33, 165.19, 142.36 for 2018, 2019 and 2020, respectively. These seasonal transpiration values of groundnut and sorghum show that the groundnut had higher transpiration compared to sorghum for all three summer seasons with overall values of 402.06 and 321.77, respectively. The cotton full season has 9 months starting from July to March for a year. The seasonal average transpiration values of cotton were 732.40, 697.94 and 708.72 mm/season with a standard deviation of 365.84, 364.76, 402.91 for 2018, 2019, and winter 2021, respectively. The cotton overall transpiration value for three years was 713.02 mm/season.

Table 4-3 Statistics of seasonal transpiration for summer sorghum and groundnut from July 2018 to November 2020 and cotton for full season from July 2018 to March 2021

Crops	Groundnut,				**Sorghum**				**Cotton(Full season)**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	0	766	415.32	180.39	89	721	382.84	153.33	0	1536	732.4	365.84
2019	30	727	378.55	173.07	0	740	339.42	165.19	0	1453	697.94	364.76
2020	47	813	412.33	174.32	1	585	243.05	142.36	3	1728	708.72	402.91
Overall			402.06	175.93			321.77	153.63			713.02	377.84

4.2.1.2. Transpiration for Winter Season

Table 4-2 shows the statistics of transpiration of the entire scheme where averaged seasonal transpiration values of onion were 370.45, 405.79 and 409.57 mm/season with a standard deviation of 198.06, 202.61, and 229.36 for 2019, 2020 and 2021, respectively. For pigeon pea, the average seasonal transpiration values were 374.07, 476.16 and 394.62 mm/season with a standard deviation of 183.68, 183.57, and 205.6 for 2019, 2020 and 2021, respectively. The seasonal transpiration of wheat was also estimated, and its average values were 389.46, 508.71 and 405.93 mm/season with a standard deviation of 190.45, 179.67 and 219.99 for 2019, 2020, and 2021, respectively. These seasonal transpiration values show that the wheat had higher transpiration compared to pigeon pea and onion for all three winter seasons with the overall transpiration values of 434.7, 414.95, and 395.27, respectively. The transpiration values of wheat are supported by FAO technical report on the data quality assessment of WaPOR database version 2 which reported wheat transpiration rate ranging between 383 to 616 mm/season (FAO, 2020b).

Table 4-4 Seasonal transpiration statistics for winter main crops from December 2018 to March 2021

Crops	**Onion**				**Pigeon pea**				**Wheat**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2019	0	817	370.45	198.06	0	745	374.07	183.68	0	833	389.46	190.45
2020	21	848	405.79	202.61	33	830	476.16	183.57	0	855	508.71	179.67
2021	9	915	409.57	229.36	6	825	394.62	205.6	0	873	405.93	219.99
Overall			395.27	210.01			414.95	190.95			434.7	196.70

4.2.2. Evapotranspiration and interception (ETIa)

In this study, the dekadal evaporation, transpiration and interception were used to calculate the dekadal evapotranspiration and interception (ETIa) by using equation 8 explained in section 3.5.1. Seasonal ETIa was calculated by summing up quantified dekadal ETIa. Also using the crop masks, the dekadal and seasonal ETIa of sorghum, groundnut, and cotton for summer and onion, pigeon pea and wheat for the winter season were extracted.

The results for the Summer and winter seasons are shown in the following time-series graphs of figure 4-7 which shows the evapotranspiration time series behaviour of sample pixels for summer groundnut, sorghum, and cotton which rotate with winter onion, pigeon pea, and wheat. The observations made show the gradual increase of evapotranspiration to reach the peak and gradually decrease from the peak as observed on transpiration indicator. The sorghum has very low peak point in 2020 season which may be caused by the change of land cover type or other causes. A sudden decrease of groundnut evapotranspiration is occurred at the end of 2018 and 2019 summer seasons, this can be caused by the early harvesting activity at the moment. The cotton has a gradual increase to the peak and decreasing from peak point in all seasons. There are also fluctuation occured in November 2020 and in February 2021 for all crops that may be caused by the water deficits at the moments. In these time series graphs, there is a change of behaviours of trends for all crops occurred in summer season of 2019 (July to November) which shows a lot of fluctuates during the entire season. This may be caused by the high variation of climatic conditions of the season or special cases (problems) occurred in irrigation management. The wheat has the highest peak point among the other crops occurred in 2020 winter season with the value of almost 118 mm/dekad and the sorghum has the lowest peak point occurred in 2020 summer season with the value of 25 mm/dekad.

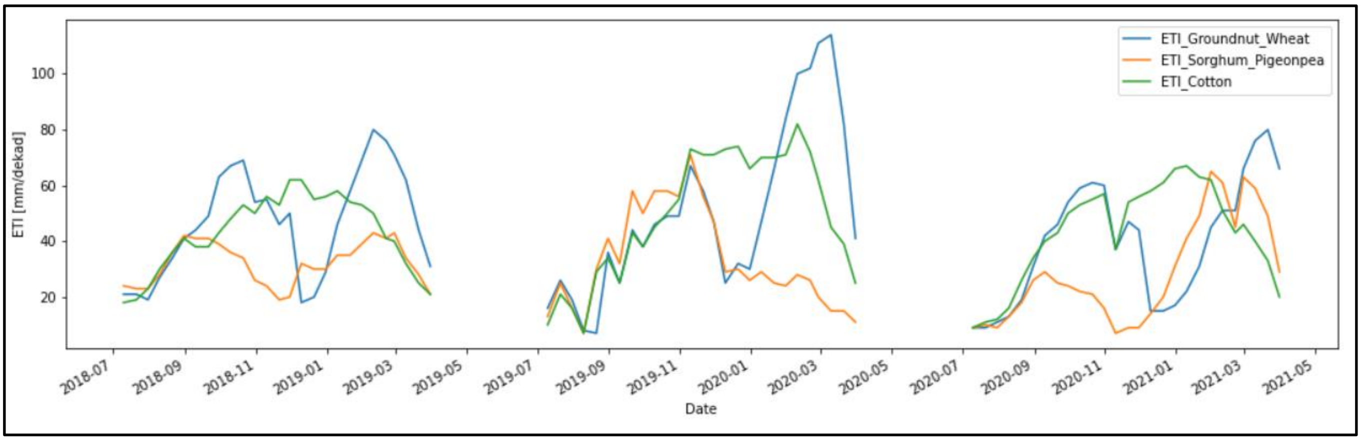

Figure 4-4 Dekadal evapotranspiration of Cotton, Groundnut, Wheat, Pigeon pea and Sorghum from July 2018 to March 2021

4.2.2.1. Evapotranspiration and interception for Summer Season

Table 4-3 shows the statistics of evapotranspiration of the entire scheme where averaged seasonal evapotranspiration and interception values of groundnut were 575.77, 553.87 and 563.78 mm/season with a standard deviation of 179.69, 169.00, 168.57 for 2018, 2019 for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported mean evapotranspiration of groundnut ranging from 500 mm to more than 600 mm depending on the environment for total growing period ranges between 120 and 140 days. For sorghum, the average seasonal evapotranspiration values are 549.84, 522.2 and 414.39 mm/season with a standard deviation of 150.78, 152.8, 137.05 for 2018, 2019 and 2020, respectively. Sorghum crop with duration range of 110 to 130 days its mean evapotranspiration varies from 450 mm to 750 mm depending on evaporative demand reported by Steduto et al., (2012). These seasonal evapotranspiration values of groundnut and sorghum show that the groundnut had higher evapotranspiration compared to the sorghum for all three summer seasons. The seasonal evapotranspiration of cotton (full season, summer, and winter) was estimated, and its average values are 976.28, 958.83 and 960.91 mm/season with a standard deviation of 383.32, 376.32, 419.08 for 2018, 2019, 2020, respectively. Different studies reported that irrigated cotton evapotranspiration varies between 410 mm and 780 mm in united states of America, southern high plains depending on applied irrigation method, the cultivar and the duration of growing period (Steduto et al., 2012).

Table 4-5 Evapotranspiration for summer groundnut and sorghum from July 2018 to November 2020 and cotton for full season from July 2018 to March 2021

Crops	**Groundnut**				**Sorghum**				**Cotton(Full season)**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	205	922	575.77	179.69	278	867	549.84	150.78	225	1750	976.28	383.32
2019	218	892	553.87	169	195	892	522.2	152.8	232	1703	958.83	376.32
2020	208	956	563.78	168.57	179	730	414.39	137.05	219	1984	960.91	419.08
Overall			564.47	172.42			495.47	146.88			965.34	392.91

4.2.2.2. Evapotranspiration and Interception for Winter Season

Table 4-6 shows the statistics of evapotranspiration of the entire selected area where averaged seasonal evapotranspiration values of onion were 463.39, 498.5 and 511.48 mm/season with a standard deviation of 215.25, 218.45 and 246.56 for 2019, 2020 and 2021, respectively. For pigeon pea, the average seasonal evapotranspiration values are 471.48, 572.57 and 505.59 mm/season with a standard deviation of 196.21, 196.92 and 216.67 for 2019, 2020 and 2021, respectively. The seasonal evapotranspiration of wheat was also estimated, and its average values are 489.74, 607.62 and 522.04 mm/season with a standard deviation of 201.32, 190.7 and 230.23 for 2019, 2020, and 2021, respectively. The total cumulative evapotranspiration of wheat may range from 200 to 500 mm and can be increase under heavy irrigation to reach 600 to 800 mm (Steduto et al., 2012). These seasonal evapotranspiration values show that the wheat had higher evapotranspiration compared to pigeon pea and onion for all three winter seasons with the overall evapotranspiration values of 539.8, 516.547, and 491.123 with a standard deviation of 207.42, 203.267, and 226.753, respectively. Faruque, (2020) carried out a validation study on Gezira irrigation scheme and reported a mean evapotranspiration of 423, 351, 355 mm/season for onion, pigeon pea and wheat, respectively.

Table 4-6 Evapotranspiration and interception for winter main crops from December 2018 to March 2021.

Crops	**Onion**				**Pigeon pea**				**Wheat**			
Statstics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2019	81	948	463.39	215.25	70	872	471.48	196.21	77	963	489.74	201.32
2020	63	966	498.5	218.45	84	943	572.57	196.92	61	960	607.62	190.7
2021	63	1051	511.48	246.56	73	947	505.59	216.67	68	1004	522.04	230.23
Overall			491.12	226.75			516.54	203.26			539.8	207.42

4.2.3. Total Biomass Production (TBP)

The dekadal total biomass production (TBP) was calculated using equation 9 explained in section 3.5.2 and seasonal TBP was calculated by summing up quantified dekadal TBP. Using the crop masks, the dekadal and seasonal TBP of sorghum, groundnut, and cotton for summer and onion, pigeon pea and wheat for the winter seasons were extracted from the quantified TBP. The behaviours of total biomass production of sample pixels for three years of 2018, 2019 and 2020 for sorghum, groundnut, cotton, onion, pigeon pea and wheat as summer and winter crops are presented in the following time series graphs indicated by figure4-5. The observations findings show that the distribution of total biomass production is different from the distribution of transpiration and evapotranspiration presented and analysed above. There are a lot of fluctuates for all crops, especially in winter seasons. The wheat and cotton crops have the highest values of productions in 2020 winter season compared to the other crops. And 2021 winter season has many ups and downs at the peak region which may be caused by the variation of climatic conditions which influences the production process.

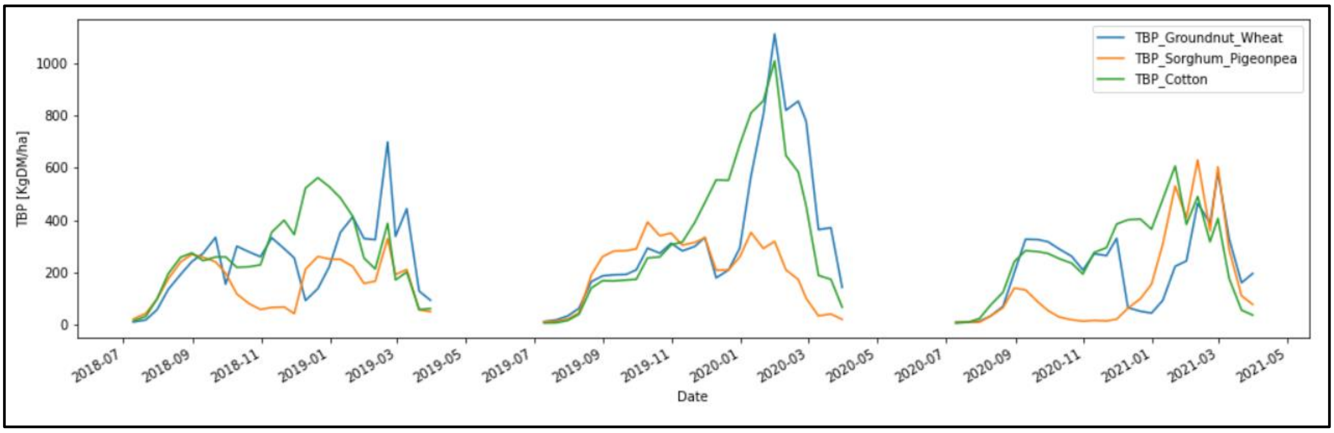

Figure 4-5 Dekadal total biomass production of Cotton, Groundnut, Wheat, Pigeon pea and Sorghum from July 2018 to March 2021

4.2.3.1. Total Biomass Production for Summer Season

Table 4-7 summarises the average seasonal total biomass production values of summer crops. Groundnut values were 3051, 2804 and 3120 KgDM/ha/season with a standard deviation of 781.29, 901.6, 692.81 for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported yield production of groundnut ranges from 3.0 to 3.8 ton/ha in favourable conditions and may vary between 0.65 and 0.85 ton/ha in semi-arid tropics, harvest index varies between 0.30 to 0.45 depending on environmental conditions and decreases under drought, temperature stress, and longer day lengths. For sorghum, the average seasonal evapotranspiration values were 2531.15, 2754.88 and 1159.81 KgDM/ha/season with a standard deviation of 770.58, 934.86, 730.8 for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported average yield of sorghum of 4.7 ton/ha in United States and Argentina and 0.6 ton/ha in Sudan, also reported a sweet sorghum fresh biomass range between 35 to 45 tonne/ha. These seasonal total biomass production values of groundnut and sorghum show that the groundnut had higher production compared to the sorghum for all these three summer seasons. The cotton has a season of 9 months starting from July and ends in March every year. The seasonal total biomass production of cotton was estimated, and its average values were 6209.19, 7017.5 and 5852.42 KgDM/ha/season with a standard deviation of 1399.3, 1811.35, 1616.38 for 2018, 2019, 2020 and winter season of 2021, respectively. Steduto et al., (2012) reported yield production of cotton ranges between 0.65 to 1.3 ton/ha for surface and sprinkle irrigation, and from 0.9 to 1.6 ton/ha for drip irrigation in United States southern high plains depending on the irrigation level.

Table 4-7 Total Biomass Production for summer groundnut and sorghum from July 2018 to November 2020

Crops	Groundnut				Sorghum				Cotton(Full season)			
Statistics	Min	Max	Avg	Std Dev	Min	Max	Avg	Std Dev	Min	Max	Avg	Std Dev
2018	624.8	5441.3	3051	781.3	696.2	5138.8	2531.1	770.5	623.7	13036.5	6209	1399
2019	267.1	5805.4	2804	901.6	35.33	5755	2754.8	934.8	198	13868.7	7017.5	1811.3
2020	588.9	6106.8	3120	692.8	112.4	4563.9	1159.8	730.8	131.5	15493.3	5852.4	1616.3
Overall			2991	792			2148	812			6359	1609

4.2.3.2. Total Biomass Production for Winter Season

Table 4-8 shows the average seasonal total biomass production values of onion were 3224.74, 4343.52, and 3267.35 KgDM/ha/season with a standard deviation of 995.64, 1083.52, and 1259.45 for 2019, 2020 and 2021, respectively. For pigeon pea, the average seasonal evapotranspiration values were 3246.33, 5025.17, and 3283.25 KgDM/ha/season with a standard deviation of 982.91, 935.27, and 1264.84 for 2019, 2020 and 2021, respectively. The wheat productions were 3093.98, 5645.71, and 3142.27 with a standard deviation of 1057.69, 1105.32, and 1380.75 for 2019, 2020, and 2021, respectively. These seasonal total biomass production values of onion, pigeon pea, and wheat show that the pigeon pea had higher production compared to the onion and wheat for the 2019 and 2021 winter seasons. The wheat production was higher in 2020. The seasonal overall total biomass productions of three crops were estimated and wheat had the highest overall production with the average values of 3960.653, 3851.583, and 3611.87 KgDM/ha/season for wheat, pigeon pea and onion, respectively, with a standard deviation of 1181.253, 1061.007, and 1112.87 for 2019, 2020 and 2021.

Table 4-8 Statistics of TBP for winter main crops from 2018 to 2021

Crops	**Onion**				**Pigeon pea**				**Wheat**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2019	3.33	6261.3	3224.7	995.6	136.8	6264.8	3246.3	982.9	199.7	6154.1	3093.9	1057.6
2020	265.7	7843.2	4343.5	1083.5	625.3	8551.0	5025.1	935.2	225.1	9204.1	5645.7	1105.3
2021	159.1	7429.9	3267.3	1259.4	160.4	6730.5	3283.2	1264.8	160.2	6812.1	3142.2	1380.7
Overall			3611.8	1112.8			3851.5	1061			3960.6	1181.2

4.2.4. Gross Biomass Water Productivity (GB_WP)

The dekadal gross biomass water productivity was calculated from dekadal total biomass production and evapotranspiration using equation 10 explained in section 3.5.3. And seasonal GBWP was calculated by summing up quantified dekadal GBWP. Also using the crop masks, the dekadal and seasonal GBWP of sorghum, groundnut, and cotton for summer and Onion, pigeon pea and wheat for the winter seasons were extracted the quantified GBWP. Figure4-11 demonstrates the time-series distribution of CWP and shows that the gross biomass water productivity behaviours are almost similar for all crops. The difference is observed for winter crops of 2020 which has the highest peak with 1.4 kg/m³. Also, summer and winter seasons of 2019 have very similar distribution compared to the other seasons. More details on GCWP statistics are presented in the following sections.

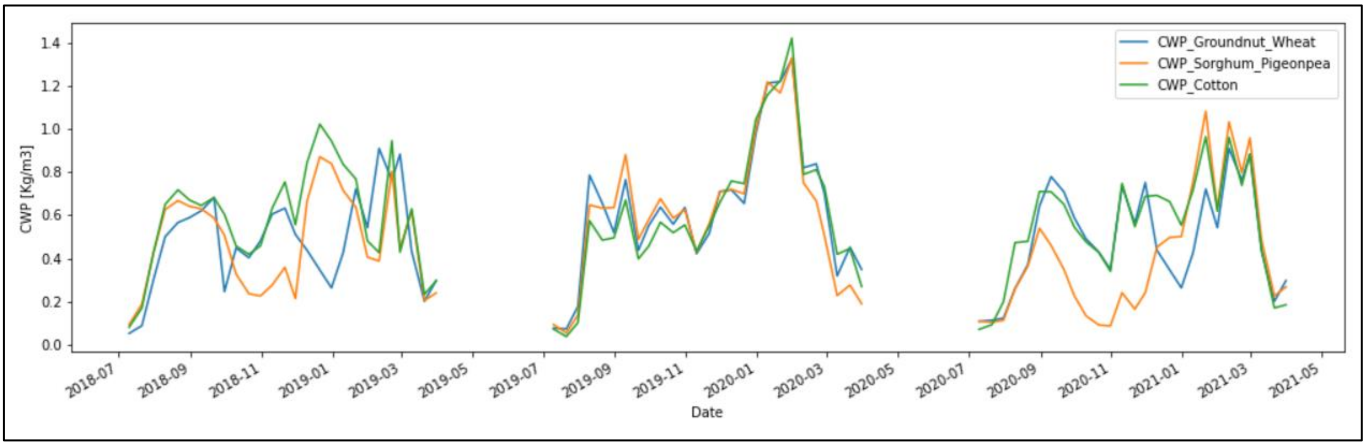

Figure 4-6 Gross Crop Water Productivity of Cotton, Groundnut, Wheat, Pigeon pea and Sorghum from July 2018 to March 2021

4.2.4.1. Gross Biomass Water Productivity for Summer Season

Table 4-9 shows the averaged seasonal gross biomass water productivity values of groundnut were 0.7, 0.2 and 0.2 kg/m^3 with a standard deviation of 0.6, 0.2, 0.2 for the entire scheme for 2018,2019 and 2020, respectively. Steduto et al., (2012) reported groundnut yield water productivity ranges from 2-3 kg/m3. For sorghum, the average seasonal gross biomass water productivity values were 0.5, 0.4, and 0.4 kg/m^3 with a standard deviation of 0.2, 0.2, 0.2 for 2018, 2019 and 2020, respectively. The seasonal gross biomass water productivity values of groundnut and sorghum show that the groundnut had higher water productivity compared to the sorghum for all these three summer seasons. The seasonal gross biomass water productivity of cotton was calculated, and its average values were 1.54, 1.2 and 1.1 kg/m^3 with a standard deviation of 0.13, 0.7, and 0.6 for 2018, 2019, 2020 and winter season of 2021, respectively. Choudhury and Bhattacharya, (2018) reported average Cotton WP of 0.41 kg/m3 over the Indian region. Note that the maps which show spatial variability of gross crop water productivity of summer crops are shown in the appendices.

Table 4-9 Statistics of Gross Crop Water Productivity for summer groundnut and sorghum from July 2018 to November 2020 and cotton for a full season from July 2018 to March 2021.

Crops	**Groundnut**				**Sorghum**				**Cotton(Full season)**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	0.2	2	0.7	0.6	0.2	0.7	0.5	0.2	0.83	3.90	1.54	0.13
2019	0.1	0.7	0.4	0.2	0	0.7	0.4	0.2	0.1	2.4	1.2	0.7
2020	0.3	0.9	0.6	0.2	0.1	0.6	0.4	0.2	0.1	2.0	1.1	0.6
Overall			0.56	0.33			0.43	0.2			1.96	1.26

4.2.4.2. Gross Biomass Water Productivity for Winter Season

Table 4-10 shows the average seasonal gross crop water productivity values of onion were 0.8, 0.8, and 0.6 kg/m^3 with a standard deviation of 0.07, 0.3 and 0.2 for 2019, 2020 and 2021, respectively. The pigeon pea seasonal average gross biomass water productivity values were 0.80, 0.9, and 0.6 kg/m^3 with a standard deviation of 0.07, 0.4, and 0.3 for 2019, 2020 and 2021, respectively. Sharma et al., (2018) carried out water productivity mapping of major Indian crops study estimated pigeon pea WP and reported a range between 0.22 and 0.72 kg/m3. Wheat had average values of 0.789, 1, and 0.5 kg/m^3 with standard deviation of 0.06, 0.4, and 0.3 for 2019, 2020, and 2021, respectively. water productivity mapping of major Indian crop study estimated wheat WP and indicated a range between 0.6 and 1.7 kg/m3 (Sharma et al., 2018), and also Zwart et al., (2010a) reported global scale range values of crop water productivity of wheat ranging from 0.2 to 1.8 kg/m^3 and found the country highest average of wheat crop water productivity of 1.42 to 1.35 kg/m^3 in France and Germany, respectively.

The seasonal gross biomass water productivity values of onion, pigeon pea, and wheat show that all crops had almost the same crop water productivity values compared to one another for the overall three winter seasons with average values of 0.73, 0.77, and 0.76, respectively.

Table 4-10 Statistics of CWP from December 2019 to March 2021

Crops	**Onion**				**Pigeonpea**				**Wheat**			
Statstics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2019	0.42	1.37	0.8	0.07	0.44	1.7	0.8	0.073	0.42	1.15	0.79	0.06
2020	0.4	1.2	0.8	0.3	0.4	1.8	0.9	0.4	0.4	1.6	1	0.4
2021	0.2	0.9	0.6	0.2	0.2	1.1	0.6	0.3	0.1	0.9	0.5	0.3
Overall			0.73	0.19			0.77	0.26			0.76	0.25

Figure4-7 shows spatial variability of gross CWP of summer and winter crops within the Gezira study area.

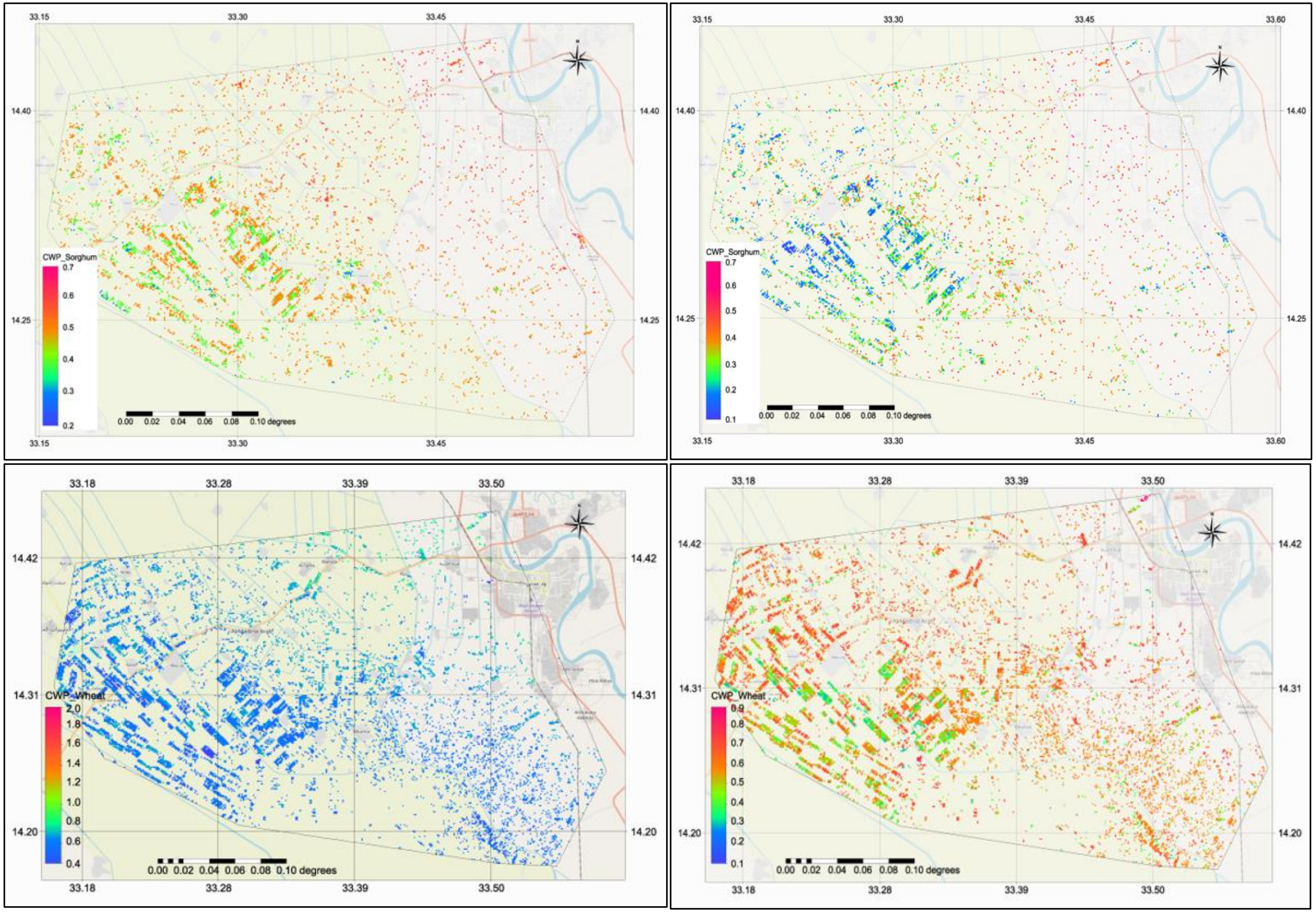

Figure 4-7 Spatial variabilities of Gross CWP in kg/m³ of sorghum (Upper) and wheat (Lower) for summer 2018 and winter 2020, respectively.

4.2.5. Seasonal comparison of crop water consumption

From quantified crop water use indicators, the transpiration and evapotranspiration of summer and winter crops were compared to each other, and more details are shown in the following sections.

4.2.5.1. Comparison of crop water consumption for Gezira Irrigation Scheme Summer Season

Figure 4-8 shows that Cotton for the entire season has the highest transpiration and evapotranspiration than others. It also shows that groundnut is higher water consumable than sorghum. There is a sudden reduction of sorghum transpiration in 2020 season with 243 mm/season which is lower compared to the other seasons. This can be caused by the change of land cover type.

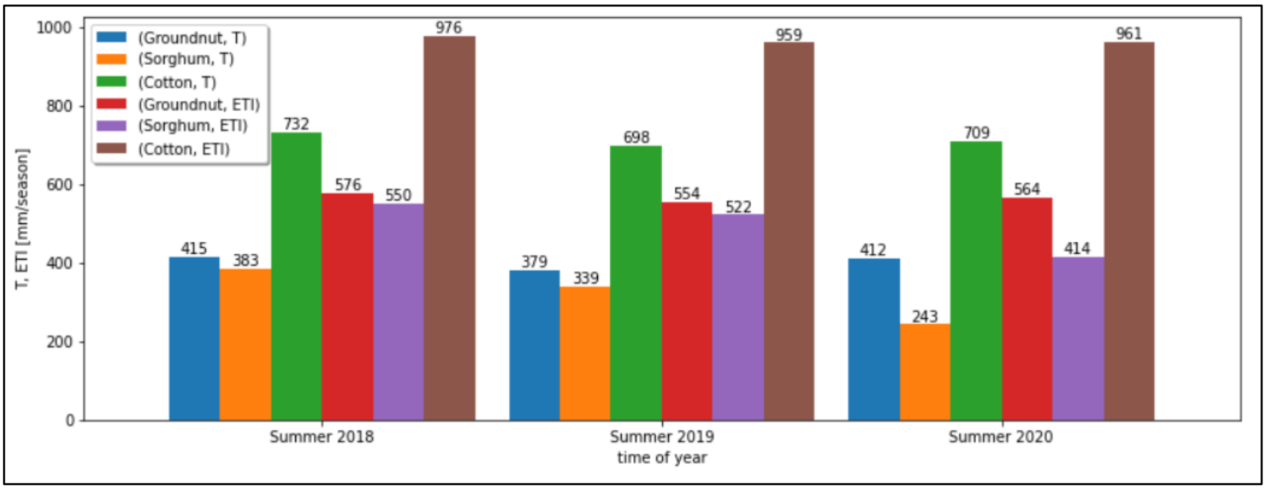

Figure 4-8 Seasonal T and ETI for groundnut, sorghum, and cotton (full season) for 2018, 2019 and 2020

Table 4-11 The statistics of T and ETI for groundnut, sorghum, and cotton

Crops	Groundnut				Sorghum				Cotton			
Indicators	T	Std Dev	ETI	Std Dev	T	Std Dev	ETI	Std Dev	T	Std Dev	ETI	Std Dev
2018	415	180	576	179	383	153	550	151	732	366	976	383
2019	378	173	554	169	339	165	522	153	698	365	959	376
2020	412	174	564	168	243	142	414	137	709	403	961	419
Overall	402	176	564	172	321	153	495	147	713	378	965	393

4.2.5.2. Comparison of crop water consumption for the winter season

Figure 4-9 shows different crop water consumption of winter crops from 2019 to 2021, the wheat has higher water use than pigeon pea and onion in 2019 and 2020 seasons. 2020 season has higher transpiration and evapotranspiration compared to the other two seasons for all crops. Wheat is the highest transpired than others in all seasons, but the difference is not big in 2021 season. Table4-12 summarises transmission and evapotranspiration for winter season.

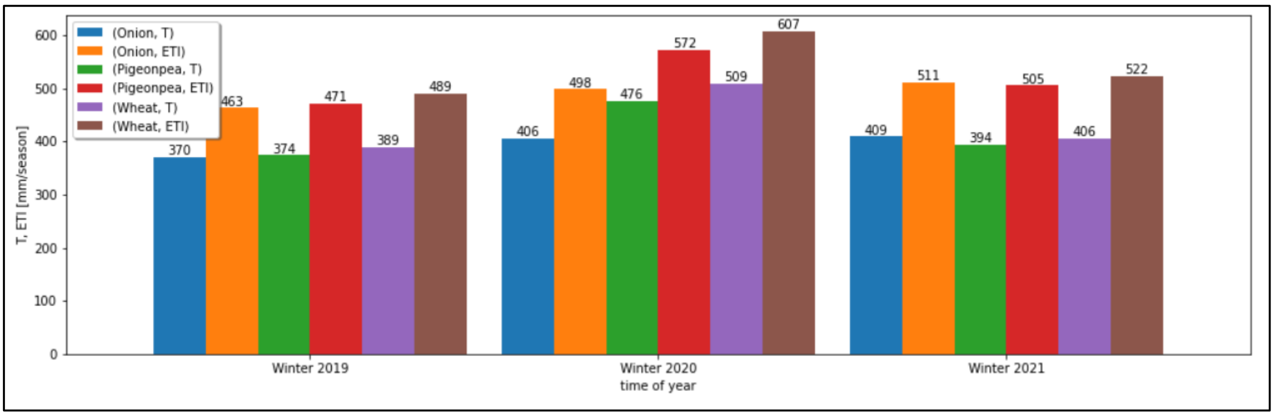

Figure 4-9 The T and ETI for winter main crops for 2019, 2020 and 2021

Table 4-12 Statistics of T and ETI for winter season main crops for 2019, 2020 and 2021

Crops	**Onion**				**Pigeon pea**				**Wheat**			
Statstics	**T**	**Std dev**	**ETI**	**Std Dev**	**T**	**Std dev**	**ETI**	**Std Dev**	**T**	**Std dev**	**ETI**	**Std Dev**
2019	370.45	198.06	463.39	215.25	374.07	183.68	471.48	196.21	389.46	190.45	489.74	201.32
2020	405.79	202.61	498.5	218.45	476.16	183.57	572.57	196.92	508.71	179.67	607.62	190.7
2021	409.57	229.36	511.48	246.56	394.62	205.6	505.59	216.67	405.93	219.99	522.04	230.23
Overall	370.45	198.06	463.39	215.25	374.07	183.68	471.48	196.21	389.46	190.45	489.74	201.32

4.2.6. Relationship between Total Biomass Production and Evapotranspiration

4.2.6.1. Relationship between Total Biomass Production and Evapotranspiration for summer season

Figure 4-10 shows linear relationships between total biomass production and evapotranspiration for the summer groundnut, sorghum, and cotton crops of 2018, 2019, and 2020. TBP varies with respect to the variation of water consumed. The strong relationship was found for sorghum, a C4 photosynthetic plant with the coefficient of determination R^2 =0.83. The R^2 of 0.71 and 0.66 were found for C3 photosynthetic plants groundnut and cotton, respectively. This means that total biomass production increases with respect to the increase of ETI for both C4 and C3 plants.

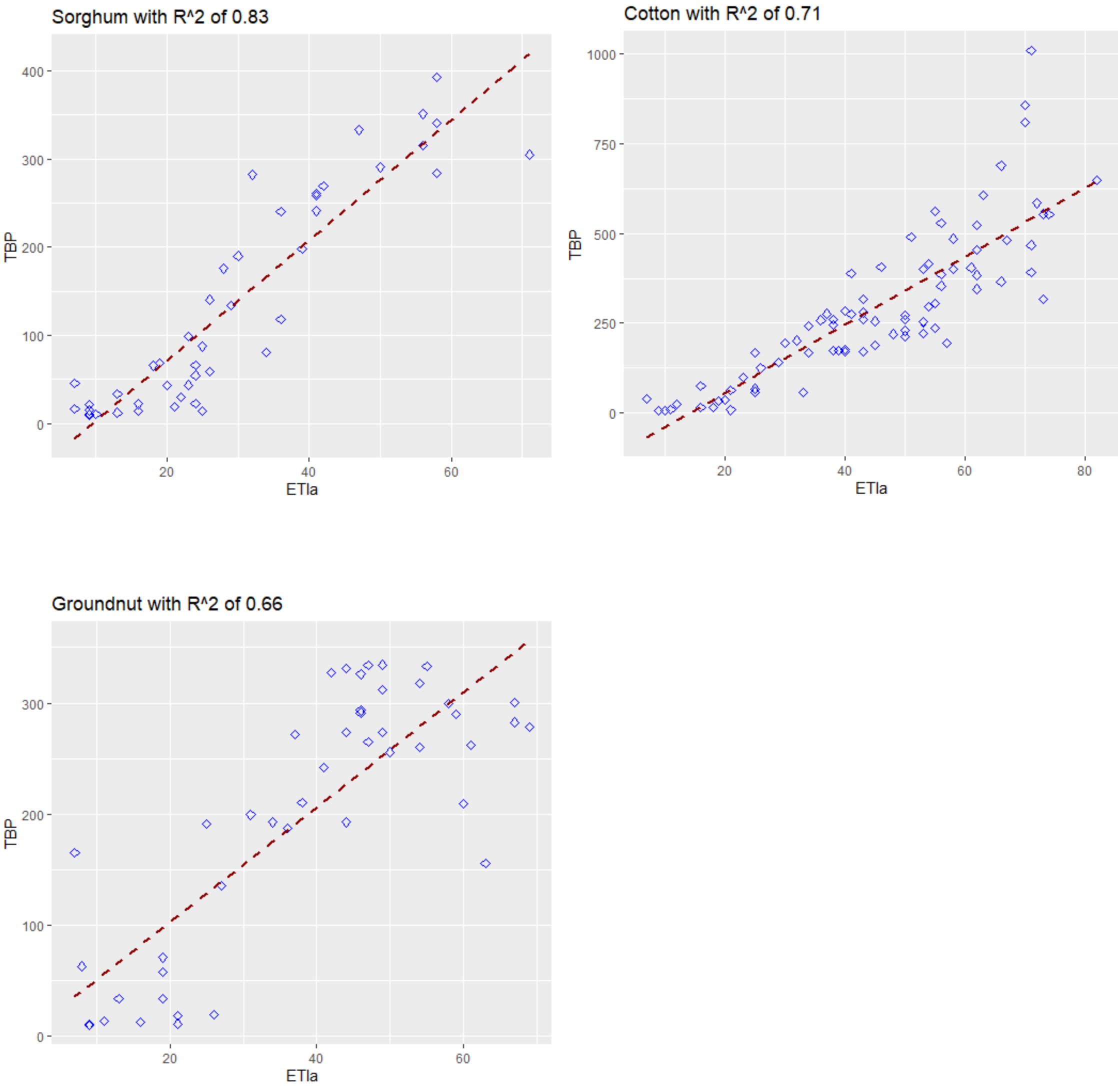

Figure 4-10: The total biomass production plotted against ETI for summer groundnut, sorghum, and cotton

4.2.6.2. Relationship between Total Biomass Production and Evapotranspiration for Winter Season

Figure 4-11 shows the linear relationships between TBP and ETI for all winter crops. Total biomass production increasing with respect to the increase of ETI. The relationships between TBP and ETI for pigeon pea, onion, and wheat show positive linear relationships to all three crops. A higher relationship was found for pigeon pea compared to onion and wheat with the coefficient of determination R^2 =0.55. The R^2 of 0.50 and 0.22 were found for wheat and onion, respectively. This shows the lower relationships compared to summer crops.

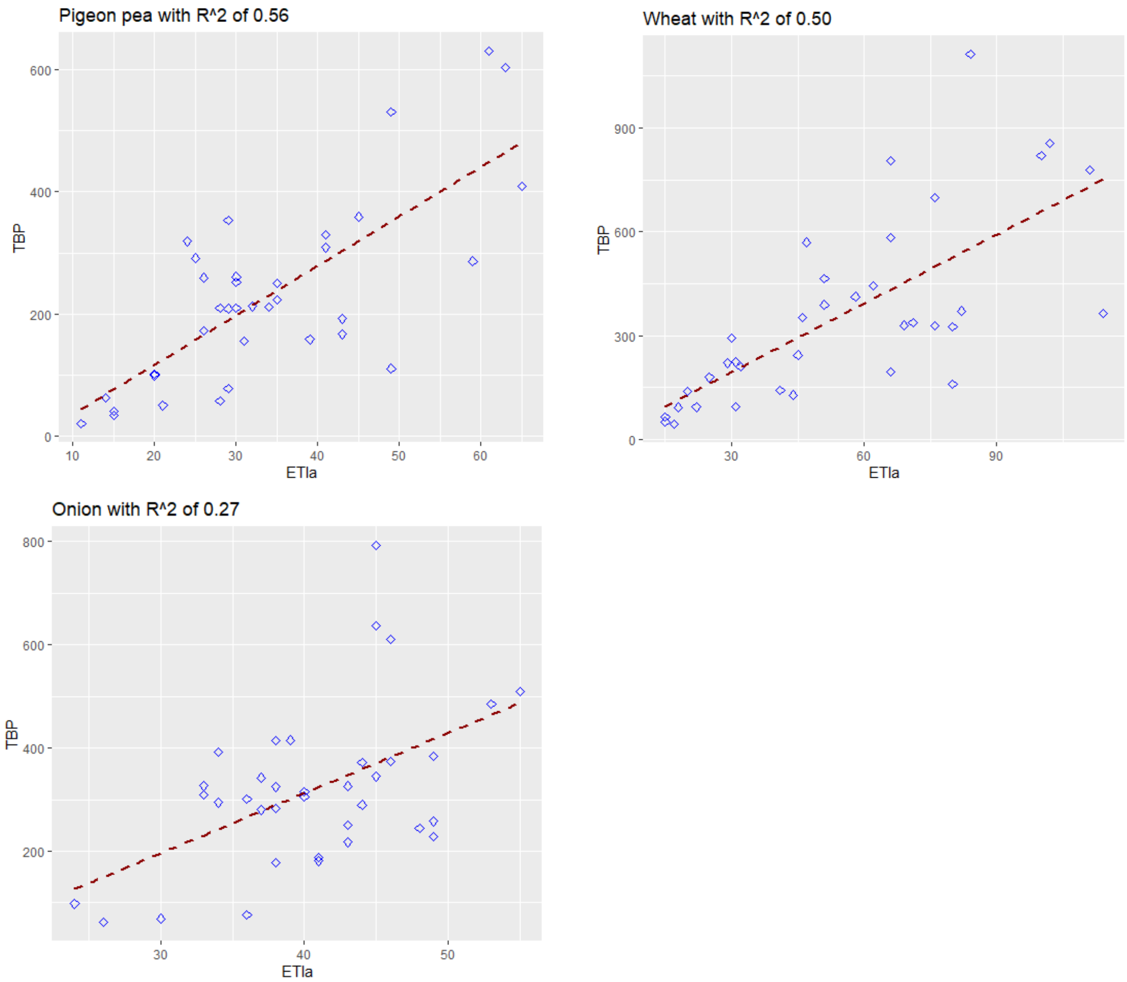

Figure 4-11 The Total biomass production plotted against ETI for winter onion, pigeon pea and wheat

4.2.7. Seasonal Comparison of Total Biomass Production and Gross Crop Water Productivity

4.2.7.1. Comparison of Total Biomass Production and Gross Crop Water Productivity for Gezira Irrigation Scheme Summer Season

Figure 4-12 shows variations of total biomass production and crop water productivity during summer seasons from 2018 to 2020. The cotton production is for a full season (summer and winter) and is the highest in all three seasons. The sorghum is the lowest productive crop in all seasons. Season 2018 is more productive compared to 2019 and 2020 seasons. For crop water productivity, cotton is the highest crop water productivity in all seasons. The sorghum is the lowest crop water productivity in 2018 and 2020 seasons. In 2019 season, groundnut and sorghum have the same crop water productivity.

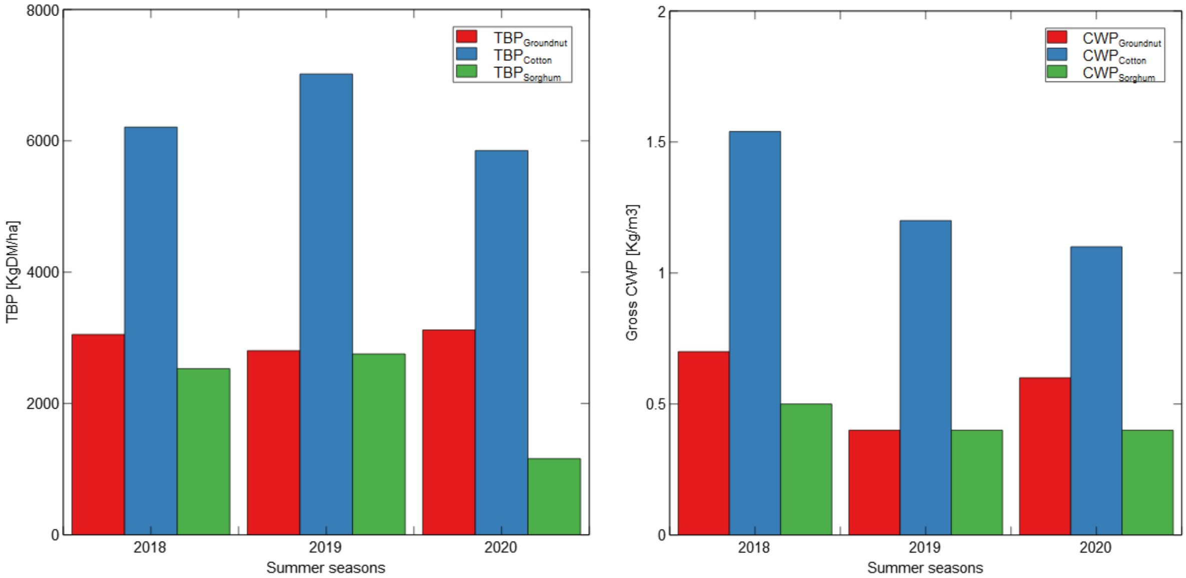

Figure 4-12 TBP (Left) and CWP (Right) for groundnut, sorghum, and cotton (full season) for 2018, 2019 and 2020

Table 4-13 Statistics of TBP and CWP for groundnut, sorghum, and cotton for 2018, 2019 and 2020

Crops	**Groundnut**				**Sorghum**				**Cotton(Full season)**			
Statistics	TBP	Std Dev	CWP	Std Dev	TBP	Std Dev	CWP	Std Dev	TBP	Std Dev	CWP	Std Dev
2018	3051.47	781.29	0.7	0.6	2531.15	770.58	0.5	0.2	6209.19	1399.3	1.54	0.13
2019	2804.34	901.6	0.4	0.2	2754.88	934.86	0.4	0.2	7017.5	1811.35	1.2	0.7
2020	3120.06	692.81	0.6	0.2	1159.81	730.8	0.4	0.2	5852.42	1616.38	1.1	0.6
Overall	2991.957	791.9	0.56	0.33	2148.613	812.08	0.43	0.2	6359.703	1609.01	1.96	1.26

4.2.7.2. Comparison of Total Biomass Production and Crop water productivity for Winter Season

Figure 4-13 shows the winter seasonal variations of TBP and gross crop water productivity during winter seasons from 2019 to 2021. Season 2020 is higher productive than others. Wheat is the highest productive crop in this season. In 2018 and 2021 seasons, the productions were almost the same for onion, pigeon pea and wheat. The crop water productivity of wheat is higher than other crops for 2020 season and season 2020 has higher crop water productivity compared to the other seasons. Season 2021 has lower crop water productivity than other seasons. While table4-14 summarises seasonal TBP and GCWP of winter crops.

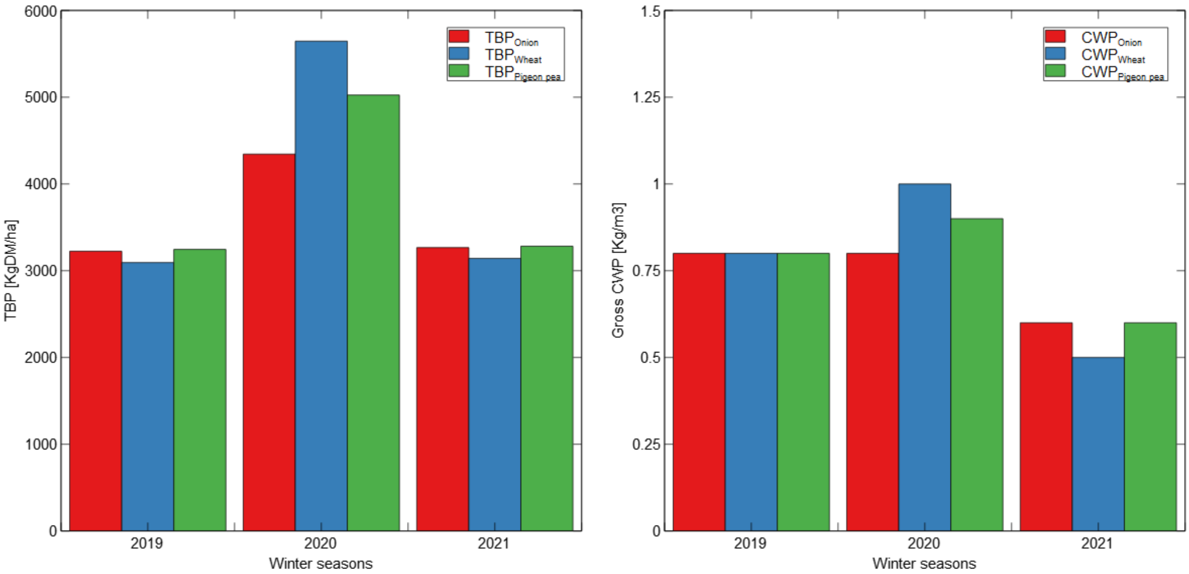

Figure 4-13 The histogram of TBP and CWP for winter season main crops for 2019, 2020 and 2021

Table 4-14 Statistics of TBP and CWP values for winter season

Crops	Onion				Pigeon pea				Wheat			
Statstics	CWP	Std dev	TBP	Std Dev	CWP	Std dev	TBP	Std Dev	CWP	Std dev	TBP	Std Dev
2019	0.80	0.07	3224.74	995.64	0.80	0.07	3246.33	982.91	0.789	0.061	3093.98	1057.69
2020	0.8	0.3	4343.52	1083.52	0.9	0.4	5025.17	935.27	1	0.4	5645.71	1105.32
2021	0.6	0.2	3267.35	1259.45	0.6	0.3	3283.25	1264.84	0.5	0.3	3142.27	1380.75
Overall	0.73	0.19	3224.74	995.64	0.77	0.26	3246.33	982.91	0.76	0.25	3093.98	1057.69

4.3. RESULT AND ANALYSIS FOR NASHO IRRIGATION SCHEME AND RAINFED AGRICULTURE

For Nasho study area, irrigation and rainfed based agriculture are considered. The irrigation and rainfed study area masks were created to separate irrigation scheme and rainfed area. Crop water use indicators like crop transpiration, evapotranspiration, biomass production, and crop water productivity of main crops were calculated and seasonally analysed in both irrigation and rainfed agriculture for two agricultural growing seasons, season A(winter) and season B(summer). More details are described in the following sections. Note that the time series graphs presented below are based on the averaged five (5) selected sample pixels as mentioned on Gezira study area.

4.3.1. Transpiration (T)

The dekadal transpiration of Nasho study area used to calculate the seasonal transpiration for irrigation scheme and rainfed agriculture. Using the crop masks, the dekadal and seasonal transpiration of beans, banana, sorghum and maize for summer and winter seasons were extracted from irrigation and rainfed masks. Figure4-14 shows the transpiration time-series behaviours of sample pixels for summer and winter seasons of 2018, 2019 and 2020 for irrigated beans and maize, and for rainfed beans, sorghum, and banana.

The observations made show that the transpiration trends of all crops have a lot of fluctuates which may be caused by the variations of climatic conditions of humid climate. The rotation of irrigated beans and maize shows the highest peak in December 2018 with the value of 42 mm/dekad. Irrigated crops also show the higher transpiration compared to the rainfed crops, the exceptional trend occurred between January 2020 and June 2020, and from November 2020 to February 2021 where the rainfed banana has higher values compared to the other crops. The high values of irrigated beans and maize have significant meaning due to the availability of irrigation water which may increase the transpiration of irrigated crops. There is a high correlation between rainfed beans and rainfed banana from March 2018 to July 2018 (summer season) which is not significant. This may be caused by the change of land cover from banana to beans at that time. More details on statistics of different crops for winter and summer seasons are described in the following sections.

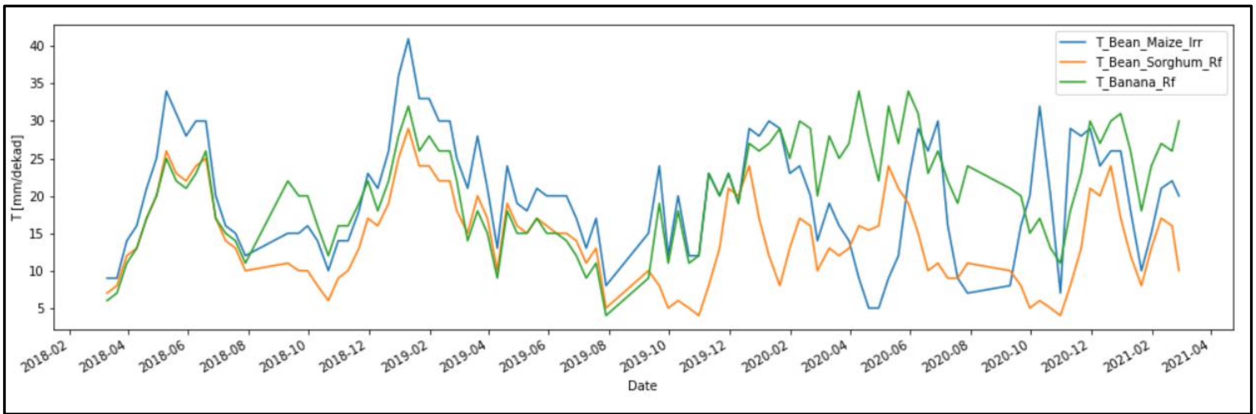

Figure 4-14 Transpiration of the crops from March 2018 to February 2021 for Nasho Irrigation and rainfed

4.3.1.1. Transpiration for the irrigation winter season

Table 4-15 shows the statistics of transpiration of the entire scheme where averaged seasonal transpiration values of beans were 414.94, 352.89, and 325.05 mm/season with a standard deviation of 92.88, 54.3 and 65.62 for 2018, 2019 and 2020, respectively. The seasonal transpiration of maize was also estimated, and its average values were 466.79, 382.89, and 409.72 mm/season with a standard deviation of 62.95, 54.3 and 32.58 for 2018, 2019 and 2020, respectively. These seasonal transpiration values show that the maize had higher transpiration compared to beans for all three winter seasons with the overall transpiration values of 409.8 and 364.29 with a standard deviation of 49.94 and 70.93 for maize, and beans, respectively.

Table 4-15 Statistics of transpiration for winter main crops of irrigation scheme from September 2018 to February 2021

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	196	596	414.94	92.88	282	599	466.79	62.95
2019	237	470	352.89	54.3	237	470	382.89	54.3
2020	171	465	325.05	65.62	342	465	409.72	32.58
Overall			364.29	70.93			409.8	49.94

4.3.1.2. Transpiration for the irrigation summer season

Table 4-16 shows the statistics of transpiration of the entire scheme where averaged seasonal transpiration values of beans were 289.95, 352.81, and 277.81 mm/season with a standard deviation of 55.52, 57.98 and 53.11 for 2018, 2019 and 2020, respectively. The seasonal transpiration of maize was also calculated, and its average values are 300.26, 451.17, and 396.13 mm/season with standard deviation of 53.96, 51.48 and 37.46 for 2018, 2019 and 2020, respectively. These seasonal transpiration values show that the maize had higher transpiration compared to beans for all three summer seasons with the overall transpiration values of 382.52 and 306.86 with a standard deviation of 47.63 and 55.54 for maize, and beans, respectively.

Table 4-16 Statistics of transpiration for summer main crops of irrigation scheme from March 2018 to July 2020

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	180	404	289.95	55.52	160	415	300.26	53.96
2019	204	493	352.81	57.98	314	551	451.17	51.48
2020	0	393	277.81	53.11	317	475	396.13	37.46
Overall			306.86	55.54			382.52	47.63

4.3.1.3. Transpiration (T) for the rainfed winter season

Table 4-17 shows the statistics of transpiration of the entire scheme where averaged seasonal transpiration values of beans were 380.46, 319.11and 298.74 mm/season with a standard deviation of 107.16, 73 and 85.61 for 2018, 2019 and 2020, respectively. For the banana full season, the average seasonal transpiration values were 686.58, 647.24 and 662.98 mm/season with a standard deviation of 179.76, 155.59 and 149.23 for 2018, 2019 and 2020, respectively. The seasonal transpiration of sorghum was also estimated, and its average values were 376.47, 327.65, and 332.99 mm/season with a standard deviation of 93.7, 64.7 and 74.75 for 2018, 2019 and 2020, respectively. These seasonal transpiration values show that the sorghum had higher transpiration compared to beans and banana for 2019 and 2020 winter seasons with the overall evapotranspiration values of 345.70, 342.86, and 332.77 mm/season with standard deviation of 77.72, 87.14 and 88.59 mm/season for sorghum, banana, and beans, respectively.

Table 4-17 Statistics of transpiration for winter main crops of rainfed agriculture from September 2018 to February 2021

Crops	**Beans**				**Banana (full seasom)**				**Sorghum**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	119	637	380.46	107.16	121.00	1072.00	686.58	179.76	117	600	376.47	93.7
2019	115	466	319.11	73	144.00	980.00	647.24	155.59	138	455	327.65	64.7
2020	75	489	298.74	85.61	160.40	1057.70	662.98	149.23	125	559	332.99	74.75
Overall			332.77	88.59			665.60	161.53			345.70	77.72

4.3.1.4. Transpiration for rainfed summer season

Table 4-18 shows the statistics of transpiration of the entire scheme where averaged seasonal transpiration values of beans were 304.2, 302.9 and 302.21 mm/season with a standard deviation of 68.19, 67.04 and 57.45 for 2018, 2019 and 2020, respectively. The seasonal transpiration of sorghum was also calculated, and its average values were 291.9, 304.14, and 293.97 mm/season with a standard deviation of 61.49, 70.52 and 56.56 for 2018, 2019 and 2020, respectively. These seasonal transpiration values show that the beans had higher transpiration compared to sorghum for 2018, 2019 and 2020 summer seasons with the overall evapotranspiration values of

303.10, and 296.67 mm/season with a standard deviation of 64.23 and 62.86 mm/season for beans, and sorghum respectively.

Table 4-18 Statistics of transpiration for summer main crops of rainfed agriculture from March 2018 to July 2020

Crops	**Beans**				**Sorghum**			
Statistics	**Min**	**Max**	**Avg**	**StdDev**	**Min**	**Max**	**Avg**	**StdDev**
2018	136	428	304.2	68.19	163	410	291.9	61.49
2019	132	465	302.9	67.04	192	475	304.14	70.52
2020	67.4	440.7	302.21	57.45	185	404.5	293.97	56.56
Overall			303.10	64.23			296.67	62.86

4.3.2. Evapotranspiration and Interception (ETIa)

The dekadal evaporation, transpiration and interception were used to calculate the dekadal evapotranspiration and interception (ETIa) by using equation 8 explained in section 3.5.1. Seasonal ETIa was calculated by summing up quantified dekadal ETIa. Also using the crop masks, the dekadal and seasonal ETIa of beans, maize, sorghum, and banana for summer and winter seasons were extracted from quantified ETIa. Figure4-15 shows the evapotranspiration time series behaviours of sample pixels for three winter seasons of 2018, 2019 and 2020 for beans, maize, sorghum, and banana. Figure4-15 is also illustrating the distribution of ETIa between irrigated beans and maize, there are fluctuates in trends. These fluctuations are caused by the different crop responses to the environmental conditions due to their different biochemical components. The observations made show that the rotation of irrigated beans and maize has the highest peak in December 2018 with the value of 46 mm/dekad. Irrigated crops also show the higher evapotranspiration compared to the rainfed crops, the exceptional trend occurred between January 2020 and June 2020, and from November 2020 to February 2021 where the rainfed banana has higher values compared to the other crops. The high values of irrigated beans and maize have significant meaning due to the availability of irrigation water which may increase the transpiration of irrigated crops. There is a high correlation between rainfed beans and rainfed banana from March 2018 to July 2018 (summer season) which is not significant. This may be caused by the change of land cover from banana to beans at that time. More details on statistics of different crops for winter and summer seasons are described in the following sections.

Figure 4-15 Evapotranspiration and interception from March 2018 to February 2021 for Nasho Irrigation and rainfed

4.3.2.1. Actual Evapotranspiration and Interception (ETIa) for irrigation for the winter season

Table 4-19 shows the statistics of evapotranspiration of the entire scheme where averaged seasonal evapotranspiration values of beans were 557.07, 464.6, and 455.68 mm/season with a standard deviation of 79.49, 46.55 and 57.98 for 2018, 2019 and 2020, respectively. The seasonal evapotranspiration of maize was also estimated, and its average values were 598.68, 494.6, and 521.72 mm/season with a standard deviation of 56.95, 46.55 and 29.32 for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported maize evapotranspiration ranges between less than 500 and more than 800 mm/season depends on the environment. These seasonal evapotranspiration values show that the maize had higher evapotranspiration compared to beans for all three winter seasons with the overall evapotranspiration values of 528.33 and 492.45 mm/season with a standard deviation of 44.27 and 61.34 mm/ season for maize, and beans, respectively.

Table 4-19 Statistics of evapotranspiration of irrigation scheme for winter main crops from September 2018 to February 2021

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	367	727	557.07	79.49	443	730	598.68	56.95
2019	372	560	464.6	46.55	372	560	494.6	46.55
2020	324	572	455.68	57.98	458	571	521.72	29.32
Overall			492.45	61.34			528.33	44.27

4.3.2.2. Actual Evapotranspiration and Interception for the irrigation summer season

Table 4-20 shows the statistics of evapotranspiration of the entire scheme where averaged seasonal evapotranspiration values of beans were 388.64, 437.04, and 371.22 mm/season with a standard deviation of 45.14, 48.91 and 38.7 for 2018, 2019 and 2020, respectively. The seasonal evapotranspiration of maize was also estimated, and its average values were 399.04, 451.17, and 396.13 mm/season with a standard deviation of 46.63, 51.48 and 37.46 for 2018, 2019 and 2020, respectively. These seasonal evapotranspiration values show that the maize had higher evapotranspiration compared to beans for all three summer seasons with the overall evapotranspiration values of 415.45 and 398.97 mm/season with a standard deviation of 45.19 and 44.25 mm/ season for maize, and beans, respectively.

Table 4-20 Statistics of evapotranspiration for summer main crops of irrigation scheme from March 2018 to July 2020

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	309	488	388.64	45.14	284	493	399.04	46.63
2019	335	558	437.04	48.91	314	551	451.17	51.48
2020	287	460	371.22	38.7	317	475	396.13	37.46
Overall			398.97	44.25			415.45	45.19

4.3.2.3. Actual Evapotranspiration and Interception for the rainfed winter season

The results were shown in table4-21 which summarises the statistics of evapotranspiration of the entire area where averaged seasonal evapotranspiration values of beans were 510.82, 402.02 and 416.34 mm/season with a standard deviation of 102.28, 68.63 and 82.75 for 2018, 2019 and 2020, respectively. For the banana full season, the average seasonal evapotranspiration values were 895.78, 810.85 and 839.03 mm/season with a standard deviation of 166.67, 146.83 and 143.02 for 2018, 2019 and 2020, respectively. The seasonal evapotranspiration of sorghum was also estimated, and its average values were 504.1, 410.14, and 432.43 mm/season with a standard deviation of 88.42, 59.36 and 432.43 for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported sorghum evapotranspiration range between 450 and 750 mm depends on evaporative demand and environmental condition for sorghum with 110 to 130 days of growing duration. These seasonal evapotranspiration values show that the sorghum had higher evapotranspiration compared to beans and banana for 2019 and 2020 winter seasons with the overall evapotranspiration values of 448.89, 445.04 and 443.05 mm/season with standard deviation of 73.15, 82.97 and 82.97 mm/season for sorghum, banana, and beans, respectively.

Table 4-21 Statistics of evapotranspiration for winter main crops of rainfed agriculture from September 2018 to February 2021

Crops	**Beans**				**Banana (full seasom)**				**Sorghum**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	252	757	510.82	102.28	386	1287	895.78	166.67	253	724	504.1	88.42
2019	208	534	402.01	68.63	366	1116	810.85	146.83	232	521	410.14	59.36
2020	198	584	416.34	82.75	360.1	1202.4	839.03	143.02	237	641	432.43	71.66
Overall			443.05	84.55			848.55	152.17			448.89	73.15

4.3.2.4. Actual Evapotranspiration and Interception for the rainfed summer season

The results were shown in table4-22 summarises the statistics of evapotranspiration of the entire area where averaged seasonal evapotranspiration values of beans were 392.61, 390.5 and 384.56 mm/season with a standard deviation of 64.34, 62.1 and 51.6 for 2018, 2019 and 2020, respectively. The seasonal evapotranspiration of sorghum was also calculated, and its average values were 375.2, 387.84, and 376.17 mm/season with a standard deviation of 57.34, 67.26 and 52.03 for 2018, 2019 and 2020, respectively. These seasonal evapotranspiration values show that the beans had higher evapotranspiration compared to sorghum for 2018, 2019 and 2020 summer seasons with the overall evapotranspiration values of 389.22, and 379.74 mm/season with a standard deviation of 59.35 and 58.88 mm/season for beans and sorghum, respectively.

Table 4-22 Statistics of evapotranspiration for summer main crops of rainfed agriculture from March 2018 to July 2020

Crops	**Beans**				**Sorghum**			
Statstics	**Min**	**Max**	**Avg**	**StdDev**	**Min**	**Max**	**Avg**	**StdDev**
2018	231	501	392.61	64.34	277	483	375.2	57.34
2019	225	529	390.5	62.1	286	541	387.84	67.26
2020	167.1	505.3	384.56	51.6	274.7	473.2	376.17	52.03
Overall			389.22	59.35			379.74	58.88

4.3.3. Total Biomass Production (TBP)

The dekadal total biomass production (TBP) was calculated using equation 9 explained in section 3.5.2. Seasonal TBP was calculated by summing up quantified dekadal TBP. Also using the crop masks, the dekadal and seasonal TBP of irrigated beans and maize, rainfed beans, sorghum, and banana for summer and winter seasons were extracted from quantified TBP.

Figure4-16 shows the total biomass production time series behaviours of sample pixels for winter and summer seasons of 2018, 2019 and 2020 of above mentioned irrigated and rainfed crops. The observations made show that irrigated beans and maize have higher values of productions in all seasons. Exceptional values are occurred between January 2020 and June 2020, and from November 2020 to February 2021 where the rainfed banana has higher values of production compared to the other crops. More details on statistics of different crops for winter and summer seasons are described in the following sections.

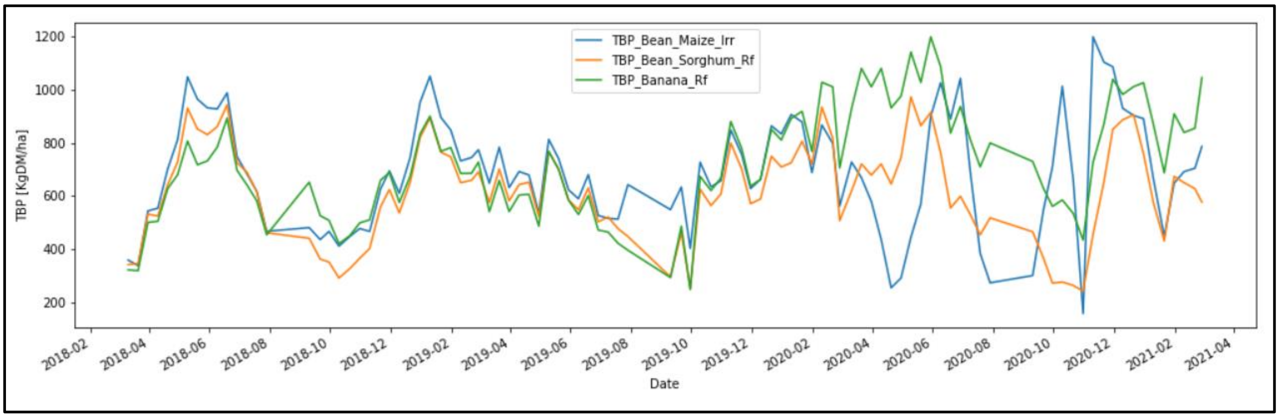

Figure 4-16 Total biomass Production of the crops from March 2018 to February 2021 for Nasho Irrigation and rainfed

4.3.3.1. Total Biomass Production for the irrigation winter season

The results for the winter seasons of 2018, 2019 and 2020 are shown in table 4-23 which shows the statistics of total biomass production of the entire selected area of the scheme where averaged seasonal total biomass production values of beans were 12397.99, 12299.94, and 12022.81 kg DM/ha/season with a standard deviation of 2234.95, 1410.4 and 1740.25 for 2018, 2019 and 2020, respectively. The seasonal total biomass production of maize was also estimated, and its average values are 13186.52, 13012.34, and 14561.61 kg DM/ha/season with a standard deviation of 1552.88, 1410.4 and 1212.27 kg DM/ha/season for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported yield production range between 11 and 14 ton/ha of maize under full irrigation and high fertile environment. Also, water productivity mapping of major Indian crop study estimated maize yield production and indicated an average of 2.42 ton/ha (Sharma et al., 2018). These seasonal total biomass production values show that the maize had higher total biomass production compared to beans for all three winter seasons with the overall total biomass production values of 13349.36 and 12240.25 kg DM/ha with a standard deviation of 1391.85 and 1795.2 kg DM/ha/season for maize, and beans, respectively.

Table 4-23 Statistics of TBP for winter main crops of irrigation scheme from September 2018 to February 2021

Crops	Beans				Maize			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	6518.39	17960.7	12397.99	2234.95	8738.39	16302.98	13186.52	1552.88
2019	8129.04	15773.83	12299.94	1410.4	8129.04	15773.83	13012.34	1410.4
2020	7660.8	17094.28	12022.81	1740.25	10759.46	16601.62	14561.61	1212.27
Avg			12240.25	1795.20			13349.36	1391.85

4.3.3.2. Total Biomass Production for the irrigation summer season

Table 4-24 shows the statistics of total biomass production of the entire scheme where averaged seasonal total biomass production values of beans were 9845.8, 10808.67, and 10947.42 kg DM/ha/season with a standard deviation of 1463.88, 1494.56 and 1517.25 for 2018, 2019 and 2020, respectively. The seasonal total biomass production of maize was also calculated, and its average values were 10401, 11364.25, and 11742.33 kg DM/ha/season with a standard deviation of 1256.37, 1456.67 and 1190.43 kg DM/ha/season for 2018, 2019 and 2020, respectively. These seasonal total biomass production values show that the maize had higher total biomass production compared to beans for all three summer seasons with the overall total biomass production values of 11169.19 and 10533.96 kg DM/ha/season with a standard deviation of 1301.16 and 1491.90 kg DM/ha/season for maize, and beans, respectively.

Table 4-24 Statistics of TBP for summer main crops of irrigation scheme from March 2018 to July 2020

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	6585.7	13107.4	9845.8	1463.88	5785.94	13555.41	10401	1256.37
2019	6538.16	15149.41	10808.67	1494.56	7250.8	15052.95	11364.25	1456.67
2020	7493.28	13930.3	10947.42	1517.25	8313.47	14031.87	11742.33	1190.43
Overall			10533.96	1491.90			11169.19	1301.16

4.3.3.3. Total Biomass Production for the rainfed winter season

Table 4-25 shows the statistics of evapotranspiration of the entire area where averaged seasonal total biomass production values of beans were 11401, 11596 and 11307 kg DM/ha/season with a standard deviation of 2170, 1724 and 1969 for 2018, 2019 and 2020, respectively. For the banana full season, the average seasonal total biomass production values were 21907, 21911 and 24352 kg DM/ha/season with a standard deviation of 3816, 3530, and 3812 for 2018, 2019 and 2020, respectively. The seasonal total biomass production of sorghum was also estimated, and its average values were 11285, 11520, and 11889 kgDM/ha/season with a standard deviation of 1862.4, 1672.6 and 1704.8 for 2018, 2019 and 2020, respectively. Steduto et al., (2012) reported average country production of sorghum of 4.7 ton/ha in United States and Argentina, and 0.6 ton/ha in Sudan. These seasonal total biomass production values show that the banana had higher total biomass production compared to beans and sorghum for all three winter seasons with the overall total biomass production values of 11619, 11565, and 11435 kg DM/ha/season with a standard deviation of 1922, 1746.6 and 1954 kg DM/ha/season for banana, sorghum, and beans, respectively.

Table 4-25 Statistics of TBP for winter main crops of rainfed agriculture from September 2018 to February 2021

Crops	**Beans**				**Banana (full seasom)**				**Sorghum**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	4557	18166	11401	2170	5851	31253	21907	3816	4712	16122	11285	1862
2019	5377	15322	11596	1724	7290	30094	21911	3530	6102	15304	11520	1673
2020	4423	16665	11307	1969	9500	37033	24352	3812	5905	18645	11889	1705
Overall			11435	1954			22723	3719			11565	1747

4.3.3.4. Total Biomass Production for the rainfed agriculture summer season

The results were shown in table4-26 which summarises the statistics of total biomass production of the entire area where average seasonal total biomass production values of beans were 10766.32, 9955.57 and 11513.34 kg DM/ha/season with a standard deviation of 1636.4, 1381.67 and 1636.16 for 2018, 2019 and 2020, respectively. The seasonal total biomass production of sorghum was also estimated, and its average values were 10458.26, 9897.15, and 11292.32 kg DM/ha/season with a standard deviation of 1494.38, 1639 and 1426.9 for 2018, 2019 and 2020, respectively. These seasonal total biomass production values show that the banana had higher total biomass production compared to beans and sorghum for all three summer seasons with the overall total biomass production values of 10745.08, and 10549.24 kg DM/ha/season with a standard deviation of 1551.41 and 1520.09 kg DM/ha/season for beans and sorghum, respectively.

Table 4-26 Statistics of TBP for summer main crops of rainfed agriculture from March 2018 to July 2020

Crops	**Beans**				**Sorghum**			
Statstics	**Min**	**Max**	**Avg**	**StdDev**	**Min**	**Max**	**Avg**	**StdDev**
2018	5587.5	14134.52	10766.32	1636.4	5870.39	13882.53	10458.26	1494.38
2019	5359.95	13017.18	9955.57	1381.67	7075.69	14484.07	9897.15	1639
2020	4213.79	16097.85	11513.34	1636.16	8352.41	14414.73	11292.32	1426.9
Overall			10745.08	1551.41			10549.24	1520.09

4.3.4. Gross Biomass Water Productivity (GB_WP)

The dekadal gross biomass water productivity was calculated from dekadal total biomass production and evapotranspiration using equation 10 explained in section 3.5.3. Seasonal GBWP was calculated by summing up quantified dekadal GBWP. Also using the crop masks, the dekadal and seasonal GBWP of beans, maize, sorghum, and banana for summer and winter seasons were extracted from quantified GBWP. Figure4-17 shows the distribution of gross crop water productivity time series for 2018, 2019 and 2020 for irrigated beans and maize, and rainfed beans, banana, and sorghum. The observations made show that rotation of rainfed beans and sorghum has higher values of GBWP compared to the crops. This has significant meaning due to the water limitation of rainfed area which results in lower evapotranspiration compared to the irrigated area. The irrigated crops have lower GBWP due to the higher evapotranspiration from irrigated area. The exceptional values are occurred in September where all crops have the highest peak with 6.7 kg/m^3 at the same point. This value has no significant meaning. Also, the lowest value is occurred to the rotation of irrigated beans and maize which has the value of less than one (1). More details on statistics of different crops for winter and summer seasons are described in the following sections.

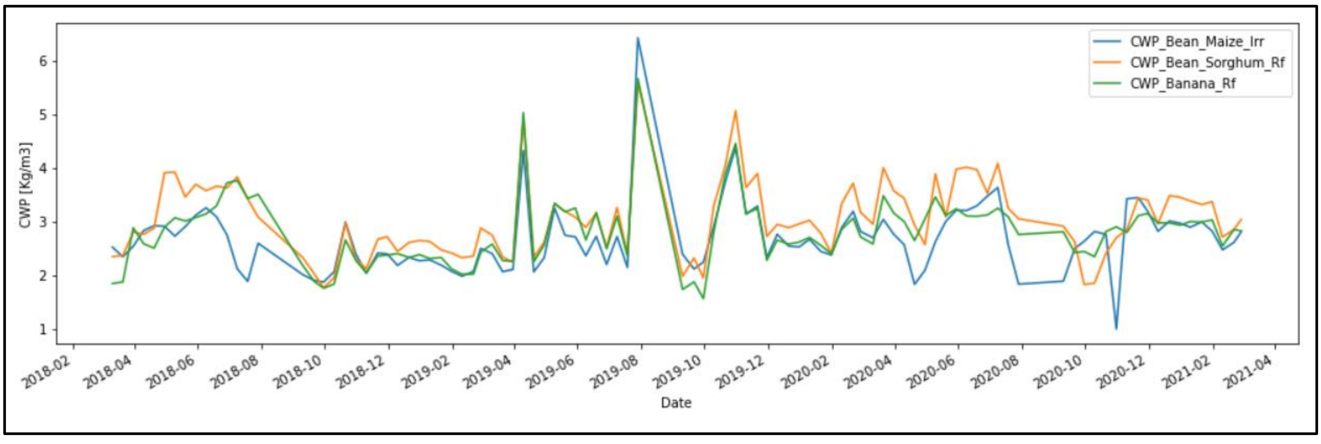

Figure 4-17 Gross biomass water productivity for Nasho Irrigation Scheme and rainfed crops.

4.3.4.1. Gross Biomass Water Productivity for the irrigation winter season

Table 4-27 shows the averaged seasonal gross biomass water productivity values of beans were 2.2, 2.5, and 2.8 kg/m^3 with a standard deviation of 0.4, 0.2 and 0.4 for 2018, 2019 and 2020, respectively. The maize seasonal average gross biomass water productivity values were 2.2, 2.2, and 2.6 kg/m^3 with a standard deviation of 0.2, 0.2, and 0.2 for 2018, 2019 and 2020, respectively. Water productivity mapping of major Indian crops study estimated maize WP and indicated an average of 1.83 kg/m3 (Sharma et al., 2018). The overall three winter seasons for irrigation have average values of 2.50, and 2.43 with a standard deviation of 0.33 and 0.2 for beans, and maize, respectively.

Table 4-27 Statistics of CWP for winter irrigated beans and maize from September 2018 to February 2021

Crops	Beans				Maize			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	1.6	3	2.2	0.4	1.8	2.5	2.2	0.2
2019	2.1	2.8	2.5	0.2	2.1	2.8	2.2	0.2
2020	2.2	3.4	2.8	0.4	2.3	2.9	2.6	0.2
Overall			2.50	0.33			2.43	0.2

4.3.4.2. Gross Biomass Water Productivity for the irrigation summer season

The results for irrigation summer seasons of 2018, 2019 and 2020 are shown in table 4-28 which summarises the statistics of gross crop water productivity. The average seasonal gross crop water productivity values of beans are 2.4, 2.4, and 3.2 kg/m^3 with a standard deviation of 0.2, 0.2 and 0.5 for 2018, 2019 and 2020, respectively. The maize seasonal average gross crop water productivity values are 2.5, 2.5, and 3.1 kg/m^3 with a standard deviation of 0.3, 0.3, and 0.4 for 2018, 2019 and 2020, respectively. The overall three summer seasons for irrigation have average values of 2.70, and 2.67 with a standard deviation of 0.33 and 0.3 for maize and beans, respectively.

Table 4-28 Statistics of crop water productivity for summer main crops of irrigation scheme from March 2018 to July 2020

Crops	Beans				Maize			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	2.1	2.7	2.4	0.2	2	2.9	2.5	0.3
2019	2	2.7	2.4	0.2	2.1	2.9	2.5	0.3
2020	2.4	4	3.2	0.5	2.4	3.8	3.1	0.4
Overall			2.67	0.30			2.70	0.33

4.3.4.3. Gross Biomass Water Productivity for the rainfed winter season

Table4-29 shows seasonal average values of rainfed crops. Beans have average values of 2.2, 2.6, and 2.6 kg/m^3 with standard deviation of 0.7, 0.5, and 0.5 for 2018, 2019, and 2020, respectively. Banana full season have average values of 4.7, 5.2, and 5.9 kg/m^3 with standard deviation of 1.1, 0.9, and 0.9 kg/m^3 for 2018, 2019, and 2020, respectively and sorghum have average values of 2.3, 2.8, and 2.8 kg/m^3 with standard deviation of 0.4, 0.4, and 0.4 kg/m^3 for 2018, 2019, and 2020, respectively. The seasonal gross biomass water productivity values of beans, banana, and sorghum show that all crops had different crop water productivity values compared to one another. The overall three winter seasons have average values for beans, banana, and sorghum of 2.47, 2.6, and 2.63 kg/m^3 with a standard deviation of 0.57, 0.43, and 0.40 kg/m^3 for beans, banana, and sorghum, respectively. Steduto et al., (2012) reported rainy season sorghum biomass water productivity ranging between 2.3 and 6.0 kg/m³ in India, and dryland sorghum water productivity ranges between 3.0 to 3.6 kg/m³ in Texas, United States but this can vary depending on the duration of growing period.

Table 4-29 Statistics of Gross CWP for winter main rainfed crops from September 2018 to February 2021

Crops	Beans				Banana (full seasom)				Sorghum			
Statistics	Min	Max	Avg	Std Dev	Min	Max	Avg	Std Dev	Min	Max	Avg	Std Dev
2018	1.1	4	2.2	0.7	2.40	6.40	4.70	1.10	1.7	2.8	2.3	0.4
2019	1.5	3.4	2.6	0.5	3.30	6.50	5.20	0.90	2.2	3.4	2.8	0.4
2020	1.5	3.4	2.6	0.5	3.80	7.30	5.90	0.90	2.2	3.3	2.8	0.4
Overall			2.47	0.57			5.27	0.97			2.63	0.40

4.3.4.4. Gross Biomass Water Productivity for the rainfed summer season

Table4-30 shows seasonal average values of rainfed crops. Beans have average values of 2.8, 2.6, and 3.1 kg/m³ with a standard deviation of 0.4, 0.3, and 0.4 for 2018, 2019, and 2020, respectively. Sorghum has average values of 2.2, 3.3, and 2.8 kg/m³ with standard deviation of 0.4, 0.4, and 0.4 kg/m³ for 2018, 2019, and 2020, respectively. The seasonal gross biomass water productivity values of beans and sorghum show that all crops had different crop water productivity values compared to one another. The overall three summer seasons have average values for beans, and sorghum of 2.83, and 2.63 kg/m³ with a standard deviation of 0.36, and 0.40 kg/m³ for beans, and sorghum, respectively.

Table 4-30 Statistics of crop water productivity for summer main crops of rainfed agriculture from March 2018 to July 2020

Crops	Beans				Sorghum			
Statistics	Min	Max	Avg	Std Dev	Min	Max	Avg	Std Dev
2018	2.1	3.4	2.8	0.4	1.7	2.2	2.2	1.7
2019	2.1	3.1	2.6	0.3	2.8	3.4	3.3	2.8
2020	2.4	3.7	3.1	0.4	2.3	2.8	2.8	2.3
Overall			2.83	0.36			2.63	0.40

4.3.5. Seasonal comparison of crop water consumption

4.3.5.1. Comparison of crop water consumption between irrigated crops for winter season

Figure 4-18 shows crop water consumption for winter seasons within the irrigation scheme. The irrigated maize had higher water use than beans in all seasons with the average evapotranspiration values of 599, 495 and 522 mm/season for maize and 557,465, and 456 mm/season for beans. Transpiration values were 467, 383 and 410 mm/season for maize and 415, 353 325 mm/season for beans for 201,2019 and 2020, respectively. This has a significant mean due to the higher transpiration of maize as a C4 crop type. The season of 2018 had higher transpiration and evapotranspiration compared to the other two seasons for all crops. The season of 2019 is the lowest crop water use. Crop water consumption is almost the same for rainfed crops in every season. The transpiration values of each crop are proportionally higher with respect to its values of evapotranspiration as indicated above.

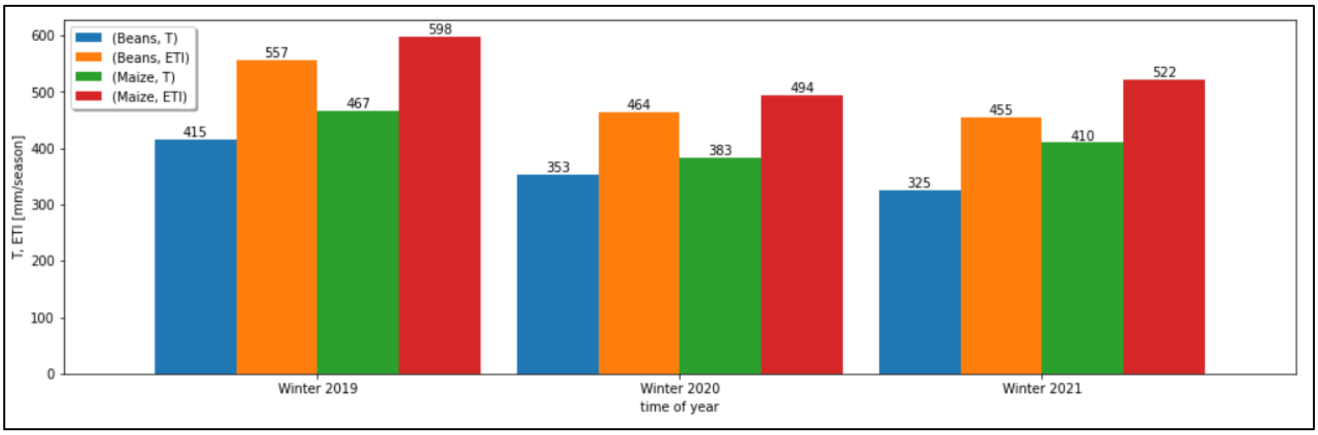

Figure 4-18 Seasonal ETI and T for irrigated crops

4.3.5.2. Seasonal comparison of crop water consumption for the irrigation summer season

Figure 4-19 shows crop water consumption for summer seasons for the irrigation scheme. The irrigated maize had higher water use than beans in all seasons with the average evapotranspiration values of 399, 437 and 396 mm/season for maize and 389,437, and 371 mm/season for beans. Transpiration was 300, 363, and 307 for maize and 290, 353 and 278 mm/season for beans for 2018,2019, and 2020, respectively. This has a significant mean due to the higher transpiration of maize as a C4 crop type. The season of 2019 had higher transpiration and evapotranspiration compared to the other two seasons for all crops. The season of 2020 is the lowest crop water consumption compared to the other seasons.

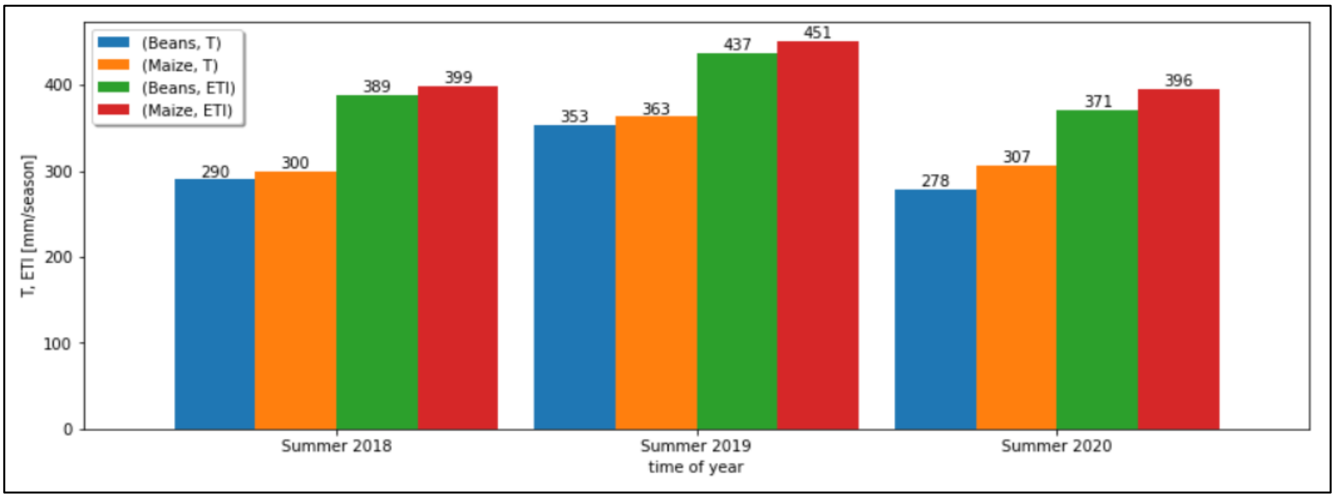

Figure 4-19 Seasonal ETI and T for irrigated crops comparison of crop water consumption between rainfed crops for the summer season

4.3.5.3. Comparison of crop water consumption for the rainfed crops winter season

The observations found that crop water consumption is almost the same for rainfed crops in three seasons. All crops have almost the same transpiration and evapotranspiration, but sorghum has higher values in 2019 and 2020 seasons. The average values of evapotranspiration are 504, 410 and 432 mm/season for sorghum for 2018, 2019, and 2020, respectively. And 896, 811, and 839 mm/season for banana (full season), and 510, 402, and 432 mm/season for beans. Transpiration values are 380, 319, and 298 mm/season for beans, 687, 647, and 663 mm/season for banana and 376, 327, and 333 mm/season for sorghum for 2018, 2019 and 2020, respectively. The higher values of banana due to the long duration of their growing season. Beans have almost the same evapotranspiration, but lower transpiration compared to the sorghum. The season of 2018 had higher evapotranspiration and transpiration compared to the other two seasons for all crops and season 2019 is the lowest crop water use season.

4.3.5.4. Seasonal comparison of crop water consumption for the rainfed summer season

The observations made found that crop water consumption is almost the same for rainfed crops in three summer seasons. All crops have almost the same transpiration and evapotranspiration, but beans have higher values of water consumed in 2018 and 2019 seasons. The average values of evapotranspiration are 393, 391, and 385 mm/season for beans and 375, 388, and 376 mm/season for sorghum. Transpiration values were 304, 303, and 302 mm/season for beans and 292, 304, and 294 for sorghum for 2018, 2019, and 2020, respectively. This has not significant mean due to the higher transpiration and evapotranspiration of sorghum as a C4 crop type. This may be caused by intercropping systems of beans and other crop types such as maize and cassava. The season of 2018 had higher evapotranspiration compared to the other two seasons for all crops. The season of 2020 is the lowest crop water use season.

4.3.6. Relationship between Total Biomass Production and Evapotranspiration

4.3.6.1. Relationship between Total Biomass Production and Evapotranspiration for irrigated crops for the winter season

Figure 4-20 shows linear relationships between TBP and ETI of winter crops from 2018 to 2020. The linear relationships between TBP and ETI were assessed for beans and maize. There were positive linear relationships between TBP and ETI to both crops. Total biomass production increasing with respect to the increase of ETI. The higher relationships were found higher for irrigated beans compared to the irrigated maize with a coefficient of determination R^2 of 0.77 and 0.66 for beans and maize, respectively.

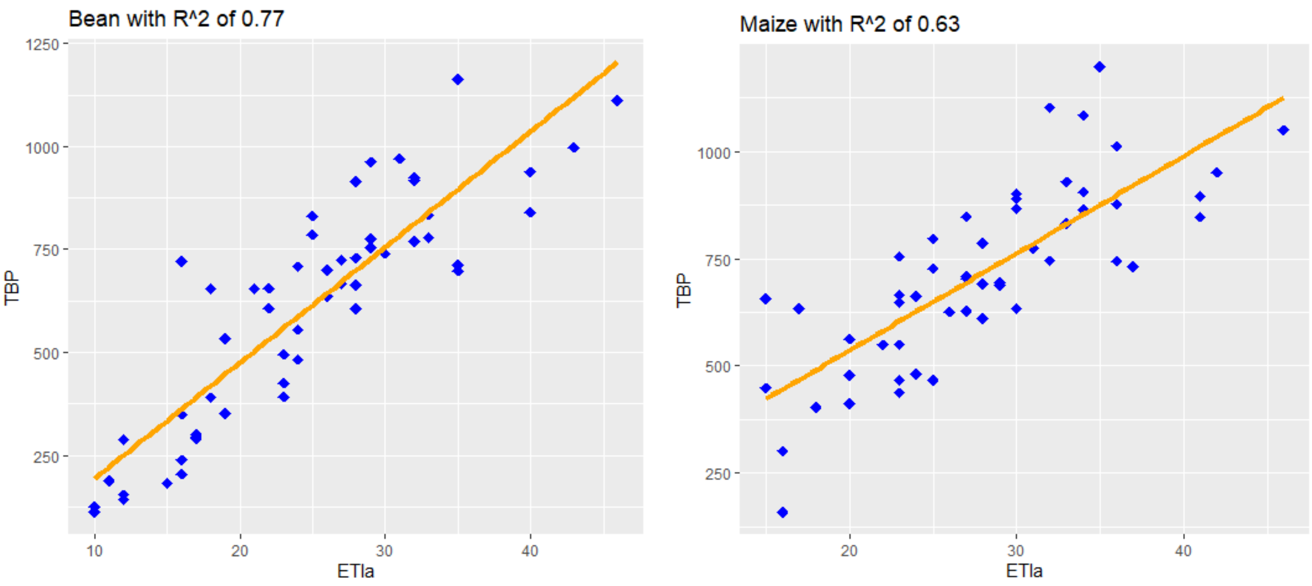

Figure 4-20 Relationship between TBP and ETI of irrigated beans and maize

4.3.6.2. Relationship between Total Biomass Production and Evapotranspiration for the irrigated crops summer season

Figure 4-21 shows relationship between TBP and ETI for irrigated crops. Total biomass production increases with respect to the increase of ETI. Time series shows how TBP varies with respect to the variation of water consumed. There were positive linear relationships between TBP and ETI to both beans and maize crops. The relationships were found to be almost the same for irrigated beans and maize with a coefficient of determination R^2 of 0.64 and 0.62 for beans and maize, respectively.

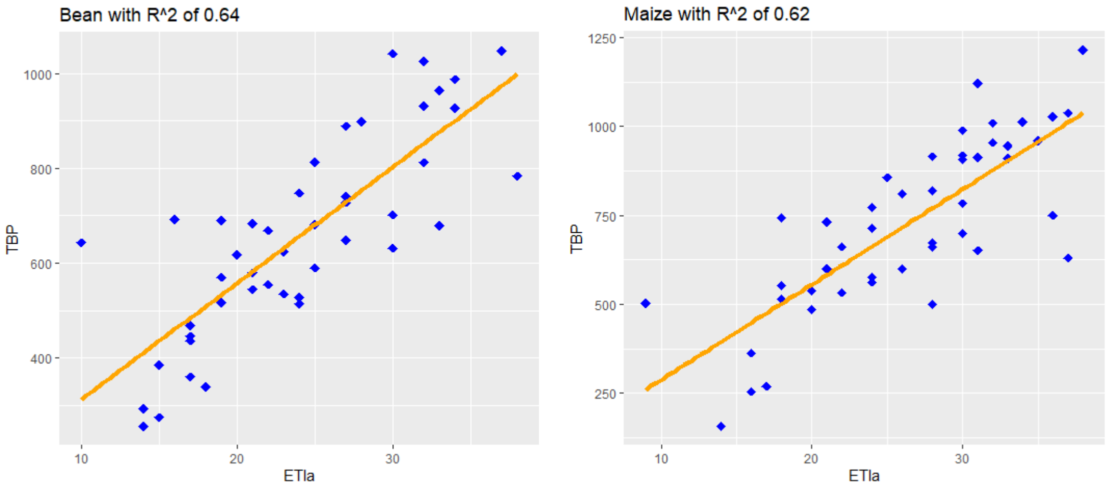

Figure 4-21 Beans and maize for irrigation scheme

4.3.6.3. Relationship between Total Biomass Production and Evapotranspiration for the rainfed crops winter season

The linear relationships between TBP and ETI were assessed for rainfed beans, banana, and sorghum. There were positive linear relationships between TBP and ETI to all three crops. Figure4-22 illustrating the relationships between TBP and ETI for rainfed crops. Banana was found with high relationship with R^2 of 0.70 compared to beans and sorghum with R2 of 0.64 and 0.59, respectively.

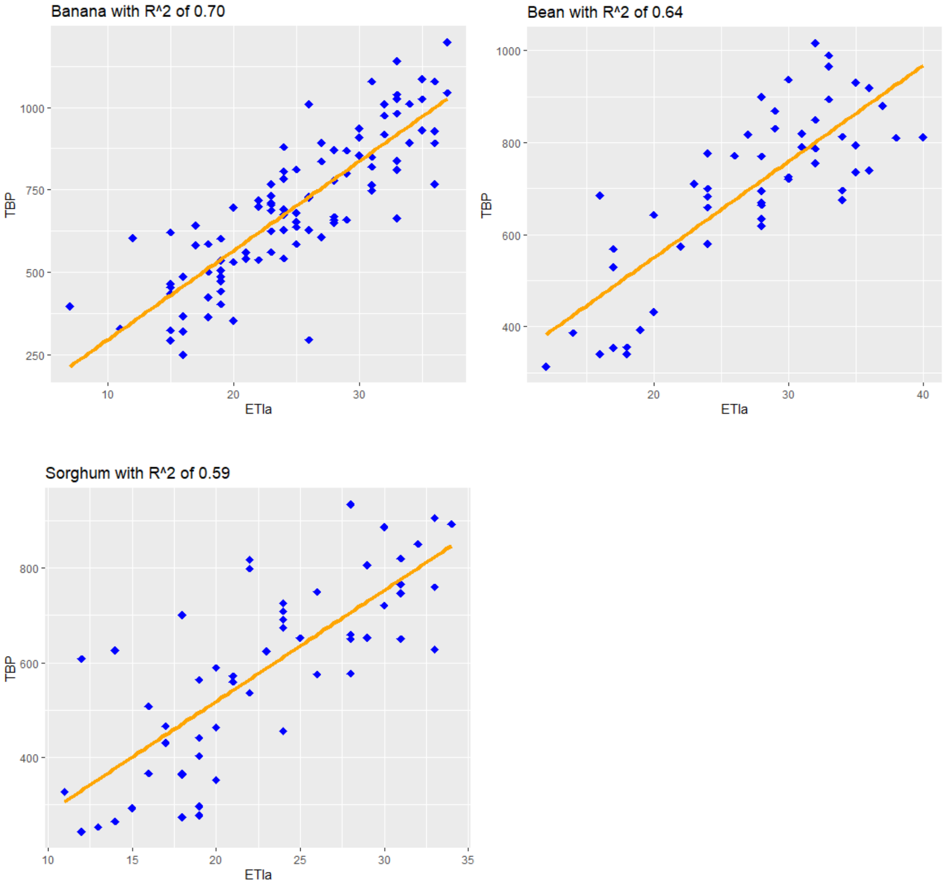

Figure 4-22 Relationship between TBP and ETI of rainfed beans, banana, and sorghum for winter season

4.3.6.4. Relationship between Total Biomass Production and Evapotranspiration for rainfed crops summer season

Figure 4-23 shows the relationship between TBP and ETI for rainfed crops of summer seasons. Total biomass production increasing with respect to the increase of ETI. This means that TBP varies with respect to the variation of water consumed. The linear relationships between TBP and ETI were assessed for beans and maize for rainfed beans, and sorghum. There were positive linear relationships between TBP and ETI to both beans and sorghum crops. The weak relationships were found and are almost the same for rainfed beans and sorghum with a coefficient of determination R^2 of 0.49 and 0.50 for beans and sorghum, respectively.

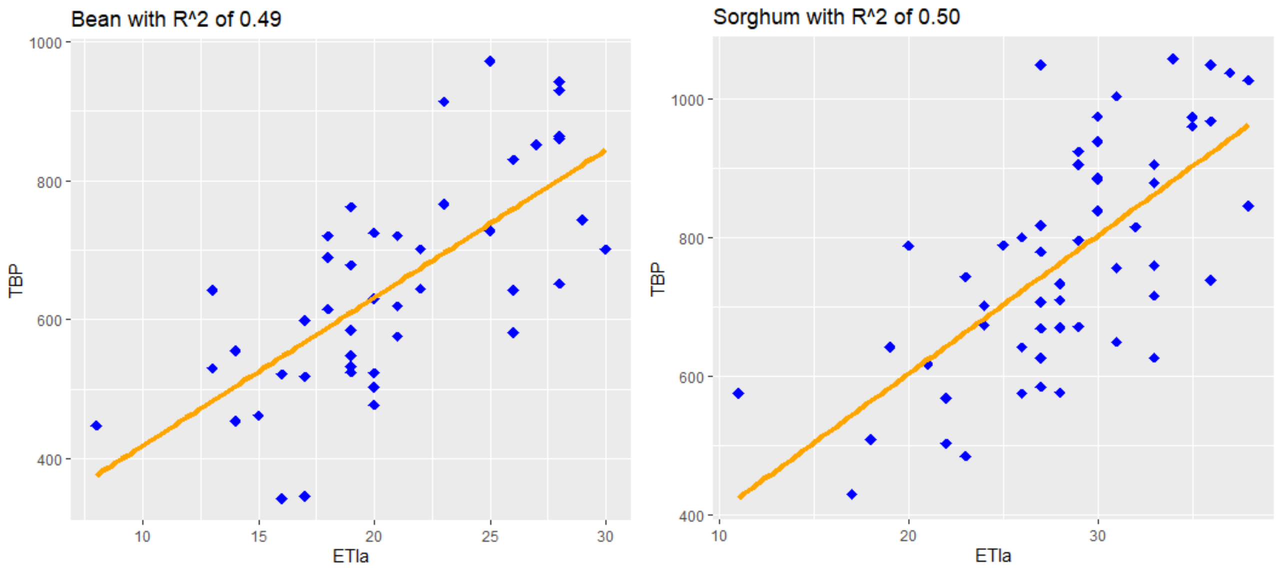

Figure 4-23 Relationships between TBP and ETIa of rainfed beans and sorghum for summer season

4.3.7. Seasonal comparison of Total Biomass Production and Crop water productivity

Seasonal comparison of total biomass production and crop water productivity was done between irrigated and rainfed crops for summer and winter seasons.

4.3.7.1. Comparison of Total Biomass Production and Crop water productivity for the irrigated crops

Comparative analysis for winter season shows the seasonal variations of TBP and gross crop water productivity for three years. In 2018 and 2021 seasons, the maize productions were higher than beans for all seasons. In 2018 and 2019 seasons, the productions were almost the same for beans and maize. But winter 2020 was more productive than other seasons for maize. The crop water productivity was higher for all crops in 2019 and 2020 compared to 2018. But also, winter 2020 has high values of CWP than other seasons with 2.8 and 2.6 kg/m^3 for beans and maize, respectively. It is also observed that the beans have high crop water productivity values compared to the maize. Summer season has seasonal variations of TBP and gross crop water productivity within the irrigation scheme for three years. In all seasons, the maize productions were higher than beans. But 2020 season was more productive than other seasons for both maize and beans. In this season, the crop water productivity was higher for all crops and for all three years. It is also observed that the maize has high crop water productivity values compared to the beans in summer. But season 2020 has high values for beans than maize with 3.2 kg/m^3 and 3.1 kg/m^3 for beans and maize, respectively.

4.3.7.2. Comparison of Total Biomass Production and Crop water productivity for rainfed crops

Comparative analysis of TBP and CWP made for rainfed beans, banana, and sorghum of winter season shows seasonal variabilities of TBP and gross crop water productivity for three years. In 2018 and 2019 seasons, the productions were almost the same for all crops. But winter season of 2020 was more productive than other seasons. The crop water productivity was higher for all crops in 2019 and 2020 compared to 2018. The observations made found that bananas have higher CWP values compared to other crops of winter season. While comparative analysis of summer crops shows the seasonal variations of TBP and gross crop water productivity for all seasons. In all seasons, the beans productions were higher than maize. But 2020 season was more productive than other seasons for maize and beans. The gross crop water productivity was almost the same for all crops for and for all three winter seasons. It is also observed that the 2020 season has lower crop water productivity values compared to the other seasons with the same value of 2.6 kg/m^3 for beans and maize.

4.3.7.3. Comparison of Total Biomass Production and Crop water productivity between irrigated and rainfed crops

Comparative analysis between irrigated and rainfed agriculture of total biomass production and gross crop water productivity for winter season show that the irrigation scheme is more productive than rainfed agriculture but rainfed agriculture has higher gross crop water productivity values compared to the irrigation scheme for summer and winter seasons. This has significant meaning due to the higher transpiration and evapotranspiration from the irrigation scheme compared to the rainfed agriculture area. This high transpiration and evapotranspiration come from the water availability from irrigation activities. Contradictory to Zwart et al., (2010a) reported that water productivity is lower in rainfed conditions compared to irrigation conditions. This higher gross crop water productivity of rainfed due to the lower evapotranspiration and transpiration of rainfed crops and may decrease or increase depending on the water availability.

4.3.8. Comparison of crop water consumption between irrigated and rainfed crops for winter and summer seasons

Figure4-24 shows the differences between water consumption of irrigated and rainfed crops where the irrigated C3 or C4 crops are high water consumers compared to the rainfed crops due to high evapotranspiration of irrigated crops. For example, irrigated beans(C3) consumed more water than rainfed sorghum(C4). The exceptions were observed on two summer seasons of 2018 and 2020, where is small differences between irrigated and rainfed summer crops. They have almost the same evapotranspiration due to less irrigation activities during summer season. This can be caused by enough precipitation during the entire season or other causes. The comparison between winter and summer seasons show that winter seasons are more water consumable than summer seasons.

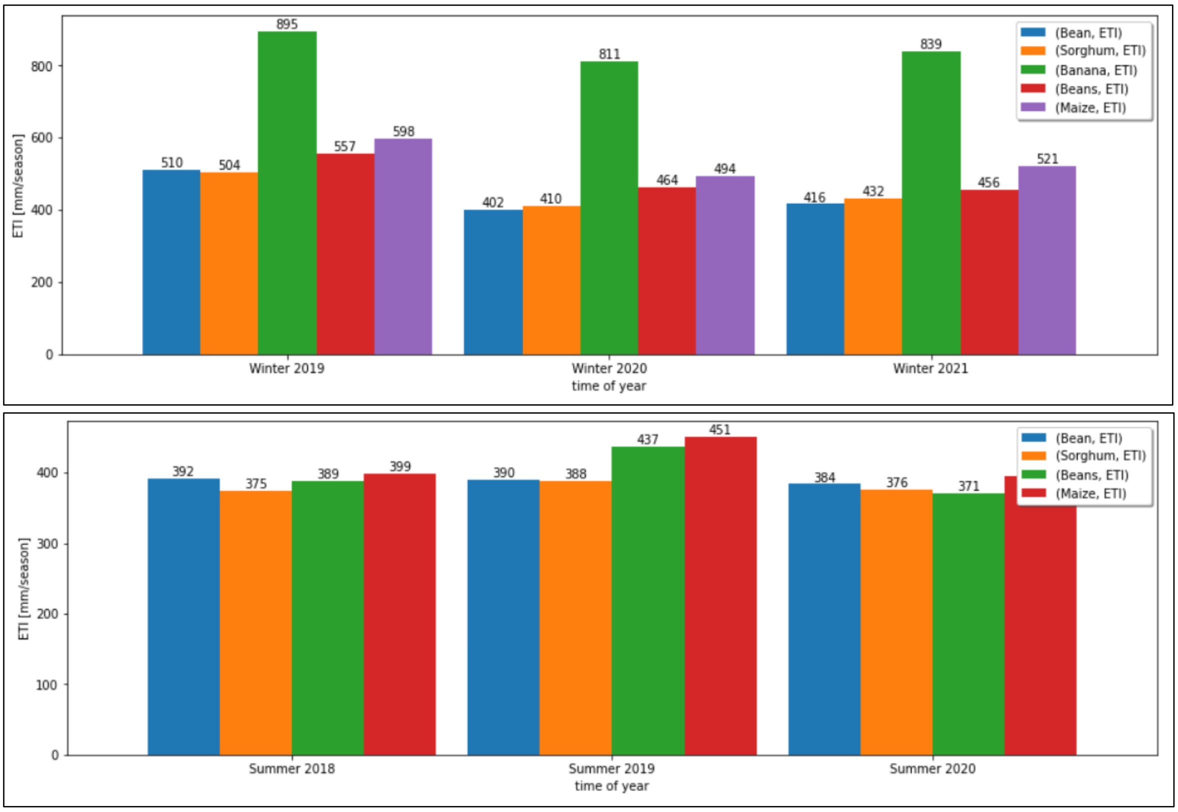

Figure 4-24 Seasonal ETI for irrigated and rainfed crops of winter (Upper) and summer (Lower) seasons

4.4. Seasonal comparison of crop water consumption between semi-arid and humid climates

4.4.1. Summer season

Figure4-25 shows seasonal transpiration and evapotranspiration of main crops in both climates during summer seasons. Transpiration and evapotranspiration of groundnut, sorghum and cotton in semi-arid climates are higher than humid climate crops such as beans and maize. The highest evapotranspiration is 976 mm/season of cotton(full season) followed by 576 mm/season of groundnut from semi-arid climate. While lowest evapotranspiration is 371 mm/season of beans from the humid climate. The maximum transpiration is 732 mm/season of cotton, followed by 415 mm/season of groundnut from semi-arid climate while the lowest is 243 mm/season of sorghum from semi-arid climate. Table4-31 shows the transpiration fractions of both climates where humid crops have higher values than semi-arid crops with the highest value of 0.81 for beans for humid climate.

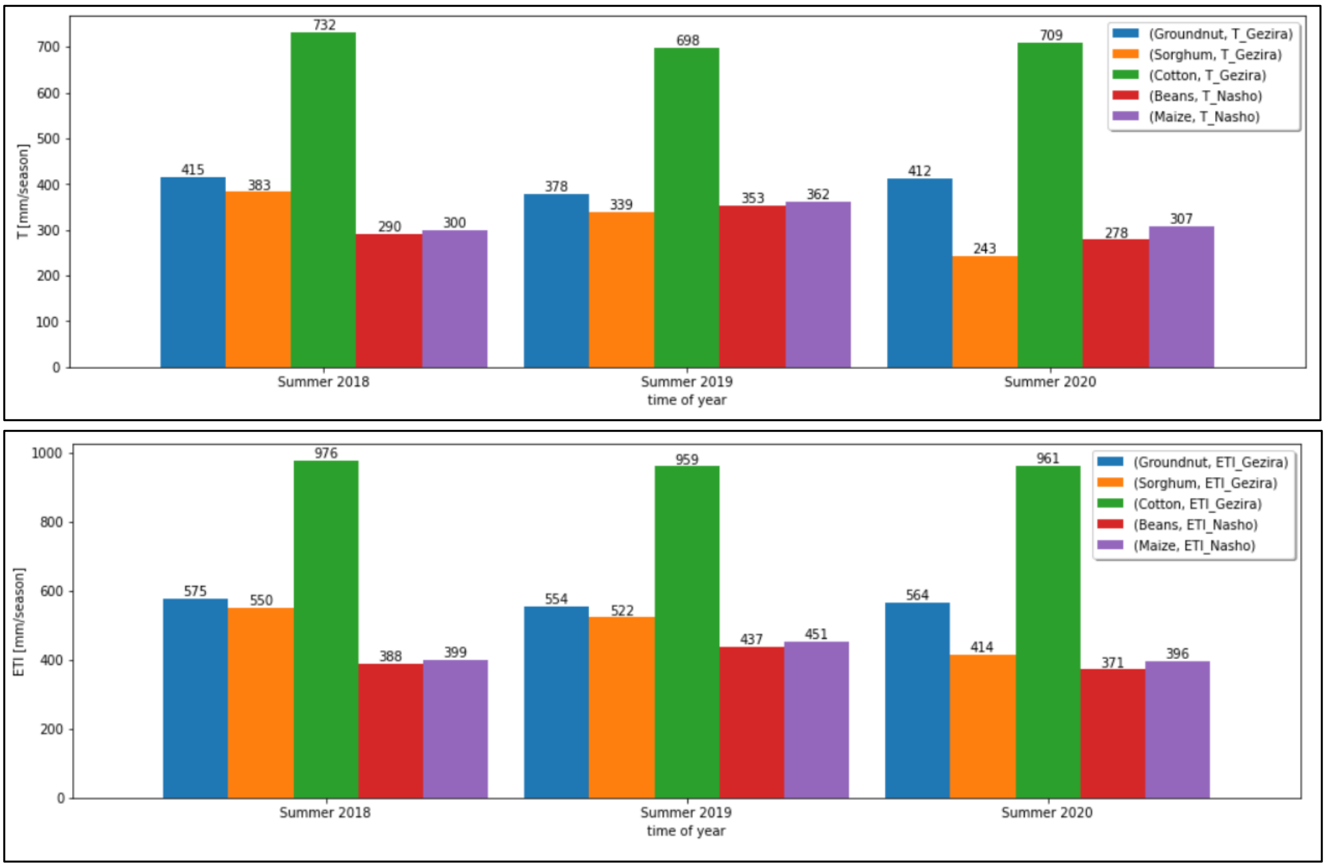

Figure 4-25 Seasonal crop T (Upper) and ETI (Lower) of Gezira and Nasho crops for summer seasons

Table 4-31 Statistics of Transpiration and Evapotranspiration with transpiration fraction for the summer season

Climates	**Semi-Arid climate**						**Humid climate**					
Crops	Groundnut			Sorghum			Beans			Maize		
Indicators	T	ETI	Tfrac	T	ETI	Tfrac	T	ETI	Tfr	T	ETI	Tfrac
2018	415	576	0.72	383	550	0.70	290	389	0.75	300	399	0.75
2019	379	554	0.68	339	522	0.65	353	437	0.81	363	451	0.80
2020	412	564	0.73	243	414	0.59	278	371	0.75	307	396	0.78

4.4.2. Winter season

Figure4-26 shows seasonal transpiration and evapotranspiration of main crops in both climates during winter seasons. There is not a big difference between transpiration and evapotranspiration of onion, pigeon pea and wheat in a semi-arid climate and humid climate crops such as beans and maize. The highest evapotranspiration is 509 mm/season of maize for 2018 season of humid climate. While lowest evapotranspiration is 456 mm/season of beans from the humid climate. The maximum transpiration is 509 mm/season of wheat while the lowest is 325 mm/season of beans from humid climates. Table4-32 shows the transpiration fractions in both climates where semi-arid crops have higher values than humid crops with the highest value of 0.84 for wheat, season 2019.

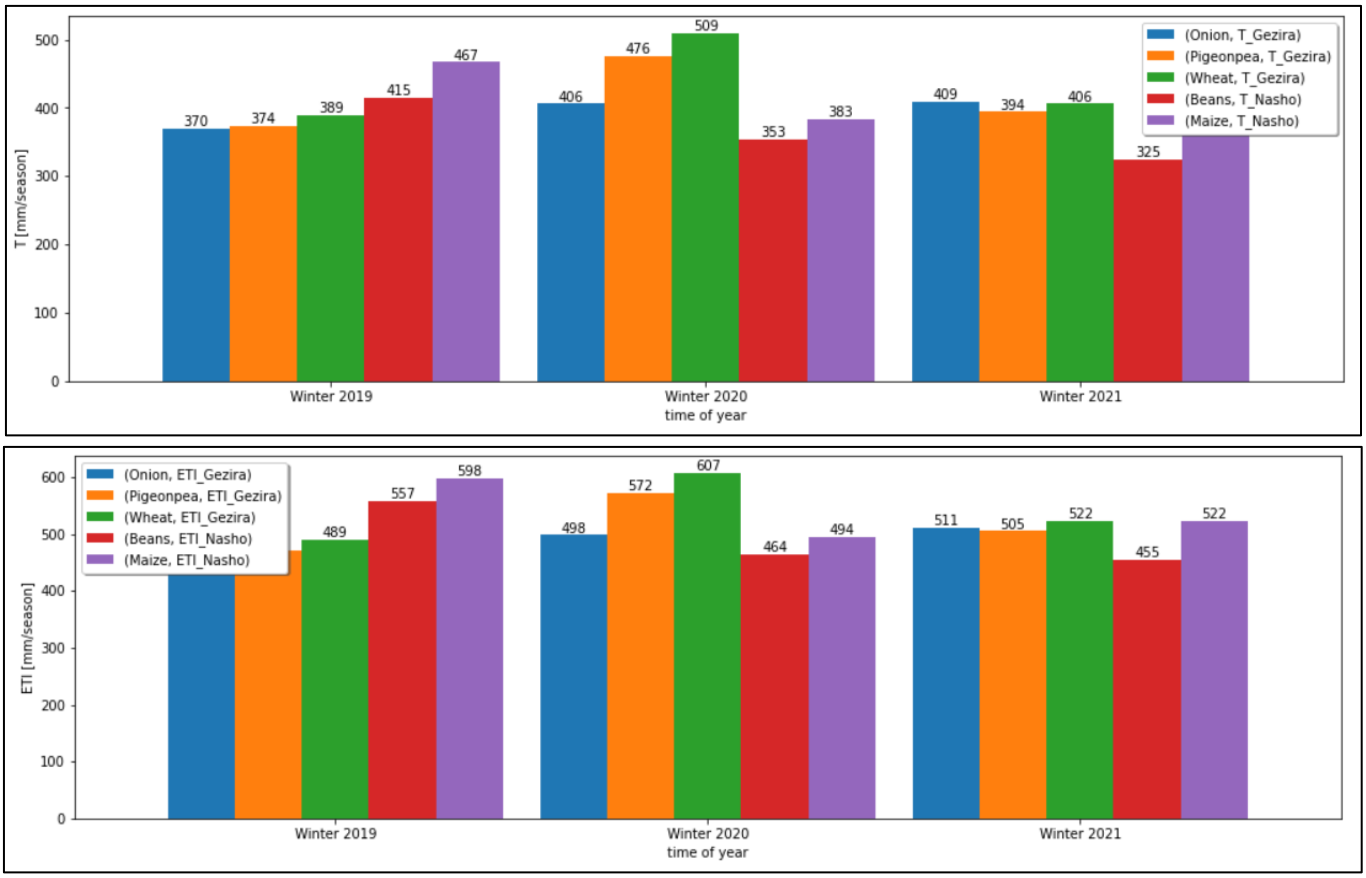

Figure 4-26 Seasonal crop T (Upper) and ETI (lower) of Gezira and Nasho crops for winter seasons

Table 4-32 Statistics of Transpiration and Evapotranspiration with transpiration fraction for the winter season

Climates	**Semi-Arid climate**						**Humid climate**					
Crops	Pigeon pea			Wheat			Beans			Maize		
Indicators	T	ETI	Tfrac	T	ETI	Tfrac	T	ETI	Tfrac	T	ETI	Tfrac
2018	374	471	0.79	389	490	0.80	415	557	0.74	467	599	0.78
2019	476	573	0.83	509	608	0.84	353	465	0.76	383	495	0.77
2020	395	506	0.78	406	522	0.78	325	456	0.71	410	522	0.79

4.5. Climate Normalisation of Crop Water Productivity

During this study, the climate normalisation of crop water productivity was performed in both semi-arid and humid climates on selected C3 and C4 photosynthetic agricultural crops. Irrigated beans and maize (C3 and C4) were normalised for climate for Nasho irrigation scheme. For the Gezira irrigation scheme, climate normalisation of crop water productivity was performed for groundnut (C3), pigeon pea(C3), wheat(C3), and sorghum(C4).

To perform climate normalisation of CWP, the study used quantified WaPOR based gross crop water productivity, reference ET, and worldwide averaged seasonal normalised reference ET. Values of worldwide averaged seasonal normalised reference ET for sorghum beans, groundnut, and pigeon pea from the literature are not available. In this regard, the assumptions made for sorghum, beans, groundnut, and pigeon pea. The worldwide averaged climatic normalised reference ET of sorghum is similar to the reported value of maize (690 mm/season) as both sorghum and maize are C4 crops. For beans, groundnut, and pigeon pea the value of wheat (545 mm/season) was adopted as all are C3 crops. All the calculations or processing steps are explained in chapter 3 of methodology, section 3.6 and the applied formula (equation 12) was used. The results of climate normalisation of CWP are presented in the following sections.

4.5.1. Normalized Crop Water Productivity for Gezira Irrigation selected area

As mentioned above, the groundnut, pigeon pea, wheat and sorghum were used to perform climate normalisation of crop water productivity in a semi-arid climate. The maps that show spatial variability of normalised CWP in figure 4-27 and table4-33 for summer and winter seasons, respectively. Figure4-27 shows spatial variation of groundnut and wheat normalised CWP for 2018 and 2020 seasons. It shows higher changes in 2020 compared to 2018. Table4-33 shows the highest CWPc values of 1.038, 0.844, and 1.077 kg/m^3 of groundnut with standard deviation of 0.64, 0.30, and 0.34 kg/m^3 for 2019, 2020, and 2021. Also shows the values of 0.72, 0.59, and 0.55 kg/m^3 with standard deviation of 0.20, 0.25, and 0.25 kg/m^3 for sorghum for 2019, 2020, and 2021. While table4-34 shows the highest CWPc values of 1.59, 1.9, and 0.89 kg/m^3 of wheat with standard deviation of 0.11, 0.60, and 0.44 kg/m^3 for 2019, 2020, and 2021. Also, the values of 1.61, 1.681, and 0.964 kg/m^3 with standard deviation of 0.13, 0.50, and 0.47 kg/m^3 for pigeon pea for 2019, 2020, and 2021 are provided. Bastiaanssen and Steduto, (2017) simulated crop water productivity of wheat using the WATPRO (WATer PROductivity) model and normalised it for the climate and reported normalised crop water productivity range between 0.1 - 2.0 kg/m^3 and average values of 2.65, 2.40, and 2.18 kg/m3 at a national scale for Egypt, Uruguay, and Mexico countries, respectively.

Table 4-33 Statistics of CWPc for summer crops

Crops	**Groundnut**				**Sorghum**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	0.39	3.857	1.038	0.642	0.308	1.071	0.717	0.204
2019	0.186	1.309	0.844	0.303	0	1.03	0.596	0.258
2020	0.574	1.741	1.077	0.343	0.151	0.94	0.545	0.258
Overall			0.986	0.429			0.619	0.24

Table 4-34 Statistics of CWPc for winter crops

Crops	**Pigeon pea**				**Wheat**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	0.87	3.37	1.61	0.13	0.86	2.27	1.59	0.11
2019	0.781	3.567	1.681	0.503	0.781	3.191	1.902	0.601
2020	0	2.01	0.964	0.476	0	1.645	0.896	0.448
Overall			1.699	0.45			1.362	0.878

The following maps of figure 4-27 show the example of spatial varialibility of normalised CWP of the area for summer and winter seasons. The high values were found in the eastern and northern parts of the area.

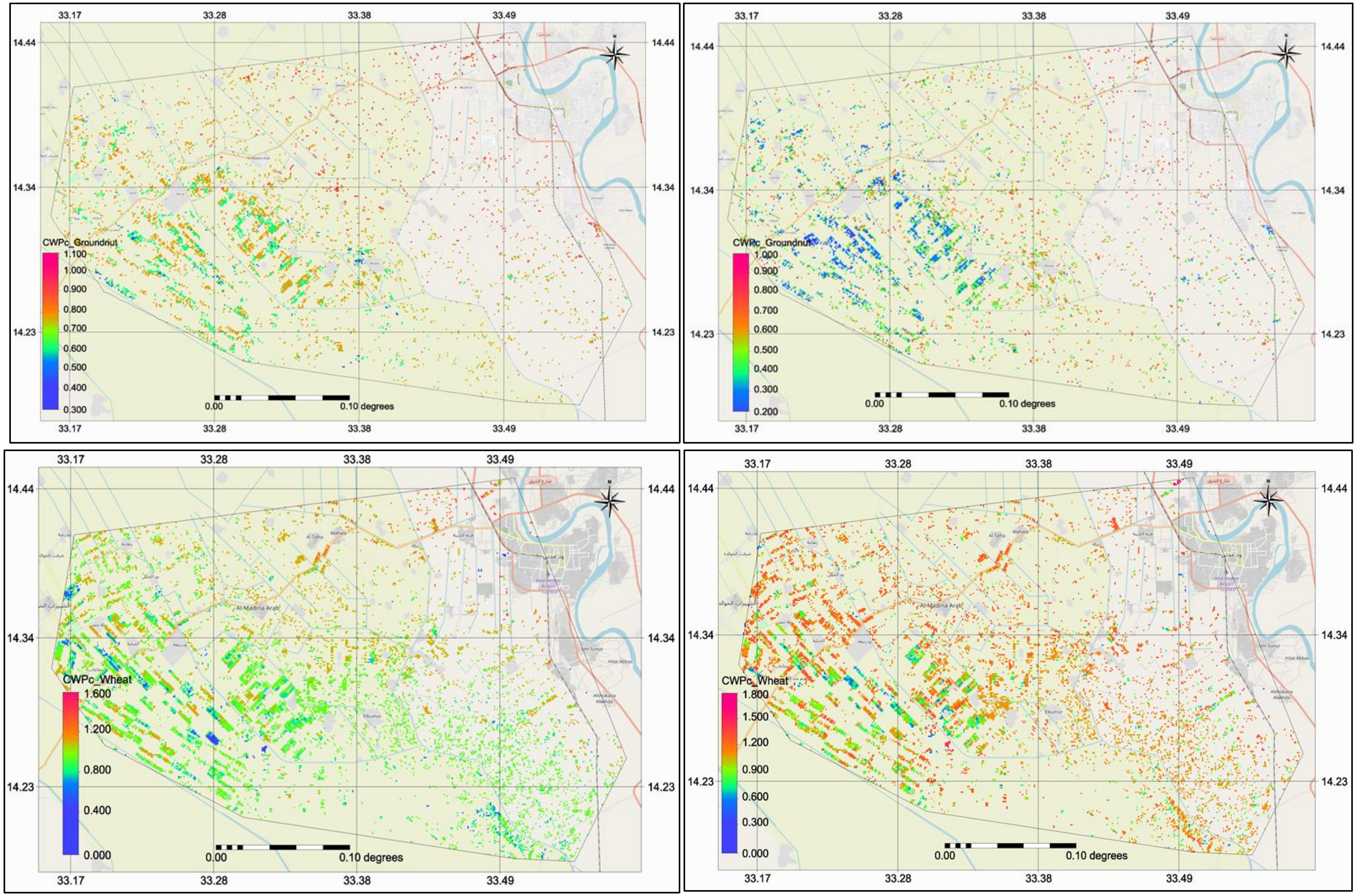

Figure 4-27 Maps of CWPc in kg/m³ of Groundnut and Wheat for 2018 (Left) and 2020(Right)

4.5.1.1. Comparison of CWP and normalised CWP values for main crops

Figure4-28 shows the differences between CWP and CWPc values for groundnut and sorghum as C3 and C4 crops of the summer season for the Gezira irrigation scheme. CWPc values of groundnut are almost double of CWP for all three summer seasons of 2018, 2019, and 2020. In 2018 season, groundnut has 0.7 and 1.0 of CWP and CWPc values, this means 0.3 kg/m^3 is crop water productivity gap from the expected normal without climate effects. For the season of 2019, groundnut has 0.4 and 0.8 kg/m^3 of CWP and CWPc values respectively. This means that a gap of 0.4 occurs for this season. And the CWP and CWPc values of 0.6 and 1.1 kg/m^3 for groundnut of 2020 season. There is a gap of 0.5 kg/m3 to achieve the expected values without climate effects.
The observations from figure4-28 show that the sorghum crop is less affected by climate compared to groundnut. In 2018 season, sorghum has 0.5 and 0.7 of CWP and CWPc values, this means 0.2 kg/m^3 is crop water productivity gap from the expected normal without climate effects. For the season of 2019, sorghum has 0.4 and 0.6 values for CWP and CWPc values, respectively. This means that a gap of 0.2 occurs for this season and the CWP and CWPc values of 0.4 and 0.55 kg/m^3 are for sorghum of 2020 season. There is a gap of 0.1 kg/m^3 to achieve the expected values without climates. Knowing the causes of these crop water productivity gaps rather than climate constraints requires further investigations and make required improvements.

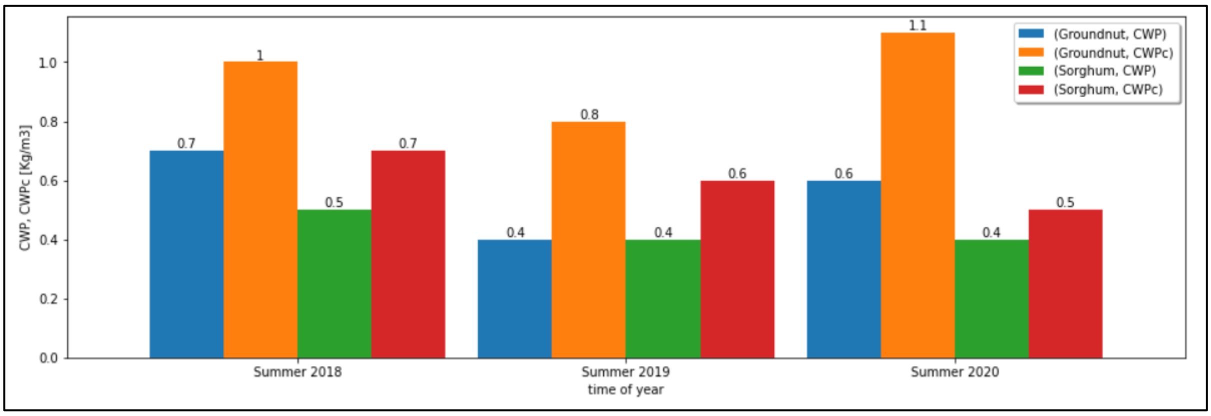

Figure 4-28 CWP against CWPc for groundnut and sorghum for the summer season

Figure 4-29 shows the differences between CWP and CWPc values for wheat and pigeon pea as C3 crops of the winter season for the Gezira irrigation scheme. CWPc values of wheat are almost double of CWP for all three winter seasons of 2018, 2019, and 2020. In 2018 season, wheat has 0.8 and 1.6 values for CWP and CWPc, respectively. This means 0.8 kg/m^3 is the crop water productivity gap from the expected normal without climate effects. For the season of 2019, wheat has 1 and 1.9 kg/m^3 of CWP and CWPc values respectively. This means that a gap of 0.9 occurs for this season. And CWP and CWPc values of 0.5 and 0.9 kg/m^3 for wheat of 2020 season. There is a gap of 0.4 kg/m3 to achieve the expected values without climate effects.

CWPc values of pigeon pea are almost double of CWP for all three winter seasons of 2018, and 2019. In the 2018 season, pigeon pea has 0.8 and 1.6 of CWP and CWPc values, this means 0.8 kg/m^3 is crop water productivity gap from the expected normal value without climate effects. For the season of 2019, pigeon pea has 0.9 and 1.7 of CWP and CWPc values respectively. This means that a gap of 0.8 occurs for this season. Also, the CWP and CWPc values of 0.6 and 0.96 kg/m^3 for pigeon pea of 2020 season. There is a gap of 0.3 kg/m^3 to achieve the expected values without climate effects. To know the causes of these crop water productivity gaps requires further investigations which are not included in the scope of this research. The observations from figure4-29 show that the pigeon pea crop is less affected by climate compared to the wheat for the season 2020.

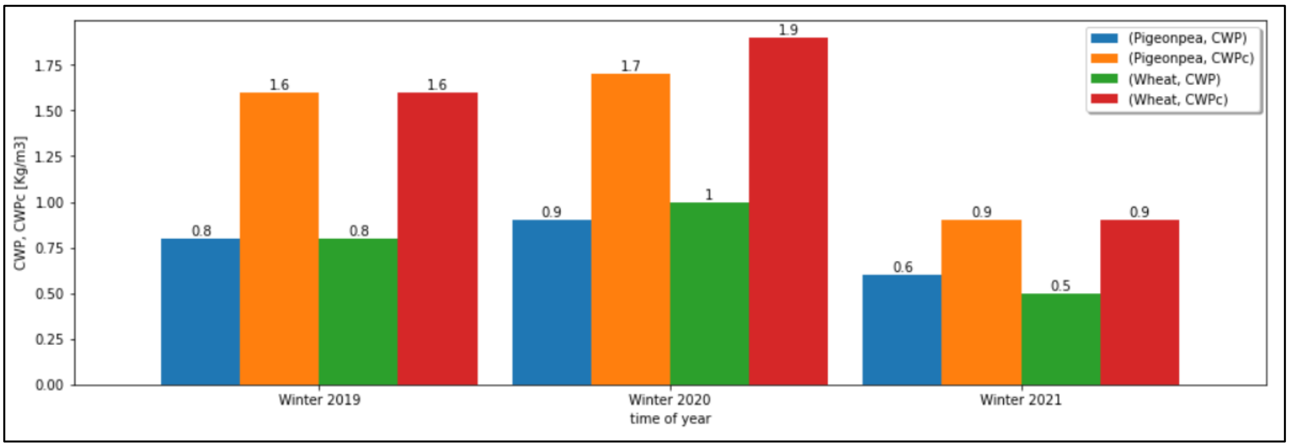

Figure 4-29 CWP and CWPc of Pigeon pea and wheat for the winter season

By comparing summer and winter seasons of all three years, winter seasons are more affected than summer seasons where the crop water productivity gaps are almost double in winter seasons for all crops.

4.5.2. Normalized Crop Water Productivity for Nasho Irrigation Scheme

As mentioned above, the irrigated beans and maize were used to perform climate normalisation of crop water productivity in humid climate, Nasho irrigation scheme. Using quantified WaPOR based gross crop water productivity and reference ET together with worldwide averaged seasonal normalised reference ET, the calculated GCWP was normalised for the climate using the equation 12. Normalised CWPc was obtained and the results that show spatial variability of normalised CWP are presented in the figure 4-30. Table 4-35 and table 4-36 show seasonal values for the summer and winter seasons, respectively. Maize has a maximum CWPc value of 2.8 kg/m^3 while beans have a maximum value of 4.4 kg/m^3. Bastiaanssen and Steduto, (2017) simulated crop water productivity of maize using the WATPRO (WATer PROductivity) model and normalised it for the climate and reported maximum normalised crop water productivity value of 4.01 kg/m^3.

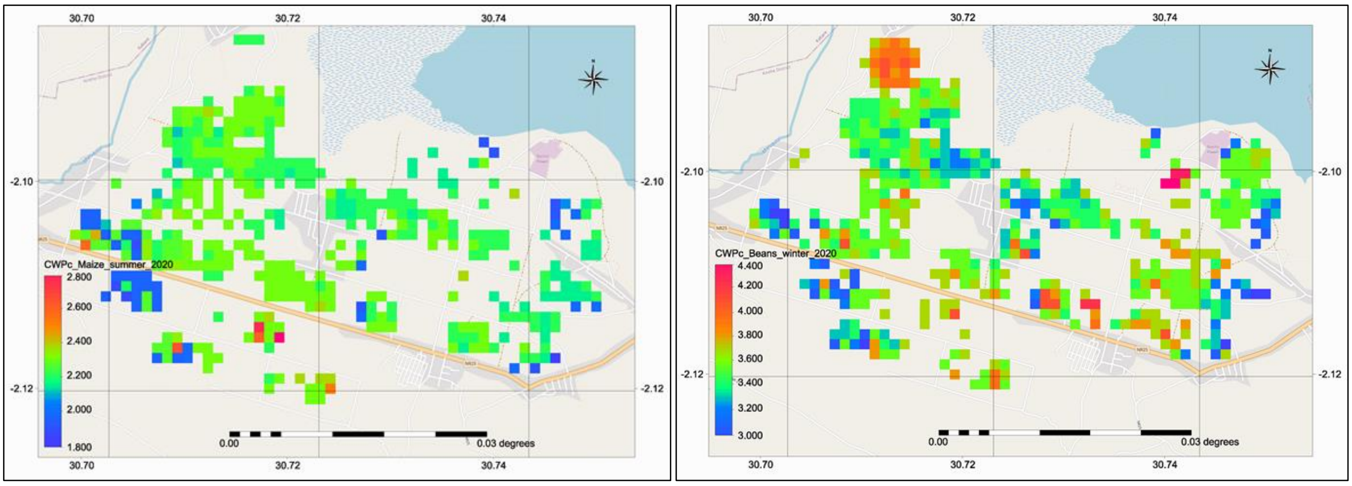

Figure 4-30 Examples of CWPc in kg/m^3 maps for summer maize (Left) and winter beans (Right) for 2020

Table 4-35 Statistics of CWPc for summer beans and maize

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	2.058	2.646	2.369	0.188	1.54	2.175	1.875	0.185
2019	2.062	2.784	2.411	0.214	1.659	2.291	1.965	0.199
2020	2.294	3.875	2.932	0.474	1.848	2.926	2.29	0.299
Overall			2.57	0.292			2.043	0.227

Table 4-36 Statistics of CWPc for winter beans and maize

Crops	**Beans**				**Maize**			
Statistics	**Min**	**Max**	**Avg**	**Std Dev**	**Min**	**Max**	**Avg**	**Std Dev**
2018	2.064	3.87	2.794	0.461	1.836	2.55	2.165	0.215
2019	2.532	3.375	2.975	0.27	2.185	2.66	2.432	0.197
2020	2.906	4.492	3.699	0.515	2.392	3.016	2.704	0.225
Overall			3.156	0.415			2.434	0.212

4.5.2.1. Comparison of CWP and normalised CWP values for Maize and Beans for summer seasons

Figure 4-31 shows the differences between CWP and CWPc values for maize and beans as C4 and C3 crops of the summer season for Nasho irrigation scheme. CWP values of maize are greater than CWPc values for all three summer seasons of 2018, 2019, and 2020. In the season 2018, maize has 2.5 and 1.9 of CWP and CWPc values, this means 0.6 kg/m^3 is crop water productivity beyond the expected normal value without climate effects. For the season of 2019, maize has 2.5 and 1.9 kg/m^3 of CWP and CWPc values, respectively. This means that no CWP gap occurs for this season. The CWP and CWPc values of 3.1 and 2.3 kg/m^3 for maize of 2020 season were obtained. There is a positive CWP of 0.8 kg/m3 beyond the expected values without climate effects. The observations from the figure4-62 show that the beans are much affected than maize. In 2018 season, beans have 2.4 and 2.37 of CWP and CWPc values, this means 0.1 kg/m^3 is crop water productivity beyond the expected normal value from climate effects. For the season of 2019, beans have 2.7 and 2.78 of CWP and CWPc values, respectively. This means that CWP equals to CWPc for this season. And the CWP and CWPc values of 4 and 3.9 kg/m^3 for beans of the 2020 season, means that CWP equals to CWPc for this season. There are no crop water productivity gaps that occurred for the summer season of humid climate.

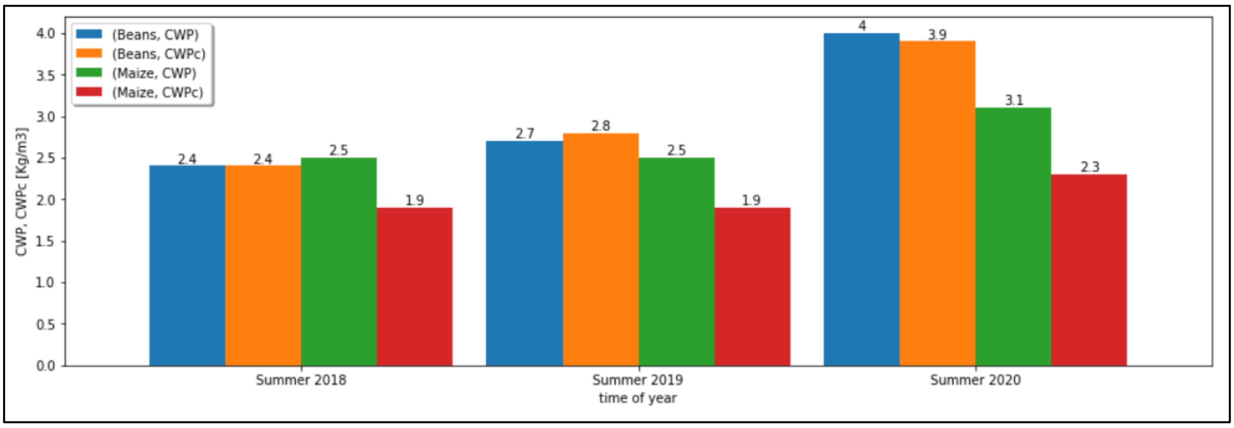

Figure 4-31 Seasonal average CWP and CWPc values of Nasho Irrigated beans and maize for summer

4.5.2.2. Comparison of CWP and normalised CWP values for Maize and Beans for the winter season

Figure4-32 shows the differences between CWP and CWPc values for maize and beans as C4 and C3 crops of the winter season for Nasho irrigation scheme. CWP values of maize are greater than CWPc values for all three winter seasons of 2018, 2019, and 2020. In the 2018 season, maize has 2.2 and 2.1 of CWP and CWPc values, which means 0.1 kg/m^3 is crop water productivity beyond the expected normal value without climate effects. For the season of 2019, maize has 2.5 and 2.4 kg/m^3 of CWP and CWPc values respectively. This means that no CWP gap occurs for this season. The CWP and CWPc values of 2.6 and 2.7 kg/m^3 for maize of 2020 season are provided. There is a CWP gap of 0.2 kg/m3 from the expected value of CWPc.

The observations made from the figure4-32 show that the beans are more affected than maize. In the 2018 season, beans have 2.2 and 2.7 of CWP and CWPc values, this means 0.5 kg/m^3 is crop water productivity gap from the expected normal value from climate effects. For the season of 2019, beans have 2.5 and 2.98 of CWP and CWPc values, respectively. This means that CWP is less than CWPc for this season with a gap of 0.5 kg/m^3. The CWP and CWPc values of 2.8 and 3.7 kg/m^3 for beans of 2020 season with a gap of 0.9 kg/m3. This means that CWP is less than CWPc for this season. There are crop water productivity gaps occurred on beans for the winter season. The winter season of 2020 was more affected than other winter seasons.

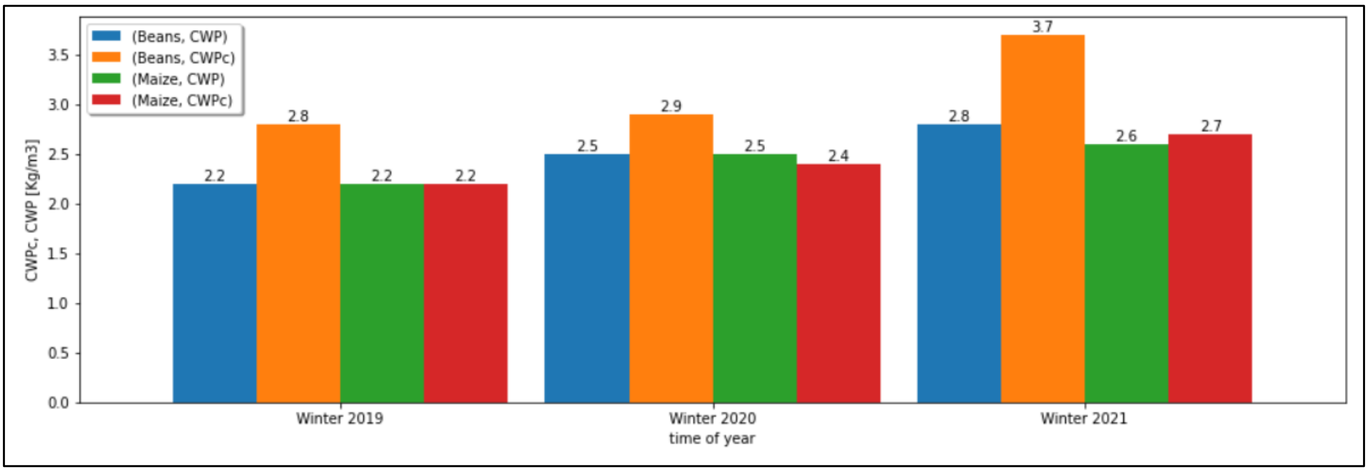

Figure 4-32 Seasonal average CWP and CWPc values of Nasho Irrigated beans and maize for the winter season

4.5.3. Comparison of CWPc values between semi-arid and Humid climates

The comparison between CWPc values of both semi-arid and humid climates was done for C3 and C4 crops for summer and winter seasons. To know the degree of climate effects on crop water productivity, percentage of crop water productivity (%CWP) from normalised CWP were determined to evaluate the level of CWP of specific crop under climatic constraints for Gezira and Nasho irrigation schemes. Crop water productivity level was calculated using the formula below.

$$\%\text{CWP} = \frac{CWP}{CWPc} \times 100 \qquad (13)$$

The evaluation of crop water productivity levels was made based on the following scenarios.

1) Level 1: %CWP less than 100% means CWP is lower than CWPc; there is a crop water productivity gap
2) Level 2: %CWP equal to 100% means CWP equals to CWPc; this means no crop water productivity gap.
3) Level 3: %CWP greater than 100% means CWP is greater than CWPc; crop water productivity is beyond the expectations.

The observations made from figure 4-33 and table 4-37 show that the C3 crops are more affected than C4 crops in both climates for all three summer seasons. The summer season of 2019 was worse than other summer seasons in semi-arid climate. Semi-arid climate has lower crop water productivity than humid climate in all summer seasons, it is almost triple for C3 and C4 crops. More details on crop water productivity levels for summer seasons are given in table 4-37.

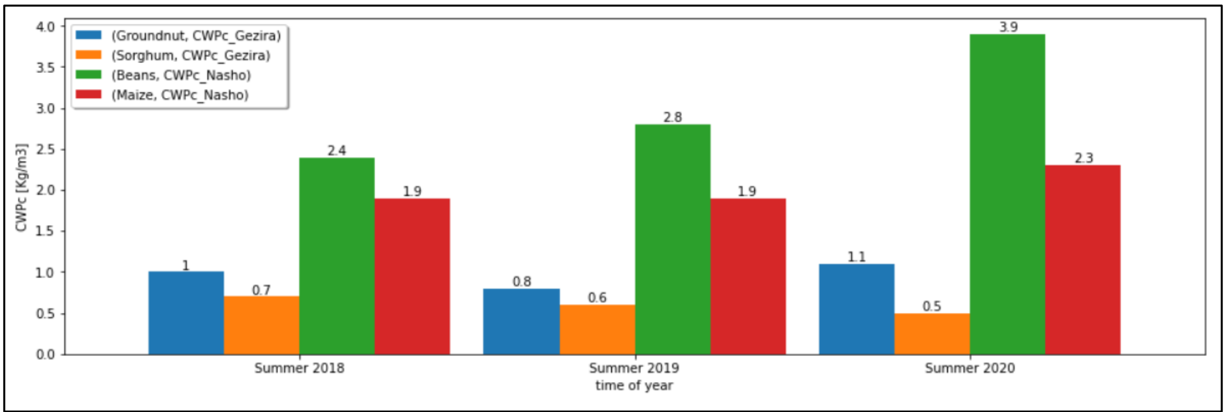

Figure 4-33 CWPc of semi-arid and humid crops for summer season

Table 4-37 Statistics of CWP and CWPc for the summer season

Climates	**Semi-Arid climate**				**Humid climate**			
Crops	Groundnut		Sorghum		Beans		Maize	
Indicators	CWPc	**%CWP**	CWPc	%CWP	CWPc	**%CWP**	CWPc	**%CWP**
2018	1.04	**67**	0.72	**70**	2.37	**101**	1.88	**133**
2019	0.84	**47**	0.60	**67**	2.41	**97**	1.97	**127**
2020	1.08	**56**	0.55	**73**	2.93	**103**	2.29	**135**
Overall Avg	0.99	**57**	0.62	**70**	2.57	**101**	2.04	**132**

The observations made from figure 4-34 and table4-38 show that the C3 crops are more affected than C4 crops in both climates for all winter seasons. The winter season of 2018 was more affected than other winter seasons in a semi-arid climate. Semi-arid climate has lower crop water productivity than humid climate in all winter seasons as well, it is almost double. More details on water productivity levels for winter crops are given in table4-38.

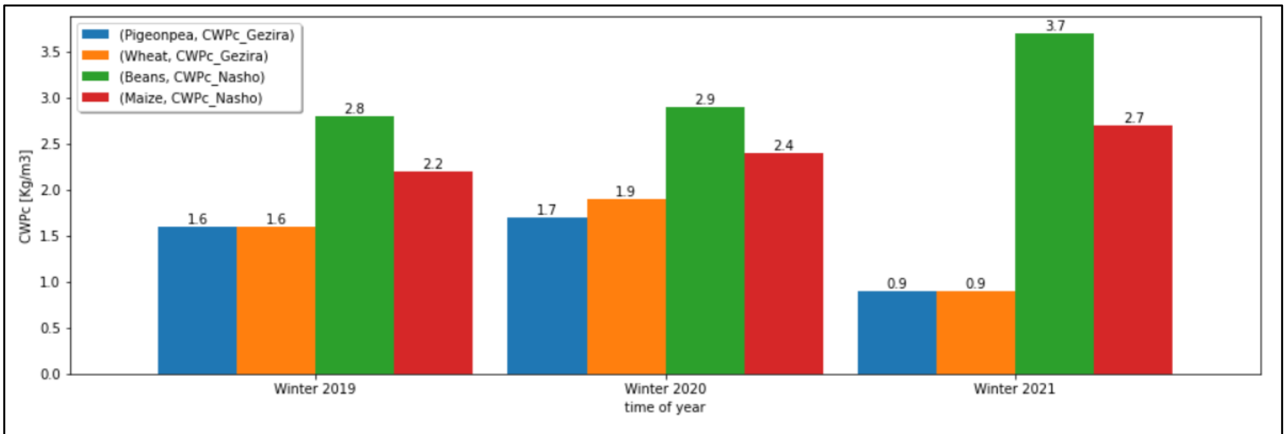

Figure 4-34 CWPc of semi-arid and humid crops for winter season

Table 4-38 Statistics of CWP and CWPc for the winter season

Climates	**Semi-Arid climate**				**Humid climate**			
Crops	Pigeon pea		Wheat		Bean		Maize	
Indicators	CWPc	**%CWP**	CWPc	**%CWP**	CWPc	**%CWP**	CWPc	**%CWP**
2018	1.61	**50**	1.59	**50**	2.79	**79**	2.17	**102**
2019	1.68	**54**	1.90	**53**	2.98	**84**	2.43	**103**
2020	0.96	**62**	0.89	**56**	3.70	**76**	2.70	**96**
Overall Avg	1.70	**55**	1.36	**53**	3.16	**79**	2.43	**100**

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The objectives of this study were: 1) To quantify the agricultural crop water productivity indicators using WaPOR level II data, 2) To analyse transpiration, evapotranspiration, total biomass production and crop water productivity and 3) To perform climate normalisation of crop water productivity for semi-arid and humid climates.

The results of the first objective for Gezira irrigation scheme crops show that the overall average seasonal transpiration values are 402, 322, and 713 mm/season for groundnut, sorghum, and cotton (full season) of summer seasons and 395, 415, and 434 mm/season for onion, pigeon pea and wheat, respectively for the winter season. While overall average seasonal evapotranspiration of 564, 496, and 965 mm/season are obtained for groundnut, sorghum, and cotton (full season) of summer seasons, respectively and 491, 517, and 540 mm/season for onion, pigeon pea, and wheat, respectively for winter seasons. The overall average seasonal transpiration fractions were also calculated, and the results show higher values for C3 crops compared to C4 crops in both winter seasons with the values of 0.80, 0.80, and 0.80 for onion, pigeon pea, wheat, respectively. And 0.71, 0.74, and 0.64 for groundnut, cotton, and sorghum summer season, respectively. Also, winter season crops have a higher transpiration fraction compared to the summer season crops in semi-arid climate regions. The results obtained for Nasho irrigation scheme crops show that the overall average seasonal transpiration is 306 and 323 mm/season for beans and maize of summer seasons and 364 and 420 mm/season for beans and maize, respectively for winter seasons. While overall average seasonal evapotranspiration of 399 and 415 mm/season for beans and maize are obtained for summer seasons and 493 and 538 mm/season for beans and maize of winter seasons, respectively. The overall seasonal transpiration fractions were also calculated, and the results show higher values for C3 crops compared to C4 crops in both winter and summer seasons with the values of 0.77 and 0.78 for beans and maize of summer season, respectively and values of 0.74, and 0.78 for beans and maize of winter season. Summer season crops have a higher transpiration fraction compared to the winter season crops in humid climate regions. The study concludes the higher water consumption of C4 crops compared to C3 crops, higher water consumption of summer compared to winter seasons of semi-arid climate region, higher water consumption of winter seasons compared to summer seasons of humid climate region, respectively. Semi-arid climate crops are higher water consumers compared to humid climate crops.

The results obtained for Nasho rainfed crops show that overall average seasonal transpiration values are 303, 666, and 297 mm/season for beans, banana, and sorghum for summer seasons, respectively and 332 and 345 mm/season for beans and sorghum as winter seasons, respectively. While overall average seasonal evapotranspiration of 389, 849, and 380 mm/season for beans, banana and sorghum are obtained, respectively for summer season, and 443 and 449 mm/season for beans and sorghum for winter season. Comparative analysis between Nasho rainfed and irrigated crops shows that rainfed transpiration and evapotranspiration values are lower compared to irrigation transpiration and evapotranspiration values.

The overall average of TBP of the Gezira irrigation scheme are 2991, 2148 and 6359 kgDM/ha/season for groundnut, sorghum, and cotton as summer crops and 3225, 3246, and 3094 kgDM/ha/season for onion, pigeon pea and wheat as winter crops. While Nasho irrigation scheme has an overall average of TBP of 10534 and 11169 kgDM/ha/season for beans and maize as summer crops and 12440 and 13349 kgDM/ha/season for beans and maize as winter crops. And Nasho rainfed agriculture has an overall average of TBP of 10745, 22723 and 10549 kgDM/ha/season for beans, banana, and sorghum as summer crops and 11435, and 11564 kgDM/ha/season for beans, and sorghum, respectively as winter crops.

The quantified overall average of gross crop water productivity for the Gezira irrigation scheme are 0.56, 0.43 and 1.96 kg/m^3/season for groundnut, sorghum, and cotton as summer crops and 0.73, 0.77, and 0.76 kg/m^3/season for onion, pigeon pea and wheat as winter crops while Nasho irrigation scheme has gross crop water productivity of 2.67 and 2.70 kg/m^3 for beans and maize as summer crops and 2.50 and 2.43 kg/m^3 for beans and maize as winter crops. And Nasho rainfed agriculture has gross crop water productivity of 2.83, 5.3 and 2.63 kg/m^3 for beans, banana (full season) and sorghum as summer crops and 2.47, and 2.63 kg/m^3 for beans and sorghum, respectively as winter crops.

The temporal analysis and comparison were done on a seasonal basis to achieve the second objective of this study. The study finds the higher values of transpiration for semi-arid compared to humid climate with overall average values of 402, 322 and 713 mm/season for groundnut, sorghum, and cotton as summer crops for Gezira scheme; 307, and 323 mm/season for beans and maize summer season for Nasho scheme. But both climates have almost the same values for winter crops with 395, 415 and 435 mm/season for onion, pigeon pea and wheat, respectively for the Gezira scheme. The values of 364, and 420 mm/season for beans and maize, respectively for Nasho scheme. Comparative analysis shows that Nasho rainfed is lower productive than Nasho irrigation scheme. But rainfed has higher gross crop water productivity values compared to irrigation schemes.

The study also finds the higher values of evapotranspiration for semi-arid climate compared to humid climate with overall average values of 399, and 415 mm/season for beans and maize, and the values of 564, 495 and 965 mm/season for groundnut, sorghum and cotton as summer main crops but both climates have almost the same values for winter crops with 492, and 538 mm/season for beans and maize for Nasho scheme, 491, 517, and 540 mm/season for onion, pigeon pea and wheat, respectively for Gezira scheme.

The overall seasonal transpiration fractions for the Gezira and Nasho irrigation schemes were analysed for summer and winter crops. The winter crops have higher values with 0.8, 0.8 and 0.8 for onion, pigeon pea and wheat, respectively and summer crops have values of 0.71, 0.64 and 0.74 for groundnut, sorghum, and cotton, respectively. The overall seasonal transpiration fractions for Nasho irrigation scheme results show that the summer crops have higher values with 0.77 and 0.78 for beans and maize, respectively and winter crops have values of 0.74 and 0.78 for beans and maize, respectively. The findings show that the winter crops are higher beneficial water consumption than summer crops in a semi-arid climate, but summer crops are higher beneficial water consumption than winter crops in humid climate. Winter crops of semi-arid climate are more efficient in water use than both winter and summer crops of humid climate, but the semi-arid summer crops are the lowest efficient crops.

The overall 3 years linear relationships between TBP and ETIa were analysed for every crop type and the study findings show that semi-arid climate crops have strong relationships compared to humid climate crops for summer seasons, but humid climate crops have strong relationships compared to semi-arid climate crops for winter seasons too. C4 crops have a strong linear relationship in semi-arid climates compared to the humid climate, C3 crops have a strong linear relationship in humid climates compared to the semi-arid climate. The R^2 of 0.66, 0.83, and 0.71 for groundnut, sorghum, and cotton as summer crops and R^2 of 0.27, 0.55, and 0.50 for onion, pigeon pea and wheat as winter crops for the Gezira irrigation scheme. While R^2 of 0.64 and 0.62 for beans and maize as summer crops and R^2 of 0.77, and 0.63 for beans and maize as winter crops for Nasho irrigation scheme. Nasho rainfed crops have R^2 of 0.64, 0.70 and 0.59 for beans banana (full season) and sorghum as summer crops and R^2 of 0.49, and 0.50 for beans and sorghum as winter crops.

To achieve the third objective of this research, the climate normalisation of crop water productivity approach was tested for groundnut, pigeon pea, sorghum, and wheat for semi-arid climate and for beans, maize, and sorghum for humid climate during summer and winter seasons. The results show significant meaning in terms of its applications at the regional scale. Comparative analysis for semi-arid crops shows the summer values of CWP and CWPc. CWP values are 0.7, 0.4, and 0.6 kg/m^3 and CWPc are 1.04, 0.84, and 1.08 kg/m^3 of groundnut for 2018, 2019 and 2020, respectively and

CWP are 0.5, 0.4, and 0.4 kg/m^3 and CWPc are 0.72, 0.60, and 0.55 kg/m^3 for sorghum. Also show winter values of CWP and CWPc with CWP of 0.8, 0.9, and 0.6 kg/m^3 and CWPc of 1.61, 1.68, and 0.96 kg/m^3 for pigeon pea and CWP of 0.8, 1.0, and 0.5 kg/m^3 and CWPc of 1.59, 1.90, and 0.89 kg/m^3 of wheat for 2019, 2020, and 2021, respectively. A comparative analysis done for humid crops shows that the summer values of CWP and CWPc. CWP values are 2.4, 2.7 and 4.0 kg/m^3 and CWPc are 2.37, 2.78, and 3.88 kg/m^3 of beans for 2018, 2019 and 2020, respectively and CWP are 2.5, 2.5, and 3.1 kg/m^3 and CWPc are 1.88, 1.97, and 2.29kg/m^3 for maize. Also show winter values of CWP and CWPc with CWP of 2.2, 2.5, and 2.8 kg/m^3 and CWPc of 2.79, 2.98, and 3.70 kg/m^3 for beans and CWP of 2.2, 2.5 and 2.6kg/m^3 and CWPc of 2.17, 2.43, and 2.70 kg/m^3 of maize for 2018, 2019, and 2020, respectively.

The study concludes that semi-arid crops are more affected by climate constraints than humid crops, especially for winter seasons. In both climates, the C3 crops are more affected than the C4 crops. And winter seasons are more affected than summer seasons in both climates. This study also concludes that the climate normalisation of the CWP approach can help at a regional scale to evaluate the spatial variability of crop water productivity gaps within the irrigation schemes, especially in arid and semi-arid climates where the agricultural crops are highly affected by the climate constraints. The study also concludes that crop water productivity of Nasho irrigation scheme is higher than crop water productivity of Gezira irrigation scheme.

5.2. Research Opportunities and Limitations

5.2.1. Opportunities

The opportunities of this study are the availability of open access remotely sensed data available from WaPOR data portal level 2 and level 1 (reference evapotranspiration only), and ERA5-Land that cover both semi-arid and humid study areas which helped to fulfil the objectives of the study.

5.2.2. Limitations

Land cover classification requires ground-truthing data, lack of training data of each growing season may result in lower quality of land classification maps due to the assumption of the same crop rotation between summer and winter seasons for all growing seasons of the study period. This study also requires a site visit and survey for field reconnaissance which were not possible due to COVID-19 measures. It was difficult to carry out this research without any information about the Gezira irrigation scheme and communication with local people or irrigation managers.

The study also requires worldwide climatic seasonal average reference evapotranspiration from literature to perform climate normalisation of crop water productivity. The lack of this parameter for beans, sorghum, groundnut, and pigeon pea caused the assumptions of its values for both semi-arid and humid climates.

5.3. Recommendations

The comparative analyses made for crop water consumption between irrigated and rainfed crops for Nasho study area and the study finds some unnecessary irrigation activities that may result into poor management of water resources. Nasho irrigation managers and engineers are recommended to improve irrigation services, especially in season A (winter) which shows higher differences in crop water use but almost the same productions.

Normalised crop water productivity (CWPc) is not only a helpful approach at a global scale but also at a regional scale to evaluate irrigation performance and mapping crop water productivity gaps within the schemes. Local authorities (agricultural sector, planners, irrigation engineers and other related organisations) are recommended to adapt CWPc approach for water resources management, planning and decision making. The findings of CWPc applied in this study show that Gezira irrigation scheme has lower crop water productivity than Nasho irrigation scheme. Gezira irrigation managers and engineers are recommended to improve CWP to grow more food. For Nasho irrigation scheme, there are few critical CWP values that need the improve for much better performance.

This study did not consider the causes of crop water productivity gaps rather than climate constraints. Other factors such as used fertilizers, irrigation management information, soil types and other practices which may influence crop water productivity indicators require further investigations to know their effects on crop water productivity. The other researchers are recommended to do further investigations on how they can influence crop water productivity in both semi-arid and humid climates.

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APPENDICES

Appendix 1: Gezira Irrigation Scheme field photos

The field photos of Cotton, Sorghum, Onion, and Groundnuts from Left to Right were taken in October and November 2019, summer season. **Source: field survey held on Oct-Nov 2019 for field data validation report.**

Field photos of wheat and pigeon peas were taken in February 2020, winter season. **Source: field survey held on February 2020 for field data validation report**

The detailed information on 50 sample points is given in the excel sheet and GPS points are nearby the sample fields but do not always coincide with them. The data were taken by the experts from the faculty of Agriculture of the University of Gezira, inspectors working in the scheme, and knowledgeable formers.

Appendix 2: Nasho Irrigation scheme field photos

Nasho irrigation field photos for Bean and Maize pivots taken on 25th March 2021, Season B

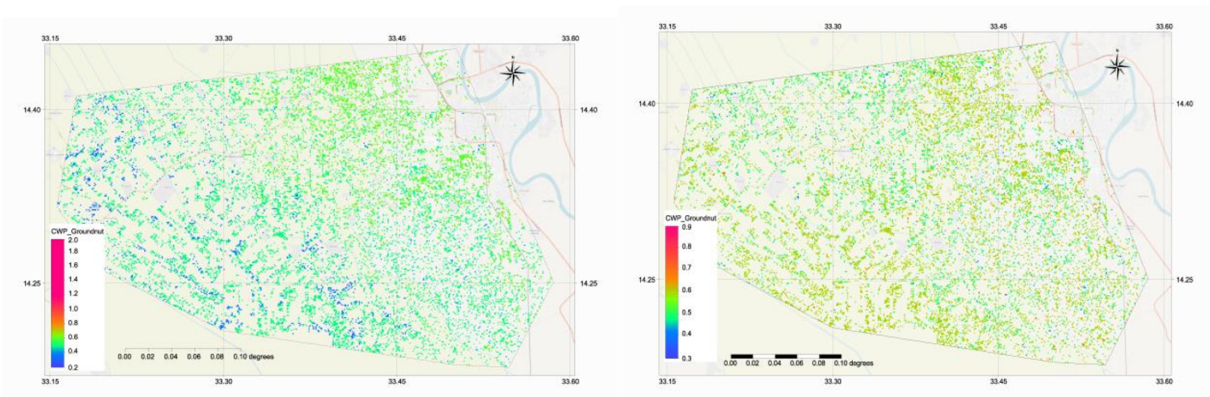
One of the sprinkler machines used to irrigate the crops.

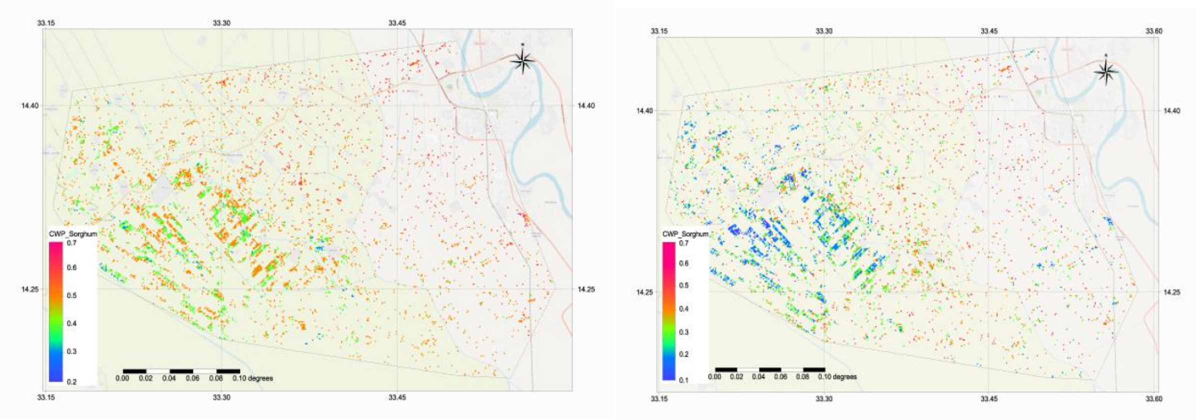
Appendix 3: Nasho Rainfed Agriculture field photos

The field photos for Beans, Sorghum and Banana rainfed crops were taken on 25th March 2021, Season B (summer season). Source: Field

The detailed information on the field samples and GPS points retrieved from google earth is supplied in excel sheets for season A and season B. For irrigation data, the data were taken by the president of Nasho irrigation cooperative and data collection assistant who is a university student in the faculty of Agriculture and drainage.

Appendix 4 Spatial variability maps of GCWP in the unit of kg/m^3 of groundnut and Sorghum





Spatial variability maps of GCWP of groundnut (Upper) and Sorghum (lower) for 2018 and 2020, respectively.

Appendix 5: CWP and CWPc values for semi-arid and humid climates for summer and winter