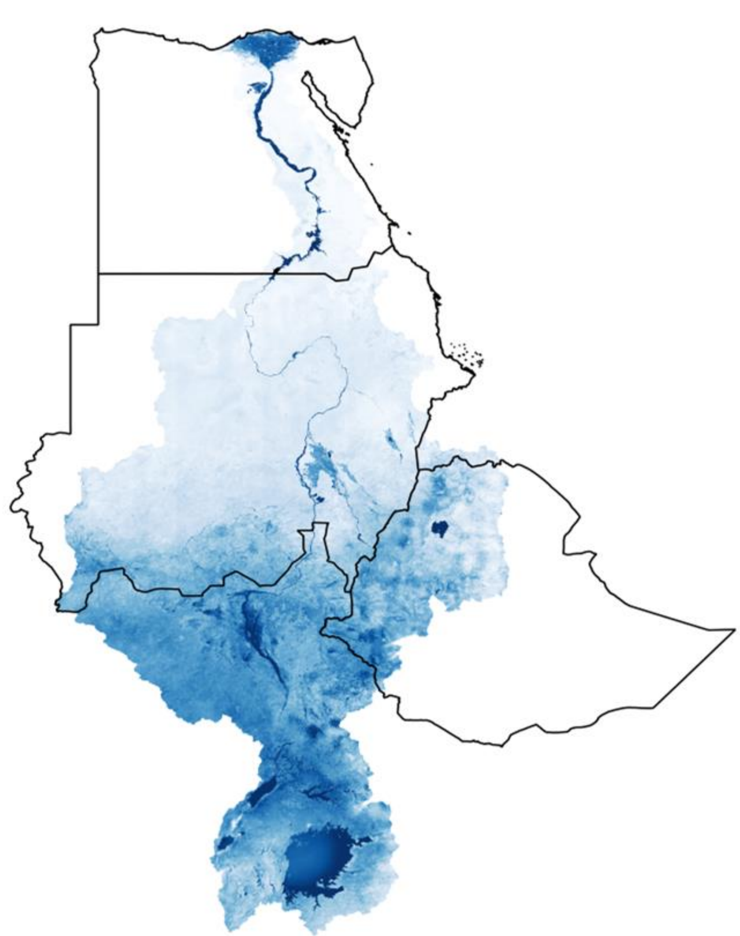
The application of the FAO WaPOR data portal to monitor efficient water use in agriculture

A case study on the Eastern Nile River Basin



I.I.O. Tantawy

On the cover

A map outlining the focus countries of this research and an impression of the total actual evaporation of the Nile River Basin in 2010, provided by the FAO WaPOR data portal. The darker the blue colour, the higher the evaporation.

The application of the FAO WaPOR data portal to monitor efficient water use in agriculture

A case study on the Eastern Nile River Basin

By

Iman Ismail Osman Tantawy

to obtain the degree of Master of Science in Civil Engineering
at Delft University of Technology,
to be defended publicly on Wednesday, February 27, 2019 at 3:00 PM.

Student number:	1523015	
Chair:	Prof. dr. ir. N.C. van de Giesen	CEG - TU Delft
Committee members:	Prof. dr. ir. P. van der Zaag	CEG - TU Delft
	Dr. ir. J. Timmermans	TPM - TU Delft
	A.M. Onencan	TPM - TU Delft

"And We have made from water every living thing"

- *Quran [21:30]*

***

To my late grandmother 'Nena';
To my second homeland;
To the people of the Nile.

Preface

> *"If you can't find good in your own country, you won't find it anywhere else."*
>
> The words slipped out from Zaki Bey, but he felt that they were ungracious, so he smiled to lessen their impact on Busayna, who had stood up and was saying bitterly:
>
> *"You don't understand because you're well-off. [...] When your house has collapsed and the government has left you sitting with your children in a tent on the street, when the police officer has insulted you and beaten you just because you're on a minibus at night, when you've spent the whole day going around the shops looking for work and there isn't any, when you're a fine sturdy young man with an education and all you have in your pockets is a Pound, or sometimes nothing at all, then you'll know why we hate Egypt."*
>
> Passage from "The Yacoubian Building", by Alaa Al Aswany (Egyptian Novelist)

The phenomenon of Egyptians emigrating from Egypt was rare until Gamal Abdel Nasser came to power in 1952. Together with roughly 9.5 million others, my father was part of the so-called Egyptian diaspora that followed in the years after. Although my father left Egypt, he did not do so to denounce his Egyptian identity; On the contrary, his love and sentiment for Egypt grew as his years living abroad increased. Consequently, second-generation Egyptians like myself, became a product of that circumstance. It is most likely for this reason that I cherish much passion and a strong desire to prove myself regarding Egypt. With water management being the Netherlands's most renowned expertise and Egypt's ongoing water scarcity challenge, the motivation to study water management was a no-brainer. Having been raised in the Netherlands also gave me the luxurious position to overlook the bad and focus on the beauty, the potential, even the magic of my second homeland. Although I am well aware of the current situation, I have been accused of romanticizing Egypt. But it is precisely this romanticized image that strengthened my dedication to tackle the water challenges faced by Egypt and the other Nile basin countries. With this thesis, I fulfilled my desire to contribute, I feel at peace.

I would like to use the rest of this chapter for words of thanks. First, I am thankful for the presence of God that I felt with me during every step. Meeting the right people at the right time felt no less than a miracle, over and over again. Nabil, my husband, I owe you a huge dept of gratitude, for your love and care throughout this important phase in my life. Thank you for your support and uplifting me during the times that I lost faith in myself and in what I was doing. Indeed, achievements do not come without hardship. Your encouragement to reach out to Google Earth Engine set the fundamental base for me to complete this thesis, although I was only convinced to go and ask for a Google sticker. Evidently, I could not have done this without you. I am thankful for my family and friends. Thijs and Rachid, thank you for our countless conversations on the topic of this research and your listening ears. Mama, Jamilah and Marijn, your unbreakable trust in my abilities and skills encouraged me to keep aiming high. Fawzia, thank you for always being able to turn moments of despair into outbursts of laughter and Elena, thank you for your companionship throughout our journey to make it to graduation day.

Job Kleijn, to you I owe so much. Thank you, for hiring me as your intern, introducing me to this amazing project and so much more. Working at the Ministry of Foreign Affairs with you as my mentor has been an invaluable asset and experience that I will carry with me for the rest of my life. Most of all, thank you for believing in me and reuniting me with Egypt after 8 years. I will never forget what you have done for me.

Sai Cheemalapati, a special word of thanks to you. It is safe to say that my thesis could not have been completed without your indispensable contribution. Meeting you in Vienna was the defining breakthrough to complete this thesis. Thank you for giving me your valuable time and willingness to help me with my model and my code. Your enthusiasm and interest in my topic, our many e-mail conversations, words of encouragement and advise have been invaluable, to say the least. I deeply value, respect and appreciate your persistence in finding a solution for every programming challenge I came up with. Thank you so much.

Last but not least, I would like to thank my graduation committee. Nick van de Giesen, Pieter van der Zaag, Jos Timmermans and Abby Onencan. Nick, I am thankful for the space you have given me to develop this thesis and to learn and discover. Thank you for our meetings, in which I always felt better afterwards. Thank you, Pieter, for your challenging questions and supporting suggestions. Abby, thank you for your willingness to step in and your support over email. Finally, Jos, thank you for agreeing to still be part of my committee despite your surgery.

To the reader, I hope you will enjoy reading this thesis.

Iman Tantawy
Cupertino, January 11th, 2019

Abstract

Water scarcity has been a growing problem for many places around the world as water usage has been increasing with double the rate of population growth in the twentieth century. As agriculture accounts for 70 percent of global freshwater withdrawals, fresh water availability will thus face even greater stress (World Bank, 2013). Sustainable Development Goals (SDG's) 2, 6 and 7 (UN, 2015) show that the achievement of water, food, and energy security have been set to a high priority on the global world agenda. However, achieving these goals cannot be done without a proper understanding of the interlinkages between the sectors. As water resources become more stretched, the energy and food sectors' dependence on water implies that decision-makers in all three domains should increasingly focus on water resource management as part of their policy and practice ("Water, Food and Energy | UN-Water," n.d.).

In light of this, the Food and Agricultural Organization (FAO) of the United Nations launched the so-called Water Productivity Open-access portal (WaPOR). The portal provides free and open access to processed satellite data that enables monitoring of land and water productivity throughout Africa and the Middle East in near real time. Crop Water Productivity is defined as the crop yield per unit of water consumed, expressed in kg/m^3. The objective of this thesis is to explore and assess the available datasets provided by WaPOR to improve current water resource management practices in agriculture in the Eastern Nile Basin countries. The study focuses on the quantification of monthly water withdrawals for irrigation purposes, as well as benchmarking physical water productivity of the main irrigated crops within so-called Agro-Ecological Zones of each country. Throughout this study, crop water productivity is assessed and defined as the amount of agricultural yield that can be attained per unit of water that was allocated for its production, expressed in kg/m^3. Data analysis and modeling are the major tools applied to assess spatial variation of water withdrawals and water productivity and subsequently to explain the results. The results are both the quantification of monthly water withdrawals for irrigation purposes, as well as benchmarking crop water productivity of the main irrigated crops within of the countries of the case study: Egypt, Sudan and Ethiopia.

Irrigation is considered the largest water-consuming sector in the world and has great potential to become more water-efficient. Rain-fed agriculture, however, does not influence the water balance within a catchment and can thus not improve its water efficiency. Separating irrigated agriculture from rain-fed agriculture can be done by splitting the total evaporation in so-called green and blue water evaporation. Evaporation from green water is the part of the actual evaporation that is derived from rainfall that infiltrated into the soil, while evaporation from blue water is due to the use of human-made infrastructure such as pumps, with the purpose of irrigation. With blue water evaporation, the total water consumption [m^3] that was used for irrigation can subsequently be calculated. This can be used to then calculate the water productivity, but also provides insight into the current water management practices of a country. The principle of the Budyko Curve has been applied to obtain blue water evaporation (Budyko, 1974), in compliance with the Water Accounting Plus procedure that was developed at IHE Delft by Wim Bastiaanssen et al. (Bastiaanssen, W.G.M., Coerver, 2017). Finally, water consumption was obtained by multiplying the pixel size with the sum of the monthly blue evaporation. The outcome of these calculations provides a water consumption expressed in m^3/month.

Water productivity is calculated by dividing agricultural yield [kg] by the amount of water that was consumed for its production [m^3]. Agricultural yield was obtained by multiplying above ground biomass production (AGBP) with a crop harvest index according to the crop that was identified with the phenology

data. To determine the specific growing season of a pixel, so-called “Start Of Season” (SOS) and “End OF Season” (EOS) phenology data are combined. By comparing the growing season of the pixel with literature from the FAO crop calendar, the crop type could be determined. The total water consumption between the SOS and EOS dekad numbers is summed to provide the total water consumption during the growing season of the crop. This way Crop Water Productivity is eventually obtained.

Throughout this thesis, the assumption was made that crops could be distinguished and recognized, based on the available phenology data. Considering the fact that a ‘no season’ label is applied when no growing season can be distinguished, agricultural cropland was thought to be identified through this method. However, from the fact that reasonable results complying with the literature are found with the use of the FAO LCC Land Cover Map, it follows that the identification of crops through phenology and blue evaporation data does not provide accurate results. This is especially the case for Ethiopia and to a lesser extent Sudan, likely due to the fact that Egypt has hardly any rainfall and therefore consists almost solely of irrigated agriculture. Similarly, ground truthing should therefore be done regarding crop identification and the presence of irrigation per pixel.

Calculating water withdrawals gave a promising outcome for Egypt, as the calculated water withdrawals were almost similar to the water withdrawals stated by AQUASTAT. However, numbers differed by a factor 10 for both Sudan and Ethiopia. When the FAO WaPOR LCC mask is applied, better results are achieved. The calculated water withdrawals for Egypt, Sudan, and Ethiopia are lower than FAO AQUASTAT’s numbers. It should, however, be noted that FAO AQUASTAT’s numbers are based on the required water withdrawals, while WaPOR calculates the effective water withdrawals. Lower values could imply low efficiencies of the irrigation systems, which is not uncommon for all three countries. With a typical irrigation efficiency of 60 to 70% (Howell, 2003), the total amount of water withdrawals can be computed with $Q_{irrigation}/0.65$ (Kwast et al., 2016). When this is taken into consideration, the results seem promising.

Overlapping phenologies of crops and the indistinct connection with the above ground biomass data are factors that caused unreliable results for the calculation of crop water productivity. The high CWP values that were found in Ethiopia are high compared to the reasonable values found in Egypt and Sudan. This could possibly be due to the fact that the pixels are wrongly identified as irrigated pixels. After all, CWP was assessed for all pixels that contain blue evaporation and was not masked with the FAO WaPOR LCC mask. It is therefore recommended to use an accurate land use mask when CWP is assessed.

Contents

List of Acronyms

AET	Actual Evaporation
AEZ	Agro-Ecological Zone
AGBP	Above Ground Biomass Production
API	Application Program Interface
BCM	Billion Cubic Meters
CWP	Crop Water Productivity
DEM	Digital Elevation Model
E	Evaporation
EO	Earth Observation
EOS	End of Season
FAO	Food and Agriculture Organization of the United Nations
FRAME	Consortium consisting of eLEAF, VITO, ITC and the Waterwatch Foundation
GBWP	Gross Biomass Water Productivity
GEE	Google Earth Engine
GERD	Grand Ethiopian Renaissance Dam
GIS	Geographic Information System
HI	Harvest Index
I	Interception
IDE	Integrated development Environment
KPI	Key Performance Indicator
FAO WaPOR LCC	FAO WaPOR Land Cover Classification
MOS	Max of Season
NBWP	Net Biomass Water Productivity
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Production
PCP	Precipitation
PHE	Phenology
RET	Reference Evaporation
SOS	Start of Season
SDG	Sustainable Development Goals
SOS	Start of Season
T	Transpiration
WA+	Water Accounting Plus
WaPOR	Water Productivity Open-access portal
Y	Agricultural yield

List of Figures

List of Tables

1. Introduction

1.1 The nexus approach and transboundary water management

Water scarcity has been a growing problem for many places around the world as water usage has been increasing with double the rate of population growth in the twentieth century. In addition, the increase of global economic wealth has led to changing diets, implying that 70 percent more food needs to be produced to be able to meet future demand. As agriculture accounts for 70 percent of global freshwater withdrawals, fresh water availability will thus face even greater stress (World Bank, 2013). Thus, the competition between overall water demand and water for food is increasing.

Anno 2018, the need for a nexus approach is, therefore, more apparent than ever. Sustainable Development Goals (SDG's) 2, 6 and 7 (UN, 2015) show that the achievement of water, food, and energy security have been set to a high priority on the global world agenda. However, achieving these goals cannot be done without a proper understanding of the interlinkages between the sectors. As water resources become more stretched, the energy and food sectors' dependence on water implies that decision-makers in all three domains should increasingly focus on water resource management as part of their policy and practice ("Water, Food and Energy | UN-Water," n.d.).

Towards the end of the twentieth century, remote sensing technology for water management and agricultural monitoring practices, became increasingly popular. With an increase in open-data availability throughout the past decade, Geographic Information System (GIS) software are now, more than ever, able to shed light on agricultural practices and tracking behavior in energy, food and water consumption. Thus, remote sensing unlocked the potential for improved nexus research on large spatial scales.

1.2 Crop Water Productivity as a performance indicator for improved policy and decision-making within the Water-Food Nexus

Given the scarcity of resources, the key strategy to increase food security should be increased production per unit of resource (Bastiaanssen & Steduto, 2017). Throughout the last decades, the conventional resource to evaluate and improve has been land productivity, expressed in kg/ha. However, considering the fact that water resources are increasingly becoming one of the major constraints to produce more food, the evaluation of food production in terms of water becomes increasingly valuable as well. Crop Water Productivity is defined as the crop yield per unit of water evaporated, expressed in kg/m^3. The United Nations embraced Crop water productivity as one of the Sustainable Development Goals (SDG 6.4) in their General Assembly (September 2015), although it is referred to as water use efficiency (Zwart, Bastiaanssen, de Fraiture, & Molden, 2010b).

Data are the basis for evidence-based decision-making. Specifically, geospatial data can provide tools to monitor and visualize processes with a high spatial variability, subsequently leading to informed decision-making. The role of geospatial data is recognized by the United Nations in supporting the achievement of the SDGs. According to a report published by the UN Office for Outer Space Affairs (UN, 2017), it is shown that European Union space technologies support the fulfilment of the SDGs and states that all SDGs are positively impacted by the benefits stemming from the use of Earth Observation (hereafter: EO) data. Out of the 169 indicators associated with the SDGs, 65 are directly benefited by either monitoring the status of the achievement of a given SDG, or by actively contributing to its fulfilment (UN, 2017).

However, extensive methodologies and infrastructure are needed to facilitate proper implementation of EO to support and/or monitor the SDGs. It is crucial that local political organizations are informed and encouraged to implement geospatial efforts in their respective countries. Without their involvement, much of the derived data and information will remain in the field of science and research (United Nations, n.d.). To reach end users, the actors, the playing field and the tangible contribution of EO in relation to the SDGs need to be identified. This can be done by translating EO data into concrete products and services that are accessible by non-technical experts, combined with capacity building.

SDG target 6.4 addresses water-use efficiency and water stress, aiming by 2030, to "substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity" (UN FAO, 2018). Two indicators were developed to track progress for this target:

- 6.4.1 Change in water-use efficiency over time
- 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources

To achieve goals such as SDG 6.4, proper monitoring and reporting tools are needed to track progress. This will help decision makers identify and prioritize what, when and where interventions are needed to improve implementation. Information on progress is also essential to ensure accountability and generate political, public and private sector support for investment. In the end, effective water management and nationwide water security is a responsibility of the government. Ensuring the implementation of SDG 6.4 and an improvement of water productivity in agriculture should therefore come from policy and decision-makers rather than farmers.

1.3 Study area: The Eastern Nile River Basin

The Nile River consists of two major tributaries, the White Nile and the Blue Nile. The White Nile is the longest tributary of which its sources are located in Rwanda and Burundi. The Blue Nile is considered to be the source of most of the water and fertile soil and begins at Lake Tana in Ethiopia. The flow of the Blue Nile is highly seasonal with more than 80% of the annual flow occurring from July to October (Awulachew et al., 2008; Conway, 1997). The annual flow of the Blue Nile ranges between 21 and 74 billion cubic meters (hereafter: BCM) with an average of around 49 BCM (Wheeler et al., 2016). The Blue and White Nile subsequently meet and form the main body in north Sudan, reaches Egypt and finally debouches into the Mediterranean Sea.

The Nile Basin nations have a combined population of over 450 million people, and estimates indicate that over 200 million rely directly on the Nile for their food and water security. An increase of the population in the riparian countries will therefore further exhaust the region's already scarce water recourses as demands from agriculture, industry and domestic use rise, leading to higher competition and risk of conflict between the nations.

The study area of this research extends over the countries that cover the Blue Nile, namely Ethiopia Sudan and Egypt (fig. 1). Cooperation among these riparian states is now more critical than ever in order to resolve emerging conflicts around issues such as hydropower and water resources.

In April 2011, Ethiopia started with the construction of the Grand Ethiopian Renaissance Dam (hereafter: GERD). Despite various attempts, the water conflict has not been resolved as nobody has managed to accommodate Egypt's concerns regarding unfavorable outcomes of the GERD. This conflict over river development and hydropower underpins the need for multifaceted approaches to enhance cooperation and context-fit solutions that consider the overall hydrological, political, economic and social circumstances of the Eastern Nile River Basin.

1.4 Problem definition and objective

Problem Statement

As of April 2017, FAO launched the beta version of WaPOR (Water Productivity Open-access portal), a data portal that provides free and open access to processed satellite data that allows monitoring of land and water productivity throughout Africa and the Middle East in near real time. WaPOR was founded with the purpose of enabling stakeholders, such as national governments, local water authorities and water user associations, to monitor and improve their current land and water management practices (FAO, 2014). Furthermore, the data is supposed to be used for yearly reports in which progress of the projects that are funded with the Dutch developing aid budget are presented to the Dutch parliament.

Although many data sets have been made available on WaPOR, its practical usability has remained unproven. The implementation of WaPOR data for the overall purpose of improved decision-making has been a challenge due, among others, to the fact that both the use of satellite technology as well as the concept of water productivity are relatively new and still need time to embed in the current policymaking sector (personal experience of author). In addition, it is not yet clear what information policymakers, such as the Dutch government and parliament, actually need to make good policy decisions with respect to SDG 6 and 2. Therefore, the possibilities of water productivity as a performance indicator as well as the available datasets need to be explored and assessed in terms of practical usability.

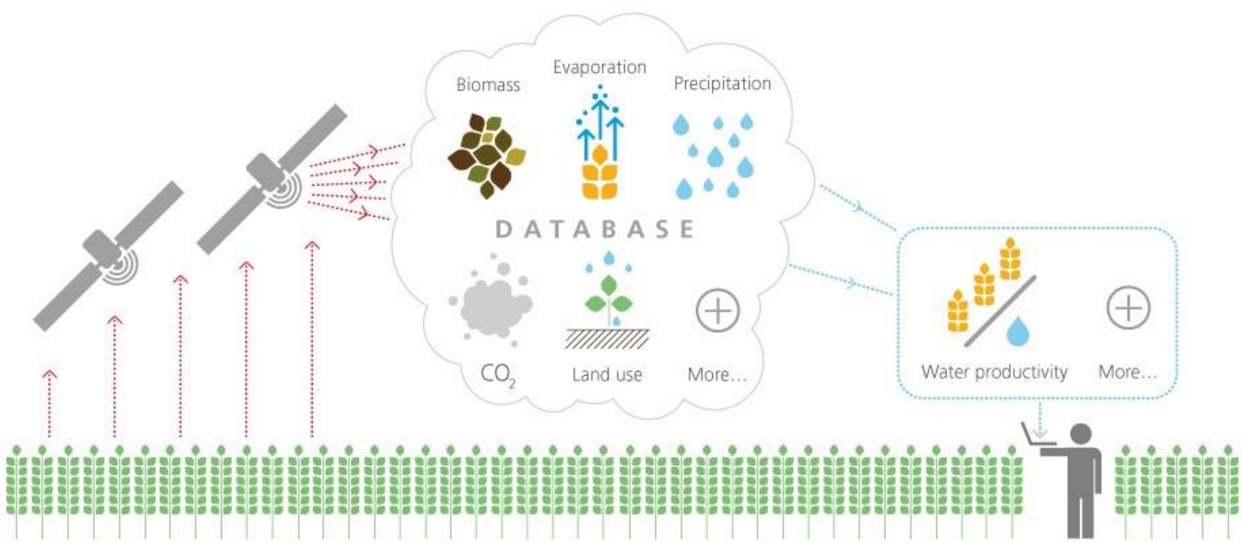


Figure 1: Impression of FAO WaPOR

As of June 2018, WaPOR 1.0 was launched with an updated methodology and additional datasets, which have been added in the course of the study.

Thesis objective

The objective of this thesis is to investigate the usability of the FAO WaPOR data portal by making an assessment of the agricultural water management practices and by assessing the Water-Food Nexus with water productivity as a performance indicator in the Eastern Nile Basin. This thesis was set up complementary to the author's internship at the Ministry of Foreign Affairs. While the internship focused on the implementation of WaPOR for improved decision-making within the policy sector, this thesis aims to research the technical boundaries and opportunities of WaPOR data.

The study will focus on the quantification of water withdrawals for irrigation and the benchmarking of physical water productivity. Throughout this study, water productivity will be assessed and defined as the amount of agricultural production (harvestable yield) that can be attained per unit of water that was allocated for its production (in terms of irrigation) for the main irrigated crops of each country. Big data analysis and modeling are the major tools applied, to quantify water withdrawals and assess spatial variation of water productivity.

Research questions

The following research questions will be answered:

1. What are the opportunities and challenges of the FAO WaPOR data?
2. What are the current water management practices per country?
3. How can water productivity play a role in the assessment of water management of the countries in the Eastern Nile River Basin?

Methods

To answer the research questions, the following methodology is used to explore the opportunities of WaPOR:

1. Perform a general assessment of the available data provided by the FAO WaPOR portal to determine the usability of various datasets;
2. Perform assessments of each country with regards to water management and agricultural practices;
3. Assess water withdrawals for 2016 and water productivity for 2015 per country;
    a. Make a distinction between green and blue water, i.e., identify irrigated areas and calculate water withdrawals for irrigation purposes on a monthly basis;
    b. Identify crops by means of phenology data; calculate irrigated crop water productivity per season;
    c. Divide the country into agro-ecological zones (AEZ) and identify irrigated crop water productivity gaps/high potential areas and anomalies.
4. Evaluate data by comparing to reviewed literature.

1.5 Thesis outline and guides for reading

In Chapter 2 the applied methodology is described. The methods include a brief explanation of the available data of WaPOR and the final selection of data that will be used to conduct this research. Furthermore, the procedure for the assessment of irrigation and water productivity is discussed. Chapter 3 introduces the area of study of this research. This chapter concerns an analysis of each country with regards to their climate, water use, and agricultural production. In Chapter 4, the results of this study are presented. This includes relevant observations on the irrigation practices of a country, as well as a brief validation assessment of the data. Secondly, the results of crop water productivity are presented. Chapter 5 provides a discussion on the results and an evaluation of the applied methods. Chapter 6 presents a brief answer to the research question and reevaluates the problem statement.

Throughout this research, the term ‘Evaporation’ has been used to replace the more common term ‘Evapotranspiration’ in accordance with the point of view of H.H.G. Savenije (Savenije, 2004) and is defined as the sum of interception I, transpiration T, surface evaporation E_s, and open water evaporation E_o.

2. Methodology

2.1 General outline of the available data on FAO WaPOR

The initial beta release provides 10 years of data of the African continent and the Near East region with a spatial resolution of 250m (Level I dataset). Later, this was extended with a Level II dataset, containing 100m resolution data for selected countries and river basins. In the near future, a Level III dataset will be released containing 30m resolution data for 5 selected irrigation schemes. Each level is defined by a unique region of interest and a specific spatial resolution. Table 1 specifies the resolution and area covered by the different levels.

Table 1: Spatial resolution and designated regions of interest of the different datasets (levels).

Dataset	Resolution	Region of Interest
Level I	~250m	Africa and the Near East (bounding box 30W, 40N, 65E, 40S)
Level II	~100m	*Countries:* Morocco, Tunisia, Egypt, Ghana, Kenya, South Sudan, Mali, Benin, Ethiopia, Rwanda, Burundi, Mozambique, Uganda, West Bank and Gaza Strip, Yemen, Jordan, Syria, and Lebanon *River Basins:* Niger, Nile, Awash, Jordan, and Litani
Level III	~30m	Irrigation schemes and rainfed areas in Egypt, Ethiopia, Mali, and Lebanon

The data components that are currently available on WaPOR are listed in Table 2. The temporality of the data varies between, daily, dekad, seasonal and yearly resolutions. A dekad or dekadal refers to a period of 10 days on average. It splits the month into 3 parts, where the first and second dekads are 10 days each and the last dekad ranges between 8 and 11 days. Seasonal refers to a time scale that covers a growing season. The length and number may vary, with a maximum of 2 growing seasons per year.

Table 2: Overview of the WaPOR data components per level, with temporal and spatial resolutions specified.

Data components	Level I (~250m)	Level II (~100m)	Remarks
Actual Evaporation (AET)	Annual/Dekadal	Annual/Dekadal	Methodology updated since June 2018 (Interception considered)
Net Primary Production (NPP)	Dekad	Dekadal	
Above Ground Biomass Production (AGBP)	Annual	Seasonal	
Phenology		Seasonal	
Reference Evaporation (RET)	Daily		Different resolution: ~5000m
Precipitation (PCP)	Daily		Different resolution: ~20000m
Transpiration (T)	Annual/Dekadal	Annual/Dekadal	
Soil Evaporation (E)*	Annual/Dekadal	Annual/Dekadal	Available since June 2018
Interception (I)*	Annual/Dekadal	Annual/Dekadal	Available since June 2018

Transpiration Fraction	Dekadal	Dekadal	
NDVI Quality Layer		Dekadal	
Gross/Net Water Productivity	Annual		Direct product from AGBP/AET (gross) and AGBP/T (net)
Land Cover Classification (LCC)*	Annual	Annual	Available since June 2018
Land Surface Temperature Quality Layer*	Dekadal	Dekadal	Available since June 2018

2.2 Data selection, assumptions, and boundary conditions

This study aims to research the opportunities of assessing the Water-Food Nexus of the Eastern Nile River Basin with WaPOR. The following boundary conditions, assumptions, and limitations should be considered throughout this research:

- The FAO WaPOR Land Cover Classification was used to filter the pixels that contain irrigated cropland;
- FAO Crop calendar and the AQUASTAT database have been used for information on agro-ecological zoning, crop growing seasons and overall agricultural and water management practices of the countries;
- Due to the large spatial scope, the case study was delineated to the three countries that are dependent on each other the most regarding their water resources; namely Egypt, Sudan, and Ethiopia;
- To calculate water productivity, Above Ground Biomass Production, Phenology, Actual Evaporation, Reference Evaporation, and Precipitation datasets were used from WaPOR. The highest resolution available is 100m*100m. Therefore, the pixel level has been set to this scale;
- Above Ground Biomass Production, Phenology and Actual Evaporation data sets have not been made available for the complete country of Sudan. Therefore, the country assessment of Sudan does not cover the complete country; only the part that is included in the raster files of the Nile River Basin;
- WaPOR distinguishes two crop cycles per year only. Therefore, water productivity can be assessed two times per year. For the assessment, we focus on the three irrigated crops that are cultivated the most.

FAO WaPOR data

The total evaporation in a catchment is the sum of a number of different processes: Interception I, Transpiration T, Soil Evaporation E_S, and Open Water Evaporation E_O (Shuttleworth, W. J., 1993). For ***Actual Evaporation [mm/day]***, the value of a pixel represents the average daily actual evaporation for that specific dekad. The calculation is based on the ETLook model (Bastiaanssen et al., 2012), which uses a modified Penman-Monteith equation that uses remote sensing data as input. The Penman-Monteith equation (Monteith, 1965) predicts the rate of total evaporation and transpiration using meteorological data and has become the FAO standard for calculating the actual and reference evapotranspiration (FAO Irrigation and Drainage paper 56, Allen et al., 1998).

Reference Evaporation [mm/day] is also derived using the Penman-Monteith equation, with the distinction that most of the variables are predefined. To calculate the Reference Evapotranspiration, incoming solar radiation and weather data (temperature, humidity and wind speed) are used.

Phenology [-] indicates the cycle of a crop and is produced for a maximum of two growing seasons annually. The phenology for one growing season is delivered as three raster files. The first raster indicates the Start of Season (SOS), the second the Maximum of Season (MOS) and the third represents the End of Season (EOS). With a maximum of 2 growing seasons annually, a full year is described by 6 raster files. The pixel values of the phenology data components are expressed in dekad numbers. The methodology that is used is described by Van Hoolst et al., which enables the possibility to derive phenological information from a time series of dekadal NDVI layers.

Above Ground Biomass Production [kg] is defined as the sum of the above-ground dry matter that is produced during the course of a growing season. The seasonal value represents the total accumulated biomass during one growing season, from the start of the season (SOS) to end of the season (EOS). To derive the accumulation of biomass production over or during a growing season, first, the start and the end of the growing season need to be identified using the phenology data component. AGBP is then calculated as the sum of NPP, converted into dry matter productivity (DMP) units (kgDM/ha), between the start of the season (SOS) and the end of the season (EOS). In addition, factor (F) is included to account for the division between the above and below-ground components or the root-shoot ratio. A fixed root-shoot ratio of 0.65 is applied as a default value when calculating dekadal and seasonal AGBP. At the end of the season, when the crops for the area can be assessed, the dekadal and seasonal AGBP values are adjusted using an additional root-shoot correction factor data layer that allows the user to correct the AGBP using the land cover specific root-shoot values. A limitation for the derivation of AGBP is the dependency on phenological information, meaning that AGBP can only be derived for areas where seasonality is detected. For ecosystems, such as tropical forests or deserts, that experience almost no seasonality, the start of the season is theoretically set at January 1st and end of the season is set at December 31st.

Precipitation [mm/day] is the daily total precipitation and is provided by the CHIRPS dataset, an existing external data source that combines satellite observations with global models and measurements at local stations. The CHIRPS dataset has a resolution of approximately 5 km.

FAO WaPOR Land Cover Classification has been made available in WaPOR 1.0 and is an experimental land cover dataset, showing a broad classification that identifies cultivated land and distinguishes between irrigated and rainfed areas. It is published on a yearly basis, while seasonal products are available upon request. Land Cover Classification makes use of the dekadal reflectance time series and seasonal phenology information from the Crop Calendar. Irrigated areas are identified by applying a water deficit index that takes into consideration seasonal cumulated values of precipitation and actual evaporation. The classification applied is based on the Land Cover Classification System (LCCS) that was developed by FAO.

FAO Crop Calendar and AQUASTAT

The FAO Crop Calendar provides timely information about seeds to promote local crop production. It contains information on planting, sowing and harvesting periods of locally adapted crops in specific agro-ecological zones. It also provides information on the sowing rates of seed and planting material and the main agricultural practices.

AQUASTAT is FAO's global water information system that collects, analyzes and disseminates data and information by country on water resources, water uses and agricultural water management, with an emphasis on countries in Africa, Asia, Latin America, and the Caribbean.

2.3 Computation Power: Google Earth Engine

Due to the large spatial scope of this research combined with the high data resolution, computation on a single device proved to be insufficient. Furthermore, the variations in characteristics of the data with regards to data type, resolution and region of interest was hard to work with; Python's GDAL package required the datasets to be preprocessed extensively before being able to use the data for actual analysis.

Google Earth Engine (GEE) provided a solution to these challenges. It is a platform made specifically for scientific analysis and visualization of geospatial datasets at petabyte scales, by providing a cloud-based processing environment to facilitate large-scale data processing. The platform furthermore includes an extensive catalog with data from various satellites. Users can access data from this public catalog as well as upload their own private data while using a library of operators provided by the Earth Engine API for further analysis. Operations are implemented in a large parallel processing system that automatically subdivides and distributes computations, thus providing high-throughput analysis capabilities.

Accessing the API can be done either through a thin client library or through a web-based interactive development environment (IDE), built on top of that client library. The majority of the library's image-based functions are per-pixel algebraic operations that operate on a per-band or band-to-band basis, covering integer and floating point math, logical comparisons, bit manipulation, typecasting, conditional replacement and multidimensional array operations for processing on array-valued pixels (Gorelick et al., 2017).

Developing the code was mostly done in the so-called code editor, referring to the web-based IDE that uses a JavaScript-based API. The code editor allows users to make changes easily and immediately assess results in a visual feedback map (fig. 3). In addition, a python API was eventually used to produce and export the final results.

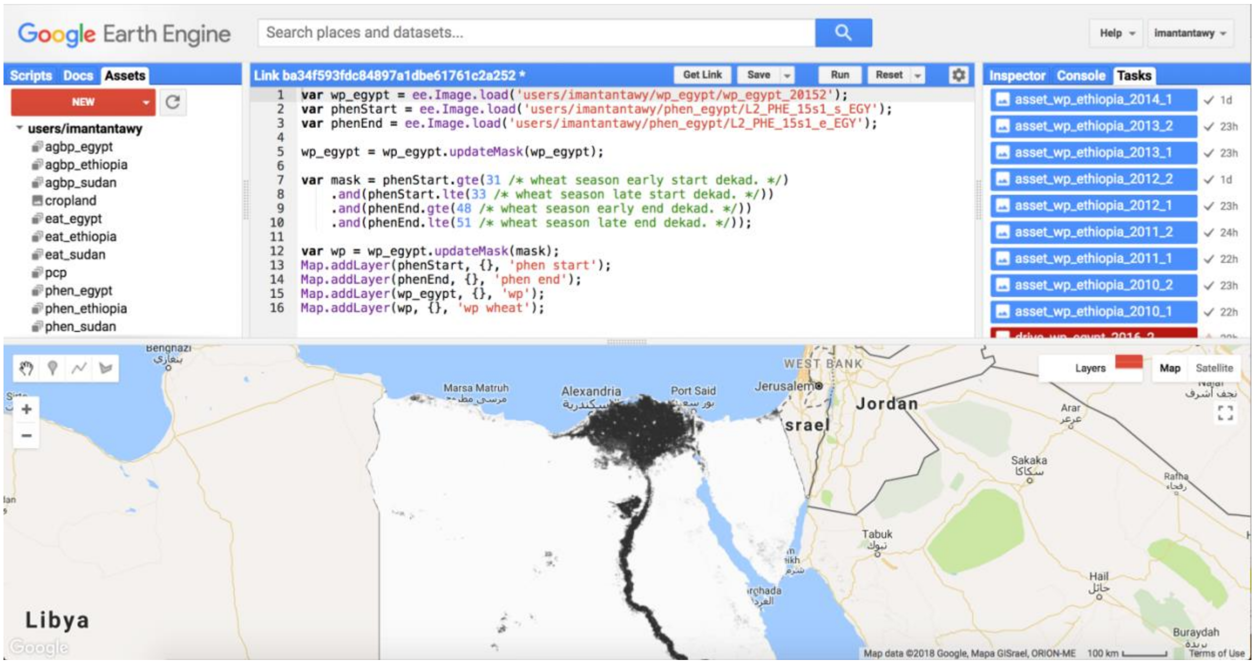


Figure 2: Impression of the Earth Engine's application programming interface (API) with the Assets tab containing uploaded FAO WaPOR data, the code editor, the task tab and the direct visual feedback map.

2.4 Calculating water withdrawals for irrigation purposes with blue evaporation

According to FAO, water productivity is defined as the ratio of agricultural yield [kg] to the amount of water that has been used (or consumed) for its agricultural yield production [m^3] (FAO, n.d.). To make water productivity a useful performance indicator within the context of this research, it is important to define the term 'water consumption correctly'. Irrigation for agricultural purposes is considered the largest water-consuming sector in the world and has great potential to become more water-efficient. Rain-fed agriculture, however, does not influence the water balance within a catchment and can thus not improve its water efficiency. It is therefore only profitable to look at water productivity for irrigated agriculture.

Separating irrigated agriculture from rain-fed agriculture can be done by splitting the total evaporation into so-called green and blue water evaporation. Evaporation from green water is the part of the actual evaporation that is derived from rainfall that infiltrated into the soil, while evaporation from blue water is due to the use of human-made infrastructure such as pumps, with the purpose of irrigation. Blue water is withdrawn from rivers, reservoirs, lakes, and aquifers and is important to quantify as it directly influences the water availability of an area. Together, the sum of blue and green water consumption equals the total actual evaporation of a catchment. With blue water evaporation, the total water consumption [m^3] that was used for irrigation can subsequently be calculated. This can be used to then calculate the water productivity, but also provides insight into the current water management practices of a country.

The Budyko Curve explains the relationship between the climatic condition and water balance. It is physically based on the combination of annual energy and water balance with the assumption that the basin is in a steady state condition (Donohue, Roderick, & McVicar, 2007). The original Budyko Curve is shown in Figure 4.

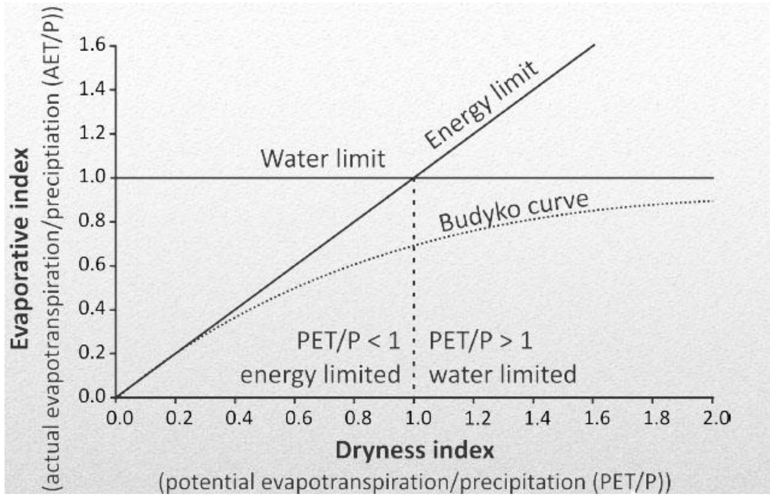


Figure 3: The Budyko Curve

In this research, the principle of the Budyko Curve has been applied to partition precipitation into evaporation and runoff (Budyko, 1974). The evaporation that follows from the Budyko Curve is per definition of green water consumption (Gerrits, Savenije, Veling, & Pfister, 2009). The additional amount of evaporation that is needed to reach the total amount of actual evaporation is ascribed to blue water consumption. This basic schematization is a standard ingredient taken from the Water Accounting Plus procedure that was developed at IHE Delft by Wim Bastiaanssen et al. (Bastiaanssen, W.G.M., Coerver, 2017).

In this schematization, actual evaporation is separated in evaporation due to irrigation (blue water) and due to rainfall (green water). Considering the fact that soil moisture that is stored in the root zone could also be a source of evaporation during dry months, 10% uncertainty (scaling factor α) is included to address the uncertainty in the empirical character of the Budyko Curve (Kwast, Bastiaanssen, Uyttendaele, & Hessels, 2016). The analytical derivation of the Budyko Curve based on rainfall characteristics and a simple evaporation model is presented with equations 1 - 4.

$$\varphi_t = \frac{\overline{E\theta_t}}{\overline{P}_t} \quad (1)$$

Where:

3 φ: Dryness index [-]

4 $\overline{E\theta_t}$: Averaged reference evaporation [mm/month]

5 $\overline{P_t}$: Averaged precipitation [mm/month]

$$\beta = \alpha \sqrt{\varphi_t * tanh\frac{1}{\varphi_t} * (1 - exp^{-\varphi_t})} \quad (2)$$

Where:

- β: Budyko Index [-]
- α: Scaling factor [-]

$$E_{G,t} = \min(\beta \cdot P_t, E_{A,t}) \quad (3)$$

Where:

- $E_{G,t}$: Green evaporation [mm/month]
- $E_{A,t}$: Actual evaporation [mm/month]

$$E_{B,t} = E_{A,t} - E_{G,t} \quad (4)$$

Where:

- $E_{B,t}$: Blue evaporation [mm/month]

For the above calculations, precipitation, actual evaporation, and reference evaporation data from WaPOR were used. Calculations were made on a monthly basis for each pixel, set to a scale of 100m*100m, with a script that made image processing feasible with the Google Earth Engine API. For this, reference evaporation and precipitation data first had to be converted from daily to monthly data. Actual evaporation subsequently had to be converted from a daily average that was produced for 10 days, into a total monthly actual evaporation.

Finally, the water consumption is calculated by multiplying the pixel size with the sum of the blue evaporation per month (equation 5). The outcome of these calculations provides a water consumption expressed in m^3/month.

$$Q_{irrigation,t} = \frac{E_{B,t}}{1000} * A \quad (5)$$

Where:

- $Q_{irrigation,t}$: Water consumption that originated from irrigation [m^3/month]
- A: Total irrigated area [m^2]

Assessing the impact of irrigation on water resources requires an estimate of the water effectively withdrawn for irrigation, i.e., the volume of water extracted from rivers, lakes, and aquifers for irrigation purposes. Irrigation water withdrawal normally far exceeds the net irrigation water requirement because of water lost in its distribution from its source to the crops. It should, therefore, be emphasized that the actual water withdrawals ought to be higher. With a typical irrigation efficiency of 60 to 70% (Howell, 2003), the total amount of water withdrawals could be computed with $Q_{irrigation}/0.65$ (Kwast et al., 2016).

2.5 Calculating Crop Water Productivity

Water productivity is calculated by dividing agricultural yield [kg] by the amount of water that was consumed for its production [m^3]. With WaPOR data, agricultural yield, as well as water consumption, can be computed on a pixel level with a resolution of 100m*100m. With two growing seasons and thus two agricultural yield productions per calendar year, water productivity can be determined with the same scale and spatiality.

To obtain agricultural yield, above ground biomass production (AGBP) is multiplied with a crop harvest index according to the crop that was identified with the phenology data (equation 6).

$$Y = AGBP * HI \quad (6)$$

Where:

- Y: Agricultural yield [kg]
- $AGBP$: Above Ground Biomass Production [kg]
- HI: Harvest Index [-]

The pixel values of the phenology data components are expressed in dekad numbers. The year that contains the Maximum of season (MOS) determines the year a growing season is attributed to (i.e., the target year) and correlates to the year and season of AGBP. As the crop calendar is determined from a three-year NDVI time series with the target year in the middle, dekad numbers range between 1 and 108 (3 x 36 = 108 dekads). Since it occurs in the target year, MOS has a value between 37 and 72. Start of season (SOS) pixel values must be smaller than 72, whilst end of season (EOS) pixel values must be larger than 36. 251 denotes either "out of season" or "no season" (if no growing season can be distinguished) (FAO, 2017).

To determine the specific growing season of a pixel, SOS and EOS phenology data are combined. By comparing the growing season of the pixel with literature from the FAO crop calendar, the crop type that is grown on a pixel, can this way be determined.

In chapter 2.4, blue water evaporation was used to compute the monthly water withdrawals used for irrigation. By multiplying blue water evaporation with the pixel size (100m*100m*), water consumption [m^3] can be calculated for each pixel. However, since the spatial scale of the phenology is expressed in dekad, blue water evaporation E_B should first be converted to a spatiality of dekad numbers, $E_{B,d}$. Subsequently, the summation of $E_{B,d}$ between the SOS and EOS dekad numbers provide the total blue water evaporation during the growing season of the crop. Multiplying the sum of the total blue water evaporation with the pixel size determines the total water consumption of a growing season. Equation 7 shows the calculation of the seasonal Crop Water Productivity (CWP):

$$CWP = \frac{Y}{\sum_{sos}^{EOS} E_{B,d} * 100 * 100 * 0.001} \quad (7)$$

Where:

- CWP: Seasonal Crop Water Productivity [kg/m^3/season]
- Y: Agricultural yield [kg]
- $E_{B,d}$: Blue water evaporation [mm/dekad]
- EOS: End of season [dekad]
- SOS: Start of season [dekad]

2.6 Assessing Crop Water Productivity

Producing more food from less water can be achieved by increasing CWP. A higher CWP results in either the same production from less water resources or a higher production from the same water resources. The latter would be a direct benefit for other local water users. Over the past decade, various research has been done on finding average CWP values for the main staple crops and finding overall reasons for the variability of CWP. It appears that most of the variability can be ascribed to climate, irrigation management, and soil nutrition management (e.g., fertilizing) (Zwart & Bastiaanssen, 2004). It is expected that large gains in CWP can be made with supplemental irrigation in dry areas with low seasonal precipitation, but the most promising conclusion is that that CWP can be increased significantly if irrigation is reduced (Zwart & Bastiaanssen, 2004).

Since many researches focus on gaining a global insight in the average values and reasons for variabilities of CWP, a full understanding of the spatial patterns by country or river basin has not yet been achieved. The latter is however greatly needed to be able to support local or national decisions on where to invest and what measures to take to make agriculture more water productive (Zwart, Bastiaanssen, de Fraiture, & Molden, 2010a). After all, regional scale governance ought to know the extent of CWP variability in their 'own' irrigation district and the magnitude of its gap towards optimization. Given that CWP variability can be attributed to both 'management' and 'physical' factors, the interest is to decouple the two factors to understand better the type of interventions that are required to raise the CWP value and bridge the gap (Bastiaanssen & Steduto, 2017). Therefore, this research will define local benchmark values of CWP within so-called agro-ecological zones (AEZ). Agro-ecological zoning, as applied in FAO studies, defines zones on the basis of combinations of soil, landform, and climatic characteristics. The particular parameters used in the definition focus on the climatic and edaphic requirements of crops and on the management systems under which the crops are grown (FAO Land and Water Division, 1996). Since each zone has a similar combination of constraints and potentials for land use, it can thus be effectively targeted with specific recommendations to improve CWP. By assessing the variability of CWP within an agro-ecological zone, the physical variability is masked, limiting the reason for variability in agricultural management. For this research, the agro-ecological zones are assumed to be according to the description in the FAO Crop Calendar database.

3. Country assessments

3.1 Egypt

Climate

Egypt has a hot desert climate according to the Köppen Climate Classification (BWh) (Britannica.com, 2018). The country is arid, with the exception of the Mediterranean coast that receives an average rainfall between 20-200 mm per year during the winter months.

Egypt has two seasons: a mild winter from November to April and a hot summer from May to October. Summer temperatures are extremely high, reaching 38 °C to 43 °C with extremes of 49 °C in the southern and western deserts. The northern areas on the Mediterranean coast are much cooler, with a maximum of about 32°C. The average daily temperatures range from 17 °C to 20 °C along the Mediterranean coast to more than 25°C in the South (Nour El-Din, 2013).

Water Use

The Nile supplies Egypt by about 95% of its total water needs, including water intensive irrigated agriculture. In 2010, 3 610 000 ha was equipped for full control irrigation (FAO, 2016a). With a growing population, Egypt is considered a water-stressed country. Moreover, climate change and competition on water resources among the riparian countries would put additional stress on Egypt's water resources (Nour El-Din, 2013).

Most of the Nile water is consumed by the agricultural sector (Abdelsalam, Aziz, & Agrama, 2014). However, reliable and recent literature on Egypt's water withdrawals is hard to find. FAO, in various publications and in its AQUASTAT database, provides data on the water withdrawals in 2000, which was estimated to be 68 BCM in total, divided between agriculture, municipalities, and industry. As can be seen in figure 5, the total water withdrawal in 2010 was estimated at 78 BCM in 2010, of which 67 BCM was used for agriculture (86 percent). It should be noted that more than 70% of the cultivated area in Egypt depends on low-efficiency surface irrigation systems, which cause high water losses, a decline in land productivity, waterlogging and salinity problems (Abdelsalam et al., 2014).

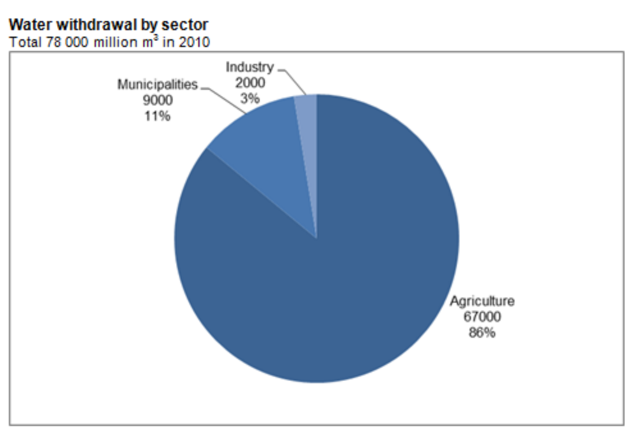


Figure 4: Water withdrawals by sector in Egypt (FAO, 2016a)

Agricultural production

There are three growing seasons in Egypt: Winter, from November until May; Summer, from April/May to October; and "Nili," from July/August to October. The main winter crops are wheat and temporary fodder, including clover or berseem. Minor winter crops are, amongst others, pulses, barley, and sugar beet. The main summer crops are maize, rice, and cotton; the latter being the most important Egyptian export crop (FAO, 2016a).

According to data that was published by FAO, Egypt's main irrigated crops are wheat, maize, rice, sorghum, and barley. In total, they consist of 47% of the total amount of irrigated crops, followed by temporary fodder, vegetables, and fruit. Cotton, pulses, sugarcane, potatoes, sugar beets, groundnut, and sesame, are also cropped under irrigation (FAO, 2016a).

For the assessment of water productivity, the three largest irrigated crops (wheat, maize, and rice) will be considered. Figure 6 shows an overview of the irrigated crops in Egypt according to the FAO WaPOR LCC. Considering that irrigated agriculture is practiced mostly in the delta and along the Nile banks (fig. 8), only the main agro-ecological zones are considered, which can be found in table 3. Table 4 gives an overview of the harvest calendar of the main crops for each of the agro-ecological zones.

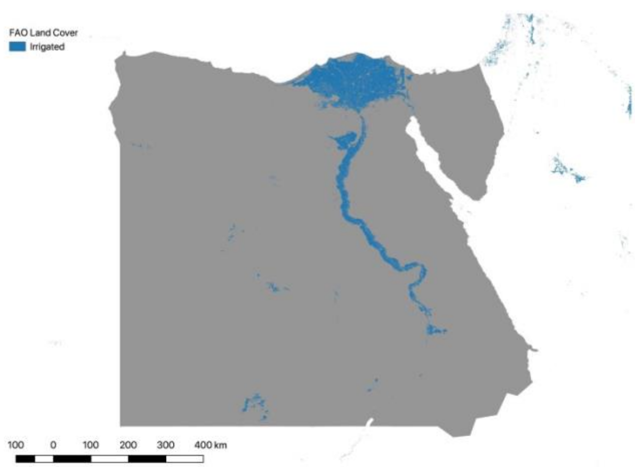


Figure 5: Overview of irrigated pixels in Egypt (FAO WaPOR LCC, 2018)

Table 3: Main Agro-ecological Zones of Egypt (FAO Crop Calendar, n.d.)

Agro-ecological zones	**Administrative areas**
Delta region	Cairo, Kalubia, Menofia, Sharqiea, Daqahlia, Gharbia, Kafer Elshiekh, Behiara, Alexandria, Demiat
Middle Egypt Region	Giza, Fayoum. Beni Sweaf and El-Minya
Upper Egypt Region	Assuit, Sohag, Qena, Luxor, and Aswan

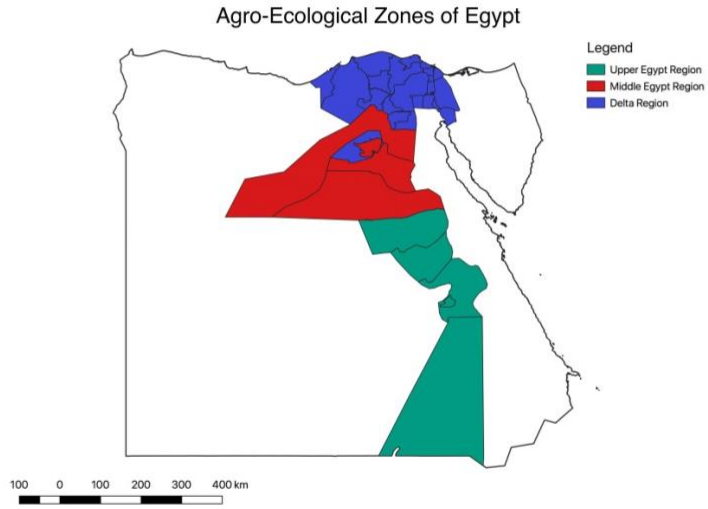


Figure 6: Main agro-ecological zones of Egypt, visualized

Table 4: Crop Calendar of Egypt's assessed crops for each main AEZ (FAO Crop Calendar, n.d.)

Crop	Agro-ecological zones	Planting onset	Planting end	Length of the cropping cycle	Harvesting onset	Harvesting end
Rice	Delta region	10/05	31/05	110-140 days	01/09	31/10
Rice	Delta region	25/04	15/05	120-160 days	01/09	31/10
Rice	Middle Egypt Region	20/04	10/05	120-150 days	01/08	30/09
Wheat	Middle Egypt Region	15/11	30/11	150-190 days	25/04	25/05
Wheat	Upper Egypt Region	15/11	30/11	150-190 days	25/04	25/05
Wheat	Delta region	15/11	30/11	150-190 days	25/04	25/05
Maize	Middle Egypt Region	20/04	31/05	120-150 days	01/09	31/10
Maize	Delta region	20/04	31/05	120-150 days	01/09	31/10

3.2 Sudan

Climate

Sudan has a tropical sub-continental climate with mean temperatures between 30 °C to 40 °C in summer and 10 °C to 25 °C in winter. The country extends from a desert climate in the north to a summer-rain climate throughout the center and a semi-dry climate in the south. Sudan can be divided into two zones according to the rainfall regime:

- Annual rainfall in the northern part of Sudan varies from 25 mm at the border with Egypt (fig. 10) to 200 mm towards the center of the country. The rainy season is limited to two to three months, while the rest of the year is virtually dry. Rainfall usually occurs in isolated showers, which vary in duration, location, and from year to year.
- In the south, annual rainfall reaches up to 700 mm and is concentrated in four months, from July to October. The average annual rainfall of that region is between 300 to 500 mm. Rainfed agriculture in Sudan is mainly practiced in this area, with a high variation in productivity from year to year due to the high variability in rainfall (FAO, 2015).

Water Use

As is the case with Egypt, limited data are available on the water withdrawals of Sudan. The total water withdrawals in former Sudan (comprising of South Sudan and current Sudan) was estimated at 27.6 BCM in 2005; agriculture is the largest consumer with 26.2 BCM. Estimates of Sudan in 2011 (fig. 8) were based on this data, keeping the same total for South Sudan and Sudan and considering that no essential changes have taken place and that almost all irrigation is located in Sudan. Water used in Sudan derives exclusively from surface water resources and mainly comprises of the Nile River system, as 72 percent of the country lies in the Nile Basin. In addition, Sudan has rainfall that varies in intensity throughout short periods over the years (FAO, 2015). The total net abstraction of water for irrigation from the Nile system is estimated at 13.3 BCM per year. The lion's share of this amount is taken by the Gezira with an estimated withdrawal of nearly 6.5 BCM followed by the New Halfa scheme with an abstraction of about 1.5 BCM (Nile Basin Initative, n.d.)

The total natural renewable water resources are equal to 103 BCM annually, while natural surface water outflow to Egypt is 84 BCM per year. According to an agreement between Egypt and former Sudan, Egypt is entitled 65.5 BCM, leaving Sudan with an accounted water withdrawal of 18.5 BCM per year. The total accounted for renewable water resources in Sudan are equal to 37.5 BCM per year (FAO, 2015).

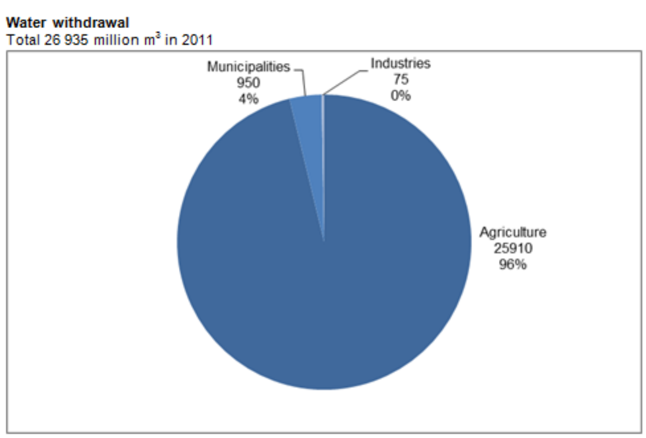


Figure 7: Water withdrawals by sector in Sudan (FAO, 2015)

Agricultural production

Most of the agricultural activities are concentrated in the southwest of the country, in the semi-arid dry savannah zone, through which the Blue Nile and the Atbara river flow. The growing season in the region is around four months. The major limiting factor is not the agricultural potential, but the short duration of the rainy season and the erratic distribution of rainfall during the growing period. This may result both in droughts and in floods, either localized due to torrential rainfall and runoff or widespread caused by the overflow of the Nile river and its tributaries (ARC, 2007). Therefore, agricultural production usually is only possible where there are irrigation systems or where there is natural and/or human-made harvesting of runoff water (FAO, 2015).

The Gezira Scheme is Sudan's oldest and largest gravity irrigation system, located between the Blue Nile and the White Nile and covers about 870 000 ha. Based on the irrigated cropping calendar, it was estimated that around 993 520 ha was irrigated in all of Sudan in 2011 (FAO, 2015).

Sorghum has become the main crop in terms of area in the Gezira scheme with an average of 35% of the total area planted, followed by wheat (25-30%). In addition to cereals (sorghum, wheat, and millet) the main irrigated crops are cotton, fodder, groundnuts, vegetables, and sugarcane. Figure 13 provides an overview of the irrigated crops in Sudan (FAO, 2015).

Water Productivity of Sorghum, Wheat, and Millet will be assessed as no information on sugarcane and cotton is available. An overview of the agro-ecological zones of Sudan can be found in table 5. The assessment will focus on the Flood and Basin Irrigated zones and the Desert and Semi-Desert Zone considering the fact that almost no irrigation is performed in the other Agro-Ecological Zones. Table 6 gives an overview of the harvest calendar of the main crops in the various agro-ecological zones (FAO, 2015).

Figure 8: Overview of irrigated pixels in Sudan (FAO WaPOR, 2018)

Table 5: Agro-ecological Zones of Sudan (FAO Crop Calendar, n.d.)

Agro-ecological zones	Administrative areas
Desert & Semi-desert Zone	Northern State, River Nile State, northern parts of North Darfur State & western parts of Red Sea State. In addition to Gadarif, Blue Nile, White Nile, Sinnar & Southern Kordofan States
Flood and Basin Irrigated Zones	Localities of Tokar, Qash, er-Rahad, Alsileim, Al-Afadh, Up-streams of Roseires, Sinnar & Jebel Awlia
Jebel Marra Zone	Parts of Northern, Southern & Western Darfur
Poor and Dense Savannah Zone	Most of Sudan, mainly in Kordofan, Darfur, White Nile & Blue Nile. North parts of Gadarif, Southern parts of Kassala & Kordofan containing Qash, Abu Habbil, and Tokar Deltas. Southern parts of Kordofan, Southern parts of Gadarif & Southern parts of Souther

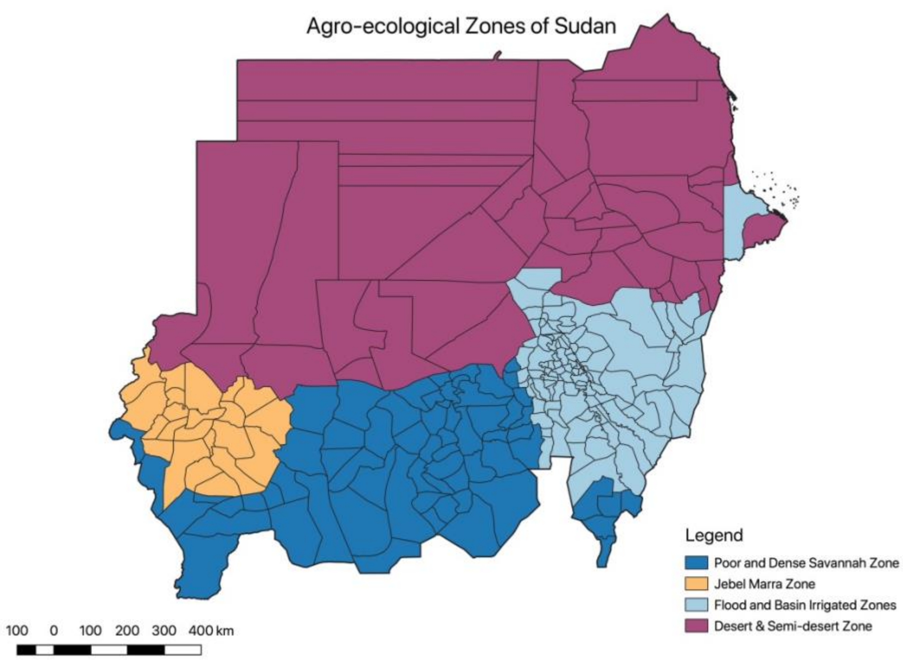


Figure 9: Agro-ecological zones of Sudan, visualized

Table 6: Crop Calendar of Sudan's assessed crops per AEZ (FAO Crop Calendar, n.d.)

Crop	Agro-ecological zones	Planting onset	Planting end	Length of the cropping cycle	Harvesting onset	Harvesting end
Millet	Desert & Semi-desert Zone	15/07	15/08	75-90 days	01/10	15/11
Millet	Flood and Basin Irrigated Zones	01/09	15/09	75-90 days	15/11	30/11
Wheat	Desert & Semi-desert Zone	15/09	15/10	100-120 days	25/12	25/01
Sorghum	Desert & Semi-desert Zone	15/06	25/08	90 days	15/10	25/11
Sorghum	Flood and Basin Irrigated Zones	01/12	15/12	75-100 days	15/02	25/03

3.3 Ethiopia

Climate

In Ethiopia, three climatic zones can be distinguished: a cool zone consisting of the central parts of the western and eastern section of the high plateaus, a temperate zone between 1500m and 2400m above sea level and the hot lowlands below 1500m. Mean annual temperatures vary from 7 to 12°C in the cool zone to over 25°C in the hot lowlands. Average annual rainfall for the country is 848 mm, varying from about 2000 mm in southwest Ethiopia to less than 100 mm in the Afar Lowlands in the northeast. Rainfall in Ethiopia is highly erratic, resulting in a very high risk of intra-seasonal dry spells and annual droughts (FAO, 2016b).

Water Use

Agriculture is by far the main water-withdrawing sector. Based on the total irrigated area, cropping pattern and calendar, annual agricultural water withdrawal was estimated at 9 BCM (fig. 11) (FAO, 2016b). Full-control irrigation was estimated at 658 340 ha in 2015. In addition, the area equipped for community spate irrigation was estimated at 200 000 ha, giving a total area equipped for irrigation of 858 340 ha. In addition, around 1 100 000 ha was estimated to be cultivated by small farmers using temporary structures. Thus, in total around 1, 958 000 ha is considered to be water managed throughout 2014 and 2015 (National Planning Commission, 2016).

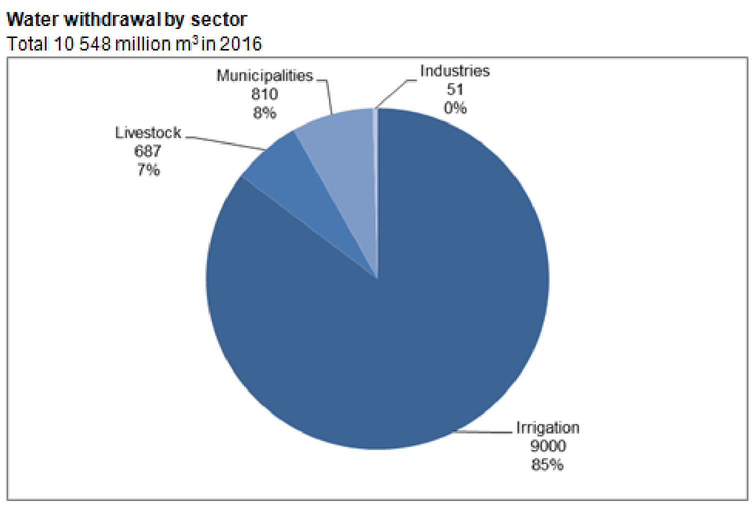


Figure 10: Water withdrawals by sector in Ethiopia (FAO, 2016b)

Agricultural production

Because Ethiopia's economy is mainly dependent on rain-fed agriculture, seasonal rainfall is incredibly decisive for the country's socio economic functioning and in particular, food production (Fekadu, 2015). Irrigated agriculture contributed to 9% of the agricultural GDP and 3.7% of the overall GDP in 2010. Over 1.2 million private holders practiced irrigated agriculture in 2014/15 in the main and small rainy season. Irrigated crops in medium and large-scale commercial farms are mostly cash crops, in particular, cotton and sugarcane. However, for the country as a whole, the main irrigated crops are maize, wheat, barley, and teff. Smallholder irrigators prefer subsistence crops rather than cash crops (MoA, 2011) and use irrigation to complement rainfed agriculture. However, during the dry season, they use full irrigation to get additional income (IWMI, 2009).

For the assessment of water productivity, maize and wheat will be considered. Figure 12 provides an overview of the irrigated crops in Ethiopia. The agro-ecological zones can be found in table 7. Table 8 gives an overview of the harvest calendar of the main crops for each of the agro-ecological zones.

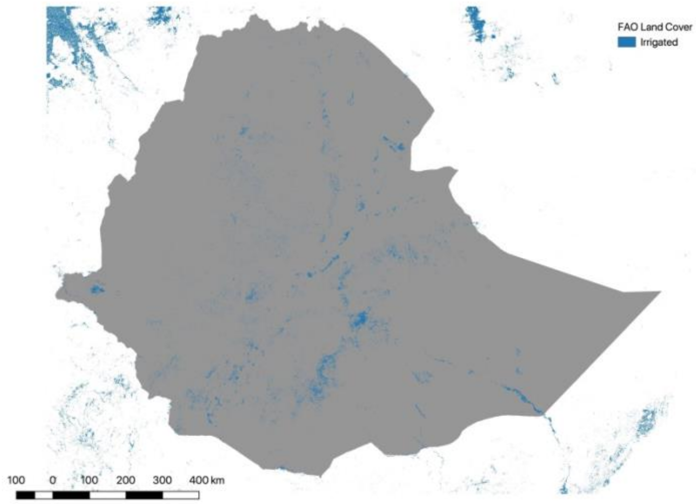


Figure 11: Overview of irrigated pixels in Ethiopia (FAO WaPOR, 2018)

Table 7: Agro-ecological Zones of Ethiopia (FAO Crop Calendar, n.d.)

Agro-ecological zone	Administrative areas
Arid (Hot to warm lowland plains and tepid to cool mid highlands)	The zone covers Afar region, Dire Dawa area, Alemaya, part of Somalia region and part of Negele borena in the Afar, Oromiya, Somaliya National Regional Stats and Dire Dawa Administrative Council.
Humid (hot to warm lowlands, tepid to cool mid highlands and cold to very cold humid sub-afroalpine to afroalpine)	Tepi, Jinka, Konso, Derashe, Masha, and Sidama zone in the Southern Nations and Nationalities People Regional state, Jima zone, Arsi zone (Ticho, Adelle, Mount Chilalo and Kaka), Bale zone (Dinsho and the surrounding area) in Oromiya National Regional Stat
Moist (hot to warm lowlands, tepid to cool moist mid highlands and cold to very cold sub-afroalpine to afroalpine)	Pawe in Benishangul Gumuz, West Afar marginal areas in Afar, South Omo and Segen valley in Southern Nations and Nationalities people Regional State, Teltelie, Borena Negele, Bale, Asebe Teferi, Bedisa, Alemaya, Kari and Tirma, West Showa, Abay gorge, Ab
Per-humid (hot to warm lowlands and tepid to cool mid highlands)	Mizan and Bench Maji zones in the Southern Nations and Nationalities People Regional State.
Semi-Arid (Hot to warm lowlands and tepid to cool mid highlands)	Situated in Humera area of western Tigray, Northeast of Alem Tena and around bulbula in the Central part of Oromiya, Metema and Abderafi in North Gonder, and Hamerbako area in the Tigray, Amhara and Southern Nations and Nationalities People Regional States.
Sub-humid (Hot-warm lowlands, tepid to cool mid-highlands and cold to very cold sub-afroalpine to afroalpine)	plains of Gambella and Benishangul Gumuz, bordering to Sudan in Beneshangul Gumuz and Gambella, Wollega, the gorge of Gibe, Gojeb, Dodola and Agarfa, Northern Harrargie and Batu Mountain in Oromiya and Kembata, Alaba and Tembaro area, Omo valley and Gurage zo
Sub-moist (hot to warm low lands, tepid to cool mid-highlands and cold to very cold sub-afroalpin to afroalpin)	North wollo and North Showa in the Amhara, Alamata, and Sheket in the Tigray, Asebot in Afar, Bale, Fike, West Harargie and Afdem in Oromiya National Regional States

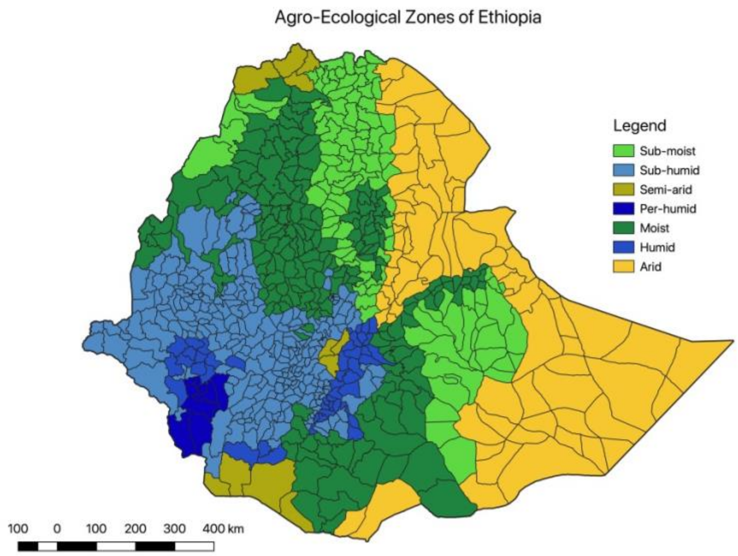


Figure 12: Agro-ecological zones of Ethiopia, visualized

Table 8: Crop Calendar of Ethiopia's assessed crops per AEZ (FAO Crop Calendar, n.d.)

Agro-ecological zones	Crop	Additional Information	Planting period - onset	Planting period - end	Length of the cropping cycle	Harvesting period - onset	Harvesting period - end
Arid	Maize		01/01	31/12	105-120 days	01/01	31/12
Arid	Wheat, common		01/01	31/12	104-170 days	01/01	31/12
Humid	Maize		20/02	30/05	105-163 days	10/06	30/09
Humid	Wheat, common	First season	12/02	30/05	104-170 days	10/06	15/08
Humid	Wheat, common	Second season	12/06	31/08	104-170 days	25/09	20/12
Humid	Wheat, durum	First season	12/02	30/05	110-160 days	10/06	15/08
Humid	Wheat, durum	Second season	25/05	30/06	110-160 days	25/09	20/12
Moist	Maize		10/03	10/06	105-163 days	01/07	31/10
Moist	Wheat, common	First season	10/03	20/04	104-170 days	10/06	31/07
Moist	Wheat, common	Second season	15/08	30/09	104-170 days	15/12	25/02
Moist	Wheat, durum	First season	10/03	20/04	110-160 days	10/06	31/07
Moist	Wheat, durum	Second season	15/08	30/09	110-160 days	15/12	25/02
Per-humid	Maize		10/02	30/04	105-163 days	10/06	30/09
Semi-Arid	Maize	Irrigated	01/01	31/12	105-163 days	01/01	31/12
Sub-humid	Maize		25/02	30/05	105-163 days	01/08	31/10

Sub-humid	Wheat, common	First season	20/02	30/04	104-170 days	25/05	31/07
Sub-humid	Wheat, common	Second season	07/06	25/08	104-170 days	12/10	20/12
Sub-humid	Wheat, durum	First season	20/02	20/04	110-160 days	10/06	31/07
Sub-humid	Wheat, durum	Second season	07/06	25/08	110-160 days	12/10	15/01
Sub-moist	Maize		01/05	12/06	105-163 days	01/09	30/11
Sub-moist	Wheat, common /durum	First season	07/06	25/07	104-170 days	25/09	15/12
Sub-moist	Wheat, common /durum	Second season	15/03	30/04	104-170 days	10/06	31/07

4. Results

4.1 Evaporation & Rainfall

To gain a good insight into the data, first, a comparison is made between actual evaporation, the calculated blue evaporation, and precipitation. The three type of data products is expressed in mm per month and visualized in a bar chart. A chart is made for each country and includes a comparison on country level, as well as selected Agro-Ecological Zones.

Initially, only the mean averaged values were used to determine the monthly evaporation data. This was done for all the pixels that contained blue evaporation (unmasked), as well as by only looking at the irrigated pixels as identified by the FAO Land Cover Classification (LCC Mask.) However, the average numbers were low, likely to be caused by the fact that many low-value pixels (noise) are considered, thus taking down the mean average. After reviewing the data's histogram, mode[1] seemed to be a good alternative and was used as an extra method to determine monthly evaporation. It must be noted that when using mode, the lower peak values were masked as they can be considered noise.

Egypt

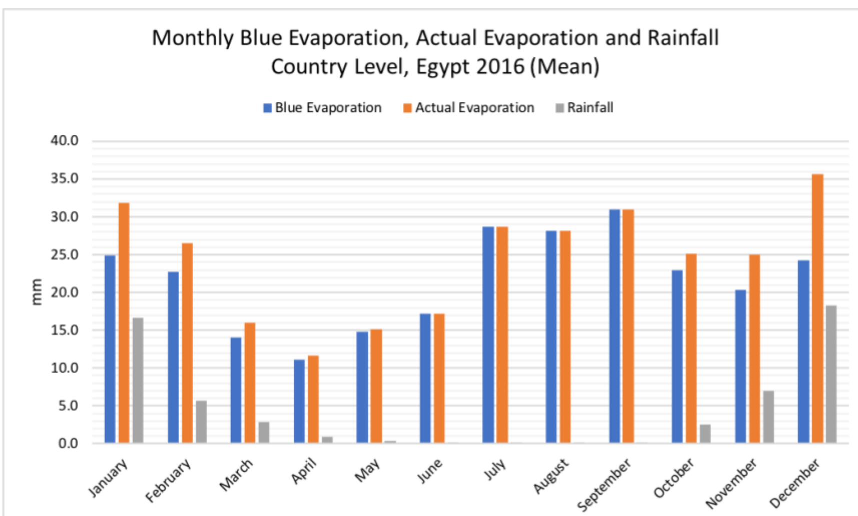


Figure 13: Mean averaged monthly evaporation/precipitation for Egypt, 2016 (unmasked)

[1] Mode is the value that occurs most often.

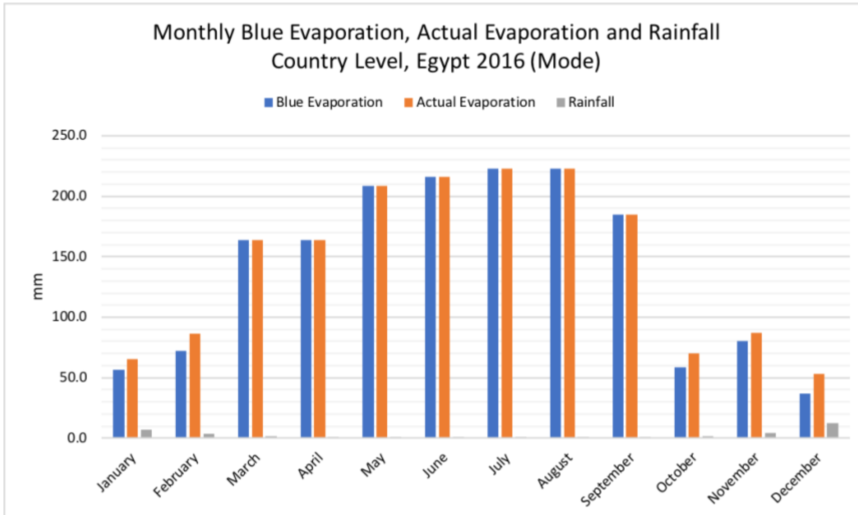


Figure 14: Mode averaged monthly evaporation/precipitation for Egypt (Mask <30), 2016

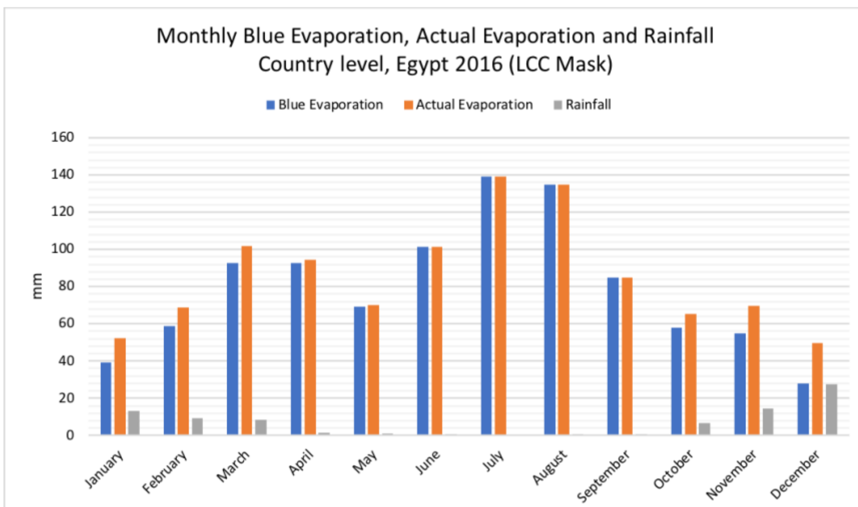


Figure 15: Mean averaged monthly evaporation/precipitation for Egypt, 2016 (LCC Mask)

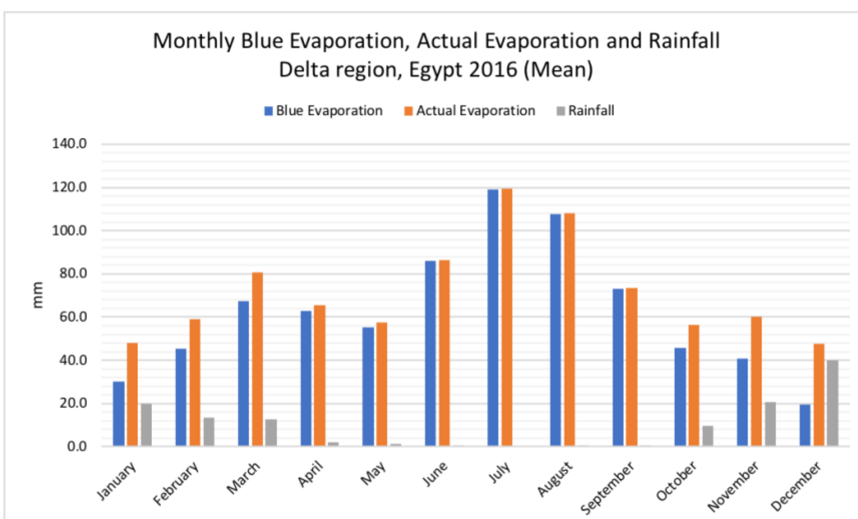


Figure 16: Mean averaged monthly evaporation/precipitation for the Delta region, Egypt 2016 (unmasked)

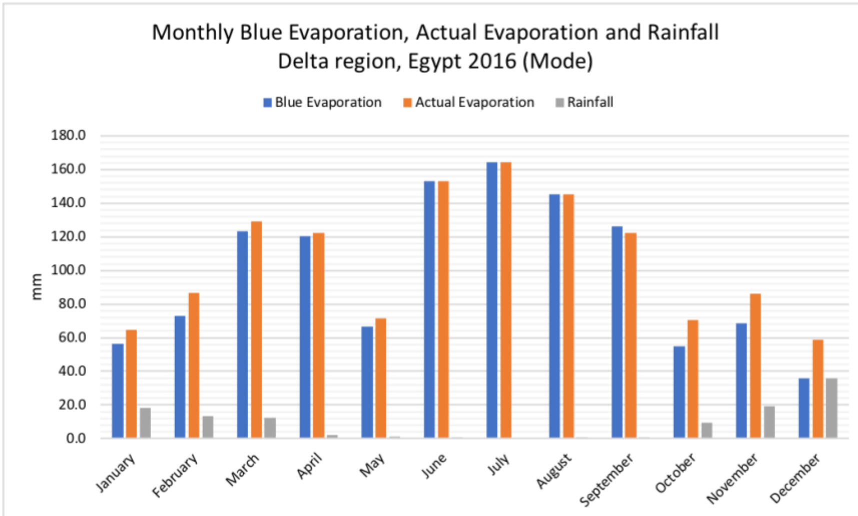


Figure 17: Mode averaged monthly evaporation/precipitation for the Delta region (Mask <30), Egypt 2016

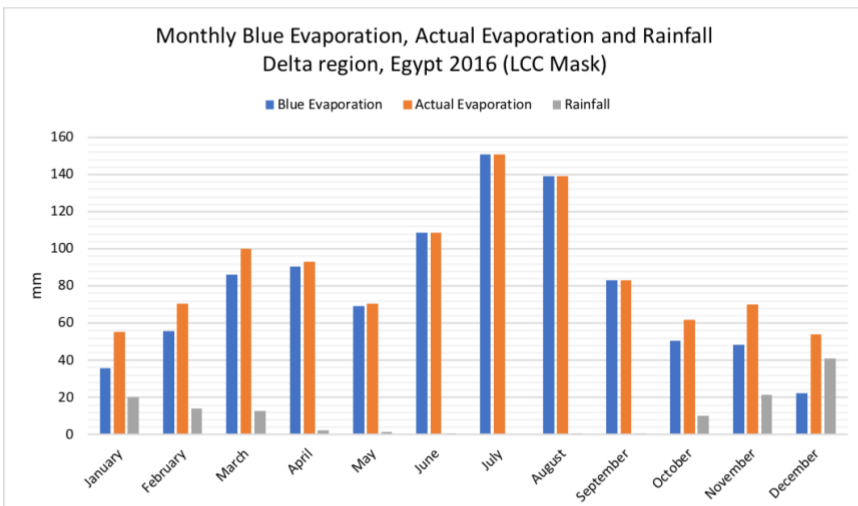


Figure 18: Mean averaged monthly evaporation/precipitation for the Delta region, Egypt 2016 (LCC Mask)

Sudan

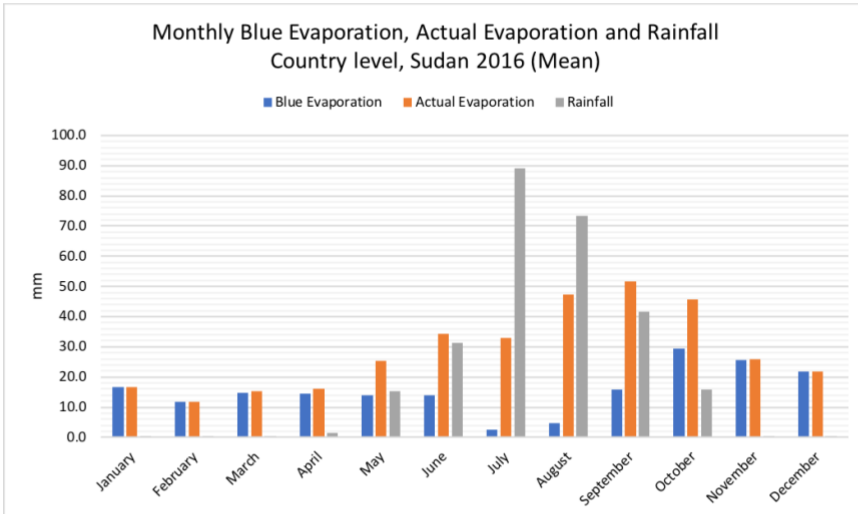


Figure 19: Mean averaged monthly evaporation/precipitation for Sudan, 2016 (unmasked)

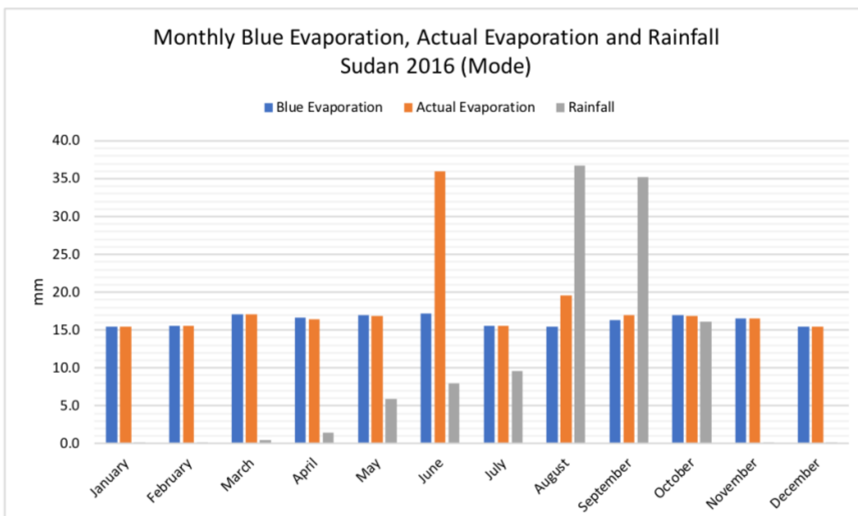


Figure 20: Mode averaged monthly evaporation/precipitation for Sudan (Mask <15), 2016

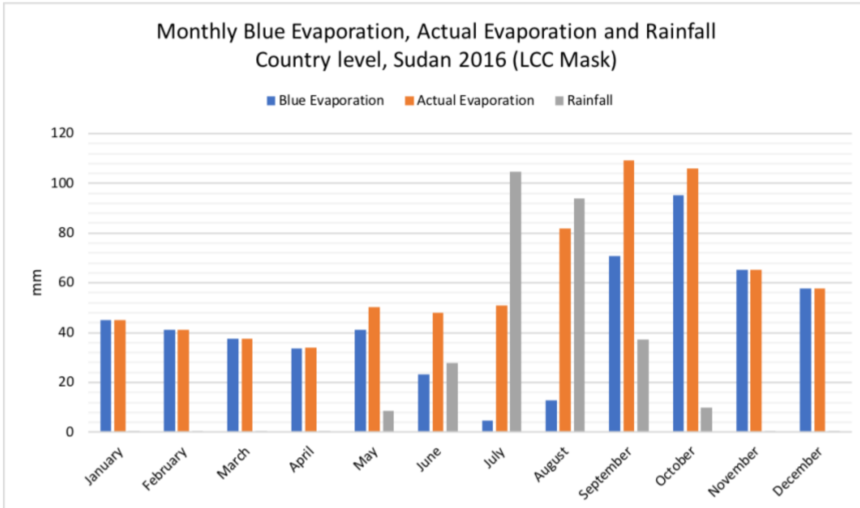


Figure 21: Mean averaged monthly evaporation/precipitation for Sudan, 2016 (LCC Mask)

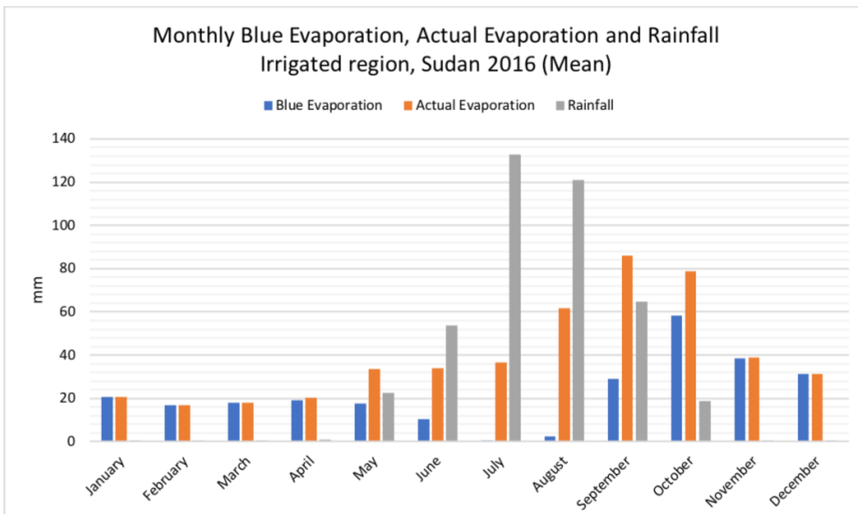


Figure 22: Mean averaged monthly evaporation/precipitation for the Irrigation Zone, Sudan, 2016 (unmasked)

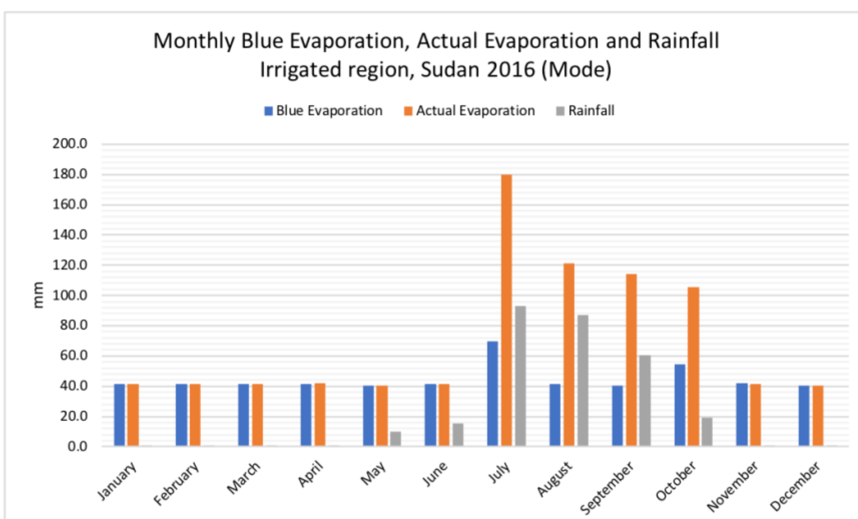


Figure 23: Mode averaged monthly evaporation/precipitation for the Irrigation Zone (mask <40), Sudan, 2016

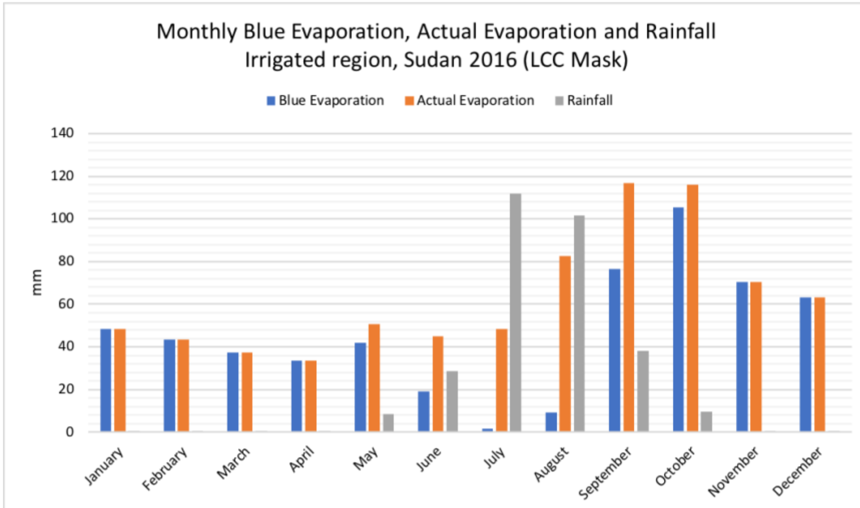


Figure 24: Mean averaged monthly evaporation/precipitation for the irrigated region, Sudan 2016 (LCC Mask)

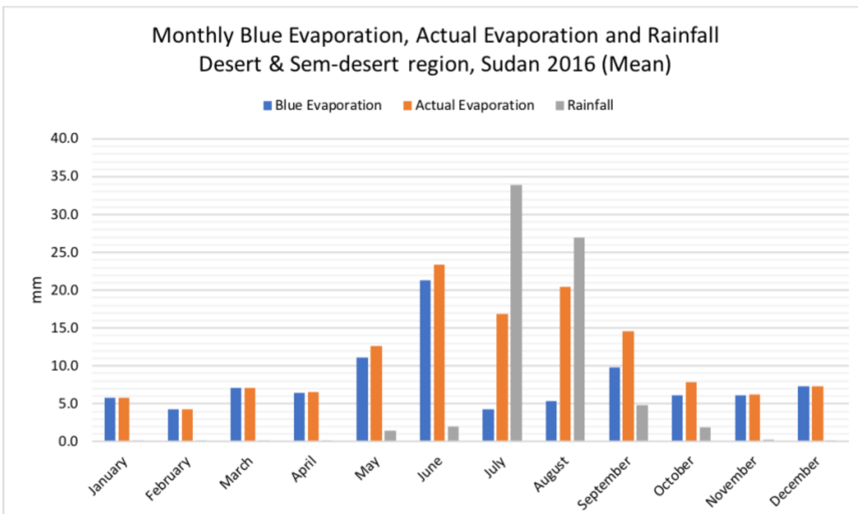


Figure 25: Mean averaged monthly evaporation/precipitation for the Desert & Semi-desert Zone, Sudan, 2016 (unmasked)

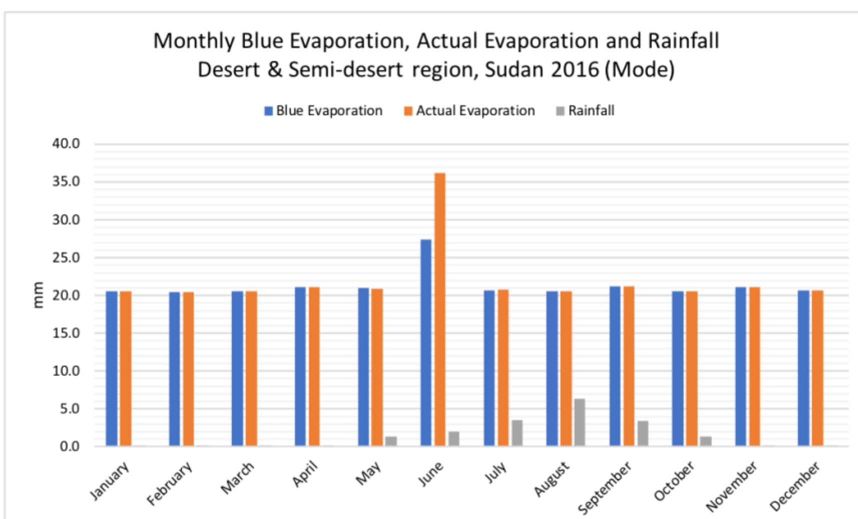


Figure 26: Mode averaged monthly evaporation/precipitation for the Desert & Semi-desert Zone (Mask <20), Sudan, 2016

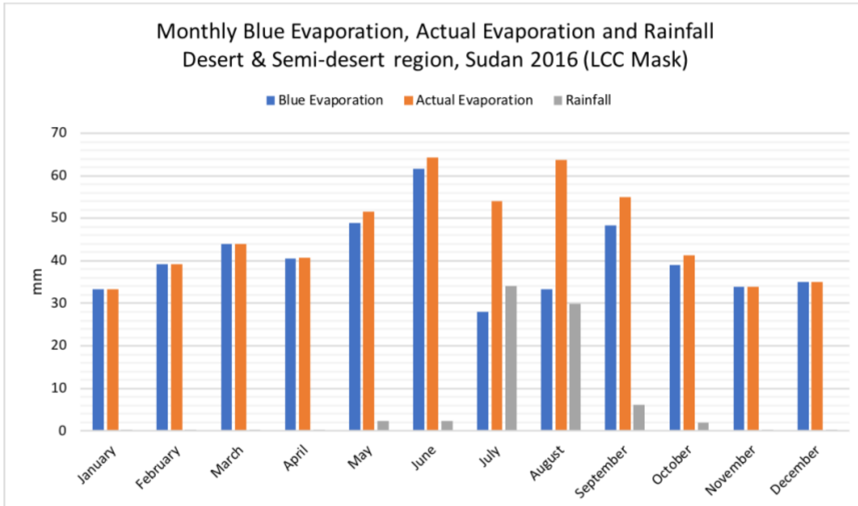


Figure 27: Mean averaged monthly evaporation/precipitation for the Desert & Semi-desert region, Sudan 2016 (LCC Mask)

Ethiopia

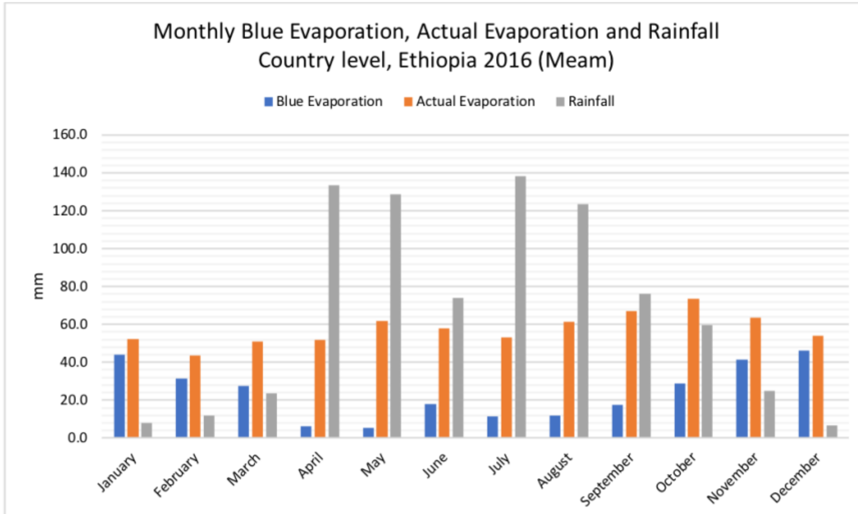


Figure 28: Mean averaged monthly evaporation/precipitation for Ethiopia, 2016 (unmasked)

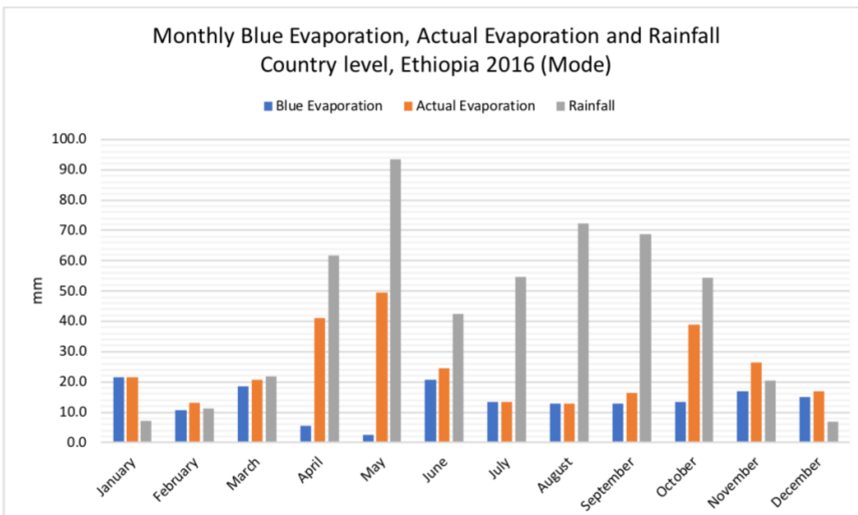


Figure 29: Mode averaged monthly evaporation/precipitation for Ethiopia (Mask <2), 2016

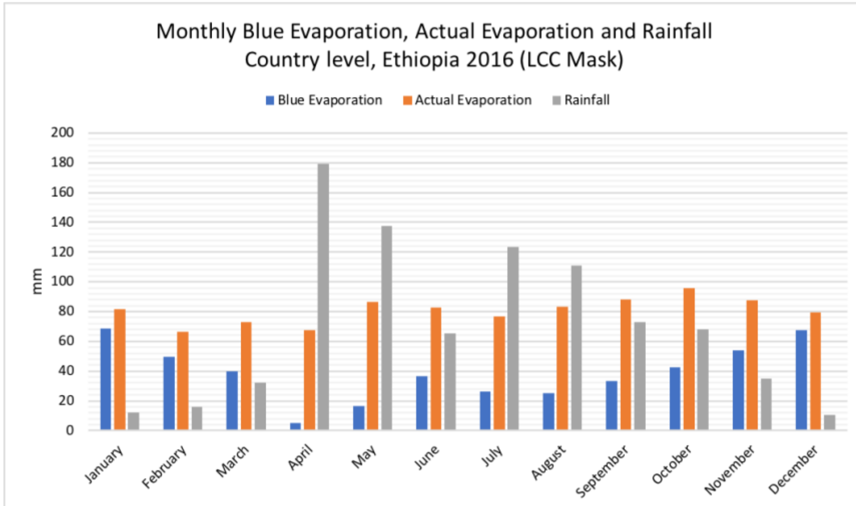


Figure 30: Mean averaged monthly evaporation/precipitation for Ethiopia, 2016 (LCC Mask)

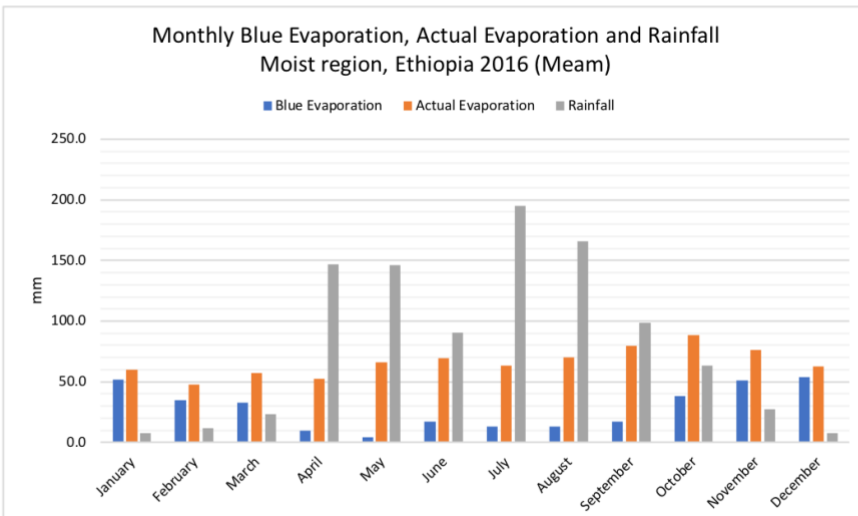


Figure 31: Mean averaged monthly evaporation/precipitation for the Moist region, Ethiopia, 2016 (unmasked)

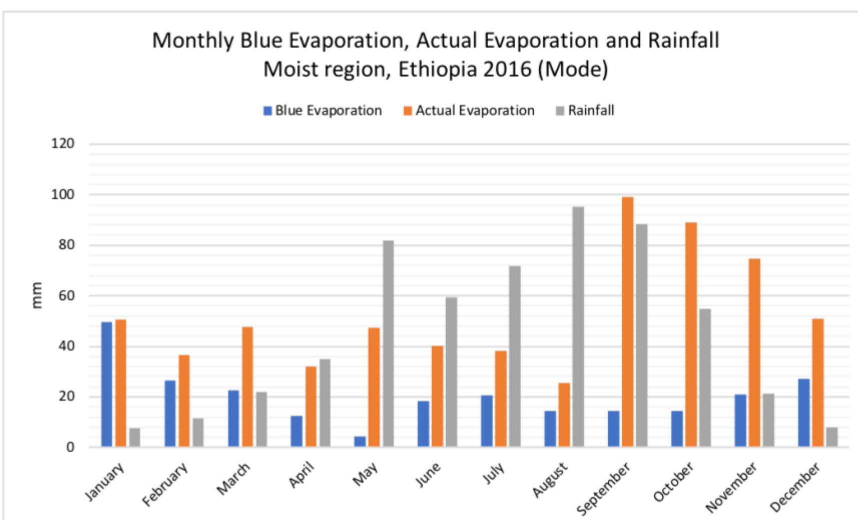


Figure 32: Mode averaged monthly evaporation/precipitation for the Moist region (Mask <2), Ethiopia, 2016

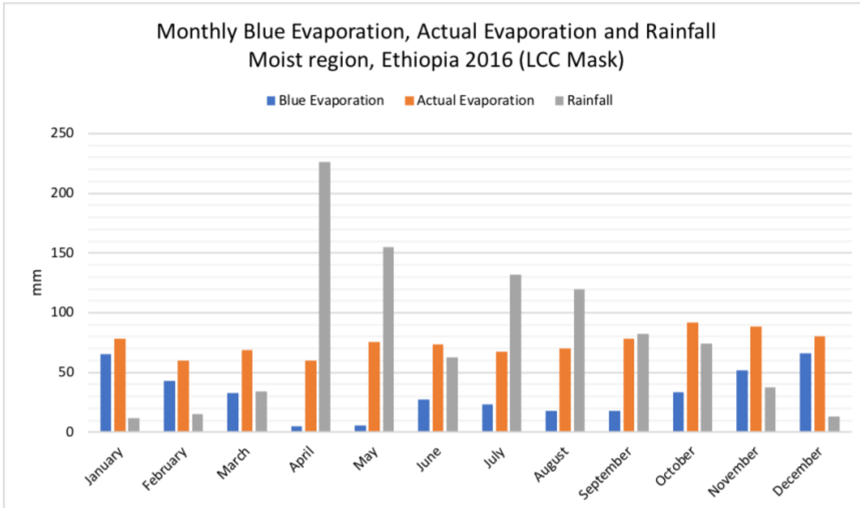


Figure 33: Mean averaged monthly evaporation/precipitation for the Moist region, Ethiopia 2016 (LCC Mask)

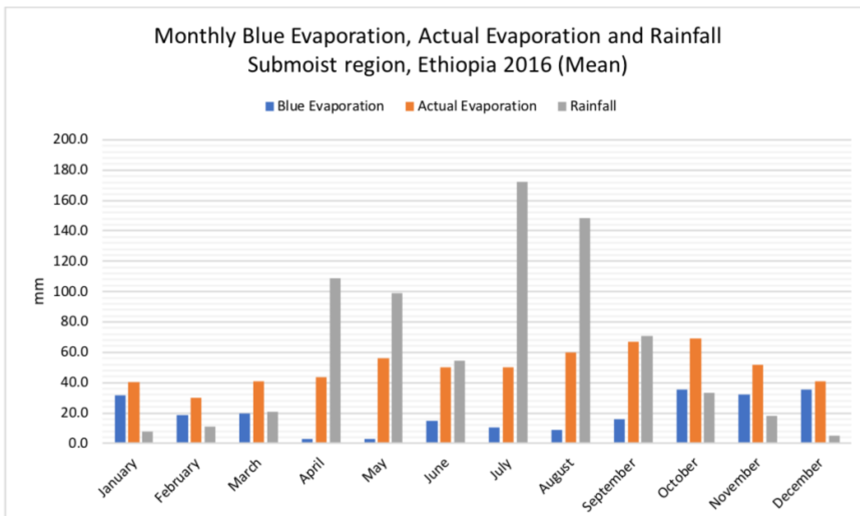


Figure 34: Mean averaged monthly evaporation/precipitation for the Submoist region, Ethiopia, 2016 (unmasked)

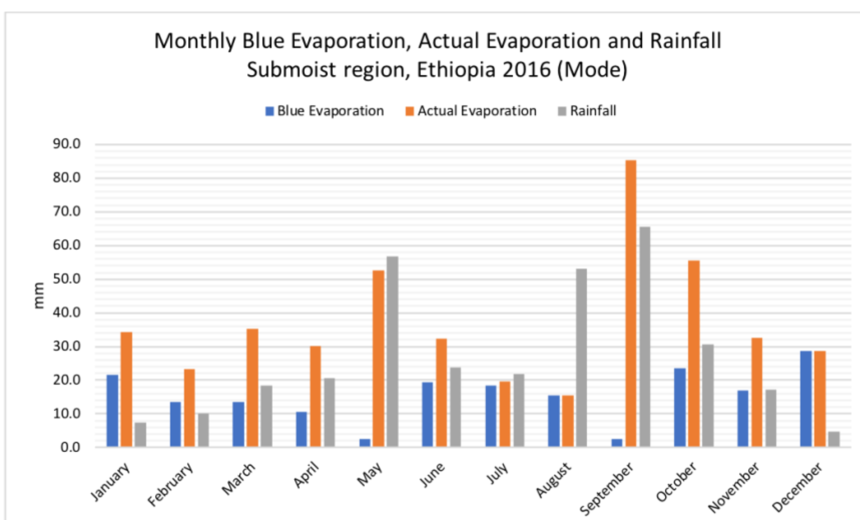


Figure 35: Mode averaged monthly evaporation/precipitation for the Submoist region (Mask <2), Ethiopia, 2016

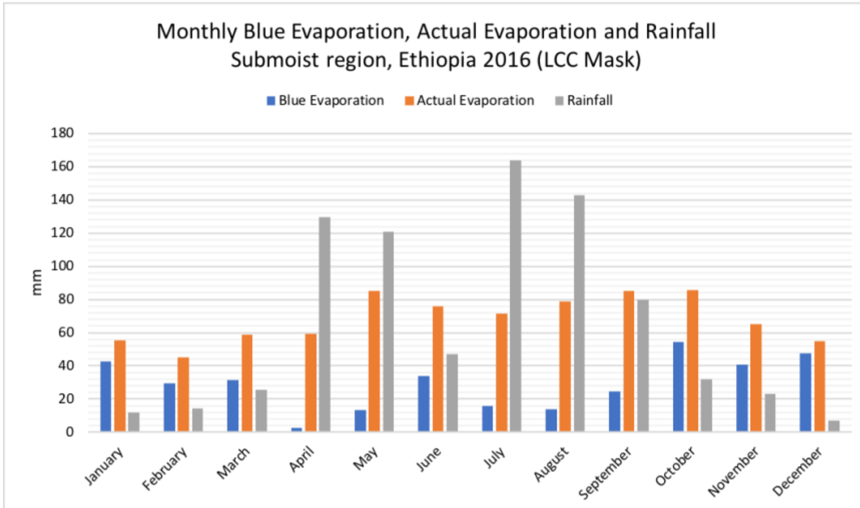


Figure 36: Mean averaged monthly evaporation/precipitation for the Submoist region, Ethiopia 2016 (LCC Mask)

4.2 Water withdrawals for irrigation

To determine monthly water withdrawals for irrigation purposes, three different methods are used:

- Unmasked: all pixels that contain values of blue evaporation (>0) are summed up and multiplied with the pixel size (100*100).
- FAO Land Cover Classification Mask: In addition to the method used to determine the unmasked water withdrawals, the FAO Land Cover Classification is used as an additional mask. In doing so, the only pixels that are contributing to determine the total withdrawal of the area are the pixels that are identified as 'irrigated.'
- Modified Mask: In addition to the method used to determine the unmasked water withdrawals, an additional mask is used in an attempt to filter out the noise. The masks correspond to the mask used to determine the monthly mode averaged evaporation for each country.

Egypt

Table 9: Monthly water withdrawals for irrigation purposes, Egypt 2016 (No Mask)

	Egypt (BCM)	Delta region (BCM)	Middle Egypt region (BCM)	Upper Egypt region (BCM)
January	2.6	1.0	0.3	1.0
February	3.7	1.5	0.5	1.3
March	6.3	2.3	0.8	1.9
April	7.3	2.6	0.9	1.9
May	6.5	2.1	0.6	2.0
June	7.8	3.1	0.8	2.1
July	9.1	4.1	0.9	2.4
August	8.9	3.8	0.8	2.6
September	5.9	2.4	0.5	2.0
October	4.6	1.5	0.5	1.8
November	3.9	1.3	0.5	1.4
December	2.2	0.6	0.2	1.0
Total (Annual)	**68.8**	**26.3**	**7.2**	**21.3**

Table 10: Monthly water withdrawals for irrigation purposes, Egypt 2016 (FAO Land Cover Classification Mask)

	Egypt (BCM)	Delta region (BCM)	Middle Egypt region (BCM)	Upper Egypt region (BCM)
January	1.4	0.8	0.3	0.3
February	2.1	1.3	0.4	0.4
March	3.3	1.9	0.6	0.7
April	3.3	2.0	0.6	0.6
May	2.5	1.6	0.5	0.4
June	3.6	2.5	0.6	0.5
July	4.9	3.4	0.8	0.7
August	4.8	3.1	0.7	0.9
September	3.0	1.9	0.4	0.7
October	2.0	1.1	0.4	0.5
November	1.9	1.1	0.4	0.4
December	1.0	0.5	0.2	0.3
Total (Annual)	**33.8**	**21.2**	**5.9**	**6.3**

Table 11: Monthly water withdrawals for irrigation purposes, Egypt 2016 (Modified Mask)

	Egypt (BCM)	Delta region (BCM)	Middle Egypt region (BCM)	Upper Egypt region (BCM)
January	2.3	0.9	0.3	0.9
February	3.2	1.4	0.4	1.2
March	4.9	2.2	0.7	1.6
April	5.1	2.5	0.7	1.6
May	4.5	2.0	0.5	1.6
June	5.8	3.0	0.7	1.7
July	7.3	4.0	0.9	2.0
August	7.1	3.7	0.8	2.2
September	4.9	2.3	0.5	1.8
October	3.5	1.4	0.5	1.4
November	3.2	1.2	0.4	1.2
December	1.8	0.4	0.2	1.0
Total (Annual)	**53.4**	**25.0**	**6.6**	**18.2**

Sudan

Table 12: Monthly water withdrawals for irrigation purposes, Sudan 2016 (No Mask)

	Sudan (BCM)	Irrigated region (BCM)	Desert & Semi-desert region (BCM)	Jebel Marra region (BCM)
January	13.7	4.3	1.1	0.9
February	13.6	3.8	2.1	1.0
March	20.0	4.1	4.8	1.6
April	18.3	4.4	3.9	1.2
May	19.2	3.9	7.9	1.5
June	19.1	2.3	15.2	0.4
July	3.2	0.1	3.0	0.0
August	6.2	0.6	3.8	0.2
September	21.5	6.5	6.8	0.7
October	33.5	13.2	2.9	1.8
November	26.1	8.5	2.2	1.6
December	16.7	6.3	1.0	1.1
Total (Annual)	**211.1**	**58.1**	**54.8**	**11.9**

Table 13: Monthly water withdrawals for irrigation purposes, Sudan 2016 (FAO WaPOR Land Cover Classification Mask)

	Sudan (BCM)	Irrigated region (BCM)	Desert & Semi-desert region (BCM)	Jebel Marra region (BCM)
January	1.39	1.22	0.12	0.02
February	1.28	1.09	0.14	0.02
March	1.16	0.94	0.16	0.03
April	1.05	0.85	0.15	0.02
May	1.28	1.05	0.18	0.03
June	0.72	0.48	0.22	0.02
July	0.14	0.04	0.10	0.00
August	0.40	0.24	0.12	0.02
September	2.21	1.93	0.17	0.04
October	2.96	2.66	0.14	0.05
November	2.03	1.78	0.12	0.03
December	1.80	1.59	0.12	0.02
Total (Annual)	**16.4**	**13.9**	**1.7**	**0.3**

Table 14: Monthly water withdrawals for irrigation purposes, Sudan 2016 (Modified Mask)

	Sudan (BCM)	**Irrigated region (BCM)**	**Desert & Semi-desert region (BCM)**	**Jebel Marra region (BCM)**
January	2.23	1.42	0.23	0.02
February	1.59	1.19	0.27	0.01
March	1.41	0.94	0.36	0.01
April	1.13	0.63	0.35	0.00
May	1.24	0.75	0.45	0.01
June	0.98	0.47	0.50	0.00
July	0.44	0.07	0.37	0.00
August	0.53	0.13	0.37	0.01
September	4.69	3.15	0.42	0.09
October	18.71	10.03	0.33	0.57
November	10.64	4.18	0.26	0.12
December	3.71	2.18	0.27	0.04
Total (Annual)	**47.3**	**25.1**	**4.2**	**0.9**

Ethiopia

Table 15: Monthly water withdrawals for irrigation purposes, Ethiopia 2016 (No Mask)

	Ethiopia (BCM)	Moist (BCM)	Submoist (BCM)	Humid (BCM)	Subhumid (BCM)
January	49.8	14.5	5.9	2.7	15.4
February	34.9	9.7	3.5	2.5	13.1
March	30.9	9.2	3.7	1.5	8.1
April	7.0	2.7	0.6	0.4	2.9
May	5.9	1.2	0.6	0.4	1.1
June	20.4	4.7	2.8	0.4	1.9
July	13.0	3.6	2.0	0.5	1.7
August	13.6	3.7	1.7	0.6	2.9
September	20.0	4.8	2.9	0.8	5.6
October	32.2	10.7	6.6	0.9	8.0
November	46.1	14.3	5.9	1.9	17.3
December	51.7	15.1	6.6	2.7	17.6
Total (Annual)	**325.4**	**94.1**	**42.7**	**15.3**	**95.6**

Table 16: Monthly water withdrawals for irrigation purposes, Ethiopia 2016 (FAO Land Cover Classification Mask)

	Ethiopia (BCM)	Moist (BCM)	Submoist (BCM)	Humid (BCM)	Subhumid (BCM)
January	1.29	0.5	0.10	0.08	0.3
February	0.93	0.3	0.07	0.06	0.3
March	0.75	0.3	0.08	0.03	0.2
April	0.10	0.0	0.01	0.00	0.0
May	0.31	0.0	0.03	0.01	0.0
June	0.69	0.2	0.08	0.03	0.1
July	0.49	0.2	0.04	0.03	0.1
August	0.48	0.1	0.03	0.03	0.1
September	0.62	0.1	0.06	0.03	0.2
October	0.80	0.3	0.13	0.02	0.2
November	1.02	0.4	0.10	0.03	0.3
December	1.28	0.5	0.11	0.05	0.4
Total (Annual)	**8.8**	**3.0**	**0.8**	**0.4**	**2.1**

Table 17: Monthly water withdrawals for irrigation purposes, Ethiopia 2016 (Modified Mask)

	Ethiopia (BCM)	Moist (BCM)	Submoist (BCM)	Humid (BCM)	Subhumid (BCM)
January	49.8	14.5	5.9	2.7	15.4
February	34.9	9.7	3.5	2.5	13.1
March	30.9	9.2	3.7	1.5	8.1
April	7.0	2.7	0.6	0.4	2.9
May	5.9	1.2	0.6	0.4	1.1
June	20.4	4.7	2.8	0.4	1.9
July	13.0	3.6	2.0	0.5	1.7
August	13.6	3.7	1.7	0.6	2.9
September	20.0	4.8	2.9	0.8	5.6
October	32.2	10.7	6.6	0.9	8.0
November	46.1	14.3	5.9	1.9	17.3
December	51.7	15.1	6.6	2.7	17.6
Total (Annual)	**325.4**	**94.1**	**42.7**	**15.3**	**95.6**

4.3 Crop Water Productivity

Harvest Indices of the following crops can be found in table 18 and are used to calculate the agricultural yield from the above ground biomass production.

Table 18: Harvest Indices of assessed crops for water productivity ("Harvest index | Plants in Action," n.d.)

Crop	Harvest Index
Maize/Sorghum/Millet	0.52
Rice	0.50
Wheat	0.55

Egypt

Wheat

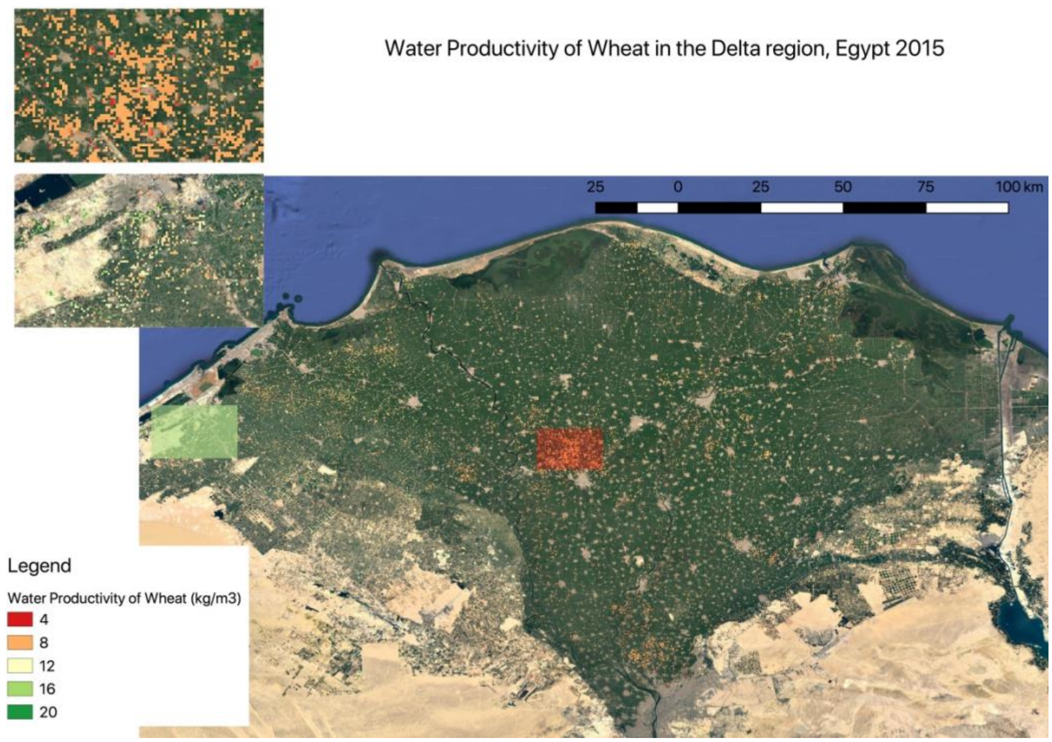


Figure 37: Water Productivity of Wheat in the Delta region, Egypt 2015 - Satellite view

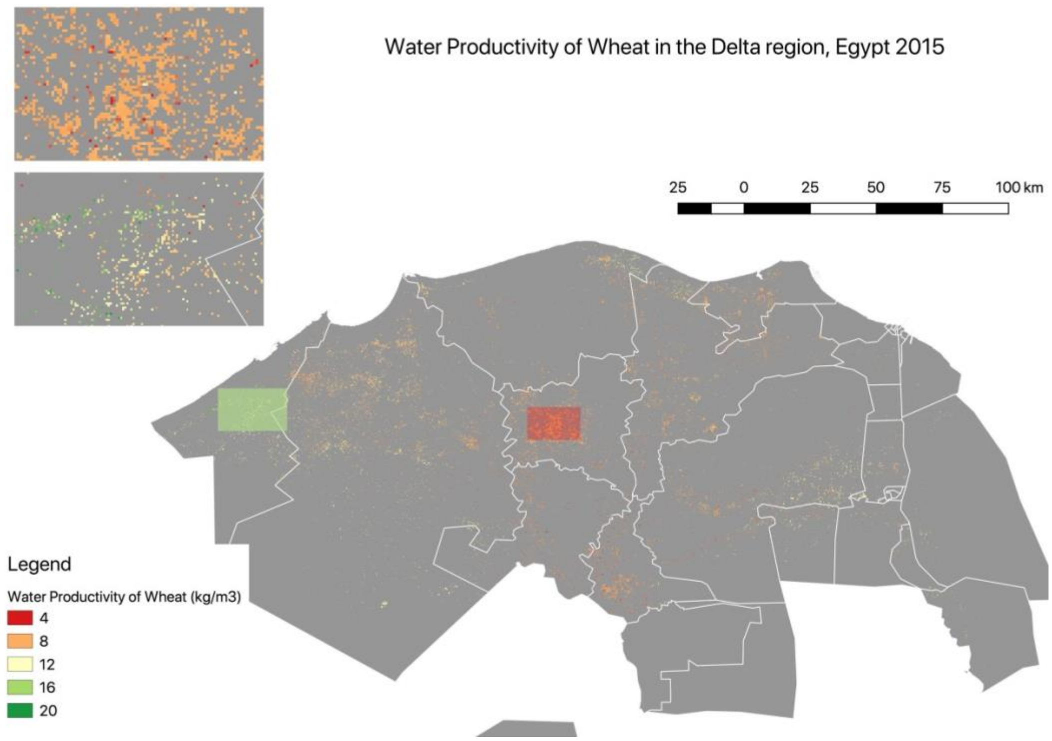


Figure 38: Water Productivity of Wheat in the Delta region, Egypt 2015

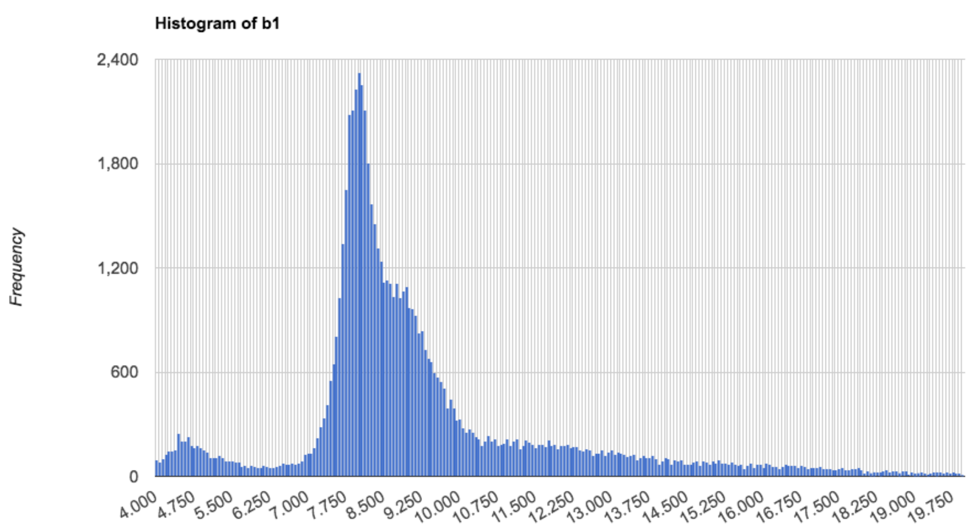


Figure 39: Water Productivity Histogram of Wheat in the Delta region, Egypt 2015

Mode average: 7.7 – 8.2 kg/m^3

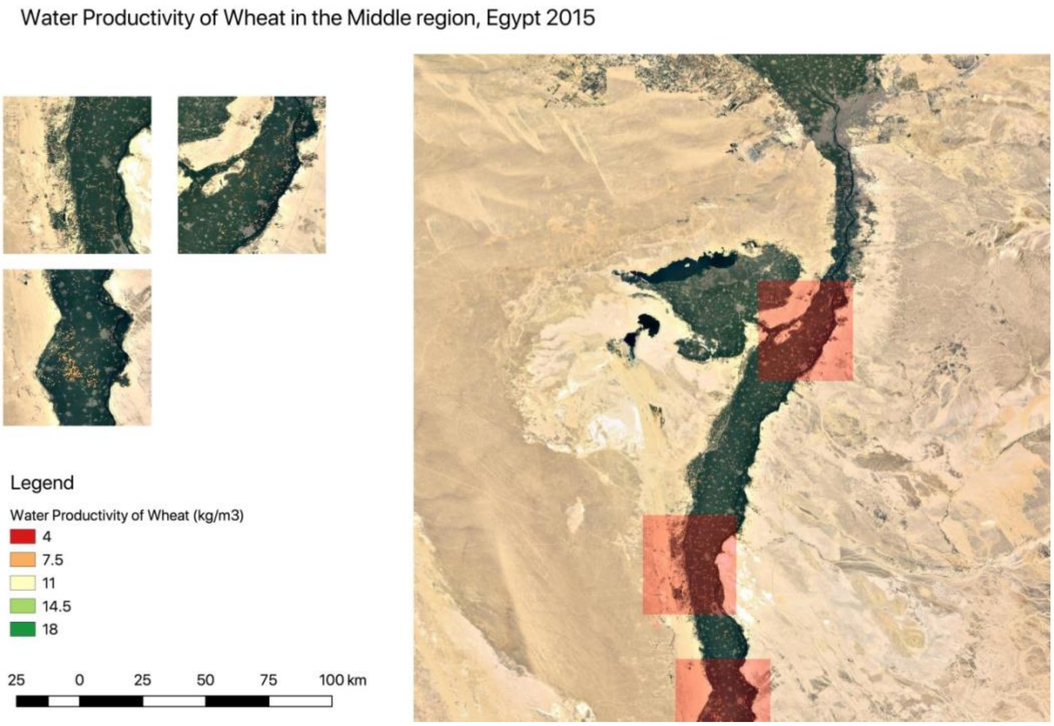


Figure 40: Water Productivity of Wheat in the Middle region, Egypt 2015 - Satellite view

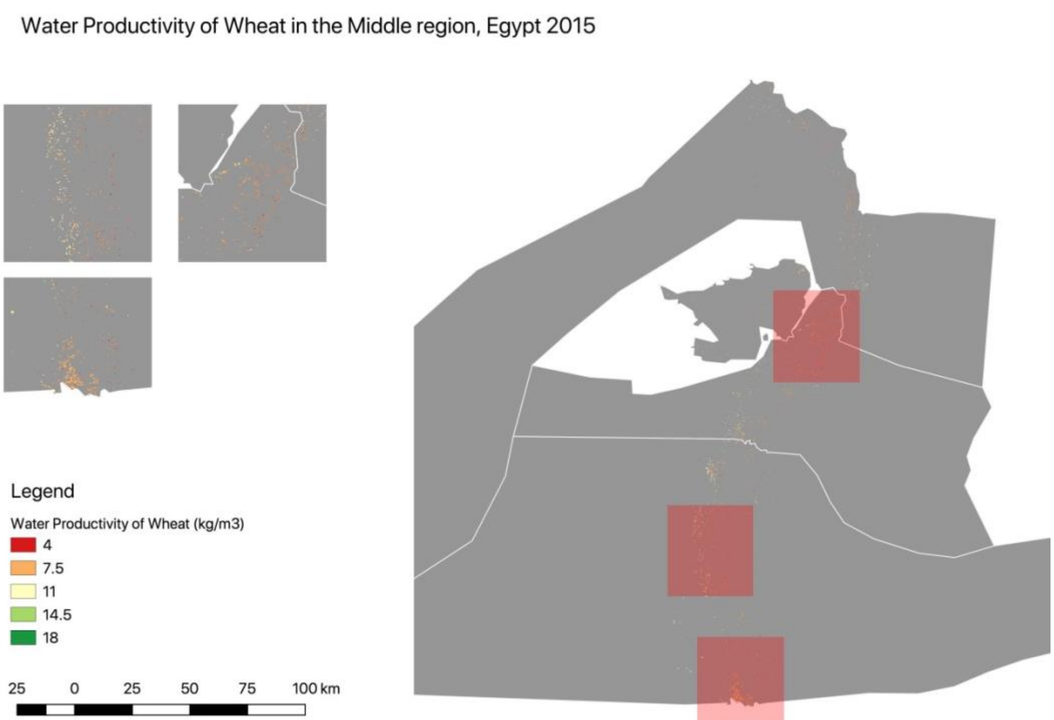


Figure 41: Water Productivity of Wheat in the Middle region, Egypt 2015

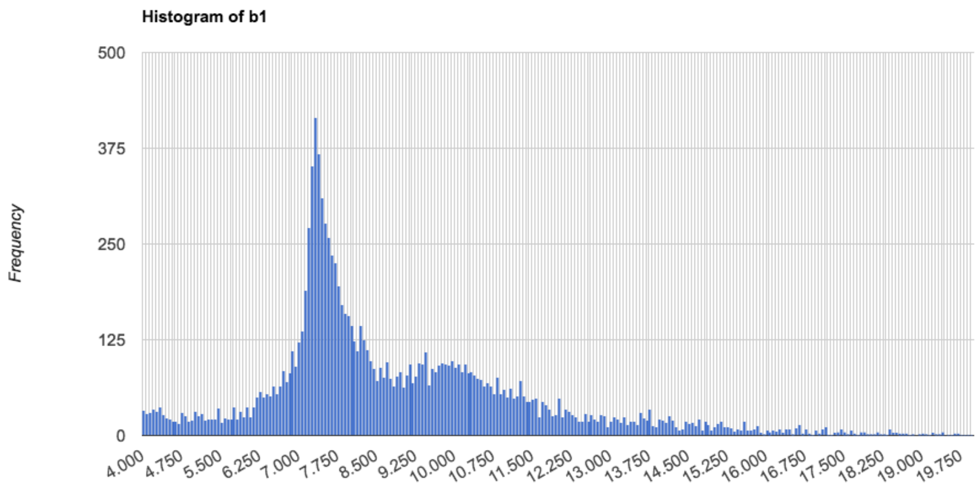
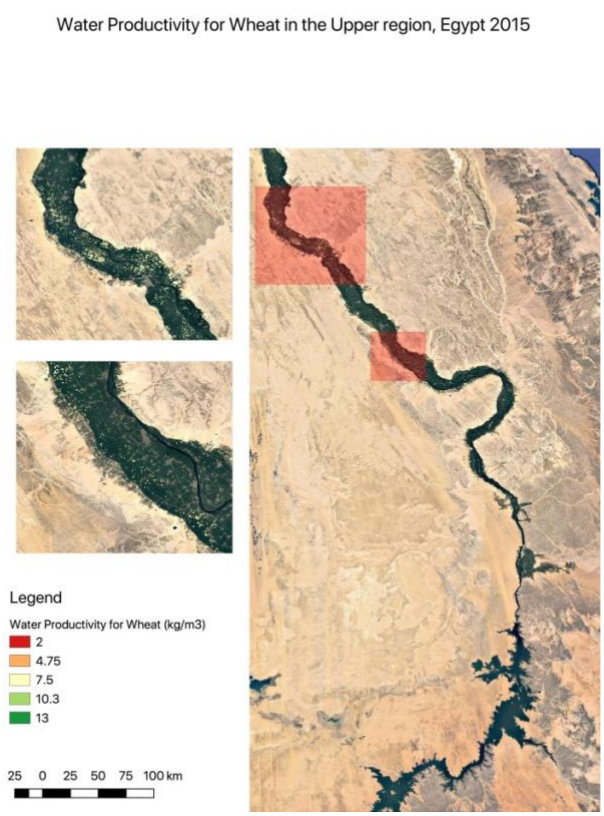
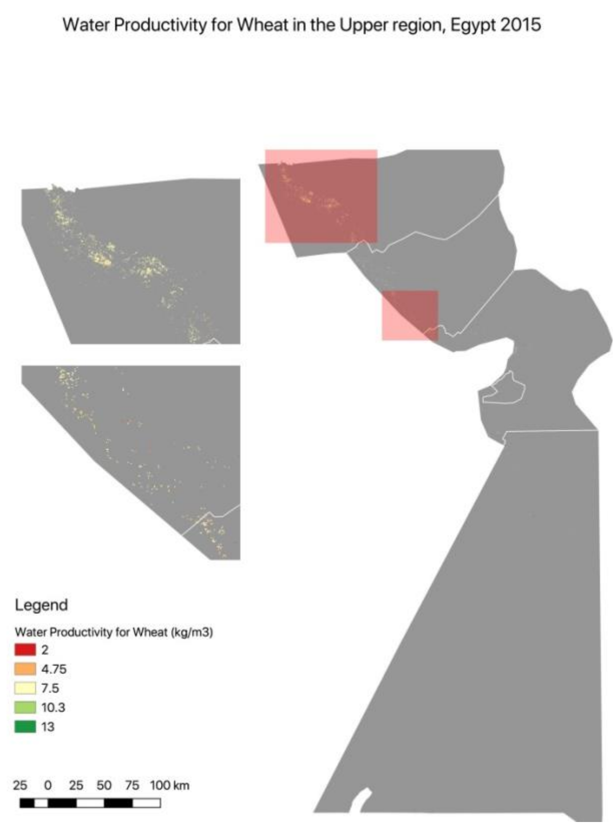


Figure 42: Water Productivity Histogram of Wheat in the Middle region, Egypt 2015

Mode average: 7.3-7.7 kg/m^3





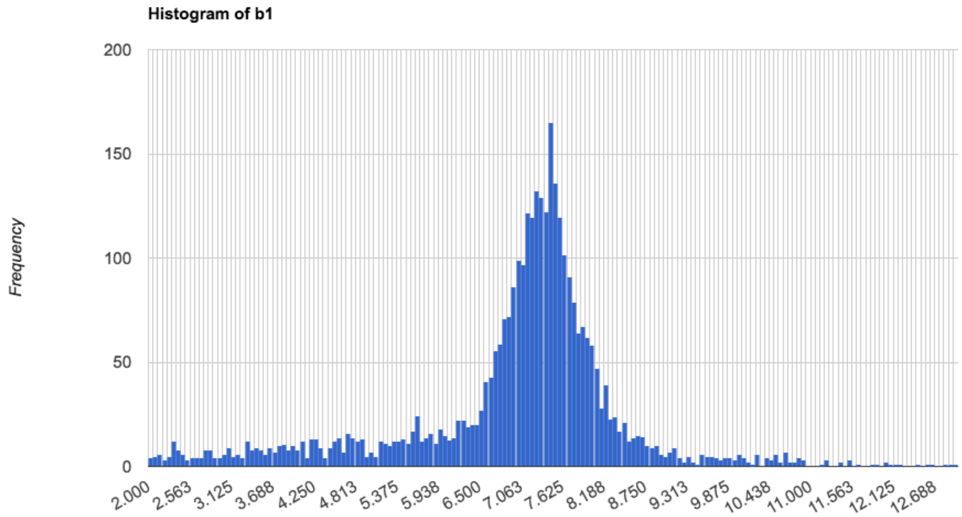


Figure 43: Water Productivity Histogram of Wheat in the Upper region, Egypt 2015

Mode average: 7.4-7.7 kg/m^3

Rice and Maize

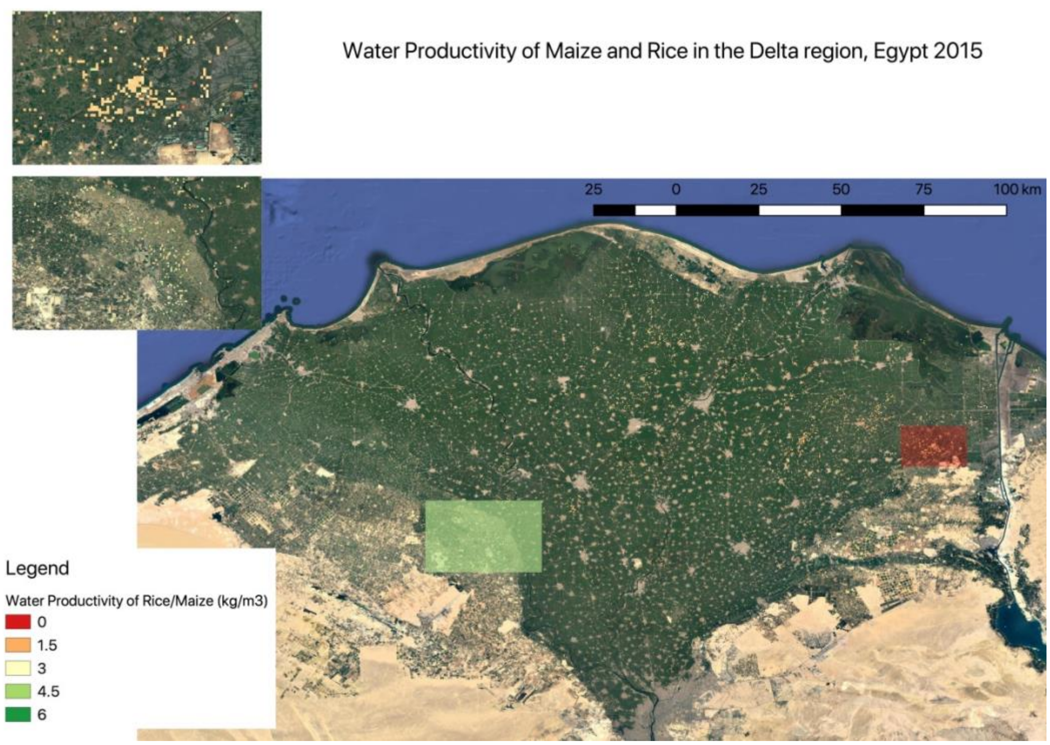


Figure 44: Water Productivity of Maize and Rice in the Delta region, Egypt 2015- Satellite view

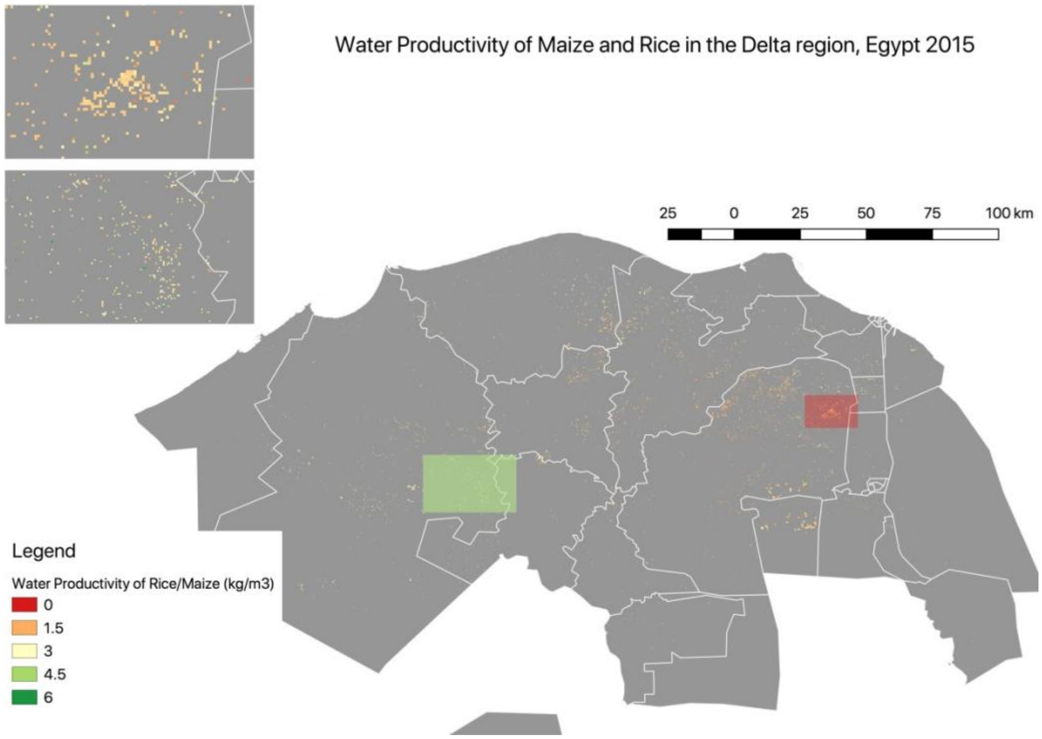


Figure 45: Water Productivity of Maize and Rice in the Delta region, Egypt 2015

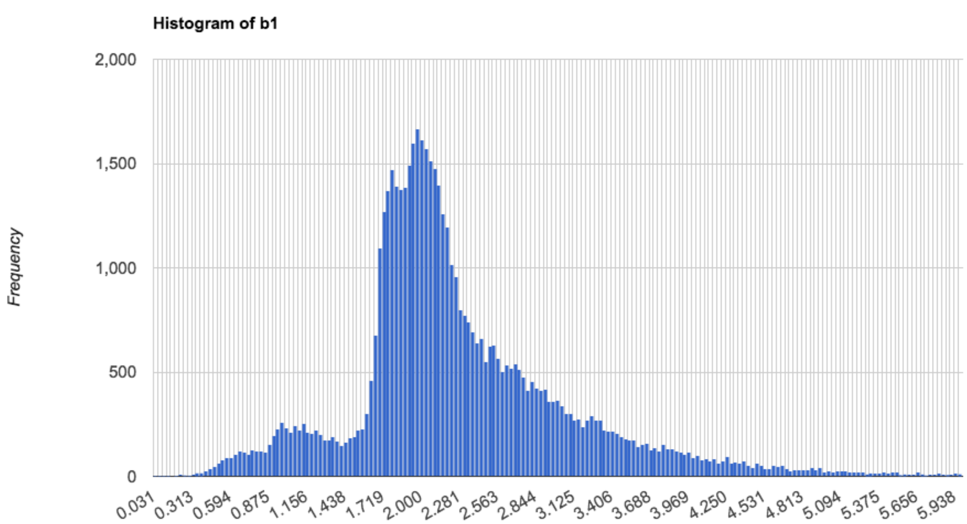


Figure 46: Water Productivity Histogram of Rice/Maize in the Delta region, Egypt 2015

Mode average: 1.8-2.1 kg/m^3

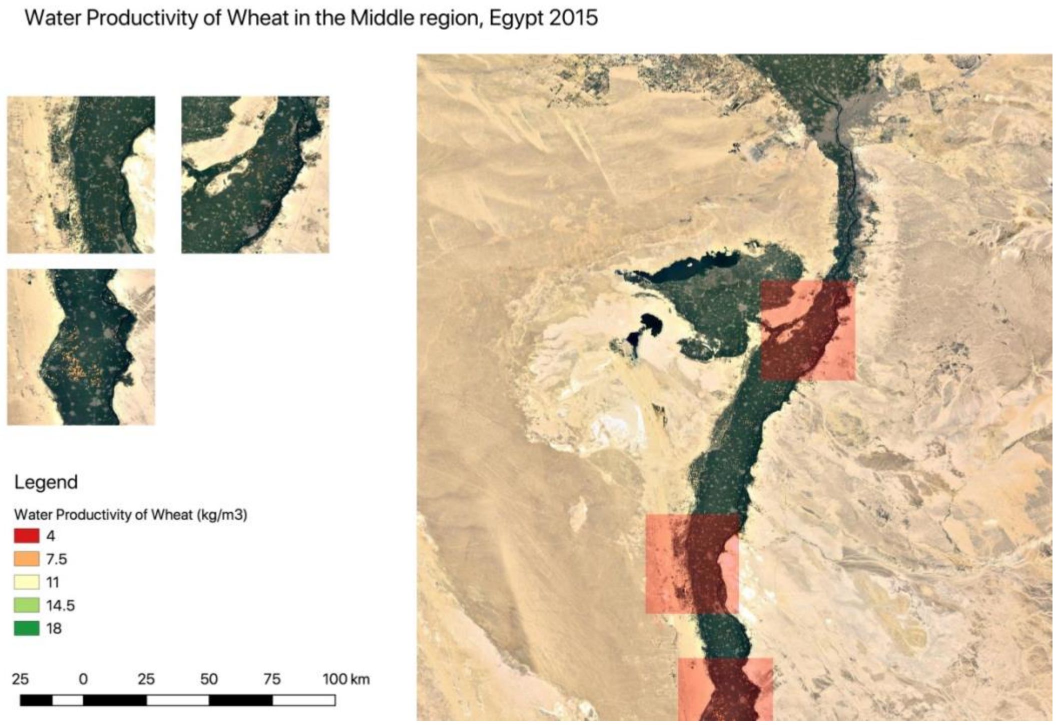


Figure 47: Water Productivity of Maize and Rice in the Middle region, Egypt 2015 - Satellite view

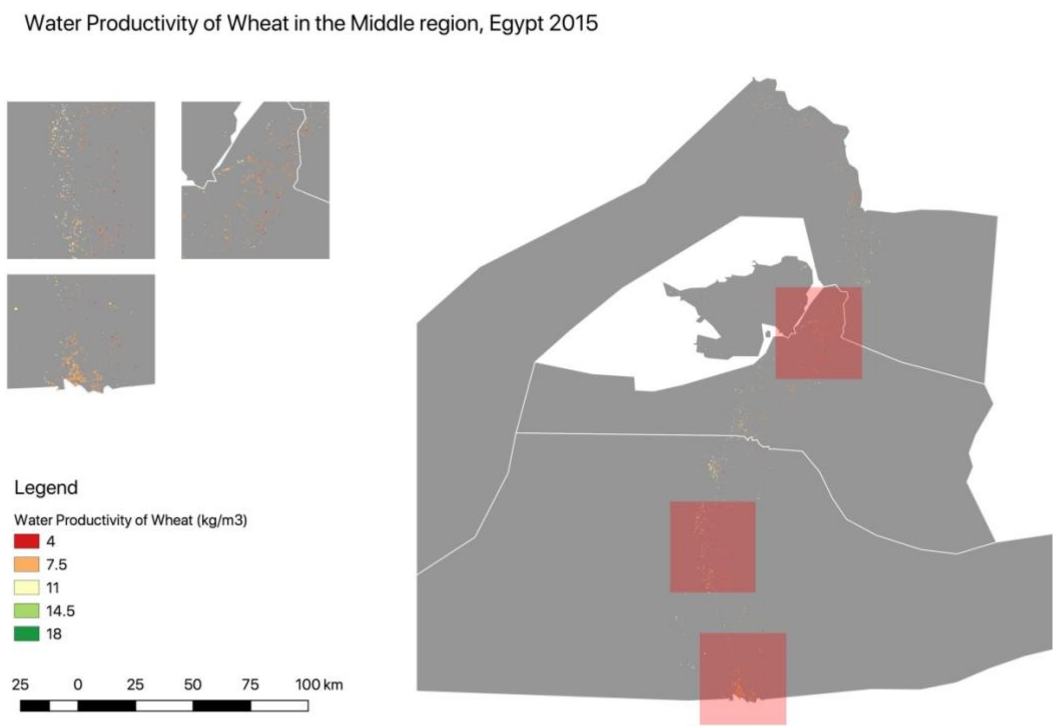


Figure 48: Water Productivity of Maize and Rice in the Middle region, Egypt 2015

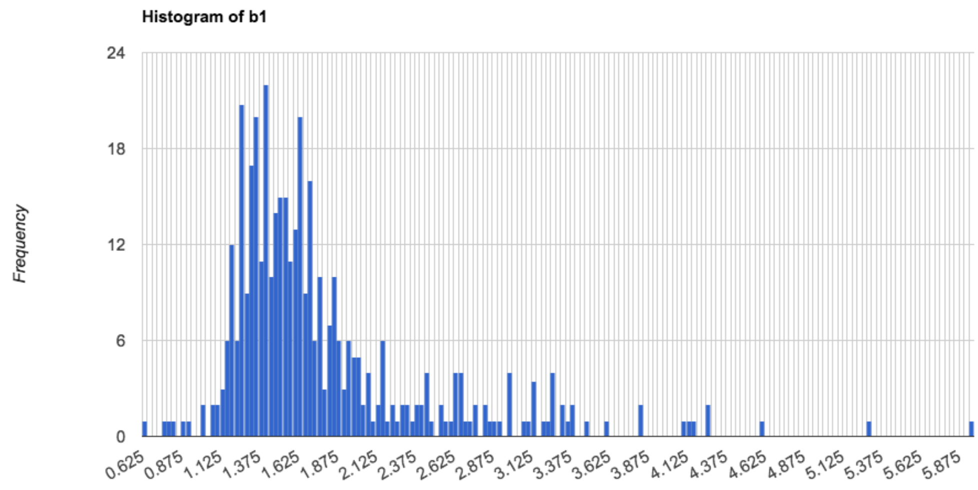


Figure 49: Water Productivity Histogram of Rice/Maize in the Middle region, Egypt 2015

Mode average: 1.4-1.7 kg/m^3

Sudan

Sorghum and Millet

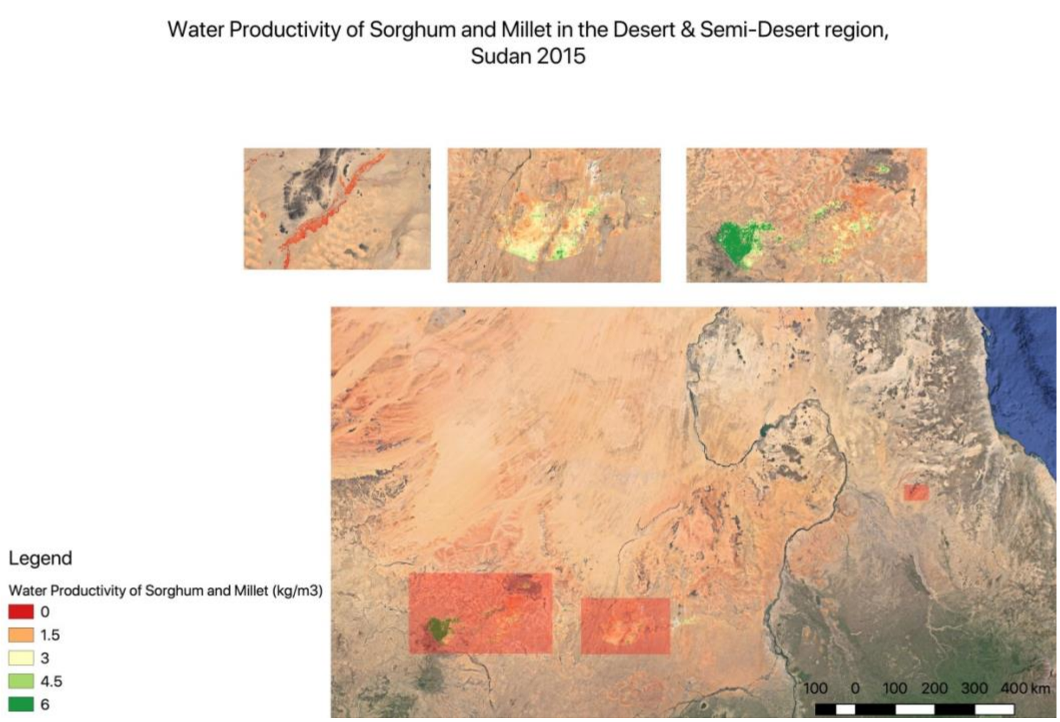


Figure 50: Water Productivity of Sorghum and Millet in the Desert & Semi-desert region, Sudan 2015 - Satellite view

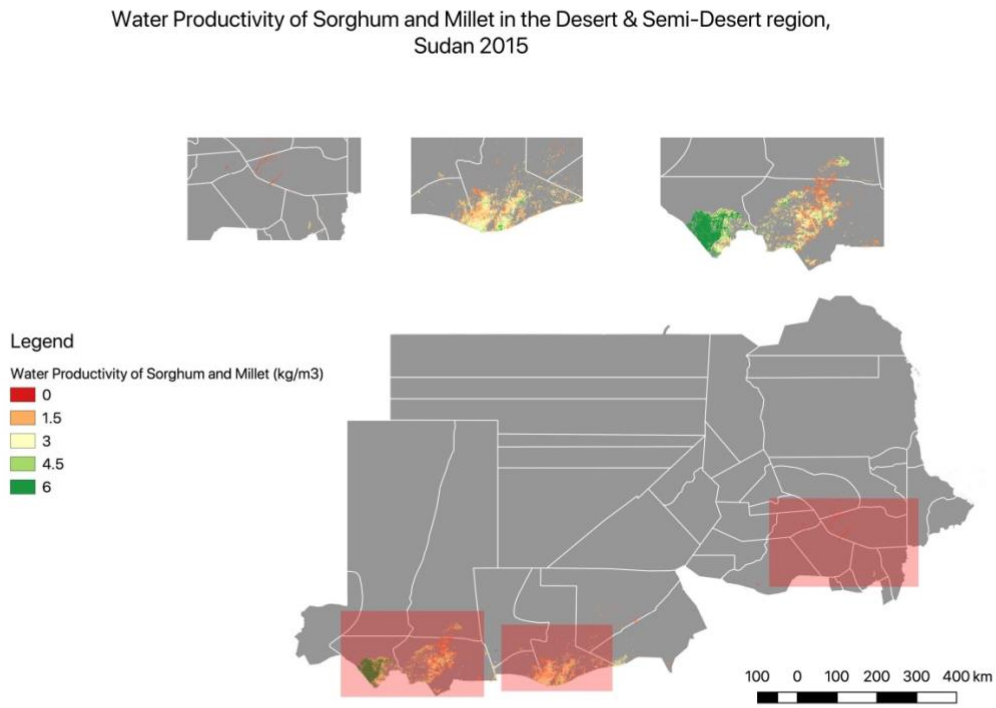


Figure 51: Water Productivity of Sorghum and Millet in the Desert & Semi-desert region, Sudan 2015

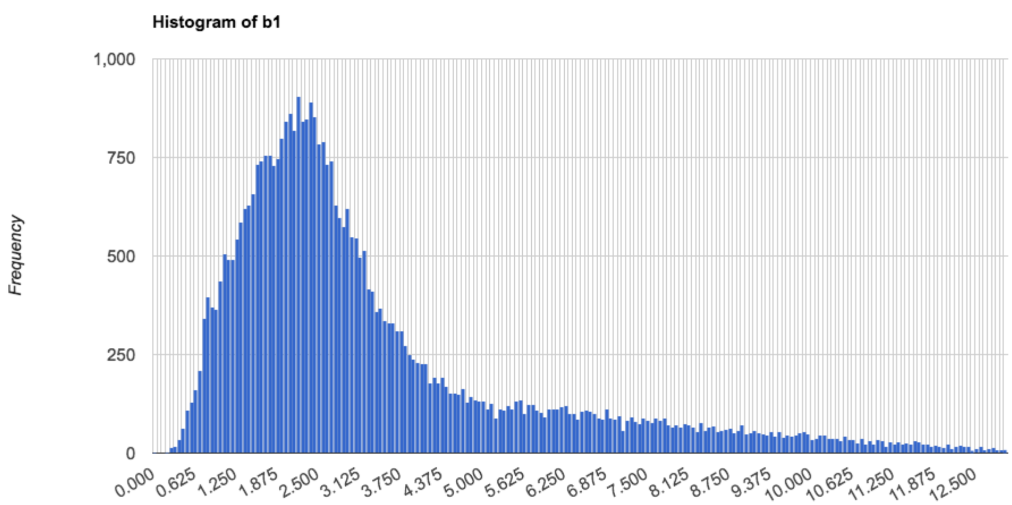


Figure 52: Water Productivity Histogram of Millet in the Desert & Semi-desert region, Sudan 2015

Mode average: 2 – 2.4 kg/m^3

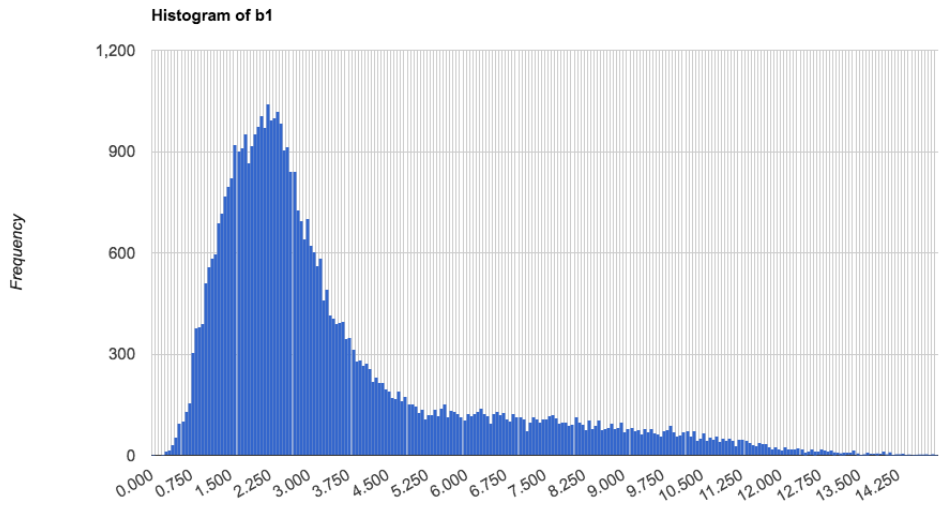


Figure 53: Water Productivity Histogram of Sorghum in the Desert & Semi-desert region, Sudan 2015

Mode average: 1.6 – 2.4 kg/m^3

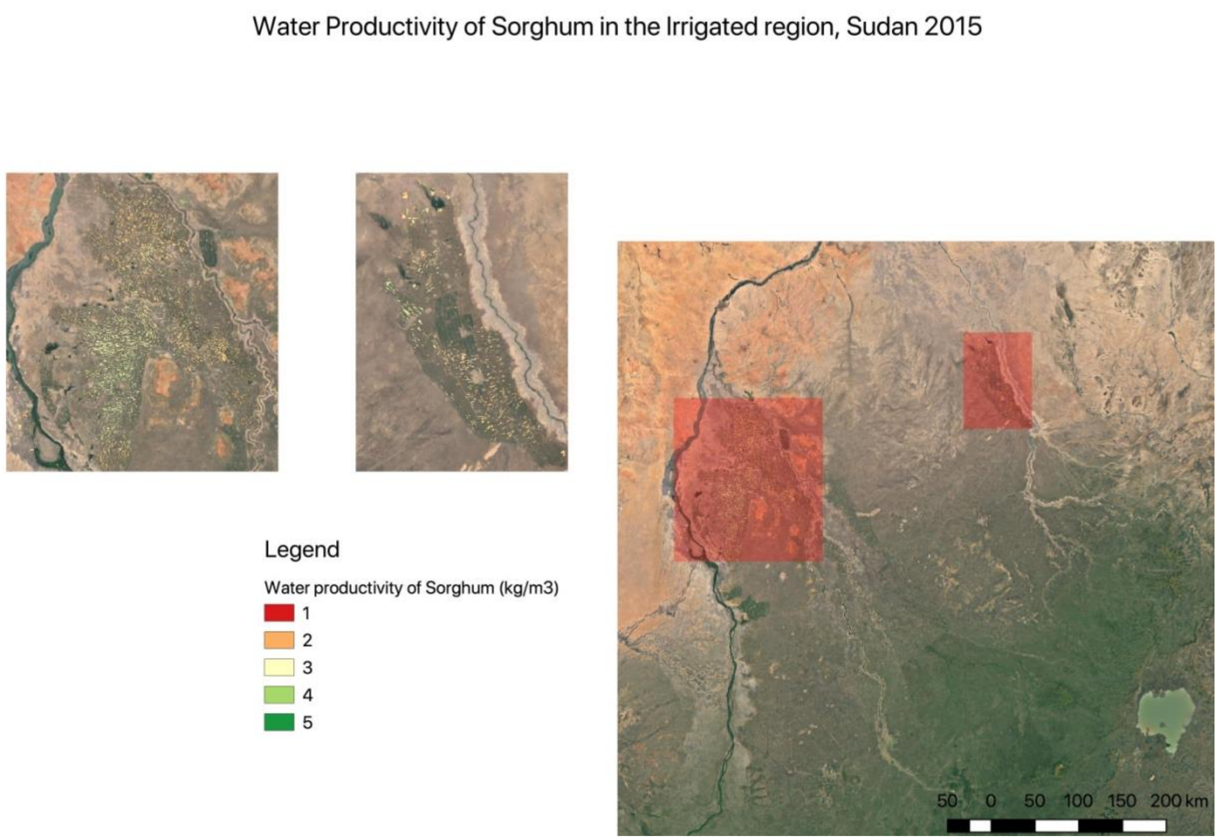


Figure 54: Water Productivity of Sorghum and Millet in the Irrigated region, Sudan 2015 – Satellite view

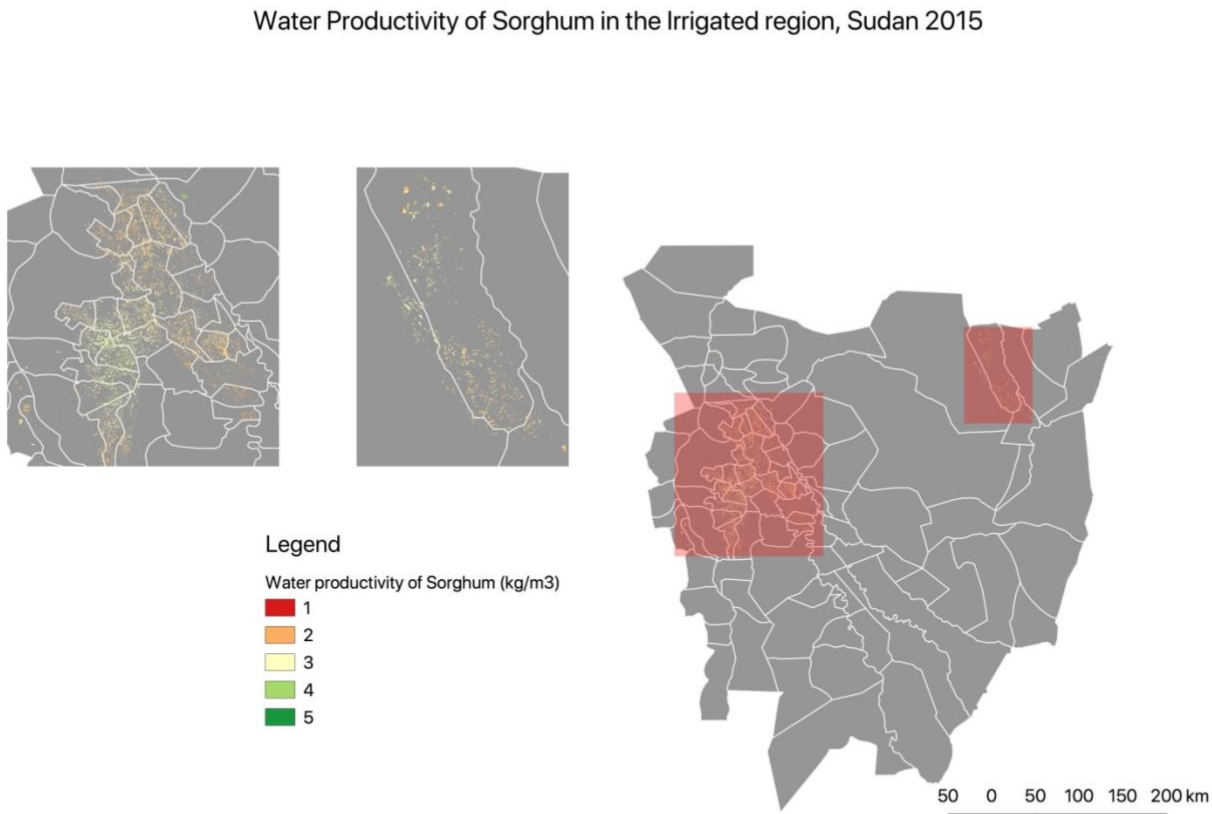


Figure 55: Water Productivity of Sorghum and Millet in the Irrigated region, Sudan 2015

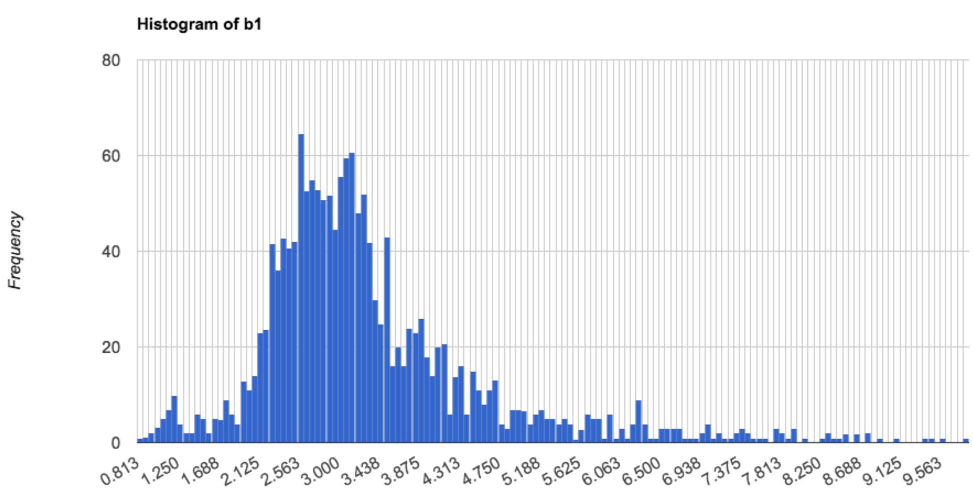


Figure 56: Water Productivity Histogram of Millet in the Irrigated region, Sudan 2015

Mode average: 2.6 – 3.1 kg/m^3

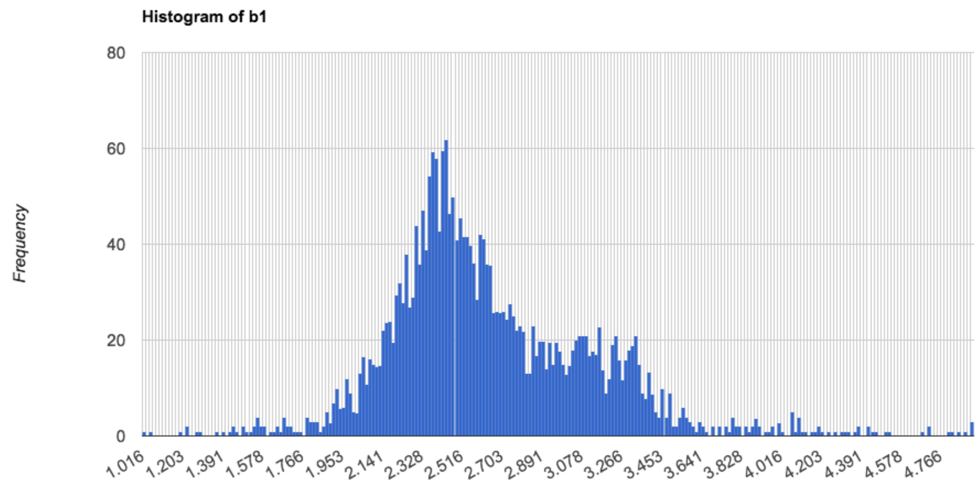


Figure 57: Water Productivity Histogram of Sorghum in the Irrigated region, Sudan 2015

Mode average: 2.6 – 31. kg/m^3

Ethiopia

Maize

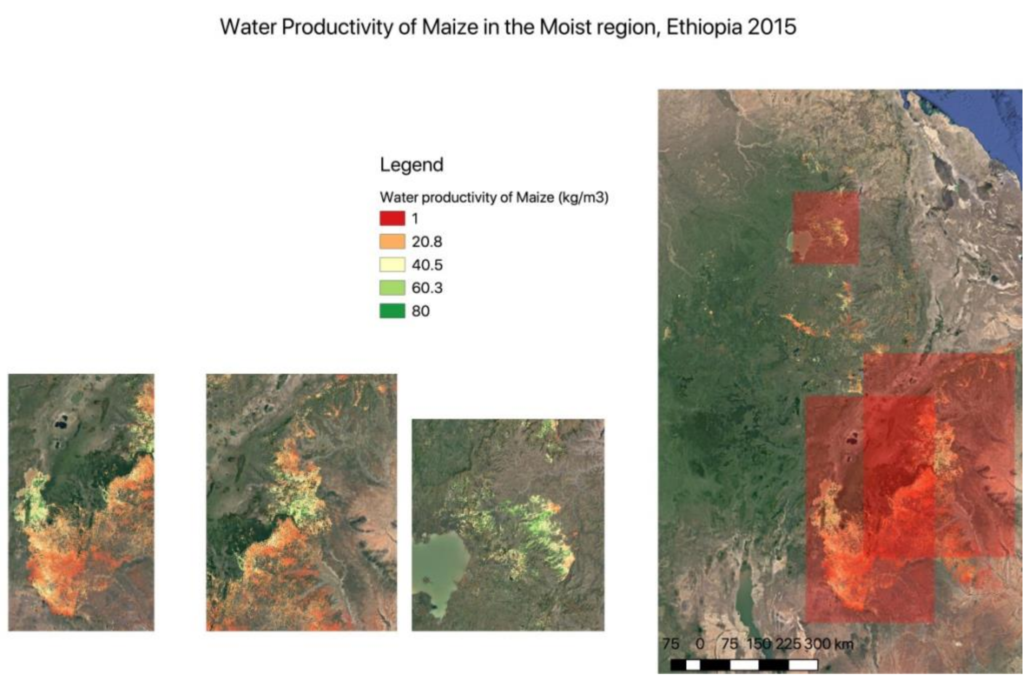


Figure 58: Water Productivity of Maize in the Moist region, Ethiopia 2015 – Satellite view

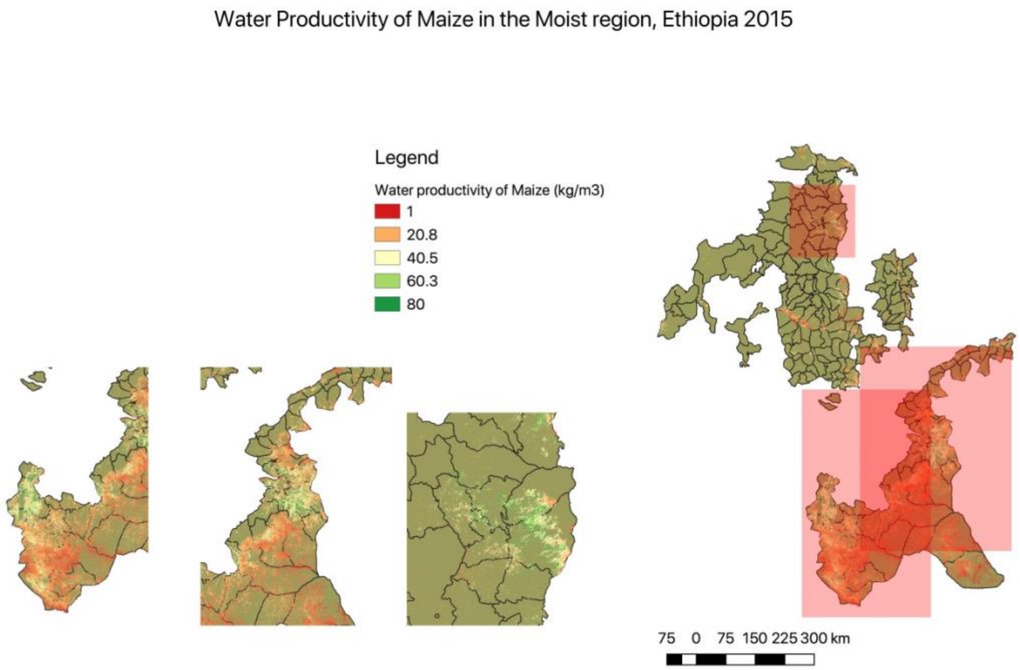


Figure 59: Water Productivity of Maize in the Moist region, Ethiopia 2015

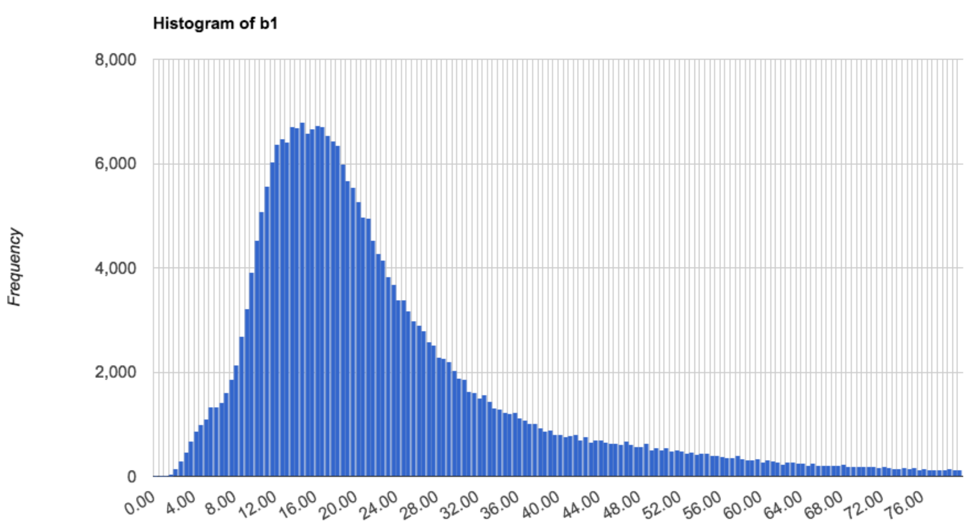


Figure 60: Water Productivity Histogram of Maize in the Moist region, Ethiopia 2015

Mode average: 13.5 – 17.5 kg/m^3

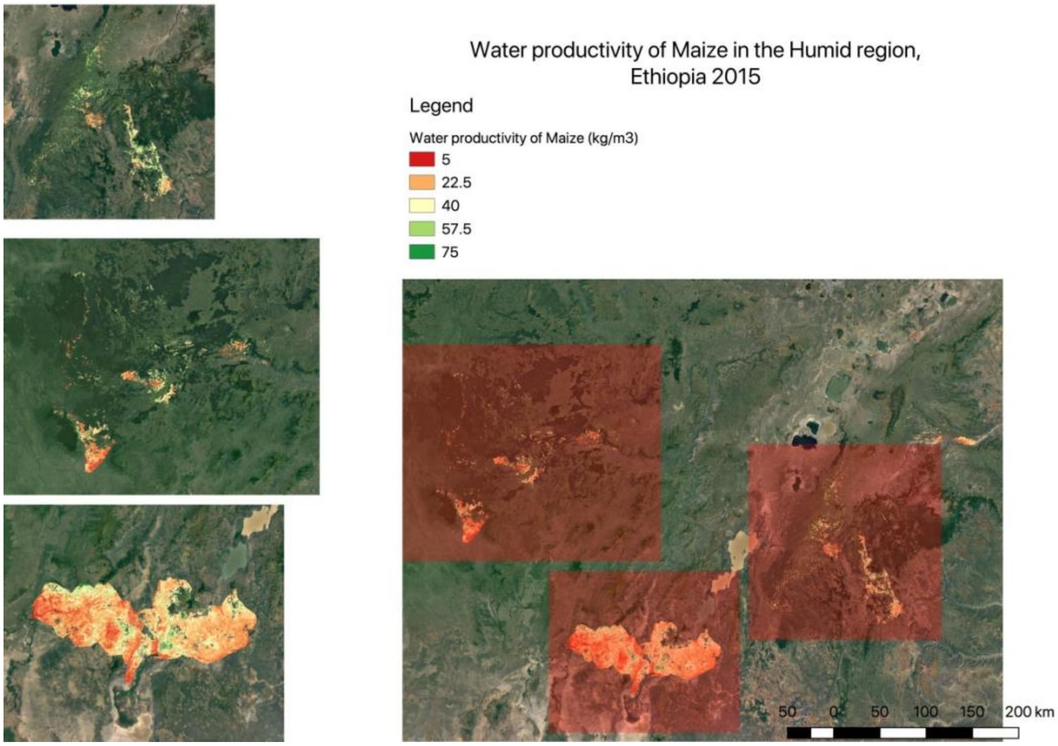


Figure 61: Water Productivity of Maize in the Humid region, Ethiopia 2015 – Satellite view

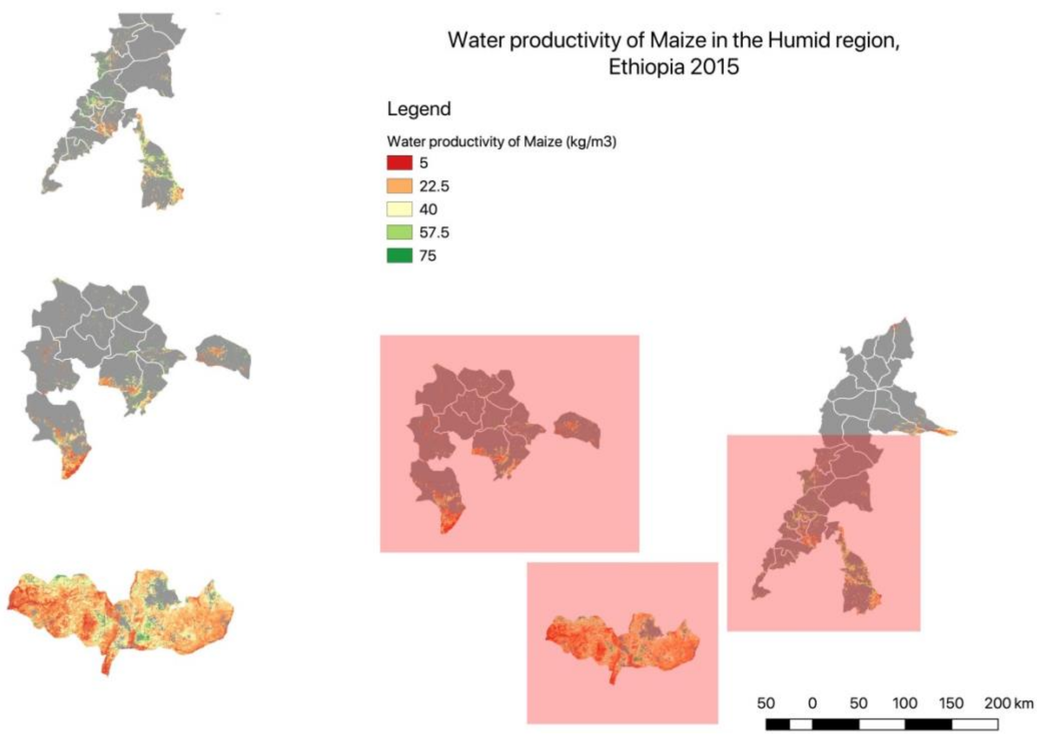


Figure 62: Water Productivity of Maize in the Humid region, Ethiopia 2015

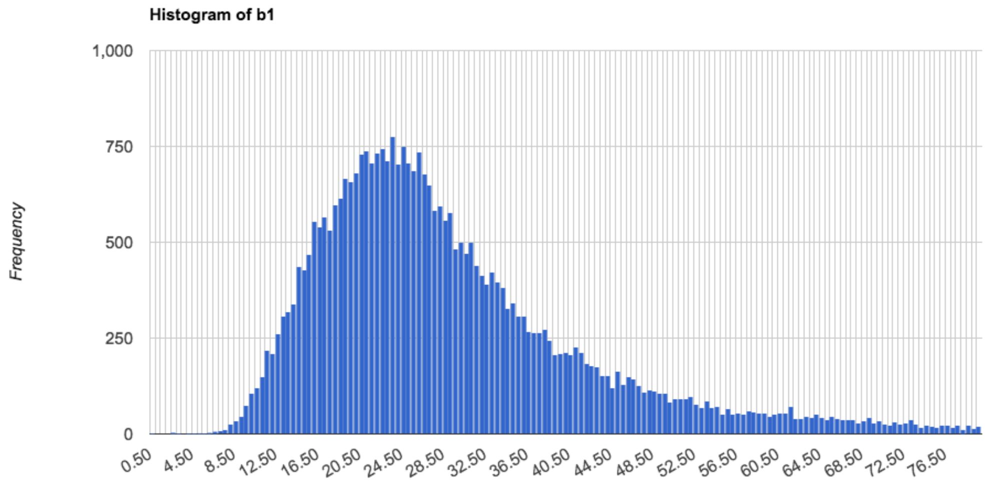


Figure 63: Water Productivity Histogram of Maize in the Humid region, Ethiopia 2015

Mode average: 21 – 26 kg/m^3

Wheat

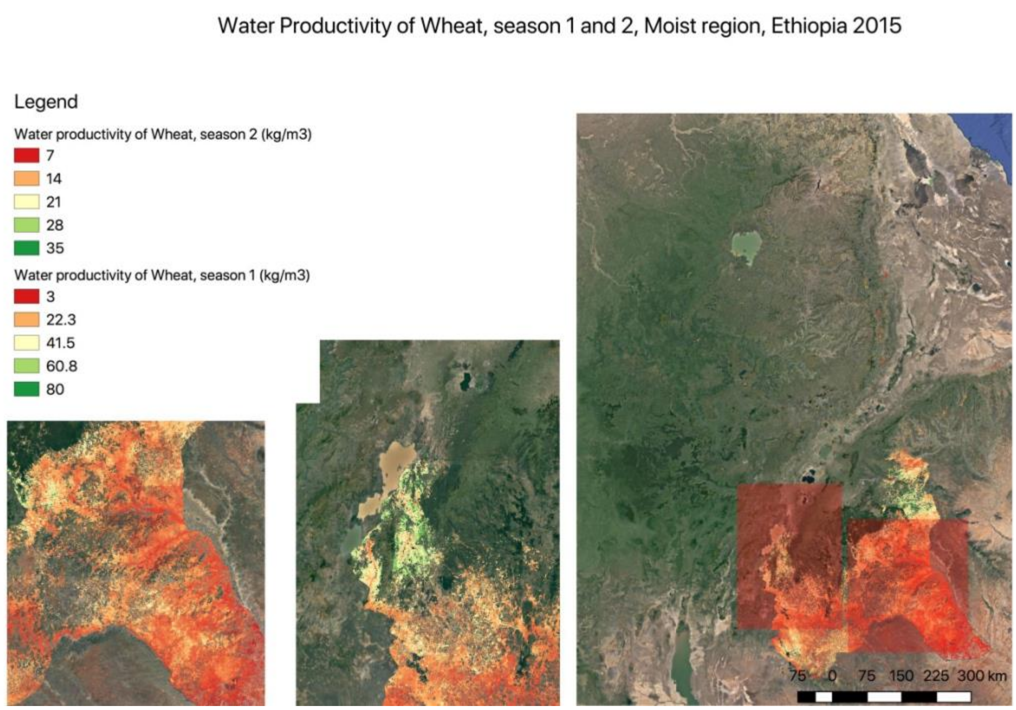


Figure 64: Water Productivity of Wheat in the Moist region, Ethiopia 2015 – Satellite view

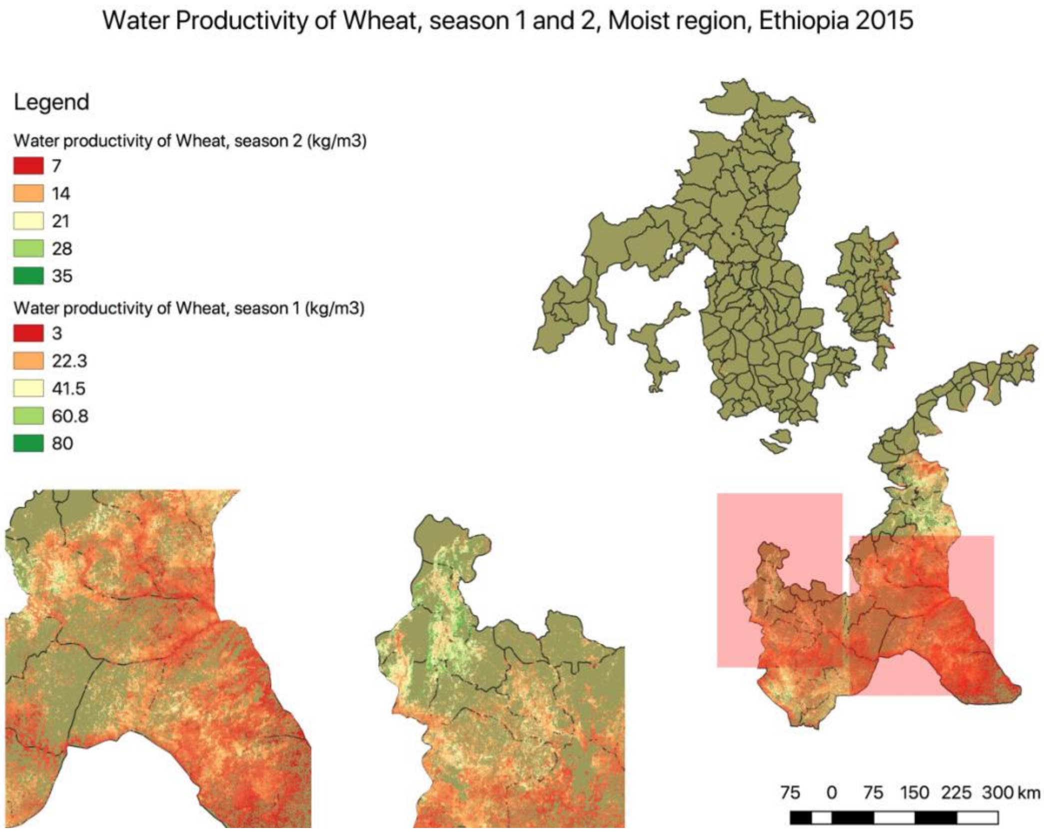


Figure 65: Water Productivity of Wheat in the Moist region, Ethiopia 2015

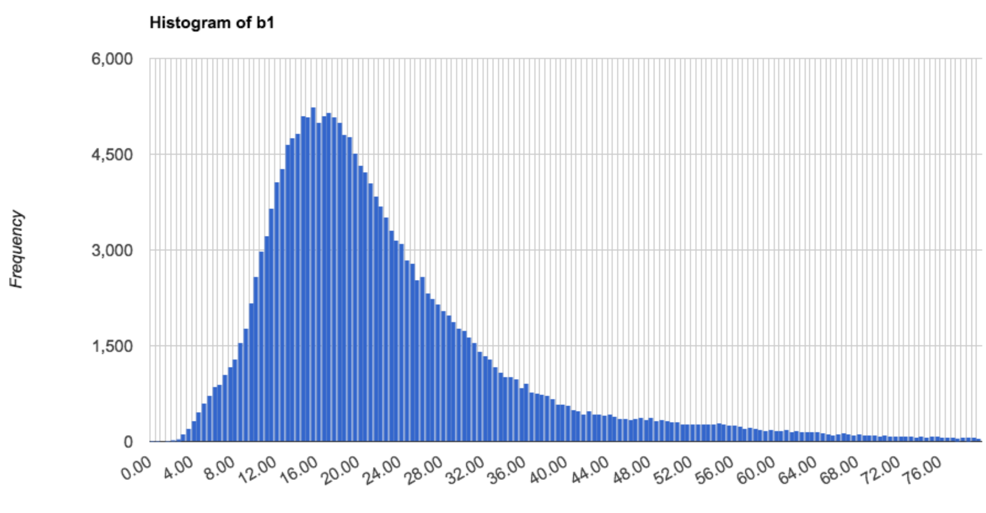


Figure 66: Water Productivity Histogram of Wheat in the Moist region, season 1, Ethiopia 2015

Mode average: 15 – 17.5 kg/m^3

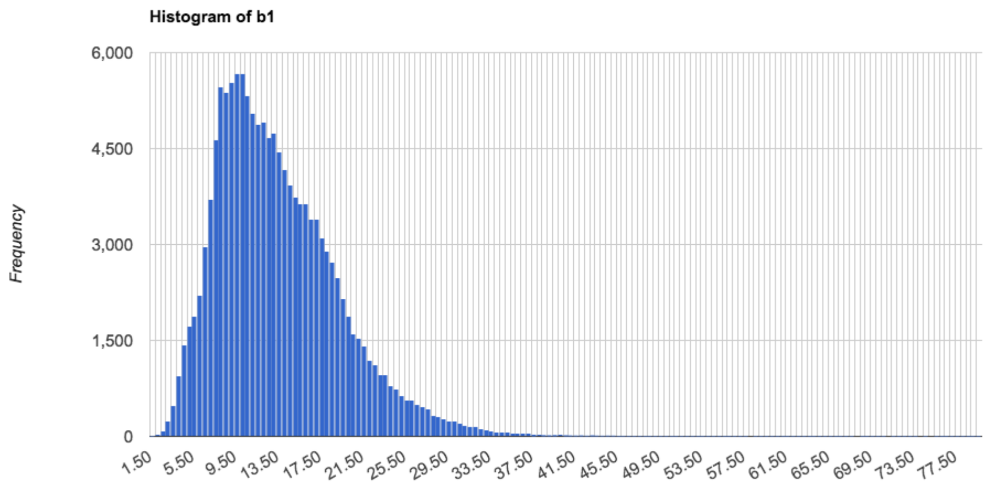


Figure 67: Water Productivity Histogram of Wheat in the Moist region, season 2, Ethiopia 2015

Mode average: 8 - 12 kg/m^3

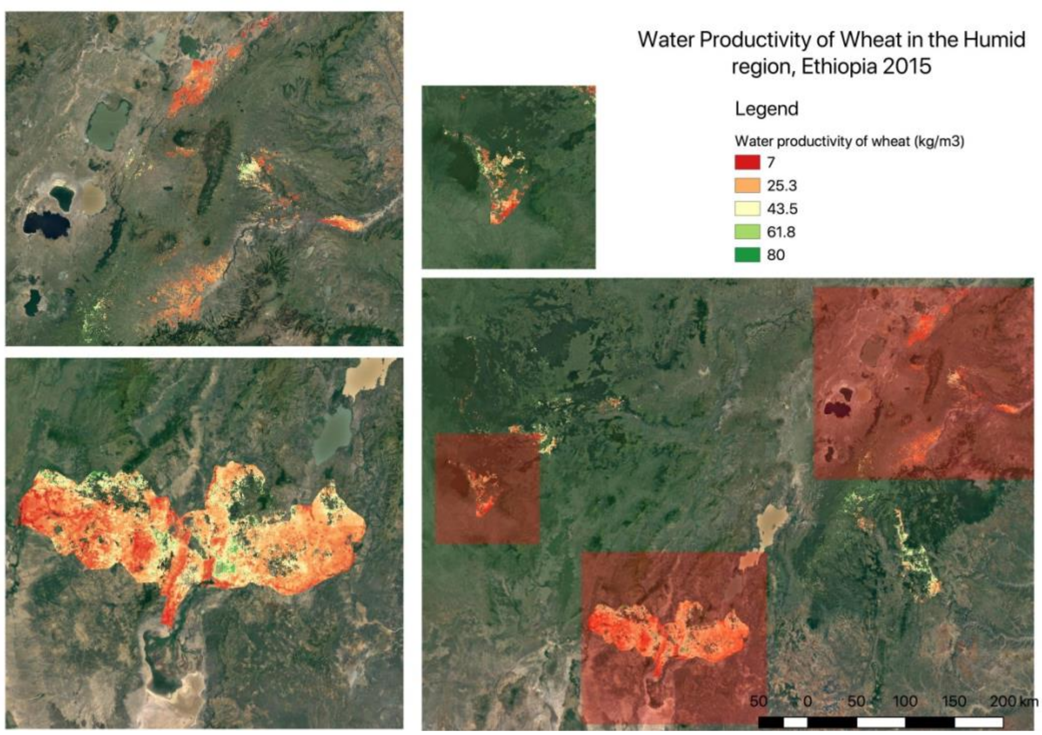


Figure 68: Water Productivity of Wheat in the Humid region, Ethiopia 2015 – Satellite view

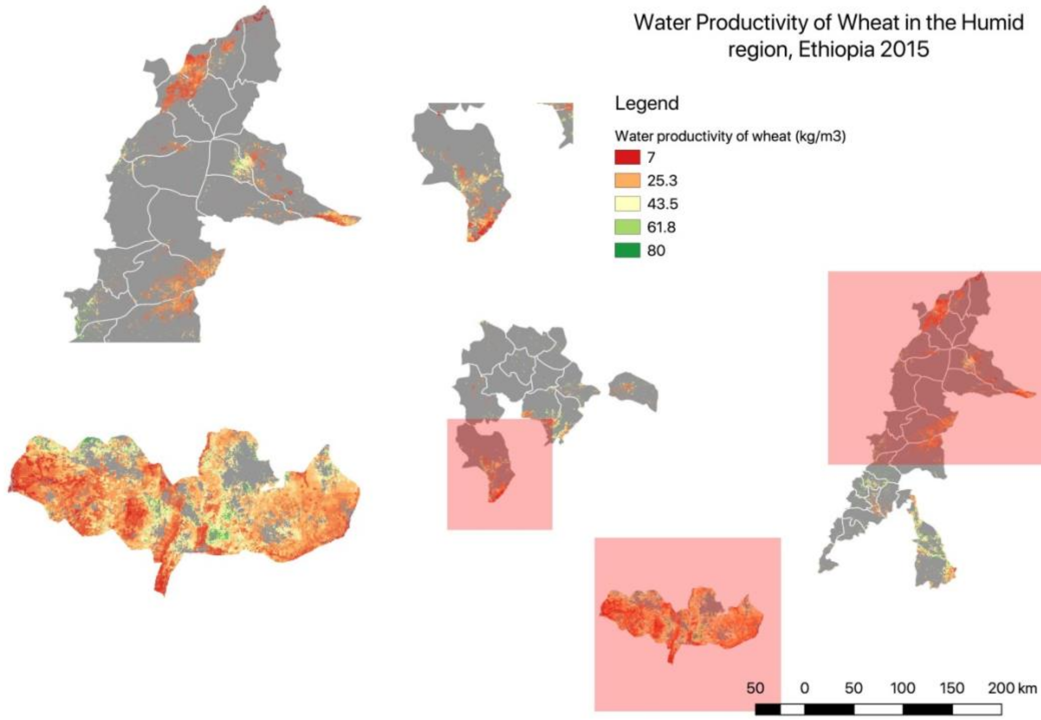


Figure 69: Water Productivity of Wheat in the Humid region, Ethiopia 2015

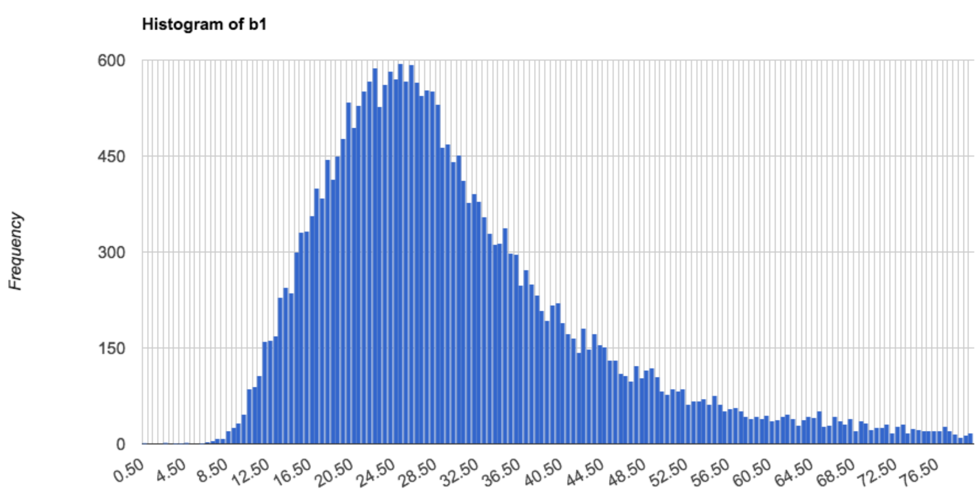


Figure 70: Water Productivity Histogram of Wheat in the Humid region, season 1, Ethiopia 2015

Mode average: 22 – 28.50 kg/m^3

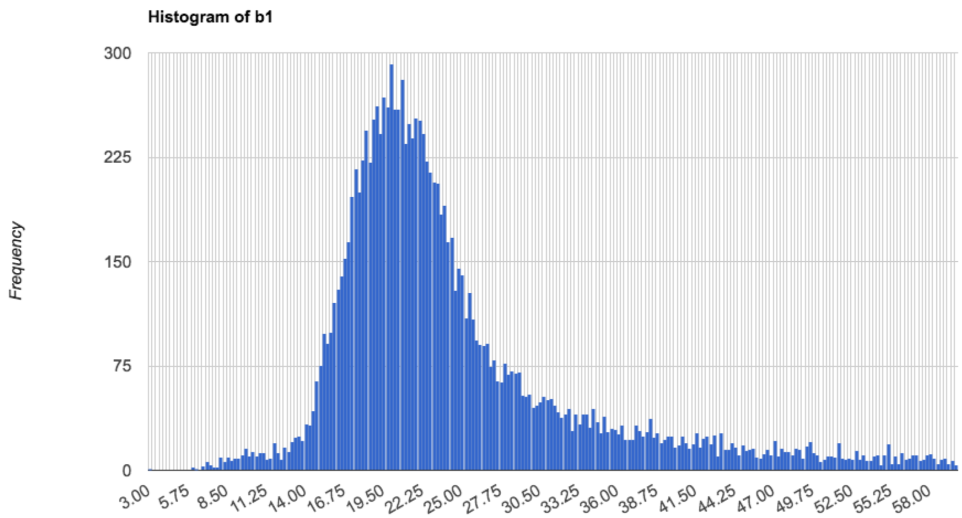


Figure 71: Water Productivity Histogram of Wheat in the Humid region, season 2, Ethiopia 2015

Mode average: 19 - 22 kg/m^3

5. Discussion

5.1 Evaporation and Rainfall

According to FAO's irrigation manual (Brouwer, Goffeau, & Heibloem, 1985), the average daily water need of crops in an arid area such as Egypt varies between 9 and 11 mm per day. Assuming an average daily evaporation of 7 mm per day during crop growth, as stated by prof. van de Giesen (personal communication, September 6, 2018), the mean monthly average results of evaporation are low on country level as well as in the Delta region, albeit the latter to a lesser extent. This could be due to the fact that the delta region is a smaller spatial scale that contains mostly irrigated pixels and thus less faulty pixels that can take the average down. In addition, Egypt's monthly rainfall complies with the literature by FAO that states that annual rainfall varies between 20-200 mm/year and that rainfall occurs in the winter months.

By using the mode average and applying a mask to filter out lower values, the average monthly evaporation data increased from a maximum of 30 – 35 mm/month to a maximum of 200 mm/month on country level, which seems more accurate considering the fact that crops in Egypt are continuously irrigated. Mode average in the Delta region also gave higher values compared to the mean average, although the increase was not as extreme as for the country level. In comparison with the averages that are found by only looking at the irrigated crops as identified by the FAO WaPOR Land Cover Classification, it can be seen that the average values are higher than the unmasked values, but lower than the mode average for both Egypt on country level as well as the Delta. The fact that the average monthly values are higher with the FAO WaPOR Land Cover Classification could imply that the mask accurately determines only the pixels that are under full irrigation, while the unmasked values also include non-agricultural pixels, which take down the average evaporation values.

Although the averages increased, the overall ratio between the months regarding the actual evaporation, blue evaporation and precipitation stayed equal. Blue evaporation clearly decreased during months where there was rainfall. It can be seen that rainfall has more influence in the Delta region, considering the fact that Egypt's rainfall almost exclusively occurs in the coastal region.

On country level, Sudan shows a representable ratio of blue evaporation, actual evaporation, and precipitation. In addition, rainfall complies with the literature, stating that rainy season occurs from May through September. From the data, it can be concluded that most irrigation occurs during the dry season, from January until April, as actual evaporation equals blue evaporation. However, like Egypt, the average values are low, probably since the fact that not all pixels are fully irrigated. Implementation of a mask and using the mode average instead of the mean did not result in higher values and moreover removed the variability between the months when looking at country level and the desert & semi-desert region. The irrigated zone, however, stayed consistent in the ratio between the three datasets and monthly variability. This is possibly due to the fact that most of the irrigation within the country takes places within the irrigated zone, while the desert & semi-desert region, as well as country level, have more low-value pixels that do not contribute to agricultural production. Overall, it proved to be more challenging to use the same mask for all months, since there is a high variability regarding the low value peeks for each month. Therefore, the mode average with a mask does not seem valid. Irrigated pixels according to the LCC mask show higher average values than the unmasked averages, while still maintaining reasonable variabilities.

Ethiopia's mean average values show a variety in precipitation and evaporation on a monthly basis, with an increase in blue evaporation during months where there is less precipitation. Not much difference is seen when mode average is used. Due to the many frequency peaks in the data, it was difficult to determine which values to mask. Therefore, values of 2 and less were masked and did not influence the average to a great extent. The LCC mask gives slightly higher averages. Considering the fact that literature states that Ethiopia's main agriculture is based on rain-fed agriculture, the amounts of blue water evaporation seem rather high when it is compared to the actual evaporation.

5.2 Water withdrawals for irrigation

According to FAO AQUASTAT, the annual water withdrawals for irrigation in Egypt was 67 BCM in 2010. Results of the unmasked summation of blue evaporation pixels, multiplied with the pixel size, gives an annual water withdrawal of 68.8 BCM for 2016. By only considering the irrigated pixels, as defined by the FAO Land Cover Classification map, the annual water withdrawal is 33.8 BCM, reaching 52 BCM, assuming an irrigation efficiency of 65%. When using the same mask as applied to compute the mode average, an annual water withdrawal of 53.4 BCM is calculated. Assuming an irrigation efficiency of 65%, this leads to a water withdrawal of 82 BCM annually. For Egypt, the unmasked calculation lies closest to the literature value of 67 BCM annually, when an irrigation of 100% is assumed. This however is not likely. Therefore, the results with the FAO LCC Mask resembles the literature the most, albeit the amount is lower than expected.

Sudan used 25.9 BCM water for irrigation in 2011, according to FAO AQUASTAT data. Calculation of water withdrawals with FAO WaPOR resulted in volumes of 211.1 BCM when all blue irrigation pixels are considered (unmasked), 16.4 BCM with the FAO LCC Mask and 47.3 BCM with the modified mode mask respectively. Assuming an irrigation efficiency between 65%, Sudan's results from the calculation with the FAO WaPOR LCC mask is in accordance with the numbers from literature.

Ethiopia used 9 BCM water in 2016 for irrigation. This number is nearly in accordance with the result when using the FAO WaPOR LCC mask. However, with an irrigation efficiency between 65%, the water withdrawal is slightly higher than what is expected. Without a mask and with a modified mask, the numbers exceed the literature by a factor 10.

With this method, fresh water withdrawals for irrigation purposes are calculated through evaporation, whereas water withdrawals from literature are obtained from government statistics that are subsequently derived from pumping station data and water authorities. As was stated on page 12, inefficient irrigation systems and/or faulty implementation may be the cause of the difference between results calculated through blue evaporation and literature. Although the FAO WaPOR LCC mask seems to provide the most accurate results for Egypt, Sudan and Ethiopia, Egypt's calculated water withdrawals are less than expected according to the literature. However, this does not provide an explanation as to why the data for Sudan and Ethiopia match better with literature than Egypt. More literature and ground validation are necessary to validate the FAO WaPOR LCC mask. Ground validation should be done in terms of determining if and which areas/pixels are under full irrigation and subsequently be compared to the results from WaPOR data. During a skype meeting with Jippe Hoogeveen & Livia Peiser (representatives of FAO WaPOR at FAO), it was stated that the FAO WaPOR LCC mask is still in beta and reliability of the results are therefore not guaranteed by FAO.

With eradicate rainfall in Ethiopia, it seems likely that the determination of blue evaporation is more difficult and unreliable. After all, the method of determining blue evaporation is based on the theory of WA+, of which rainfall and actual evaporation data are the two most important hydrological variables

(Karimi et al., 2015). This can already be seen in the results of the blue water evaporation, which consists for a big part of the actual evaporation. When water withdrawals are being calculated, the error is increased due to the fact that all pixels that are determined with blue evaporation, are included and multiplied with the surface of the pixel (100x100m). Albeit to a lesser extent, this probably also occurred in Sudan and is likely the cause for the astronomically high numbers regarding fresh water withdrawals.

5.3 Crop Water productivity

Table 19, 20 and 21 give an overview of the mode averaged water productivity of several crops in various agro-ecological zones in Egypt, Sudan, and Ethiopia respectively.

Table 19: Overview of the average water productivity (kg/m³) per crop, per AEZ in Egypt, 2015

	Wheat	Maize	Rice
Delta region	7.7-8.2	1.8-2.1	1.8-2.1
Middle region	7.3-7.7	1.4-1.7	1.4-1.7
Upper region	7.4-7.7	-	-

In Egypt, the Delta region performs better than the Middle and Upper region. The latter show the same values. Due to the fact that the phenology of Maize and Rice are overlapping, no distinction could be made. A smaller peak can be seen in the histogram of the Delta (figure 46), but the histogram of the Middle region seems more scattered.

According to articles on the evaluation of CWP in the delta region, CWP of wheat varies between 1 and 2 kg/m^3 with an average of 1.52 kg/m^3 in the Delta region, while maize varies between 0.5 and 1 kg/m^3 (Zwart & Bastiaanssen, n.d., Abd El-Hafeez, Samiha, Wael, & S., 2017; El-Marsafawy, Swelam, & Ghanem, 2018). Therefore, the results of wheat are likely to be inaccurate. Considering that the same methodology was used to determine water productivity for maize, which gave a realistic result, a possible reason for unrealistic wheat water productivity may be the fact that the phenology data was incorrect or that the ranges of planting and harvesting have overlap with other crops.

Table 20: Overview of the average water productivity (kg/m³) per crop, per AEZ in Sudan, 2015

	Sorghum	Millet
Desert & Semi-desert region	1.6-2.4	2-2.4
Irrigated region	2.6-3.1	2.6-3.1

In the desert & Semi-desert region of Sudan, Sorghum and Millet partially overlap in their phenology, which is the reason for equal results. Compared to the irrigated region, the desert has a lower mode average water productivity. Millet and Sorghum have different growing seasons in the irrigated season, but their average water productivity is equal. According to a study made on the spatial-temporal performance of the Gezira Irrigation Scheme (Al Zayed, Elagib, Ribbe, & Heinrich, 2015), water use efficiency for sorghum was found to be 0.1 to 0.38 kg/m^3, while worldwide values are 0.3 to 2.2 kg/m^3. Values for sorghum therefore seem to be too high compared to what is expected according to literature. Unfortunately, no clear literature regarding water productivity of Millet in the Gezira scheme could be found for comparison.

Table 21: Overview of the average water productivity (kg/m3) per crop, per AEZ in Ethiopia, 2015

	Maize	Wheat, season 1	Wheat, season 2
Moist	13.5-17.5	15-17.5	8-12
Humid	21-26	22-28.5	19-22

Ethiopia shows the highest values of water productivity, where the Humid region scores above an average of 20 kg/m^3 for both assessed crops. Water productivity for Maize in Ethiopia lies between 1.7 and 2.6 kg/m^3, according to a paper by Erkossa, Awulachew, & Aster, 2011. The average water productivity for wheat is between 1 and 2 kg/m^3 in the Delta region, and 1 kg/m^3 in Sub-Saharan Africa (El-Marsafawy et al., 2018; Rattalino Edreira et al., 2018). It is therefore highly unlikely that the process of determining Crop Water Productivity in Ethiopia succeeded. As was mentioned in paragraph 5, Ethiopia did not achieve accurate results, most probably due to eradicate rainfall. This is in accordance with a research on the usability of WA+ in the Awash Basin that (Karimi et al., 2015), where it was concluded that accuracy increased during years with low rainfall. In addition, results indicated that the relative standard deviation for available water, exploitable water, utilized flow, and the outflow, vary from year to year, as a consequence of the combination of the temporal variable rainfall and temporal constant ET (actual evaporation) values.

6. Conclusions and Recommendations

With the launch of the FAO WaPOR data portal, the possibility to obtain more insight into the African continent regarding the hydrological processes and biomass production was expanded. The high spatial and temporal variability of the data allows users to practice various ways of monitoring: Analyzing trends over several years as well as monitoring and comparing differences on different spatial scales are just one of the few options available. Throughout this research, the usability of the FAO WaPOR data portal was assessed by assessing agricultural water management practices and water productivity as a performance indicator in the Eastern Nile Basin. As stated in the introduction chapter, three research questions were defined and attempted to be answered during this thesis. The following paragraphs give an overview of the answers found to each research question respectively.

6.1 Opportunities and Challenges of WaPOR

To answer the first research question, an overall evaluation was done regarding the data and its usability for improved water resource management and efficient water use in agriculture. This study has shown that WaPOR data can be processed into actionable information for various stakeholders and policymakers in particular. However, much data processing and analysis is necessary, leading to the conclusion that a third party should always be involved to translate the data into actionable information. In addition, it has become evident that an accurate land use map is required to cross reference the data that was derived from WaPOR. Throughout this thesis, the assumption was made that crops could be distinguished and recognized, based on the available phenology data. Considering the fact that a 'no season' label is applied when no growing season can be distinguished, agricultural cropland was thought to be identified through this method. However, from the fact that reasonable results complying with the literature are found with the use of the FAO LCC Land Cover Map, it follows that the identification of crops through phenology and blue evaporation data does not provide accurate results. This is especially the case for Ethiopia and to a lesser extent Sudan, likely due to the fact that Egypt has hardly any rainfall and therefore consists almost solely of irrigated agriculture. Similarly, ground truthing should therefore be done regarding crop identification and the presence of irrigation per pixel. The fact that this study covered a large spatial scope within a limited time meant that the analysis had to be narrowed down to small temporal variability. For this reason, only 2016 and 2015 have been used for analysis.

The following findings should be considered when WaPOR data is used for similar objectives such as the results of this thesis:

- With the outcome of this thesis, WaPOR data has successfully proven its capability to be used for monitoring in terms of showing trends and variability. In addition, results show that crop water productivity can be used as a key performance indicator for efficient water use in agriculture on national level. However, performing a qualitative assessment that is based purely on WaPOR data is not recommended without using additional ground data for validation. This is especially the case for water productivity, as crops have been distinguished based on phenology and above ground biomass production. With ground data, reliable crop information can be used for a more accurate assessment of water productivity as well as for validation of the phenology and biomass data.
- Processing the data was an unforeseen challenge. Due to the large scope of the thesis, many pixels had to be processed simultaneously. Although Google Earth Engine was able to perform the

calculations and compute the results, it is recommended to work with smaller scales to optimize computational abilities. This is especially the case for water productivity, as it requires additional datasets for its computation. In addition, an assessment on a smaller scale would allow for better data optimization and analysis. With an emphasis on water resource management, there is great potential to optimize data quality by a thorough assessment, so that noise data can be filtered out.

6.2 WaPOR for water resource management (Irrigation practices)

Overall ratios and variability for each month regarding the actual evaporation, blue evaporation and precipitation seem valid; Blue evaporation clearly decreases during months where there is rainfall, implying that less irrigation occurs during wet months. The application of the FAO WaPOR LCC mask showed an increase in average values while maintaining the same ratios. The higher average values seem to be more accurate considering the high amount of evaporation that should occur during crop growth.

To answer the second research question, water withdrawals were calculated by means of blue evaporation, multiplied with the pixel resolution. Calculating water withdrawals by summing up all pixels that contain blue evaporation and subsequently multiplying this with the pixel size gave a promising outcome for Egypt, as the calculated water withdrawals were almost similar to the water withdrawals stated by AQUASTAT. However, numbers differed by a factor 10 for both Sudan and Ethiopia, implying that blue evaporation becomes less reliable when there is more (eradicate and heavy) rainfall present, subsequently leading to a high soil moisture content. When soil moisture subsequently evaporates when it could be perceived as blue evaporation in areas where no irrigation takes place but is then considered as an irrigated pixel.

When the FAO WaPOR LCC mask is applied, better results are achieved. The calculated water withdrawals for Egypt, Sudan, and Ethiopia are lower than FAO AQUASTAT's numbers. For Egypt, the discrepancy is the highest, with a factor 2 difference, and lowest for Ethiopia, which' result is in exact accordance with AQUASTAT's data. It should, however, be noted that FAO AQUASTAT's numbers are based on the required water withdrawals, while WaPOR calculates the effective water withdrawals. Lower values could imply low efficiencies of the irrigation systems, which is not uncommon for both Egypt and Sudan. With a typical irrigation efficiency of 60 to 70% (Howell, 2003), the total amount of water withdrawals can be computed with $Q_{irrigation}/0.65$ (Kwast et al., 2016). When this is taken into consideration, the results seem promising.

Calculating the mode average with an additional filter was done, in an attempt to investigate whether better results could be obtained by assessing the data statistically and filter out what could be considered noise data. First, a histogram visualizing blue evaporation of a month was created to assess which low values occurred in high frequencies. Subsequently, these values were masked, assuming that they were wrongly perceived as blue evaporation due to, for example, a high soil moisture content. The result of the modified mask seemed reasonable for Egypt but far less for Sudan and Ethiopia. The simple reason for this was the fact that the same mask could be applied for each month in the case of Egypt since Egypt has no high variability due to lack of rain. For Sudan and Ethiopia, every month had completely different histograms and much variability. In addition, assessing large spatial areas contributes to higher variability in data, making it more difficult to distinguish noise. By looking at a smaller scale, it is most likely easier to distinguish noise. In addition, customized masks for each month would maybe give more accurate results.

In conclusion, the application of WaPOR data to calculate water withdrawals has great potential. By looking at the monthly variations, it is able to show accurate trends regarding irrigation versus the amount of rainfall that takes place during a month. In addition, the qualitative analysis shows promising results when compared to the data derived from FAO AQUASTAT, mentioned in chapter 3. It would be interesting to track the performance of a specific month over several years, to see how water management progresses over the years and to investigate the influence of climate change. It goes without saying that ground data would be a valuable asset to validate the calculated results. Most importantly, a reliable irrigation map would particularly be valuable for the validation of blue evaporation.

6.3 WaPOR for efficient water use in agriculture (Crop Water Productivity)

Although the methodology to determine crop water productivity is relatively straightforward, overlapping phenologies of crops and the indistinct connection with the above ground biomass data are factors that caused unreliable results. In addition, accurate results also depend on the ability to distinguish between irrigated and rainfed areas. The high CWP values that were found in Ethiopia are high compared to the reasonable values found in Egypt and Sudan. This could possibly be due to the fact that the pixels are wrongly identified as irrigated pixels. After all, CWP was assessed for all pixels that contain blue evaporation as the FAO WaPOR LCC mask was not applied. It is therefore recommended to use an accurate land use mask when CWP is assessed. In addition, the fact that Ethiopia has multiple crop seasons could also be a reason for unreliable results, considering the fact that only two cropping seasons are distinguished with Above Ground Biomass Production Data, as well as the phenology data within WaPOR.

The objective of this research was to decouple the ‘management’ and ‘physical’ factors that affect variability in Crop Water Productivity (hereafter: CWP). By assessing CWP within an agro-ecological zone (hereafter: AEZ), the physical factor is neutralized, leaving the possible factor affecting the variability to agricultural and/or water management practices. Throughout the assessment, it became evident that agro-ecological zones still have a considerate spatial scale. Therefore, the resolution had to be downscaled from 100m to 250m for Google Earth Engine to produce results.

The frequency distribution of CWP data within an AEZ show the most occurring values as well as the outliers. These latter values give a good indication to what extent CWP values could be improved (so-called “best practices”). Furthermore, the subtle differences in average CWP values indicate that there are different optimums for each crop per AEZ.

In conclusion, small-scale assessments and monitoring of CWP can give good indications on best practices and indicate low-hanging. However, water productivity becomes more valuable when it is linked to the individual biomass and/or water consumption data of a pixel. In doing so, the reason for low or high CWP values can be better understood. Depending on the objective, a higher yield, or less water consumption, action can be taken accordingly.

Eventually, CWP values could be scored and compared to other countries, sub-basins or water catchments, to make a final conclusion on water productivity within the transboundary context of the Nile River Basin. However, to make meaningful comparisons between CWP values in different climates (e.g., the different countries) feasible, an analysis of CWP would require a climatic normalization, such as proposed by Bastiaanssen et al. (Bastiaanssen & Steduto, 2017).

Crop Water Productivity will become available on WaPOR in the near future and is calculated by dividing AGBP by the AETI (Personal communication with Jippe Hoogeveen and Livia Peiser, FAO WaPOR).

References

Abd El-Hafeez, Z., Samiha, O., Wael, H., & S., E.-S. (2017). Evaluation of different crop sequences for wheat and maize in sandy soil. *Acta Agriculturae Slovenica.*, *109*(september), 383–392. https://doi.org/10.14720/aas.2017.109.2.21

Abdelsalam, N. M., Aziz, M. S., & Agrama, A. A. (2014). Quantitative and financial impacts of Nile river inflow reduction on hydropower and irrigation in Egypt. *Energy Procedia*, *50*, 652–661. https://doi.org/10.1016/j.egypro.2014.06.080

Al Zayed, I. S., Elagib, N. A., Ribbe, L., & Heinrich, J. (2015). Spatio-temporal performance of large-scale Gezira Irrigation Scheme, Sudan. *Agricultural Systems*, *133*, 131–142. https://doi.org/10.1016/J.AGSY.2014.10.009

Bastiaanssen, W.G.M., Coerver, B. (2017). *Water Accounting Plus (WA+) Framework* (Vol. 1). Delft. Retrieved from http://wateraccounting.org/

Bastiaanssen, W. G. M., & Steduto, P. (2017). *The water productivity score (WPS) at global and regional level: Methodology and first results from remote sensing measurements of wheat, rice and maize*. *Science of The Total Environment* (Vol. 575). Elsevier. https://doi.org/10.1016/J.SCITOTENV.2016.09.032

Brouwer, C., Goffeau, A., & Heibloem, M. (1985). Irrigation Water Management: Training Manual No. 1- Introduction to Irrigation. *Irrigation Water Management*.

Budyko, M. I. (1974). *Climate and Life*. Orlando.

Donohue, R. J., Roderick, M. L., & McVicar, T. R. (2007). On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth System Sciences*, *11*(2), 983–995. https://doi.org/10.5194/hess-11-983-2007

El-Marsafawy, S. M., Swelam, A., & Ghanem, A. (2018). Evolution of crop water productivity in the Nile Delta over three decades (1985-2015). *Water (Switzerland)*, *10*(9). https://doi.org/10.3390/w10091168

Erkossa, T., Awulachew, S. B., & Aster, D. (2011). Soil fertility effect on water productivity of maize in the upper blue nile basin, Ethiopia. *Agricultural Sciences*, *02*(03), 238–247. https://doi.org/10.4236/as.2011.23032

FAO. (n.d.). Remote sensing for water productivity. Retrieved July 6, 2018, from http://www.fao.org/in-action/remote-sensing-for-water-productivity/water-and-land-productivity-assessment/wl-productivity-overview/en/

FAO. (2014). *FAO Project Proposal WaPOR*.

FAO. (2015). AQUASTAT - FAO's Information System on Water and Agriculture (SUDAN). Retrieved May 12, 2018, from http://www.fao.org/nr/water/aquastat/countries_regions/SDN/

FAO. (2016a). AQUASTAT - FAO's Information System on Water and Agriculture (EGYPT). Retrieved May 12, 2018, from http://www.fao.org/nr/water/aquastat/countries_regions/EGY/

FAO. (2016b). AQUASTAT - FAO's Information System on Water and Agriculture (ETHIOPIA). Retrieved May 12, 2018, from http://www.fao.org/nr/water/aquastat/countries_regions/ETH/

FAO. (2017). *WaPOR Database methodology: Level 2 data*. Rome.

FAO Crop Calendar. (n.d.). FAO Crop Calendar. Retrieved May 1, 2018, from http://www.fao.org/agriculture/seed/cropcalendar/welcome.do

FAO Land and Water Division. (1996). *AGRO-ECOLOGICAL ZONING: Guidelines*.

Fekadu, K. (2015). Ethiopian Seasonal Rainfall Variability and Prediction Using Canonical Correlation Analysis (CCA). *Earth Sciences*, *4*(3), 112. https://doi.org/10.11648/j.earth.20150403.14

Gerrits, A. M. J., Savenije, H. H. G., Veling, E. J. M., & Pfister, L. (2009). Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model. *Water Resources*

Research, *45*(4), 1–15. https://doi.org/10.1029/2008WR007308
Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031
Harvest index | Plants in Action. (n.d.). Retrieved October 5, 2018, from http://plantsinaction.science.uq.edu.au/content/641-harvest-index
Howell, T. A. (2003). Irrigation Efficiency. *Encyclopedia of Water Science*, (2003), 467–472. https://doi.org/10.1081/E-EWS
Karimi, P., Bastiaanssen, W. G. M., Sood, A., Hoogeveen, J., Peiser, L., Bastidas-Obando, E., & Dost, R. J. (2015). Spatial evapotranspiration, rainfall and land use data in water accounting-Part 2: Reliability of water acounting results for policy decisions in the Awash Basin. *Hydrol. Earth Syst. Sci*, *19*, 533–550. https://doi.org/10.5194/hess-19-533-2015
Kwast, J. Van Der, Bastiaanssen, W., Uyttendaele, T., & Hessels, T. (2016). *Estimating Water Consumption with a 30 m Grid for Irrigated Land in Colombia During 2012*.
National Planning Commission. (2016). Federal Democratic Republic of Ethiopia: Growth and Transformation Plan II (GTP II), *I*(May), 236.
Nile Basin Initative. (n.d.). Irrigation areas in Sudan – Nile Basin Water Resources Atlas. Retrieved July 4, 2018, from http://atlas.nilebasin.org/treatise/irrigation-areas-in-sudan/
Nour El-Din, M. M. (2013). *Proposed Climate Change Adaptation Strategy for the Ministry of Water Resources & Irrigation in Egypt*. Cairo. Retrieved from http://www.eeaa.gov.eg/portals/0/eeaaReports/CCRMP/7. CC Water Strategy/CC Final Submitted 8-March 2013 AdptStrtgy.pdf
Rattalino Edreira, J. I., Guilpart, N., Sadras, V., Cassman, K. G., van Ittersum, M. K., Schils, R. L. M., & Grassini, P. (2018). Water productivity of rainfed maize and wheat: A local to global perspective. *Agricultural and Forest Meteorology*, *259*, 364–373. https://doi.org/10.1016/j.agrformet.2018.05.019
Savenije, H. H. G. (2004). The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes*, *18*(8), 1507–1511. https://doi.org/10.1002/hyp.5563
Shuttleworth, W. J., M. (1993). Evaporation. In D. R. Maidment (Ed.), *Handbook of Hydrology*. New York: McGraw-Hill.
UN. (2017). Satellite System and Copernicus : Supporting the Sustainable Development Goals.
UN FAO. (2018). *Progress on Water-use Efficiency*. Rome.
United Nations. (n.d.). Transforming our world. https://doi.org/10.1007/s13398-014-0173-7.2
Water, Food and Energy | UN-Water. (n.d.). Retrieved June 20, 2018, from http://www.unwater.org/water-facts/water-food-and-energy/
Zwart, S. J., & Bastiaanssen, W. G. M. (n.d.). SEBAL for detecting spatial variation of water productivity and scope for improvement in eight irrigated wheat systems. https://doi.org/10.1016/j.agwat.2007.02.002
Zwart, S. J., & Bastiaanssen, W. G. M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, *69*(2), 115–133. https://doi.org/10.1016/J.AGWAT.2004.04.007
Zwart, S. J., Bastiaanssen, W. G. M., de Fraiture, C., & Molden, D. J. (2010a). A global benchmark map of water productivity for rainfed and irrigated wheat. *Agricultural Water Management*, *97*(10), 1617–1627. https://doi.org/10.1016/j.agwat.2010.05.018
Zwart, S. J., Bastiaanssen, W. G. M., de Fraiture, C., & Molden, D. J. (2010b). WATPRO: A remote sensing based model for mapping water productivity of wheat. *Agricultural Water Management*, *97*(10), 1628–1636. https://doi.org/10.1016/j.agwat.2010.05.017