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# THE ECONOMIC IMPORTANCE OF WATER IN THE AGRICULTURAL SECTOR OF THE ARAB REGION: CASE STUDY OF WATER FOOTPRINT IN EGYPT

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The aim of this dissertation is to obtain a doctoral (PhD) degree in the scientific field of
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# INTRODUCTION

Since the dawn of history, people have settled places near water sources, whether they are rivers, springs, oases, or wells, in order to meet their main needs, whether in agriculture or domestic uses (drinking, cooking, etc.). Despite the current great technological progress that affects all aspects of life, especially the economy, the latter remains strongly dependent on natural resources, particularly the water.

The vitality of water for the economy throughout the ages has resulted in the emergence of what is known as “water economies,” which are meant to calculate its impact on growth rates and estimate the effects of its absence or scarcity on the economy, in all its agricultural, industrial, or service activities. The Global Risk Insight group notes that even in the modern era, large companies prefer to base their headquarters in cities like Chicago over Michigan because of the availability or absence of water. Therefore, 41% of the world's population is concentrated around rivers, and despite the advances in infrastructure and methods of delivering them to cities, preferences remain in settlement of areas near the water, even in developed countries with high technology. With the world population more than doubling during the last fifty years and the relative decline of renewable water resources, it has become vital to know the nature of water consumption in various countries of the world and its impact on the economy (Dubois, 2011; Gielen et al., 2019).

According to a study by "FAO", various industries consume 59% of water in developed countries, while an accurate percentage of consumption is not available in developing countries, but the percentage of water consumption for agricultural and domestic purposes exceeds industrial purposes in most countries. This is due to two reasons, the first is the abundance of water enjoyed by the majority of water countries, as most of them are classified as water-rich countries, which allows for increased use of the industry (thriving in those countries), as well as the relatively efficient use of water in developed countries (Food & Nations, 2017).

The proportion of water used in agriculture globally is estimated at 70% of freshwater (that are not subject to desalination processes or reused), indicating the large proportion that developing countries consume in agriculture compared to those developed. Perhaps this prompted UNESCO to warn that producing one kilogram of rice requires the consumption of 3 cubic meters of water. Therefore, the organization called on countries that suffer from water crises to stay away from cultivating it and be satisfied with it in countries that depend on rain and floodwaters (Steduto et al., 2012).

A World Bank study indicates that global warming and the reduction in the amount of available water will cost some economies up to 6% of GDP, due to the inability to provide water for agriculture or industry, or even the need to move factories or make infrastructure changes (Bank, 2016).

The countries of the Middle East and sub-Saharan Africa are at the forefront of countries that are threatened with losing large proportions of their GDP by 2050 if they do not make drastic changes in the way water is used to impact the shortage on agriculture, industry, and public health. In sub-Saharan Africa, the World Bank estimates that these countries need to invest 3% of their GDP annually to improve irrigation methods, water use, building dams, and so on to avoid a significant decline in the size of their economy. Despite this, the percentage of investment in water and technology related to its storage and consumption in sub-Saharan countries does not exceed 0.3% of their GDP, which indicates the possibility of an escalation of the crises they suffer from due to water scarcity and plunge them into a cycle of economic decline and even humanitarian crises. On the other hand, countries that have worked to improve their use of water by reducing losses by 25%, their GDP will improve by 3-4% due to the abundance of water, which is what happened in South Africa, which is cited by the "FAO" organization, for example. The state approved a new irrigation system and extensive programs to improve water use in homes and industries, which resulted in reducing the use of water for irrigation from 80% in the early third millennium to 62% in 2016, without affecting crops while public health and industry benefited from the abundance (Faurès & Santini, 2008).

Estimates by the World Resources Institute indicate that 37% of the world's countries suffer from "great pressures" on their water resources, while a third comes in "acceptable risks" and 30% in water abundance, while 20% of the world's countries are threatened with regression in the ranking. water security” with the increase in population. Indeed, two-thirds of the world's population will be threatened by water shortages by 2025, between normal and severe shortages, especially if population growth rates and agricultural, industrial, and household consumption remain the same. In countries that suffer from “great pressures” on water, the percentage of its use in agriculture rises to 80% in an attempt to provide food for the population of those countries, but this leaves only 20% of the water resources for industry and household uses and indicates an escalating crisis in those countries (Watson et al., 2000).

Singapore is one of the countries suffering the most from a shortage of water resources, as there are no lakes in the city-state, and there are no rivers that can be relied on for irrigation or industrial uses. Perhaps this is what prompted the small country to invest heavily in “water technology” where rainwater directing systems contribute to 20% of the country’s water needs, 40% are imported from Malaysia, while “grey water” (reused water) contributes After purification by 30%), seawater desalination contributes to 10% (Frenken, 2012).

The countries of water abundance are limited to Europe and Canada, while some countries vary internally. In China, there are some areas that are considered to be water-abundant, and the same is true in the United States, but some areas of the two countries are vast in size and suffer from a water shortage. For example, China suffered from a severe drought in 2006 that destroyed crops valued at more than 300 million dollars, and this affected the resources of 95 million Chinese, prompting the Chinese government at the time to adopt a wide compensation program for those affected by drought (Xie, 2008).

FAO monitors the attempts of countries to use water efficiently, using a combination of market mechanisms and "state sponsors", by raising water prices for water users extensively, while supporting those who are economical in using water. In this context, the World Bank stresses the need to invest in the technology of water extraction, rain exploitation, water reuse and seawater desalination, in light of the continuous increase in demand for water with the steady increase in the global population (Bank, 2018).

In one of its sustainable development reports, the United Nations points out the importance of accessing reused (grey) water to about 50-60% of the water used in homes and factories, which allows for significant savings in renewable water and improves levels of public health and even economic activity. This water can be used for multiple purposes such as cleaning, washing clothes and sanitation, giving more space that does not serve clean water for drinking, cooking and agricultural purposes. The World Bank warns that the continued impact of water shortages in many regions will lead to higher food prices, which may eventually lead to conflicts between countries due to lack of resources, so that water becomes a crucial element not only for life but for the economy and "global peace" (Nations, 2019).

Thus, to preserve the water resources and their sources in the world requires greater efforts by researchers and the creation of new and innovative ideas such as the water footprint that will be the subject of research.

# 1. TOPICS AND OBJECTIVES

This structure of the thesis was chosen since the research, in general, discusses water management, water efficiency, and agricultural practices, which is a complex and rather broad topic. To make use of numerous concepts provided in the realm of water and agriculture, the thesis was organized into five chapters. Furthermore, different research methods were applied for each segment to better explain the results. This dissertation employs fifth chapters: In the first chapter of the dissertation, the general literature was reviewed regarding the water footprint, the concept of virtual water, the state of renewable water and food security in Egypt. Additionally, through the hydro-analysis of the reality of the Arab region - known as drought and the lack of available water resources - to reach the concept of sustainability, especially in the agricultural sector, which is what was discussed in the second part of the literature.

In the second chapter of the research, the water situation was assessed by applying the principle of virtual water and the concept of the water footprint of some selected crops in the agricultural sector, and the case study of Egypt. The third chapter of the thesis was utilized by calculating the internal water footprint for three critical crops in Egypt and determining whether there is an effect of temperature, precipitation, crop productivity, and renewable water resources on crop production throughout the study period.

In the fourth chapter, the food-gap in Egypt has been optimized due to the possibility of reaching the desired food security for some crops and their water consumption.

Finally, in the fifth chapter, the impact of water policy on economic development in Egypt for three sectors and its impact on GDP was evaluated.

## 1.1. The objectives of the research

The main objective of this research is to delve into the concepts of the water footprint and virtual water and try to collect the ideas of researchers and heal the rift that occurred as a result of lack of data, especially in developing countries that are already suffering from water shortage. The objectives of the research can be summarized as follows:

1. Achieving sustainable agriculture and food development through the efficient use of water resources in the agricultural sector in the Arab region;
2. To benefit from the principle of virtual water and water footprint indicators for:
    - Knowing the true magnitude of the water deficit in Egypt;

   - Using water more efficiently in the agricultural sector.
3. Analysis of the internal water footprint IWFP variation for three major crops (rice, maize, and wheat), in terms of several related factors that are: annual average precipitation, annual average temperature, productivity of the crops and the renewable water resource during the period between 2000-2018 in Egypt;
4. Determine and calculate the Food-Gap during 2000-2018 for the most important food crops in Egypt:
   - Minimizing the Food-Gap in Egypt by building a mathematical model to find the optimum land reallocation and production distribution for main important crops;
5. Determining the water consumption and the food demand for the same study period;
6. Evaluating the water policy during the study period 1988-2018 and develop results and recommendations that enable building rational and correct policies to raise the efficiency of utilizing and allocating water resources for the purpose of development.

In this research, all objectives will be analyzed to reach practical results and proposals that can be applied anywhere, especially in areas that suffer from water shortage.

## 1.2. Research questions and research hypotheses

The dissertation is composed of fifth chapters, the first chapter is the research background about the water footprint, virtual water, and the sustainable agricultural development in the Arab region and after that each chapter has a research questions and research hypotheses as following:

**RQ1 (Chapter 2):** *How to use the principles of virtual water and water footprint indicators to estimate the volume of water deficit in Egypt and to achieve water efficiency consumption in the agricultural sector?* To answer this question, the following has applied:

- Calculating the virtual water for the most important agricultural crops in Egypt;
- Calculating the virtual water for the agricultural products;
- Assessment of the water footprint and its indicators in Egypt;
- Evaluating the food security and estimating food self-sufficiency for some selected crops and products.

**RQ2 (Chapter 3):** *How the climatic factors; the temperature and the precipitation; the renewable water resource and the targeted productivity influence the internal water footprint of three crops (wheat, maize, and rice) in Egypt?* The following questions were discussed:

- **RQ2.1:** *Are there any fluctuations in the annual average precipitation, annual average temperature, the productivity of the crops and renewable water resource during 2000-2018?*
- **RQ2.2:** *Is there any effect of the selected variables (renewable water resource, productivity, temperature, and precipitation) on the internal water footprint? And this effect can be proved statistically?*

To answer these questions, the existence of long run relationship or cointegration between the variables was investigated under the following hypotheses:

- <u>The Null hypothesis</u>: the negative and the positive change of (precipitation, renewable water resource, temperature, and productivity) are statistically different in the long run.

- <u>The alternative hypothesis:</u> the negative and the positive change of (precipitation, renewable water resource, temperature, and productivity) are not statistically different in the long run.

A joint null hypothesis of $\left(-\frac{\alpha_2}{\alpha_1} = -\frac{\alpha_3}{\alpha_1}\right)$ was tested. The rejection of the hypothesis will indicate sufficient evidence for long run asymmetry.

**RQ3 (Chapter 4):** *How the food gap affects the staple commodities for the Egyptian state that bears the burden of providing a high budget to stipend the importations usually being paid for with foreign currency?*

**RQ4 (Chapter 4):** *Can the reallocation of agricultural land in Egypt help in bridging the food gap and saving food for the high population increase, as well as providing foreign exchange through the export of some crops?*

**RQ5 (Chapter 4):** *Is the water consumption of the crop a significant variable to explain the food gap changes, or not?* The following hypotheses were addressed:

- If the $T_{count} > T_{table}$ or sig. (*p*-value) $< 0.05$, then the variable water consumption influences food gap;
- and if the $T_{count} < T_{table}$ or sig. (*p*-value) $> 0.05$, then the variable water consumption does not influence food gap.

**RQ6 (Chapter 5):** *How can the water policy, by directing the water use, contribute to raising the standard of living of the population in Egypt and accelerate the pace of development?* The following hypotheses were addressed:

- $H_0$: There is no statistically significant relationship between water withdrawal in the different sectors (municipal, agricultural, and industrial) and Egyptian GDP growth.
- $H_1$: There is a statistically significant relationship between water withdrawal in the different sectors (municipal, agricultural, and industrial) and Egyptian GDP growth.

### 1.3. Research Approach

The dissertation will begin with a research background to reveal the research gap and confirming the theory about water footprint, virtual water, water resources and food security in Egypt. In addition, studying sustainable agriculture and food development through efficient water use in the Arab agricultural sector. And Figure 1 shows the progression approach for this study.

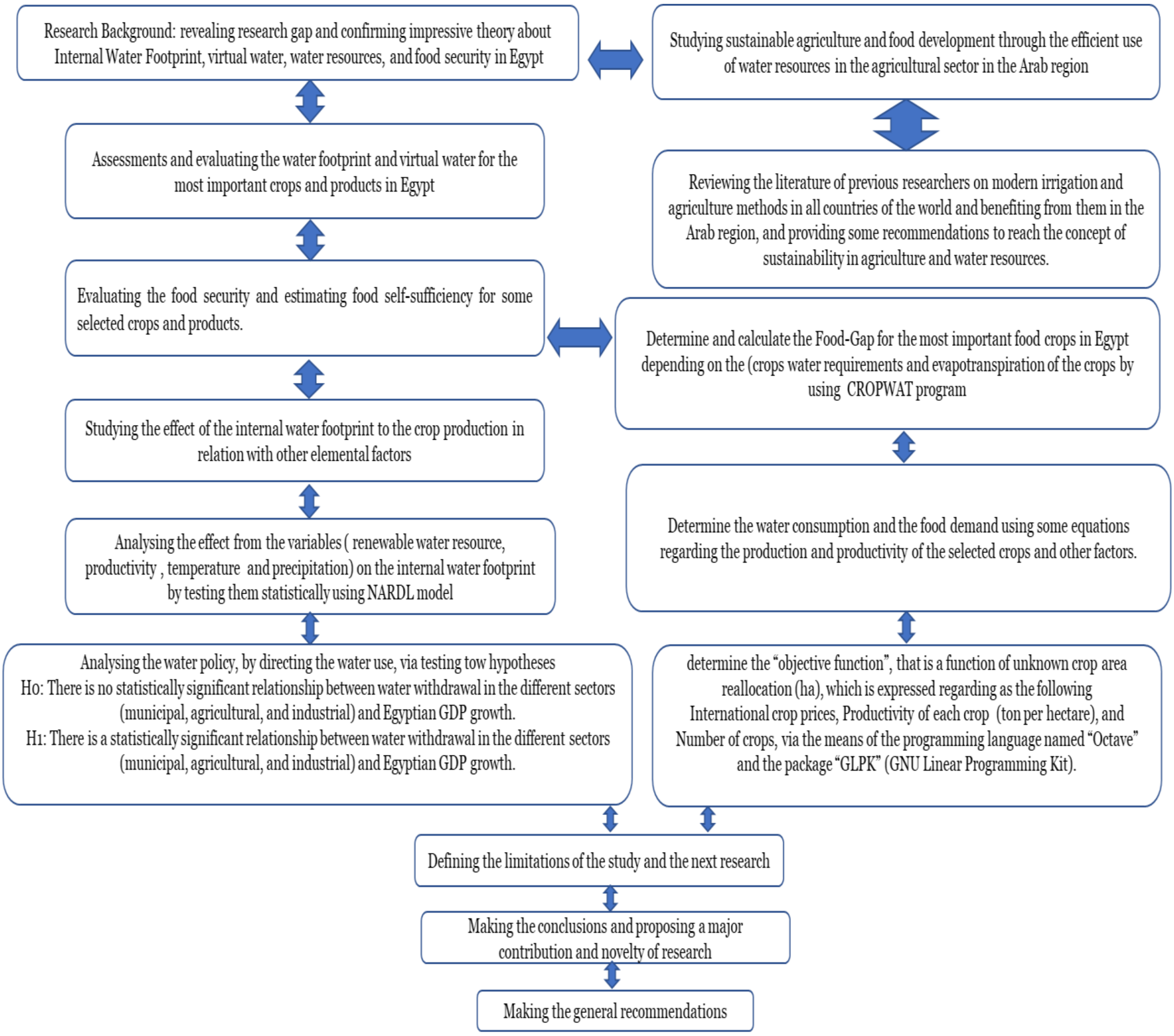

**Figure 1: Logical framework of the research approach**

*Source: Own constructed, 2021*

The next chapters will go deeper into all of the factors depicted in Figure 1, beginning with the research's overall literature review.

# 2. GENERAL LITERATURE REVIEW

The main topic of this research is the economic importance of water in the agricultural sector in the Arab region: a case study of the water footprint in Egypt, where the researchers attempt to discover new techniques and ideas to preserve water resources and their sources around the world, such as the water footprint and virtual water, as mentioned in the introduction, and given the importance of this, the concerns are relatively new, particularly in the Arab world, mainly based on the water footprint. In order to create and organize thoughts, the literature on the concepts of water footprint and virtual water was analyzed, as well as the gaps in it, in order to develop and arrange thoughts, along with produce and adopt new ideas to meet the research objectives. sustainable agricultural development in the Arab region, on the other hand, was discussed after gathering a number of methodologies in irrigation, water management, and crop science during a discussion of about three concepts in order to provide some recommendations if these methods are used effectively in the Arab region.

## 2.1. Water Footprint

Human activities consume and pollute a lot of water at national and international levels. The agricultural sector is the largest one consuming and polluting water, followed by industrial and household sectors (Parris, 2011). Water consumption and pollution are closely related to many different human activities such as irrigation, bathing, washing, cleaning, cooling, and several other industrial activities. In the past, there was insufficient attention paid to the relationship between total water consumption and pollution in local communities (ARJEN Y. HOEKSTRA, 2017), and the structure of the global economy that provides consumer goods and various services (Satterthwaite et al., 2010). Until a few years ago, there were a few ideas in the science and practice of water resource management in terms of consumption and pollution during the production processes, and as a result, there was insufficient knowledge about the quantities of water that could be consumed and that could be contaminated in conjunction until the final product arrived for the consumer (HOEKSTRA & HUNG, 2003).

In 2008, both HOEKSTRA and CHAPAGAIN showed that the demonstration and evaluation of the virtual water behind the products can help in understanding the global importance of freshwater. They had also shown that measuring the effects of consumption and trade on the use of local and global water resources and a good awareness of these concepts can improve the water resource management at the national and global levels (CHAPAGAIN & HOEKSTRA, 2008).

Freshwater is quickly becoming a very important global resource due to the continuous and steady increase in trade in commodities that are intensively using freshwaters such as crops and their products, livestock, and their products, and bio-energy. This trade is not limited to local and regional markets but extends to international markets as well (Hertel & Liu, 2019). As a result of the global trade in products and commodities, there is no so-called spatial connection between the use of water resources and consumers, for example, cotton, which goes through many stages of production in time and space with different impacts and water needs, in terms of quantity and quality, until reaching the final consumer (Hoekstra, 2010). For example, Malaysia does not plant cotton, but it imports the raw cotton from China, India, and Pakistan, and after processing and industrializing, it is exporting it to Europe in the form of textiles and clothing (OECD et al., 2018; Ward et al., 2016). Hence, the impact of using cotton products on freshwater cannot be assessed in the world except keeping the tracking of the origin of the product and the steps of its manufactures and productions (Chapagain, Hoekstra, Savenije, et al., 2005). Uncovering the hidden link between the consumption of products, commodities, and water uses will be the basic concepts of the new strategies for managing water resources at the local, regional, and global levels. Although the end consumers, retailers, and food industry owners of water-intensive products are outside the scope of those who have studied water management well, they are the new players who will enter the picture, not as direct water users, but also as indirect consumers of freshwater (Unies, 2009).

The idea of tracking the use of freshwater along with the supply and production stages gained a lot of importance after the introduction of the concept of "water footprint" by HOEKSTRA in 2002 (A. Hoekstra, 2003). The water footprint is not an indication of the use of fresh water in the direct use of the consumer or commodity only, but also in the other use direct. The water footprint can be considered as a comprehensive indicator of freshwater dependence, along with other traditional indicators of water consumption. The water footprint of a commodity is the volume of freshwater used in the production of this commodity, and it is measured over the entire process, preparation, and production stages. It is a multidimensional indicator that includes the volume of water consumption, the size and type of pollution resulting from production processes (Hoekstra et al., 2011). All components of the water footprint are determined by the place and time. Figure 2 shows the main types of water footprints:

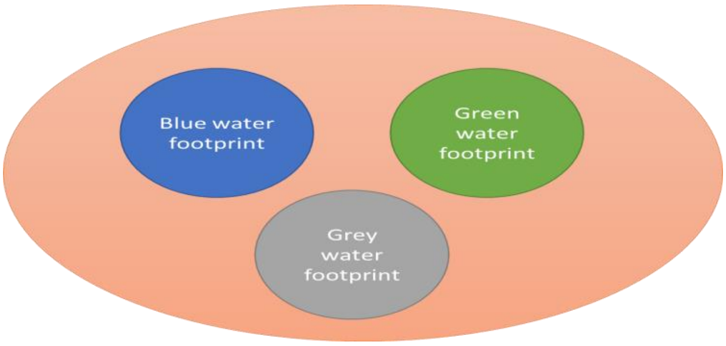

**Figure 2: The main types of water footprints. Source** ***Hoekstra et al., 2011***

1) **Blue water footprint**: the blue water can be defined as the water coming from rivers and groundwater. The blue water footprint indicates the volume of blue water consumed across all production lines, stages, and processes of a product or commodity. "Consumption" refers to the loss of available water, whether its source is groundwater or surface water in the area of water harvesting basins. The loss of water is either by evaporation or by moving to other areas through surface runoff, or by transport through pipelines, or through a product that is produced (DICTIONARY OF WATER TERMS-USGS).
2) **Green water footprint:** it refers to the consumption of green water resources; which is mostly rainwater, used directly for the production of crops or the development of livestock through natural pastures or any other uses. Green water is not left to flow to other areas outside the catchment area.
3) **Grey water footprint:** generally, refers to pollution, and it is defined as the volume of fresh water required to absorb the pollutant load resulting from a particular process, and it gives a background on the naturalness of the basic concentrations and the existing standards for water quality in the surrounding area.

The water footprint as an *indicator* of water use differs from other traditional indicators that rely on measuring water consumption in three basic and important points as shown in Figure 3, and these points are following:

- This indicator does not include the use of blue water only, but rather, it indicates the source, type, and its origin;
- This indicator is not limited to the use of blue water but also includes green and grey water;
- This indicator is not restricted to the direct use of water but also includes indirect water uses.

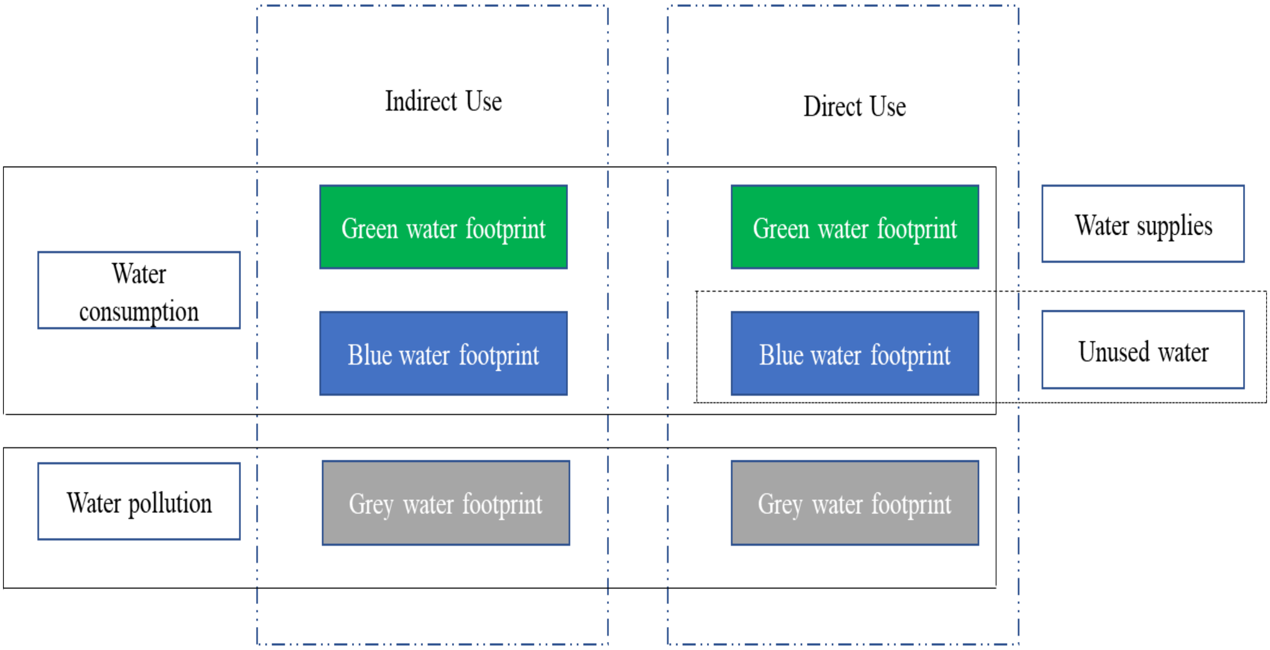

**Figure 3: The water footprint for commodity or consumer**

*Source: MEKONNEN & HOEKSTRA, 2011a*

The water footprint, in general, does not take into account the unused water in production, and takes into account the grey water, green water, and other elements of indirect water usage. The water footprint provides, on a large scale, a better perspective on how to use the freshwater systems for any consumer or producer, and it is a measure of volumetric water consumption and pollution incident to it, and not a measure of the severity of the local environment's vulnerability to consumption and pollution of freshwater, because the environmental impact of water consumption and pollution is due to water systems - the number of consumers and sources of pollution (Chapagain & Tickner, 2012; Hogeboom, 2020). Water footprint calculations give clear information about how water is allocated for various human purposes, and it is also a good and important basis for assessing the local, environmental, social, and economic impacts of freshwater uses.

### *2.1.1. Types of Water Footprint*

It is known that blue water resources are scarce, and are costly than that of green water. This may be a reason to focus on what represents the blue water footprint only. However, green water resources are also finite and scarce, which gives an excuse for calculating the green water footprint. Green water can also be replaced by blue water in agriculture, and vice versa, so that a complete picture can only be obtained by calculating the two altogether (Mao et al., 2018). The argument for including green water in the calculations of the water footprint is that; over the ages, only blue water was relied upon, which led to the neglect of green water, despite it being a very important factor in agricultural and animal production (Mekonnen & Hoekstra, 2010). The grey water footprint is estimated in order to express water pollution in terms of the volume of pollution so that it can be compared with water consumption, which is also expressed as a unit of volume. The relative cost of water pollution and consumption of the available resources will be closely related to the calculation of the grey water footprint and the blue footprint (A. Y. Hoekstra et al., 2009).

### *2.1.2. Water Footprint Estimation*

Estimating the water footprint of a consumer, a group of consumers, or an entire economic sector of consumers has become a matter of interest, and this is done within a specific geographical area such as a governorate or state, and also for surface water collection basins or river basins. The water footprint of a region is the product of the aggregation of several water footprints for many products, goods, and services in this region. The water footprint, as an analytical tool, can be useful in understanding the activities and services related to the scarcity and pollution of fresh water and the expected impacts, as well as understanding what can be completed to ensure that these activities and products do not affect the sustainability of freshwater, in terms of quantity and quality of water, and it is a tool that provides insight to learners to helps them understand what needs to be done related to the saving water worldwide (Hoekstra, 2009).

#### *2.1.2.1. The Stages of Water Footprint Estimation*

The estimation and calculation of the water footprint refers to a whole group of diverse and successive activities. Determining the location of the water footprint from the production or consumption process, determining the place and time of the water footprint in a specific geographical area, assessing the environmental, social, and economic sustainability of this water footprint, and then developing a strategy to respond and ward off the dangers (Hoekstra et al., 2011; Kuiper et al., 2010). In general, the aim of assessing the impacts of the water footprint is to analyse how specific human activities or products related to issues of water scarcity and pollution become more sustainable from a water perspective. Estimating the water footprint is important for several reasons, for example:

- Some governments may need to know the extent of dependence on foreign water resources to meet their requirements, and perhaps to also know the extent to which freshwater is sustainable for use in an area when producing any of the crops of intensive usage of fresh water (Mittal & Mousseau, 2011; Zoomers, 2010).

- The management of a basin may be able to know whether the combined water footprint of human activities inside the basin violates the requirements of environmental flow or water quality standards at any time, and also know the feasibility of growing low-value crops in times and during the years of water scarcity (Zeng et al., 2012).
- There are production companies that would like to know the extent of their dependence on water resources in their production lines or how they can contribute to reducing impacts on the water system in all production steps within their operations (Cosgrove & Loucks, 2015).

The water footprint can be estimated and calculated for a single step, for some production steps, for an integrated production chain, or a product as shown in Figure 4.

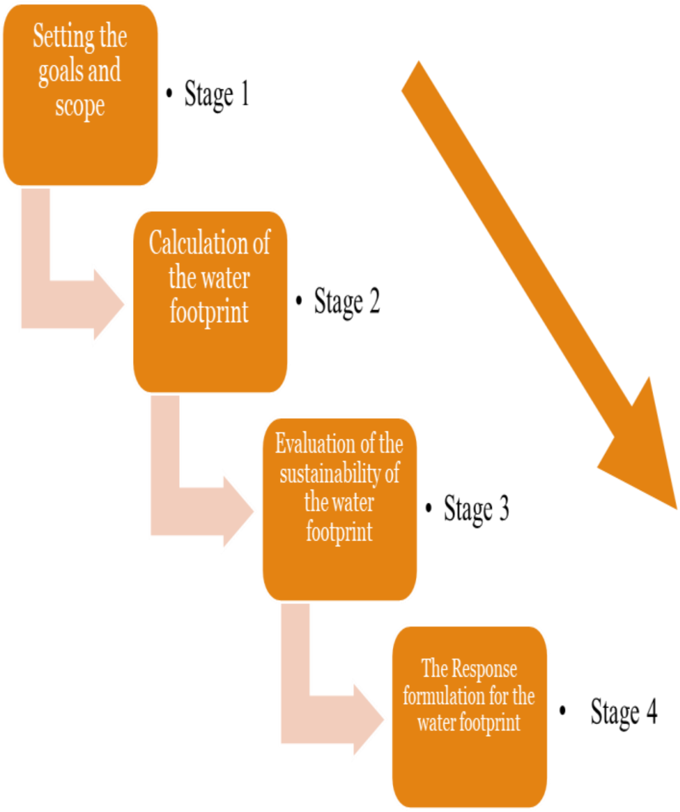

**Figure 4:The stages of assessing and evaluating the water footprint**

*Source: (A. Y. Hoekstra et al., 2009).*

From the previous figure, it is clear that the water footprint is calculated in four stages, which are in following:

- *Determine the objectives and scope of the study:* it must be started to clarify and define the objectives and scope of the study.
- *Water footprint calculation:* it is the stage in which data are collected, and calculations are performed on the scale and level of required details, which depend on the decisions taken in the previous stage.
- *Assessment of the sustainability of the water footprint:* it is the stage in which the impact of the water footprint is assessed from an environmental perspective, as well as from a social and economic perspective.
- *Water footprint response formulation:* in this stage, policies, strategies, and response options are formulated to prevent risks.

It is not necessary for water footprint studies to contain the previous four steps. In the first stage of defining the objectives and scope, one can focus only on the water footprint calculations, and stop after the sustainability assessment phase and leave the discussion on formulating the response for a later time. It may be necessary in some cases, to return from the fourth step, for example, to the second or first step. The model with its four steps and its arrangement is not binding, but it can be adapted or modified according to the situation and according to the requirements of the study (A. Y. Hoekstra et al., 2009). In some cases, it may require a quick initial study to reach the area, product, procedure, or step that must be studied in more detail.

#### *2.1.2.2. The Goals of Water Footprint Estimation*

Water footprint studies have different purposes. It is applied in many contexts, and each purpose requires its own scope for analysis. The water footprint can be estimated for different entities, so it is very important to determine which water footprint can be studied and estimated as mentioned in Table 1.

**Table 1: Goals of water footprint assessment**

| N | Type of water footprint | N | Type of water footprint |
|---|---|---|---|
| 1 | The water footprint of a process | 7 | The water footprint of consumers in a province, municipality, or another administrative unit |
| 2 | The water footprint of a commodity | 8 | The water footprint of consumers in the catchment area. |
| 3 | Consumer water footprint | 9 | The water footprint within a municipality, province, or another administrative unit |
| 4 | The water footprint of a group of consumers | 10 | The water footprint of a catchment or river basin area. |
| 5 | The water footprint of consumers in a country | 11 | The water footprint of the business sector |
| 6 | The water footprint of a business | 12 | The water footprint of humanity |

*Source: (A. Y. Hoekstra et al., 2009).*

The formulation of the goal to estimate the water footprint requires a several things that must be defined, such as: *What kind of detail to be studied?* If the purpose is to increase public awareness, average national or global estimates of the product's water footprint are likely to suffice. When the goal is to identify the critical points, there is a need for more detail in the scope of business, calculations, and evaluation, so that it is possible to determine exactly where and when the local water footprint has significant environmental, social, or economic impacts (A. Y. Hoekstra et al., 2009). If the goal of estimating the water footprint is to formulate the policies and set goals to reduce the value of the water footprint, then the study must be at a higher degree of spatial and temporal detail, and in this case, there will be broader factors in the study that must be discussed, and not water alone.

#### *2.1.2.3. The Ranges of Water Footprint Estimation*

When preparing the water footprint calculations, the confine of the components must be clear, and the confine here refers to the components that must be taken into account and the others that must be neglected. The following indicative list can be used when preparing the water footprint account (A. Y. Hoekstra et al., 2009):

- The type of water footprint in terms of being blue, green, or grey;

- The limitation of calculation in the production chain, and the spatial extent of the water footprint;
- Time periods of data;
- Consumers and businesses – it is important to know whether the water footprint is direct or indirect;
- For countries: the water footprint of consumption must be looked at whether the water source is internal or external.

#### *2.1.2.4. The Limitations of Water Footprint Estimation*

The issue of cutting off a part or step of the supply chain or production is the fundamental question in the field of calculating the water footprint, and it is one of the similar questions as in calculating the carbon footprint, ecological footprint and energy, and life cycle assessment (Ercin & Hoekstra, 2012). So far, there are no general guidelines set in the field of water footprint calculation, but the general rule includes the following:

- The water footprint must include all the processes within the production system (production tree), which contribute significantly to the overall water footprint (Mekonnen & Gerbens-Leenes, 2020). Some estimate this contribution as 1% of the total water footprint, while others estimate it to be 10% of the total water footprint in the major components (Konar & Marston, 2020).
- It may be seen that supply chains are endless and widely disparate due to the variety of inputs used in each process step, but in actual practice, there are only a few practical steps that contribute significantly to the overall water footprint of the final product (Arjen Y Hoekstra, 2017).
- It is expected that when a product includes the components of agricultural origin, these components often make a significant contribution to the overall water footprint of the product because an estimated 86% of the human water footprint comes from within the agricultural sector. As for the industrial components, they are likely to contribute (Hoekstra et al., 2011). Obviously, they cause pollution (grey water footprint).
- The issue of appropriation needs to be clearly defined with regard to calculating the water footprint of the worker, which contributes to almost all operations, and an argument can be made that employees are input factors that require food, clothing and drinking water, and therefore all direct and indirect water needs of workers should be

included in the footprint - the indirect water of the product (Hoekstra et al., 2011). This creates a very serious accounting problem, known in the field of life cycle assessment, which is that double-counting can occur because the use of natural resources is ultimately due to the consumers who are workers at the same time, which creates an endless cycle of double and triple counting and so forth, in short, the factor should be excluded as one of the indirect factors when calculating the resource used water (Chomkhamsri & Pelletier, 2011).

### *2.1.3. The Water Footprint for Power and Transportation*

Transportation does not consume a large amount of fresh water when compared to the total consumption of the products or commodities that are transported (Oki et al., 2017), in general, the water footprint of transport is included in the analysis depending on the selection rule and how the analysis is applied! When the contribution of transport and energy to the overall water footprint of a product is negligible, components of the analysis and calculation can be neglected. In case of using biofuels or hydropower as a source of transport energy (Hoekstra et al., 2011), it is recommended to consider the water footprint of transport as a key component of the analysis and calculation of the final water footprint of the product because it is known that these forms of energy have a relatively large water footprint per unit of energy (Scown, 2010).

### *2.1.4. The Spatial Extent of the Water Footprint Estimation*

Water footprints can be evaluated at different levels of spatial details as shown in Table 2, and it is as follows which are created by HOEKSTRA and others 2009.

**Table 2: Evaluate water footprints at different levels of spatiotemporal details**

| Level | Spatial range | Temporal range | The data uses | Water footprint evaluation uses |
|---|---|---|---|---|
| **Level A** | International average | Yearly | Previous studies and international databases related to water production, pollution, and consumption | Rough estimates for purpose, awareness-raising, and initial identification of the Earth's global footprint |
| **Level B** | National or regional | Monthly or yearly | Previous studies and local and regional databases related to water production, pollution, and consumption | Rough estimates for feasibility studies and highlighting some important points affecting spatially and temporally |
| **Level C** | Water basins | Monthly or daily | Field measurements and experimental data on water consumption and pollution | Basic knowledge of conducting a footprint sustainability analysis and estimating the footprint of a product, place, or consumer |

*Source: (A. Y. Hoekstra et al., 2009).*

- *Level (A):* It is the lowest level of detail in which the water footprint is estimated based on the global average of the water footprint data available from databases, and these data mostly refer to an average number of years. This level of detail is sufficient and useful for raising the level of public awareness. It is also appropriate when the goal is specifically the products and components that contribute most to the water footprint in general. It is also useful for developing future projections of global water consumption due to major changes in consumption patterns (such as a shift towards consuming more meat or bioenergy) (Ercin & Hoekstra, 2014).
- *Level (B)*: The water footprint at level B is estimated based on national or regional averages and data is compiled from a clear and geographically defined database. The water footprint is preferably calculated at monthly averages. This level of calculation is appropriate to provide a basis for understanding what can be expected in local watersheds and catchment basins, and for making decisions about water allocation (Speed et al., 2013).
- *Level (C):* The water footprint calculations are made geographically and temporally based on accurate data from the inputs used and sources of verification for those inputs.

The spatial minimum is the level of small water collection basins from about 100 to 1000 square kilometres, but when the data allows, it can be calculated at the field level; for example, for the calculations of the water footprint of farms, residential, and industrial areas, the minimum time is a month, provided that the annual changes are taken as part of the analysis (A. Hoekstra et al., 2009). The calculation at this level is based on the best actual estimates in terms of local water consumption and pollution, and it is preferable to verify this data on the ground. This high level of spatial details is suitable for developing in situ strategies to reduce the water footprint (McGlade et al., 2012).

### *2.1.5. The Time Span of the Water Footprint Data*

The availability of water varies in a region from year to year and from month to month, as a result of climate fluctuations or the availability of water supplies in the area, and also due to the change in water demand with the passage of time (Bisselink et al., 2018). When calculating the direction of the water footprint, one must be careful and choose the appropriate time period, because the final results of the water footprint calculations will, of course, be affected during a period due to the availability of data; for example, in drought years, the blue water footprint of a crop would be much higher than in wet years (Marston & Konar, 2017). Because in this case, more irrigation water will be needed. The water footprint can be calculated for a year or a specific number of years, and different periods can be combined in one analysis, such as taking productivity data for the last five years and climate data (temperature and precipitation) as an average for the last thirty years (Mekonnen, 2011).

### *2.1.6. The Direct and Indirect Water Footprint*

In general, the calculations for estimating the water footprint should include both the direct water footprint and the indirect water footprint. Although, the direct water footprint is the one that is focused on by consumers and companies, while the indirect water footprint, in general, is larger than expected - consumers neglect the fact that the largest part of the water footprint is related to the products they buy from the market or anywhere else; not just the water they consume at home (Hoekstra et al., 2011).

### *2.1.7. The Water Footprint of the Country and National Consumption*

The water footprint inside the country indicates the volume of fresh water consumed or polluted within the country’s territory, and this includes the water used to make products consumed locally and also the water used to make export products (Hoekstra & Chapagain, 2006). The “water footprint inside the country” differs from the “water footprint for national consumption,” which refers to the amount of water used to produce goods and services consumed by the country’s population, whether these goods and services are locally produced or imported from abroad (Hogeboom, 2020). The calculation of the water footprint for national consumption includes the internal and external elements, including analysing the external water footprint. So, it is the key to obtaining a picture of the national consumption and water use, not only in the country itself but also outside the country, and then relying on imports of sustainability. From the previous definitions, it can be concluded that the water footprint within a country is sufficient as an indicator when water resources are used for domestic purposes only (Spiess, 2014).

### *2.1.8. Evaluation of the Water Footprint Sustainability*

The first stage of the assessment of the sustainability of the water footprint is to know that whether the water footprint is for a geographical area or for a stage in the production of a product, commodity, or consumer if the water footprint is for a geographical area. From the latter, it is preferable to focus on the catchment area or the entire river basin because they are the natural units whose water footprint can easily be compared to the water in them (Hoekstra, 2014). If the water footprint is a production process, a commodity, or a consumer, then the focus, in this case, is not on the combined water footprint in a geographical area but on the extent to which the water footprint contributes to the production process, the commodity, or the consumer to the combined water footprint in the geographically defined area (Haie et al., 2018). Given the limited freshwater resources in the world, there should be a concern with any contribution that is more than the maximum reasonable technically or socially. The water footprint collected in certain basins or river basins must be paid attention to if it is more than the maximum reasonable limit since in this case, basic environmental needs might not be met, or inequitable distribution of water is not socially or economically sustainable. In the case of the geographical perspective (Zeng et al., 2012), the following list can be used (Hoekstra et al., 2017; Sala et al., 2013):

- Sustainability of the green, blue, and grey water footprint.
- The environmental, social, and economic dimensions of sustainability.
- Defining critical areas only or detailed analysis of primary and secondary effects in critical areas as well, which affects the required level of detail in the evaluation.

- Highly accurate spatial and temporal calculations are important when comparing the water footprint and available water resources at critical points and regions.

In the case of assessing the sustainability of the water footprint in production processes or for a consumer or a commodity, it will be preferable to focus on exploring and clarifying a number of points, the most important of which are the following:

- Whether the water footprint makes an insignificant contribution to the water footprint of humanity (Hoekstra & Mekonnen, 2012).
- Whether the water footprint contributes to the water footprint of critical geographical areas (Vanham, 2016).
- It is sufficient to compare the water footprint of each separate process or product with its global counterpart standards when such standards already exist, and in the absence of these standards, the scope of the assessment needs to be expanded to also include the study of what would be a reasonable standard (Arjen Y. Hoekstra, 2017).

To explore whether the water footprint of a consumer process or a commodity contributes to critical areas, it can suffice to examine each element of the water footprint, and whether or not it exists. This requires a database of critical areas around the world at the level of spatial details and temporal, and when these data are not available, it is necessary to expand the scope of the study to include studies of water harvesting basins from a geographical perspective, as well as study the elements and components of the water footprint of a process or commodity to find out the most important ones.

### *2.1.9. The Response Formulation of the Water Footprint*

In case of the water footprint within a geographically defined area, the question is: *What can be done to reduce the water footprint in that region, and by what amount, time, and in which method?* When defining a scope for formulating a response to this, the question will be specifically about "who's the response!" It can be seen what governments, consumers, farmers, companies, and investors can do. Perhaps, what should be done will be through intergovernmental cooperation (Kuiper et al., 2010). About government, a distinction can be made between different levels and bodies of government. At the national level, for example, the required response may translate into actions in different ministries, from the ministries of water, environment, energy, agriculture, and planning to the ministries of economy, trade, and foreign affairs.

When defining measures to reduce the impact of water footprint, it is important to be clear from the outset, the angle of view that will determine those measures, and for example, in the case of the water footprint of a consumer or a community of consumers, it is possible to determine what the consumer or communities can do. If response measures are identified in the context of assessing a company’s water footprint, it is more logical to know what kind of measures the company can develop on its own, in which case the measures can also be formulated on a larger scale (Hoekstra, 2008).

## 2.2. Virtual Water Theory

The theory of "virtual water" is based mainly on the fact that humans not only consume water through its regular and well-known uses such as drinking or bathing and all household uses, but there are many other uses that had not been taken into consideration in the past, especially in cases of food production, consumer products, recreational activities, and services. Tony ALLAN, a British scientist, first proposed the concept of "virtual water" in the early 1990s, and it took nearly a decade for the concept to achieve global recognition for its usefulness in ensuring regional and global water security. The first international conference on virtual water was conducted in Delft, Netherlands, in December 2002. In March 2003, at the third World Water Forum in Japan, a special session was held to discuss virtual water barter trade. According to that theory, the cup of coffee that you drink in the morning consumes about 140 litres of fresh water, which was used to grow, produce, package, and ship the used coffee beans, and this amount is roughly equal to the amount of water that an average person in most countries of the developed world uses for all his daily household needs (WEF, 2019). American person on an average consumes about six thousand litres of virtual water per day as part of the goods, services and household uses he consumes, and this amount is equivalent to more than three times the average person’s consumption in China (Renault, 2003). To give a clearer picture of the concept of virtual water content for some commodities and products, some illustrative examples must be mentioned for example, one kilogram of grain needs from one to two thousand litres of water, and animal products require more fresh water, so producing one kilogram of beef on average needs about 16 thousand litres of water (Food & Nations, 2017). There is another example when a country imports a ton of wheat or corn, it actually imports "virtual water" with it, meaning the water needed to produce those crops. Importing countries achieve savings through virtual water trade (Renault, 2003). For example, the total savings in fresh water that Egypt achieved through imports of corn alone in

2000 is estimated at 2.7 billion cubic meters of water (Chapagain, Hoekstra, & Savenije, 2005).

Furthermore, HOEKSTRA and HUNG defined virtual water as water that is incorporated in a product, commodity, or service, but not in the literal sense, but in the hypothetical sense, as it relates to the water required to manufacture the product or commodity. It is also sometimes called "external water," which refers to the virtual water imported to a country, which means that this water is used in the importing country and is added to the "original water in the country" (Hoekstra & Hung, 2003). To arrive at a more accurate definition of virtual water, two different approaches are applied: The first approach, in which, the virtual water content is defined, is by the volume of water that was used to produce the product, commodity or service and this, of course, will depend on the production conditions, including the place and time of production and the efficiency of water usage. For example, producing one kilogram of grain in arid countries requires two to three times more water than is needed to produce the same amount in humid countries (A. Y. Hoekstra, 2003b). The second approach takes the calculation process from the perspective of the end-user of the goods and not from the perspective of the commodity producer. The user determines the virtual water content of the product and the amount of water required to produce the product, commodity, or service in a place where there is a need for this product, and this definition is related to the amount of available water and the comparison between production and import of goods (A. Y. Hoekstra, 2003b). The difficulty in this definition is if a product or commodity is imported to a place where it cannot be produced, for example, due to climatic conditions, *what is the virtual water content of rice in the Netherlands*? It is not produced there but is only imported. RENAULT proposed in 2003 that we look at the content of virtual water as a suitable alternative to products and commodities (setting the price of the commodity according to its content of virtual water), and this, of course, will open another door in calculating the content of virtual fresh water in products of the sea and ocean water (Zimmer & Renault, 2003).

### ***2.2.1. The Benefit of Virtual Water Trade***

Fresh water trade in its true meaning, by transferring water from a place of the abundance of water to another place that suffers a shortage of water resources, is not economically feasible, at least so far, in terms of engineering and financing obstacles and challenges; as for the virtual water trade, it has a number of benefits from which:

- Virtual water trade can be used as a tool to achieve water security for some countries (Zimmer & Renault, 2003).
- The ability to efficiently employ imported virtual water relieves strain on limited water resources in water-scarce regions (El-Sadek, 2011).
- Virtual water can be seen as an alternative source of water and as an additional tool for achieving regional water and food security (Wichelns, 2001).
- There is a possibility that the virtual water trade can be a tool in solving geopolitical problems and even in preventing wars due to conflict over water resources (Josef, 2014).
- The possibility of taking benefit of the comparative advantages in the production of some commodities that are achieved by the countries with the abundance of water instead of storing water, and the technologies and high economic and environmental costs it may require (Hoekstra, 2010).
- Pricing and technology can be a means to increase domestic water use efficiency - virtual water trade between countries can be a tool for more efficient global water use (Yang et al., 2006).
- Producing water-intensive products in places where water is abundant (GWP, 2017).
- Virtual water trade from a country where water productivity is relatively higher as compared to another country with relatively lower water productivity is working to achieve real water savings worldwide (Yang et al., 2006).
- Virtual water trade is a more realistic, sustainable, and environmentally friendly alternative to transporting the water itself (D'Odorico et al., 2019).
- The application of the idea of virtual water trade seriously affects the management of international river basins (Tian et al., 2020).
- Optimal production is not only a matter of choosing the production sites wisely, but also choosing the appropriate timing for production, and periods of water shortage can be overcome by creating artificial water tanks, but as an alternative, water can also be stored in its default form in the form of foodstuffs, and this can be done. It is a more efficient and environmentally friendly way of bridging dry periods than building large dams to temporarily store water (A. Y. Hoekstra, 2003b).

### 2.2.2. *Measurement of the Virtual Water*

Estimating and measuring the actual water content of a product or commodity is not an easy task because many factors affect the amount of water used in the production processes, and at least the following factors should consider when estimating and calculating the virtual water content of any product or commodity! (A. Hoekstra, 2003; Renault, 2003)

- The place and time period (season) for producing the product or commodity.
- Measuring the quantity of water used in case of the production of irrigated crops, as well as the quantity of polluted water as a result of irrigation, if it exists.
- Measuring the efficiency of water use in the production of goods and products.
- Calculate and include wasted and contaminated water in the estimation process.
- Calculation of virtual water ratios of intermediate inputs to the virtual water content of the final commodity or product.

As a rough example of these concepts, Table 3 summarizes estimates of virtual water content for a number of products and crops via professionals and scientist in this field. As for the terminology used, it is noted that “virtual water content” is the currently common term, and there are other terms that were and still are used; the most important of which is" special water "or "water use intensity ".

**Table 3: Virtual water estimates for a number of products.**

| Product | HOEKSTRA and HUNG (2003)* | HOEKSTRA and CHAPAGAIN (2003)* | ZIMMER and RENAULT (2003)** | OKI and others (2003)*** |
|---|---|---|---|---|
| Wheat | 1150 | - | 1160 | 2000 |
| Rice | 2658 | - | 1400 | 3600 |
| Maize | 450 | - | 710 | 1900 |
| Potatoes | 160 | - | - | - |
| Soya | 2300 | - | 2750**** | 2500 |
| Beef meat | - | 15977 | 13500 | 20700 |
| Chicken | - | 2828 | 4100 | 4500 |
| Eggs | - | 4657 | 2700 | 3200 |
| Milk | - | 856 | 790 | 560 |
| Cheese | - | 5288 | - | - |

*International average **California ***Japan ****Egypt

*Source: (A. Y. Hoekstra et al., 2009)21.*

### *2.2.3. Virtual Water Trade*

The quantitative research of global virtual water trade began a few years ago with three independent studies conducted in the Netherlands, the second by the World Water Council (WWC) in cooperation with the Food and Agriculture Organization (FAO), and the third by the Japanese Research Group. Following is a summary of the estimates of these three studies:

1) The ***Dutch study*** was carried out by HOEKSTRA and HUNG in 1995 and 1999, and CHAPAGAIN and HOEKSTRA in 2003 to estimate the global trade of virtual water between countries. They had found about 1040 billion cubic meters per year as an average during the period from 1995 to 1999 in which the rate of international trade in crops was about 67%, 23% for livestock and their products, and 10% for trade in industrial products.

2) The ***study of the FAO and the WWC***, which was conducted by ZIMMER and RENAULT in 2003, stated that the virtual water trade among the countries of the world amounted to around 1,340 billion cubic meters in 2000, of which 60% was related to plant products, 14% to fish and seafood, 13% animal products and 13% for the meat trades. This estimate is based on calculating the virtual water content of products in the exporting countries.

3) In contrast to the Dutch study, which was based on the virtual water content of products in importing countries, the ***Japanese Research Group*** (OKI et al., 2003) estimated global trade in virtual water from the viewpoint of exporting and importing countries. From the point of view of the exporting countries, the Japanese group estimated the virtual water trade at about 683 billion cubic meters per year, and this estimate is lower than the estimates by the research group in the Dutch study, which may be because the Japanese have taken fewer products into the calculation. The point of view of importing countries when estimating the global trade in virtual water was estimated at 1138 billion cubic meters annually, and this estimate is less than an estimate from the study of the FAO and the WWC, and again this is due to the number of products based on which the calculation was made.

Table 4 shows a summary of the results of the three studies to estimate the volume of virtual water trade in the world as an average for the year 2000.

**Table 4: Global virtual water trade in 2000 in billion cubic meters per year.**

| **Type** | **Netherland (Exported countries)** | | **FAO & WWC (Imported countries)** | | **Japanese Studies (Exported countries)** | | **Japanese Studies (Imported countries)** | |
|---|---|---|---|---|---|---|---|---|
| | **Volume** | **%** | **Volume** | **%** | **Volume** | **%** | **Volume** | **%** |
| Crops trade | 695 | *67* | 795 | *60* | 427 | *69* | 868 | *76* |
| Livestock | 245 | *23* | 180 | *13* | 84 | *12* | 118 | *10* |
| Industrial Products | 100 | *10* | 173 | *13* | 127 | *19* | 152 | *13* |
| Fishes and Sea Food | - | - | 192 | *14* | - | - | - | - |
| **Total** | **1040** | ***100*** | **1340** | ***100*** | **683** | ***100*** | **1138** | ***100*** |

*Source: (A. Y. Hoekstra et al., 2009)that based on Water footprint network and UNESCO reports*

The estimates of the three studies mentioned are conservative. The three studies were conducted independently, as the approach, data source, and assumptions were partly different, and therefore the close estimates for each other were surprising. The three studies show that the countries did not have similar participation in the global trade of virtual water. The Dutch study concluded that the dominant countries in the export of virtual water in the world are the United States, Canada, Argentina, Australia, and Thailand. Most countries that import virtual water are Japan, Sri Lanka, and Italy. Table 5 gives an overview of the contributions of the largest countries to the global virtual water trade.

**Table 5: Countries most involved in virtual water trade in the world.**

| **Country** | **Crops and agricultural products** | | **Livestock products** | |
|---|---|---|---|---|
| | **% Import** | **% Export** | **% Import** | **% Export** |
| Sri Lanka | 12% | | | |
| Canada & USA | | 30% | | 9% |
| Japan | 9% | | 9% | |
| Italy | | | 8% | |
| Thailand | | 7% | | |
| Australia and New Zealand | | | | 18% |

*Source: Water Footprint Network: https://waterfootprint.org/en/*

There may be water savings due to international trade in virtual water, for example, the trade of one kilogram of corn from France to Egypt saves about 0.52 cubic meters of global water, this is because the virtual water content of French corn is about 0.6 cubic meters per kilogram, while the virtual water content of Egyptian corn is about 1.12 cubic meters per kilogram. Global freshwater savings in 2003 as a result of the global food trade were estimated at 255 billion cubic meters per year (A. Y. Hoekstra, 2003b).

### 2.3. Water Resources in Egypt

*Water resources of a country:* it is the total availability of conventional and non-conventional water resources for this country in a certain period. Conventional water resources consist of surface resources, which include rain, rivers, streaming valleys, and floods, the renewable and non-renewable groundwater. Whereas non-conventional water resources include desalination of saline water, saline groundwater, treatment of sewage, and reuse of agricultural drainage water (FAO, 2003). The population increase and the accompanying growth in various industrial and commercial activities in addition to the limited agricultural area are the most important challenges facing most countries of the world these days. The population of Egypt has increased from about 38 million in 1977 to about 98 million in 2018, and it is expected that the population will exceed 104 million in 2025 if it continues at the same current growth rate (Rosegrant et al., 2002). Egypt has begun to face a problem of shortage in the per capita share of freshwater, and this problem may turn into a stifling crisis, with which the state cannot meet food requirements and provide food security for the entire population, as the average per capita share of water in Egypt will fall below the water poverty line (Dakkak, 2014), which is estimated at 1000 cubic meters per year (Brown, 2008). The per capita share of water resources in Egypt was about 2,189 cubic meters in 1966 and continued to decline until in 1986 it became about 1,110 cubic meters, then it reached about 770 cubic meters in 2005 (Abdin & Gaafar, 2009). This decline will continue as long as the rates of population increase remain the same with the lack of an increase in the available water resources. It is expected that the per capita share will reach less than 500 cubic meters in 2025, which will cause a stifling crisis for the Egyptian economy if the government does not move with comprehensive national plans. Figure 5 shows the change in the per capita share of available water resources in Egypt.

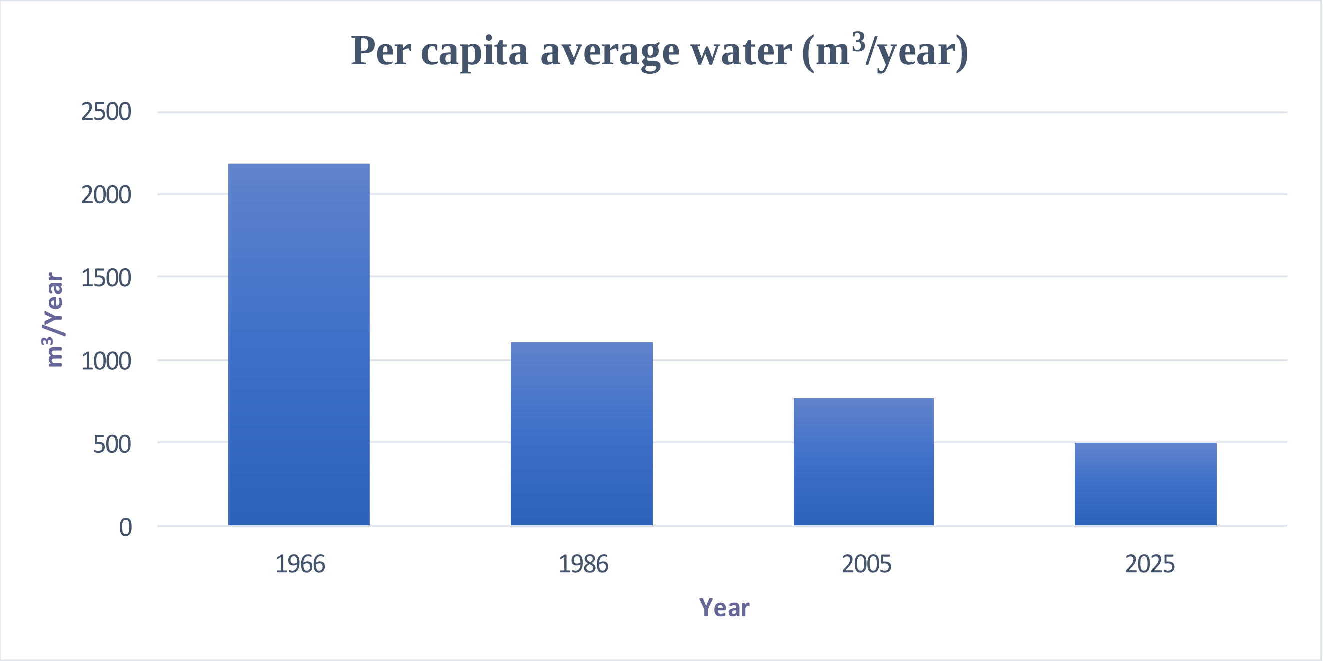

**Figure 5: Change in per capita share of available water resources in Egypt ($m^3$/year).**

*Source: Own calculating depends on World Bank and CAPMAS different issues*

### 2.3.1. Natural Characteristics and Conditions of Egypt

Egypt has a diverse range of natural resources, including water on the Red Sea and Mediterranean Sea coasts, as well as ten natural lakes such as Manzala, Burullus, Qarun, and Nasser. The Nile River, which runs through Egypt and finishes in the two parts of Rashid and Damietta, is also the country's main supply of freshwater. The presence of the Nile River also contributed to the spread of agricultural land along its banks, as well as in Egypt there are mountain chains that extend in the Red Sea Mountains and Saint Catherine Mountains in Sinai, and there are large areas represented in the eastern and western deserts (which are characterized by the presence of a number of oases in them Such as Siwa, Farafra, Dakhla and Kharga) in addition to the Sinai desert.

Diversity in terrain and geographical locations also contributed to the availability of many natural resources such as iron, gold, manganese, and phosphates, as well as stones such as granite, basalt, marble, limestone, and glass sand, in addition to coal, petroleum and natural gas.

#### 2.3.1.1. *The climate conditions of Egypt*

Egypt is in the tropical dry zone, with the exception of the north, which enters the temperate, mild zone of the Mediterranean climate, which is characterized by heat and drought in the summer months, and moderate weather in the winter and spring, with little rain falling along the shores (Hurst, 2020). In Lower Egypt, the average annual temperature in winter is about 20°C during the day, 10°C at night, and in summer the average temperature is approximately 35°C during the day and 23°C at night. In Upper Egypt, the average maximum temperature in winter reaches 25°C and lows are 8°C, and in summer the average maximum temperature reaches 41°C, while the minimum temperature reaches approximately 24°C. Frost forms in the middle of the Sinai Peninsula and on the crops in Central Egypt in winter, while snowfalls in the winter on the Sinai Mountains and on some coastal cities such as Baltim, Damietta, Sidi, and Alexandria[1].

The humidity in the air rises clearly along the coasts of the Mediterranean throughout the year; especially the summer months, and the humidity decreases sharply when the country is exposed to the blowing of the Khamaseen winds, during the period between March and June, which are dry, hot, and dusty winds that lead to the excitation of fine sand, to a degree that may obscure the vision[2].

There are limited amounts of rain during the winter months, and it may be abundant in the west, less towards the east, and almost no rain, to the south of Minya Governorate. The Red Sea Mountains and separate destinations from the Sinai Peninsula, especially in the southern part of it, are exposed to rain in the form of heavy showers accompanied by thunderstorms which result in the occurrence of torrential torrents, which flow in the dry valleys and their reefs, which are scattered in those regions (IDSC, 2011).

#### *2.3.1.2. Landforms in Egypt*

Egypt has an area of about one million square kilometres. The topography of Egypt is distinguished by its homogeneous surface, in general, as the Nile Valley and its delta are the most important geographical phenomena. The lowest elevation in Egypt is the Qattara Depression, which descends to 133 meters below sea level. Mount Catherine is the highest point in Egypt, it rises to about 2,629 meters above sea level. Egypt can be divided into four terrain regions, as follows (A.M.Hegazi et al., 2005):

- *The Nile Valley and its Deltas:* It has an area of approximately 33 thousand square kilometres from the north of Wadi Halfa to the Mediterranean Sea and is divided into Nubia extending from Wadi Halfa to Aswan, followed by (Upper Egypt) to southern

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[1] The Egyptian Meteorological Authority: https://www.nwp.gov.eg
[2] https://www.nationsencyclopedia.com/Africa/Egypt-CLIMATE.html

Cairo, then the Delta (Lower Egypt) from the north Cairo to the Mediterranean coast, which is located between the two branches of the Nile, Damietta, and Rashid.

- *Western Sahara:* Occupies approximately 680 thousand square kilometres, and it is the part located within the borders of Egypt from the Greater African Desert, and extends between the Nile Valley in the east to the western borders, and from the Mediterranean in the north to the Nubian borders and is also known as the Libyan Desert. From the great desert.
- *The Eastern Desert:* Its area is about 225 thousand square kilometres, and it extends between the Nile Valley in the west, and the Red Sea and the Sinai Peninsula in the east, and from the borders of the Delta in the north to the borders of Egyptian Nubian, and extends along the eastern desert, the Red Sea Mountain, which reaches a height of about 1000 meters above the surface the sea, penetrated by dry valleys.
- *The Sinai Peninsula:* Its area is about 61 thousand square kilometres, and it is the Asian part of Egypt and constitutes 6% of the area of Egypt. It is in the form of a triangle with its base tangent to the Mediterranean in the north and its head to the south, between the Gulf of Suez in the west and Aqaba to the east.

### *2.3.2. Types of Water Resources in Egypt*

The water resources in Egypt, including the local ones, mean the groundwater in both the Western and Eastern Sahara and the Sinai, and rainwater in the north-western and south-eastern regions of Egypt on the Red Sea coast. Also includes the waters coming from outside the borders, and they mean the waters of the Nile River and these resources are called conventional water resources. There is what is called non-conventional water resources which is the reuse of both agricultural drainage water, and treated wastewater; the former used alone or mixed with fresh water to irrigate crops and the latter is used so far in planting woody tree forests only, in addition to desalinating seawater, which is often used in the eastern and northern coastal regions and Sinai (FAO, 2016; Noaman, 2017). Each of these resources are highlighted below.

#### *2.3.2.1. Conventional Water Resources of Egypt*

***Rainwater:*** Egypt is a desert country and rainfall is a limited source of water, as the rates of rainfall in Egypt range between 20 to 150 millimetres per year over the north-western coast, while it sometimes increases to reach 500 millimetres per year on the coasts of the Red Sea, and that rate gradually decreases in various regions (FAO, 2016). Sometimes the rain is almost non-existent in south-central and south-western Egypt, and the rate of evaporation from the earth's surface is estimated at 30 millimetres per year. Therefore, Egypt falls under the classification of very dry areas. Often, rains are characterized by irregularity in time and space, and such a rate of rain, at its highest rates, does not provide the minimum that Egypt needs for rain-dependent agriculture, as this rate should not be less than 700 millimetres per year to be able to benefit from it (Abdel-Shafy et al., 2010; Yletyinen, 2009). Therefore, the rainwater's current role is limited to irrigating some of the crops in the northern coast and growing limited areas of pastures. One study estimated that the total annual precipitation falls on the country at about 1.8 billion cubic meters, only about 10% of which is used (RNE, 2014). The area of Egypt can be divided into several water basins as follows (Strzepek et al., 1996):

- *The Nile Basin:* It covers about 326.8 thousand square kilometres, or 33% of the total area of Egypt, and is located in the central part of the north and south of Egypt.
- *The Northern Interior Basin:* It covers 520.9 thousand square kilometres, or 52% of the total area of Egypt, and is located in the east and southeast of the country.
- *The Mediterranean Coast Basin:* It covers 65.6 thousand square kilometres, and represents 6% of the area of Egypt.
- *The Northeast Coast Basin:* It is a narrow strip covering 88.25 thousand square kilometres along the coast of the Red Sea, and it represents 8% of the area of Egypt.

***Surface Water (Nile River):*** The annual water allocation of the Nile River is the main source of water resources in Egypt, and it represents about 95% of Egypt's renewable water resources. Egypt's share of the Nile water amounts to 55.5 billion cubic meters annually according to the 1959 agreement with the Republic of Sudan (Kimenyi & Mbaku, 2015).

**Groundwater:** Groundwater is an important source of fresh water in Egypt, and its importance is due to it being the only and basic resource in the deserts of Egypt. The volume of groundwater used during the past few years is estimated at 7.4 billion cubic meters per year, of which 6.1 billion cubic meters of groundwater in the valley and the delta, and about 1.1 billion cubic meters of groundwater in the deserts, as published on the Central Agency for Public Mobilization and Statistics website CAPMAS, depending on the data of the Ministry of Water Resources and Irrigation. As for the internal renewable groundwater resources, it is estimated at 1.3 billion cubic meters per year in the aquifer in the Nile and Delta basins, and the main source of internal recharge of groundwater is filtration from irrigation water in the valley and the delta, bringing the total renewable groundwater resources to about 2.3 billion cubic meters per year. Therefore, the total actual renewable water resources for Egypt are estimated at 58.3 billion cubic meters per year (the share of the Nile River is 55.5 billion cubic meters, and the quantities of recharging groundwater reservoirs are about 4.3 billion cubic meters per year) (Zektser & Everett, 2004).

#### *2.3.2.2. Non-conventional Water Resources of Egypt*

***Re-use of Agricultural Drainage Water:*** The agricultural sector is the largest consumer of fresh water in Egypt; using about 86% of the available supplies. All agricultural drainage water in Upper Egypt, south of Cairo, goes back to the Nile River and the irrigation canals. This water is collected, transported, and reused by the large-scale agricultural drainage network that is managed and planned by the Ministry of Water Resources and Irrigation. The reuse of agricultural drainage water has taken place on a large scale over the past decades as water is pumped from the main drains into the main channels. More than 5.5 billion cubic meters of wastewater is being reused annually after mixing with fresh water, in addition to another unofficial amount, used by farmers in many locations, without coordination or legalization with the Ministry of Water Resources and Irrigation, and it is estimated at 2 billion $m^3$ per year (AGWA, 2017; Noaman, 2017).

***Recycling of Treated Wastewater:*** The use of treated wastewater, as an alternative to fresh water in irrigation, has accelerated since 1980 and according to a recent study, 0.7 billion cubic meters per year of treated wastewater are currently used for irrigation, of which 0.26 billion cubic meters per year is secondary treatment and 0.44 billion cubic meters primary treatment in general. The use of treated wastewater has enormous potential for Egypt (Khalifa, 2011). Table 6 shows the quantities of wastewater in Egypt (2005-2010).

**Table 6:The quantities of wastewater used during the years 2005-2010.**

| Year | Quantity Billion $m^3$ | Year | Quantity Billion $m^3$ |
|---|---|---|---|
| 2005 | 1.1 | 2008 | 1.3 |
| 2006 | 1.2 | 2009 | 1.3 |
| 2007 | 1.3 | 2010 | 1.3 |

*Source: CAPMAS, 2012.*

### *2.3.3. Agricultural Water Use in Egypt*

Egypt is located in the arid and semi-arid regions of the world. Therefore, agriculture depends entirely on irrigation water, which requires a lot of effort to manage it, tighten its distribution, and properly use it to meet the requirements of agriculture in its various stages. The total water used for agriculture was about 60 billion cubic meters in 2010 (Amer et al., 2017). Table 7 shows the quantities of water used in agriculture in Egypt during the years 2005-2010.

**Table 7:The quantities of water used in agriculture in Egypt (2005-2010).**

| Year | Quantity Billion $m^3$ | Year | Quantity Billion $m^3$ |
|---|---|---|---|
| 2005 | 59 | 2008 | 60 |
| 2006 | 59 | 2009 | 1.360 |
| 2007 | 59.5 | 2010 | 1.361 |

*Source: CAPMAS, 2012.*

Figure 6 shows the average water consumption of five basic commodities in Egypt, estimated at 59.1% of Egypt's share in the Nile water, taking into account that the irrigation efficiency in Egypt is about 51% according to the data from FAO and this shows that more than 20 billion $m^3$ can be saved in the case of raising irrigation efficiency only.

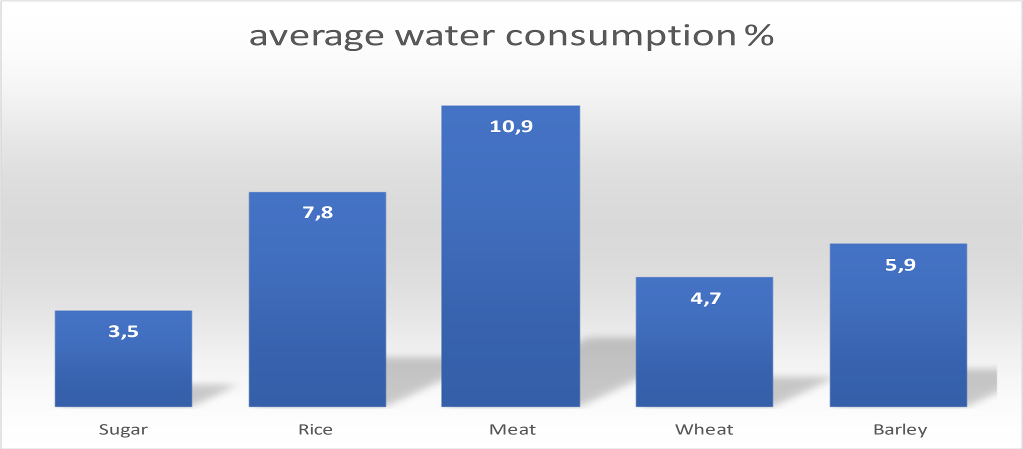

**Figure 6:The average water consumption of five basic products in Egypt.**

*Source: FAO, different issues 2013.*

Therefore, it is imperative for us in the coming period to reconsider the way for using water in agriculture, which leads to the need to develop the irrigation system in Egypt and the necessity to define certain crops for cultivation in different regions, especially in newly reclaimed lands, and to stop any irresponsible practices.

## 2.4. Agriculture and Food Security in Egypt

Food is considered the primary necessity for human needs. this need is based around the work of economic sectors such as agriculture, industry and trade, thus food security is a significant issue that represents the usefulness and efficiency of sustainable development policies (economically, socially and environmentally), especially in light of the demand increase in food products and the continuous rise in their prices, which is accompanied by the increase in the number of people and their change in consumption patterns (Godfray et al., 2010; Godfray & Garnett, 2014).

Food security is of paramount importance in times of economic, natural, and human crisis due to shifts in food supply and demand, scarcity of food, lack of consumer stability and loss of income, all are among the factors affecting the essence and content of food security (Mc Carthy et al., 2018; Timmer, 2015).

On the other hand, food security is a complex and interrelated issue (Clover, 2003). It is a holistic issue whose dimensions overlap in most economic, social, and environmental sectors, and defined as one of the main goals of any development process, as it is reflected in important development goals, related to living the human, health, and expected age (Costanza et al., 2007; Lang & Barling, 2012). Consequently, the dimensions of food security are related to the dimensions of economic development (agriculture, industry, trade, prices, etc.), social (poverty and human development, especially the health dimension, etc.), the environmental dimension related to climate and desertification and its impact on agricultural production, and the food security related to population stability and commodity stability (Bircher & Kuruvilla, 2014; Lang & Barling, 2012).

According to the World Food Security Summit in 2009, food security is achieved when all people, at all times, have physical, social, and economic opportunities(Grainger, 2010)(GRAINGER, 2010)(GRAINGER, 2010). As for food insecurity, it is the situation in which people lack access to adequate quantities of safe and nutritious foods; to ensure a normal and healthy life (Grainger, 2010).

Herein, it is necessary to distinguish between two levels of food security (*absolute and relative*):

- ***Absolute food security*** means the production of food within a single country equivalent to or greater than local demand. This level is synonymous with complete self-sufficiency, or complete food security. This absolute definition is not realistic, as though the state is missing out on the ability to benefit from international trade based on specialization, division of labour and the exploitation of comparative advantages (Babu et al., 2014; Maxwell & Smith, 1992).

- ***Relative food security*** means the ability of a country, or a group of countries, to provide commodities and foodstuffs partially or totally. In the sense of providing the society's needs of basic food commodities, partially or completely at a minimum, as it does not mean the production of all the basic food needs, rather, it is to provide the necessary materials to secure these food needs, in cooperation with other countries (Ehrlich et al., 1993; Eide et al., 1991).

Indeed, the components of food security in the country represented by geographic and climatic characteristics and an abundance of water resources, human resources, agricultural lands, pastures and forests, livestock, and possession of modern technology (Capone et al., 2014; Ringler et al., 2010).

### *2.4.1. Food Security in Egypt*

The problem of food security and food production and its insufficiency is the most important problems Egypt is facing these days. Since Egypt's dependence on food imports makes it under the control of countries which are ruling food production, that is putting it under risk, and it may compel it to submit to demands that may not coincide with its interests or with its sovereignty, which may help disrupt security. Despite all these challenges and their seriousness, there are many Egyptians who do not realize the causes or nature, nor even the extent of these challenges reflecting their reality now and in the future. However, this does not deny its existence, does not diminish its significance, or mitigate its damages, but on the contrary, increases its importance because the danger Egypt is facing is great for offering food to the population. Whereas the provision of food depends mainly on agriculture and animal production, which in turn depend entirely on the availability of water resources for irrigation.

### *2.4.2. The Role of Irrigation in the Agricultural Productions in Egypt*

Irrigation is a very important factor for the world's food supply, as developing countries are expected to expand the area of their irrigated lands to about 314 million hectares by 2030 (Bruinsma, 2003). At the global level, sufficient quantities of water are available to irrigate these areas, but this water is not distributed fairly on these areas; some regions will face a serious shortage in the quantities of water required and necessary for irrigation to produce food by 2030, including Egypt, at a rate of 14%, and a fifth of the developing countries will suffer from water scarcity (AGWA, 2017; Mekonnen & Gerbens-Leenes, 2020).

### *2.4.3. The Role of the Agriculture Sector to Achieve the Food Security*

The agricultural sector in Egypt plays a vital role in achieving food security for the community as a significant component of achieving national security. The agriculture sector covering a large proportion of the human resources arriving at 27% of the total workforce. In addition, the agriculture sector is considered by far the largest labour sector in Egypt, and the responsibility of this sector also comes in one way or another, to increase the state's foreign exchange earnings by increasing the proceeds of agricultural exports, as well as his responsibility as a strategic goal to fill part of the domestic demand for those agricultural products. Thus, that is led to achieve food security in Egypt (Group, 2018). Table 8 shows the percentage of the economically active population in the agricultural sector and its share of the total GDP.

**Table 8: The percentage of the economically active population in the agriculture sector and its share of the total GDP.**

| Year | Contribution to GDP % | Percentage of population in the agricultural sector out of the total population % |
|---|---|---|
| 1995 | 16.9 | 35 |
| 2000 | 15.6 | 31 |
| 2005 | 15.4 | 28 |
| 2006 | 14.9 | 28 |
| 2007 | 14.4 | 27 |
| 2010 | 14,0 | 26 |

*Source: (Roser, 2013)*

There is a relationship between achieving food security and available agricultural resources in terms of land, water, trained labour, availability of capital elements, and administrative capabilities of achieving maximum benefit from these resources, and availability of technology capable of attaining high levels. In addition, achieving food security is also linked to food consumption levels.

In general, the challenges that affect achieving food security in Egypt are many and varied, for example (ESCWA 2017; Ramadan, 2015):

- The steady population increase compared to a dramatic decrease in the area of agricultural lands, especially the old ones, the limited available agricultural resources, especially water resources, and the lack of self-sufficiency in strategic crops.
- Opening up markets for world trade, within the framework of the WTO markets for all products.

- Rising living standards, which lead to an increase in the demand for food products and thus a higher average per capita consumption which reduces the ability to achieve food security.

## 2.5. Egyptian Water Footprint and Water Security

The intensity of use and pollution of the Earth's freshwater resources is increasing; this recognizes that freshwater resources are subject to global changes, and globalization has led several researchers and scientists in the field of water and food to argue the importance of placing freshwater issues in a global context. Estimating the global dimension of freshwater resources can be considered a key to solving some of the world’s most pressing water and food problems (Gurría, 2017). Many governments have taken water plans from a purely national perspective, aiming to cover the water needs within their borders, and so they began to look for ways to meet the requirements of water users without questioning the quantities of water required (Tundisi, 2008). At present, many countries are moving to reduce their water needs, in addition to what they are doing to increase and develop their water resources. The global dimension of water demand patterns is not considered, as production processes in the global economy can move from one place to another. Water demands are fulfilled outside the borders of a country through the import of commodities (Hoekstra, 2011).

Measuring and mapping the "national water footprint" has evolved a lot since the concept of a water footprint was introduced at the beginning of this century.

HUNG and HOEKSTRA in 2002 conducted the first global study on the water footprint of countries, and in 2005 HOEKSTRA and CHAPAGAIN made a second, more comprehensive study, and the aim of this study was estimating the countries ‘water balance from production from the point of consumptions, also estimating international virtual water flows related to trade in agricultural and industrial commodities, and drawing a map of the water footprint of consumption for all countries, explaining the internal and external sources of the water footprint for national consumption. There was a clear distinction between the types of water footprint whether it was blue, green, or grey.

The studies, assumptions, and data sources in these country studies differed widely, so these studies cannot be used to make comparisons between countries, but rather allow for comparison between the water features of different countries to apply the same method, assumptions, and databases for all countries. The study of the water footprint is developing and an update of the previous studies of HOEKSTRA and CHAPAGAIN (2008) in many areas, the most important of which are:

- Estimation of the water footprint in crop production, industrial production, and domestic water supply.
- In the case of crop production, there is a clear distinction between green and blue water footprint.
- The grey water footprint was calculated in the estimation of the water footprint of agricultural production.
- Irrigation requirements are not taken as a substitute for consuming blue water.
- Utilizing the best estimates for the production of animal feed.
- Distinguishing between different livestock production systems.
- Clearly distinguishing between the blue and grey water footprint in industrial production and household supplies, and the wastewater treatment calculations for the country.
- Applying the bottom-up approach in estimating the water footprint of the national consumption of agricultural products.

Calculations are made in most of the researchers mentioned above as averages over ten years from 1996 to 2005.

In this research and when calculating the water footprint of Egypt, the methodology for calculating the global water footprint will be adopted, which contains the global standard for assessing the water footprint, as well as calculating the internal water footprint for three main crops. In addition, appraising the water footprint of some crops and commodities, and the water footprint for national consumption, furthermore, the total water footprint of Egypt for the period 2000-2018, because from the literature review it was clear that there is no available data after 2005 on the Water Footprint Network which is accredited by UNESCO, so each country, students, authors, and scientist have to make own data for their country because water footprint method will save the humanity in the future.

## 2.6. Water Footprint of Global Production

The water footprint of China, India, and the United States is the largest, with a total of 1,107, 1182 and 1053 billion $m^3$ per year, respectively, as an annual average in the period 1996-2005, and it represents about 38% of the global water footprint, followed by Brazil, and its water footprint is about 482 billion $m^3$ per year (Hoekstra & Chapagain, 2006).

India ranks first in the world in terms of the blue water footprint with a total of 243 billion m3 per year, which represents about 24% of the total blue water footprint in the world, as irrigation of wheat consumes the largest percentage of the blue water footprint in India at an estimated rate of about 33%, followed by irrigation of rice at a rate of 24%, then sugar cane by 16% and China ranks first in the world in terms of grey water footprint, with a total of 360 billion $m^3$ per year, which represents about 26% of the total grey water footprint in the world (Hoekstra & Mekonnen, 2012).

The water footprint associated with agricultural production accounts for the majority of the total water footprint in all countries. China's water footprint connected to industrial production accounts for around 22% of the world water footprint related to industrial production, whereas the United States' water footprint is roughly 18% of the global water footprint related to industrial production. In addition, Belgium is the country in which industrial production takes the largest share of the total water footprint in the country, as it contributes about 41% of the total footprint (Mekonnen & Hoekstra, 2011). Table 9 shows the water footprint of global production in billion $m^3$ per year.

**Table 9:The water footprint of global production (billion $m^3$/year).**

| **Type** | **Crop production** | **Pastures** | **Animal husbandry** | **Industrial production** | **Household supply** | **Total** |
|---|---|---|---|---|---|---|
| Green water footprint | 5771 | 913 | - | - | - | 6684 |
| Blue water footprint | 899 |  | 46 | 83 | 42 | 1025 |
| Grey water footprint | 733 |  | - | 363 | 282 | 1378 |
| Total | 7404 | 913 | 46 | 400 | 324 | 9087 |

*Source:(Mekonnen & Hoekstra, 2011)*

The global water footprint related to agricultural and industrial production and household supplies for the period 1996-2005 was about 9087 billion cubic meters per year, of which 74% were green, 11% blue, and 15% were grey. Agricultural production takes the largest share of this footprint, which represents 92%. Industrial production contributes 4.4% and domestic water supplies contribute about 3.6% of the global water footprint.

## 2.7. Virtual Water Trade and Water Security Indicators

The concepts of virtual water have achieved remarkable effects on the level of global trade policies and research, and have redefined the ways to deal with national water policies, methods, and management. For water-intensive commodities such as rice, wheat, sugar cane, and oil crops; they can be exchanged with countries that can bring them large returns that cannot be for its economy to achieve it in other areas (Hoekstra, 2010). The concepts of virtual water trade have also influenced international trade, and have important implications for the global balance of freshwater resources. The application the of virtual water provides the possibility of using trade to alleviate regional water scarcity and make the use of water resources more effectively and this improves the capacity for sustainable management of global water resources for future generations and works to reduce the risks of entering into regional conflicts due to scarcity freshwater resources (Allan, 1998). For example, if a country exports water-intensive products to another country, then it exports virtual water with the products, in this way, some countries of the world support the necessary water needs of other countries. Water trade in its traditional form between water-rich and water-poor regions is almost impossible due to the large distances and the high costs associated with it (Cosgrove & Loucks, 2015). But trade in agricultural and industrial products is considered a realistic and acceptable activity, and therefore countries that suffer from water scarcity can achieve water and food security for them by importing water-intensive products rather than locally produced, and conversely, countries with abundant water resources can produce water-intensive products for export and increase their national income (Earle, 2001; Yang & Zehnder, 2007).

It should be mentioned that the countries of the Middle East and North Africa import about 50 million tons of grain per year, and the production of this quantity requires more than 50 billion cubic meters of freshwater (OECD, 2018), which is approximately equal to Egypt’s share of the Nile River annually, and this amount also represents the equivalent of about 30% of freshwater resources for the Middle East and North Africa. The virtual water trade is achieving real global savings of large freshwater, which the average global water saving as a result of trade in agricultural products only in the period 1996-2005 was about 369 billion cubic meters, which is equivalent to 4% of the global water footprint related to global agricultural production (A. Y. Hoekstra, 2003b).

Egypt covers most of its water needs from the Nile River, and almost most of its agricultural production depends on irrigation, as the annual rates of precipitation are not sufficient to depend on it for irrigation. The demand for water in Egypt for agriculture, industry, and household consumption is constantly increasing due to population growth and an increase in overall income. Improving water resource management and increasing agricultural total production is a very important factor to contribute to reducing the growing and accelerating levels of poverty and achieving water and food security, which is one of the most important challenges Egypt is facing these days (Moghazy & Kaluarachchi, 2020). Agriculture accounts for about one-fifth of Egypt's gross domestic product, and at the same time, it provides about a third of the total job opportunities available to Egyptians, so the social and economic importance of agriculture is greater than its percentage of GDP (Barsoum et al., 2014). Therefore, improvement and development in the performance of the agricultural sector contribute very much to the reduction of poverty and enhancing Egyptian food security; which is currently being achieved through a combination of local production and imports of products, crops, and agricultural commodities (Thomas, 2003).

### *2.7.1. Virtual Water Trade in Egypt*

Egypt faces numerous challenges related to its water resources, including a dispute over the Nile waters over the "Ethiopian Renaissance Dam and the impact of its share around of 55.5 billion cubic meters annually," as well as rising population, climatic changes, pollution, and deterioration of water quality, which may lead to the occurrence of a water gap in Egypt estimated at about 18 billion cubic meters in the year 2050. Hence the importance of virtual water as one of the tools used to address crises resulting from the water gap and achieve water security, as the virtual water trade allows countries suffering from water scarcity to import high-use products for water, which guarantees water-scarce countries to preserve their water resources, and knowing the amount of virtual water included in goods and products allows calculating the cost of an alternative village for water use by comparing many options for crop production, and for estimating the benefits from the process of importing or exporting goods and products in order to use water at the maximum.

#### *2.7.1.1. Imported Virtual Water in Egypt*

Egypt's imports of food products, especially wheat, oils, meat, and fodder crops, and what these imports bear of virtual water have contributed to Egypt's ability to maintain its food security since the beginning of the sixties of the last century, despite the increased productivity of Egyptian farmers with water-intensive crops with low economic value, which is used locally and part of it exported abroad. Egypt, like most countries of the world, imports, and exports virtual water through its effective and strong participation in international trade (A. Y. Hoekstra, 2003b; Lee et al., 2018). Table 10 shows the average virtual water imports in Egypt during ten years from 1996 to 2005 in million cubic meters per year, and from this table many facts are clear; the most important of which are: Egypt's average imports of virtual water from 1996 to 2005 amounted to about 27.132 billion m3 per year, of which crops, agricultural, and animal products formed the largest percentage, reaching 98.35% of total imports, and industrial products amounted to about 1.65% of Egypt's total imports from Virtual water for the same period. The source of the virtual water that Egypt imported was three main sources: green water by 87.29% of total imports of virtual water, blue water by about 5.26%, and grey water by 7.46%.

**Table 10: Average of Egypt's imports of virtual water in Egypt from 1996 to 2005 in million m$^3$ per year.**

| **Water Type** | **Crops and agriculture and animal products. (Million m$^3$/year)** | **Industrial products (Million m$^3$/year)** | **Total (million m$^3$/year)** | ***Share (%)*** |
|---|---|---|---|---|
| Green Water | 23682.2 | - | 23682.2 | *87.29* |
| Blue Water | 1394.1 | 32.2 | 1426.3 | *5.26* |
| Grey Water | 1609.1 | 414.6 | 2023.7 | *7.46* |
| Total | 26685.4 | 446.8 | 27132.2 | *100* |
| ***Share (%)*** | *98.35* | *1.65* | *100* | - |

*Source: Collected from (El-Sadek, 2010; Roth & Warner, 2008; Wichelns, 2001)*

### *2.7.1.2. Exported Virtual Water in Egypt*

Egypt has contributed since long ago in providing food security for itself and the neighbouring regions. Until the beginning of the sixties of the last century, Egypt was one of the countries exporting crops and food products. So far, Egypt has been exporting a number of crops such as rice, cotton, fruits, and vegetables (Kassim et al., 2018). Table 11 shows the average of virtual water exports in Egypt during ten years from 1996 to 2005 in million m$^3$ per year, from which it becomes clear that: Egypt's average exports of virtual water amounted to about 10.68 billion m$^3$, in which crops and agricultural products accounted for 66.35% of total exports, while the percentage of animal products amounted to about 26.57%, and the percentage of industrial products amounted to about 7.01%, in addition, green water represented 14.45% of total exports, while the percentage of blue water reached 63.8%, and grey water amounted to 21.76%.

**Table 11: Average of Egypt's exports of virtual water in Egypt from 1996 to 2005 in million m$^3$ per year.**

| **Water Type** | **Crops and agriculture and animal products. (Million m$^3$/year)** | **Industrial products (Million m$^3$/year)** | **Total (million m$^3$/year)** | ***Share (%)*** |
|---|---|---|---|---|
| Green Water | 1542.7 | - | 1542.7 | *14.46* |
| Blue Water | 6761.8 | 38.1 | 6799.9 | *63.76* |
| Grey Water | 1605.1 | 717.4 | 2322.5 | *21.78* |
| Total | 9909.6 | 755.5 | 10665.1 | *100* |
| ***Share (%)*** | *92.9* | *7.08* | *100* | - |

*Source: (A. Y. Hoekstra, 2003b)*

The virtual water trade achieves valuable water savings, especially for countries importing crops and agricultural products. This is shown in Table 12, where the annual savings for Egypt from trade in virtual water, expressed as the difference between exports and imports, amounted to about 16.467 billion cubic meters of freshwater as an annual average during the period from 1996- 2005.

**Table 12: Average saving due to virtual water trade in Egypt (1996 - 2005).**

| **Attribute** | **Green Water (million m$^3$/year)** | **Blue Water (million m$^3$/year)** | **Grey Water (million m$^3$/year)** | **Total Water (million m$^3$/year)** |
|---|---|---|---|---|
| Total Imported virtual water | 23682.2 | 1394.1 | 1609.1 | 27132.2 |
| Total exported virtual water | 1542.7 | 6799.9 | 2322.5 | 1066.1 |
| The difference between exported and imported virtual water | 22139.5 | -5405.8 | -713.4 | 16467.1 |

*Source: Own calculating depends on the data on Table 10 and 11, respectively*

Finally, it can conclude this chapter by, a many researchers tried to build and explain well how it can benefit from the concepts of water footprint and virtual water principle but there is still a gap on these concepts related to calculations of them and the characteristics of each country in relations with the crops grown, climate conditions and the resources of water. In addition, virtual water trade is a reality in Egypt, but it has not been taken into account in water resources planning and management policies yet, as the value of virtual water for products must be entered into the accounts of costs and economic returns when making economic decisions, related to production, export and import policies and the need to educate farmers about the scarcity of water supplies in Egypt in order to ensure that water is used efficiently in local production, stimulate the production of crops with high values for export, and reduce the area planted with water-intensive crops. It is also important to create environmental awareness among individuals, to benefit from water, as knowledge of virtual water for various goods and services creates awareness among individuals of the environmental impact of their consumption of these goods and services.

### 2.8. Sustainable agricultural development in the Arab region

Agriculture is responsible for about 70% of the total water withdrawals worldwide, and it is the first sector to be put under significant pressure due to increasing water scarcity. This figure increases in the dry regions by more than 90% and it is unfortunate that all uses, whether agricultural or industrial etc., consume a large amount of water (Ritchie & Roser, 2017). Efficiency of use is low, especially in agriculture, and this is true for all countries in the world, since only a small part of the water taken from agriculture is used by plants effectively, while the rest is poorly located, or lost. This means there is a need to find effective ways to improve efficiency and conservation and demand management for all users, including agriculture.

Many studies indicate that the amount of fresh water in the world is limited and its distribution in terms of space and time is irregular, leading to frequent waves of floods and droughts, whose negative effects influence many human beings and all aspects of life (Turral et al., 2011). This occurs as a result of unfair practices and irrational use, which leads to the depletion of some renewable and non-renewable groundwater-carrying formations, in addition to the increasing pressures of the impact of climate change (Treidel et al., 2011).

It is known that various uses, especially agricultural ones, consume an enormous amount of water, estimated at 70% of resources available worldwide (FAO, 2017; Taniguchi et al., 2008), but that percentage rises in dry areas, which are areas of scarcity, to more than 90% (FAO, 2017) and unfortunately, is characteristic of all uses - agricultural, industrial and others consumed a large amount of water with low efficiency, especially for agricultural use, in all countries of the world, particularly in dry areas, which means we must find effective means to increase the efficiency of use, rationalize consumption and manage demand for all uses, mainly in agriculture (Hertel & Liu, 2019; Mancosu et al., 2015; uncertainty & risk, 2012). There is no doubt that the efficiency of the use of water resources - in the agricultural sector in particular - is an important element of water security in Arab countries, and represents a fundamental pillar for the achievement of sustainable agricultural and food development, given that this region is classified as the poorest region in terms of renewable water resources. Thus, imperative to develop in all directions to make the most of the limited water resources available and to exploit them as efficiently as possible (Al-Zubari, 2013; Dubois, 2011; El-Khoury, 2014; Jiménez & Asano, 2008). Therefore, through this literature, I will try to answer the following research question and give a recommendations at the final thesis: *How sustainable agriculture and food development can be achieved through the efficient use of water resources in the Arab region?*

To answer this question, this research has addressed the following topics: (1) the economics of water resources in the Arab region; (2) sustainable agricultural and food development, and (3) efficiency in the use of water resources in the agricultural sector.

### 2.8.1. The economics of water resources in the Arab region

Water is one of the most important resources on the earth. The notion of water resources is multidimensional. It is not only confined to its physical measure (hydrological and hydrogeological), but encompasses other more qualitative, environmental, and socio-economic dimensions (FAO, 2003).

#### *2.8.1.a. Water Resources and Uses*

Water Resources are divided into *conventional* and *non-conventional* resources. ***Conventional resources:*** include surface water, groundwater and rainwater, and covers all resources that humans are used to dealing with and have exploited from ancient times, due to their easy access and low cost (Qadir et al., 2007):

- *Surface-water:* these sources include rivers, springs, lakes, and streams. These resources can be subject to fluctuations due to their dependence on rainfall rates in relation to the quantities which are consumed (Winter et al., 1998).
- *Groundwater* includes all types of water under the ground, stored in the earth's various layers over time, as a result of the leakage of amounts of rainwater to these layers. One third of the world's population depends on these water sources, of which there are two types: renewable and non-renewable (Bethke & Johnson, 2008; Foster & Loucks, 2006).
- *Rainwater:* represents the main source of water in many regions of the world where populations depend on this and other conventional sources, such as surface and groundwater (Shiklomanov, 1991). Some countries depend mainly on rainwater for the cultivation and production of their food crops, and the element of uncertainty is

the most important problem that can affect the possibility of exploitation (FAO, 2003). With rainfall there is also - in theory - a large disparity in precipitation rates between different areas of the same country (Sun et al., 2018).

***Non-conventional resources:*** are usually used when the utilization of conventional sources has reached its maximum, yet does not meet the needs of different users due to high costs, since these sources need a very high expenditure on capital equipment to take advantage of and develop them, which leads to a high average cost of water per unit (Santos Pereira et al., 2009). They include:

- *Treated wastewater*, which is used for certain - but not all - purposes, as it is not used extensively as drinking water, but for other purposes such as bottled water, toilet tanks, or irrigation for domestic gardens. This resource has industrial and other uses. The importance of this resource is growing because wastewater is constantly increasing, and trying to treat and then reuse it can bring many environmental benefits (Ibrahim et al., 2019; Warsinger et al., 2018).
- *Desalination of salt water* is the conversion of saltwater into pure water from usable salts, and this is done through many methods of desalination (hatchery, membranes, etc.). This desalinated water-primarily feeds domestic and industrial uses (Thimmaraju et al., 2018). It produces high-quality water but is one of the methods that adopts complex technology which raises the cost of water production compared to conventional water sources.
- *Rain-making:* the method of rain-making is a newly developed technology to obtain water, through the injection of clouds with chemicals that stimulate water vapour to condense, and then fall in the form of rain. This method is still in the testing phase and has not yet become a widely used practical application (Moran et al., 1970).
- *Water conveyance:* depends on either pipelines or giant tankers from areas with abundant water (Plappally, 2012); this alternative is one of the least used alternatives and is considered only in extreme cases.

According to Glossary of Statistical Terms, ***water use*** refers to use of water by agriculture, industry, energy production and households, including in-stream uses such as fishing, recreation, transportation, and waste disposal. Generally, water is distributed among the following basic uses:

- *Agricultural use:* agricultural activity ranks first in the world in water consumption compared to other industrial and domestic activities, consuming nearly 70% of the world's total water (up to 90% in dry areas) (Ritchie & Roser, 2017). The demand for water in agricultural production is influenced by several factors, including the cultivated area - which is directly proportional to the amount of water consumed -, the climatic conditions of temperature, wind speed, and the associated evaporation and water erosion rates. All these factors affect the amount of water available for consumption; the type of crop planted, the irrigation method and the quality of the soil also affect the quantities of water consumed agriculturally, as well as waste that results from neglect and lack of maintenance of water pipes on farms, and other factors (Chartzoulakis & Bertaki, 2015; Hatfield, 2015).
- Industrial use: industry comes second in the consumption of water after agriculture, and consumes about 23% of the total, but this quantity decreases in developing countries and rises in developed countries; furthermore, wastewater is used for industrial purposes, and has economic returns. This is represented by the added economic value of industrial production, in addition to the possibility of recycling and reusing water used for industry (Connor et al., 2017; Statistics, 2008).
- Domestic and municipal use: for drinking, cooking, washing, cleaning, house cleaning, etc., these uses vary from region to region around the world depending on the temperature of the atmosphere, geographical location, the pressure used in the distribution of water and the level of income of individuals, as well as customs and traditions (Faures et al., 2001). Population growth is the main factor that will determine the amount of water required in the future for this type of use, and it should be noted that the amount lost due to waste, lack of maintenance and misuse is directly proportional to the demand for freshwater (Food & Nations, 2017).

#### *2.8.1.b. The Distribution of Freshwater in The Arab Region*

USGS indicated that the amount of water in the world is estimated at 1386 billion cubic meters, of which freshwater constitutes a small percentage, estimated at 2.5%; the percentage of saltwater in the seas and oceans is 97.5%. If we take into account the fact that 68.9% of freshwater is frozen water, what is available for human use is approximately 31% of the total freshwater, and of this 29.9% is groundwater, i.e., non-renewable, and 1.2% is renewable water, and the latter is divided into 0.3% from lakes and rivers and 0.9% which depends on the humidity of the air, water, and swamps and so on (Shiklomanov, 1998). More than one billion people around the world do not have access to clean water, and one billion people in developing countries suffer from a lack of drinking water; 80% of the health problems in developing countries are due to inadequate water and sanitation, which kills 18 million children every year (Nations, 2015).The Arab world has an area of 1.4 billion hectares and represents approximately 10.2% of the world's land and had a total population of 414.5 million in 2017, accounting for nearly 5.5% of the world's population. It receives only 2% of the world's renewable freshwater and only 1% of the world's annual rainfall. Furthermore, demand for water is increasing rapidly as a result of the increase in the population which studies indicate will reach half a billion by 2050 (Council, 2012). This rapid increase has led to a reduction in per capita water available from 4000 m$^3$/p/y in 1950 to 1233 m$^3$/p/y in 1988, and is expected to fall to 547 m$^3$/p/y by 2050 (Council, 2012). According to the international index the water poverty threshold is 1000 m$^3$/p/y, and thirteen Arab countries fall into the category of water-poor countries at the moment, and the number of these countries will certainly increase if the population growth rates continue to be the same (Sub-Saharan). The Figure 7 shows the change in the per capita renewable water and population between 1995 and 2025 for some Arab countries for the scarcest water resources.

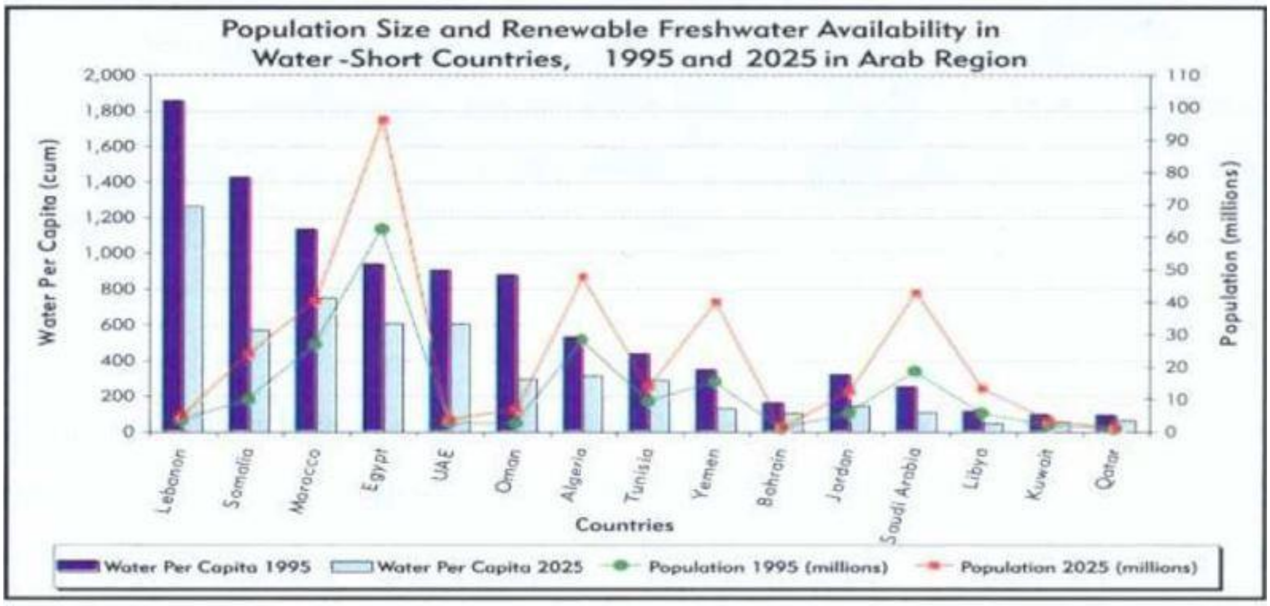

**Figure 7:Simulated per capita water availability between 1995 and 2025 for various Arab countries.**

*Source: Document of the Arab Water Council for the Middle East, North Africa, and Arab Countries*

The use of water in the Arab world occurs in three main areas: agriculture, industry, and household consumption. Agriculture is the largest consumer of water and its estimated average consumption is about 85% of the total available water, while the rest is shared between domestic consumption and the industrial sector at 8% and 7%, respectively (AFED, 2012). Although the agricultural sector in the Arab region Assimilate a large number of the population as its labour force, its contribution to national income is very small due to the lack of production and unplanned expansion of agricultural projects. If the situation continues as it is, the water gap in the Arab world will certainly increase, as many studies have shown. This is further complicated by the phenomenon of climate change and the resulting shortage of water resources, as mentioned above, in addition to the increased pollution in those resources, particularly groundwater, which is used as a safety valve in drought spells (Madbouly, 2009; Weerasekara, 2017).

Therefore, it is necessary to make joint Arab efforts politically, economically, and scientifically to identify priorities in the distribution of water resources and rationalize their use, in addition to developing water and environmental awareness and developing the technologies used so that Arab water security can be achieved.

#### *2.8.1.c. The Threat of Water Insecurity in The Arab Region*

As is known, water is the foundation of life and is the main pillar of a safe life, economic and social development, and sustainable ecosystems. Scientists and researchers have agreed in many global forums that freshwater in most regions of the world has become a scarce and exposed resource. The risks of pollution and unguided use present grave threats if the situation continues as it is, and consequently, many initiatives, have emerged over the past 20 years (Spring & Brauch, 2009). The definition of water security in the World Water Council (WWC) document is that "any member of the community has access to enough clean and safe water at reasonable cost so as to be able to lead a healthy and productive life without affecting the sustainability of the natural environment" (Cosgrove & Rijsberman, 2014). The most important results of achieving water security include achieving a balance between the protection of water resources and their use, avoiding pollution threats, and improving human health, well-being and productivity along with environmental sustainability (Merrey et al., 2015).

The issue of water security is particularly important in the Arab region, given the nature of its geographical location and the extension of most of its territory through very dry areas characterized by water scarcity and frequent droughts, due to climate change which has begun to affect the world, including the Arab region (UNDP, 2018). The Arab region has been greatly affected by climate change phenomenon, resulting in a decrease and significant changes in rainfall rates. Some future projections of rainfall over the next 50 years indicate that it will decrease by 20% from the current situation in most regions of the Arab world, and of course this will harm water resources on the one hand and agricultural production on the other, and this, in turn, exacerbates the crisis. The economic and social situation has already deteriorated in the Arab region, particularly in rural areas, where the spread of poverty among the rural population has increased, forcing them to migrate to large cities, and this has hurt agricultural production as a result of the lack of labour (Davis, 2003). This migration affects the city water supply and sanitation systems and increases the causes of water pollution. The situation is made more complicated by the fact that 66% of its water resources, consisting of large rivers, originate from beyond the limits of the Arab world, where most of the Arab countries concerned make up the downstream countries of these rivers, and therefore the division of water is subject to many disputes because there are no fair and equitable agreements (Jagannathan et al., 2009a). The problem of water distribution thus remains a major threat to security and stability in the Arab region. On the other hand, it should be noted that poor efficiency is one of the most important reasons for the worsening of the water crisis in the Arab region, as there is much wasting of water in various areas of use, for example, irrigation studies and research have shown that water is lost in the surface irrigation systems that prevail in most Arab countries (States & utvecklingssamarbete, 2013). About 62% of all water is used for irrigation and the application of modern irrigation methods helps to save more than 50% of this wasted water. This is in addition to increasing productivity, decreasing employment and the cost of production.

From the foregoing, it is important that Arab countries give the development and conservation of water resources the highest priority when developing their strategies, and water security must be at the top of the list of these priorities and the rationalization of water resources is one of the most important alternatives to bridge the gap. There is a good international experience in the field of rationalizing consumption and increasing the efficiency of use, which can be used to bridge the gap between the available quantities and the demand for water in the Arab region and thus contribute to the achievement of water security in the region (Amer et al., 2016; Jagannathan et al., 2009b).

### 2.8.2. Sustainable Agricultural and Food Development in The Arab Region

Agricultural development plays a key role in improving food security by increasing the quantity and diversity of food, and as an engine of economic transformation. Agriculture is the main source of income for the majority of the population living in extreme poverty and is considered to be an adequate source of income. Around 1.3 billion people work in the agriculture sector and it directly determines their food security, in addition, the international experience over the years shows that agricultural development and economic growth are both a sign of improvements in food security and nutrition (F. FAO, 2017).

Agricultural development is defined as the process of improving agricultural production in both quantity and quality to achieve food security and reduce dependence on imports, by revolutionizing the methods and means of production adopted and bringing about social, cultural and health changes in rural society; sustainable agricultural development means the management and maintenance of living resources, and the capacity to produce them for present and future generations (Galluzzi et al., 2011; Giovannucci et al., 2012).

According to the experts on food security and nutrition, sustainable agricultural development is agricultural development that contributes to increasing resource efficiency, enhancing resilience and ensuring social equity for agriculture and food systems to ensure food security and nutrition for all in both the present and future (El Bilali et al., 2019). The idea of sustainable agricultural development evolved in the 1980s in response to the growing consensus that agricultural policies and programs should involve a range of economic, environmental, and social issues as well as traditional areas of agricultural productivity and food security; this has been demonstrated by the importance of the idea of sustainable agricultural development which was confirmed at the Earth Summit held in Rio de Janeiro in 1992 (Declaration, 1992). Since this conference, some valuable new approaches and policies have emerged as a result of the focus on sustainability which has had environmental and social benefits in some areas, such as land resource planning, agriculture education, and integrated pest control (Faurès et al., 2013; Messerli et al., 2019; Swaminathan, 1996).

Agriculture in most developing countries, including the Arab countries, is - except for oil - the main element of national output, in addition, the main area of employment, and the main source of income (FAO., 2001). Accordingly, for developing countries and the Arab world sustainable agricultural development can be considered the key to sustainable inclusive development, which inevitably requires the preservation of natural resources from degradation, for use by future generations (Sachs et al., 2019). The contemporary world had to observe a series of phenomena that lead to the belief that in a few decades' humanity will face the problem of a lack in food production, as plant and animal organisms are declining alarmingly on earth, reaching 15% of their total in 2000, coupled with steady population growth, especially in developing countries whose population has risen from 1.07 billion in 1900 to 4.75 billion in 1998, introducing food crises in these countries. In this context the availability of food for the large population of developing countries in the first quarter of the 21st century is one of the main problems facing these countries in the future (Alexandratos, 2009; Barrett et al., 2018; Bishay, 2003).

### *2.8.2.a. The Importance of the Agricultural Sector in The Arab Region*

Although interest in the agriculture sector in developing countries declined in the 1960s and 1970s as many of these countries turned to industrialization as a key tool for development, economic and social development in many Arab countries continue to rely heavily on the agricultural sector (Yousef, 2004).

This sector contributes in four main ways (Da Silva, 2009; Goods, 2020):

- The growth of non-agricultural sectors depends heavily on local agriculture and its food products, and the raw materials used in the manufacture of many products such as fabrics (production contribution).
- People engaged in agriculture constitute an important part of the domestic market for industrial products due to the large trend towards agriculture during the early stages of economic growth (contributing to the market).
- Agriculture is a source of capital and labour for the rest of the economic sectors because the relative importance of the agricultural sector decreases with increasing economic growth (contributing to factors of production).
- Domestic agriculture contributes to the balance of payments either by increasing the value of exports or by expanding the production of local alternatives to agricultural imports.

The Arab region's agricultural land extend over a total area of about 1.4 billion hectares, or the equivalent of a tenth of its land, and the agricultural area expanded during the last decade of the last century, reaching about 70 million hectares in 2000, an increase of about 11 million hectares from 1990, and there is abandoned land with an area of more than 18 million hectares, meaning that there is abundant land suitable for agriculture (OECD et al., 2018).

Despite the importance of the agricultural sector in the economic structure of a large number of Arab countries (and the relative improvement experienced during the 1990s), its contribution to the GDP of Arab countries as a whole is still around 11%, and the structure and characteristics of this sector make it unable to meet the growing food needs of the population, resulting from the increase in their number and incomes (Woertz, 2017). Consequently, this deficiency has exacerbated the problem of food deficit, where the size of the food gap reached about 27 billion USD in 2010 compared to about 11.7 billion USD in 1991 and is expected to rise to 44$ billion in 2020 (ESCWA 2017).

From the above, it is clear that the problems of Arab agriculture are not only the lack of agricultural land, but also other factors which are no less important related to the efficient exploitation of available resources, as lands become an economic and productive resource for agriculture only when exploited, and this will only be achieved with the availability of water (Gelil & Saab, 2015).

### *2.8.2.b. Provision of Water Resources in The Arab Region*

Provision of water resources is a condition for sustainable agriculture and food supply. Limited water resources on the one hand, and consumption patterns on the other, have led to the emergence of a clear imbalance between the available water resources and the demand for them in many Arab countries, and this imbalance has led to the emergence of a water deficit reached about 162 billion in 2010 and expected to reach 377 billion in 2025 Table 13, if the same policies continue in the future (Abu-Zeid & Shiklomanov, 2003).

**Table 13: The Reality and Prospects of the Arab Water Balance per Billion m$^3$.**

| Attribute | 2000 | 2010 | 2025 |
|---|---|---|---|
| Currently continuing water resources | 191 | 191 | 191 |
| Water Demand | 254 | 253 | 568 |
| Expected water shortage | 63 | 162 | 377 |
| Food procurement rate | 72% | 48% | 24% |

*Resource: collected from different sources (Brooks & Mehmet, 2000; Droogers et al., 2009; Droogers et al., 2012; Jagannathan et al., 2009b; States & utvecklingssamarbete, 2014)*

Providing water to sustain agricultural development in the Arab region to meet the needs of the population is one of the most important challenges facing the Arab agricultural sector, as the available water resources do not allow us to keep up with the growing demand for these needs. The agricultural sector uses 88% of the available water resources, meaning that it is very difficult to increase production levels and improve food security conditions without addressing the water crisis and increasing the efficiency of its use in agriculture, and this requires taking effective steps at various institutional and legislative levels (Food & Nations, 2017). This can be done by developing successful policies and programs for available water resources, aimed at rationalizing their use to help increase irrigated agricultural land, as the productivity of irrigated land far exceeds that of rain-fed lands, although the area of irrigated land does not exceed 11 billion hectares, or about 15% of the area.

Water efficiency is the most important option available to Arab countries for horizontal expansion in agriculture, and this is possible through adjustment procedures in current irrigation techniques, systems, and methods, and through the rehabilitation of existing facilities. Note that many of the irrigation methods used in the Arab region have increased salinity in the soil, which reduces its future productivity, and results in land unfit for agriculture in the long term. Therefore, Arab countries should adopt irrigation policies that contribute to sustainable agricultural development in addition to their contribution to increasing land productivity and expanding the area of agricultural land (Abul-Naga, 2009).

It is known that surface irrigation methods are still prevalent in most Arab countries, and this may result in significant problems, including a decrease in irrigation efficiency estimated at 40-50%, or about half the amount of water used in agriculture, which shows the urgent need for improvements to irrigation systems. Also important are the following: reducing water losses during the transfer of water from the source to the farms, isolating water channels from the growing grass on their sides, and providing the optimal water needs for field crops during the growth phase etc. However, the best solution for some countries remains the introduction of irrigation methods, despite their high cost (Perry et al., 2017; Walker, 1989).

### 2.8.3. Efficiency in the Use of Water Resources in the Agricultural Sector

The link between the amount of water required for a specific purpose and the amount of water utilized or delivered is measured by water efficiency. (Hatfield & Dold, 2019; Machibya et al., 2004). A related concept is the preservation of water by emphasizing the completion of any work or task that needs water by using the lowest amount of water. There is a distinction between water conservation and water efficiency, with the latter focusing on reducing wastewater rather than reducing water use, and emphasizing the impact that users can have on water consumption by adopting water-saving behaviours and selecting more efficient process-related steps and products. Procedures can include repairing wattless hydrant, using sprinklers instead of bathtubs, etc. Another aspect of water efficiency is the emphasis on closing the water cycle through recycling and reuse; for example, water drained from one activity can be utilized in another activity of the same or similar nature. In other circumstances, the water may not be suitable for the same activity, but it can be reused in a different activity that can tolerate lower quality water after treatment. Hence it is clear that reuse and recycling will improve water efficiency at the network level, and on the whole, all these steps fall under the definition of water efficiency, because their purpose is access to a service with the minimum amount of necessary water (Directive, 2003).

### *2.8.3.a. The Related Concepts*

***Water productivity:*** it is a useful measure of the amount of wastewater needed to generate a quantity or value of a product, and is commonly used to evaluate improvements in agricultural water productivity such as in the production of crops, livestock, and aquatic farms. The convention is increasingly to measure water productivity in industrial production; for example, the amount of water used in the same industrial product by several different companies or countries (Cook et al., 2006).

***Water footprint:*** this is an indicator of water use Figure 8.

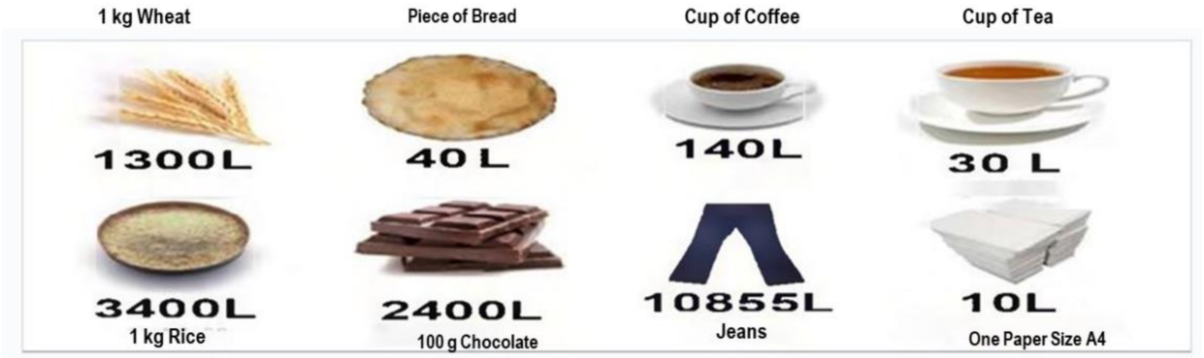

**Figure 8: Water footprint of a range of products.**

*Source: http://www.waterfootprint.org*

The water footprint of a person or work process is defined as the total volume of freshwater used to produce goods and services consumed by the individual or society, or produced by the business. For businesses, the water footprint is useful when a company wants to take into account not only the use of water in its operations but also its supply chain. This perspective can be very helpful in assessing a water threat to the business (A. Y. Hoekstra et al., 2009; Hoekstra et al., 2011).

### *2.8.3.b. Motives for Attention to the Water Use Efficiency in the Agriculture*

As mentioned earlier, agriculture consumes about 70% of the freshwater used in the world, although this percentage may reach above 90% in the dry areas of some Arab countries, making it the main consumer of water when compared to other uses such as municipal and industrial. Agricultural use is also considered a consumptive use where a large amount of water is lost by erosion and evaporation and cannot be reused, as can wastewater from industry and the city (Nazari et al., 2012).

The Earth Conference, held in Rio de Janeiro, Brazil, in 1992, estimated that the world needs to increase its agricultural production by 3% to 4% annually to meet the growing need for food and, as is known, the amount of fresh water in the world is limited and its distribution in terms of space and time varies. Large areas of the world suffer from a scarcity of fresh renewable water, and these are the same areas that use a high proportion of their water resources in agriculture and usually resort to irrational uses of renewable and non-renewable groundwater. Many studies indicate that there is a continuous decline in groundwater levels in many countries which use this water for agriculture, including China, India, Mexico, the United States of America, and many Arab countries, especially the Gulf states (F. FAO, 2017).

Increased water efficiency often provides benefits far beyond the economy of the water used, such as reducing water and pumping costs, reducing the costs of fertilizers and other agricultural chemicals, maintaining soil and crop quality, and increasing crop production by nearly 100 %.

There is a recognition by all that the current pattern of water use for irrigation will not continue in the same extravagant manner and with the low efficiency that wastes limited and non-renewable renewable resources that are vulnerable to attrition as a result of pollution and climate change.

### *2.8.3.c. Methods of Water Efficiency Improvement in Agriculture*

Food needs for the world's population have been increasing, and many research has deal with water efficiency in agriculture for many years, but globally viable solutions are difficult to benefit from, especially because of different environments and the high specificity of agricultural practices. However, efficiency gains (improving efficiency of water used in irrigation) are essential, especially in the Arab region with a desert and semi-dry environment where irrigation is inevitable. This is often possible by following a range of water methods and policies, which can be listed as follows (WATER FOOTPRINT NETWORK, 2013):

a) Selecting appropriate crops;
b) Indicating appropriate schedules for irrigation;
c) Using effective irrigations techniques;
d) Soil enhancement measures;
e) Using an alternative source of irrigation water.

***(a) Selecting appropriate crops:*** crops vary in terms of their daily water needs and the length of their overall planting period, and as a result, the type of crop is a major factor affecting the need for irrigation water. Crops with high daily needs and a long total planting season have more water requirements than those with fewer daily needs and relatively shorter planting seasons, so an essential step towards reducing irrigation water needs is to choose crop types that require less water but provide sufficient added value (Brower & Heibloem, 1986). This is shown through the following two tables, where the Table 14 shows the total planting period of the crop group, and the Table 15 shows the water needs of each of the previous crops during the total planting period, as follows:

**Table 14: "Indicative Values of The Total Growing Period".**

| Crop | Total Growing Period (days) | Crop | Total Growing Period (days) |
|---|---|---|---|
| Alfalfa | 100-365 | Millet | 105-140 |
| Banana | 300-365 | Onion green | 70-95 |
| Barley/Oats/Wheat | 120-150 | Onion dry | 150-210 |
| Bean green | 75-90 | Peanut/Groundnut | 130-140 |
| Bean dry | 95-110 | Pea | 90-100 |
| Cabbage | 120-140 | Pepper | 120-210 |
| Carrot | 100-150 | Potato | 105-145 |
| Citrus | 240-365 | Radish | 35-45 |
| Cotton | 180-195 | Rice | 90-150 |
| Cucumber | 105-130 | Sorghum | 120-130 |
| Eggplant | 130-140 | Soybean | 135-150 |
| Flax | 150-220 | Spinach | 60-100 |
| Grain/small | 150-165 | Squash | 95-120 |
| Lentil | 150-170 | Sugar beet | 160-230 |
| Lettuce | 75-140 | Sugarcane | 270-365 |
| Maize sweet | 80-110 | Sunflower | 125-130 |
| Maize grain | 125-180 | Tobacco | 130-160 |
| Melon | 120-160 | Tomato | 135-180 |

*Source: FAO, 1986 (Brouwer & Heibloem, 1986)*

In addition, modern genetic engineering also plays an important role in accessing the right crops, relying on modern technology in agriculture, such as tissue culture and the production of drought-resistant hybrid seeds of high economic value, especially vegetable seeds, flowers, and fruit tree seedlings whose irrigation water needs are modest compared to regular seeds and seedlings. No doubt this will involve genetically modified products, and – as is the case with every new product - the ideal and rational way of dealing with them is not to accept or reject all of them, but to study each cases one by one (Oliver, 2014).

**Table 15: Approximate Values of Seasonal Crop Water Needs.**

| Crop | Crop waters needed (mm/total growing period) | Crop | Crop waters needed (mm/total growing period) |
|---|---|---|---|
| Alfalfa | 800-1600 | Pea | 350-500 |
| Banana | 1200-2200 | Pepper | 600-900 |
| Barley/Oats/Wheat | 450-650 | Potato | 500-700 |
| Bean | 300-500 | Rice (paddy) | 450-700 |
| Cabbage | 350-500 | Sorghum/Millet | 450-650 |
| Citrus | 900-1200 | Soybean | 450-700 |
| Cotton | 700-1300 | Sugarbeet | 550-750 |
| Maize | 500-800 | Sugarcane | 1500-2500 |
| Melon | 400-600 | Sunflower | 600-1000 |
| Onion | 350-550 | Tomato | 400-800 |
| Peanut | 500-700 | - | - |

*Source: FAO, 1986 (Brouwer & Heibloem, 1986)*

Therefore, the real use of this technique in the field of agriculture to provide more water for irrigation depends on the way humans use it and the way it is managed and directed, which in turn depends on the extent to which those working in this field adhere to the ethical and scientific controls governing research into genetic engineering, as well as how much researchers understand the needs of society and the capabilities of the surrounding environment (Jacobsen et al., 2013).

***(b) Setting appropriate irrigation schedule:*** scheduling irrigation helps to exclude or reduce cases in which small or very large amounts of water are used for crop irrigation. Setting appropriate irrigation schedule requires precise control of the time and amount of water which crops are irrigated. This involves understanding the water in the crop root area, the amount of water consumed by the crop since last operational irrigation, the stage of crop development, and the direct measurement of moisture content in the soil. In this area, direct measurement of the moisture content in the soil is one of the most effective ways to determine the crop's water needs and therefore the appropriate irrigation schedule. A simple automatic controller can constantly monitor the moisture content of the soil which will enable significant savings in water, and compensate for its purchase price through the reduction of water use, cost, and manpower (Smith et al., 1997). A wide range of methods are available to monitor soil moisture, each with its advantages and disadvantages.

As regards the stages of crop development, it is noted that the need for water at the beginning of the planting season is usually about 50% lower than what is required at the mid-season stage, where the crop has grown completely and reached its peak water need (Critchley et al., 2013; Er-Raki et al., 2007). Farmers must be attentive to the irrigation schedule and the irrigation system, which must be adaptable to changing water needs (Pereira et al., 2012). In addition to all this, it should be noted that the provision of excess water can also have adverse effects because crops cannot use excess water and may be stressed by low oxygen levels in saturated soils, and these practices not only dissipate water but also increase energy and pumping costs (Bhattarai et al., 2005; Jackson, 2004).

As a result, it is necessary to plan appropriately for irrigation and to bring the right amount of water needs of the crop – not increasing or decreasing it –, by setting good irrigation dates to achieve optimal production and water efficiency. This requires farmers to know the following: (1) the amount of water required by the crop during different growth cycles; (2) the soil moisture content and the soil's ability to consume water and (3) the climatic conditions.

***(c) Using effective irrigation techniques:*** after determining the quantitative and temporal characteristics of the ideal demand for water, a method to make this water available in the most effective way should be chosen. There are three main types of irrigation (Brouwer et al., 1988):

1) *Surface irrigation:* this is the easiest and least expensive type, but it is usually highly inefficient, as the plant receives less than 10% of the water directed to it. Unfortunately, this type is most widely used in the Arab region.
2) *Sprinkler irrigation:* these systems are more efficient than surface irrigation, but their installation and operation are more expensive due to the need for compressed water.
3) *Drip irrigation:* this has been shown to help achieve a 100% increase in yields and save from 40 to 80% of water used, with accompanying savings in fertilizers, pesticides, and labour, beyond the savings provided by traditional irrigation systems.

Drip irrigation systems operated by solar-powered pumps may be a particularly promising alternative for the MENA region, creating a more efficient system. The following Figure 9 shows that soil moisture levels usually define the type of irrigation adopted.

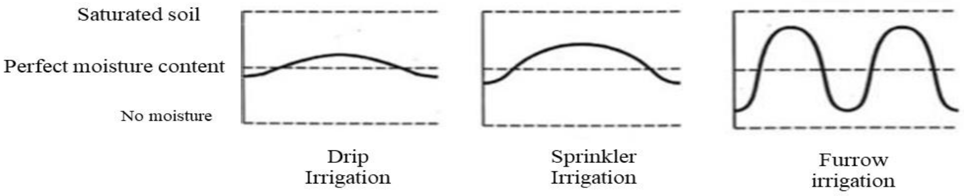

**Figure 9: The relationship between soil moisture rate and the irrigation type selected.**

*Source: (ICID & FAO, 1996).*

*Supplementary irrigation:* supplementary irrigation is a pattern or irrigation system that offers great help in improving the productivity of winter crops (rain-fed) such as wheat, barley, chickpeas, lentils. In practical terms, it is intended to bridge the gap between the water consumption of a crop and the rate of precipitation. It is necessary to determine the critical period and growth phase that requires an increase in supplementary irrigation in order to obtain good water efficiency and a good productivity relationship involving the quantity and timing of the irrigation. The goal of supplementary irrigation is not only to obtain the highest production but to increase production and stabilize it. Drought mitigation in rain-fed farming areas, as well as supplementary irrigation, are mainly located in dry and semi-arid lands where evapotranspiration rates typically exceed rainfall rates at some stage of crop growth (Fox & Rockström, 2003; Nangia et al., 2018).

Experience in many Arab countries has shown that the addition of an average of 150 mm in the agricultural season in the form of supplementary irrigation increases grain production by two to four times (Oweis & Hachum, 2003). The use of 1 cubic meter of water in a supplementary irrigation form amounts to about 1.8 kg of grain, while in rain-fed agriculture and without supplementary irrigation, the production rate of a cubic meter of grain is about 0.34 kg, which means that the efficiency of the use of water in supplementary irrigation is about five times that of rainwater, and the use of supplementary irrigation can be expanded by the use of seasonal floodwaters, water harvesting and local groundwater (Oweis & Hachum, 2006; Oweis et al., 1999).

Therefore, we must work seriously to stop waste in the field of agricultural watering by expanding the use of modern irrigation methods. In recent years it has been reported that in

Algeria, Tunisia and Morocco the use of drip irrigation system has grown significantly and at an accelerated rate, although sprinkler irrigation is still the dominant method, and despite the fact that sprinkler irrigation has advantages compared to the old methods, it is a major source of loss, and experts estimate that more than 70% of irrigation water used in this way is not utilized but is lost (Jacobs & van't Klooster, 2012; Valipour & Singh, 2016). The shift to drip irrigation reduces water use by 30% to 60% and improves the yield by 5% to 50%, and our situation obliges us to evaluate all types of crops through the prism of output or economic return against the need for irrigation water. We should abandon the cultivation of voracious species, and promote night irrigation to reduce the amount of evaporation during daylight hours. Another recommendation is to increase and develop water and agricultural awareness centres to transfer state-of-the-art water use technologies to farmers, and train them to use them optimally and solve the problems they face in this area (Broccoli, 2019; Burton, 2016).

***(d) Soil enhancement steps:*** there are several steps to enhance the soil, which will improve the efficiency of irrigation. These include (Council, 1993):

- *The suitable flatness of the field:* to make the water flow with optimal speed, which helps in the distribution of water regularly and reduces water flow.
- *Water barriers:* small earth dams allowing the irrigation or drainage water to be trapped within the field's stream, which may reduce runoff and increase irrigation efficiency.
- *The plant waste management:* where crop and plant residues are managed and distributed on the surface of the soil, such practices improve the soil’s ability to preserve moisture and reduce water runoff in the field, as well as reduce surface evaporation and thus are more suitable for fields that use sprinkler or drip irrigation.
- *Impact on water systems:* the use of clay or cement to cover the surface of a water-carrying channel can greatly reduce water infiltration. In addition, covering canals and placing them under the surface of the earth reduces water loss by evaporation.

***(e) The use of alternative sources of irrigation water:*** more efficiency gains can be achieved at local or regional levels, using alternative sources of irrigation water. There are two main ways of doing this:

- *Rainwater harvesting:* rainwater harvesting, and floods are defined as the techniques used to hold and store rainwater and torrential rains in different ways, depending on the purpose of their collection, facilitating reuse when needed, whether, for drinking or irrigation, supplementary irrigation or providing groundwater. This method is increasingly popular in those parts of the world where heavy rains occur for short periods and are followed by prolonged droughts, by creating water-impermeable surfaces that cover a large area to reduce rainwater infiltration into the soil (Boers & Ben-Asher, 1982). By controlling the flow of harvested rainfall, diverts the water to reservoirs, aquifers or surface ponds dedicated to this purpose. Although this method is the least expensive alternative, it causes a significant loss of water through evaporation. However, the harvest of rainwater can be successfully employed in parts of India, where there are many small farms (Helmreich & Horn, 2009).

- *Using treated wastewater:* using modern technology, household wastewater can be treated following strict health and environmental guidelines, allowing for safe irrigation use. However, the use of treated wastewater in irrigation practices is only possible on farms located near cities to operate an effective wastewater treatment system.

Treated wastewater is used to irrigate agricultural land in Jordan, Tunisia, and Syria, and to irrigate public parks in some GCC countries and North Africa. It is believed that the reuse of municipal (domestic) wastewater is a potential intervention strategy for the development of non-traditional water resources, which can contribute to a significant reduction in water stress and water scarcity in the Arab region as part of an integrated management approach to water resources (Abdel-Dayem et al., 2011; Dawoud, 2007).

### 2.8.4. Irrigated and Protected Agriculture as the Future of Sustainable Arab Agricultural Development

It is noted that the productivity of irrigated land is three times higher the rain-fed land. Besides, protected agriculture is one successful way to make the most of water resources, through which it can achieve record levels of productivity more than twenty times higher of greenhouses compared to bare-agriculture (Shaxson & Barber, 2003). This means that the efficiency of irrigation water in greenhouses is about 40 times higher compared to bare-agriculture, in addition to focusing on the production of high-value exportable crops. It also makes it possible to grow vegetable crops in the off season and throughout the year instead of in only one season, which doubles total production, reducing dependence on imports from abroad and increasing the contribution of the agricultural sector to GDP (Badran, 2018).

With regards to irrigated agriculture – in addition to protected one – it is the way how agricultural crop productivity can be increased compared to low yield traditional methods.

This method attains sustainable agricultural development and reduces the widening food-gap. Because of the water factor is a fundamental determinant of expansion in irrigated agriculture, the solution lies in the necessity of increasing the efficiency of water use in irrigation. Additionally, water efficiency in agriculture is a low-cost element of the good management of facilities, and studies have shown that water savings can result in additional resource savings in areas including wastewater treatment, energy use and chemical consumption. However, a comprehensive program of energy efficiency requires political, administrative, and financial support from senior management. Without the support of the latter, it is often difficult to mobilize the necessary resources to start a water efficiency programme (Hamdy et al., 2003; USEPA, 2013). To obtain sufficient support, senior management must be convinced of the magnitude of the opportunities and threats expected, which are the main drivers of the adoption of the strategy of efficiency of water resources in agriculture in the Arab land (Dabour, 2006).

Therefore, the application of an agricultural development strategy that meets the needs of the present generation without damaging the needs of the future generation for food, requires the sustainability of agricultural production as well as an improvement in quantity and quality of foods. It was found in this research that efficient water use in agriculture and irrigation is the most appropriate solution to face water scarcity. Through efficient methods such as: choosing suitable crops, setting appropriate schedules for irrigation, using effective irrigation techniques, and using alternative water sources for irrigation, that's lead the agricultural sector in the Arab region to ensure a supply of water despite the scarcity of resources. In addition, the goal of maximizing the productivity of water to make the most of the marginal water resources, maximizing the production value of the water and reducing the focus on horizontal expansion, can succeed through the following: working with irrigated and protected agriculture more than rainfed one, drip and supplementary irrigation, protected agriculture, and choosing the economic crops based on genetic technology. These methods can effectively contribute to achieving water use efficiency in Arab agriculture, given that they respond to the conditions for increasing production on the one hand, and the specificities of climate and resources in the Arab region on another, which would improve agricultural production in terms of quantity and quality and thus improve the food security in the Arab countries.

After analyzing the optimal use of available water resources through sustainable agricultural development in the Arab region, the following research will focus on the water footprint and virtual water in the agricultural sector of Egypt.

# 3. APPRAISING THE WATER STATUS IN EGYPT THROUGH THE APPLICATION OF THE VIRTUAL WATER PRINCIPLE IN THE AGRICULTURAL SECTOR

Egypt suffers from a major problem with its water resources, which is the imbalance between the increase in demand of water and the availability of the accessible quantity of water. To solve this problem, it was necessary to coordinate with the ten Nile Basin countries, to ensure an abundant water future (Okoth-Owiro, 2004).

Egypt depends on 97% of its water needs on the Nile River. The maximum rainfall is 175 mm per year, and most of it falls during the fall and winter seasons. In 1959, the Nile Water Treaty was concluded between Egypt and Sudan, allocating 55.5 billion cubic meters of water annually to Egypt, without specifying any allocation to the upstream countries that are located next to Sudan 18.5 billion cubic meters per year (Whittington & McClelland, 1992). There was no agreement to share water between all the ten riparian states of the Nile. However, the riparian countries are cooperating through the Nile Basin Initiative (Mekonnen, 2010). The management of water resources in Egypt depends on a complex set of infrastructure along the river. Egypt's water resource management is reliant on a complex network of infrastructure along the Nile. The Aswan High Dam, which forms Lake Nasser, is the most essential part of this infrastructure. Egypt is protected from floods by the High Dam, which also stores water for year-round irrigation and generates hydropower. After the downstream of the river from the Aswan Dam, there are seven canals to increase the river’s water level, so that it can flow into irrigation channels from the first level as shown in Figure 10 .

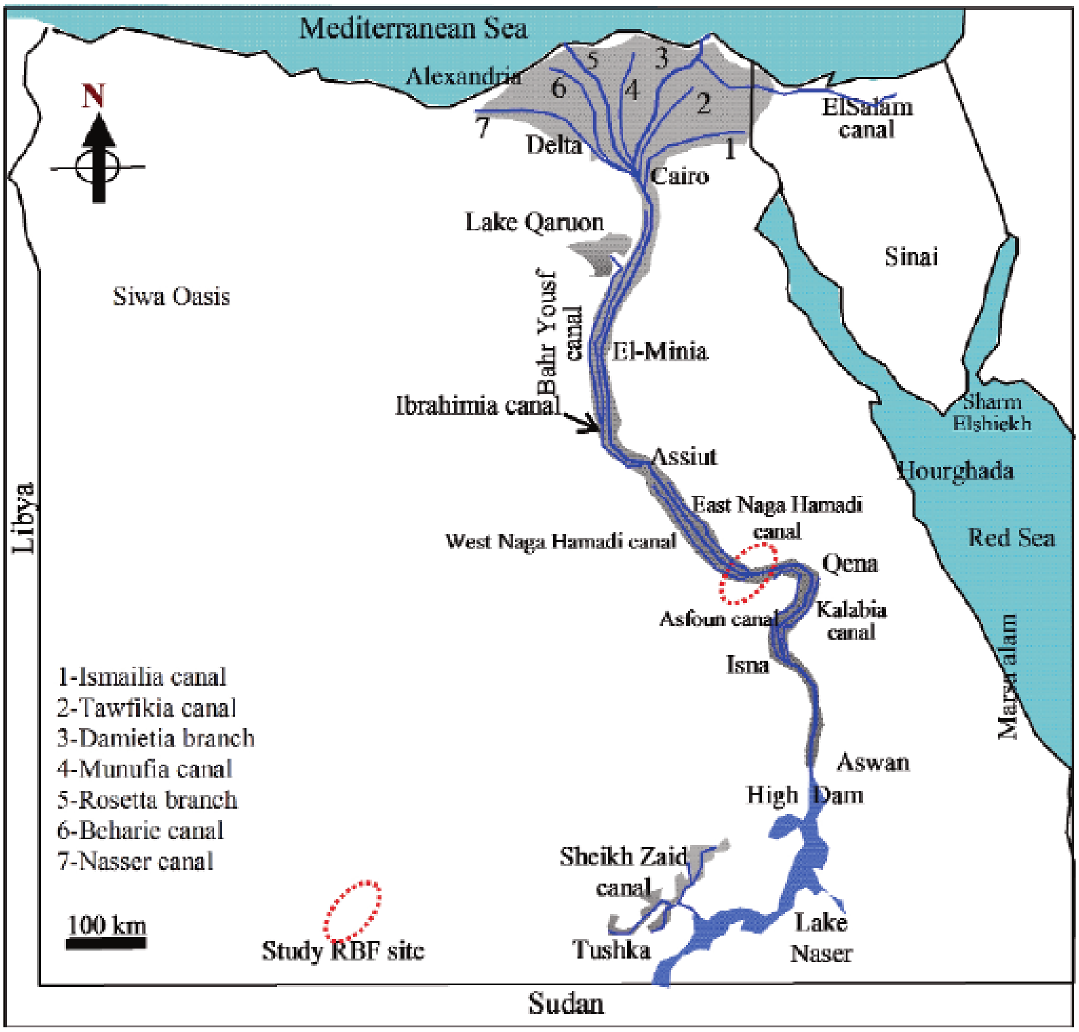

**Figure 10: Map of Egypt with Nile River.**

*Source: (Shamrukh & Abdel-Wahab, 2011)*

In addition, the Figure 11 show the water balance between water supply and water loss as an average water capacity of the Nile river (billion $m^3$/year) (Ashour et al., 2009; Land, 1997).

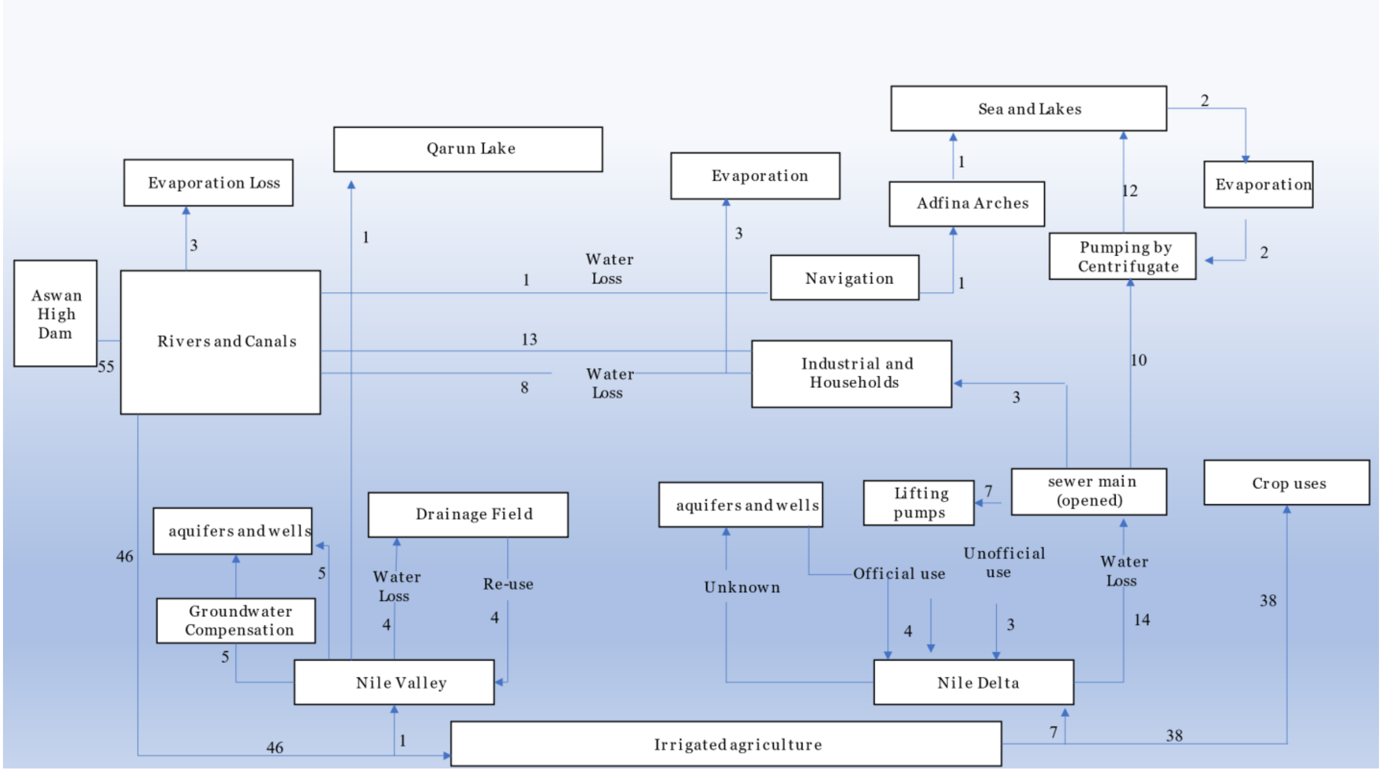

**Figure 11: The average water capacity of the Nile River (billion $m^3$/year).**

*Source: Own constructed from* (Ashour et al., 2009; Land, 1997).

Providing water to the agricultural sector is one of the main strategic objectives that Egypt aims to secure enough water to serve the population whose numbers are increasing as resources remain limited. But the volume of the potential savings in water and agriculture, and how best to achieve a breakthrough on such a topic, have caused some controversy (Negm, 2019). While the irrigation efficiency at the field level may be low due to the predominance of flood irrigation, the public system efficiency is generally high due to the return of flows. Egypt's water conservation initiatives do not place a high priority on water-saving irrigation technology like sprinklers or drip irrigation. Instead, it is dependent on farmer experience, which lacks the ability to predict when and how much water will be available. They irrigate in close proximity to each other and waste a lot of water. So, Egypt has to take into considerations a lot of factors from which the water footprint and virtual water to save water and achieve food security.

## 3.1. The main objective and research question

The main objective of the study is to benefit from the principle of virtual water for: (1) knowing the true magnitude of the water deficit in Egypt; (2) using water more efficiently in the agricultural sector. To achieve the goals of this research, the following has applied:

- Calculating the virtual water for the most important agricultural crops in Egypt;
- Calculating the virtual water for the agricultural products;
- Assessment of the water footprint and its indicators in Egypt;
- Evaluating the food security and estimating food self-sufficiency for some selected crops and products.

**RQ1:** *How to use the principles of virtual water and water footprint indicators to estimate the volume of water deficit in Egypt and to achieve water efficiency consumption in the agricultural sector?*

## 3.2. Material and methods

*The main sources of the data* to assess the water footprint, virtual water for some selected crops and products in Egypt and the value and quantity of the food gap in Egypt during 2000-2018 are mainly based on the National Water Footprint Website, the Central Agency for Public Mobilization and Statistics (CAPMAS) in Egypt , the Ministry of Water Resources and Irrigation in Egypt, and the Ministry of Agriculture in Egypt . In addition, the average world market prices USD/ton for the crops was collected from the World Bank Open Data Resource and “Water footprints of nations Volume 2: Appendices” (A. Chapagain & A. Hoekstra, 2004),

### *3.2.1. Calculating the virtual water for agricultural crops*

The amount of virtual water had calculated in this research for most important crops grown in Egypt and for the main plant products (oils and refined sugar) equation 3.1. As for calculating the amount of virtual water in agricultural crops, it was done according to the following relationship:

$$VWC\,(c) = \frac{CWU(c)}{production(c)} \qquad (3.1)$$

Where:

**VWC :** is the virtual water C of a crop ($m^3$ / ton)

**CWU:** amount of water consumed by the crop C $m^3$ / year

**Production:** production in tons of yield C

The crop water use for each crop included in the study were calculated with the following equation 3.2:

$$\mathbf{CWU\ (c) = CWR(c) \times \frac{production\ (c)}{Yeild\ (c)}} \qquad (3.2)$$

Where:

**CWU:** amount of water consumed by the crop C $m^3$ / year.

**CWR**: the amount of water requirements for each crop (c) measured in the field in $m^3$/ ha. It is defined as the amount of water required for evapotranspiration from the planting until the harvest for a specific crop that grows in soil containing sufficient water for it.

**Production:** production in tons of yield C

**Yield:** yield of crop (c) per unit area, measured in tons/ha.

The quantity of water requirements of crop (c) is calculated from the following relationship equation 3.3:

$$\mathbf{CWR} = 10 \times \sum_{d=1}^{lp} ET_c(c,d) \qquad (3.3)$$

Where:

**CWR**: the amount of water requirements for each crop (c) measured in the field in $m^3$/ ha. It is defined as the amount of water required for evapotranspiration from the planting until the harvest for a specific crop that grows in soil containing sufficient water for it.

**The "factor 10** is meant to convert mm into $m^3$/ha, and the summation is done over the period from the first to the final day of the growing period";

**lp**: represents the length of growth, measured in days;

**Etc**: is the amount of daily evapotranspiration of the crop (c) and it is measured in mm. This evapotranspiration is obtained by the process of multiplying the reference evapotranspiration amount Eto by the coefficient of the crop Kc. The crop coefficient is taken from four stages of the crop growth; initial, crop development, mid-season, and late season Figure 12, that is the stage where the crop is ready for harvest Equation 4.4 (Allen et al., 1998; Droogers & Allen, 2002).

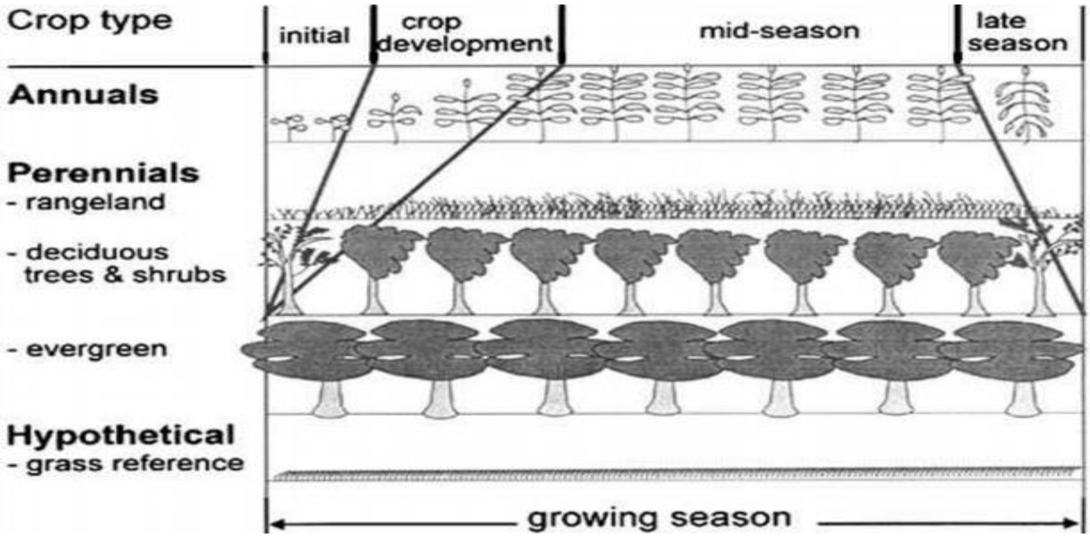

**Figure 12: Crop growth stages for different types of crops.**

*Source: (Allen et al., 1998)*

$$ET_c\, c = Kc_c \times ET_0 \qquad (3.4)$$

**$ET_0$** the amount of reference evapotranspiration, which is the percentage of evapotranspiration from the grass in specific growth conditions, is affected by climatic conditions only (Hargreaves & Samani, 1985).

The water consumption of crops varies according to their growth stage. In fact, the water consumption is at a low rate at the beginning of the crop growing season, when it is mostly in form of evaporation from the soil surface, then it increases with the plant growth as a result of the leaf mass surface increase and becomes in form of transpiration from the leaves up to the maximum growth stages (Allen et al., 1998). The crop coefficient (Kc) indicates the relationship between the evapotranspiration of the crop (ETc) and the reference evapotranspiration ($ET_0$). Kc differs according to the type of the crop, the growth phase, the growing season, and the associated climatic conditions. Kc expresses the effect of the properties that distinguish the field crop from the reference grass, whose appearance is stable and covers the entire ground, and therefore different crops have different Kc (Snyder, 1992).

Several weather conditions effects have been incorporated into the $ET_0$, that then represents an indicator of the atmospheric requirements needed for the process of evapotranspiration from green grass surfaces. Accordingly, the crop coefficient (Kc) varies greatly with the characteristics of the crop and to a small extent with the climate. Thing that explains the possible transfer of the crop coefficient (Kc) values that were calculated at one of the irrigation research stations for generalization between sites and climatic regions by (Hargreaves & Merkley, 1998)(HARGREAVES & MERKLEY, 1998)(HARGREAVES & MERKLEY, 1998) (HARGREAVES & MERKLEY, 1998) to the ($ET_0$) reference, that represents the incorporation of the effects of four basic characteristics distinguishing the evapotranspiration of the crop from the reference evapotranspiration according to (Allen et al., 1998; Van der Gulik & Nyvall, 2001), namely:

- Resistance to air movement and the turbulent transfer of vapour from the crop to the atmosphere, in addition to leaf properties, stomata and spacing between plants.
- Reflected radiation albedo, which is affected by the part of the earth covered by vegetation, and the amount of wetness of the soil surface, which is the main source of energy exchange for the evaporation process.
- Crop resistance to heat transfer and its relationship to leaf area, number of pores, age, and condition.
- The amount of wetness of the soil surface and the portion of the ground covered by vegetation on the surface resistance.

The $ET_0$ was calculated as an average of all the months of the year through the CROPWAT program. As for the Kc values, it was derived from a previous study performed by the researchers (Allen et al., 1998; A. K. Chapagain & A. Y. Hoekstra, 2004).

### 3.2.2. Calculation the virtual water for agricultural products

The virtual water for plant products in $m^3$/ton Equation 3.5:

$$VWCp\ (p) = VWCc\ (c) \times \frac{vf[p]}{pf[p]} \qquad (3.5)$$

Where:

**pf** is the production factor that indicates the weight of the primary product resulting from one ton of the main crop;

**vf** is the value factor (USD / ton), and the product value in USD is the sum of the product values resulting from this main crop.

As for the secondary products from crops, they are calculated from the following relationship Equation 3.6:

$$VWCp\ (p) = VWC\ (primary\ product) \times \frac{vf[p.p]}{pf[p.p]} \qquad (3.6)$$

Where:

**pf** is the production coefficient that indicates the weight of the secondary agricultural product resulting from one ton of the primary product;

**Vf** is the value coefficient (USD / ton), and it is the sum of the value of the secondary product to the sum of the values of the products produced from the primary product (Hofwegan, 2003).

### 3.2.3. Water footprint and its indicators

The concept of a country's water footprint is defined as the total freshwater volume used in service sectors and in the production of consumed products of all kinds by that country.

This concept was discovered by the researcher HOEKESTRA in 2002 (A. Y. Hoekstra, 2003a) in order to determine the actual water consumption per capita or country and give real information for water consumption other than the traditional information about the quantities of surface and groundwater withdrawal used in the agricultural, industrial and domestic sectors usually in calculating the annual water balance and from them, the quantities of water actually used are greater than the quantities of withdrawal from local ground and surface water, hence the concept of virtual water imported or exported, and then the so-called virtual water trade between countries.

The water footprint consists of two parts, as in the following relationship Equation 3.7:

$$\mathbf{WFP = IWFP + EWFP} \qquad (3.7)$$

Where:

**IWFP:** Internal Water Footprint;

**EWFP:** External Water Footprint.

As for the **IWFP**, it is calculated from the following relationship Equation 3.8:

$$\mathbf{IWFP = DWW + IWW + AWU - VWE} \qquad (3.8)$$

As **DWW** is the amount of water withdrawals for the domestic sector, **IWW** is the amount of water withdrawals for the industrial sector depending on the principle of virtual water and **AWW** is the amount of water consumption in the agricultural sector and is calculated depending on the method of calculating the amount of virtual water for crops and agricultural products as previously explained and **VWE** is the amount Water exported through agricultural products to other countries.

**External water footprint** calculated from the following relationship Equation 3.9:

$$\mathbf{EWFP = VWI - VWE\ re\_export} \qquad (3.9)$$

Where:

**VWI** is the volume of the imported virtual water;

**VWE re-export**: the volume of virtual water re-exported from imported products.

In this research, the water footprint was calculated based on the calculation of the water included in agricultural products only and did not include animal and industrial products to give an initial picture of the true water scale if the water included in the products was taken into account when calculating the annual water balance.

**Water footprint indicators:**

1) **Water Import Dependency Index (WIDI):** which is equal to the ratio of the external water footprint on the total water footprint as shown in the following relationship Equation 3.10:

$$\mathrm{WIDI} = \frac{\mathrm{EWFP}}{\mathrm{WFP}} \mathrm{x100} \qquad (3.10)$$

2) **Water Self-sufficiency Index (WSSI),** which is equal to the ratio of the internal water footprint to the total water footprint. It is calculated as relationship Equation 3.11:

$$\mathrm{WSSI} = \frac{\mathrm{IWFP}}{\mathrm{WFP}} \mathrm{x100} \qquad (3.11)$$

This indicator is 100% if the available water within the country meets all needs in all consumption and product sectors (A. K. Chapagain & A. Y. Hoekstra, 2004).

### *3.2.4. Food security and food self-sufficiency in Egypt*

Most countries are trying hard to achieve food security locally without relying on external resources and food imports. It must be pointed out the close relationship between food security and water security, as the volume and quality of available water will have a negative impact on food production and hence on food security. Water security is defined as the ability to meet all water needs in all sectors of water use with the necessary quantity and quality (Mouailli, 2005).

As for food security, it is defined as the ability of production to adequately fill food while increasing stability in production processes and ensuring food access to all citizens naturally and economically (Declaration, 1996; Hendriks, 2015). From previous definitions we can define the food-gap which is the difference between available supply and consumption in the country. The data were estimate the food-gap was conducted from different resources mentioned later. The **Self-sufficiency Ratio (SSR)** is defined as Equation 3.12:

$$\mathbf{SSR = Production\ x\ 100\ /\ (Production + Imports - Exports)} \qquad (3.12)$$

In this research, only agricultural crops, sugar, and oils were discussed according to the calculations of the volume of virtual water.

## 3.3. Results and Discussions

### *3.3.1. Virtual water for agricultural crops*

The amount of crop evapotranspiration Etc (mm), crop water requirements CWR ($m^3$/hectare) production (tons/year), productivity (kg/hectare),water use by crop $CWU_{[c]}$ ($m^3$/year), virtual water requirements for crops Vwc $_{[c]}$ ($m^3$/ton) have calculated for the studied crops, and appendix 1 shows the volume of those variables, and Table 16 shows the virtual water volume $m^3$/ton for most important crops.

**Table 16: The virtual water volume for most important crops.**

| Crop | Volume of virtual water $m^3$/ton |
|---|---|
| Wheat | 728.56 |
| Rice | 1025.14 |
| Maize | 1072.31 |
| Potato | 330.59 |

*Source: Own calculation, 2021*

### *3.3.2. The virtual water for agricultural products*

Table 17 shows the volume of virtual water for plant oils (olive, soybean, and cotton seeds) as a primary product and for sugar as a by-product.

**Table 17: The virtual water volume for some selected plant products.**

| Plant oils produced by | Volume of virtual water $m^3$/ton |
|---|---|
| Olive | 37274 |
| Soybean | 12490 |
| Cotton seeds | 4091 |
| Average | 17952 |
| Refined sugar | 1426 |

*Source: Own calculation, 2021*

### *3.3.3. Indicators of Water footprint*

#### *3.3.3.1. Volume of exported and imported water and water balance in Egypt*

Table 18 shows the volume of water included in the exported and imported agricultural products only for three strategic crops grown for the years 2000-2018.

**Table 18: The volume of virtual exported and imported water for the three main crops (rice, maize, and wheat).**

| The volume of virtual water | Egypt |
|---|---|
| Exported million $m^3$/year | 1040 |
| Imported million $m^3$/year | 17300 |
| The difference between imported and exported Billion $m^3$/year | -16260 |

*Source: Own calculation, 2021*

It is clear that Egypt is an importer of virtual water and not an exporter of maize and wheat crops, and for the rice crop Egypt export an important amount of their productions which is appear from the amount of exported virtual water. Based on the calculation of the volume of virtual water included in crops and plant products, the water balance of Egypt was calculated during the years 2000-2018 as shown in the following Table 19:

**Table 19: The water balance in Egypt using the concept of virtual water.**

| **The water balance in Egypt using the concept of virtual water** | | |
|---|---|---|
| Renewable water billion $m^3$/year | | 58.5 |
| Population / million | | 98.42 |
| Water uses million $m^3$ | Households | 9000 |
| | Agriculture | 67000 |
| | Industry | 2000 |
| Exported VW in agricultural sector million $m^3$ for (rice, maize, and wheat) | | 1040 |
| Imported VW in agricultural sector million $m^3$ (rice, maize, and wheat) | | 17300 |
| Internal water footprint IWFP billion $m^3$ (rice, maize, and wheat) | | 19.34 |
| External water footprint EWFP billion $m^3$ for (rice, maize, and wheat) | | 5.19 |
| The Total water footprint WFP billion $m^3$ for (rice, maize, and wheat) | | 24.53 |

*Source: Own calculation, 2021*

From the results of the previous table, it was found that the volume of real water consumption in Egypt is about 24.53 billion cubic meters / year, only for the three major crops and the volume of real individual consumption in the years between 2000-2018 is about 232.49 cubic meters / year for those crops. It is clear that the consumption of the agricultural sector is about 33 billion cubic meters “blue water” and around 6.5 billion cubic meters “green water” , which are less than the number of renewable water resources 58.5 billion cubic meters per year. The explanation for this is that the calculation of the volume of consumption of the agricultural sector was based on the volume of virtual water for agricultural products. It is known that a high percentage of crops in Egypt depend on irrigated water, the total cultivated area is 7.2 million feddans (1 feddan = 0.42 ha), representing only 3 percent of the total land area. The entire crop area is irrigated, except for some rain-fed areas on the Mediterranean coast according to the estimates of the Arab Organization for Agricultural Development and Irrigated Agriculture in Egypt (Noaman, 2017; Shetty, 2006) , meaning that Egypt is one of the countries that relies heavily on the waters of the Nile River in agriculture.

Depending on the percentage of irrigated land from the total agricultural lands, the amount of water used in irrigation operations (blue water) is calculated from the available water resources in irrigation operations, which is about 34 billion cubic meters, and the rest is about 11 billion cubic meters of rainwater (green water) Figure 13.

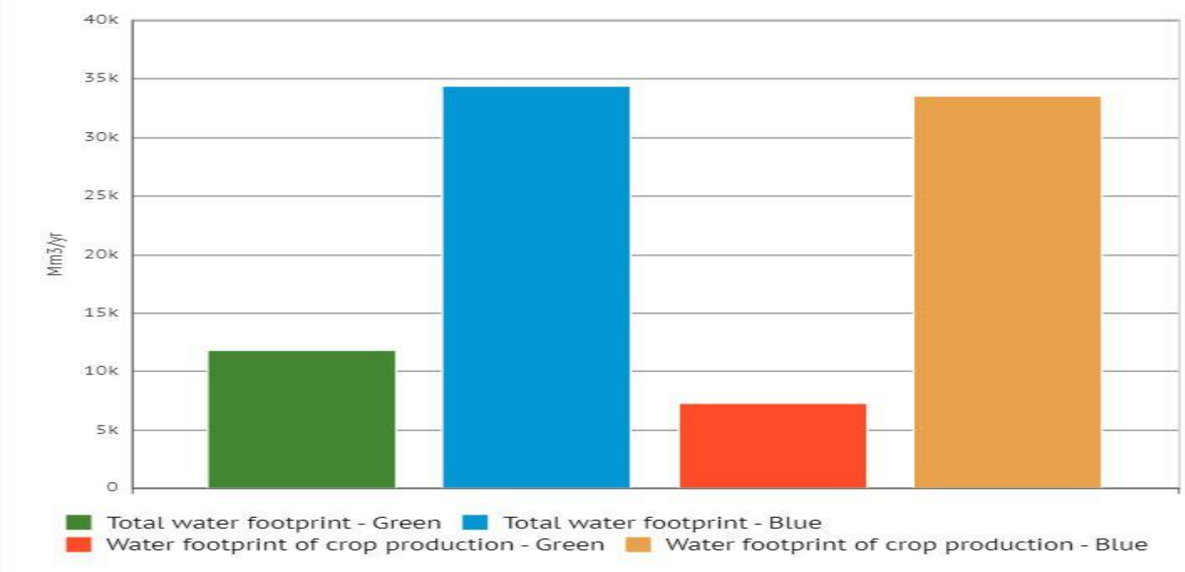

**Figure 13: The consumptions of green and blue water in the agricultural sector.**

*Source: The National Water Footprint Statistics “(https://knoema.com/WFPNWFPS2015/national-water-footprint-statistics?location=1000590-egypt&action=export&gadget=visualization)”*

From the Figure 14 it turns out that 18% of the water consumed in agriculture (which is about 45 billion cubic meters according to the foregoing) is consumed from maize, which is one of the most important strategic crops that the Egyptian government supports its cultivation and it is one of the crops that depend on irrigation mainly, then rice 15 % and wheat 14%, afterward cotton crop with 7 % (especially the last 10 years because the government support farmers in planting wheat and maize other than cotton) and other crops 35%.

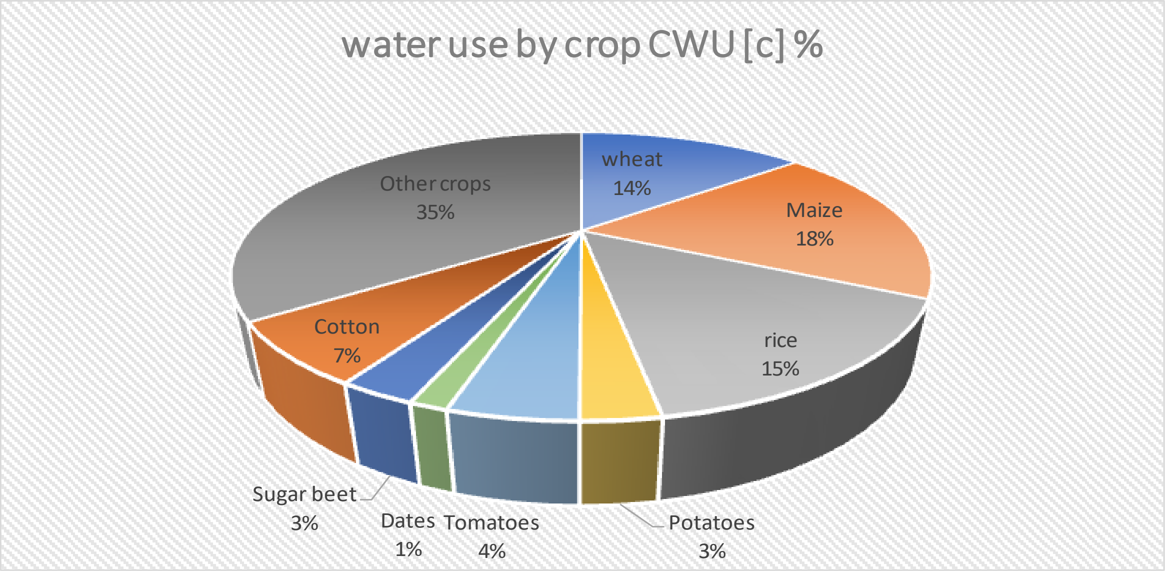

**Figure 14: The percentages of water distribution consumed in agriculture among crops.**

*Source: Own calculation, 2021*

The increase in agricultural production Egypt as most Arab countries “especially after the Arab spring” does not meet the increasing demand for foodstuffs due to the high population growth rate and the most important factors impeding the growth of agricultural production in Egypt are mainly water, desertification, and the lack of arable land (Woertz, 2017).

### *3.3.3.2. Water Import Dependency Index and Water self-sufficiency Index*

Table 20 shows the value of these two indicators in Egypt, based on the previous calculations of the volume of virtual water in main crops and in the exported and imported agricultural products.

**Table 20: The Water Footprint Indicators in Egypt.**

| Denomination | Value |
|---|---|
| The renewable water in Egypt billion $m^3$/year | 58.50 |
| Exported water in agricultural sector million $m^3$ for (rice, maize, and wheat) | 17300.00 |
| Imported water in agricultural sector million $m^3$ for (rice, maize, and wheat) | 1040.00 |
| Internal Water Footprint (IWFP) billion $m^3$ (rice, maize, and wheat) | 19.34 |
| External Water Footprint (EWFP) billion $m^3$ for (rice, maize, and wheat) | 5.19 |
| The Total Water Footprint (WFP) billion $m^3$ for (rice, maize, and wheat) | 24.53 |
| Water Import Dependency Index (WIDI) % | 21.15 |
| Water Self-sufficiency Index (WSSI) % | 78.84 |

*Source: Own calculation, 2021*

From the previous Table 20, it turns out that the extent of Egypt dependence on external resources to meet its agricultural crops needs is about 21.15%, and this is not a large percentage, and its dependence on its water resources and self-sufficiency is about 78.84%.

### *3.3.4. Food Security and Food Self-sufficiency*

As mentioned in the material and method the food gap is the difference between available supply and consumption. Appendix 2 shows food gap of Egypt during the period 2000-2018 as an example for some selected crops (wheat, rice, and maize). Egypt suffers from food gap in various agricultural food commodities (except rice).

The lack of development of agricultural production in most Arab countries results in dependence on external resources to bridge the deficit in food products, especially the main ones.

Relying on the data mentioned on the table 21 in estimating the average value of the food gap in relation to the main crops in the food balance in Egypt for the years 2000-2018 as shown in Table 21.

**Table 21: The value and quantity of the food gap in Egypt during 2000-2018.**

| Food gap | Egypt |
|---|---|
| The Quantity million tons | 19,34 |
| The value million USD | 17,987 |
| Cereals million tons | 12,21 |
| Cereals million USD | 3,539 |
| Population (1000) | 98,420 |
| The value of food gap per capita (USD/year) | 560 |

*Source: Collected and calculated from different resources (FAO,FAOSTAT online database),(http://agri.sprograming.com/), (https://www.indexmundi.com/) and (http://www.aoad.org/)*

The value of the food-gap is affected by the fluctuation of international food prices and food support policies, as well as the change in food reserves and the stock of exporting countries.

This research focused on the main elements of the food balance in relation to crops to show the food and water demands to meet this need and the extent to which food security can be achieved from local production and by relying on available water resources.

The main elements of the food balance, according to the estimates of the World Food Organization, are wheat, maize, rice, legumes, vegetables, fruits, sugar, plants oil, meat (red meat, white meat), white fish, milk, and dairy products.

As mentioned previously, Table 22 shows the self-sufficiency ratio of the main crops in the food balance of the Egyptian Arab Republic for the years 2000-2018 see also Appendix 3.

**Table 22: Self-sufficiency ratio through the main elements in the food balance in Egypt.**

| Products | Self-sufficiency ratio % |
|---|---|
| Wheat | 52.81 |
| Maize | 59.47 |
| Rice | 94.9 |
| Barley | 65.34 |
| Potatoes | 99.3 |
| Legumes | 7.6 |
| Vegetables | 99.92 |
| Fruits | 101.1 |
| Refined sugar | 69.6 |
| Plant Oils | 11.3 |

*Source: Calculated from (http://agri.sprograming.com/) and (http://www.capmas.gov.eg/).*

Egypt has a high rate of self-sufficiency in relation to the (rice, potatoes, vegetables, and fruits) which are (94.9, 94.84, 99.3, 99.92, and 101.1) respectively, and this has led to a decrease in the degree of dependence on external water resources to meet food needs. On the other hand, we can see that Egypt has a low rate of self-sufficiency in (wheat, maize, legumes, barley and plants oil) with ratio (52.81, 59.47, 7.6, 65.34 and 11.3) respectively, and this has led to an increase in the degree of dependence on the external water resources to meet food demand in the country.

### *3.3.5. The volume of virtual water required for self-sufficiency*

Water, and especially irrigations, has an important effect on food production, especially in countries that depend on irrigations for agriculture, such as Egypt, where the percentage of irrigated lands exceeds 95% of the total cultivated land (Osman et al., 2016).

The amount of food requirement of each element in the food balance was calculated during the years 2000-2018 based on the data of the World Food Organization and only by knowing the quantity of import and export from each component as well as local production see Appendix 4 (a,b), and then the volume of virtual water for the crops mentioned in the previous table was calculated.

The main crops imported in Egypt to bridge the food-gap are wheat, maize and barley, and the most important exports are cotton, rice, and tomato.

Table 23 shows the volume of water needed to meet the food requirement of the main elements in the food balance and to obtain self-sufficiency from these elements locally.

The negative sign in the Table 23 indicates that it had used an additional amount of water to produce a higher amount of the crop than the appropriate food requirement.

**Table 23: The volume of virtual water required to stopping food-gap for the main crops in Egypt.**

| Products | The quantity needed 1000 ton | Required Water needed million $m^3$ |
|---|---|---|
| Wheat | 7193.27 | 728.56 |
| Maize | 4878.47 | 1072.31 |
| Rice | 374.62 | 1023.16 |
| Barley | 6.84 | 1940.35 |
| Potatoes | -290.74 | -329.30 |
| Legumes | 17.36 | 37.25 |
| Vegetables | -6.89 | -18.67 |
| Fruits | -30.62 | -79.74 |
| Refined sugar | 3650 | 6741 |
| Plant Oils | 212 | 3266 |

*Source: Collected and calculated depends on the data from FAO database (http://www.fao.org/faostat/en/#data/QC)*

### 3.4. Research Conclusion

The virtual water principle is a good tool in managing water resources due to its close connection with the water footprint principle because it helps in determining the true water balance for Egypt, and it helps in trying to provide water for more economic uses than agriculture. It was found that Egypt is an importer of virtual water and not an exporter of maize and wheat crops, and for the rice crop Egypt export an important amount of their productions which is appear from the amount of exported virtual water. In addition, the consumption of the agricultural sector is about 33 billion cubic meters of “blue water” and around 6.5 billion cubic meters of “green water”, which are less than the number of renewable water resources 58.5 billion cubic meters per year. The explanation for this is that the calculation of the volume of consumption of the agricultural sector was based on the volume of virtual water for agricultural products. Furthermore, it was noticed that the amount of water used in irrigation operations (blue water) was calculated from the available water resources in irrigation operations, which is about 34 billion cubic meters, and the rest is about 11 billion cubic meters of rainwater (green water). Additionally, as it turns out that the extent of Egypt dependence on external resources to meet its agricultural crops needs is about 21.15%, and this is not a large percentage, and its dependence on its water resources and self-sufficiency is about 78.84%. Also, Egypt has a high rate of self-sufficiency in relation to (rice, potatoes, vegetables, and fruits) which are (94.9, 94.84, 99.3, 99.92, and 101.1) respectively, and this has led to a decrease in the degree of dependence on external water resources to meet food needs, this idea will be discussed in detail in the fifth chapter of this dissertation.

# 4. MODELLING THE INTERNAL WATER FOOTPRINT OF RICE, MAIZE AND WHEAT CROPS IN EGYPT

This chapter, it will be gained from the idea of the water footprint mentioned in the previous chapter to know if there is an effect related to other variables thus the effects on the crop production.

Water is considered one of the essential and vital issues to achieve economic development in general and agricultural one in particular, which is facing Egyptian society recently due to its scarcity on the one hand and the growing needs required of it on the other hand. So, there is an imperative to develop new mechanisms for water policies additionally to find conscious and effective ways to raise the efficiency of water resources (Steduto et al., 2018). Because the demand for food is essentially a demand for water in one way or another, this has led to the emergence of the concept of virtual water, which is defined as the water contained in a product, not in a realistic sense, but rather in the estimated meaning (Allan, 2003). From the previous definition, virtual water can be considered a resource of an alternative to water that can decrease the pressure which is applied to the familiar water sources of each country by reducing production and exports of crops that have a high content of virtual water, taking into account an adequate level of food security for each country, and replacing them with crops that have a low content of virtual water and achieve a higher return (A. Y. Hoekstra, 2003b). Relatively speaking, another concept emerged, known as the water footprint, which expresses the total water that is consumed to obtain a good or service starting from the production stage until reaching the final consumers (A. Y. Hoekstra et al., 2009).

Indeed, a lot of Scientific research has developed in the field of climate change all over the world, included Egypt, to confirm in turn that the country as a whole will be exposed to the most severe climatic changes, whether in terms of reduced rainfall rates or in terms of higher temperatures and a significant increase in the frequency of drought cycles (Hoegh-Guldberg et al., 2018). These factors mentioned before negatively affect the agricultural productivity in relation to rainfed crops and to some irrigated ones (Gitz et al., 2016).

Therefore, in this study, it will be seen if there is a fluctuation in the internal water footprint and thus a variation in the amount of water used in production, and this, in turn, leads to a change in the amount of virtual water exported from the crops (Rice, Maize and Wheat) in Egypt during a period 2000-2018. This change will be analyzed statistically through a set of variables related to climate (annual average temperature and annual average precipitation), and crop productivity, in addition to the renewable water sources in Egypt.

## 4.1. The Objective and Research Question

Analysis of the internal water footprint IWFP (billion $m^3$) variation for three major crops (rice, maize, and wheat), in terms of several related factors that are: annual average precipitation (mm), annual average temperature (Ta) Celsius, productivity (prod) kg/ha of the crops and the renewable water resource (RWr) in billion $m^3$ $year^{-1}$ during the period between 2000-2018 in Egypt.

The Above stated objective of the research can be translated into the following research question: **RQ2:** *How the climatic factors; the temperature and the precipitation; the renewable water resource and the targeted productivity influence the internal water footprint of three crops (wheat, maize, and rice) in Egypt?*
The following questions will be discussed:

- **RQ2.1:** *Are there any fluctuations in the annual average precipitation, annual average temperature, the productivity of the crops and renewable water resource during 2000-2018?*
- **RQ2.2:** *Is there any effect of the selected variables (renewable water resource, productivity, temperature, and precipitation) on the internal water footprint? And this effect can be proved statistically?*

## 4.2. Material and Method

### *4.2.1. Data collection*

The research is based on published data issued by the Central Agency for Public Mobilization and Statistics (CAPMAS), the Ministry of Water Resources and Irrigation, the Ministry of Agriculture, and different issues published in Arabic in the journal of Sustainable Agricultural Sciences (JSAS) in Egypt for the assessments of the Internal Water Footprint. In addition, the data issued by the FAOSTAT were collected for the productivity of the crops and the FAO-AQUASTAT database for the renewable water resources, additionally for the Annual Average Temperature and Annual Average Precipitation were collected from the world bank database as well as the FAO-AQUASTAT database during the years 2000-2018 see Appendix 5 (a, b, and c) for the Rice, Maize, and Wheat, respectively.

### *4.2.2. Reliability of the data and the methodology used*

The research relied on to achieve the objective of the study and to answer the research questions by following:

- *First,* to check whether the time series data is suitable for scrutinizing the short and long run effect of set of covariates on the response variable measured at time.
- *Second*, the method was used to analyse and to see the variation of the four variables (RWr, Productivity, Ta and Precipitation) on the response variable IWFP is the quantitative economic analysis through the use of Nonlinear Autoregressive Distributed Lag (NARDL) by using EVIEWS software.

### *4.2.3. Assessment of the Internal Water Footprint*

The estimation of the internal water footprint is based on the following data (Hoekstra et al., 2011):

1. The Quantity of Water Used in Production = The Quantity of Production per ton X Water Requirements of the Crop per ton.
2. The Quantity of Exported Virtual Water = The Quantity of Exported Crops per ton X the Water Requirement per ton.
3. The Internal Water Footprint = The Quantity of Water Used in Production - The Quantity of Exported Virtual Water.

### *4.2.4. NARDL Model Specification*

The time series model that is suitable for investigating the short and long run effect of set of covariates on the response variable measured at time t when there is a mixed order of integration of at most one is autoregressive distributed lag (ARDL) model (Ndoricimpa, 2017). ARDL model though provides framework to model variables with mixed order of integration, yet it does not give allowance for studying both short and long run asymmetry. It assumes that the increasing and decreasing effect of the covariates included in the model produce similar effect on the dependent variable. In many instances, this may not be the case and it may be of interest to check for asymmetry cointegration. Aside, estimating a relationship which possibly has asymmetry with symmetric techniques seems unfair and may lead one to some serious inappropriate policy conclusions (Dabwor & Ezie; Enders, 2008).

An extension of conventional ARDL developed by (Y Shin et al., 2014) is one of the approaches that has been successfully employed to study the increasing and decreasing effect of the independent variables on the dependent variables simultaneously. This framework is commonly regarded as Non-linear Autoregressive Model (NARDL). In this study, this approach is used to investigate the asymmetry effect of some covariates (productivity, renewable water resource, temperature, and precipitation) on the internal water footprint on the three major crops (rice, maize, and wheat). Considering the variables mentioned above, the long run NARDL model specification is given as following Equation 5.1:

$$IWFP_t = \alpha_0 + \alpha_1 Prod_t + \alpha_2 RWr_t + \alpha_3 Ta_t + \alpha_4 Prep_t + \varepsilon_t \qquad (5.1)$$

In equation 5.1, $\alpha_0$=constant term, $\alpha_1 - \alpha_4$ are the parameters of the model to be estimated. The independent variables prod, RWr, Ta and prep are used to denote production, renewable water resource, temperature, and precipitation, respective. IWFP is the internal water footprint for a particular crop.

A situation in which the interest is to capture the possible asymmetry effect of each independent variables on the internal water footprint, each of the independent variables needed to be decomposed into partial sum of positive and negative changes and included in the model as a separate variable (Yongcheol Shin et al., 2014). For example, the partial sum of productivity is given as equation 5.2.

$$\left.\begin{aligned} \boldsymbol{Prod_{t-1}^{+}} &= \sum_{j=1}^{t} \boldsymbol{\Delta Prod_j^{+}} = \sum_{j=1}^{t} \mathbf{max}\,(\boldsymbol{\Delta Prod_t}, \mathbf{0}) \\ \boldsymbol{Prod_{t-1}^{-}} &= \sum_{j=1}^{t} \boldsymbol{\Delta Prod_j^{-}} = \sum_{j=1}^{t} \mathbf{min}\,(\boldsymbol{\Delta Prod_t}, \mathbf{0}) \end{aligned}\right\} \qquad (5.2)$$

Specifically, the NARDL representation of equation 5.1 has the following form:

$$\Delta IWFP_t = \alpha_0 + \alpha_1 IWFP_{t-1} + \alpha_2 Prod_{t-1}^{+} + \alpha_3 Prod_{t-1}^{-} + \alpha_4 RWr_{t-1}^{+} + \alpha_5 RWr_{t-1}^{-} + \alpha_6 Ta_{t-1}^{+} + \alpha_7 Ta_{t-1}^{-} + \alpha_8 Prep_{t-1}^{+} + \alpha_9 Prep_{t-1}^{-} + \sum_{i=1}^{m} \beta \Delta IWFP_{t-1} + \varepsilon_t \qquad (5.3)$$

The long coefficients can be computed from the estimated model (5.3) by dividing the negative of the coefficient of the partial sum (i.e each of $\alpha_{\downarrow}2 - \alpha_{\downarrow}9)$ by $\alpha_1$, For example, the long coefficient of productivity is given as $\left(-\frac{\alpha_2}{\alpha_1}\right)$ and $\left(-\frac{\alpha_3}{\alpha_1}\right)$, respectively.

To investigate the existence of long run relationship or cointegration, a joint null hypothesis of $\left(-\frac{\alpha_2}{\alpha_1} = -\frac{\alpha_3}{\alpha_1}\right)$ was tested. The rejection of the hypothesis will indicate sufficient evidence for long run asymmetry.

### *4.2.5. Statistical Analysis*

The model described above was estimated using EVIEWS statistical software version 9. Prior to the model estimation, preliminary time series testing was carried. The steps involved as summarized below;

1) Unit root test was carried out on each of the variables to ascertain their order of integration;
2) Partial sum of all independent variables was computed;
3) NARDL model was estimated for each crops (rice, maize, and wheat);
4) Wald F-test was conducted for nonlinear cointegration;
5) Asymmetries was checked in each of the estimated models.

*Note; EVIEWS code for each step are available upon request.*

## 5.3. Results and Discussion

### *4.3.1. Descriptive statistics of the variables*

The descriptive features of the variables under investigation were examined and summarized in term of their minimum, mean and maximum values (Table 24). Precisely, the highest value of internal water footprint for rice, maize and wheat were recorded in the year 2008, 2011 and 2017, respectively. Also, the productivity of rice, maize, and wheat during the period under investigation were maximum in the year 2006, 2011 and 2017, respectively. It was noted that the internal water footprint and productivity were uppermost in the same year. However, this was not the pattern in the case of crops considered. Further, the peak value of temperature, renewable water resources and precipitation were recorded for the period under investigation in the 2009, 2012 and 2017, respectively.

**Table 24: Variable’s summary statistics and determination of order of integration.**

| Denomination | Variables | Minimum | Mean | Maximum | Integration |
|---|---|---|---|---|---|
| Internal Water Footprint | Rice (IWFPRC) | 5.32 | 7.39 | 10.56 | I(0) |
| | Maize (IWFPMZ) | 5.00 | 6.36 | 7.60 | I(1) |
| | Wheat (IWFPWT) | 3.80 | 5.58 | 7.60 | I(1) |
| Productivity | Rice (ProdRC) | 8826.50 | 9514.29 | 10075.00 | I(0) |
| | Maize (ProdMZ) | 6979.80 | 7751.47 | 8370.50 | I(1) |
| | Wheat (ProdWT) | 5574.10 | 6462.25 | 6859.70 | I(0) |
| Temperature | Ta (Celsius) | 22.35 | 23.28 | 24.73 | I(0) |
| Renewable water resource | RWr (billion $m^3$) | 51.80 | 54.35 | 57.12 | I(1) |
| Precipitation (mm) | Prep (mm) | 1.45 | 2.34 | 3.22 | I(1) |

*Source: Own calculation, 2021*

As a custom in the analysis of time series data, the first tested statistical properties is stationarity. This is important to determine the level of the integration of the variables under study and to avoid spurious regression. This study used augmented Dickey Fuller (ADF) Test to establish the order of integration of the variables considered in the study. As shown in the last column of table 1, the variables are mix of stationary and integrated variables. For instance, IWFPRC, ProdRC and Ta were stationary at level, I(0) while RWr and Prep were integrated of order one, I(1). Also, IWFPMZ, ProdMZ, RWr and Prep were integrated of order one I(1) while Ta was a level stationary variable. Equally, IWFPWT, RWr and Prep were I(1) variables while ProdWT and Ta were integrated of order zero.

On the ground that our variables contained a mixed order of integration, it has adopted nonlinear autoregressive distributed lag (NARDL) model which has the capability to model variables of mixed order of integration as well as investigating asymmetry. As discussed in the methodology section, the partial sum of each covariates was computed prior to the model estimation. For example, the partial sum of productivity was computed using the EVIEWS code below:

- **genr dprod = prod-prod(-1)**
- **genr ros = dprod >=0**
- **genr dprod_p = ros*dprod**
- **genr dprod_n = (1-ros)*dprod**
- **genr prod_p = @cumsum(dprod_p)**
- **genr prod_n = @cumsum(dprod_n)**

The **prod_p and prod_n** are the positive and negative value of productivity, respectively. This code was modified to compute the partial sum of other covariates included in the model. The result of three separate NARDL using the internal water footprint of each of rice, maize, and wheat the dependent variables were discussed in the next section.

### *4.3.2. Analysis of Internal Water Footprint of rice*

Table 5.2 showed the correlation analysis of water footprint with the independent variables. It was noted that each of the independent variables have negative and insignificant relationship with internal water footprint of rice (see column 1 of table 25). The implication of this result is that there is an inverse relationship between of these variables and internal water footprint. This implies that an increase in any of these variables will produce a decrease the response variable (IWFPRC).

**Table 25: Correlation analysis of internal water footprint of Rice and Covariates.**

| Variables | IWFPRC | ProdRC | RWr | Ta | Prep |
|---|---|---|---|---|---|
| **IWFPRC** | 1 | | | | |
| **ProdRC** | -0.013 | 1 | | | |
| **RWr** | -0.022 | -0.240 | 1 | | |
| **Ta** | -0.110 | -0.242 | $0.598^{**}$ | 1 | |
| **Prep** | -0.085 | -0.358 | -0.011 | 0.319 | 1 |

*Source: Own calculation, 2021*

Estimated coefficient of NARDL model presented in Table 26 indicates that the lagged negative change of precipitation has a statistically significant effect on internal water footprint while the lagged positive change is statistically insignificant. In this case, it can be deduced from the long run coefficient that a unit negative change of precipitation leads to 1.22052 decrease in the internal water footprint. However, asymmetry test failed to reject the hypothesis that the negative and the positive change of precipitation are statistically different in the long run. In term of productivity, the lagged positive change is found to be significantly related with the internal water footprint at 5% level with a long run coefficient 0.011226. However, the long run asymmetry of the lagged negative and the positive change of productivity was also not rejected. The renewable water resource produced a different result with a long run coefficient of 1.542207 and -3.74627 for lagged negative and positive change, respectively. This indicates that a unit negative change in the RWr will lead to 1.542207 increase in the footprint of rice while a unit point increase will reduce footprint by 3.74627. This implies that the impact of renewable water resources on the internal water footprint is asymmetric. Also, the impact of temperature on the internal water footprint is negative and asymmetric.

Table 26: NARDL Model Estimate for Rice.

| Variables | NARDL Coefficient | P-value | Long run Coefficient | Long run Asymmetry Test |
|---|---|---|---|---|
| **IWFP(-1)** | -0.84875 | 0.7961 | | |
| **PREP_N(-1)** | -1.03591 | 0.0146 | -1.22052 | F= 0.098293 (0.7645)<br>DF= (1, 6) |
| **PREP_P(-1)** | -0.13394 | 0.6677 | -0.15781 | |
| **PROD_N(-1)** | -0.01274 | 0.9273 | -0.01501 | F= 0.098293 (0.1211)<br>DF= (1, 6) |
| **PROD_P(-1)** | 0.009528 | 0.0227 | 0.011226 | |
| **RWR_N(-1)** | 1.308942 | 0.1597 | 1.542207 | F= 6.799207 (0.0403)<br>DF= (1, 6) |
| **RWR_P(-1)** | -3.17963 | 0.2344 | -3.74627 | |
| **TA_N(-1)** | -5.96533 | 0.0279 | -7.02841 | F= 1.633715 (0.2484)<br>DF= (1, 6) |
| **TA_P(-1)** | -4.46399 | 0.0188 | -5.25951 | |

*Source: Own calculation, 2021*

### 4.3.3. Analysis of Internal Water Footprint of maize

The correlation analysis result presented in table 27 indicates that renewable water resources, temperature and precipitation have positive relationship with internal water footprint of maize. However, only the renewable water resource showed a statistically significant relationship at 1% level. Whereas productivity has negative and insignificant relationship with the dependent variable.

Table 27: Correlation analysis of internal water footprint of Maize and Covariates.

| Variables | IWFPMZ | ProdMZ | RWr | Ta | Prep |
|---|---|---|---|---|---|
| **IWFPMZ** | 1 | | | | |
| **ProdMZ** | -0.135 | 1 | | | |
| **RWr** | $0.752^{**}$ | -0.051 | 1 | | |
| **Ta** | 0.236 | -0.177 | $0.598^{**}$ | 1 | |
| **Prep** | 0.089 | -0.121 | -0.011 | 0.319 | 1 |

*Source: Own calculation, 2021*

The NARDL estimated coefficient presented in Table 28 showed that only precipitation has asymmetry impact on the internal footprint in relation to maize. The impact of the negative and the positive change of other variables on the internal water footprint appeared to be the same. In the case precipitation, the estimated long run coefficient for the lagged negative and positive change were found to be -0.6265 and 0.6242, respectively. This implies that a unit point increase will lead to a reduction of 0.6265 while a unit point increase will lead to a corresponding increase of 0.6242 in the long run.

**Table 28: Estimation of Long run Coefficient for Maize Crop.**

| Variables | NARDL Coefficient | P-value | Long run Coefficient | Long run Asymmetry Test |
|---|---|---|---|---|
| **IWFP(-1)** | -1.560684 | 0.0170 | | |
| **PREP_N(-1)** | -0.977838 | 0.1338 | -0.6265 | F= 10.83628 (0.0133)<br>DF= (1, 7) |
| **PREP_P(-1)** | 0.974150 | 0.0754 | 0.6242 | |
| **PROD_N(-1)** | -0.001016 | 0.3044 | -0.0007 | F= 0.008120 (0.9307)<br>DF= (1, 7) |
| **PROD_P(-1)** | -0.001143 | 0.1666 | -0.0007 | |
| **RWR_N(-1)** | 0.545360 | 0.1001 | 0.3494 | F= 1.969594 ( 0.2033)<br>DF= (1, 6) |
| **RWR_P(-1)** | -0.336282 | 0.3772 | -0.2155 | |
| **TA_N(-1)** | -0.260960 | 0.5345 | -0.1672 | F= 0.256986 ( 0.6278)<br>DF= (1, 7) |
| **TA_P(-1)** | -0.450594 | 0.4773 | -0.2887 | |

*Source: Own calculation, 2021*

### *4.3.4. Analysis of Internal Water Footprint of Wheat*

The correlation analysis table presented in Table 29 showed that all the independent variables have positive and insignificant relationship with the exemption of renewable water resources which is positive and statistically related with internal water footprint of wheat crop. It is also noted that the relationship between a pair of independent variable are moderate indicating multicollinearity.

**Table 29:Correlation analysis of internal water footprint of rice and Covariates.**

| Variables | IWFPWT | ProdWT | RWr | Ta | Prep |
|---|---|---|---|---|---|
| **IWFPWT** | 1 | | | | |
| **ProdWT** | 0.317 | 1 | | | |
| **RWr** | $0.715^{**}$ | 0.090 | 1 | | |
| **Ta** | 0.364 | 0.041 | $0.598^{**}$ | 1 | |
| **Prep** | 0.254 | 0.130 | -0.011 | 0.319 | 1 |

*Source: Own calculation, 2021*

The estimated NARDL coefficient for wheat crop internal water footprint is presented in Table 30 It is noted that the negative and positive change in each of the independent variables produce similar impact on the response variable with the exemption of temperature in which the asymmetric impact of the negative and positive change was noticed.

**Table 30: Estimation of Long run Coefficient for Wheat Crop.**

| Variables | NARDL Coefficient | P-value | Long run Coefficient | Long run Asymmetry Test |
|---|---|---|---|---|
| **IWFP(-1)** | -0.935225 | 0.0337 | | |
| **PREP_N(-1)** | 0.168774 | 0.6985 | 0.1805 | F= 0.549912 (0.4825)<br>DF= (1, 7) |
| **PREP_P(-1)** | 0.466101 | 0.1570 | 0.4984 | |
| **PROD_N(-1)** | 0.000901 | 0.0823 | 0.0010 | F= 0.521211 (0.4937)<br>DF= (1, 7) |
| **PROD_P(-1)** | 0.000450 | 0.3944 | 0.0005 | |
| **RWR_N(-1)** | 0.350629 | 0.1798 | 0.3749 | F= 0.549806 (0.4825)<br>DF= (1, 7) |
| **RWR_P(-1)** | 0.025536 | 0.9176 | 0.0273 | |
| **TA_N(-1)** | -0.186522 | 0.6037 | -0.1994 | F= 10.17358 ( 0.0153)<br>DF= (1, 7) |
| **TA_P(-1)** | 0.800662 | 0.0399 | 0.8561 | |

*Source: Own calculation, 2021*

Summarily, Asymmetry impact of renewable water resources, precipitation and temperature was established in the rice, maize, and wheat model, respectively.

## 4.4. Conclusion and recommendations

Agriculture is a major cause of water scarcity, and it suffers from this shortage at the same time. It accounts for about 76.7 per cent of all water withdrawal operations in Egypt. But there are improvements we can make in how water is used to produce food. The choice of crops, for example, greatly affects the amount of water required. For example, legume crops have a small water footprint, which means that the production of one kilogram of lentils requires only 1,250 litres of water, compared to the amount of 13 thousand litres of water needed to produce beef.

Egypt is expected to face water scarcity by 2025, according to the United Nations. Egypt cannot meet food demand by depending on Nile water for irrigation, assuming sustained population increase, taking into account desert land reclamation initiatives, and the fact that more than half of the grain consumed is already imported (Radwan, 1998). In addition to this precarious situation, Lake Nasser's surface water evaporation is thought to be higher than previously predicted. The present average evaporation rate is 7 mm, with 7.3 mm projected by 2050 (Badawy, 2009). In other words, Egypt is already using most of the Nile's flows, and it plans to use more. According to the Ministry of Water Resources and Irrigation, there is a deficit in the national water budget of about 19.5 billion cubic meters (Gad, 2017).

In addition, Egypt has been affected by climate change, which affects the entire Nile Basin. Economic developments in upstream countries and measures they may take to adapt to climate change are likely to increase Egypt's water resources pressure. Several studies have shown that the Nile is very sensitive to changes in temperature and precipitation, mainly due to its low runoff/precipitation rate (4%) (Badawy, 2009; Radwan, 1997).

In this study, the internal water footprint of three strategic crops in Egypt (rice, maize, and wheat) was analyzed for a period of 19 years. In addition to analyzing the average annual temperatures, the average annual precipitation, the renewable water in the country, and crop productivity for the period 2000-2018.

Additionally, the study concluded that there are an effects on the IWFP during the years study by the four variables (RWr, Prod, Ta and Precipitation), that is led to the effect on the crop production, which is included in the IWFP, which are proved statistically as follows:

The study found that the highest value of internal water footprint for rice, maize and wheat were recorded in the year 2008, 2011 and 2017, respectively. Also, the productivity of rice, maize, and wheat during the period under investigation were maximum in the year 2006, 2011 and 2017, respectively. It was noted that the internal water footprint and productivity were uppermost in the same year. However, this was not the pattern in the case of crops considered. Further, the peak value of temperature, renewable water resources and precipitation were recorded for the period under investigation in the 2009, 2012 and 2017, respectively.

**1- Rice crop:**

- Each of the independent variables has negative and insignificant relationship with internal water footprint.
- *Precipitation:* the long run coefficient that a unit negative change of precipitation leads to 1.22052 decreases in the internal water footprint.
- *Productivity:* the lagged positive change is found to be significantly related with the internal water footprint at 5% level with a long run coefficient 0.011226.
- *Renewable water resource:* a unit negative change in the RWr will lead to 1.542207 increase in the footprint of rice while a unit point increase will reduce footprint by 3.74627.
- *Temperature:* the impact of temperature on the internal water footprint is negative and asymmetric.

**2- Maize crop:**

- The correlation analysis result indicates that renewable water resources, temperature and precipitation have positive relationship with internal water footprint of maize.
- The NARDL estimated coefficient showed that only precipitation has asymmetry impact on the internal footprint in relation to maize.

**3- Wheat crop:**

- The correlation analysis Table showed that all the independent variables have positive and insignificant relationship with the exemption of renewable water resources which is positive and statistically related with internal water footprint of wheat crop.

- It is noted that the negative and positive change in each of the independent variables produce similar impact on the response variable with the exemption of temperature in which the asymmetric impact of the negative and positive change was noticed.

# 5. FOOD GAP OPTIMIZATION FOR SUSTAINABILITY CONCERNS, THE CASE OF EGYPT

Food security is of paramount importance in times of economic, natural and human crisis due to shifts in food supply and demand, scarcity of food, lack of consumer stability and loss of income, all of which are among the factors affecting the essence and content of food security (Mc Carthy et al., 2018; Timmer, 2015).

The reality of the Arab countries requires that they provide food security to their citizens, at least. If we take Egypt, it was once considered the food basket of the Arab world and is a historical model of food self-sufficiency, due to the availability of large agricultural areas and the abundance of labour (Lacirignola et al., 2015). Egypt relied on beans and wheat during the historical crises, but today, it has become one of the largest importers of these two commodities (Asseng et al., 2018; Woertz, 2017).

The definition of a food gap (FG) is the disproportion between the required food quantities and the population, which leads the concerned country to import food from abroad, thus any shortage of food resources is matched by an increase in the population (Conway, 1998).

Many research papers have been published on the study of the FG and ways to reduce it in Egypt; most of these studies discuss the main crops such as wheat and maize, which are highly consumed in Egypt and their production does not cover the local market (Ouda et al., 2017). Other studies explain the factors that contribute to widening the FG, for example, the limited investment in agricultural and food projects (Tuttle, 2012), and the impact of climate change and water scarcity on the FG (Abdelkader et al., 2018; ElMassah, 2013).

In the fifties and sixties of the last century, a large number of simulation and optimization models have been used for the appropriate planning and management of water use in irrigated agriculture and FG (Patel & Bhavsar, 2018; Shenava & Shourian, 2018). Soon after the simplex algorithm was found by DANTZIG in 1947 (Dantzig, 1963), agricultural economists started to use linear programming for farm planning. Linear programming was once thought to be one of the greatest strategies for allocating land and water resources optimally in agriculture, according to early publications (Afshar & Mariño, 1989; Maji & Heady, 1980; Smith, 1973) perhaps intended at disseminating mathematical information by describing the procedure's properties (Boles, 1955; Heady, 1954) or aimed at highlighting its potential for agricultural management and other applications (McCorkle, 1955; Swanson, 1961) and applied linear programming to the hypothetical agricultural holding in order to find optimal production plans by minimizing the FG in a country (Zgajnar et al., 2007).

In this research, the FG calculating, and analysing has applied during 2000-2018, as well as the water consumption for the crops studied and food demands for the country. Additionally, we will reallocate the land cultivations under a set of constraints to reduce the FG.

The problem is the follows:

- Egypt as a developing country is facing a crucial challenge in providing the citizens' needs of basic food commodities to keep pace with the steady population growth. To that end, it should work to raise the productivity of the agricultural sector in order to achieve self-sufficiency and to lessen food imports. The FG that affects the staple commodities is a major problem for the state that bears the burden of providing a high budget to stipend the importations usually being paid for with foreign currency. This requires studying FG for the most important crops that represent the biggest portion in the contribution of the national food security in Egypt.

### 5.1. The Objective and Research Question

The objectives of the topic are:

- Determine and calculate the Food-Gap during 2000-2018 for the most important food crops in Egypt:
    - Minimizing the Food-Gap in Egypt by building a mathematical model to find the optimum land reallocation and production distribution for main important crops;
- Determining the water consumption and the food demand for the same study period.

**RQ3:** *How the food gap affects the staple commodities for the Egyptian state that bears the burden of providing a high budget to stipend the importations usually being paid for with foreign currency?*

**RQ4:** *Can the reallocation of agricultural land in Egypt help in bridging the food gap and saving food for the high population increase, as well as providing foreign exchange through the export of some crops?*

**RQ5:** *Is the water consumption of the crop a significant variable to explain the food gap changes, or not?* The following hypotheses were addressed:

- If the $T_{count} > T_{table}$ or sig. (*p*-value) $< 0.05$, then the variable water consumption influences food gap;
- and if the $T_{count} < T_{table}$ or sig. (*p*-value) $> 0.05$, then the variable water consumption does not influence food gap.

## 5.2. Materials and Methods

The data used for this study describe several variables in relation to thirteen crops for the period between 2000 and 2018. The data were collected and used in all calculations (area, crop yield, crop exports, and crop imports,) from the on-line database of the Food and Agriculture Organization of the United Nations (FAOSTAT), World Bank Open Data, Central Agency for Public Mobilization and Statistics (CAPMAS) of Egypt. In addition, the average world market prices USD/ton was collected from the World Bank Open Data and "Water footprints of nations Volume 2: Appendices" (A. Chapagain & A. Hoekstra, 2004).

Regarding the statistical analysis, it was performed by using SPSS software. In this part, the linear relationship between the water consumption and the FG will be assessed and modelled for a period of nineteen years (2000–2018).

### *5.2.1. Crop Water Requirements*

The crop water use for each crop included in the study were calculated depends on the equation (3.2), and the quantity of water requirements of crop (c) is calculated from the following relationship Equation (3.3), additionally the calculating of $ET_0$ was done by the equation (3.4).

As for the $K_c$ values, they were derived from a previous study performed by the researchers: (Allen et al., 1998) and CHAMPAGAIN & HOEKSTRA (2004) Table 31.

**Table 31: Crop water requirements (CWR) for the studied crops.**

| Crop | Crop Water Requirements CWR $m^3$/hectare |
|---|---|
| Wheat | 4912 |
| Maize | 8312 |
| Barley | 4562 |
| Potatoes | 8487 |
| Legumes | 18,723 |
| Vegetables | 10,481 |
| Fruits | 12,446 |
| Sugar beets | 8460 |
| Oil seeds | 9770 |
| Cotton | 9667 |
| Nuts | 15,503 |
| Aromatic plants | 8412 |
| Rice | 10,346 |

*Source: Own calculation, 2021*

### *5.2.2. Describing the Mathematical Model and the Resources Constraints*

Mathematical modelling is an approach allowing one to assess and to understand any system interactions, as well to solve optimization problems along with different constraints. In such problems, the decision maker aims to optimize the solution according to some criteria and limitations.

In other words, a mathematical model can be used for optimizing f(x) under the constraint g(x). Particularly, if f(x) and g(x) are linear functions, the problem will be linear. Correspondingly, the agricultural activity problems are usually evaluated through linear programming (Boussard & Daudin, 1988). In the present study, the optimization of the system studied seeks to minimize the FG (Equations 6.1 and 6.2) under four different constraints.

Considering that we are assessing several key crops of economic importance, we aim to reduce the FG that is expressed by the disproportion between the required food amounts of the population and the local production, which leads the concerned country to import food from abroad (Conway, 1998). The FG optimization means the production optimization according to the limited resources and the population need increase. In the model created in the scope of this study, we tried to reorganize the factors that contribute to the widening of the FG, such as the crop area that can be re-allocated on the basis of different aspects in relation to the crop value and the population needs.

The objective of our model is to determine the so-called "objective function", that is a function of unknown crop area reallocation (ha) $A_j$, which is expressed mathematically as the following:

$$\mathbf{Min:}\quad \sum_{j=1}^{NC}(D_j - S_j) * Pri_j \tag{6.1}$$

$$\mathbf{Min:}\quad \sum_{j=1}^{NC}(D_j - Pro_j A_j) * Pri_j \tag{6.2}$$

**$D_j$**: The amount of food demand for each crop j (ton). It can be calculated following the relationship Equation 6.3:

$$D_j = S_j + I_j - E_j \tag{6.3}$$

**$I_j$, $E_j$, $S_j$** are, respectively, imports, exports, and productions of each crop j (ton).

**$Pri_j$**: International crop price (USD per ton) from the World Bank Open Data and (A. K. Chapagain & A. Y. Hoekstra, 2004).

**$Pro_j$**: Productivity of each crop j (ton per hectare).

**NC**: Number of crops.

The minimization of FG is modelled, taking into consideration a set of constraints, that are as follows:

1) The area allocation set for each crop should be positive, this constraint is known as the non-negative variable (Equation 6.4):

$$A_j \geq 0 \qquad \forall\ j \tag{6.4}$$

2) The total crops land allocation should not exceed the maximum exploitable land (Landconst = 3.5 million hectares) (Equation 6.5):

$$\sum_{j=1}^{NC} A_j \leq Land_{const} \tag{6.5}$$

3) The total crops water consumption should be less than the renewable water volume ($Water_{const}$ = 45 billion $m^3$) (Equation 6.6):

$$\sum_{j=1}^{NC} CWR_j \times A_j \leq Water_{max} \tag{6.6}$$

**$CWR_j$**: Crop water requirement for each crop j ($m^3$ per hectare).

4) The production of the allocated area should not exceed the required amount for each crop (the demand) (Equation 6.7). Actually, this constraint is necessary, especially for the strategic crops in order to determine the volume of production for each crop which have a high economic return whose production may exceed the market need in Egypt (Moghazy & Kaluarachchi, 2020):

$$\mathbf{Pro_j \times A_j \leq D_j} \qquad (6.7)$$

As mentioned previously, the problem consists of finding the crops' area reallocation $A_j$ that minimizes the FG per year. We say that a constraint is saturated when the optimal solution uses the total available resources.

The first algorithm used for solving linear programs was presented by DANTZIG in 1947. It was used the so-called simplex algorithm even though there are many competitive alternative algorithms at the present time. By the means of the programming language named "Octave" and the package "GLPK" (GNU Linear Programming Kit), our linear programming (LP) problem was successfully solved, and the model output expresses the optimum land reallocation for minimizing the FG.

The model was applied on two types of data (average and annual) only for the production and food demand. A temporal evaluation of the model outputs was established to follow the fluctuation of the FG, the water consumption, and the crop land reallocation throughout the study period.

## 6.3. Results and Discussions

As it was disclosed previously, our model outputs express the optimal propositions in terms of crop area reallocation, in such a manner to reduce the FG as much as possible depending on several constraints. Mentioning that, the constraint for the total cultivated land was saturated in all the proposed scenarios.

### ***5.3.1. Crops Land Reallocation for the Studied Crops During 2000–2018***

As mentioned previously, the problem consists of setting a new crops' area al-location (Aj) that minimize the FG per year. The area for the whole crops should not exceed the total available area in the country which is equal to 3.5 million hectares. Figure 15 represents the real allocation of all crops through the studied period while Figure 16 illustrates the model output, indeed, all the crops except rice, wheat, potatoes, sugar beet, and maize, are reallocated fairly close to the real situation. Mostly, the crops that are similarly distributed converge to the maximum allowed area (for non-exceeding the crop demand). The excepted crops are critical, in which their allocation is affected by the policy followed by the government as well as other factors, some of which were mentioned heretofore.

As it is known, land allocation refers to assigning land to be used in a certain manner, however, it may not mean that the actual use of the land reflects the initial plan of its allocation (Yao et al., 2018). That is what happened with rice, wheat, potatoes, sugar beet and maize crops in Figure 16.

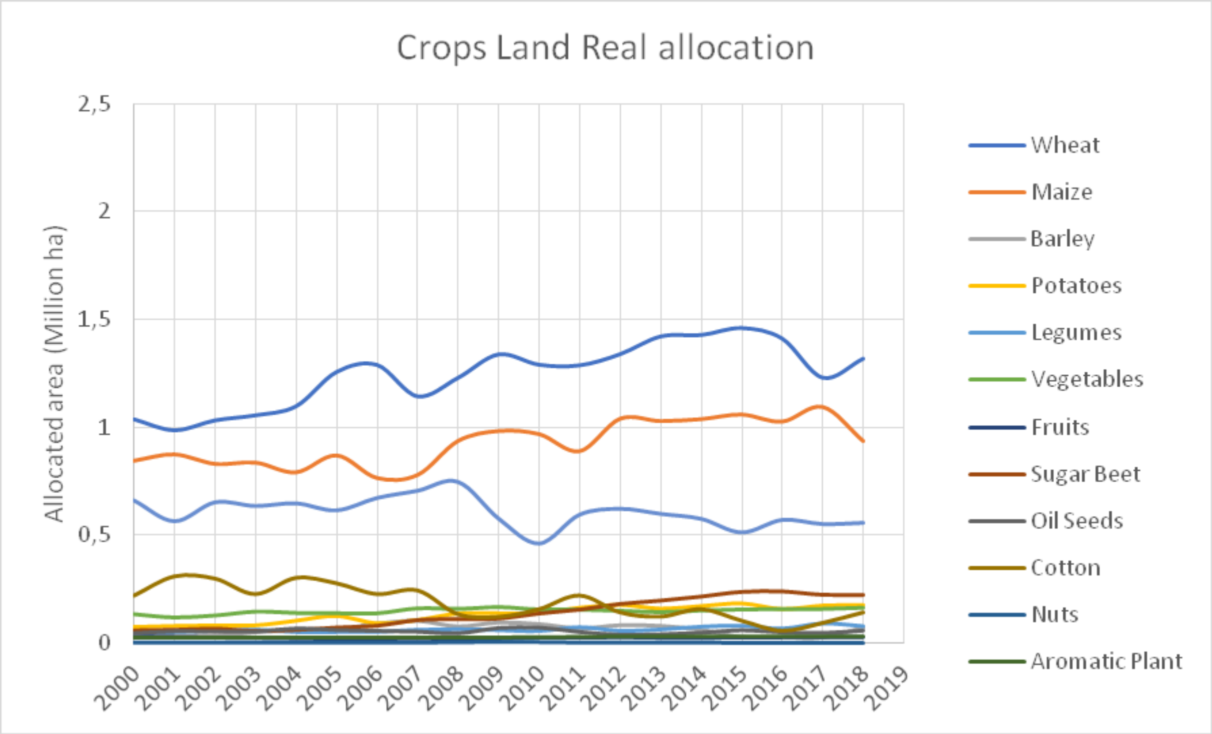

**Figure 15: “Crops Land Real Allocations for the studied crops”.**

*Source: Own construction, 2021*

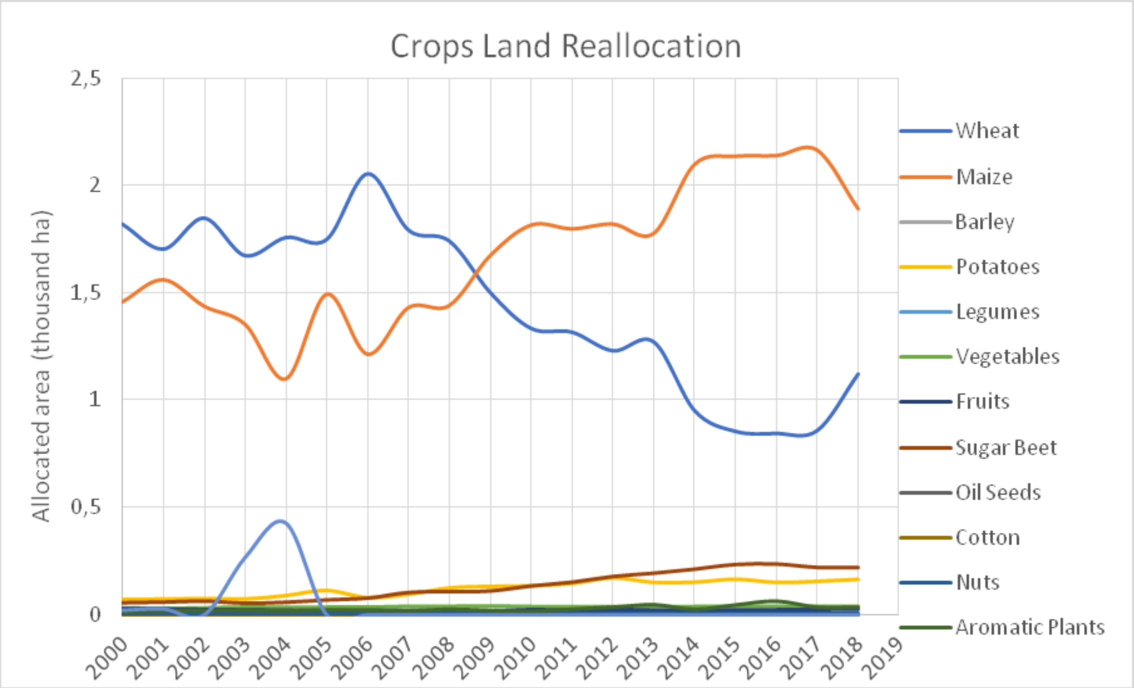

**Figure 16: "Crops land reallocations for the studied crops".**

*Source: Own construction, 2021*

### *5.3.2. Food Gap*

From Figure 17, it is clear that the FG has increased with the years, starting from 2005 to 2017. This that can be explained by several reasons in relation to different aspects. In fact, the steady increase in the population growth rate is an important factor amongst others in the widening of the FG, particularly for the period from 2000–2018, during which it had reached 2.56% according to the Central Agency for Public Mobilization and Statistics in Egypt, ensuing an increase in the food demand notably for strategic crops such as wheat, maize, and rice. Furthermore, the global financial crisis in 2008 engendered volatile global prices for these strategic crops. Additionally, the technical integration of the production procedures is still low and does not cover the whole cultivated area (Ghonem, 2019). Over and above, there are two important aspects of the widening FG in Egypt for these crops:

- Firstly, the supply in the food market (the adopted agricultural policies, the loss of agricultural production and its impact on public consumption, the availability of agricultural production requirements, the agricultural sector's share of investments, environmental problems and climate change, the costs and prices of crop production, and government support provided to farmers) (Soliman et al., 2010; Tellioglu & Konandreas, 2017; Yassin, 2016).
- Secondly, demand in the food market (population increase and growth as mentioned above, per capita national income, price policies adopted, customs, traditions and

consumption patterns, migration and economic openness of the country) (Goueli & El Miniawy, 1994; Nin-Pratt et al., 2017). All these reasons have led to the widening of the FG in Egypt recently.

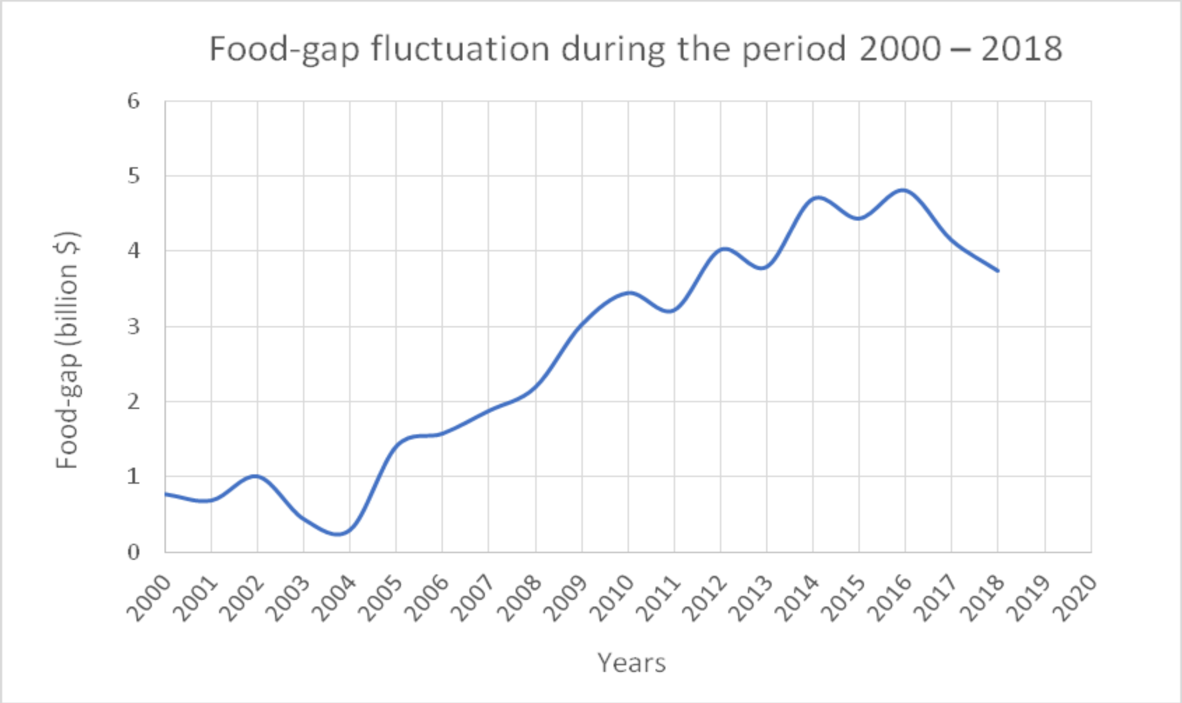

**Figure 17: Food gap fluctuation of some important crops (2000–2018).**

*Source: Own construction, 2021*

### *5.3.3. The Water Consumption for the Studied Crops*

The mathematical model applied under different constraints gave us an estimation of the water consumption of the studied crops considering their CWR. One of the model constraints is that the water consumption of the crops should not exceed the renewable water resource for the agricultural sector in the country and that is about 45 billion $m^3$. Through the analysis period, a huge difference, reaching around 25 billion $m^3$, between the water consumed for the studied crops and the total amount of renewable water ($Water_{const}$) was observed (Figure 18).

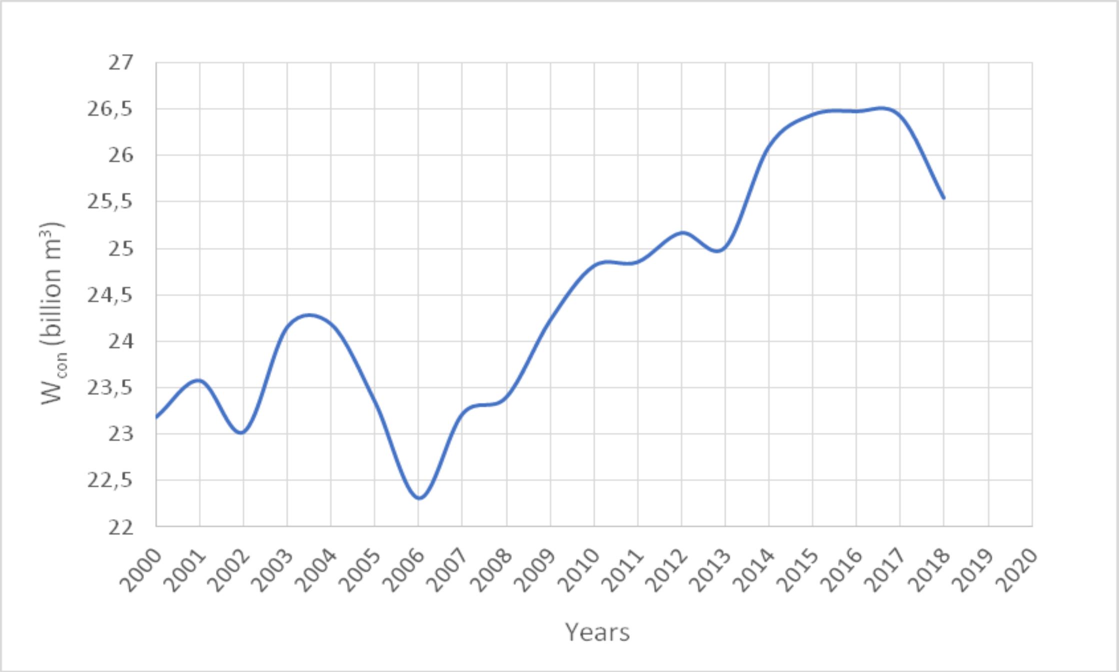

**Figure 18: The water consumption for the studied crops.**

*Source: Own construction, 2021*

Even though this water amount difference is supposed to be exploited to irrigate other crops, it is clear that there is an important water loss. This can be explained by several reasons, including the traditional irrigation methods as well as the used technique such as surface irrigation in many nearby areas of the Nile river, where the water use efficiency is very low (Amer et al., 2017). In addition, the lack of use of modern technology skills in irrigation and the lack of guidance for the farmers through the establishment of introductory courses that contribute to teaching them some methods about using modern irrigation that reduce the water waste, such as sprinkler and drip irrigation (Omran & Negm, 2020). This is as well as the environmental impact (high temperature, low precipitation), especially for the crops which need high amounts of water.

### *5.3.4. Statistical Analysis for the Food Gap and the Water Consumption*

Figure 19 reveals in a better way the trend between the FG and the water consumptions during 19 years for the studied crops. We noticed that the variation is a direct proportion between water consumption and the FG, and this can also be proved statistically by modelling them through SPSS program using the simple linear regression (LR) model.

- The response variable (dependent variable) is the FG;
- The covariate (independent variable) is the water consumption (Wcon);
- The observations (OBS) from 2000 to 2018.

The question was to check whether the water consumption was a significant variable to explain the FG changes, or not.

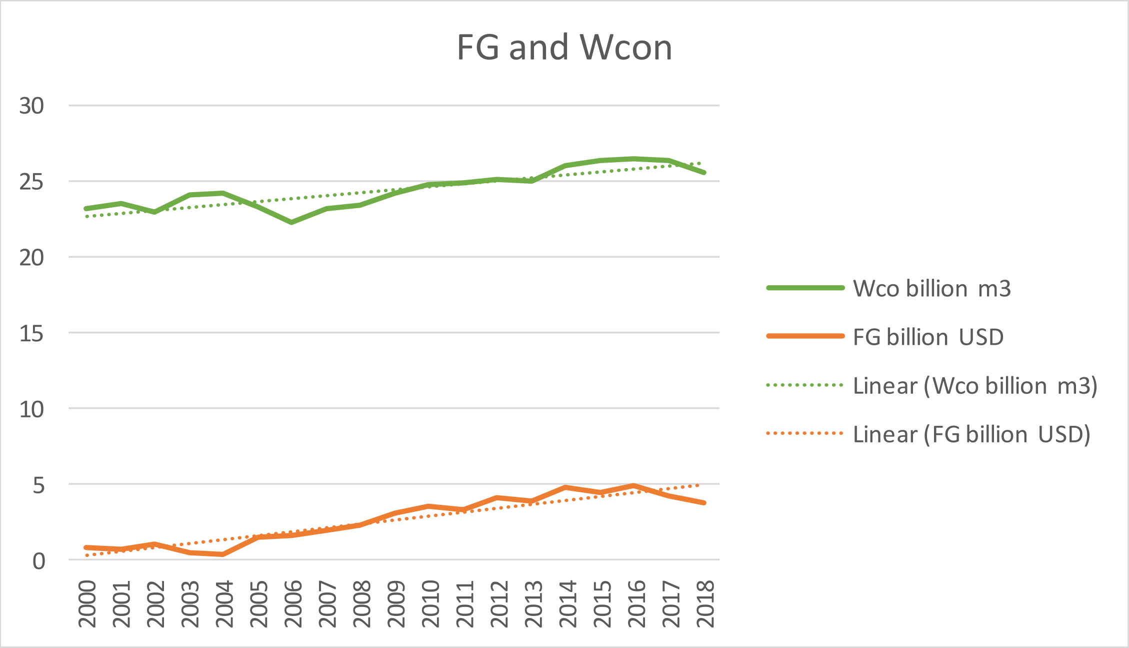

**Figure 19: The FG and the water consumption trend for 19 years' period.**

*Source: Own construction, 2021*

Simple linear regression was used in order to determine the influence of the independent variable Wcon on a dependent variable FG. In addition, it was necessary to transform the data by Square Root Transformation (SQRT), since there is a noticeable moderate negative skewness in the studied data (Garson, 2012). The results are reported in the Table 32, and they can be expressed in the following regression Equation (6.8):

$$FG = 8986.700 + 26{,}877.114\ Wcon + e \qquad (6.8)$$

The intercept value shows the influence of Wcon on FG. It means that if all the independent variables are zero, FG as the dependent variable is predicted to be 8986.700. Furthermore, the value 26,877.114 represents the coefficient of Wcon, obviously meaning that if Wcon increases by one unit then FG is predicted to increase by 26,877.114.

**Table 32: The LR model applied on the studied data.**

| Variable | B |
|---|---|
| Constant | 8986.700 |
| Wcon | 26,877.114 |

*Source: Own calculation, 2021*

Afterwards, the test of goodness to fit was used Table 33. Based on the analysis, the correlation coefficient (R) is equal to 0.875 indicating the strong relationship of independent variable to the dependent variable. The coefficient of determination ($R^2$) is equal to 0.766, which means that the independent variable affected the dependent variable with 76.6% in this model.

**Table 33: Test of goodness of the LR model applied on the studied data.**

| R | $R^2$ |
|---|---|
| 0.875[a] | 0.766 |

[a]. Dependent Variable: SQRT(k-FG).

*Source: Own calculation, 2021*

A classical assumption test was needed to ensure that there was no impediment to use the regression analysis, verifying the homoscedasticity, the normality, and the autocorrelation.

Figure 20 shows that the pattern of points is spread from both sides of the zero line of the ordinate, revealing that there is no heteroscedasticity in this regression.

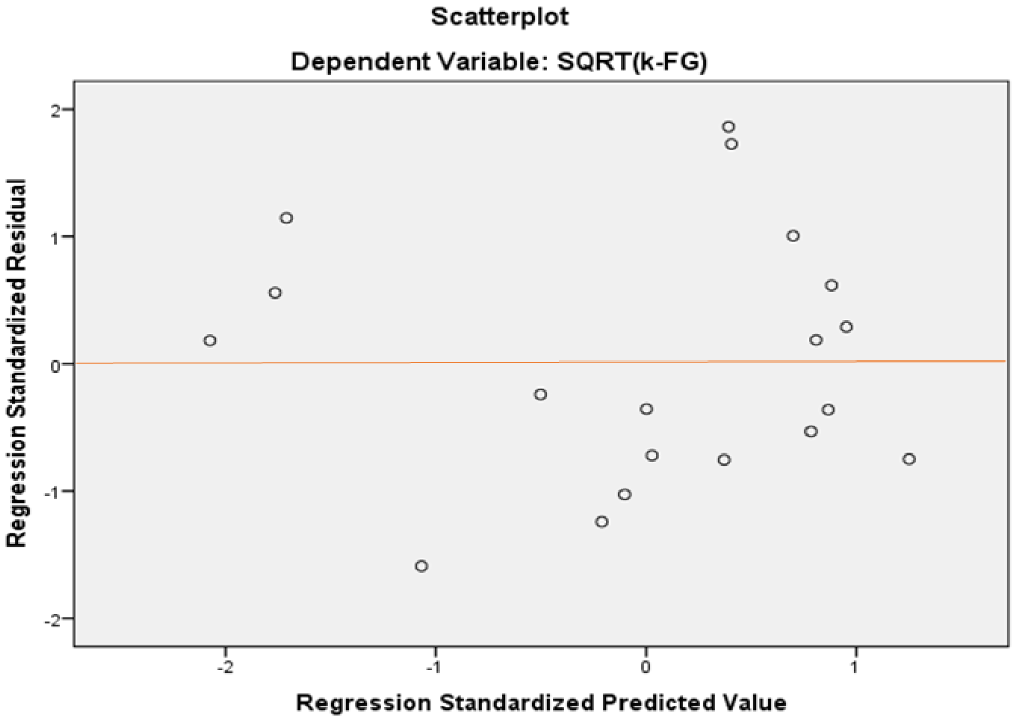

**Figure 20: The heteroskedasticity of the residuals resulted from the LR model applied on the studied data.**

*Source: Own construction, 2021*

Later, the normality test was used, and the resulted graph Probability Plot (Figure 21) shows that the expected values are strongly correlated to the observed values of the FG.

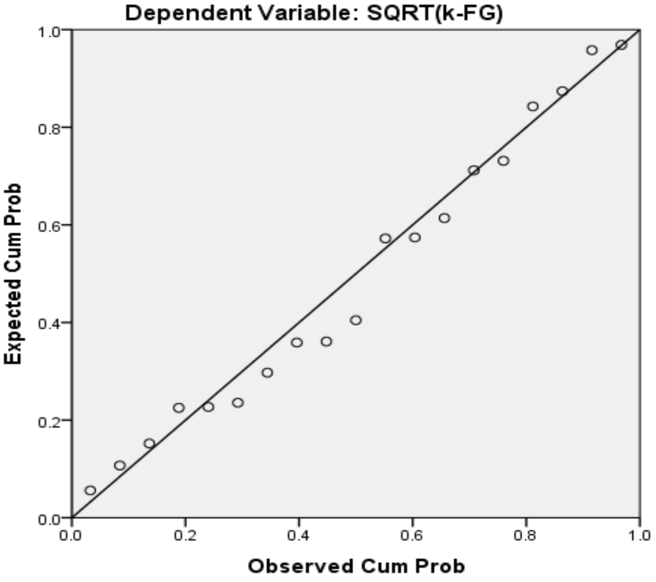

**Figure 21: Normal probability plot of regression standardized residual displaying expected vs. observed values of the studied data using LR model .**

*Source: Own construction, 2021*

Additionally, the Shapiro–Wilk test were used since the data observations are less than 50 (Yap & Sim, 2011). In this test, we set the following assumptions:

- If the value of Shapiro–Wilk (sig.) > 0.05, this means that the data are normally distributed;
- If the value of Shapiro–Wilk (sig.) < 0.05, this means that the data are not normally distributed.

Table 34 illustrates the (sig.) values of the Shapiro–Wilk test for both variables, are > 0.05. This means that the data can be said to be normally distributed even though the data are at risk of a lower bound of true significance because of its small size.

**Table 34: Tests of normality resulted from the LR model on the studied data.**

| | **Kolmogorov–Smirnov[a]** | | | **Shapiro–Wilk** | | |
|---|---|---|---|---|---|---|
| | **Statistic** | **Df** | **Sig.** | **Statistic** | **Df** | **Sig.** |
| FG | 0.135 | 19 | 0.200* | 0.916 | 19 | 0.094 |
| Wcon | 0.131 | 19 | 0.200* | 0.940 | 19 | 0.269 |

*This is a lower bound of the true significance; [a]. Lilliefors significance correction; Df signifies degree of freedom .*Source: Own calculation, 2021*

Later on, the autocorrelation test (the Durbin–Watson (DW)) was used to determine the correlation of variables in the regression model along the time.

Based on the Table 35, we can see that the DW value is equal to 1.915, which means there are no autocorrelation symptoms in the current model.

**Table 35: Durbin–Watson test for autocorrelation of the residuals resulted from the LR model on the studied data.**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Durbin-Watson |
|---|---|---|---|---|---|
| **1** | 0.875[a] | 0.766 | 0.753 | 9380.63939 | 1.915 |

[a]. Predictors: (Constant), SQRT(k-Wcon)

*Source: Own calculation, 2021*

Finally, the hypothesis test is intended to determine the effect of Wcon as the independent variable to the FG as the dependent variable. The $T_{test}$ is used to determine the partial effect of the independent variable on the dependent variable. This test is carried out by comparing the $T_{count}$ with the $T_{table}$ with the level of significance of 95% ($\alpha = 0.05$). The assumptions of this test are as follows:

- If the $T_{count} > T_{table}$ or sig. ($p$-value) $< 0.05$, then the variable Wcon influences FG;
- and if the $T_{count} < T_{table}$ or sig. ($p$-value) $> 0.05$, then the variable Wcon does not influence FG.

Table 36 displays that the $T_{count}$ is 7.468. The $T_{table}$ is 1.729 ($n = 19$, $p = 0.05$); the result is $T_{count} > T_{table}$, and the sig. ($p$-value) is also $< 0.05$. It means that the variable Wcon is significantly influencing the FG variation.

**Table 36: T-test applied on the studied data.**

| Model | T | Sig. |
|---|---|---|
| Wcon | 7.468 | 0.000 |

*Source: Own calculation, 2021*

### *5.3.5. Average Demand and Production of the Crops During the Period 2000–2018*

The calculation of the crop demand allowed us to re-estimate the productions with the aim to achieve the best model fit between crops in terms of minimizing the FG in Egypt. This analysis was performed by taking into consideration the annual average of the variables used during the 19-year period (2000–2018). Our model recommended the best solution in comparison to the real situation of the crops production. Figure 22 illustrates an analogy between the calculated average demand and the recommended average production of the studied crops during the 19-years period. For many crops such as maize, potatoes, sugar beet, legumes, vegetables, fruit, nuts, and aromatic plants, we notice that the production is equal to the demand, which reflects the saturation of the constraint (the maximum production should not exceed the demand for each crop for the reason mentioned above). For the wheat, barley, rice and cotton crops, their demands are higher than their productions. This can be elucidated by the fact that the above-mentioned crops (especially cotton and wheat) are more valuable in Egypt, thus their price is higher as well. Consequently, the government revenues benefit from purchasing these valuable crops from the farmers at reasonable prices and then exporting them at high prices besides importing other varieties with lower prices and in larger quantities, in order to achieve the economic balance in the country (Perrihan, 2013).

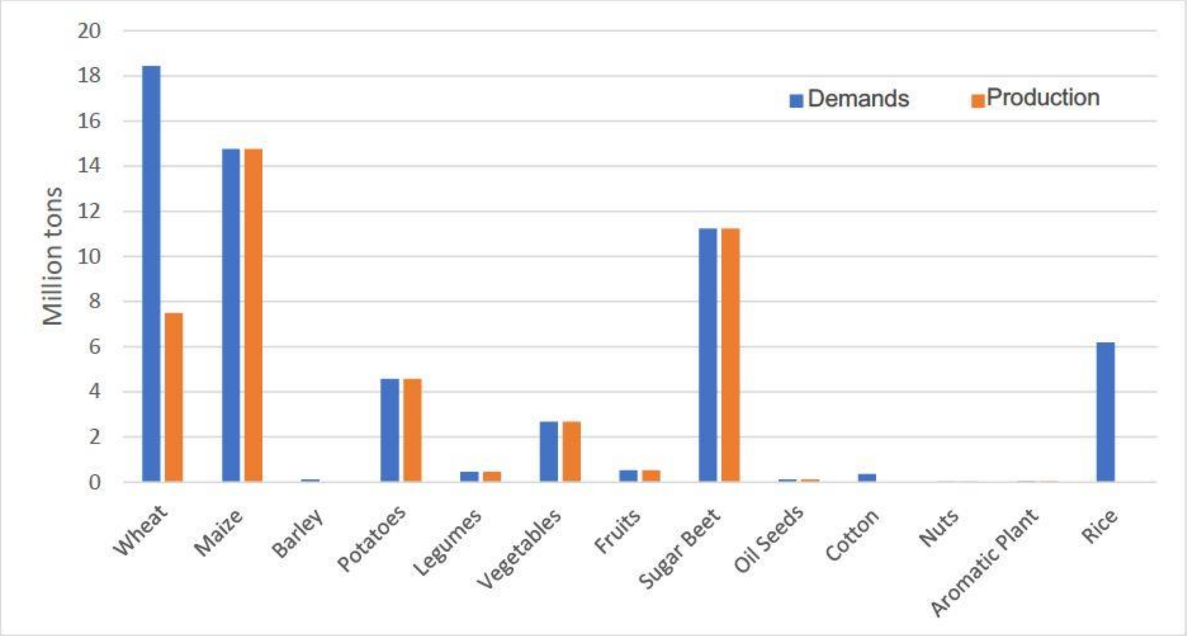

**Figure 22: The average demand and the average recommended production of the crops.**

*Source: Own construction, 2021*

### *5.3.6. The Deficit Between the Crop Demands and Production of the Crops (2000-2018)*

With regard to the mathematical model used, the main goal is to reduce the FG in the country as much as possible for thirteen important crops. After calculating the annual productions and demands redistribution for minimizing the FG, the new resulted annual production amounts were subtracted from the new annual demands, to assess the deficit produced from the suggested redistribution carried out by our linear model on the basis of the crops' priority. As the production for each crop should not exceed the demand, we have determined the term deficit as the difference between the demand and the production. In the best case, the deficit is equal to zero, which means a self-sufficiency was reached for that crop. With regard to the four crops mentioned above, the results were not equal to zero. This result can be related to several factors, among which are the preferences of the farmers in terms of choosing these crops over the years, and the political strategy issues related to the economic balance and the laws applied on exportations and importations of the country (mentioned above). To achieve the self-sufficiency in the agricultural sector at the long term, considering only some strategic crops in this study, we can say that the suggestions provided by our mathematical model can be considered as ideal solutions if applied appropriately, regardless the political conditions of the country. Indeed, Figure 23 illustrates the deficit between the crops demand and the production from the year 2000 to 2018. For all the crops, the deficit in the suggested model resulted in zero, except for the wheat, barley, cotton, and rice crops.

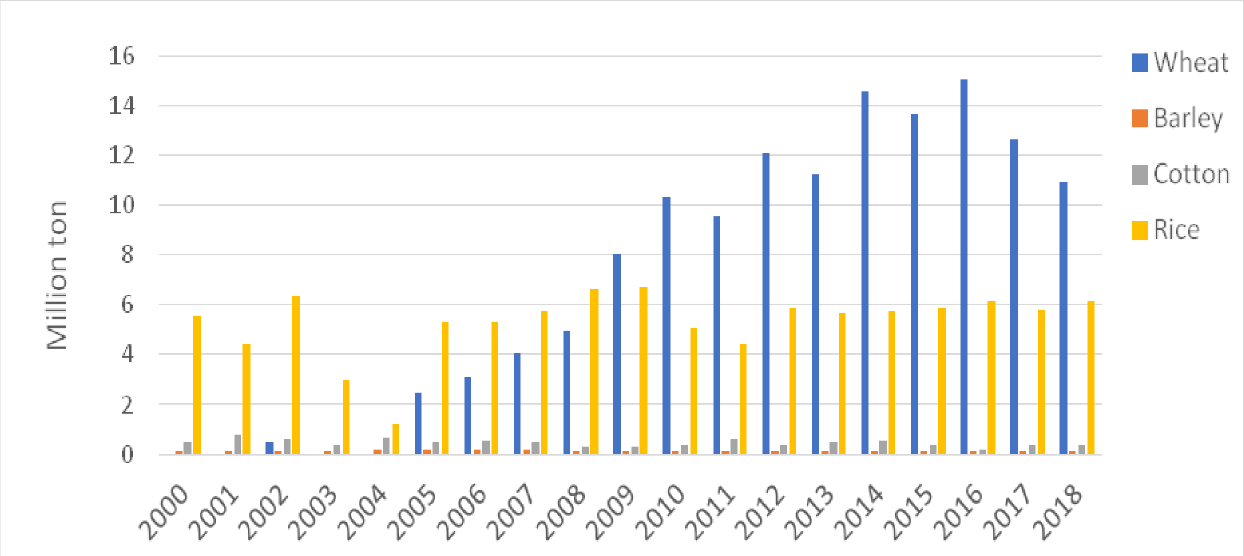

**Figure 23: The deficit between the crops' demand and production of the crops from 2000–2018 for the wheat, barley, cotton, and rice crops.**

*Source: Own construction, 2021*

## 5.4. Conclusions and Recommendations

In this chapter, I have concluded important results that may help the government and/or the decision-makers to improve the reality of agricultural production and farmers. By calculating the FG from 2000-2018, we noticed an increased with the years, starting from 2005 to 2017. Maybe the essential reason was the increase in the population growth rate that has led to an increase in food demands.

Through the estimation of water consumption and the comparison with renewable water resources for the agricultural sector in the country, an immense difference, reaching around 25 billion $m^3$, between the water consumed for the studied crops and the total amount of renewable water was detected. Perhaps the reasons for this may be in the traditional irrigation methods used to irrigate crops, where water losses are large and also have environmental causes.

I also noticed that the FG and water consumption are positively correlated over the years and that was proved statistically. The model was quite good in predicting the FG variation, nevertheless, it needs to be improved by incorporating other significant covariates adding fair contribution to recompense the error term. Likewise, the available data were restricted to a 19-year duration, which gives a quite small number of observations needed for a better statistical analysis.

The main objective of the chapter was to identify the size of the FG in Egypt to help in reducing it. So, by calculating the crop demands and re-estimating the productions, it will help in achieving the best model fit between crops in terms of minimizing the FG in Egypt. For many crops such as maize, potatoes, sugar beet, legumes, vegetables, fruit, nuts, and aromatic plants, we noticed that the production is equal to the demand, which reflects the saturation of the constraint of maximum production which should not exceed the demand for each crop. For the wheat, barley, rice and cotton crops, their demands are higher than their productions. Regarding the crops land reallocation and by comparing with the real allocation, it was found that all the crops except rice, wheat, potatoes, sugar beet, and maize, are reallocated relatively close to the real situation.

Among the research recommendations are the following:

- Study the effect of annual international crop prices on the crops needed and the FG to find the most appropriate way of importing crops, especially strategic ones.
- The possibility of developing a mathematical model to redistribute the optimum yield through fixing precise constraints and assumptions so that the number of possibilities that give better results increases.
- Vertical expansion (increase in hectare productivity) through new varieties that are resistant and/or tolerant to environmental conditions, for example.
- Horizontal expansion (increasing the cultivated area outside the Nile Valley). This comes about by confronting the problem of water scarcity in these lands by introducing strains that tolerate drought and water stress.

- The government should give more importance to solving FG issues and to increasing the production by supporting the farmers as well as using efficient irrigation techniques to reduce water use.

# 6. EVALUATION OF THE IMPACT OF WATER POLICY ON ECONOMIC DEVELOPMENT IN EGYPT

After analysing the water footprint indicator and the FG optimization in Egypt, it can be concluded in this chapter by evaluation of the water policy and its impact on the economic development in Egypt.

The importance of water bets in the social, economic, environmental, security and political fields shows that water is a strategic resource and an essential element for life and has no alternative, in addition to being an actor in development activities and thus achieving economic development. The wagers increase over time unless the necessary care and attention are given, and here the role of water policy emerges as the tool that is used as a basis for decision-making in order to achieve the goal of maximizing the economic and social benefits of the water resource, achieving its sustainability, and preserving it for future generations.

Egypt is suffering from a water crisis as a result of limited water resources available to meet increasing demand, in addition to climate change, pollution, and other issues, and no one is currently oblivious to the problem of the Grand Ethiopian Renaissance dam between Egypt and Ethiopia, which reduces Egypt's share of the Nile River basin (Dakkak, 2014; El-Nashar & Elyamany, 2018; El Bedawy, 2014). The latter leads to a deterioration in the economic quality of this resource, and in view of this reality, we believe that it is necessary to assess the impact of the current water policy on achieving economic development in Egypt to arrive at a set of results and recommendations that help direct this policy towards rationalizing and exploiting the water resource in modern, economical ways that protect it from pollution and waste and thus achieve its sustainability.

The problem of the study lies in trying to answer the following question: **RQ6:** *How can the water policy, by directing the water use, contributes to raising the standard of living of the population in Egypt and accelerates the pace of development?*

## 6.1. The objectives and Hypotheses

The study aims to evaluate the water policy during the study period and develop results and recommendations that enable building rational and maybe correct policies to raise the efficiency of utilizing and allocating water resources for the purpose of development. Water policy has an important role in achieving economic development as it is the tool that guides the water resource towards the most productive uses by directing investment towards the water sector to raise the efficiency and effectiveness of utilizing the water resource in a way that leads to improving the welfare of individuals and revitalizing the agricultural sector (by increasing agricultural production), in addition, the industrial sector through (increasing the number of industrial units) and thus achieving the basic consumer and productive requirements of society, which will positively affect the sustainable development process, and it can be expressed as follows:

- $H_0$: There is no statistically significant relationship between water withdrawal in the different sectors (municipal, agricultural, and industrial) and Egyptian GDP growth.
- $H_1$: There is a statistically significant relationship between water withdrawal in the different sectors (municipal, agricultural, and industrial) and Egyptian GDP growth.

The importance of this study lies in the fact that it seeks to assess the impact of the current water policy on achieving economic development in Egypt during the period (1988-2018) by analyzing the extent to which the water resource contributes to accelerating the pace of local development by studying the correlation between the Egyptian GDP and water withdrawal in the sectors. The GDP was chosen as it reflects the conditions of economic, development and living requirements, as for the choice of water use in the various sectors, this is due to the fact that the production of products, the provision of services and the achievement of the well-being of individuals requires the consumption of water in the required quantity and quality.

## 6.2. Methodology

### *6.2.1. Data collection*

The indicators used in this study to evaluate the water policy in Egypt are water withdrawal in the three major sectors which are agricultural, industrial and municipality while economic wellbeing is measured by gross domestic product (GDP). Data on water use in agriculture, industrial and municipal sectors are collected from FAO Aquastat database, the Central Agency for Public Mobilization and Statistics (CAPMAS), and different reports from Ministry of Water Resources and Irrigation in Egypt. While that of GDP is sourced from the World Bank data base for the period of 1988-2018 (Table 37).

The study proposes that there is no statistically significant relationship between water withdrawal in the different sectors (municipal, agricultural, and industrial) and GDP growth and the alternative that there is a statistically significant relationship between water withdrawal in the different sectors (municipal, agricultural, and industrial) and GDP growth.

**Table 37: The GDP and Water Withdrawal by Sectors in Egypt during 1988-2018.**

| Year | Gross domestic product (GDP) (in billion U.S. dollars) | Agricultural water withdrawal (10^9 $m^3$/year) | Industrial water withdrawal (10^9 $m^3$/yr) | Municipal water withdrawal (10^9 $m^3$/yr) |
|---|---|---|---|---|
| 1988 | 92.53 | 48.97 | 5.14 | 2.97 |
| 1989 | 115.36 | 50.88 | 5.09 | 3.02 |
| 1990 | 96.09 | 52.80 | 4.96 | 3.12 |
| 1991 | 48.43 | 53.19 | 4.89 | 3.24 |
| 1992 | 44.17 | 54.69 | 4.81 | 3.34 |
| 1993 | 49.53 | 52.97 | 4.68 | 3.57 |
| 1994 | 54.55 | 51.70 | 4.56 | 3.61 |
| 1995 | 63.26 | 50.71 | 4.43 | 3.73 |
| 1996 | 71.11 | 51.16 | 4.39 | 4.08 |
| 1997 | 79.77 | 54.03 | 4.26 | 4.36 |
| 1998 | 89.19 | 55.34 | 4.24 | 4.78 |
| 1999 | 95.04 | 57.64 | 4.11 | 5.01 |
| 2000 | 104.75 | 59.00 | 4.00 | 5.30 |
| 2001 | 102.27 | 59.98 | 3.91 | 5.92 |
| 2002 | 90.26 | 60.32 | 3.60 | 6.04 |
| 2003 | 85.16 | 60.55 | 3.48 | 6.42 |
| 2004 | 82.86 | 60.87 | 3.27 | 6.74 |
| 2005 | 94.13 | 61.54 | 3.08 | 7.02 |
| 2006 | 112.9 | 62.40 | 2.91 | 7.59 |
| 2007 | 137.06 | 64.60 | 2.60 | 7.89 |
| 2008 | 170.8 | 63.70 | 2.51 | 8.06 |
| 2009 | 198.32 | 62.47 | 2.43 | 8.11 |
| 2010 | 230.02 | 61.57 | 2.07 | 8.86 |
| 2011 | 247.73 | 63.74 | 1.84 | 9.27 |
| 2012 | 278.77 | 61.50 | 1.20 | 9.60 |
| 2013 | 288.01 | 61.56 | 2.32 | 9.66 |
| 2014 | 305.57 | 61.76 | 2.94 | 9.96 |
| 2015 | 332.08 | 61.25 | 3.46 | 10.08 |
| 2016 | 332.48 | 61.48 | 4.05 | 10.34 |
| 2017 | 236.53 | 61.35 | 5.40 | 10.75 |
| 2018 | 250.25 | 61.11 | 5.64 | 10.88 |

*Source: The data were collected from FAO Aquastat database, the world bank, the Central Agency for Public Mobilization and Statistics (CAPMAS), and reports from Ministry of Water Resources and Irrigation in Egypt*

An autoregressive distributed lag (ARDL)  is the main statistical tool employed in this study to investigate the stated hypothesis in this study. However, since the variables used in the study are time series, it is important to examine their properties so as not to end up with a spurious regression, which is modelling the relationship among non-stationary series. Therefore, all variables are investigated using their descriptive features, time plots, unit root tests and cointegration analysis and the software used is EVIEWS v9. Each of these methods is discussed below.

### 6.2.2. *Descriptive analysis*

The standard descriptive statistics are computed for each variable as explained in the appendix 6.

### 6.2.3. *Unit Root Tests*

Unit Root tests are usually used in time series analysis to determine whether the variable(s) under study are stationary as well as to their level of integration (that is, the number of times the variable is differenced to attain stationarity). There are numbers of statistical tools to achieve this, but the commonly used techniques are Augmented Dickey-Fuller (ADF), and Phillips-Perron (P-P) tests the standard DF test is carried out by estimating the following;

$$y_t = \rho y_{t-1} + x_t^{'}\delta + \varepsilon_t \qquad (7.1)$$

After subtracting $y_{t-1}$ from both sides of the equation:

$$\Delta y_t = \alpha y_{t-1} + x_t^{'}\delta + \varepsilon_t \qquad (7.2)$$

Where $\alpha = \rho - 1$

The null and alternative hypotheses may be written as:

$H_0 : \alpha = 0$

$H_1 : \alpha < 0$

The above-mentioned simple Dickey-Fuller unit root test is only valid if the series is an AR(1) process. The assumption of white noise disruptions is violated when the series is coupled at higher order lags. By assuming that the y series follows an AR(P) process and adding P delayed difference terms of the dependent variable y to the right-hand side of the test regression, the Augmented Dickey-Fuller (ADF) test provides a parametric adjustment for higher-order correlation:

$$\Delta y_t = \alpha y_{t-1} + x_t^{'}\delta + \beta_1 \Delta y_{t-1} + \beta_2 \Delta y_{t-2} + ...\beta_p \Delta y_{t-p} v_t \qquad (7.3)$$

The usual practice is to include a number of lags sufficient to remove serial correlation in the residuals. Therefore, the ADF test given in equation (7.3) above is first used and then the Phillips Perron (P-P) test described below.

Phillips and Perron propose when testing for a unit root, suggest a non-parametric alternative way of controlling for serial correlation. The P-P method computes the non-augmented DF test equation (7.4) and adjusts the coefficient's t-ratio so that serial correlation does not alter the test statistic's asymptotic distribution.. The P-P test is based on the statistic:

$$t_{\alpha} = t_{\alpha}\left(\frac{\gamma_0}{f_0}\right)^{\frac{1}{2}} - \frac{T(f_0 - \gamma_0)(se(\hat{\alpha}))}{2 f_0^{\frac{1}{2}} s} \qquad (7.4)$$

Where $\hat{\alpha}$ is the estimate, and $t_{\alpha}$ the t-ratio of $\alpha$, $se(\hat{\alpha})$ is the coefficient standard error, and *s* is the standard error of the test regression. In addition, $\gamma_0$ is a consistent estimate of the error variance in equation (2) (calculated as $(T - K)s^2$ where *k* is the number of regressors). The remaining term, $f_0$, is an estimator of the residual spectrum at frequency zero. Therefore, both equation (6.3) and (6.4) are used to test for the stationarity of the variables.

### *6.2.4. Cointegration analysis*

Cointegration is the idea that the linear combinations of non-stationary series can be stationary, implying a long-run relationship, thus they can be modelled. In testing for *Cointegration*, the Johansen Efficient Maximum Likelihood test was used to examine the existence of a long-term relationship among the variables.

Consider a VAR or order *P*.

$$y_t = A_1 y_{t-1} + \ldots + A_p y_{t-p} + \beta x_t + \varepsilon_t \qquad (7.5)$$

Where $y_t$ is a *k*-vector of non-stationary *I*(1) variables, $x_t$ is a *d*-vector of deterministic variables, and $\varepsilon_t$ is a vector of innovations. We can rewrite this VAR as:

$$\Delta y_t = \Pi y_{t-1} + \sum_{i=1}^{p-1} \Gamma \Delta y_{t-1} + \beta x_t 9 + \varepsilon_t \qquad (7.6)$$

Where,

$$\Pi = \sum_{i=1}^{p} A_i - I, \qquad \Gamma = -\sum_{j=i+1}^{p} A_i \qquad (7.7)$$

Granger's representation theorem asserts that if the coefficient matrix $\Pi$ has reduced rank, *r* < *k*, then there exist *k* x *r* matrices $\alpha$ and $\beta$ each with rank *r* such that $\Pi = \alpha\ \beta^1$ and $\beta^1 y_t$ is I(0), r is the number of cointegrating relations (the rank) and each column of $\beta$ is the cointegrating vector. As explained below, the elements of $\alpha$ are known as the adjustment parameters in the error correction model. Johansen's method is to estimate the matrix from an unrestricted VAR and to test whether we can reject the restrictions implied by the reduced rank of $\Pi$.

### *6.2.5. Error Correction Model*

This is the final specification that includes a short run dynamic process, consistent with data and converging to the long run equilibrium. The Error Correction Model (ECM) attempts to integrate economic theory useful in characterizing long run equilibrium with observed disequilibrium by building a model that explicitly incorporates behaviour that would restore equilibrium. *Error Correction Mechanism* has the cointegrated relations built into the specification so that it restricts the long-run behaviour of the endogenous variables to converge to their cointegrating relationships while allowing for short-run adjustment dynamics. The Error Correction Term (ECM) is the one-period lagged value of the residual from a static model.

In this study, after establishing the cointegration relationships among variables, an *over-parameterised* error correction model was estimated which initially consisted of 1 lag length of each variable. The over-parameterised error correction model estimated is given in the equation below;

$$\Delta Y_t = \alpha_0 + \alpha_1 X_t + \alpha_2 (Y - \beta_1 X)_{t-1} \qquad (7.8)$$

Where $Y_t$ is the GDP (dependent variable); $X_t$ is a vector of independent variables and this include agricultural water withdrawal (AWD), industrial water withdrawal (IWD) and municipal water withdrawal (MWD) while $(Y - \beta_1 X)_{t-1}$ are stationary residuals from that cointegration static model. In the analyses, the E-views, version 9.0 was adopted. However, robust M-estimation technique was used instead of the Ordinary Least Squares (OLS) estimation technique in order to remedy the presence of outliers in the dataset.

Following the *'general to specific'* modelling methodology, the over-parameterised model was continually simplified and re-parameterised by removing variables with low explanation until a *parsimonious* and *encompassing* representation of the data generation process was obtained with the choice of optimum lag length guided by the FPE, SC and HQ *Akaike and Schwarz Information Criteria*.

## 6.3. Results and Discussion

This section presents the result of analysis as well as some discussions. It is organized into three broad sections, namely; descriptive analysis, empirical analysis, and discussions of results. Each of these sections is further broken down appropriately.

### *6.3.1. Descriptive Analysis of Variables*

This section of the study presents the summary statistics of the variables under study. In Table 38, it is shown on the average that AWD, IWD and MWD between 1988 and 2018 are 58.22, 3.75 and 6.56, respectively with standard deviation of 4.69, 1.14 and 6.42. In addition, the table showed AWD values ranged from 48.97 (1988) and 64.60 (2007), IWD values is between 1.20 (2012) and 5.64 (2018) while MWD took value between 2.97 (1988) and 10.88 (2018), from 1988 to 2018. GDP that value fluctuate between $44.17 and $332.48 between 1988 and 2018 with an average and standard of $147.71 and $92.79, respectively. The skewness showed that GDP and MWD have right tailed distribution while AWD and IWD have left tailed distribution. In term of Kurtosis, all the variables have a flat distribution. Contrary to the value of skewness and kurtosis, Jarque-Bera statistic indicated that the null hypothesis that all the variables are normally distributed can't be rejected at 5% level of significance. Therefore, the variables under consideration can be assumed to satisfy normality assumption.

**Table 38: Descriptive Characteristics of Variables under Study.**

| **Statistics** | **GDP ($B)** | **AWD** $(10^9 m^3$ /year) | **IWD** $(10^9 m^3$ /year) | **MWD** $(10^9 m^3$ /year) |
|---|---:|---:|---:|---:|
| Minimum | 44.17 | 48.97 | 1.20 | 2.97 |
| Mean | 147.71 | 58.22 | 3.75 | 6.56 |
| Median | 102.27 | 60.55 | 4.00 | 6.42 |
| Maximum | 332.48 | 64.60 | 5.64 | 10.88 |
| Std. Dev. | 92.59 | 4.69 | 1.14 | 2.69 |
| Skewness | 0.77 | -0.56 | -0.36 | 0.14 |
| Kurtosis | 2.13 | 1.83 | 2.25 | 1.59 |
| Jarque-Bera | 4.0482 | 3.4153 | 1.3855 | 2.6557 |
| Probability | 0.1321 | 0.1813 | 0.5002 | 0.2650 |
| Observations | 31 | 31 | 31 | 31 |

*Source: Own calculation, 2021*

Figure 24 shows the trends of the variables used in the regression analysis. It is shown that GDP erratic movement between 1990 and 2015. It fell sharply between 1990 and 1993 but has a steady upward movement between 1994 and 2001, and 2004 to 2015. However, the boxplot revealed that GDP has some lower outliers. In the case of AWD, it decreased between 1993 and 1995, 2008 and 2010 but has a steady upward trend between 1996 and 2007. Equally, there is clear presence of upper outliers in the AWD dataset as shown by the boxplot. The time plot of IWD showed it has a download trend between 1988 and 2012 but move upward from 2012 to 2018 while MWD showed a clear evidence of upward movement from the beginning to the end of the series. The undulating movement observed in the variables is a clear evidence that they are not stationary and that they needed to be verified using standard unit root test to determine their order of integration.

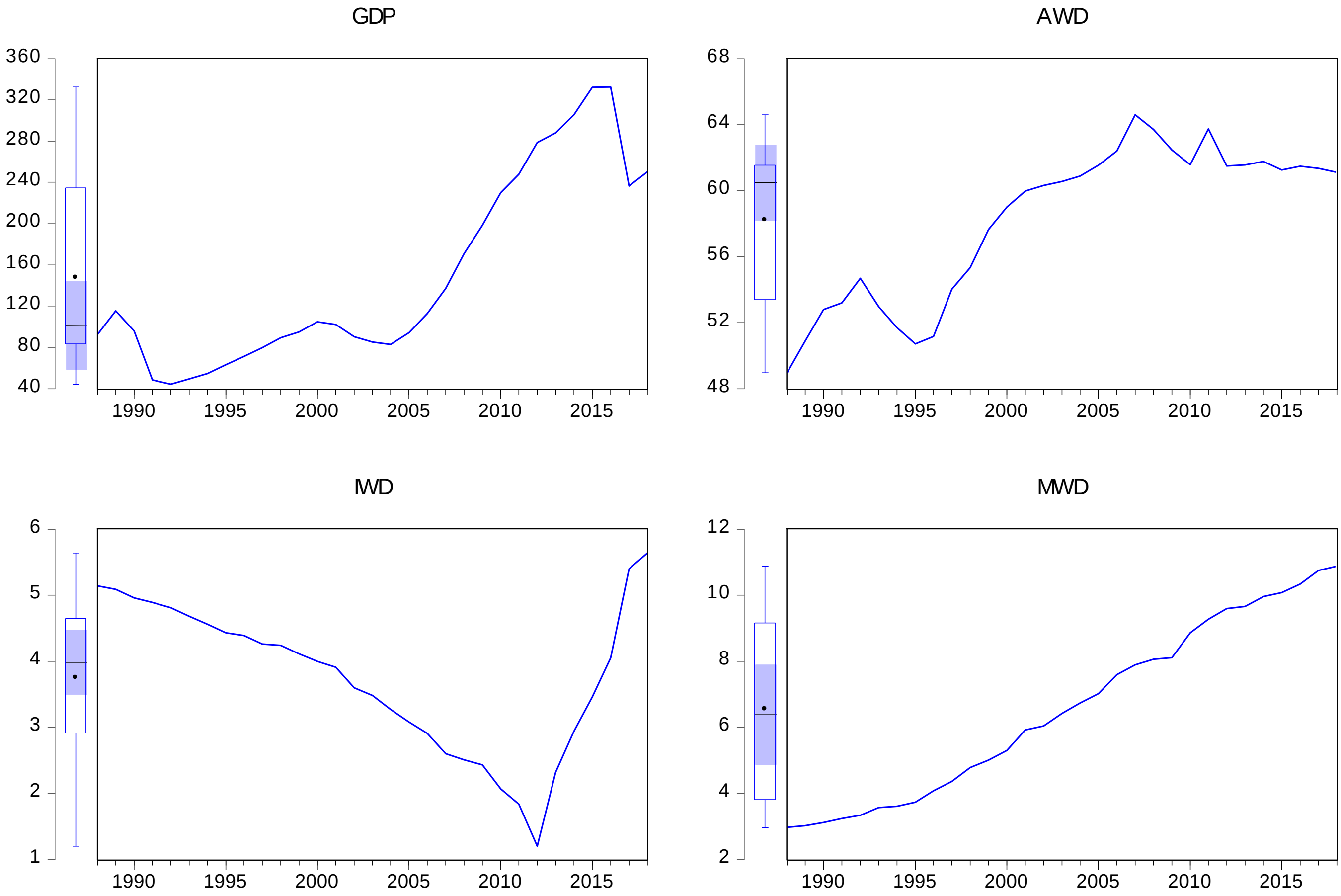

**Figure 24: Time plot of the variables between 1988 and 2018.**

*Source: Own construction, 2021*

### *6.3.2. Empirical analysis*

This section presents the results of the unit root (stationarity) tests, cointegration tests and error correction model. Prior to these, maximum lag length to be used in the unit root test, cointegration analysis and error correction model was determined. Table 39 showed that the maximum length of one was selected by Final prediction error (FPE), Schwarz (SC) and Hannan-Quinn information criteria.

## Table 39: Maximum lag length selection.

| Lag | LogL | LR | FPE | AIC | SC | HQ |
|---|---|---|---|---|---|---|
| 1 | -150.7385 | NA | 2.740877* | 12.35100 | 13.11890* | 12.57934* |
| 2 | -135.5766 | 21.33898 | 3.110670 | 12.41308 | 13.94889 | 12.86976 |
| 3 | -123.3557 | 13.57871 | 4.992818 | 12.69302 | 14.99673 | 13.37803 |
| 4 | -97.43061 | 21.12418 | 3.738908 | 11.95782* | 15.02944 | 12.87117 |

* indicates lag order selected by the criterion

LR: sequential modified LR test statistic (each test at 5% level)

FPE: Final prediction error

AIC: Akaike information criterion

SC: Schwarz information criterion

HQ: Hannan-Quinn information criterion

*Source: Own calculation, 2021*

The result of unit root test presented in Table 40, showed that three models were used to carry out both ADF and P-P unit root tests to ensure robustness of the result. Using ADF and P-P approaches, the results showed that the variables are not stationary at level and needed to be integrated to attain stationarity. The result of unit root at first difference of the variables is presented in the second panel of Table 40 and it showed that all the variables attained stationarity after first difference. This indicates that the variables under study are integration of order 1.  It is worthy of note that the intercept and trend and intercept models of ADF test failed to reject the claim that GDP is stationary after first difference. However, further investigation of the variable using ADF with a model without trend and intercept and all P-P tests indicated that GDP is integration of order one, even at 1%.

**Table 40: Unit Root Test at level and First difference.**

| Variable | ADF | | | PP | | | Decision |
|---|---|---|---|---|---|---|---|
| | Intercept | Trend & Intercept | None | Intercept | Trend & Intercept | None | |
| GDP | -0.430892 | -1.679165 | 0.717319 | 0.598435 | -2.000291 | 0.508421 | I(0) |
| AWD | -2.047497 | -1.136094 | 1.543963 | -1.996903 | -1.300351 | 1.392499 | I(0) |
| IWD | -1.398927 | 1.543912 | -0.181008 | -1.393779 | 1.164656 | -0.264844 | I(0) |
| MWD | 1.024607 | -3.112694 | 7.552492 | 1.024607 | -3.208168 | 6.566931 | I(0) |
| **FIRST DIFFERENCE** | | | | | | | |
| GDP | -2.264551 | 1.491327 | -4.085667 | -4.138668 | -4.134118 | -4.114838 | I(1) |
| AWD | -4.309316 | -4.438060 | -4.178374 | -4.308286 | -4.448499 | -4.143324 | I(1) |
| IWD | -3.163682 | -3.815012 | -3.215508 | -3.139216 | -3.820830 | -3.193994 | I(1) |
| MWD | -5.138233 | -5.202652 | -1.120834 | -5.136012 | -5.199866 | -1.884955 | I(1) |
| | Critical value | Critical value | Critical value | Critical value | Critical value | Critical value | |
| | 1%=-3.679322 | 1%=-4.309824 | 1%=-2.647120 | 1%=-3.679322 | 1%=-4.309824 | 1%=-2.647120 | |
| | 5%=-2.967767 | 5%=-3.574244 | 5%=-1.952910 | 5%=-3.574244 | 5%=-3.574244 | 5%=-1.952910 | |
| | 10%=-2.622989 | 10%=-3.221728 | 10%=-1.610011 | 10%=-3.221728 | 10%=-3.221728 | 10%=-1.610011 | |

*Source: Own calculation, 2021*

### *6.3.3. Cointegration Test*

Cointegration analysis was carried out using the trace and maximum eigenvalue tests. The results of these tests are presented in Table 41. The Table 41 showed that the null hypothesis of no cointegration among the variables can be rejected at 5% level of significance using both trace and maximum eigenvalue tests criteria. The results revealed that one cointegrating vectors existed among the variables in the model. Based on the fact that the variables are cointegrated, there is existence of a long run relationship, and this means that the study can proceed to estimating the Error Correction Model.

**Table 41: Cointegration Result.**

| **Trace Test k = 1** | | | | **Maximum Eigenvalues Test k =1** | | | |
|---|---|---|---|---|---|---|---|
| **Ho** | **HA** | **( λ trace)** | **Critical values (5%)** | **Ho** | **HA** | **( λ Max)** | **Critical values (5%)** |
| r ≤ 0 | r > 0 | 54.26892* | 40.17493 | r ≤ 0 | r > 0 | 31.03501* | 24.15921 |
| r ≤ 1 | r > 1 | 23.23391 | 24.27596 | r ≤ 1 | r > 1 | 18.54668* | 17.79730 |
| r ≤ 2 | r > 2 | 4.687230 | 12.32090 | r ≤ 2 | r > 2 | 4.631549 | 11.22480 |
| r ≤ 3 | r > 3 | 0.055681 | 4.129906 | r ≤ 3 | r > 3 | 0.055681 | 4.129906 |

*Note: r represents number of cointegrating vectors and k represents the number of lags in the unrestricted VAR model. *denotes rejection of the null hypothesis at the 5% level.*

*Source: Own calculation, 2021*

### *6.3.4. Correlation Analysis and Error Correction Model*

Correlation analysis presented in Table 42 gives the degree and direction of independent variables with GDP as well as the level of interrelationship among the predictors. As shown in the table, the null hypothesis that there is no significant relationship between GDP and each of the predictors can be rejected at 1% (AWD and MWD) and 5% (IWD), respectively. It was noted that both AWD and MWD have positive correlation with GDP. However, AWD is fairly correlated with GDP while MWD is strongly correlated with GDP. Conversely, IWD has a negative and low relationship with GDP. This result implied that there is direct relationship (both increase together) between each of AWD and MWD and GDP while IWD has inverse relationship (as IWD increases, GDP decreases) with GDP. Aside, the interrelationship among the predictor's variables showed that AWD and MWD are strongly correlated $(r = 0.857, p < 0.01)$ , AWD and IWD are fairly correlated $(r = -0.691, p < 0.01)$ while a moderate relationship is observed between MWD and IWD $(r = -0.524, p < 0.01)$ . This higher level of interrelationship between pair of predictor variables is suggestive of presence of multicollinearity problem.

**Table 42: Correlation analysis.**

| Variables | GDP | AWD | IWD | MWD |
|---|---|---|---|---|
| GDP | 1 | | | |
| AWD | 0.621** | 1 | | |
| IWD | -0.439* | -0.691** | 1 | |
| MWD | 0.888** | 0.857** | -0.524** | 1 |

Note: ** and * indicate significant correlation at 1% and 5%, respectively

*Source: Own calculation, 2021*

### *6.3.5. Error Correction Model (ECM)*

Error correction model is estimated to determine the impact of the predictors on the dependent variables. The long run OLS model was first estimated, and its residual was saved. Further, test was carried out using variance inflation factor (VIF) to ensure that multicollinearity problem is not present in the model. The estimated coefficient of the long run OLS model and VIF values of each predictor is presented in table 43. The table showed that VIF values of each predictor is far less than 10 indicating that multicollinearity is not a serious problem in our model. However, to remedy the problem of outliers early detected in some of the variables included in the model, robust m-estimation technique to obtain parsimonious parameter estimates of the ECM model. This estimation technique yields a reliable regression estimates when there is outlier problem and little deviation from classical assumption. The parsimonious regression estimate produced by robust estimation technique is presented in Table 44.

**Table 43: Long run regression model.**

| Variable | Coefficient | Std. Error | t-Statistic | Prob. | VIF |
|---|---|---|---|---|---|
| AWD | -4.944121 | 1.609843 | -3.071183 | 0.0048 | 6.41 |
| IWD | -0.242203 | 0.192087 | -1.260901 | 0.2181 | 5.72 |
| MWD | 1.927107 | 0.284341 | 6.777457 | 0.0000 | 1.72 |
| C | 21.74250 | 6.197798 | 3.508101 | 0.0016 | |
| R-squared | 0.805444 | Durbin-Watson stat | | 0.557861 | |
| Adjusted R-squared | 0.783827 | S.D. dependent var | | 0.620103 | |
| F-statistic | 37.25917 | | | | |
| Prob(F-statistic) | 0.000000 | | | | |

*Source: Own calculation, 2021*

Table 44 showed that all the variables included in the model jointly explained the dependent and that about 35.7% of the variation in the GDP can be explained by the model $(R^{\uparrow}2 = 0.357826)$ . In term of individual significance of the variables, it is noted that the last year value of GDP, AWD and IWD have positive and significant impact on the GDP. Specifically, a 10% unit increase in each of the last year value of GDP, AWD and IWD produce and increase of 7.7%, 13.1% and 1.0% in GDP at 1%, 5% and 10% level of significance, respectively. Conversely, AWD has a negative influence on GDP. This result indicates that a 10% unit increase in AWD lead to a reduction of 18.7% in GDP value at 1% level of significance. However, MWD has a positive and insignificant influence on GDP.

Worthy of note is the error correction term (ECT) included in the model. Its negative sign and value less than 1 confirm to economics and it can be interpreted as about 33.9% of the errors are corrected yearly.

**Table 44: Result of parsimonious ECM regression.**

| Variable | Coefficient | Std. Error | z-Statistic | Prob. |
|---|---|---|---|---|
| D(GDP(-1)) | 0.771037 | 0.059301 | 13.00204 | 0.0000 |
| D(AWD) | -1.870327 | 0.505765 | -3.698013 | 0.0002 |
| D(AWD(-1)) | 1.308665 | 0.548789 | 2.384643 | 0.0171 |
| D(IWD(-1)) | 0.104653 | 0.061784 | 1.693837 | 0.0903 |
| D(MWD) | 0.317595 | 0.240220 | 1.322103 | 0.1861 |
| ECT(-1) | -0.339349 | 0.041951 | -8.089195 | 0.0000 |
| Robust Statistics | | | | |
| R-squared | 0.357826 | Adjusted R-squared | | 0.218223 |
| Rw-squared | 0.814180 | Adjust Rw-squared | | 0.814180 |
| Akaike info criterion | 55.11982 | Schwarz criterion | | 67.48563 |
| Deviance | 0.112385 | Scale | | 0.048754 |
| Rn-squared statistic | 260.6584 | Prob (Rn-squared stat.) | | 0.000000 |

*Source: Own calculation, 2021*

## 6.4. Conclusion and recommendations

Based on the above, the regression model used in the analysis has well explained the relationship between the dependent variable and the independent variables that are explained, i.e., between water withdrawal in the various sectors (municipal, agricultural, and industrial sectors) and the Egyptian GDP, as this model explains that the GDP is a linear function of the variables. The three (water withdrawal in different sectors) the municipal, agricultural, and industrial sectors) and these independent variables explain the change in the Egyptian GDP, in addition, the evidence for this is the existence of the constant value differs from zero as shown in the following equation:

$$GDP = 0.77\ GDP_{t-1} - 1.87\ AWD + 1.31\ AWD_{t-1} + 0.10\ IWD_{t-1} + 0.31\ MWD_{t-1} - 0.34\ ECT_{t-1}$$

The parameters of water withdrawal in the industrial and municipal sectors are positive indicating the direct proportionality between them and the rates of development, as the increase in water withdrawal in these two sectors will contribute to increasing consumer welfare and raising the standard of living for him, thus increase the GDP in Egypt, while water withdrawal in the agricultural sector it negatively affects the GDP and this is what is proven by the parameter of the variable water withdrawal in agriculture AWD with a negative sign - except for the last year 2018-, meaning that the relationship between the two variables is an inverse relationship, and this indicates the weakness of the efficiency and effectiveness of water use in this sector.

Accordingly, it can evaluate the current Egyptian water policy, especially in light of the inverse proportionality between water consumption in agriculture and economic development, which indicates the neglect of the current water policy in Egypt for aspects of agricultural water supply management, as the legislation, strategies and water policies that regulate water withdrawal are absent in Egypt (Jagannathan et al., 2009a). On the part of the agricultural sector, and there are no binding strategies for recycling treated water, whether on-site or from plants to address the centralization of its use in agricultural operations and the rationalization of water use, by following methods that enable him to use water in rational ways, there are modern technologies that help him in treating and reusing water and reducing waste, especially since statistics reveal an excessive indirect consumption of water in our daily life, where it is possible. Converting all industrial and agricultural products into equivalent quantities of water, for example, jeans need 8,000 litres of water to reach us in this way, and whoever consumes 50 sheets per day in printing or fax machines actually consumes more than a litre of water used in making paper and inks, as well as most of the food production factory, use between 1-7 litres of water to produce one kilogram of food.

**Recommendations:**

- Focusing on rationalizing water withdrawal in the Egyptian agricultural sector through administrative policy and technological tools.
- The application of reuse of treated water within agricultural establishments and their recycling in order to achieve an economic reduction in water withdrawal from the source.
- Informational and data support by providing laws, environmental standards and rules governing the fields of water use.
- Financial support by offering financing and lending opportunities to eligible projects that support the efficient implementation and use of water in the agriculture.
- Training and rehabilitation by organizing workshops, and training courses in the fields of water rationing, increasing the efficiency of its use, and encouraging a change in traditional methods, with a focus on water conservation.

- Supporting investors in the agricultural field to understand water use systems and create water budgets and suggest ideas to help implement water rationalization and facilitate the participation of service providers and propose financing programs, and give limited priority to controls for water investment in agriculture.

# 7. MAIN FINDINGS OF THE DISSERTATION, NEW AND NOVEL RESULTS

The main findings of the dissertation can be divided within two parts which are explained bellow:

**Novel and gap-filling calculations and analysis:**

- **CA1:** Calculating the virtual water for most important agricultural crops in Egypt after 2005. Additionally calculating the virtual water for some agricultural products after 2005.
- **CA2:** Evaluating the Food security and estimating food self-sufficiency for some selected crops and products.
- **CA3:** Analysing of the IWFP variation for three major crops (rice, maize, and wheat) from 2000-2018, in terms of several related factors that are: annual average precipitation, annual average temperature, the targeted productivity of the crops and the renewable water resource, to see the effects of those variables on the IWFP, therefore, the effect on the production of the crops in Egypt.
- **CA4:** Determine and calculate the FG, water consumption and the food demand during 2000–2018 for the most important food crops in Egypt. In addition, Build a mathematical model to find the optimum land reallocation and production distribution for minimizing the FG.
- **CA5:** Evaluating the water policy during 1988-2018 and develop results and recommendations that enable building rational and correct policies to raise the efficiency of utilizing and allocating water resources for the purpose of development.

**Novel and gap-filling methodological work:**

- **MW1:** Assessment the Water footprint and its indicators in Egypt.

Summary

*Importance of the Topics:*

The importance of this research was to increase interest in the concept of water footprint and virtual water in the agricultural sector to preserve the depleting traditional water resources in the whole world, especially in the Arab region and Africa, as explained in the research background, many researchers, such as Allan and Hoekstra, were able to shed light on the concept of water footprint and virtual water, especially its calculation in crops. Due to the difficulty of the calculation process, researchers sometimes relied on data issued by some international organizations such as the FAO. However, the lack of data requires all researchers in this field to cooperate so that the water footprint concept becomes the most important to achieve efficiency in the use of water. Additionally, in this research the optimal use of available water resources to achieve sustainable agricultural development was also investigated in this study.

*Main Goals of the Dissertation:*

The main topic of this research is the economic importance of water in the agricultural sector in the Arab region: a case study of the water footprint in Egypt. In this research, an attempt was made to complete what the researchers started in the process of calculating the water footprint and virtual water for the selected agricultural crops, taking into account Egypt's water and agricultural situation. The study also discussed how to make the most use of available water resources in order to achieve agricultural sustainability in the Arab world. Likewise, by using some mathematical models to re-allocate agricultural lands for some agricultural crops, the research was able to provide some solutions to help the government and/or the decision-makers in Egypt. In addition to analyzing three main water withdrawals sectors in Egypt (agriculture, industry, municipalities) and comparing them to GDP in Egypt.

*Main Results of the Dissertation:* The three types of water (blue, green, and grey) and their uses were determined in the research background. additionally, the four steps of estimating the water footprint, as well as the aims of studying the water footprint and the problems that the researcher faces when calculating it, were indeed addressed. The concept of virtual water was also discussed, as well as how to use it in trade, particularly with crops. Egypt's climate, landforms, and water resources, as well as agriculture, food security, water footprint, water security, and virtual water commerce, were all detailed. These methods can efficiently contribute to attaining water use efficiency in Arab agriculture, as they respond to the

conditions for increasing production on the one hand, and the specificities of climate and resources in the Arab region on the other, improving agricultural production in terms of quantity and quality and thus improving food security in Arab countries.

Then the study discussed, the optimum way for dealing with water scarcity, according to this study, is to use optimal water usage in agriculture and irrigation. This has aided the agricultural sector in the Arab region by utilizing efficient methods such as choosing suitable crops, setting appropriate irrigation schedules, employing effective irrigation systems, and the use of alternative water sources for irrigation. Furthermore, the following can be implemented to meet the goal of optimizing water productivity to make the most of marginal water resources, maximizing the water's production value, and lowering the focus on horizontal growth can be achieved by implementing the following: irrigated and protected agricultural rather than rainfed agriculture, drip irrigation usage, supplemental irrigation, protected agriculture, and crop selection based on genetic technology. The later methods can efficiently contribute to attaining water use efficiency in Arab agriculture, as they respond to the conditions for increasing production on the one hand, and the specificities of climate and resources in the Arab region on the other, improving agricultural production in terms of quantity and quality and thus improving food security in Arab countries.

As well as , in the chapter 3 an attempt had done to appraise the water status in Egypt through the application of the virtual water principle in the agricultural sector. And because of its close link to the water footprint concept, a virtual water principle is a useful tool for managing water resources because it aids in identifying Egypt's genuine water balance and attempting to provide water for more economic applications and agricultural ones. It was noticed that Egypt is an importer of virtual water and not an exporter of maize and wheat crops, and for the rice crop Egypt export an important amount of their productions which is appear from the amount of exported virtual water. In addition, the consumption of the agricultural sector is about 33 billion cubic meters of “blue water” and around 6.5 billion cubic meters of “green water”, which are less than the number of renewable water resources 58.5 billion cubic meters per year. The justification for this is that the calculation of the volume of consumption of the agricultural sector was based on the volume of virtual water for agricultural products. Furthermore, it was observed that the amount of water used in irrigation operations (blue water) was calculated from the available water resources in irrigation operations, which is about 34 billion cubic meters, and the rest is about 11 billion cubic meters of rainwater (green water). Additionally, as it turns out that the extent of Egypt dependence on external resources to meet its agricultural crops needs is about 21.15%, and this is not a large percentage, and its dependence on its water resources and self-sufficiency is about 78.84%. Also, the study found that Egypt has a high rate of self-sufficiency in relation to (rice, potatoes, vegetables, and fruits) which are (94.9, 94.84, 99.3, 99.92, and 101.1 ) respectively, and that's  led to a decrease in the degree of dependence on external water resources to meet food needs in Egypt.

In the next chapter of the research, the internal water footprint of three strategic crops in Egypt (rice, maize, and wheat) was analyzed for a period of 19 years. In addition, the average annual temperatures, the average annual precipitation, the renewable water in the country, and crop productivity for was analysed to know the effect of those four variables to the IWFP. From the statistical analysis it was noticed that the highest value of internal water footprint for rice, maize and wheat were recorded in the year 2008, 2011 and 2017, respectively. Also, the productivity of rice, maize, and wheat during the period under investigation were maximum in the year 2006, 2011 and 2017, respectively. It was noted that the internal water footprint and productivity were uppermost in the same year. However, this was not the pattern in the case of crops considered. Further, the peak value of temperature, renewable water resources and precipitation were recorded for the period under investigation in the 2009, 2012 and 2017, respectively. Furthermore, Asymmetry impact of renewable water resources, precipitation and temperature was established in the rice, maize, and wheat model, respectively. Actually, by using a statistical model (NARDL) to analyze the time series data for the three main crops in Egypt the following conclusion had found as mentioned in the chapter4. It is noted that the negative and positive change in each of the independent variables produce similar impact on the response variable with the exemption of temperature in which the asymmetric impact of the negative and positive change was noticed.

After analysing and estimating the water footprint, the virtual water, and the internal water footprint for selected crops grown in Egypt, it was necessary to analyse the FG and food security in Egypt and trying to give a good recommendations to help a decision makers and/or the government in Egypt for the best solution to achieve the goal which is to improve the reality of agricultural production and farmers. So, the chapter fifth and after making the calculations of the FG it was noticed an increased within the years in the FG, starting from 2005 to 2017. Maybe the essential reason was the increase in the population growth rate that has led to an increase in food demands.

Moreover, Throughout the estimation of water consumption and the comparison with renewable water resources for the agricultural sector in the country, an immense difference, reaching around 25 billion $m^3$, between the water consumed for the studied crops and the total amount of renewable water was detected. Perhaps the reasons for this may be in the traditional irrigation methods used to irrigate crops, where water losses are large and also have environmental causes. Also, by calculating the crop demands and re-estimating the productions, it will help in achieving the best model fit between crops in terms of minimizing the FG in Egypt. For many crops such as maize, potatoes, sugar beet, legumes, vegetables, fruit, nuts, and aromatic plants, we noticed that the production is equal to the demand, which reflects the saturation of the constraint of maximum production which should not exceed the demand for each crop. For the wheat, barley, rice and cotton crops, their demands are higher than their productions. Besides, the crops land reallocation and by comparing with the real allocation, it was found that all the crops except rice, wheat, potatoes, sugar beet, and maize, are reallocated relatively close to the real situation.

The last chapter of the research was about evaluating the water policy in Egypt for about 31 years by analyzing the GDP with water withdrawals for three sectors (agricultural, industrial, and municipal). The regression analysis model was used in the analysis has well explained the relationship between the dependent and independent variables that are explained between water withdrawal in the various sectors (municipal, agricultural, and industrial sectors) and the Egyptian GDP, as this model explains that the GDP is a linear function of the variables. The three water withdrawal in different sectors the municipal, agricultural, and industrial sectors, and these independent variables will explain the change in the Egyptian GDP it was observed that the parameters of water withdrawal in the industrial and municipal sectors are positive demonstrating the direct proportionality between them and the rates of development, as the increase in water withdrawal in these two sectors will contribute to increasing consumer welfare and raising the standard of living for him, thus increase the GDP in Egypt, while water withdrawal in the agricultural sector it negatively affects the GDP and this is what is proven by the parameter of the variable water withdrawal in agriculture AWD with a negative sign - except for the last year 2018-, meaning that the relationship between the two variables is an inverse relationship, and this indicates the weakness of the efficiency and effectiveness of water use in this sector.

*Main Recommendations of the Dissertation:* the study recommends the following:

I. Previous research has demonstrated the importance of including virtual water trade in the development of national water policy plans, as virtual water trade between countries can assist alleviate water scarcity on a local and global scale. Understanding the virtual water trade balance is also critical for formulating sound policies.

II. Food security, economic growth, and the creation of job possibilities are all dependent on a thorough understanding of the influence of virtual water trade on the social, local, and economic circumstances. More research on the natural, social, and economic implications of adopting virtual water trading as a strategic tool in organizing water policies is clearly needed. The results of some studies in this field showed that:

- Water trading is one of the measures that can be suitable for obtaining the highest value for water uses in irrigation;
- Work to transfer water uses for irrigation to a more economically and environmentally beneficial system.

III. Efficient use of water in irrigation by : efficiency of irrigation; sustainable ground water use; enhancing water quality; using high technology in irrigation application.

IV. Alternative sources of water supplementation

- Evaluation and identification of alternative resources, including desalination, to enhance existing supplies; non-conventional water re-use.

V. Integrating water resource management throughout:

- Conservation and upgrading of sectoral allocations are encouraged; Institutional support; Water audits and resource use investigations; drafting a national water conservation strategy that includes water legislation and water pricing.

VI. Organizing country effort by public recognition campaigns, local participation, engagement of water user associations, supporting NGO forums between the government and the community.

VII. Because of its importance in raising awareness of water conservation and defining efficient and inexpensive irrigation methods, extension work must play a prominent and continuous role in this matter. All of this would contribute to providing additional quantities of water that could be directed to reclaim new agricultural lands, thus increasing agricultural production, and ensuring better food security.

VIII. Study the effect of annual international crop prices on the crops needed and the FG to find the most appropriate way of importing crops, especially strategic ones.

IX. The possibility of developing a mathematical model to redistribute the optimum yield through fixing precise constraints and assumptions so that the number of possibilities that give better results increases.

X. Vertical expansion (increase in hectare productivity) through new varieties that are resistant and/or tolerant to environmental conditions, for example.

XI. Horizontal expansion (increasing the cultivated area outside the Nile Valley). This comes about by confronting the problem of water scarcity in these lands by introducing strains that tolerate drought and water stress.

XII. The government should give more importance to solving FG issues and to increasing the production by supporting the farmers as well as using efficient irrigation techniques to reduce water use.

XIII. Focusing on rationalizing water withdrawal in the Egyptian agricultural sector through administrative policy and technological tools.

XIV. The application of reuse of treated water within agricultural establishments and their recycling in order to achieve an economic reduction in water withdrawal from the source.

XV. Informational and data support by providing laws, environmental standards and rules governing the fields of water use.

XVI. Financial support by offering financing and lending opportunities to eligible projects that support the efficient implementation and use of water in the agriculture.

XVII. Training and rehabilitation by organizing workshops, and training courses in the fields of water rationing, increasing the efficiency of its use, and encouraging a change in traditional methods, with a focus on water conservation.

XVIII. Supporting investors in the agricultural field to understand water use systems and create water budgets and suggest ideas to help implement water rationalization and facilitate the participation of service providers and propose financing programs, and give limited priority to controls for water investment in agriculture.

XIX. Finally, The Egyptian government should take a number of incentive and regulatory policies to educate farmers about the value of water scarcity in Egypt and work to shift from crops that are intensive in using low-value water, to high-value crops that require less irrigation water through following:

- Imposing fees for delivering irrigation water on an area-based basis to have a higher price for crops with greater water requirements;
- Additionally, to allocate water among farmers and to remove any restrictions on crop production and marketing options;
- In addition, the government have to encourage and promote farmers access to short- and long-term loans to produce crops of higher value;
- Also, provide farmers with training programs to enhance their ability to produce alternative crops and use limited resources efficiently.

*Limitations of the Study and the Next Research:* this study has several limitations that should be considered. First, the lack of data collections especially regarding the water footprint for the studied crops after 2005 because as mentioned in the research background most of the studies had done in the world which was depended on the Water Footprint Network and UNESCO publications, so in this dissertation, the water footprint for the studied crops was calculated manually after 2005 depends on the data constructed from the FAO and the World Bank data resources in additions the CAPMAS in Egypt. Second, nowadays most of the country especially the developing ones doesn’t take care much about the importance and the benefits of the water footprint and virtual water concepts, on contrast, we can see the developed countries like example Canada, Singapore and Netherlands working a lot to deal with these concepts and maybe in the future we can see the water footprint certificate labelled with all kinds of products to know the actual amounts of water consumed. Third, the difficulty of calculating the water footprint in the industrial and municipal sectors is due to the entry of many factors, such as the multiplicity of industrial production and the unwillingness of business owners to access water consumption information. Fourth, the small number of the studied years in this research may have given approximate results in chapters 3 and 4, despite the attempt to make the most of these results to reach the desired goals. Finally, In the fourth chapter, the NARDL model was used, because the relationship between the variables was not linear, due to the few years of study, although the mentioned model has interpreted the results well.

*The potential is a continuation of research work:* (1) Calculating the water footprint of all sectors in the country, as well as introducing some new variables such as energy consumption in the agricultural and/or industrial sector, in addition, the $CO_2$ emission and its impact on the agricultural sector. (2) Comparing the water footprint between countries, and encourages taking advantage of this idea in saving water, especially in the Arab region, which suffers from drought and the lack of available water resources. (3) Study the impact of climate changes according to the principle of virtual water, which leads to reducing the risks caused by these changes, especially on the agricultural sector.

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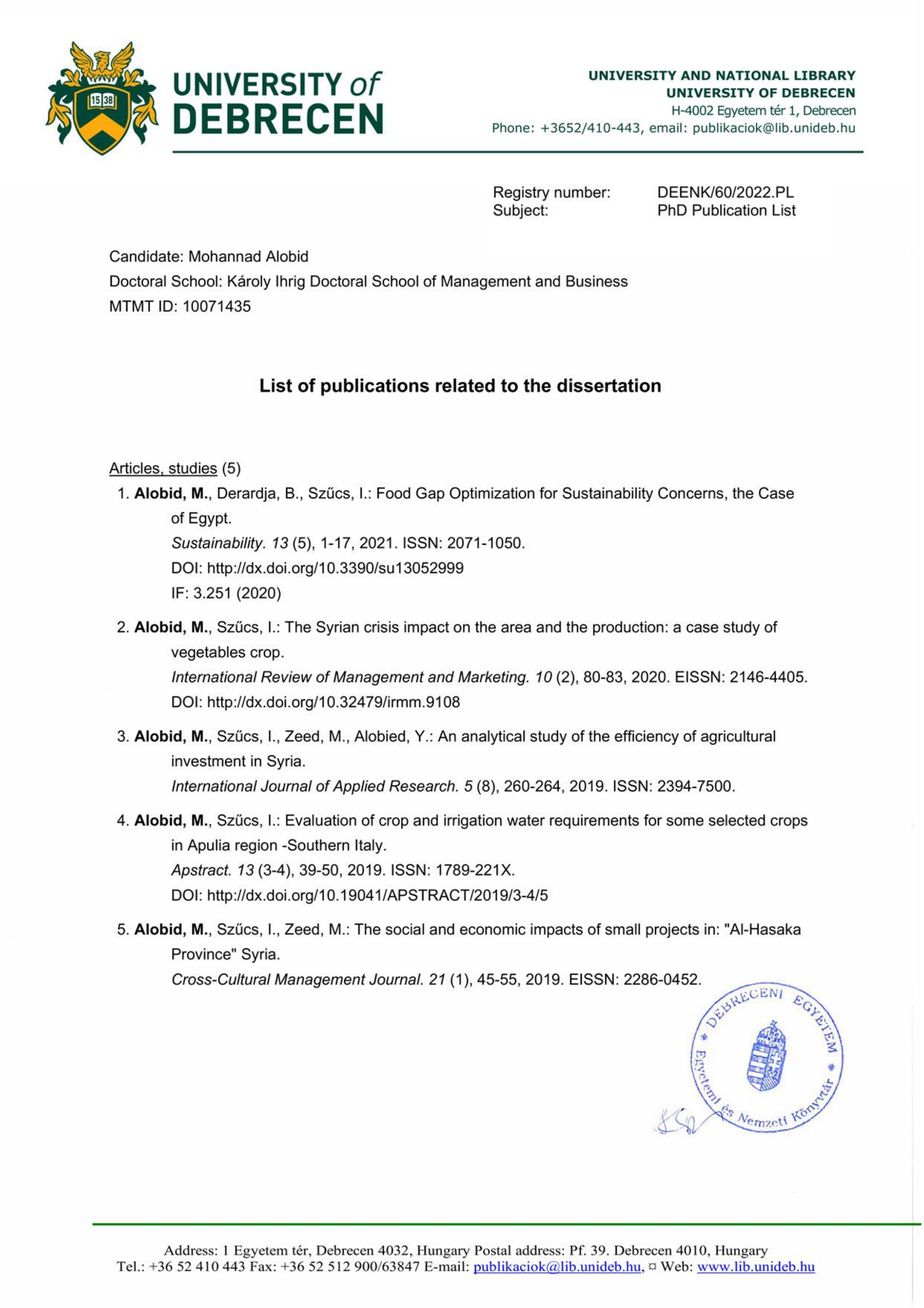
# LIST OF PUBLICATIONS



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MTMT ID: 10071435

## List of publications related to the dissertation

Articles, studies (5)

1. **Alobid, M.**, Derardja, B., Szűcs, I.: Food Gap Optimization for Sustainability Concerns, the Case of Egypt.
   *Sustainability. 13* (5), 1-17, 2021. ISSN: 2071-1050.
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2. **Alobid, M.**, Szűcs, I.: The Syrian crisis impact on the area and the production: a case study of vegetables crop.
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4. **Alobid, M.**, Szűcs, I.: Evaluation of crop and irrigation water requirements for some selected crops in Apulia region -Southern Italy.
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5. **Alobid, M.**, Szűcs, I., Zeed, M.: The social and economic impacts of small projects in: "Al-Hasaka Province" Syria.
   *Cross-Cultural Management Journal. 21* (1), 45-55, 2019. EISSN: 2286-0452.

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## List of other publications

Articles, studies (7)

6. Ogundele Lasun, T., Okunlola, O. A., **Alobid, M.**, Szűcs, I., Kassouri, Y.: Sources and Sectoral Trend Analysis of CO2 Emissions Data in Nigeria Using a Modified Mann-Kendall and Change Point Detection Approaches.
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7. **Alobid, M.**, Hammo, A., Szűcs, I.: Estimating the Economic Efficiency of Sheep Rearers in Al-Hasakah Governorate/Syria Using the Data Envelopment Analysis.
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8. Salman, M., Fertő, I., **Alobid, M.**, Pék, É.: Farmers can substantially deploy irrigation potential through improved management environment: enabling factors of farmers' involvement in resource-efficient irrigation management.
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9. Okunlola, O. A., **Alobid, M.**, Olubusoye, O. E., Ayinde, K., Lukman, A. F., Szűcs, I.: Spatial regression and geostatistics discourse with empirical application to precipitation data in Nigeria.
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10. **Alobid, M.**, Pék, É.: Nyomásos öntözőrendszerek teljesítményértékelésének lehetséges módszertana a megbízhatóság növelése érdekében = Performance analysis by pressure-driven model to increase reliability of water services in pressurized irrigation systems.
    *Hidrológiai közlöny. 100* (2), 59-69, 2020. ISSN: 0018-1323.

11. Pék, É., Fertő, I., **Alobid, M.**: Evaluating the Effect of Farmers' Participation in Irrigation Management on Farm Productivity and Profitability in the Mubuku Irrigation Scheme, Uganda.
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    DOI: http://dx.doi.org/10.3390/w11112413
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12. **Alobid, M.**, Alfaraj, N., Szűcs, I.: The impact of the crisis on the area, production, and productivity of major crops in syrian agriculture: a case study of wheat, barley, and cotton. *SEA - Practical Application of Science. 21* (3), 183-196, 2019. EISSN: 2360-2554.

**Total IF of journals (all publications): 14,506**
**Total IF of journals (publications related to the dissertation): 3,251**

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

26 January, 2022

## LIST OF TABLES

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# APPENDICES

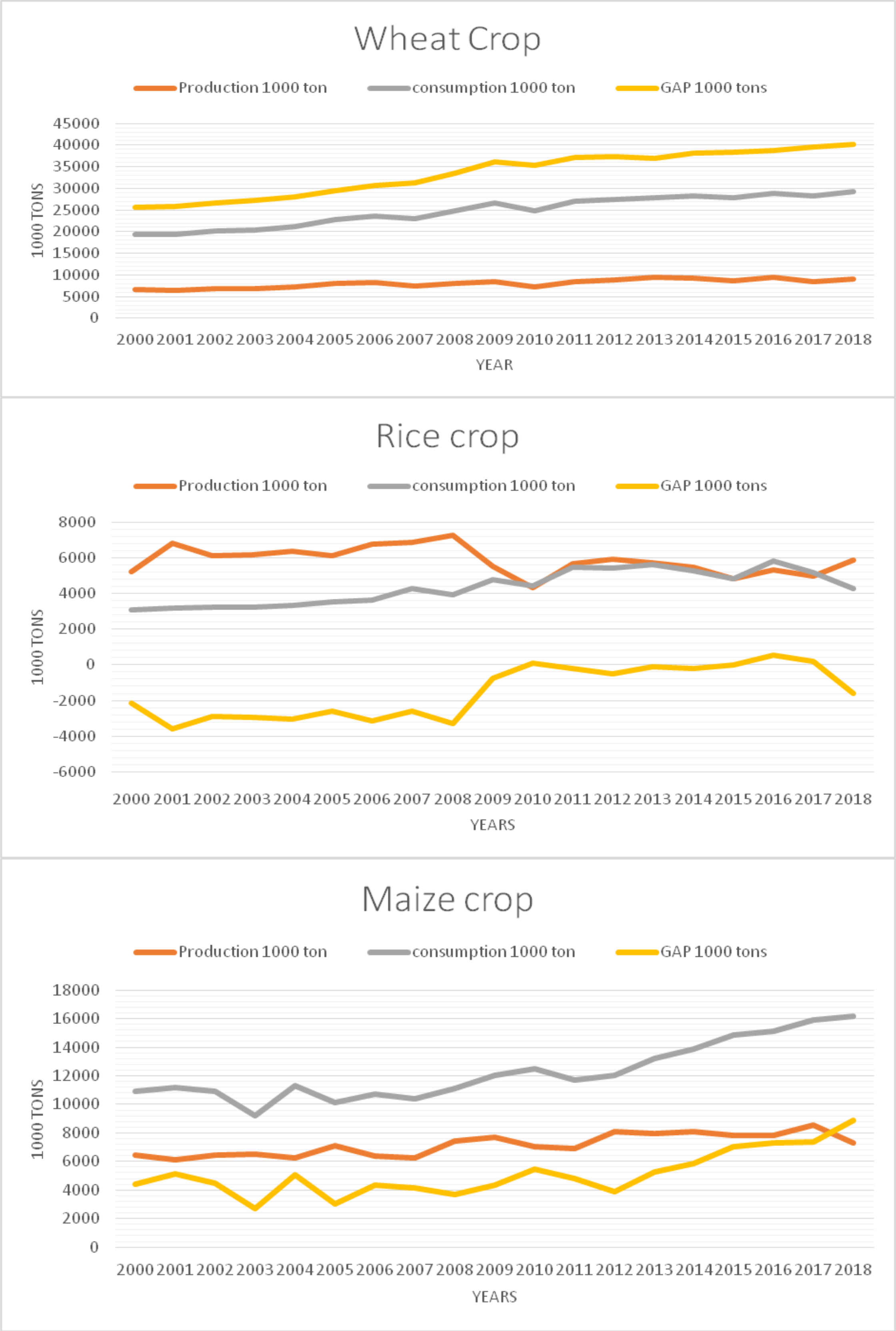
Appendix 1. The virtual water volume for selected crops

| **Crop** | **Crop Evapo-transpiration Etc (mm)** | **Crop Water Requirements CWR $m^3$/hectare** | **Production tons/year** | **Productivity kg/hectare** | **Water use by crop CWU [c] $m^3$/year** | **Virtual water requirements for crops Vwc [c] $m^3$/ton** |
|---|---|---|---|---|---|---|
| Wheat | 492 | 4912 | 8052105.26 | 6742.08 | 5866430.10 | 728.56 |
| Barley | 456 | 4562 | 125710.47 | 2351.12 | 243922.54 | 1940.35 |
| Maize | 831 | 8312 | 7160365.53 | 7751.47 | 7678151.15 | 1072.31 |
| Rice | 1034 | 10346 | 6045263.16 | 10111.81 | 6185271.74 | 1023.16 |
| Potatoes | 848 | 8487 | 3480719.42 | 25772.47 | 1146217.87 | 329.30 |
| Sugar cane | 1687 | 17120 | 15929216.84 | 116848.15 | 2333868.29 | 146.51 |
| Sugar beet | 846 | 8460 | 6765547.11 | 50180.84 | 1140605.23 | 168.59 |
| Broad beans, horse beans, dry | 481 | 4814 | 243489.79 | 3332.21 | 351766.50 | 1444.69 |
| String beans | 562 | 5628 | 278.16 | 6721.44 | 232.91 | 837.32 |
| Chickpeas | 428 | 4281 | 7618.74 | 2048.57 | 15921.27 | 2089.75 |
| Lentils | 881 | 8814 | 1917.74 | 1899.64 | 8897.98 | 4639.83 |
| Sesame seed | 595 | 5950 | 39848.53 | 1290.87 | 183673.61 | 4609.29 |
| Olive | 1083 | 10837 | 507148.63 | 8686.01 | 632738.13 | 1247.64 |
| Soybeans | 978 | 9782 | 32346.53 | 3173.29 | 99711.58 | 3082.61 |
| Tomatoes | 916 | 9164 | 7854596.21 | 38613.73 | 1864091.34 | 237.32 |
| Onions, dry | 1007 | 10073 | 1751625.16 | 32503.97 | 542829.70 | 309.90 |
| Watermelons | 648 | 6489 | 1668401.16 | 28803.03 | 375872.09 | 225.29 |
| Melons, other (inc. cantaloupes) | 601 | 6012 | 826307.95 | 24461.97 | 203081.08 | 245.77 |
| Peas, green | 646 | 6465 | 234780.79 | 9976.85 | 152137.98 | 648.00 |
| Peas, dry | 714 | 7148 | 199.16 | 1873.69 | 759.78 | 3814.93 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Cabbages and other brassicas | 925 | 9250 | 592925.32 | 30100.09 | 182210.72 | 307.31 |
| Cucumbers and gherkins | 783 | 7833 | 574737.11 | 21445.53 | 209923.27 | 365.25 |
| Pumpkins, squash, and gourds | 602 | 6022 | 610512.74 | 18168.72 | 202353.70 | 331.45 |
| Artichoke | 1486 | 14860 | 188478.58 | 20729.18 | 135113.48 | 716.86 |
| Beans, green | 560 | 5608 | 262763.68 | 10475.51 | 140668.92 | 535.34 |
| Carrots and turnips | 461 | 4617 | 177560.79 | 28911.67 | 28355.27 | 159.69 |
| Garlic | 958 | 9586 | 244759.89 | 23515.83 | 99774.00 | 407.64 |
| Beans, dry | 662 | 6627 | 77613.21 | 2766.89 | 185892.01 | 2395.11 |
| Okra | 1013 | 10133 | 88126.79 | 13733.99 | 65020.34 | 737.80 |
| Lettuce and chicory | 617 | 6172 | 115418.95 | 23386.88 | 30460.06 | 263.91 |
| Berries | 1540 | 15405 | 596.32 | 7292.98 | 1259.61 | 2112.31 |
| Dates | 1458 | 14581 | 1323964.53 | 34264.75 | 563399.03 | 425.54 |
| Figs | 1040 | 10406 | 199124.84 | 6357.76 | 325915.59 | 1636.74 |
| Pears | 1348 | 13480 | 51790.53 | 14948.8 | 46701.83 | 901.74 |
| Apple | 1348 | 13480 | 575130.21 | 22755 | 340705.57 | 592.40 |
| Grapes | 831 | 8312 | 1414360.63 | 21380.33 | 549858.94 | 388.77 |
| Peaches and nectarines | 1348 | 13480 | 326216.26 | 11253.95 | 390742.38 | 1197.80 |
| Oranges | 1040 | 10407 | 2410495.05 | 23098.44 | 1086048.32 | 450.55 |
| Lemons and limes | 1040 | 10407 | 322586.89 | 20318.62 | 165225.87 | 512.19 |
| Bananas | 1747 | 17471 | 188478.58 | 43722.86 | 75313.22 | 399.59 |
| Lupins | 607 | 6075 | 2435.11 | 1861.89 | 7945.31 | 3262.81 |
| Groundnuts, with shell | 1550 | 15509 | 203457.58 | 3268.12 | 965516.45 | 4745.54 |
| Cauliflowers and broccoli | 857 | 8571 | 129018 | 26833.25 | 41210.56 | 319.42 |
| Linseed | 816 | 8160 | 14642.05 | 1655.82 | 72157.08 | 4928.07 |
| Cotton | 966 | 9667 | 491432.58 | 2732.89 | 1738335.48 | 3537.28 |
| Nuts | 1550 | 15503 | 12383.63 | 5089.27 | 37723.17 | 3046.21 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Anise, Fennel, and other aromatic plants | 841 | 8412 | 24565.47 | 865.25 | 238826.62 | 9722.05 |
| Chillies and peppers, dry | 855 | 8550 | 52159.53 | 3172.46 | 140573.56 | 2695.07 |
| Chillies and peppers, green | 842 | 8427 | 588170.32 | 16248.67 | 305041.05 | 518.63 |
| Eggplants (aubergines) | 832 | 8323 | 1143314.74 | 25507.25 | 373062.90 | 326.30 |
| Fruit, tropical fresh | 1246 | 12467 | 19356.32 | 7845.76 | 30757.41 | 1589.01 |
| Fruit, citrus | 1040 | 10406 | 4304.05 | 14675.89 | 3051.80 | 709.05 |
| Fruit, fresh | 1245 | 12458 | 419430.11 | 18483.31 | 282701.55 | 674.01 |
| Mangoes, mangosteens, guavas | 1347 | 13471 | 679717.74 | 9925.06 | 922561.44 | 1357.27 |
| Sorghum | 760 | 7603 | 827291.32 | 5451.87 | 1153713.48 | 1394.57 |
| Spinach | 926 | 9267 | 42717 | 16370.4 | 24181.35 | 566.08 |
| Strawberries | 1341 | 13476 | 210111.05 | 33855.28 | 83634.12 | 398.05 |
| Sweet potatoes | 846 | 8460 | 333758.53 | 28999.85 | 97365.92 | 291.73 |

Appendix 2. Consumption and Food Gap for wheat, rice and maize crops



Appendix 3.a. Self Sufficiency Ratio SSR for the Wheat Crop

| | **Year/wheat** | **Productions tons** | **Export tons** | **Imports tons** |
|---|---|---|---|---|
| | 2000 | 6650000 | 880 | 4896000 |
| | 2001 | 6420000 | 945 | 4413000 |
| | 2002 | 6790000 | 784 | 5575000 |
| | 2003 | 6820000 | 1120 | 4057000 |
| | 2004 | 7160000 | 864 | 4363000 |
| | 2005 | 8150000 | 457 | 5688000 |
| | 2006 | 8270000 | 264 | 5817000 |
| | 2007 | 7390000 | 7150 | 5911000 |
| | 2008 | 7970000 | 3520 | 5205000 |
| | 2009 | 8530000 | 4580 | 4092000 |
| | 2010 | 7170000 | 4530 | 9804780 |
| | 2011 | 8380000 | 2786 | 9800060 |
| | 2012 | 8790000 | 265 | 6537632 |
| | 2013 | 9460000 | 34 | 7869653 |
| | 2014 | 9270000 | 599 | 8515058 |
| | 2015 | 8670000 | 498 | 8981777 |
| | 2016 | 9570000 | 1390 | 10788295 |
| | 2017 | 8410000 | 1125 | 12025245 |
| | 2018 | 9120000 | 4766 | 12369230 |
| | average | 8052105 | 1924 | 7195196 |
| **SSR=** | **52.8167** | | | |

Appendix 3.b. Self Sufficiency Ratio SSR for the Maize Crop

| | **Year/Maize** | **Productions tons** | **Export tons** | **Imports tons** |
|---|---|---|---|---|
| | 2000 | 6474450 | 2110 | 3968020 |
| | 2001 | 6093578 | 1247 | 4945481 |
| | 2002 | 6430962 | 941 | 3876921 |
| | 2003 | 6530427 | 2547 | 4128741 |
| | 2004 | 6236140 | 965 | 3978450 |
| | 2005 | 7085190 | 1478 | 4268746 |
| | 2006 | 6374300 | 490 | 3958740 |
| | 2007 | 6243220 | 1550 | 4428310 |
| | 2008 | 7401412 | 1010 | 2463190 |
| | 2009 | 7686091 | 930 | 1872520 |
| | 2010 | 7041099 | 16080 | 4844481 |
| | 2011 | 6876473 | 753 | 6861685 |
| | 2012 | 8093646 | 2100 | 3131351 |
| | 2013 | 7956593 | 306 | 5738431 |
| | 2014 | 8059906 | 405 | 4326802 |
| | 2015 | 7803183 | 270 | 6779475 |
| | 2016 | 7817640 | 482 | 6036522 |
| | 2017 | 8542635 | 340 | 8703411 |
| | 2018 | 7300000 | 702 | 8414392 |
| | average | 7160366 | 1827 | 4880298 |
| **SSR=** | **59.477218** | | | |

## Appendix 4. Required Water Needed for Crops (million $m^3$)

| Crop | Crop Evapo-transpiration Etc (mm) | Crop Water Requirements CWR $m^3$/hectare | Productions tons | Productivity kg/hectare | Water use by crop CWU [c] $m^3$/year | Virtual water requirements for crops Vwc [c] $m^3$/ton |
|---|---|---|---|---|---|---|
| Wheat | 492 | 4912 | 7193270 | 6742.08 | 5240718.33 | 728.56 |
| Barley | 456 | 4562 | 6840 | 2351.12 | 13272.00653 | 1940.35 |
| Maize | 831 | 8312 | 4878470 | 7751.47 | 5231245.511 | 1072.31 |
| Rice | 1034 | 10346 | -374620 | 10111.81 | -383296.217 | 1023.16 |
| Potatoes | 848 | 8487 | -290740 | 25772.47 | -95742.09922 | 329.30 |
| Fruits | 3531 | 35331 | -30620 | 443090.48 | -2441.567284 | 79.74 |

## Appendix 5. (a, b, and c) for the Rice, Maize and Wheat crops Respectively

**Table (5.a): The Data Were Used in the Model to Analyse the IWFP Variation for the Rice Crop**

| Year | Rice Crop | | | | |
|---|---|---|---|---|---|
| | IWFP | RWr | Productivity | Ta | Precipitation |
| | billion $m^3$ | Billion $m^3$ $year^{-1}$ | Kg/Ha | Celsius | mm |
| 2000 | 7.89 | 52.08 | 9102.50 | 23.1285 | 3.21577 |
| 2001 | 7.21 | 51.80 | 9283.30 | 23.1901 | 1.89678 |
| 2002 | 6.43 | 52.26 | 9388.90 | 22.3457 | 2.3418 |
| 2003 | 7.49 | 52.66 | 9748.40 | 23.0467 | 1.45347 |
| 2004 | 6.86 | 52.17 | 9838.40 | 23.1941 | 2.59356 |
| 2005 | 6.85 | 53.09 | 9987.40 | 23.0280 | 1.96633 |
| 2006 | 5.80 | 53.38 | 10075.00 | 23.0661 | 2.19336 |
| 2007 | 7.46 | 53.21 | 9767.50 | 23.0779 | 2.71153 |
| 2008 | 10.56 | 54.17 | 9734.90 | 22.9806 | 1.91344 |
| 2009 | 9.99 | 55.10 | 9593.00 | 23.1440 | 2.02872 |
| 2010 | 6.86 | 55.42 | 9421.70 | 23.5117 | 2.33414 |
| 2011 | 7.19 | 56.29 | 9567.00 | 23.4048 | 1.94263 |
| 2012 | 5.93 | 57.12 | 9529.60 | 24.7271 | 2.69287 |
| 2013 | 5.32 | 56.63 | 9586.50 | 22.8719 | 1.96707 |
| 2014 | 9.04 | 56.17 | 9530.00 | 23.5320 | 2.1495 |
| 2015 | 8.63 | 55.11 | 9431.20 | 23.3878 | 3.02228 |
| 2016 | 6.71 | 54.29 | 9335.30 | 23.6309 | 3.16321 |
| 2017 | 7.32 | 55.66 | 9024.50 | 23.5347 | 2.83109 |
| 2018 | 6.85 | 56.12 | 8826.50 | 23.5437 | 2.11474 |

**Table (5.b): The Data Were Used in the Model to Analyse the IWFP Variation for the Maize Crop**

| Year | Maize Crop | | | | |
|---|---|---|---|---|---|
| | **IWFP** | **RWr** | **Productivity** | **Ta** | **Precipitation** |
| | **billion $m^3$** | **Billion $m^3$ $year^{-1}$** | **Kg/Ha** | **Celsius** | **mm** |
| 2000 | 5.00 | 52.08 | 7680.00 | 23.1285 | 3.21577 |
| 2001 | 5.40 | 51.80 | 6979.80 | 23.1901 | 1.89678 |
| 2002 | 5.60 | 52.26 | 7765.60 | 22.3457 | 2.3418 |
| 2003 | 5.30 | 52.66 | 7829.30 | 23.0467 | 1.45347 |
| 2004 | 5.60 | 52.17 | 7908.70 | 23.1941 | 2.59356 |
| 2005 | 5.80 | 53.09 | 8160.70 | 23.0280 | 1.96633 |
| 2006 | 5.80 | 53.38 | 8370.50 | 23.0661 | 2.19336 |
| 2007 | 6.20 | 53.21 | 8046.30 | 23.0779 | 2.71153 |
| 2008 | 6.60 | 54.17 | 7905.30 | 22.9806 | 1.91344 |
| 2009 | 7.00 | 55.10 | 7818.40 | 23.1440 | 2.02872 |
| 2010 | 6.70 | 55.42 | 7270.00 | 23.5117 | 2.33414 |
| 2011 | 7.60 | 56.29 | 7740.90 | 23.4048 | 1.94263 |
| 2012 | 5.90 | 57.12 | 7772.30 | 24.7271 | 2.69287 |
| 2013 | 7.00 | 56.63 | 7722.30 | 22.8719 | 1.96707 |
| 2014 | 7.20 | 56.17 | 7755.60 | 23.5320 | 2.1495 |
| 2015 | 7.40 | 55.11 | 7354.60 | 23.3878 | 3.02228 |
| 2016 | 7.10 | 54.29 | 7607.10 | 23.6309 | 3.16321 |
| 2017 | 7.30 | 55.66 | 7789.50 | 23.5347 | 2.83109 |
| 2018 | 6.40 | 56.12 | 7801.00 | 23.5437 | 2.11474 |

**Table (5,c): The Data Were Used in the Model to Analyse the IWFP Variation for the Wheat Crop**

| Year | Wheat Crop | | | | |
|---|---|---|---|---|---|
| | **IWFP** | **RWr** | **Productivity** | **Ta** | **Precipitation** |
| | **billion $m^3$** | **Billion $m^3$ $year^{-1}$** | **Kg/Ha** | **Celsius** | **mm** |
| 2000 | 3.90 | 52.08 | 6342.20 | 23.1285 | 3.21577 |
| 2001 | 3.80 | 51.80 | 6358.00 | 23.1901 | 1.89678 |
| 2002 | 3.90 | 52.26 | 6434.50 | 22.3457 | 2.3418 |
| 2003 | 4.20 | 52.66 | 6500.10 | 23.0467 | 1.45347 |
| 2004 | 4.40 | 52.17 | 6556.70 | 23.1941 | 2.59356 |
| 2005 | 4.70 | 53.09 | 6492.90 | 23.0280 | 1.96633 |
| 2006 | 5.60 | 53.38 | 6430.30 | 23.0661 | 2.19336 |
| 2007 | 5.10 | 53.21 | 6467.30 | 23.0779 | 2.71153 |
| 2008 | 5.40 | 54.17 | 6503.10 | 22.9806 | 1.91344 |
| 2009 | 5.30 | 55.10 | 6382.90 | 23.1440 | 2.02872 |
| 2010 | 5.30 | 55.42 | 5574.10 | 23.5117 | 2.33414 |
| 2011 | 5.10 | 56.29 | 6542.80 | 23.4048 | 1.94263 |
| 2012 | 5.40 | 57.12 | 6582.30 | 24.7271 | 2.69287 |
| 2013 | 7.10 | 56.63 | 6668.20 | 22.8719 | 1.96707 |
| 2014 | 7.30 | 56.17 | 6175.20 | 23.5320 | 2.1495 |
| 2015 | 7.10 | 55.11 | 6591.90 | 23.3878 | 3.02228 |
| 2016 | 7.50 | 54.29 | 6631.10 | 23.6309 | 3.16321 |
| 2017 | 7.60 | 55.66 | 6859.70 | 23.5347 | 2.83109 |
| 2018 | 7.40 | 56.12 | 6689.50 | 23.5437 | 2.11474 |

Appendix 6. Descriptive statistics

- **Mean:** This is obtained by adding up the values of each variables and divided by the number of years considered in the
- **Median:** This is a robust measure of the center of distribution and it is less sensitive to outliers than the mean. It is computed as the middle value (or average of two values) of the data after arrangement in ascending or descending order of magnitude.
- **Maximum** and **Minimum:** This is the highest and smallest values of each variable during the period under consideration in the study.
- **Standard deviation:** It **is** the measure of distance of each value of the variables used in the study from their mean. This is given by: $S = \sqrt{(\sum_{i=1}^{N}(X - \bar{X})^2/(N-1)}$ where $N$ is the number of observations in the current sample and $\bar{X}$ is the mean of the series.
- **Skewness:** This is computed as: $SK = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{X - \bar{X}}{S}\right)^3$ and it is a measure of symmetry of the data. Its positive and negative value indicates that the variable is right and left tailed, respective while its value of zero indicates that the variable is normally distributed.
- **Kurtosis:** This is another measure of shape of distribution of a variable, and it is defined as $K = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{X - \bar{X}}{S}\right)^4$. When a variable has a normal distribution tis kurtosis is 3 while the kurtosis value that exceeds (below) 3 indicates that the variable is leptokurtic (platykurtic) relative to the normal distribution.

- **Jarque-Bera:** Skewness and kurtosis are not standard measure to determine whether a variable follows normal distribution or otherwise. Jarque Bera test is a standard statistical tool decide the distribution of a variable. The test claimed that the variable is normally distributed against the alternative hypothesis that the variable is not normally distributed. The test follows a chi-square distribution with 2 degrees of freedom, and it is computed as: $Jarque - Bera = \frac{N}{6}(SK^2 + \frac{(K-3)^2}{4})$ where *SK* and K are Skewness and Kurtosis, respectively.

# Dedications

To

Amore, My parents, my lovely aunt

,brothers and sisters

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WITH ALL MY LOVE
ALOBID MOHANNAD
JANUARY 2022
DEBRECEN-HUNGARY

# DECLARATION

I, undersigned (name: **Mohannad Alobid**, date of birth: 11/02/1988) declares under penalty of perjury and certify with my signature that the dissertation, I submitted in order to obtain doctoral (PhD) degree is entirely my own work.

Furthermore, I declare the following:

- I examined the code of the Karoly Ihrig Doctoral School of Management and Business Administration and I acknowledge the points laid down in the code as mandatory;
- I handled the technical literature sources used in my dissertation fairly and I confirmed to the provisions and stipulations related to the dissertation;
- I indicated the original source of other authors' unpublished thoughts and data in the references section in a complete and correct way in consideration of the prevailing copyright protection rules;
- No dissertation, which is fully or partly identical, to the present dissertation was submitted to any other university or doctoral school for the purpose of obtaining a PhD degree.

Debrecen, 21.01.2022

**Mohannad Alobid**