THESIS OF THE DOCTORAL (Ph.D.) DISSERTATION

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

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1. INTRODUCTION, RESEARCH OBJECTIVES, RESEARCH QUESTIONS AND HYPOTHESES

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. 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. 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. 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. 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. 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. 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. 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. 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".

This study will try to assess the water footprint indicator as a function for saving water and food security in a country as well, especially there is a lack of the data about this concept after 2005 worldwide. In addition, the hydro-analysis was studied of the reality of the Arab region to reach the concept of sustainability, especially in the agricultural sector. Then by applying the principle of virtual water and the concept of the water footprint of some selected crops in the agricultural sector the water situation was assessed in Egypt. Additionally, the study will compare the internal water footprint for three strategic crops in Egypt with other elemental factors. Finally, the research tried to evaluate the impact of water policy on economic development in Egypt for three sectors and its impact on GDP.

1.1 The objectives of the research

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;
5. Determine the water consumption and the food demand for the same study period;
6. Minimizing the Food-Gap in Egypt by building a mathematical model to find the optimum land reallocation and production distribution for main important crops;
7. Evaluate the water policy during the study period 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.

1.2 Research questions and research hypotheses

The research work is about the analysis of the water footprint and the virtual water in the agricultural sector. Several research questions and research hypotheses as following are discussed as follows:

- 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.
- 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:

- Are there any fluctuations in the annual average precipitation, annual average temperature, the productivity of the crops and renewable water resource during 2000-2018?
- 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:

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

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

- ❖ 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?
- ❖ 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?
- ❖ 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.

❖ 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.

2. 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.

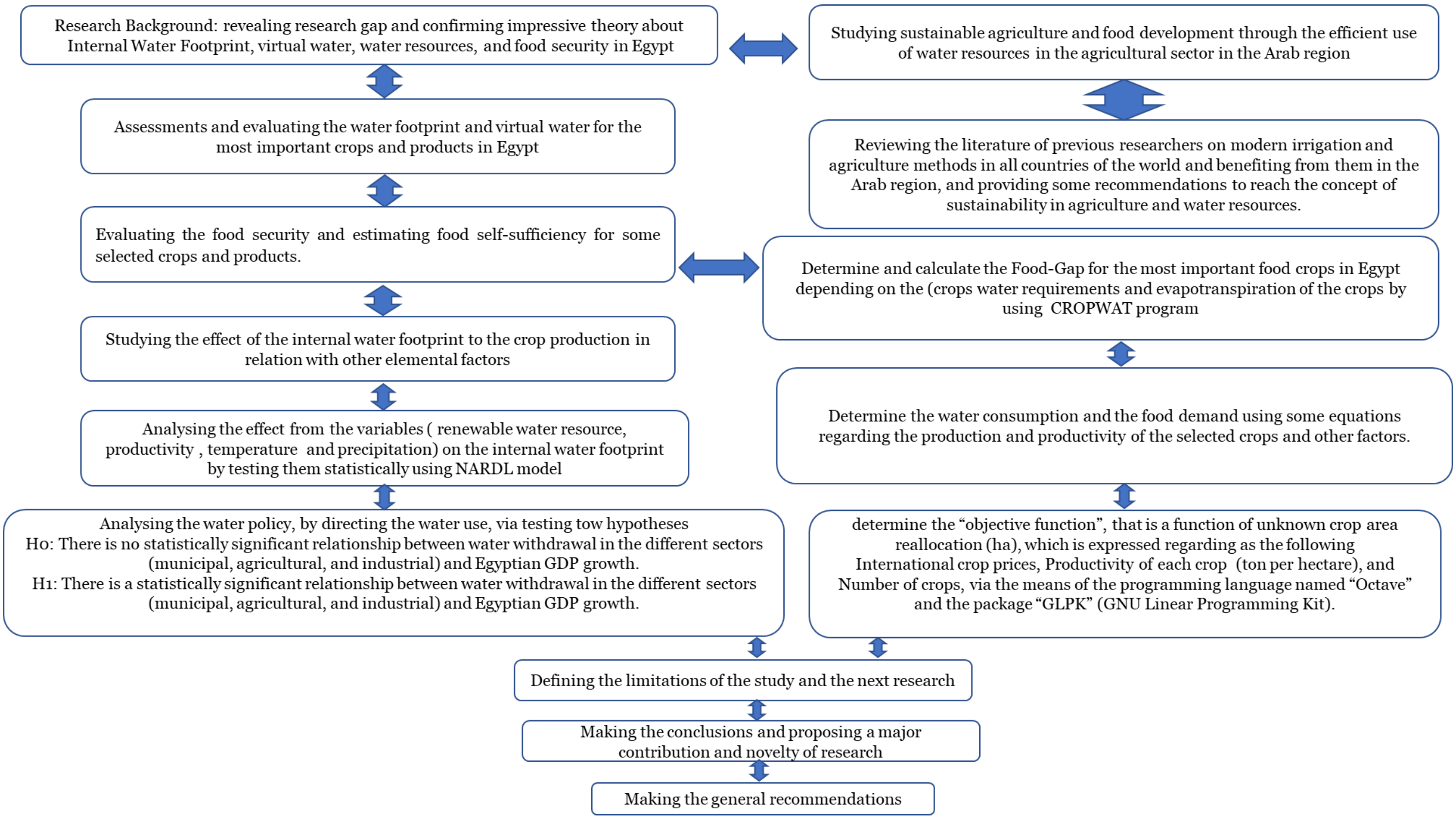

Figure 1: **Logical framework of the research approach**. (Source: own constructed)

3. RESEARCH BACKGROUND

3.1 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, McGranahan, & Tacoli, 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 (Arjen Y 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 water resource management at the national and global levels (A. K. 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 (A. 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, Food, & Nations, 2018; Ward, Smith, & Tran, 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 (A. Chapagain, Hoekstra, Savenije, & Gautam, 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 (Arjen Y Hoekstra, Chapagain, Mekonnen, & Aldaya, 2011). All components of the water footprint are determined by the place and time.

3.2 Virtual Water

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. The concept of "virtual water" was introduced by British scientist Tony Allan in the early 1990s, and it took nearly a decade to gain global recognition about the importance of this concept for achieving regional and global water security. The first international meeting on the subject of virtual water was held in December 2002 in Delft, Netherlands. And during the third World Water Forum in Japan, in March 2003, a special session was devoted to the issue of 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 (A. Chapagain, Hoekstra, & Savenije, 2005).

In addition, Hoekstra and Hung defined the virtual water is the water included in the product, commodity, or service, not in the real sense but in the hypothetical sense, as it refers to the water needed to produce 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" (Arjen Y 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, 2003). 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, 2003).

3.3 Agricultural water use 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. 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. There is no doubt that the efficient use of water resources, especially in the agricultural sector, is an important issue for water security in Arab countries, and in turn represents a fundamental pillar of development in order to achieve sustainable agricultural and food security.

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, Burke, & Faurès, 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, Martin-Bordes, & Gurdak, 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, Burnett, Fukushima, Haigh, & Umezawa, 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, Snyder, Kyriakakis, & Spano, 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.

3.4 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, Cai, & Cline, 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 2 shows the change in the per capita share of available water resources in Egypt.

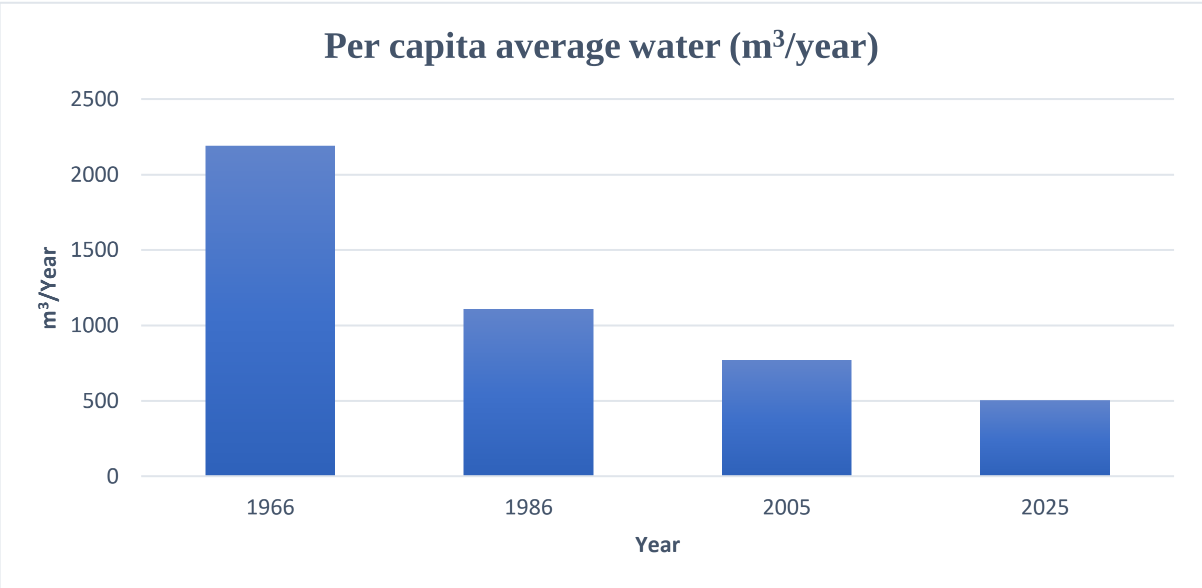

Figure 2. Change in per capita share of available water resources in Egypt in m^3 per year. Source: Own calculating depends on (World Bank and CAPMAS different issues).

3.5 Food security in Egypt

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).

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, Gajanan, & Sanyal, 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, Ehrlich, & Daily, 1993; Eide, Oshaug, & Eide, 1991).

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.

3.6 The water policy 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.

What increases the importance of the role of water policy in Egypt is its suffering from a water crisis as a result of the limited water resources available to the increasing demand for it, in addition to the problem of climate change, pollution and others, and no one is currently hidden from the problem of the grand Ethiopian Renaissance dam between Egypt and Ethiopia, which reduces Egypt's share of the Nile water (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.

4. DATABASE AND DESCRIPTION OF THE METHODOLOGY USED

4.1Data collection

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, the Ministry of Agriculture in Egypt, 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 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),

Furthermore, 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 during the years 2000-2018 for the Rice, Maize, and Wheat crops.

Also, the data used for the analyzing the food-gap in Egypt 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.

Moreover, 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 the FAO Aquastat database, the Central Agency for Public Mobilization and Statistics (CAPMAS), and different reports from the Ministry of Water Resources and Irrigation Egypt. While that of GDP is sourced from the World Bank database from 1988 to 2018.

4.2 Reliability of the data and the methodology used

At the first stage of the research, the water situation in the Arab region was analyzed to reach the concept of sustainability in agriculture, based on research published in the Arab world and internationally.

Then, the water footprint and virtual water for most agricultural crops in Egypt were studied and calculated based on the above-mentioned sources. Crop Evapotranspiration Etc (mm) was calculated by the CROPWAT program, also, the Crop Water Requirements CWR m3/hectare and water use by crop CWU [c] m3/year were calculated in this research.

In addition, the consumption of the crops and food gap for some selected crops in Egypt, the Self Sufficiency Ratio SSR for some crops in Egypt and Required Water needed for crops (million m3) were also calculated.

4.3 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 1.

As for calculating the amount of virtual water in agricultural crops, it was done according to the following relationship:

$$\boldsymbol{VWC\ (c)} = \frac{\boldsymbol{CWU(c)}}{\boldsymbol{production(c)}} \qquad \textbf{(1)}$$

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 2:

$$\mathbf{CWU\ (c) = CWR(c) \times \frac{production\ (c)}{Yeild\ (c)}} \qquad \mathbf{(2)}$$

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.

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:

$$\mathbf{CWR\ =\ 10 \times \sum_{d=1}^{lp} ET_c\ (c, d)} \qquad \mathbf{(3)}$$

Where: 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 Et_o 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, that is the stage where the crop is ready for harvest Equation 4 (Allen, Pereira, Raes, & Smith, 1998; Droogers & Allen, 2002).

$$\boldsymbol{E}\mathrm{Tc}\ \boldsymbol{c} = \boldsymbol{Kc}_{\ c} \times \mathrm{ET}_0 \qquad \mathbf{(4)}$$

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).

4.4 Calculation the virtual water for agricultural products

The virtual water for plant products in m^3/ton Equation 5:

$$\boldsymbol{VWCp\ (p) = VWCc\ (c) \times \frac{vf[p]}{pf[p]}} \qquad \mathbf{(5)}$$

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 (Us $/ ton), and the product value in dollars 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 6:

$$\boldsymbol{VWCp\ (p) = VWC\ (primary\ product) \times \frac{vf[p.p]}{pf[p.p]}} \qquad \textbf{(6)}$$

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 (Us $ / 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).

4.5 Water footprint and its indicators

The water footprint consists of two parts, as in the following relationship Equation 7:

$$\textbf{WFP} = \boldsymbol{IWFP} + \textbf{EWFP} \qquad \textbf{(7)}$$

Where: **IWFP:** internal water footprint, **EWFP:** external water footprint.

As for the **internal water footprint**, it is calculated from the following relationship Equation 8:

$$\textbf{IWFP} = \boldsymbol{DWW} + \textbf{IWW} + \textbf{AWU} - \textbf{VWE} \qquad \textbf{(8)}$$

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 4.9:

$$\textbf{EWFP} = \boldsymbol{VWI} - \textbf{VWE re\_export} \qquad \textbf{(9)}$$

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.

4.6 Water footprint indicators

1) Water Import Dependency index

Water Import Dependency k (WD), which is equal to the ratio of the external water footprint on the total water footprint as shown in the following relationship Equation 10:

$$\boldsymbol{WD = \frac{EWFP}{WFP} \times 100} \qquad \textbf{(10)}$$

2) Water self-sufficiency index (WSS), which is equal to the ratio of the internal water footprint to the total water footprint. It is calculated as in the following relationship Equation 4.11:

$$\boldsymbol{WSS = \frac{IWFP}{WFP} \times 100} \qquad \textbf{(11)}$$

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).

4.6 Food security and food self-sufficiency in Egypt

The self-sufficiency ratio (SSR) is defined as Equation 12:

$$\textbf{SSR = production x 100/(production + imports-exports)} \qquad \textbf{(12)}$$

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

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

4.7 The Internal water footprint methodology

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 t.

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 A Nonlinear Autoregressive Distributed Lag (NARDL) by using EVIEWS software.

4.8 The food gap optimization methodology

Describing the Mathematical Model and the Resources Constraints:

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 13 and 14) under four different constraints.

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

$$\textbf{Min}: \quad \sum_{j=1}^{NC} \left(D_j - S_j\right) * Pri_j \qquad (13)$$

$$\textbf{Min}: \quad \sum_{j=1}^{NC} \left(D_j - Pro_j A_j\right) * Pri_j \qquad (14)$$

relationship Equation 15:

$$D_j = S_j + I_j - E_j \qquad (15)$$

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:

$$A_j \geq 0 \qquad \forall \; j \qquad (16$$

1. The area allocation set for each crop should be positive, this constraint is known as the non-negative variable (Equation 16):

2. The total crops land allocation should not exceed the maximum exploitable land (Landconst = 3.5 million hectares) (Equation 17):

$$\sum_{j=1}^{NC} \mathbf{A_j} \;\leq\; \mathbf{Land_{const}} \qquad (17)$$

3. The total crops water consumption should be less than the renewable water volume ($Water_{const}$ = 45 billion m^3) (Equation 18):

$$\sum_{j=1}^{NC} \mathbf{CWR_j} \times \mathbf{A_j} \;\leq\; \mathbf{Water_{max}} \qquad (18)$$

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 19). 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):

$$\mathbf{Pro_j} \times \mathbf{A_j} \;\leq\; \mathbf{D_j} \qquad 19)$$

To get the results 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.

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

4.9 The water policy methodology analysis

Regression analysis 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 modeling 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.

5. MAIN FINDINGS AND CONCLUSION OF THE STUDY

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 4 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

Rice crop : Each of the independent variables have negative and insignificant relationship with the internal water footprint.

- Precipitation : the long run coefficient that a unit negative change of precipitation leads to 1.22052 decrease 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.

Maize crop:

- The correlation analysis result presented in table 6.4 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.

Wheat crop:

- The correlation analysis presented in table 6 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.

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 six 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.

6. MAJOR CONTRIBUTION AND NOVELTY OF RESEARCH

1) Attempting to collect the advanced methods used around the world in the field of agriculture in order to benefit from them in the Arab region that suffers from drought to achieve sustainable agricultural and food development through the effective use of water resources in the agricultural sector in the Arab region;
2) Calculating the virtual water for most important agricultural crops in Egypt after 2005;
3) Calculating the virtual water for agricultural products after 2005;
4) Assessment the Water footprint and its indicators in Egypt;
5) Evaluating the Food security and estimating food self-sufficiency for some selected crops and products.
6) 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 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.
7) Determine and calculate the FG, water consumption and the food demand during 2000–2018 for the most important food crops in Egypt;
8) Build a mathematical model to find the optimum land reallocation and production distribution for minimizing the FG.
9) 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.

7. 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 2 and 3, 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.

8. CONCLUSION and RECOMMENDATIONS

The research recommends the following:

I. Studies so far indicate the importance of including virtual water trade in the formulation of national plans for water policy, as virtual water trade between countries can relieve pressure on scarce water resources, and contribute to alleviating water scarcity at the local and global levels. in addition, knowing the trade balance of virtual water is necessary to develop rational policies regarding.

II. A comprehensive understanding of the impact of virtual water trade on the social, local and economic situation is necessarily related to food security, promoting economic growth and creating job opportunities for people. It is clear that more research should be conducted to study the natural, social, and economic implications of using virtual water trade as a strategic tool in planning water policies. 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.

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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.

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