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# Economic Evaluation of the Virtual Water Concept in Relation to the Agri-food Sector in Nile Basin Countries

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## الملخص العربى :

**تعرف المياه الافتراضية بأنها كمية المياه المطلوبة لانتاج منتج زراعي وما يرتبط به من منتجات صناعية.ولذلك يتم معرفه الاحتياج المائي لكل محصول ثم يتم الحصول علي الصادرات والواردات من منظمه الأغذيه والزراعه (الفاو) لكل محصول مطلوب زراعته ومن ذلك يكون هناك محاصيل ذات احتياج مائي أقل وأسعارها العالميه عاليه فهذه هي نوعيه المحاصيل التي نحتاج زراعتها وتصدير الفائض منها ,وهناك نوعيه اخري من المحاصيل التي يجب استيرادها وهي التي احتياجها المائي كبير واسعارها العالميه منخفضه ,وبهذه الطريقه يمكننا تحديد كميات المياه المطلوبه لأي محصول في حالات الاستيراد والتصدير وتحديدا ما اذا كنا نريد استيراد المحصول أم لأ في دول حوض النيل .وبذالك يمكننا الوصول الي الاكتفاء الذاتي من المحاصيل الزراعيه في دول حوض النيل وتوفير المياه علي الجانب الأخر وبذلك يمكننا الوصول الي الجانب الاقتصادي للدراسه وهو تحويل هذه الكميه الي نقود ويختلف تقديرها بمرور الوقت ,ولذلك تم حساب الصادرات و الواردات لبعض المحاصيل علي مختلف السنين التي تم الوصول اليها وتحويليها الي مياه افتراضيه ومعرفه ما اذا كنا نستطيع تصدير او استيراد لهذه المحاصيل**

## ABSTRACT :

This thesis focuses on the quantification of virtual water (VW) associated with agricultural products in countries located within the Nile basin. We propose a methodology to measure water scarcity and enhance the gross domestic product (GDP) in the Nile Basin Commission (NBC). Our study examines 22 various crops, analyzing their prices and virtual water consumption patterns. One of the challenges in NBC arises from the need to accurately calculate the water requirements of crops based on their productivity during their cultivation period. This calculation involves determining the crop water requirements (CWR) by considering the quantity of water needed by each crop. Additionally, obtaining the yield constant for each crop helps to determine the specific water demand (SwD) required to achieve a particular yield. By precisely quantifying the water needs of different crops, NBC can effectively manage its water resources and optimize agricultural practices. This approach enables the country to ensure sustainable and efficient water usage, addressing the specific challenge related to water calculation in crop cultivation. To convert the exports and imports of crops into virtual water (v.w), the data on exports and imports from the Food and Agriculture Organization (FAO) is obtained for the specific crops of interest. The conversion is done by multiplying the value of the export or import

(in tons) by the water needs of the crop (ton m3/t). This calculation allows for the estimation of the virtual water associated with the traded quantities of crops, providing insights into the water footprint of agricultural trade. By utilizing this approach, we can accurately determine the water quantities necessary for any crop in both import and export scenarios. This allows us to assess whether it is more beneficial to import the crop or if we have sufficient water resources to meet its requirements domestically. By comparing the virtual water associated with the crop's import and export quantities, we can make informed decisions on whether to import the crop or if it is feasible to meet its water needs internally. This analysis aids in optimizing water usage and making strategic choices regarding crop import and export patterns. Certainly, the economic aspect of the study involves converting the quantity of virtual water into monetary values and estimating these values, which can vary over time. The conversion of virtual water quantities into monetary units allows for a better understanding of the economic significance of water usage in agriculture. However, it's important to note that the estimation of these monetary values is subject to various factors, including market conditions, price fluctuations, and economic indicators
.

**KEYWORDS :** Virtual water, virtual water trade, Crop replacement, water footprint, water scarcity, Evapotranspiration ,CropWatt,ClimWatt.

## 1. INTRODUCTION

Egypt has effectively achieved and sustained food security at the national level through a dual approach of expanding domestic crop and livestock production while also relying on imports of food and fodder. Despite a notable rise in population size since 1962, Egypt has successfully increased per capita food consumption. However, the ongoing challenge arises from the continuous population growth alongside the limited and unalterable availability of land and water resources for agriculture. With the population reaching approximately 70 million in 2003 and projected to reach 110 million by 2020, the agricultural sector faces additional pressure to meet the rising demands. In order to maintain the existing levels of food consumption and facilitate economic growth, it is crucial to make additional advancements in agricultural production. This may include implementing strategies that improve agricultural practices, enhance productivity, and promote efficient water usage. Moreover, Egypt may need to increasingly rely on international trade to effectively meet its food demands. By adopting these measures, Egypt can strive towards sustaining its food requirements while supporting its economic development. In this context, virtual water trade assumes a critical role as it enables NBC to import agricultural commodities and the accompanying virtual water from regions abundant in water resources. By depending on virtual water imports, NBC can supplement its domestic production and overcome the constraints imposed by limited land and water resources. This approach can contribute to maintaining a stable food supply and ensuring food security, even in the face of a growing population. Nevertheless, it is crucial to acknowledge that while virtual water trade can offer temporary solutions to food security challenges, promoting sustainable agricultural practices and responsible water management is essential in the long run. Striking a balance between domestic production and virtual water imports, while also considering the environmental consequences of trade, becomes paramount in maintaining food security and fostering sustainable economic growth. By prioritizing sustainability, Egypt can ensure a resilient and secure food system for the future.In conclusion, Egypt has attained food security by leveraging both domestic production and food imports. However, in light of a growing population and constrained land and water resources, it becomes imperative to enhance agricultural production and rely more on international trade, including virtual water trade, to maintain existing levels of food consumption and facilitate economic growth in the future. By pursuing these strategies, Egypt can strive towards sustained food security and continued economic prosperity.

You have provided additional information about the concept of virtual water trade, which was introduced by British researcher Tony Allan. Virtual water refers to the water used in the production of goods and products, including agricultural and industrial commodities. The amount of water required to produce a specific product can vary significantly, ranging from 1,000 to 2,000 liters of water per kilogram of crop, and even higher for some products. Water-rich countries have the ability to export products that require a significant amount of water, effectively transferring virtual water to water-scarce countries. This allows water-scarce countries to meet their water needs by importing water-intensive products instead of producing them domestically. By engaging in virtual water trade, countries can address their water security concerns and allocate their limited water resources more efficiently. While natural trade of physical water between countries may be impractical due to distance and cost, the trade of products that require water (virtual water trade) is a viable solution. Water-rich countries can focus on producing water-intensive products and exporting them to countries in need, while water-scarce countries can import such products to meet their water requirements. This trade mechanism can contribute to water security and resource management at a global level. The concept of virtual water trade brings attention to the interdependence of water resources and international trade. It provides a framework for understanding the indirect water flows embedded in trade and can help countries optimize their resource allocation decisions. By considering virtual water in trade policies, countries can strategically manage their water resources and promote sustainable development. Tony Allan's work on virtual water has been influential in highlighting the importance of water in global trade and resource management. His research has contributed to discussions on water security, resource sustainability, and the economic implications of water use in production processes (Allan, 1993; 1994).

## Definitions of Virtual Water were introduced

Virtual water considers the total volume of water required during agricultural planting. Consider the creation of t-shirts to highlight the significance of the Virtual water trade. Rain that fell on the cotton field, as well as water used to irrigate and dye the cotton, are all part of the virtual water utilised to make the t-shirt. When that t-shirt is exported, it absorbs all of these rivers. Allan,(1997) . (Mekonnen and Hoekstra,2011) The "Virtual Water" idea, which is valuable to water resource managers and decision makers, necessitates such calculations on a watershed or river basin size. Annual water balances are only achievable in a watershed context because they allow us to determine water inputs (rainfall and snow) and outputs (discharge, groundwater losses, and evapotranspiration), which serves as the foundation for water allocations for various applications. examined the analysis of global VW flows. Producing goods and services generally requires water. The water used in the production process of an agricultural or industrial product is called the virtual water contained in the product. Producing one kg of grain needs for instance 1000-2000 liters of water(Chapagain and Hoekstra, 2003) . If one country exports a water-intensive product to another country, it exports water in virtual form. In this way, some countries support others in their water needs. The trade of real water between water-rich and water-poor regions is generally impossible due to the large distances and associated costs, but trade in water-intensive products (virtual water trade) is realistic. For water-scarce countries it could therefore be attractive to achieve water security by importing water-intensive products instead of producing all water-demanding products domestically Reversibly, water-rich countries could profit from their abundance of water resources by producing water-intensive products for export . Virtual water is the water embodied in a product, not in real physical sense, but in virtual sense. It refers to the water needed for the production of the product. Virtual water has also been called embedded water or exogenous water, the latter referring to the fact that import of virtual water into a country means using water that is exogenous to the importing country. Exogenous water is thus to be added to a country's 'indigenous water' (Haddadin, 2003). Blue, grey, and green water are available. Green water is precipitation-derived water that is retained in the soil's root zone before being evaporated, transpired, or absorbed by plants. Water that has been supplied from surface or groundwater resources and evaporated is referred to as having a blue water footprint. The amount of fresh water necessary to assimilate contaminants in order to fulfil specified water quality criteria is referred to as the grey water footprint.

Imports and exports of virtual water Land-rich countries with favourable climates and ample water resources will have an edge in producing water-intensive food and plant products, whereas countries with limited arable land and inadequate water resources will likely import food that requires a lot of water to cultivate. A water-scarce country may choose to import water-intensive items and export water-extensive products. This indicates net import of 'virtual water' (as opposed to real water import, which is usually prohibitively expensive) and will relieve pressure on the nation's own water supplies.

Virtual water trade between or within countries might be viewed as a substitute to actual inter-basin water transfers. This is especially important in China, where substantial real water transfer initiatives (from the south to the north) are being proposed. Virtual water trade is also a realistic, sustainable, and environmentally beneficial alternative to genuine water transfer schemes in the Southern African region (Earle and Turton, 2003) ; (Meissner, 2003). According to Nakayama (2003), the use of the concept of virtual water commerce could have a significant impact on the management practise of international river basins. Renault (2003) noted that the issue of optimal production is not only a matter of wisely choosing the locations of production, but also a matter of proper timing of production. One can try to overcome periods of water shortage by creating artificial water reservoirs, but – as an alternative – one can also store water in its virtual form, e.g. by food storage. This can be a more efficient and more environmentally friendly way of bridging dry periods than building large dams for temporary water storage.

## 2 - Methodology

The Crop-wat model is a specialized software developed by the Food and Agriculture Organization of the United Nations (FAO). Its purpose is to accurately determine the water requirements for various crops by considering factors such as weather conditions, crop type, soil characteristics, and the impact of rainfall. By utilizing this model, we can ascertain the precise amount of water needed to irrigate a specific crop throughout its entire planting period. In conjunction with the FAO's comprehensive database on crop export and import statistics, we can further analyze the water consumption associated with the production of a given crop. This allows for a meaningful comparison between the amount of water required for cultivating specific quantities of the crop and the cost implications of importing equivalent quantities. This study focused on the analysis and classification of 22 different crops according to their water consumption and prices. The aim was to identify crops that exhibit high water consumption but are available at relatively low prices, thereby determining potential candidates for importation. By doing so, the saved land and water resources can be redirected towards cultivating crops that have high market value and require less water, addressing the issue of water scarcity in Egypt and boosting the national income. The water consumption during crop harvesting is influenced by various factors, including the climate in which the crops are grown. Crops cultivated in hot and sunny climates tend to require more water compared to the same crops grown in cooler and cloudier environments. Conversely, the prices of crops are determined based on their water requirements rather than the actual water consumed during harvesting. For instance, the water footprint for producing 1kg of eggs is 3265, while for milk, it is 1020. This indicates that the price of eggs is more than three times higher than that of milk. Figure 1 displays the proposed technique, as well as the related flowchart. The first step in estimating virtual water is to determine evapotranspiration for each crop. Several equations have been used to do this. In Egypt, a CropWatt model was built utilising FAO data to compute evapotranspiration (ETo) throughout the year. This model has a single interface and accepts temperature, humidity, wind speed, sunrise time, latitude, and month number as inputs. The yield coefficient (Kc) for each crop under consideration was then collected from the FAO website's Cropwat programme. The evaporation and transpiration of crops (and so on) were computed using equation (2).

$$ETc = Kc \ x \ \mathrm{ETo} \qquad (1)$$

Subsequently, the crop water requirements (CWR) for the 22 crops were determined according to the methodology outlined in Table II. A comparative analysis was conducted between the CWR values derived from the proposed model and those obtained from CropWat. The average absolute error between the two models was found to be 9.6%. This discrepancy can be attributed to factors such as variations in climatic parameters and location-specific effects.

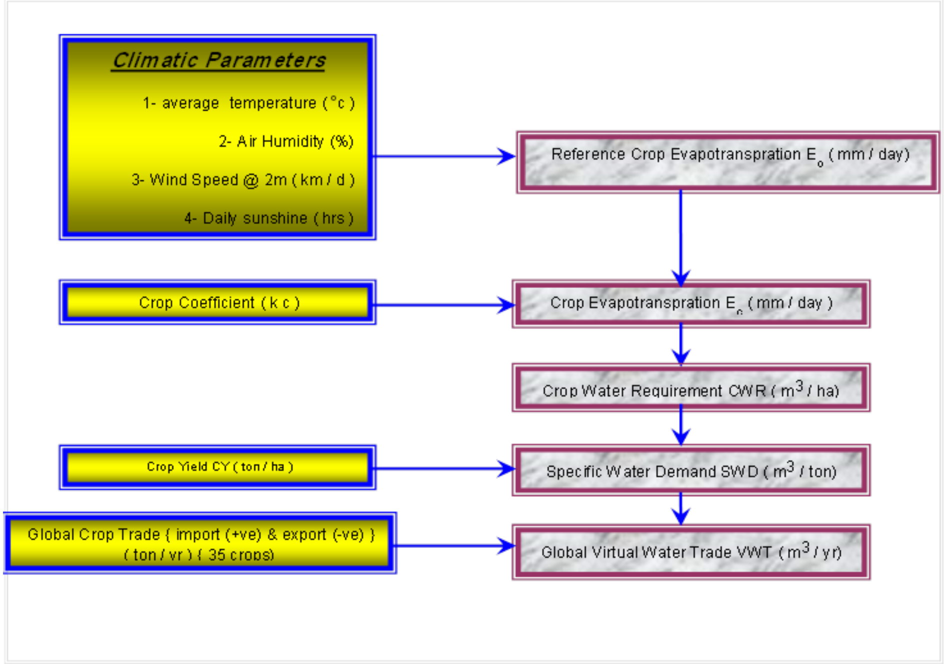

Figure (1) introduce Steps in the calculation of global virtual water trade

## 2.1. Determining the Specific Water Requirement for Each Crop Type.

After the calibration process, the model is applied to calculate the SWD for the 22 selected crops based on equations from 1 to 3; the results are shown in Table III. Then, the crops are classified according to the world price and the SWD into four groups. Group A includes; Maize, Wheat, Soybean, Dry Beans, Potato, Grapes, Cabbage and represents the crops of low price and low water requirements. Group B includes; Tomato, Vegetables, Melon, Artichoke and represents crops of high water and low water requirements. Group C includes Millet, Barely, Grains, Sorghum and represents the crops of low price high water requirements. Finally, group D includes; Pepper, Cotton, Pulses, Mango, Groundnut, Rice, Citrus and represents the crops ofhigh price high water requirements.

$$SWD\left[e,c\right]=\frac{CWR\left[e,c\right]}{CY\left[e,c\right]} \qquad (2)$$

Table (I): Calibration results for CWR values

| crop | Cropwat (mm) | FAO (mm) | Error (%) |
|---|---|---|---|
| Barely | 295.3 | 562 | 47.45552 |
| Cotton | 1194.2 | 1143 | 4.47944 |
| Cabbage | 781.2 | 458 | 70.56769 |
| Grains | 697.5 | - | - |
| Groundnut | 518 | 693 | 25.25253 |
| Maize | 760.4 | 449 | 69.35412 |
| Mango | 1952.8 | 2011 | 2.894083 |
| Pepper | 389.2 | 457 | 14.83589 |
| Citruses | 1307.1 | 1365 | 4.241758 |
| Potato | 450.6 | 473 | 4.735729 |
| Pulses | 678.6 | - | - |
| Rice | 1133.1 | 960 | 18.03125 |
| Sorghum | 676.6 | 479 | 41.25261 |
| Soybean | 356.6 | 779 | 54.22336 |
| Vegetables | 571.5 | 517 | 10.54159 |
| Tomatoes | 495.5 | 589 | 15.87436 |
| Melons | 393.2 | 674 | 41.66172 |
| Grapes | 1105.9 | 1025 | 7.892683 |
| Artichoke | 1647.2 | 1380 | 19.36232 |
| Dry Beans | 379.9 | 452 | 15.95133 |
| Wheat | 462 | 638 | 27.58621 |
| Millet | 426.4 | 421 | 1.28266 |

**Table (II): SWD for the selected crops based on Matlab model results, World Prices, Crop Yield.**

| | **SWD ($m^3$/ton)** | **Pric (1000$/ ton)** | **Crop Yield (ton/ha)** |
|---|---|---|---|
| Millet | 7532.2 | 325 | 481.8 |
| Cotton | 3488.6 | 1500 | 3181.8 |
| Pulses | 2937.4 | 2304.3 | 2213.9 |
| Barely | 1995.7 | 362.5 | 1548.3 |
| Grains | 1645.6 | 150 | 3880.7 |
| Mango | 1602.4 | 1176.5 | 11295.4 |
| Sorghum | 1433.6 | 438.5 | 4520.7 |
| Groundnut | 1373.5 | 1415.6 | 3290.8 |
| Rice | 1341.9 | 1246.6 | 9366.9 |
| Citruses | 1189 | 1500 | 10042 |
| Dry Beans | 1023.9 | 486.1 | 3313.5 |
| Maize | 983.7 | 186.9 | 7389.8 |
| Artichoke | 822 | 1740 | 18928.5 |
| Soybean | 751.4 | 396.7 | 3500 |
| Wheat | 618.9 | 195.4 | 6575.3 |
| Grapes | 437.4 | 807.7 | 22930.2 |
| Vegetables | 382.2 | 1340 | 13774.9 |
| Cabbage | 226.2 | 1075 | 30758.6 |
| Potato | 155.6 | 627.2 | 27244 |
| Melon | 138.5 | 1705.2 | 27275 |
| Tomato | 127.1 | 1333.3 | 39773.7 |
| Pepper | 52834.1 | 2378.66109 | 1593.1 |

| | | |
|---|---|---|
| High Price | Group (B)<br>Tomato - Vegetables- Melon –- Artichoke | Group (D)<br>Cotton– Mango - Pulses - Pepper – Rice- Citrus- Groundnut |
| Low Price | Group (A)<br>Soybean, – Wheat – Maize – Dry Beans – Potato, - Vegetables – Grapes – Cabbage | Group (C)<br>Milet- Barely- Grains- Sorghum. |
| | Low Crop Water Requirements | Hilgh Crop Water Requirements |

Table (III). Classification of the 22 crops based on prices and water requirements

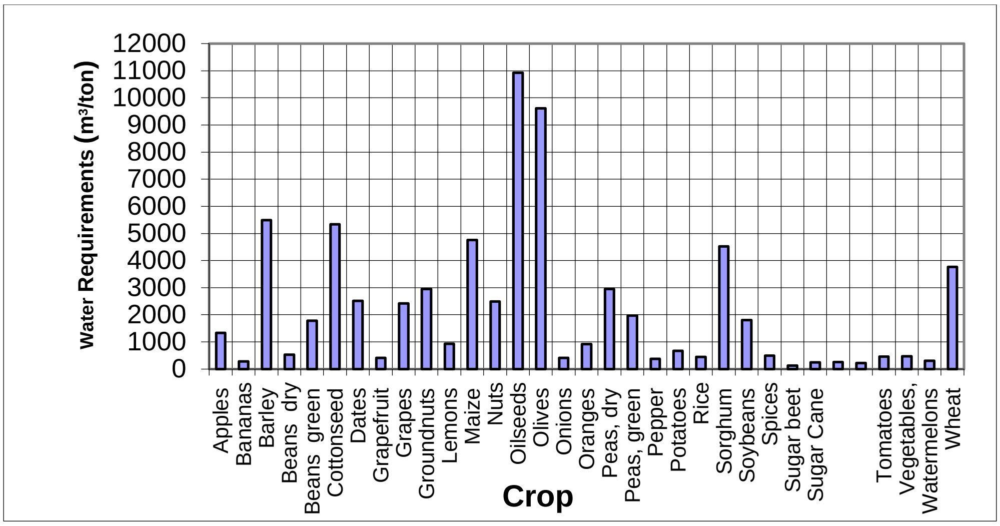

Figure 1 The CWR in Egypt

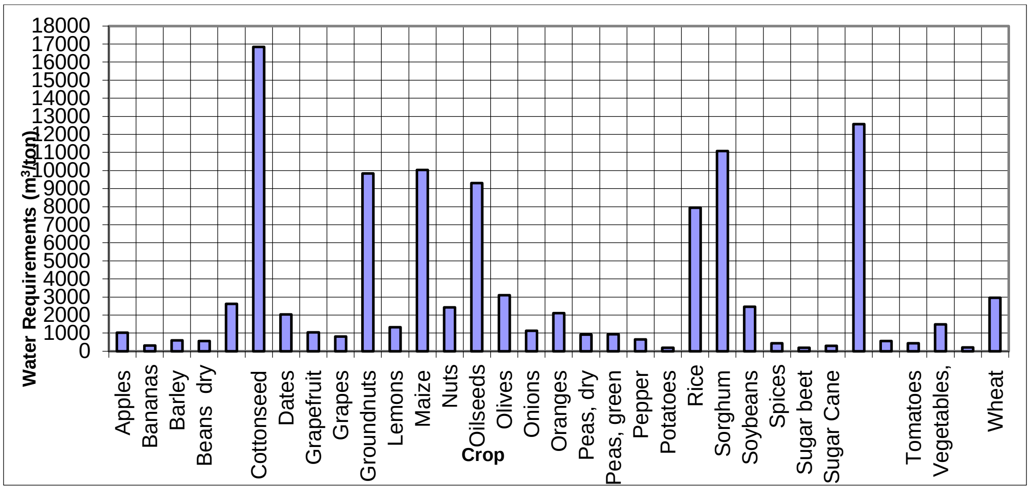

Figure 2 The CWR in Sudan

## 2.2. Calculation of virtual water trade flows and the national virtual water trade balance

The calculation of virtual water trade flows between nations involves multiplying international crop trade flows by the corresponding virtual water content. The virtual water content is determined by the specific water demand of the crop in the exporting country, where the crop is grown. Therefore, the virtual water trade can be calculated using the following formula:

$$VWT\left[c,t\right] = CT\left[c,t\right] \times SWD\left[c\right] \qquad (3)$$

The gross virtual water import for a country, represented as "ni," is determined by summing up all the imports of virtual water.

$$GVWI\left[t\right]=\sum VWT\left[c,t\right] \qquad (4)$$

The gross virtual water export from a country, denoted as "ne," is calculated by adding up all the exports of virtual water.

$$GVWE\left[t\right]=\sum VWT\left[c,t\right] \qquad (5)$$

The net virtual water import of a country is obtained by subtracting the gross virtual water export from the gross virtual water import. Therefore, the virtual water trade balance of country "x" for year "t" can be expressed as follows:

$$NVWI\left[x,t\right]=GVWI\left[x,t\right]-GVWE\left[x,t\right] \qquad (6)$$

Calculation of a nation's 'water footprint'

Water footprint = WU + NVWI (7)

Weather data is inputted into an application, which serves as a program featuring monitoring stations located in various countries, including Egypt. In this process, the impact of rainfall is considered, although it is typically disregarded in Egypt due to its scarcity. A specific country is chosen for the study, and data such as average minimum and maximum temperatures, humidity, and wind are collected. In the case of Egypt, an average of 32 monitoring stations is utilized, while the number may vary for other countries within the Nile Basin. Next, a crop is selected from the crops listed in the FAO database, and the corresponding soil type is specified as clay soil, which is prevalent in Egypt. These inputs enable the calculation of the water requirements necessary for irrigating the crop during the planting period.

## 2.3. Calculation of national water scarcity, water dependency and water self-sufficiency

$$WS=\frac{WU}{WA}\times 100 \qquad (8)$$

The impacts of the replacement process will be assessed by evaluating three key factors. Firstly, the amount of virtual water that can be saved will be measured. This involves calculating the Relative Specific Water Demand (RSWD) for the crops in group B as well as the 22 crops, using equation (9). This calculation determines the volume of virtual water saved in cubic meters (m³) when one ton of these crops is replaced with the 22 crops. This information helps identify the most suitable crops for importation instead of cultivating them in Egypt. Secondly, the RSWD will be calculated for the crops in group C and the 22 crops. This evaluation aims to determine the best crops for export based on the saved virtual water, cultivated areas, and financial returns. By considering these factors, the optimal crops for exportation can be identified.

$$RSWDn = SWDn/ SWDS \tag{9}$$

**RSWDn** , is the relative specific water demand of crop n,

$SWDn$, , is the SWD value of crops, n=1, 2, 3 …... 22 and

, is the value of the SWD of selected crop.

The second factor was the relative area (RAn) which was estimated based on RSWD and according to equation (10), as follow:

$$RAn = (RSWDn / cy_{(n)})*1000 \tag{10}$$

Where

$\mathbf{cy_{(n)}}$ , is the Crop yield of the crops in (ton /ha), n=1,2,3,..22.

The third factor was the relative price ( ) of all crops with respect to the SWD, it is based on the RSWD calculated from equation (4). The RP calculated from equation (6) is as follows:

$$RPn = RSWDn * Pn \tag{11}$$

Where:

RPn , is the relative price of all crops, n=1,2,3,.......22 and

,is the price of crop (n ) in (1000 $).

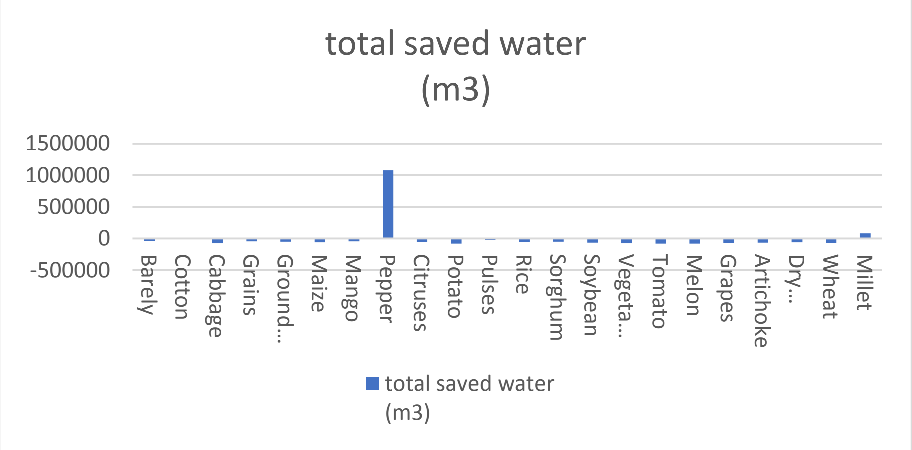

Figure 3-Total saved water

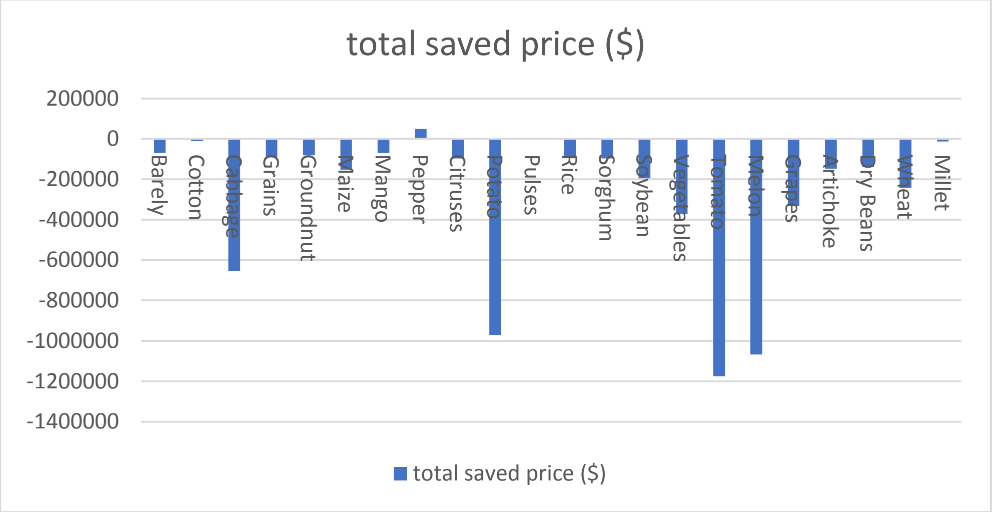

Figure 4-Total saved price

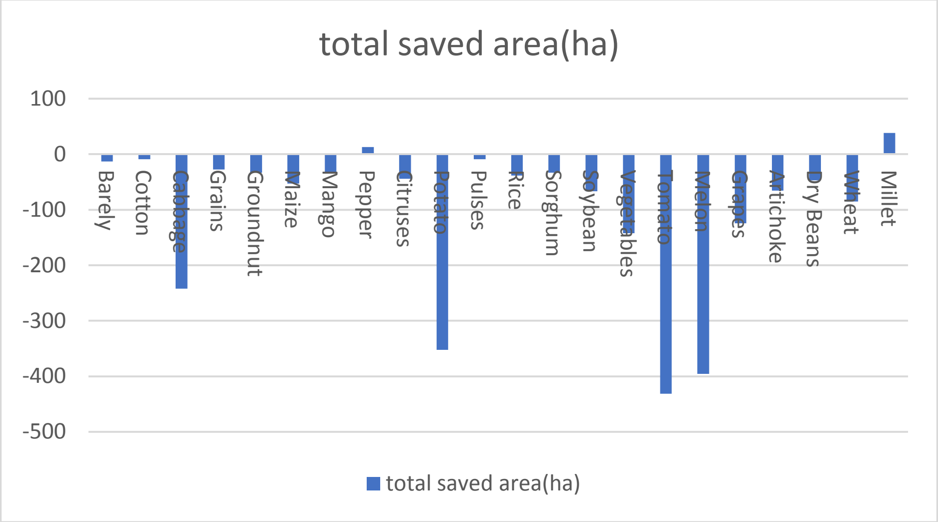

Figure 5-Total saved area

## Data sources

**1- Information pertaining to crop water requirements** are computed using FAO's CropWat model for Windows, which is available on FAO's website (www.fao.org). The CropWat model calculates reference crop evapotranspiration using the FAO Penman-Monteith equation, as discussed in the previous chapter (Clarke et al., 1998). The CropWat model analyses crop water requirements for various crop kinds using the following assumptions:

(1) Crops are sown in optimal soil water conditions with no effective rainfall throughout their lives; the crop is developed under irrigation circumstances.

(2) Crop evapotranspiration under standard conditions (Etc), evapotranspiration from disease-free, well-fertilized crops cultivated in wide fields with 100% coverage.

(3) Crop coefficients are chosen using the single crop coefficient approach, which entails a single cropping pattern rather than a dual or triple cropping pattern..

## 2-Climatic data

The climatic data required as input to CropWat were obtained from FAO's climatic database ClimWat, which is also accessible via FAO's website. ClimWat is a database that contains climatic data for over a hundred nations. Climate data for several climatic stations are available for numerous nations. As a rough estimate, the capital climatic station data were used as the country representative.

## 3-Crop parameters

Crop parameter settings for 24 different crops are available in the CropWat package's crop directory (Table 3.1). CropWat uses the following crop parameters as input data: crop coefficients in distinct crop growth stages (initial, medium, and late stage), crop length in each development stage, root depth, and planting date. Crop parameters for the 14 crops for which crop parameters are not available in the CropWat package have been based on Allen et al. (1998).

## 4-Crop yields

Crop yield data were obtained from the FAOSTAT database, which is also accessible via the FAO website.

## 5. conclusions

1) Virtual water is a concept that is now being developed and refined for use by decision-makers at the strategic level in societies and determine the agricultural and industrial strategies.

2) Virtual water can be considered as an alternative source of water. Virtual water import can be used by national governments as a tool to release the pressure on their domestic water resources as the most direct and positive impact of virtual water trade is the water saving which is related to countries that import products.

3) Virtual water trade between nations is a means of increasing the efficiency of water use;

4) Countries of NBC region are not self-sufficient in producing food commodities to meet the national consumptive demand.

5) The program implemented in this study, helps in identifying the actual water needs of different agricultural crops included in the study and therefore improves water distribution and consumption in the agricultural sector.

6) The aim of the study of virtual water is providing food security. A market of virtual water within NBC countries will be highly appreciated.

7) Import of virtual water from foreign countries is very risky and if the virtual water trade is not possible within countries of the same region, then it would be better to choose to be water independent rather than self-sufficient.

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