FOOD GAP OPTIMIZATION MODELUSING VIRTUAL WATER CONCEPT (CASE STUDY:NILE BASIN COUNTRIES)

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ABSTRACT

A mathematical optimization model using Virtual Water Concept is developed to examine the possibility of improving the agricultural water use and decreasing the food gap. The model was developed by solver in excel program.This model is applied on selected Nile Basin countries as a case study.These countries are Egypt, Sudan, Ethiopia, Kenya and Uganda. The model is developed for certain cropping pattern distributions and designed to minimize the food gap without violating the existing limitation of both available water and land resources as well as strategic crop requirements.

Two cases were analyzed. The first case assumes that integrated agricultural planning for the countries can be developed and implemented. The second deals with each country individually. These cases were examined under the future conditions of the year 2030. The total food gap for the studied Nile countries is estimated to be $ 46.3 billion in the year 2030. Results demonstrated that the food gap can greatly be reduced among these countries through co-operation, and some countries can even achieve a surplus (e.g. Ethiopia, Kenya, and Uganda).

KEY WORDS: food gab; virtual water; optimization model
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1 INTRODUCTION

Recently, water resource management has focused on demand management and water use conservation. The virtual water concept is one of the most important tools used in demand management. Virtual water is defined as the amount of water that is in food or other products needed for its production.

The trade of commodities is the exchange of virtual water in products. For water-shortcountries, it appears to be reasonable not to produce water intensive goods but rather import these from water-abundant regions, thus saving the natural resource and enabling its efficient use. Virtual Water Trade (VWT) represents a plausible approach.

The concept of virtual water is closely linked to the water footprint concept. The water footprint is defined as the total volume of freshwater used to produce the goods and services consumed by the individual or community. It consists of two terms: external water footprint (EWFP) and internal water footprint (IWFP). The water footprint is an indicator of the actual water used by a nation. When assessing the water footprint of a nation, it is essential to quantify the flows of virtual water leaving and entering the country.

Allan (2003) introduced the concept of virtual water in London after finding the term “embedded water" in the early 1990’s when studying the option of importing virtual water as a partial solution to problems of water scarcity in the Middle East(Hofwegen, 2003). Virtual water is the water ‘embodied’ in a product, not in a real sense, but in the virtual sense. It refers to the water needed for

the production of the product (Hoekstra, 2003). For example, to produce one kilogram of wheat it requires 1000 liters of water, and meat requires five to ten times that much (Hofwegen, 2003).
It is worth mentioning that rain-fed crops play a vital role in securing the food requirement. The total internal water use includes both blue water (referring to the use of surface and groundwater) and green water use (referring to the use of an infiltrated volume of precipitation)(Chapagain and Hoekstra, 2004). The green water is used for rain-fed crops where its importance varies with the amount of rainfall.

2 METHODOLOGY AND DATA

The main objective of this study is to develop a mathematical optimization model for cropping pattern distributions that can be applied to selected Nile Basin countries (Egypt, Sudan, Ethiopia, Kenya and Uganda); Figure (1).The virtual water concept is used as a tool to improve water use efficiency through redistributing the cropping patterns in the Nile basin countries and through improving food trade among Nile basin countries.
Data was collected from organized sources such as (FAO-AQUASTAT, 2009), for the period (2001-2009) as a base case. This data includes:

- Available water resource (green and blue).
- Cultivated land.
- Cropping pattern, crop production and crop yield.
- Domestic supply quantity of crops.
- Crop prices.

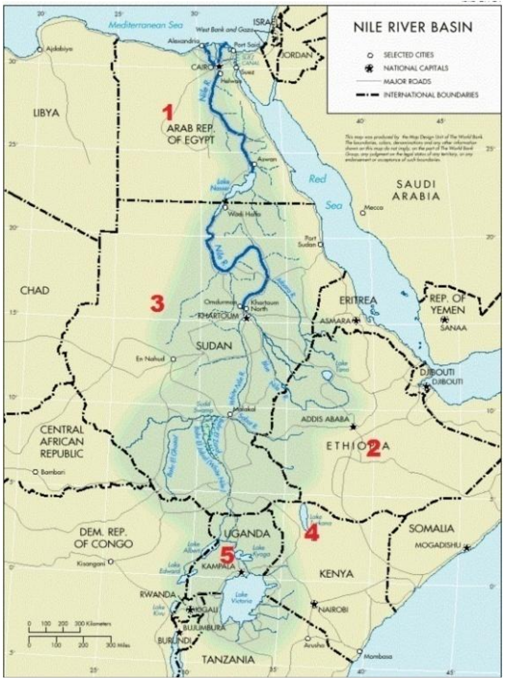

Figure 1. The five selected Nile Basin countries

Table (1) illustrates the percentage of blue and green water use in each of the selected countries. This depends on the percentage of irrigated and rain-fed areas to the total cultivated area in each country during the period (2001-2009). Egypt is highly dependent (98%) on blue water compared to Sudan (10%). Uganda however, depends entirely on rainfall where the rain-fed area equals 99.9% of the total cultivated area. In Ethiopia and Kenya, the rain-fed area forms about 98% of the total cultivated area. The rain-fed area in Sudan equals 90% of the total cultivated area.

Table 1. Percentage of Blue and Green Water for some Nile basin countries

Area	Egypt	Ethiopia	Kenya	Sudan	Uganda
Cultivated Area 1000 ha	3,550	13,555	5,789	18,860	8,317
% Irrigated Area	98	2	2	10	0.1
% Rain-fed Area	2	98	98	90	99.9

Source (FAO-AQUASTAT, 2009)

2.1 Computing the Virtual Water Content and Crop Water Requirements

The virtual water content is estimated for selected crops that are produced in the Nile basin countries, including (Bananas, Barley, Groundnuts, Maize, Onions, Potatoes, Rice, Cottonseed, Sesame seed, Sorghum, Soybeans, Sugar cane, Sunflower seed, Tomatoes and Wheat) using the following equation:

$$VWCc = \frac{CWUc}{Pc} \qquad (1)$$

Where VWCc is the virtual water content of the crop “c” in (m^3/ton); CWUc is the crop annual water use (m^3/year); and Pc is the annual production of the crop “c” (ton/year).
Crop water use is the total water used in order to produce the crop “c”, estimated as follows:

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

Where, CWR(c) is the on-farm crop water requirement (m^3/fed) that is defined as the total water needed for evapotranspiration from planting to harvesting for a specific crop growing under adequate soil-water. Production (c) is the total volume of crop (c) produced and Yield (c) is the land productivity (ton/fed). The production and yield of crops for the studied country are taken from FAO, FAOSTAT on-line database(FAOSTAT, 2009)

2.2 Water Footprint and its Indicators

The water footprint of a country (WFP, m^3/yr) is equal to the total volume of water used, directly or indirectly, to produce the goods and services consumed by the inhabitants of the country (Chapagain and Hoekstra, 2004). A national water footprint has two components, the internal and the external water footprints:

$$WFP = IWFP + EWFP \qquad (3)$$

The internal water footprint (IWFP) is defined as the use of domestic water resources to produce goods and services consumed by inhabitants of the country.

$$IWFP = DWW + IWW + AWU - VWE \qquad (4)$$

The first three components represent the total water volume used in the national economy (in m^3/yr), Where DWW is the water withdrawal for domestic sector, IWW is the water withdrawal for the industrial sector and its calculation depends on the virtual water concept. AWU is the agricultural water consumed depending on the evapotranspiration of the crop and the virtual water contained in livestock products, and VWE is the virtual water exported to other countries/regions.
The external water footprint (EWFP) of a country is defined as the annual volume of water resources used in other countries to produce goods and services consumed by the inhabitants of the country concerned.

$$EWFP = VWI - VWE_{re-export} \qquad (5)$$

Where VWI is the virtual water imported into the country and VWE re-export is the virtual water exported to other countries as a result of re-exports of imported products. Both the internal and the external water footprint include the use of blue water (ground and surface water) and the use of green water (moisture stored in soil strata).

2.3 Water scarcity, water import dependency of a nation and water self-sufficiency

Water scarcity (WS) of a nation is defined as the ratio of the nation's water footprint (WFP) to the nation's water availability (WA).

$$WS = \frac{WFP}{WA} \times 100 \qquad (6)$$

The national water scarcity can be more than 100% if there is more water needed for producing the food and services consumed by the people of that nation than is available.
Water import dependency (WD) is the ratio of the external water footprint (EWFP) to the total water footprint (WFP).

$$\mathrm{WD} = \frac{\mathrm{EWFP}}{\mathrm{WFP}} \times 100 \qquad (7)$$

Water self-sufficiency (WSS) is defined as the ratio of the internal water footprint (IWFP) to the total water footprint (WFP).

$$WSS = \frac{IWFP}{WFP} \times 100 \qquad (9)$$

WSS is near to or 100% if the water needed is available within the own country, and when close to 0.0% means that all the good and services in a country are largely met with imported virtual water. This means it has a large external water footprint in comparison to its internal water footprint.
Table (2) outlines the indicators for the studied countries. Ethiopia, Sudan and Uganda respectively have the highest water self-sufficiency followed by Kenya and Egypt (Mekonnen and Hoekstra, 2011). These indicators provide a clear picture of the real water status in each country.

Table 2. Water Self-Sufficiency and Water Import Dependency

Country	IWFP billion m^3/year	EWFP billion m^3/year	Total WFP billion m^3/year	Water Self sufficiency %	Water Import Dependency %
Egypt	68	27.1	95.2	71	29
Ethiopia	75.9	1.8	77.6	98	2
Sudan	58.8	2.4	61.1	96	4
Kenya	29.1	6.1	35.2	83	17
Uganda	25.7	1.3	26.9	95	5

3 BUILDING THE OPTIMIZATION MODEL

The following outlines the detail for the developed linear programming model using theexcel program.The developed mathematical optimization model is able to analyze the potential for the following:

- Achieving food security in the countries under consideration.
- Improving the food trade among the countries.
- Reducing the food gap in the countries.

3.1 Main assumptions

1. Crops are divided into 2 groups (summer and winter crops).
2. The available water in each country is equal to the current water consumption that is calculated using virtual water concept.
3. The size of cultivated area is fixed for each country and is equal to the present cultivated area.
4. The demand of each crop group in the present scenario is taken as an average for the period 2001-2009. For future scenarios, it is assumed that the demand increases 2% per year for each crop.
5. International prices are used in the model.
6. Minimum production of strategic crops has been taken into consideration.
7. Crops that are not grown in the base case in any country are not grown in the proposed scenarios.
8. Transportation costs, according to (TAD, 2009), are assumed to be 6% of the average cost of the imported crops.

3.2 Objective Function

The objective function is to minimize the food gap value that is the difference between the food import and export values or difference between demand and production values. Minimizing the food gap value implies maximizing the total value of crop production.

Food Gap Value (Fg) for crop i can be expressed mathematically as follow:

$$\mathrm{Fg_i} = (\mathrm{I_i} - \mathrm{E_i}) \times \mathrm{Pr_i} \qquad (10)$$

$$= (\mathrm{D_i} - \mathrm{S_i}) \times \mathrm{Pr_i} \qquad (11)$$

Where: Di: food demand (ton) for crop i, Si: production (ton) for crop i, Ii: imports (ton) for crop i, Ei: exports (ton) for crop i, Pri: international price ($) for crop i

$$\mathrm{D_i} = \mathrm{S_i} + \mathrm{I_i} - \mathrm{E_i} \qquad (12)$$

The objective function can be expressed mathematically as:

$$\mathrm{Min} \sum_{k=1}^{m} \sum_{i=1}^{n} fg_{ik} \qquad (13)$$

The previous equation (15) is equal to:

$$\mathrm{Min} \sum_{k=1}^{m} \sum_{i=1}^{n} (D_{ik} - S_{ik}) \times \mathrm{Pr_i} \qquad (14)$$

Where: m: number of selected Nile countries, n: number of crops

3.3 Constraints

The main constraints that are applied in the developed model are as follows:

a) Water Constraint:

Total available water for crops is limited to the total water use calculated via the virtual water concept for the base case (current conditions).

$$\sum_{i=1}^{n} S_{ik} \times VWC_{ik} - TVW_k \leq 0 \quad k=1, 2 \ldots 5 \qquad (15)$$

Where:S_{ik} = Production of crop i in country k, VWC_{ik} = the virtual water content of crop i in country k, TVW_k = the total virtual water content of the base case for country k, n = total number of crops.

b) Land Constraint:

Total available land for crops is limited to the available land for agricultural development in each studied country.

$$\sum_{i=1}^{n} \left(\frac{S_{ik}}{Y_{ik}} \right) - TA_{ik} \leq 0 \qquad k=1, 2 \ldots 5 \qquad (16)$$

Where: S_{ik} = Production of crop i in country k, Y_{ik} = the yield of crop i in country k, TA_{ik} = the total actual land of the base case in country k, n = total number of crops.

c) Production Constraint:

Total production of any crop is limited to the total demands in the studied countries.

$$\sum_{k=1}^{m} \sum_{i=1}^{n} (S_{ik} - D_{ik}) \leq 0 \qquad k=1, 2 \ldots 5 \qquad (17)$$

Where: S_{ik} = Production of crop i in country k, D_i = the demand for crop i in country k, m = number of selected Nile countries, n = total number of crops. This constraint is necessary to limit the volume of production of any crop that has a high return and thus gives the results of planting quantities that can be more than the market needs.

d) Economic Return Constraint:

Economic return resulting from any cropping pattern redistribution for each studied country must be greater or equal to the present economic return resulting from the current situation.

$$\sum_{i}^{n} IN_{sik} \geq \sum_{i}^{n} IN_{bik} \qquad k=1, 2 \ldots 5 \qquad (18)$$

Where: IN_{sik} = the income from crop i in country k for scenario s, IN_{bik} = the income from crop i in country k for base case b, n= total number of crops.

$$IN_{sik} = S_{sik} \times Pri \qquad (19)$$

$$IN_{bik} = S_{bik} \times Pri \qquad (20)$$

Where: Ss_{ik} = the present production (ton) for crop i in country k, S_{bik} = the production of crop i resulting from scenario s, Pri = international price ($) for crop i.

Decision Variables and Input Data

Decision variables are the cropping patterns in each country. The data required for the model are:

a) International crop prices are used in the formulation of the model. The prices used for the different crops are as follows: wheat 278 $/ton, maize 215 $/ton, rice 359 $/ton, sorghum 252 $/ton, barley 237 $/ton, millet 620 $/ton, soybeans 283 $/ton, sunflower seed 314 $/ton, sesame seed 718 $/ton, cotton 507, groundnuts 467 $/ton, potatoes 382 $/ton, sweetpotatoes195 $/ton, tomatoes 449 $/ton, onions 324 $/ton, sugarcane 36 $/ton, bananas 341 $/ton, tea 1857 $/ton , fruits 966 $/ton and vegetables 788 $/ton; (FAO, 2009).

b) Cultivated areas that are calculated from present production and the current yield of each crop.
c) Available water for each country is calculated according to the virtual water content and present production of crops.
d) Demand for each crop.

4 CASES FOR MINIMIZING FOOD GAP AND IMPROVING THE FOOD TRADE AMONG THE SELECTED NILE BASIN COUNTRIES USING THE DEVELOPED OPTIMIZATION MODEL

The developed virtual water model is used to analyzetwocases for cropping patterns that reduce the food gap in the selected Nile basin countries. It usesminimizing of the food gap as an objective function.The developed mathematical optimization model is able to analyze the following conditions:

- The potential opportunities for achieving food security in the countries under consideration.
- Improving the food trade among the countries.
- Reducing the food gap in the countries.

Two caseswere developed and analyzed:

1. The first case is based on the assumption that integrated agricultural planning for the five studied countries will be developed and implemented.
2. The second case deals with each country individually.

Two scenarios are considered in the study.

1. Minimizing the food gap using; Present scenario,
2. Minimizing the food gap in the future for year 2030; Future scenario.

5 RESULTS AND DISCUSSION

Case 1: Integrated Agricultural Planning for the Five Studied Countries

- Regional Integration Using Scenario No (1) (Present scenario)

The results of this scenario showed that the total food gap for the selected crops could be reduced by about 84%. The food gap can be reduced from $ 4.6 billion/year to $ 832 million/year. The food gap can be decreased in each country, and some countries can achieve a surplus (e.g. Kenya and Uganda) as shown in Figure (2). One of the main concerns of these scenarios is to improve the inter-trade.

The resulting cropping pattern from the optimization model that minimizes the usage of water and maximizes the economic profit is shown in Table (3).

The demand of most of the crops was covered. In this scenario, the cropping pattern varies greatly from country relevant to the high productivity practices and the available water resources. For instance, Sudan and Uganda plant more wheat than their requirements and export the surplus; Figure (3).

There are two important constraints regarding the size of the cultivated land and the amount of available water. Scenario No.1 resulted in saving some of the water or cultivated land in several countries as shown in Table (4). There is unused water in Egypt (2.42 billion m^3) but no surplus in the cultivated land. This water maybe used in reclaiming new land or to be utilized in other sectors. On the other hand, the countries with unused cultivable land but without water surplus are Sudan and Uganda.

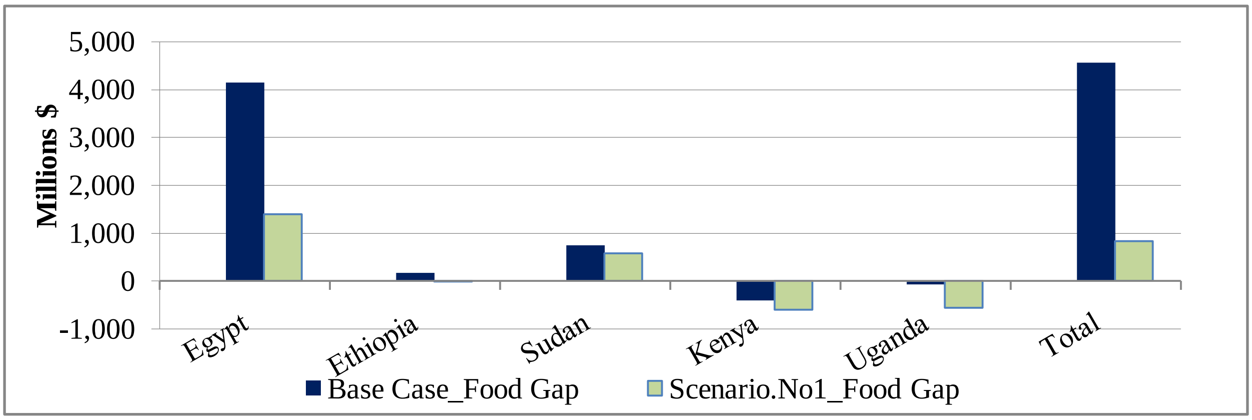

Figure 2. Comparison of the Food Gap in the Base Case and Scenarios No (1)of case 1 -Integrated Planning

Table (3) Crop Production Resulted from Scenario No (1) of case 1 - Integrated Planning (1000 ton)

Crops	Egypt	Ethiopia	Sudan	Kenya	Uganda
Wheat	4,987	964	10,992	281	1,386
Maize	10,805	3,984	1,229	2,575	361
Rice	3,865	10	19	78	42
Sorghum	2,224	3,784	1,018	0	0
Barley	32	645	0	856	4
Millet	0	100	172	18	1,554
Soybeans	0	0	0	22	774
Sunflower seed	9	0	204	4	49
Sesame seed	0	102	53	3	232
Cotton	136	19	820	8	15
Groundnuts	38	14	742	5	34
Potatoes	712	139	969	2,613	180
Sweet potatoes	92	127	2,960	192	789
Tomatoes	2,398	12	180	6,461	6
Onions	1,581	649	94	8	19
Sugarcane	4,866	727	2,054	1,419	23,499
Bananas	93	20	2,532	63	59
Tea	0	0	0	83	0
Other Fruits	14,333	218	547	584	8,081
Other Vegetables	15,415	2,678	755	1,227	3,356

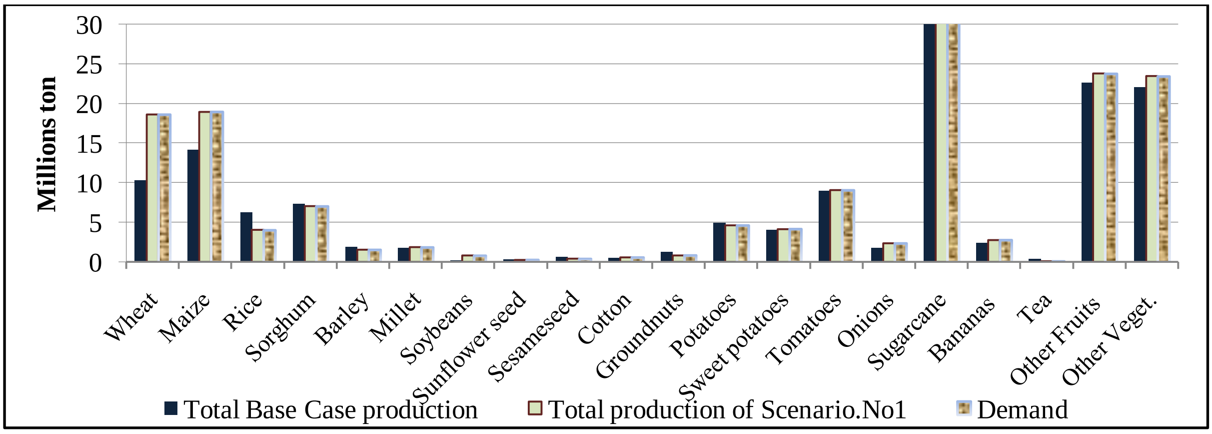

Figure 3. Comparison of Crop Production and Demand for the Base Case and Scenarios No (1)in case 1- Integrated Planning

Table (4) Unused Water and Arable Land under Scenario No (1) in case 1- Integrated Planning

Country		Egypt	Ethiopia	Sudan	Kenya	Uganda
Water (in summer)	billion m^3	0	0	0	1.01	0
Water (in winter)	billion m^3	2.42	1.07	0.80	0	0.48
Area (in summer)	million fed	0	0	5.44	0	0.35
Area (in winter)	million fed	0	0	0	0	0

Case 2: Individual Agricultural Planning for Studied Countries

In this case, the total food gap decreased to $3.4 billion for scenario No (1) Figure (4).Reduction of the total food gap in this case is less than the reduction under case (1).

The improvement of the inter food trade in this case is less than case 1 because the production cannot meet the demand for several crops in most of the studied countries (e.g. wheat, maize, rice and sugar cane in Egypt and Ethiopia, sorghum and sugar cane in Sudan, wheat, maize and sugar in Kenya, maize, potatoes and sugar cane in Uganda). On the other hand, production of some crops increased such as tomatoes in Egypt and Kenya, fruits in Ethiopia, Sudan and Uganda.
The unused water under this case is summarized in Table (5).

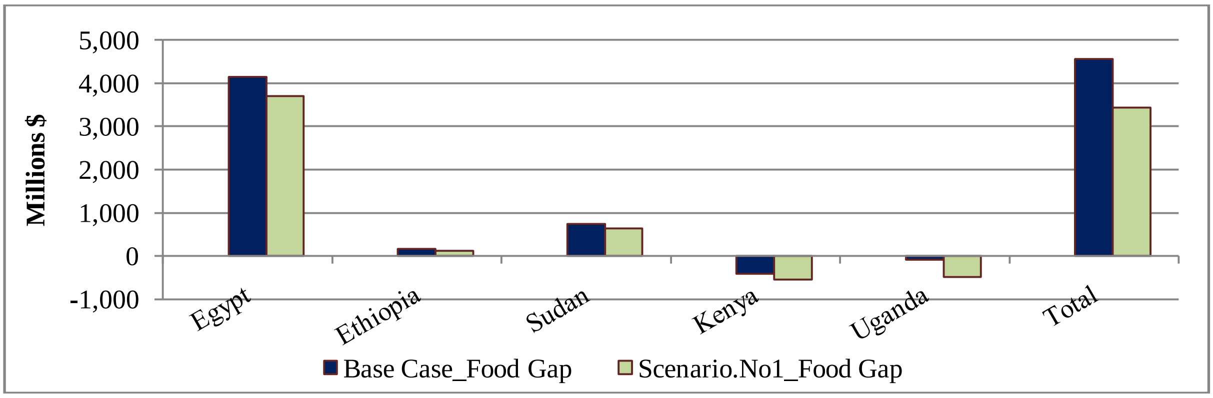

Figure 4. Food gap of Base Case and Results of Scenario No (1) in case 2- Individual Planning

Table (5) The Unused Water of Scenario No (1) in case 2- Individual Planning

Country		Egypt	Ethiopia	Sudan	Kenya	Uganda
Water (in summer)	billion m^3	6.95	5.95	8.01	3.34	4.38
Water (in winter)	billion m^3	1.73	5.62	9.18	0.18	4.41

Results of Future conditions Scenarios

The previous scenarios were examined under the future conditions of the year 2030. The requirements of food are assumed to increase by 2% annually. The total food gap for all the studied Nile countries is estimated to be $ 46.3 billion in the year 2030.Table (6) outlines the resulting food gap for the base case and the two cases of the agricultural planning.

The deficit crops in future (2030) are (wheat, maize, sorghum) in the case of regional integration as shown in Figure (5), and there is deficitin most of crops in case of individual planning. The unused water under the two cases of planning is summarized in Table (7).

Table 6. Food Gap predicted for 2030 in the Studied Countries for the two Cases of Planning and the Base Case

Country	Base Case	Regional Integration	Individual Planning
		Future Scenario	Future Scenario
Egypt	26.17	21.6	22.9
Sudan	5.6	-9.7	-0.9
Ethiopia	3.3	-7.7	-1.5
Kenya	3.25	1.14	-6.1
Uganda	7.9	7.3	-3.7

(Unit: billion $/year, negative values mean surplus)

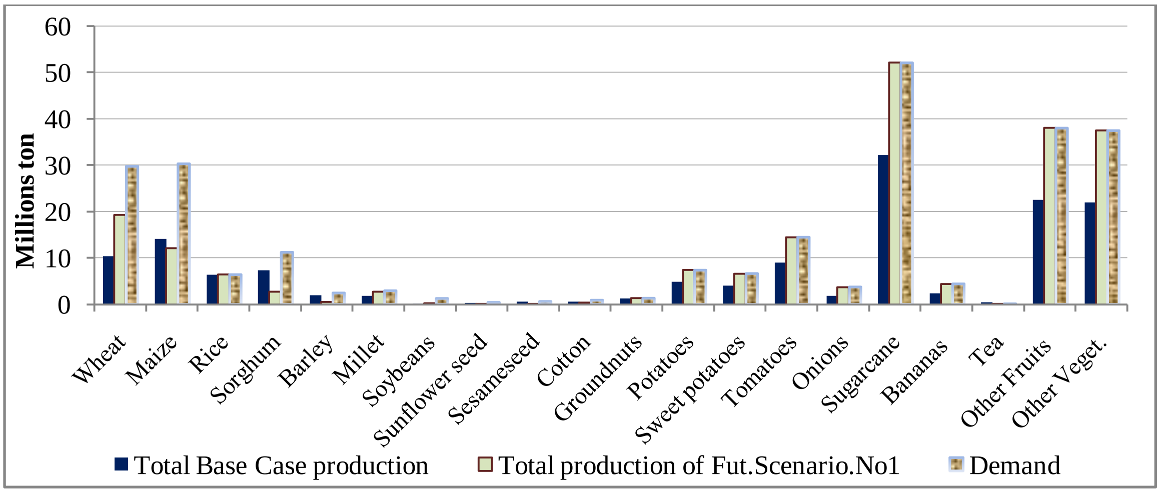

Figure 5. Comparison of Crop Production and Demand for the Base Case and Future Scenario No(2) in case 1- Integrated Planning

Table (7) Unused Water for 2030 in the Studied Countries for the two Cases of Planning and the Base Case

Country	Regional Integration	Individual Planning
	Future Scenario	Future Scenario
Egypt	0.75	0
Sudan	0	0.8
Ethiopia	0	0
Kenya	0	0
Uganda	2.88	2.1

(Unit: billion m^3 /year)

6 SUMMARY AND CONCLUSIONS

The virtual Water Concept as a new water management tool for improving the use of agricultural water and decreasing the resultant food gap was developed and applied to five Nile countries. These countries are Egypt, Sudan, Ethiopia, Kenya and Uganda.

A linear programming optimization model using Excelis developed for certain cropping patterns distribution for the selected countries. This model can minimize the food gap without violating the existing limitation of both available water and land resources as well as strategic crops requirements.Two cases with two scenarios were analyzed using this model.

The case of integrated agricultural planning showed the best optimizationresults because water and land resources for all studied countries are managed under one umbrella. This leads to effective distribution of crops among the studied countries. In addition, these scenarios improve the inter-food trade. Case of integrated agricultural planning under future conditions can decrease the food gap in each country and even a surplus can be achieved in some countries.

For the case of individual agricultural planning, most of the studied Nile countries were found to plant similar crops. In addition, no food surplus is achieved to be exported to other countries.

The following outlines the major findings of the developed optimization model and its application for the various scenarios:

1. The optimization model developed in this research can be used to reduce the food gap.
2. The total water footprint varies from one country to another within the Nile basin. These differences are due to climate, variation in crop yield and the diet in each country. Water import dependency in Egypt was estimated at 29%, while in Ethiopia only 2%.
3. The food gap in the future will increase drastically for all Nile nations. This may be reduced through optimum utilization of available land and water resources and improved trade. Integrated water resources management can reduce this problem significantly.
4. Results showed that Co-operation between Nile basin countries is a vital necessity for all nations.

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