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Distribution Of Agricultural Crops Using Water Footprint and Virtual Water Analyses Model

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K_y	A yield response factor, [dimensionless]
e_a	Actual vapour pressure, [kPa]
NJS	Agriculture-based northern Jiangsu
PERC	Amount of percolation and seepage losses, [mm]
SAT	Amount of water to saturate the soil by land preparation by puddling, [mm]
$cons_{annual}$	Annual consumption in the interested country, [ton/capita]
Ea	Application efficiency, [%]
AW	Available water holding capacity, [mm/m]
T	Average air temperature, [°C]
WF_{blue}	Blue water footprint, [m3/ton]
BWS	Blue water scarcity
E	Class is the highest value
A	Class is the lowest value
K_s	Crop coefficient by the water stress coefficient, [dimensionless]
K_c	Crop coefficient, [dimensionless]
$ET_{c\ adj}$	Crop evapotranspiration under soil water stress conditions, [mm / day]
P_{crop}	Crop price, [$/ton]
T_{crop}	Crop trade, [ton/year]
CVWAM	Crop virtual water analysis model
CWR	Crop water requirement
CWR	Crop water requirement (either green or blue), [m3/ha]
CWU	Crop water use
R	Daily rainfall, [mm / day]
Z_r	Development stage effective root zoon depth, [m]
R_e	Effective rainfall, [mm/ day]
EC_w	Electrical conductivity of the irrigation water, [dS/m]
$EC_{e\ threshold}$	Electrical conductivity of the saturation extract at the threshold of ECe when crop yield first reduces below min yield, [dS/m].
En_g	Energetic water productivity, [kcal/m3]
En_{output}	Energy output of the crop, [kcal/ton]
P_{EN}	Energy price, [$/kcal]
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
a	Fixed percentage insert by user which range (0.7-0.9)
GADM	Global Administrative Areas
LULC	Global map of land use/land cover
WF_{green}	Green water footprint, [m3/ton]
GWS	Green water scarcity
Dg	Gross irrigation water depth, [mm]
V.W.I	Imported virtual water, [m3/year]
SJS	Industry-based southern Jiangsu
IWRM	Integrated water management
LR	Leaching requirement, [mm / day]
LCA	Life cycle assessment

Max EC_e	Maximum tolerable Electrical conductivity of the soil saturation extract, [dS/m]
EC_e	Mean electrical conductivity of the saturation extract for the root zone, [dS / m]
CJS	Middle-type central Jiangsu
MU	Municipal unit
R_n	Net radiation, [MJ / m2 day]
NVWI	Net virtual water trade, [m3/year]
A_{CP}	Planted area for each crop in each polygon (he)
P_{CP}	Production for each crop in each polygon (ton)
γ	Psychrometric constant, [kPa /°C]
RAW	Readily available water, [mm]
b	Reduction in yield per increase in ECe, [% / (dS / m)]
ET_o	Reference evapotranspiration [mm/day]
D_{ri}	Rice soil water depletion on day i, [mm]
$D_{(ri-1)}$	Rice soil water depletion on day i-1, [mm]
D_r	Root zone depletion, [mm]
e_s	Saturation vapor pressure derived from air temperature, [kPa]
Δ	Slope of the vapour pressure curve, [kPa/ °C]
G	Soil heat flux density [MJ / m2 day]
p	Soil water depletion fraction, [%]
D_i	Soil water depletion on day i, [mm]
D_{i-1}	Soil water depletion on day i-1, [mm]
Appl	The application rate of chemicals to the field per hectare, [kg/ha]
CWE	The comprehensive water efficiency
CPWF	The crop production water footprint
Y	The crop yield, [ton/ha]
C.W.P	The economic water productivity, [$/m3]
$C.W.P_{Ex}$	The exported economic water productivity, [$/m3]
$WF_{\text{Exported country}}$	The exported water footprint, [m3/ton]
WF_{grey}	The grey water footprint, [m3/ton]
$C.W.P_{Imp}$	The imported economic water productivity
VW	The imported virtual water
$WF_{\text{import country}}$	The imported water footprint, [m3/ton]
GIS	The integration of geographic information systems
α	The leaching-run-off fraction, [dimensionless]
c_{max}	The maximum acceptable concentration for Nitrogen, [kg/m3]
c_{nat}	The natural concentration for Nitrogen, [kg/m3]
NCP	The North China Plain
h	The Plant height for each growth stage, [m]
F_{prod}	The product fraction, [dimensionless]
SWAT	The Soil and Water Assessment Tool
WF_{tot}	The total water footprint, [m3/ton]
WD	The water dependency, [%]
WF_{prod}	The water footprint of a product, [m3/ton]
WSS	The water self-sufficiency, [%]
C_{ha}	Total costs per hectare, [$/ha]
C_{ton}	Total costs per ton, [$/ton]

A_{crop}	Total planted area
P_{total}	Total production
TAW	Total root zone available water, [mm]
WU_{crop}	Total water use for a crop
WU	Total water use for a crop, [m3/year]
UTRB	Upper Tigris river basin
e_s-e_a	Vapour pressure deficit, [kPa]
V.W.X	Virtual water exported, [m3/year]
Ec_w	Water electrical conductivity
WF	Water footprint
WFA	Water footprint assessment
WFN	Water footprint network
WFP	Water footprint of crop production
WU_{CP}	Water footprint used by each crop for each polygon ($m^3$of water)
WPL	Water pollution level
WUBR	Water use benefit ratio
WUER	Water use efficiency ratio
u_2	Wind speed 2 m above the ground surface, [m/s]

CHAPTER FIVE

SUMMARY AND CONCLUSION

By Appreciating the water footprint and virtual water trade analysis, many problems (such as inefficient water use, water scarcity, Poor irrigation water management, and bad trade decisions for crops) could be solved. These analyses linked a lot of sectors and issues together so, researchers face great difficulty in using water footprint analysis to overcome the poor integrated water management in water-scarce countries. Water footprint and virtual water trade analysis are used as an index for irrigation consumption and irrigation efficiency; however, this analysis can be used as an integrated water management tool. So, Crop Virtual Water Analysis Model (CVWAM model) was designed and developed using Microsoft visual studio 2019 (C sharp language). The model was divided into three modules:

1- First module: Crop Water Footprint Analysis

2- Second module: Virtual Water Trade Analysis

3- Third module: Distributing one/many crops on cultivated area/nation module

5.1 First module: Crop Water Footprint Analysis

The calculation steps for the module were based on the Water Footprint Assessment Manual **(Hoekstra *et al.*, 2011)**. This module is divided into eight tools, each tool contained three choices (one/many crops, one/many years, and one/many regions). These multiple tools help users to identify the main objective of analysis.

As a case study of this module, the water footprint and virtual water flow analyses for summer, nili, and winter seasons were evaluated for Egypt over 2017 by using the CVWAM model. The chosen summer and nili crops were potato, tomato, cotton, maize, sunflower, groundnut, and soybeans. While studying crops in the winter season were clover, flax, wheat, potato, and tomato.

The results indicated that cotton had the highest blue water footprint (4556.75 m^3/ton) due to the growth period, followed by groundnuts and sunflowers about 2486.8 and 222.9 m^3/ton. While the lowest blue water footprint was for potato nili, potato winter and clover (53.29, 129.3, and 181.6 m^3/ton, respectively) due to climatic conditions and crop requirements. The output data for blue water footprint agreed with **El-Marsafawy and Mohamed, 2021**. The green water footprint depends on yield, governorate rainfall data, and the period of crop growth. The highest green water footprint was for wheat, and cotton about 18.3 and 13.01 m^3/ton. Grey water footprint depends on yield and fertilizer application rate for each crop, it was observed flax and clover have the lowest grey water footprint about 2.98 and 5.30 m^3/ton. The highest value for grey water footprint is about 90.94 m^3/ton for Cotton.

In the summer season, cotton had the highest total water footprint and the lowest Yield (about 4660.71 m^3/ton). While the lowest total water footprint (62.94 m^3/ton) was founded on potato nili. However, in the winter season, the highest yield was for clover, which had a lower water footprint of about 190.01 m^3/ton.

Reference evapotranspiration was estimated by the CVWAM model and calibrated with CROPWAT 8.0 model. A very good correlation was found between the Two models. This calibration was conducted to reference evapotranspiration for each governorate in Egypt and the overall R-square value for reference evapotranspiration was about 0.99.

To make sure that the water footprint calculated using the CVWAM model was accurate, the net irrigation was estimated by the model for each crop in each governorate in Egypt. Then the output data compared with CROPWAT8.0 model data. The overall R-square value for net irrigation between the CVWAM model and CROPWAT 8.0 model was about 0.97.

5.2 Virtual water trade analysis module:

Virtual water trade is a highly complex index because many sectors are linked together. Virtual water trade is influenced by water resources per capita, arable land, geographic distance, and population. So, virtual water trade analysis needs more concentration and observation to make correct decisions.

Virtual water trade (VWT) methodology would be conducted as set out by **Chapagain and Hoekstra (2003; 2004)**. This module is divided into two tools. The first one is virtual water trade for one country (one product/crop or many products/crops), however, the second one is virtual water trade for many countries (one product/crop or many products/crops). The main goal of this module is to estimate virtual water trade easily moreover provides a chance to concentrate on results analysis and future challenges.

As a case study for this module, Egypt's VWT for 149 agricultural products derived from 70 crops in 2017. Detailed results from this analysis were discussed from three perspectives:

a. VWT analysis for crops

According to the results, we should stop importing the following crops: for example, in the cereals group, maize and sweet corn had exported economic water productivity (6.83 and 2.61$/m^3) higher than imported ones (0.27 and 0.61$/m^3). All crops' Forages, Oil, and Fibre crops group, they are better to be export, but flax, cotton, and cotton seed had the highest export economic water productivity (about 3.06, 1.2, and 0.94 $/m^3, respectively). In the Fruit Trees group, olive, peaches, and apples had imported economic water productivity lower than exported. In the Legumes, Roots, and Tubers group, sugarcane, potatoes, peas, chilies, and beans had shipped economic water productivity (16.12, 6.53, 3.5, 2.75, and 2.26 $/m^3) higher than the imported ones. In the Perennial Vegetable and Small Vegetable group, strawberries, tomatoes, watermelon, onion, pumpkins, eggplants, and cauliflowers had more economic productivity for exported quantity units than the imported ones. In Tropical Fruits and Trees, pineapple and banana had imported economic water productivity (3.1 and 0.99 $/m^3) lower than exported one.

b. VWT analysis for countries

For trade strategy between Egypt and world countries, the suggestions have been built on the economic water index because it depends on the water footprint and economic value. From the observed situation in 2017, Ukraine had the highest import VWT with Egypt about 26.85% of total import VWT. Followed by the United States, Australia, Bulgaria, Paraguay, Russia, Uruguay, South Korea, Italy, Spain, and Brazil, where they had 53.45% of total import VWT. However, the export VWT from Egypt to Djibouti was 7.58% of the total export VWT, the highest quantity. About 51.79% of total export VWT was traded from Egypt to Jordan, Qatar, Poland, Russia, Kuwait, Iraq, Oman, United States, Mauritius, Netherlands, Palestinian National Authority, Pakistan, and Germany.

The recommended situation according to economic water productivity (CWP), a 10 $/m^3 of CWP or higher was observed when agricultural products were exported from Egypt to the following countries: Malawi, Togo, Brunei, Zambia, Zimbabwe, Guatemala, Rwanda, Ethiopia, Namibia, Nepal, Eritrea. On the other hand, Norway, Iran, Afghanistan, Eritrea, Belize, Benin, Burkina Faso, Turkmenistan, Qatar, Ecuador, Bosnia and Herzegovina, Costa Rica, Colombia, Honduras, and Croatia had imported CWP of less than 0.5 $/m^3 when import to Egypt.

c. VWT analysis for the continent

Africa had the highest export CWP (6.28 $/m^3) and the lowest import CWP (0.44 $/m^3), so the analysis recommended trading more agricultural products with Africa.

Future factors should be more interesting in virtual water trade, such as the opening of the economy, Sustainable agricultural practices in all countries, and water endowment. Furthermore, comparing this data with global trade and with the national water supply and demand in Egypt. Also, these results need to link with the driving Forces of virtual water trade in Egypt, such as social pressures, physical variables, political forces, customer taste, and quality of products coming from other countries, or exported from Egypt. Finally, the CVWAM model can help to get a virtual water trade analysis for any region or product with little effort, so we save effort and time to insert all previous sectors to analyse and build an optimal nation virtual water trade scenario.

5.3 Distributing many crops on cultivated area/nation module:

This Module consists of two main objectives (analysis for cultivated area and analysis for the nation) so, its divided into two tools as follows:

1. Distributing one crop on cultivated area/nation
2. Distributing many crops on cultivated area/nation

This module, water footprint analysis was employed to find optimal crop planting structures with the objectives of getting minimum total water use and highest economic water productivity. The module variables are water footprint for each crop under study, soil texture, soil salinity, and irrigation method.

As a case study for this module, six scenarios were defined to optimize Egypt's crop pattern, subject to two general constraints. The first constraint is water use efficiency (WUE) and the second one is water self-sufficiency (WSS). The first constraint was applied as increasing WUE by 10%, however, the second constraint was considered two levels of increasing WSS by 10% and 20%. The six scenarios were defined as follows:

1. S1: Crop reallocated, Fixed WUE, Fixed WSS.
2. S2: Crop reallocated, Fixed WUE, With 10% WSS increase.
3. S3: Crop reallocated, Fixed WUE, With 20% WSS increase.
4. S4: Crop reallocated, With 10% WUE increase, Fixed WSS.
5. S5: Crop reallocated, With 10% WUE increase, 10% WSS increase.
6. S6: Crop reallocated, With 10% WUE increase, 20% WSS increase

The results indicated that:

- In comparing the current situation and scenarios S1 and S4:

The total water use for all winter crops in the current situation was about 14.57 billion m^3 however in scenarios S1 and S4 was about 13.83 and 11.31 billion m^3. Therefore, the water saving was about 0.74 and 3.27 billion m^3 when scenario S1 and S4 were applied. In addition to that, the total water use for all summer crops in the current situation was about 23.12 billion m^3 however in scenarios S1 and S4 were about 22.64 and 19.28 billion m^3, respectively. Scenario S1 produced the same quantity of crops with saving in water and area, without any changes in water footprint in the current situation. The total water uses for all winter crops decreased by 22.41% when water use efficiency increased by 10% in scenario S4. So, it’s recommended to use scenarios S1 and S4 because these scenarios achieved the objectives of this module.

- In comparing the current situation and scenarios S2 and S3:

The total water use for all winter crops in the current situation was about 14.57 billion m^3 however in scenarios S2 and S3 was about 20.9 and 20.5 billion m^3. In addition to that, the total water use for all summer crops in the current situation was about 23.12 billion m^3 however in scenarios S2 and S3 were about 27.40 and 30.40 billion m^3. Scenarios S2 and S3 produced a higher quantity of crops than the current situation due to an increase of about 10% and 20% in WSS, without any changes in water footprint in the current situation.

- In comparing the current situation and scenarios S5 and S6:

The total water use for all winter crops in the current situation was about 14.57 billion m^3 however in scenarios S5 and S6 was about 18.40 and 17.84 billion m^3. In addition to that, the total water use for all summer crops in the current situation was about 23.12 billion m^3 however in scenarios S5 and S6 were about 23.60 and 25.58 billion m^3. Scenarios S5 and S6 produced a higher quantity of crops than the current situation due to increase of about 10% and 20% in WSS, with changes in water footprint according to increasing in WUE by about 10% in the current situation.

Finally, it's recommended to use the CVWAM model in:

- water footprint analysis for its ease and accuracy of results where, the CVWAM model give a chance for researcher to study multi variables factors in the same research.
- virtual water trade analysis under three levels: agriculture crops, countries, and continents.
- Distributing many crops on cultivated area/nation module, this module employed water footprint analysis to find optimal crop planting structure with the objectives of minimum total water use and highest economic water productivity.