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Geographic information systems-based framework for water–energy–food nexus assessments

Anas Azzam [a,b,d,*], Ghada Samy [a], Mona A. Hagras [a], Rasha ElKholy [c]

[a] Ain Shams University, Faculty of Engineering, Irrigation & Hydraulics Department, 1, Elsarayat St., Abbaseya, 11517 Cairo, Egypt
[b] NuriWEF Company, Obour city, Qalyubia Governorate, Egypt
[c] National Water Research Center, Cairo, Egypt
[d] Delphy, Agro Business Park 5, 6708 PV WAGENINGEN, The Netherlands

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ABSTRACT

This study introduces a developed Water Energy Food nexus (WEF) framework based on Geographic Information Systems. The objective of the developed framework is to enable stakeholders in Food, Water, and Energy sectors to evaluate resources utilization for sustainable productivity. The framework shows that the interdependence of water and energy requirements can be modeled using public domain data. Three different scenarios were structured using five components: location of the farm and market, irrigation system, crops and area. The scenarios were applied in the study area which is Moghra as a part of the Egyptian national 1.5 million feddan project to investigate the effect of crop type, size and location of the farm on the water and energy consumption. Based on the scenarios' results, the model is a helpful tool for stakeholder to include their data in the model to design their scenarios to get quantitative and spatial information about the WEF.

1. Introduction

The goal of the nexus method is to formalize linkages and provide tools to evaluate resource utilization [8]. It's a system-wide strategy that acknowledges the food, water, and energy sectors' intrinsic resource interdependencies, attempts to maximize trade-offs, and synergies as well as considers social and environmental implications [4]. Understanding the connections between food, energy, and water may lead to more efficient resource usage, as well as improved cooperation and policy coherence between the three sectors. The nexus viewpoint should help in the promotion of cross-disciplinary and mutually beneficial actions [34].

Planning for water, energy, and food requirements necessitates studies and tools that aid decision-making, employing a multi-criteria analysis. As shown by a number of studies, various different WEF-Nexus approaches have been described [12,6,8] and usually conclude that a nexus approach should be used when making policy decisions in any of the areas of water security, energy security, or food security rather than acting independently [5,23]. This concept can even be extended to transportation Infrastructure, renewable energy Sources, and economic Growth [41].

Although significant advances have been made by the scientific community to comprehend and quantify persisting challenges, open questions still remain on how information could be applied most effectively to truly support evidence-based policy and decision-making. Endo and colleagues concluded in a recent *meta*-review [12] that "there are no standalone methods and tools for practicing and implementing the nexus approach" and hence "a nexus methodology should be developed by combining multiple methods and tools, including qualitative and quantitative, and natural and social science mixed methods". Similarly, [29] found that "the similarity index between the content messages of the academic articles and the project implementers' reports show a low similarity" indicating an "imbalance in understanding and adapting nexus concepts" In addition,Taguta and coworkers [37] observed that there "is a critical mismatch between the requirements of geospatial capabilities in most WEF nexus tools and the dynamic nature of WEF resources whose nexus they are supposed to quantify, analyse, and visually map". Therefore, there is still a need for a general, comprehensive framework that takes into account interconnections between the systems and uses geographic information system to provide decision- and policymakers with a strong framework for deliberation, discussion, and action.

By starting the 1.5 million Feddans project, Egypt took important steps towards greening the desert and building new communities to produce more food locally, create more jobs and increase commercial activities. The 1.5 million feddan project is the first

* Corresponding author at: Ain Shams University, Faculty of Engineering, Irrigation & Hydraulics Department, 1, Elsarayat St., Abbaseya, 11517 Cairo, Egypt.

E-mail address: a.azzam@delphy.nl (A. Azzam).

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step of a four-million-feddan redevelopment plan. According to the 2030 strategy, the project aims to increase agricultural land by 20% while also creating promising investment opportunities in a variety of fields, including agricultural land reclamation, food industry projects, and logistics areas, as well as developing these urban areas to create an integrated and sustainable environment [35,1]. However, in the past "Egypt's Desert Dreams" of occupying and greening the desert have proved challenging and good planning, as well as sound resource utilization, are required to achieve ecological, cultural and socioeconomic sustainability [36].

The main goal of this research is to further the development of a framework through GIS linked models for WEF nexus Assessment. The target is modelling different forms of water and energy consumption rates and correlate them to different crop patterns, to enable the user to choose the best scenario for sustainable productivity. Towards achieving this goal and maximising food production, a multi-stage methodology was adopted: first, a literature review was conducted on WEF nexus assessment approaches to identify the key WEF performance indicators as well as their existing assessment algorithms, and to collect all necessary data and information on the investigated case study area. Using the data gathered in the first stage, for each of the studied crops, WEF interrelationships were assessed and assembled into a functional model. Furthermore, a geospatial data analysis of the generated outcomes, using the ArcGIS platform, was performed to visualise and investigate the WEF potential for each proposed crop.

2. Tool design principles

2.1. Operating procedure

The operational procedure of the model is shown in Fig. 1, which shows the data flow between the three main parts, which is available data and data input, calculation, and results. First, data input is designed, so users can enter their chosen parameters for a specific scenario as described below. The databases utilised in the Model include geodatabases and non-geodatabase, as detailed below. Second part includes the employed formulae and equations described below. Based on the inputs provided by the user and scenario settings relevant values are retrieved form database and processed, using the formulae and equations for measuring and simulating the WEF nexus assessment. Finally, the results of the model are saved as a table in Excel file format which provides estimates for total water and energy requirements (direct and indirect energy consumption) as well as crop yields. The main objective of these calculations is, to assess the sustainable productivity of the farming sector by modelling different forms of water and energy consumption rates and correlating them to different crop patterns.

2.2. User interface

The model has been built using ArcPy. ArcPy has been selected because of its demonstrated practical and efficient method for using Python, to execute geographic data analysis, data translation, and data management. The model has been written on ArcPy and transferred to be toolboxes that can be run on any ArcGIS software.

3. Technical background

3.1. Conceptual model

The suggested conceptual framework provides a basis to describe the interconnectedness between the three systems. In order to accurately evaluate various different scenarios and to provide guidance for decision-making, explicit quantification of these linkages is essential, by calculating the following:

- Total energy requirement (direct and indirect energy consumption) for the scenario
- Total water requirement for the scenario (m^3/ha and m^3/ area).
- The Estimated food production

Fig. 2 depicts inputs and outputs representing food, water, and energy that enable the design and evaluation of multiple scenarios at different locations. In the block diagram Fig. 2, the value of a pixel of each raster is identified by the input location by the user, and the other inputs from the user select the specific values from the other database. In the end, the user builds the scenario by selecting one of the options below:

- Location: is used to get the values from raster (GIS Static data) like evapotranspiration, water salinity, groundwater level . . .etc.
- Irrigation system: is used to determine irrigation efficiency, and water head to run the irrigation system.

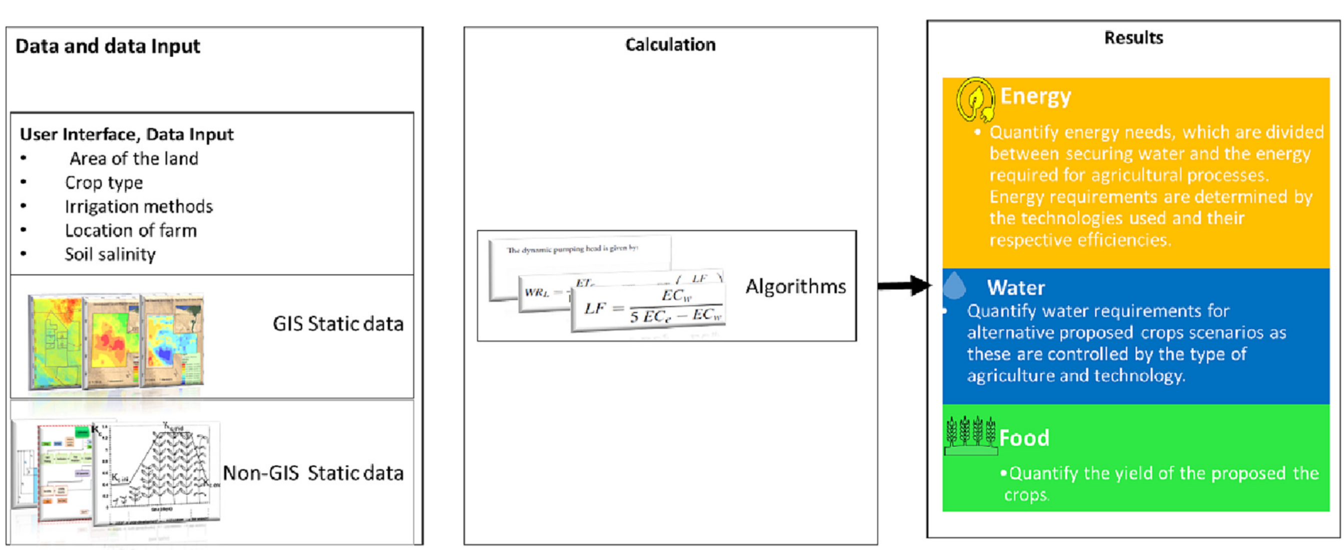

Fig. 1. Operating procedure of the model.

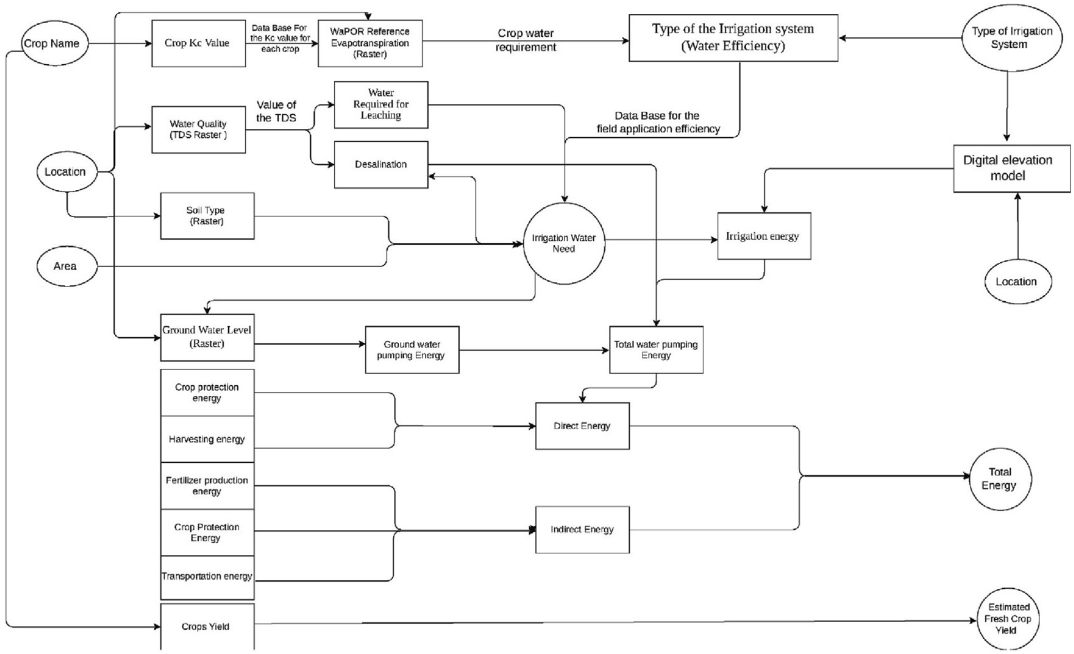

Fig. 2. Block diagram demonstrating the water–energy–food nexus framework.

- Crop: is used to calculate the irrigation recruitment from the Kc value, number of days for the growing period and fertilization needs.
- Location of the market is used to calculate the average estimated transportation energy consumption.
- Area of the land is used for scaling and to calculate the average irrigation head, depending on the surrounding topography.
- Soil salinity: used to calculate the water requirements for leaching and estimated desalinisation requirements.
- Spacing between the trees or crops is a function on the work width on (Eq. (10)), used to calculate the cultivation and harvesting energy.
- The start and end months are used to obtain estimated values from the climate rasters.

The amount of water needed (m3) for a proposed crop depends on the plants' water requirements, which are predominantly affected by the climate, the type of irrigation system, timing and the technology used, soil type and water salinity. Other factors, like plant variety are increasingly likely to play a role, but due to lack of available structured data, were not considered in this version of the model. Energy is required to secure water through pumping for the irrigation system and groundwater.

In addition to the energy required to secure water, energy is also needed for food production, including cultivation, harvest, fertiliser production and logistics, like local transport. To cater for the selected scenario, because its aim is to provide input for stakeholders in newly reclaimed desert areas, including the study locations used to test the model.

Food products are quantified in tons (t). Depending on the type of food product and their respective local yields (tone/hectare).

Based on the aforementioned inputs and the characteristics of the study area, all values will be calculated through the equation on section 3.3 and the tool evaluates the set scenario.

3.2. Data

The model utilises two kinds of data, first the input data which are entered into the model by the user. Second, the databases used in the model which are utilised for particular sites or scenarios, as described below.

3.2.1. Model data requirement

Several vector layers, databases, and remote sensing Data were used to achieve the model's objective. These include the following datasets to investigate the spatiotemporal variability of water evaluation, energy consumption, and food production, to delineate the nexuses. Table 1 lists datasets, data types, and spatial scope.

3.3. Model calculation

3.3.1. Water consumption

The water requirement (in m^3), which refers to water consumption, is categorised based on the following parameters.

1. Crop water requirement. A crop's rate of evapotranspiration (measured in millimeters per day) is influenced by its growth stage, the environment, and crop management practices to maximize crop output. Etc calculated by means of the penman monteith equation (Eq. (1)) [3].

$$ETc = Kc \times ETo \tag{1}$$

ETc: crop evapotranspiration (mm/day).

Kc: presents the crop factors for the three crops stages utilised and were retrieved from FAO [3].

ETo: reference evapotranspiration, values are collected as raster for 12 months though API from WaPORFAO portal [13].

2. Water requirement for Leaching The amount of irrigation water needed to remove the excess salt from the root zone depends on the leaching fraction, which is calculated from Rhoades, 1974 as follows.

$$LF = EC_w/5EC_e - EC_w \tag{2}$$

$$WRl = ETc \times LF/1 - LF \tag{3}$$

LF: the minimum leaching requirement fraction.

ECe: the average soil salinity tolerated by the crop as measured on a soil saturation extract (dS/m), entered by the user. Alternatively, it can be taken as 1 dS/m (default).

Table 1
Data type and description.

	Data Set	Description	Data Type	Spatial scope
1	Boundaries	present the boundaries of the study area and its climatic zone	Vector polygon	Water/Energy demand
2	Local single crop coefficient (Kc) for the proposed crops	The crop coefficient (Kc value) describes the crop type and its development. Depending mainly on the growth stage of the crop, the type of crop and the climate, a single crop may have three-Kc values. The model incorporates the Kc values for the proposed crops, as published [3]	Database Table	Water Demand
2	Elevation (DEM)	Depicts the topographic surface of the earth's bare ground (bare earth) without trees, buildings, or other surface covering. The DEM used on the model for calculation of the dynamic from topographic maps. The DEM used in the model is developed by the United States Geological Survey (USGS) [38].	Raster	Water/Energy demand
3	Solar radiation	Solar radiation is the most significant energy source, capable of converting significant amounts of liquid water into vapour [3], and pivotal to consider when building PV facilities. For efficient use of solar resources, it is therefore required to identify regions with high levels of solar radiation, based on forecast, as well as geographical and temporal distribution [7]. Furthermore, it effects evapotranspiration and plant growth.	Raster	Water Demand/ Energy Supply
4	Groundwater level	data processed using ArcGIS tools for interpolation predicting values for cells in a raster using data from water wells (points) as basis.	Raster	Water/Energy demand
5	Fertiliser amounts required for different crops	Fertiliser use by crop as reported by the Food and Agriculture Organization [14], It considers the average fertility status of Egyptian soils and the production, imports, exports and consumption of fertilisers. The database generated from the report was used as one reference for indirect energy consumption.	Database Table	Energy consumption
6	Groundwater quality	data processed using ArcGIS and interpolation to predict the value for each cell in a raster, based on data of total dissolved solids from water wells	Raster	Water/Energy demand
7	WaPOR (Reference Evapotranspiration)	predicts the behaviour of a well-watered grass surface and is defined as the evapotranspiration from a fictitious reference crop. Each pixel's value corresponds to the total daily reference evapotranspiration for that particular month [13]. The model connects with the WaPOR portal through an Application Programming Interface (API(to get the value of the Reference Evapotranspiration from the input location	Raster API	Water Demand
8	(WaPOR) Precipitation	Data derived from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) quasi-global rainfall dataset, which covers the years 1981 to present. The value of each pixel represents the year total of daily precipitation in mm [13]. The model connects with the WaPOR portal through an API to get the value of the effective Precipitation from the input location	Raster API	Water supply
9	Crop Yield	Yield in tons (t) (" [17]. Food and Agriculture Data.," 2022)	Database	Food production

EC_W: the salinity of the applied irrigation water (dS/m). ECw is coming from the water quality raster (TDS), and it includes an equation to switch from PPM to dS/m.

WRl: the leaching water requirement.

3. Effective precipitation The effective component of the precipitation which utilized by plants is the water retained in the root zone. It can be calculated by Eq. (4) [3].

$$Pe = 0.7 \times P \tag{4}$$

P presents precipitation. It was collected as raster for the 12 months connected through API to the portal WaPor FAO. The value of each pixel represents the total of daily precipitation in the month expressed in mm (1 mm = 1 L/m^2).

4 Crop water Need.

It is the quantity of water required for different crops to thrive at their best.

$$NIR = (ETc + LF) - Pe \tag{5}$$

NIR: The irrigation water requirement during the growing period.

Etc: crop evapotranspiration [mm/day] for the month, calculated through Eq. (1).

LF: leaching [mm/day], calculated through Eq. (2 and 3).

Pe the effective precipitation [mm/day], calculated through Eq. (4).

5 Seasonal scheme water demand (m^3).

it is one of the main elements for estimating the electrical consumption necessary for pumping throughout a season.

Seasonal scheme water demand M3 = Monthly crops water needed × Crops area × Irrigation efficiency.

Where:

The Monthly water crops needed is calculated by.

Monthly water crop water needs (m^3/ha) = NIR*10.

Where NIR is a net irrigation requirement which calculated by Eq. (5).

Crop area: the area of the land input by the user.Irrigation efficiency: taken from the model database.

3.4. Energy consumption

Energy requirements for agriculture can be divided into direct and indirect energy demands. Examples of direct energy include energy used for land preparation (including lowing, tilling, and seeding), cultivation (including weed control applications), irrigation, harvest, post-harvest processing, food production, and storage of agricultural inputs and outputs. All of these activities are directly measurably at the farm or further down the agro-food value chain. On the other hand, sequestered energy is regarded as indirect energy and can be found in fertilizers, herbicides, pesticides, and insecticides [15].

- Direct Energy.

1 Energy requirement for pumping (PE).

The energy consumed to supply irrigation water from the water well and via the irrigation system. The following formula is used to calculate the amount of electrical power required to drive the pump motor:

$$P_e = Q(\rho g h)/\mu\left(3.6 \times 10^6\right) \tag{7}$$

P_e: power delivered to the fluid by the pump expressed in kW.
Q: fluid flow expressed in m^3/h,
ρ : fluid density expressed in kg/m^3 (water),

h: differential head expressed in meters.

μ : pump efficiency.

g: acceleration of gravity (9.81 m/s^2).
2 Harvesting energy (HE).

Harvesting energy refers to the volume of diesel fuel consumed (in litres per hectare) to power the tractor needed to cultivate the land. The harvesting energy calculated by (Eq. (8)) [24].

$$HE = HHV \times CF \tag{8}$$

HE: the amount of energy consumed as diesel fuel to operate a tractor used to harvesting the field.
HHV: the higher heating value of diesel fuel (41.24 MJ/kg).
CF: the amount of fuel required in L/ha calculated by [24] as followed:

$$CF = TDC \times \tau \tag{9}$$

TDC: the tractor diesel consumption (L/h).
τ: the seeding time or the harvesting time (h/ha) and by [25] as followed.

$$\tau = 1000 workwidth \times (Workspeed \times 1000) \times effectivness\% \tag{10}$$

Regarding the Guide for Machinery Cost, the diesel consumption of a harvesting machine with a 140 kW engine is 7.50 L per hour [25]. At the same time, the working width, speed, and effectiveness are six meters, 5.0 km/h, and 90%, correspondingly. As a result, the harvesting time (t) is projected to be 0.37 h per hectare.
3 Cultivation energy (CE).
cultivation energy is the amount of diesel fuel needed (measured in litres per hectare) to power the tractor and operating the machinery used to cultivate the land, (Eq. (8)) is used to determine the Cultivation energy (Eq. (9)) is used to get the value of the CF, while (Eq. (10)) is used to determine the value of.τ
According to Lubbe and Archer [25], the fuel consumption of a 4 wheel drive (4 WD) regular-size tractor is 3.62 L/h the working width, working speed, and effectiveness are 1.5 m, 3.0 km/h, and 85 percent, respectively [24]. As a result, the CE and t (seeding time) are projected to be 2.6 h/ha and 9.4 L/ha, respectively.
4 Desalination Energy.
Over 80% of the desalination brackish water is produced using reverse osmosis (RO), which dominates the desalination capacity worldwide [20]. [30] calculated the energy consumption of the RO (without energy recovery) as a function of salt removal (Rs), shown in Fig. 3 which has been included in the model to calculate the energy consumed by desalination depending on the feed salinities. The value of the feed salinity (groundwater salinity) got from the water quality raster by the location. The model is developed to neglect calculation of desalination energy when the value of the feed salinity is less than 2000 ppm.
5 Total direct energy consumption (DE).
The summation of energy consumed by machinery used for field operations, including preparing and maintenance in the field, irrigation, and harvesting of the product.
The direct energy is calculated by (Eq. (11))

$$DE = PE + HE + CE \tag{11}$$

PE: the energy requirement for pumping.
HE: the harvesting energy.
CE: the cultivation energy.

- Indirect Energy.

1 Fertiliser production energy (FE).
The energy needed to produce the three main types of mineral fertilisers: potassium, phosphorus, and nitrogen. Based on the results of Lewis and Kongshaug [22,21], nitrogen (N) fertiliser (40.3 MJ/ kg), phosphorus (P) fertiliser (8.6 MJ/ kg), and potassium (K) fertiliser (6.4 MJ/ kg) are the three relevant elements. Consequently, the following equation is used to get the FE (MJ/ha):

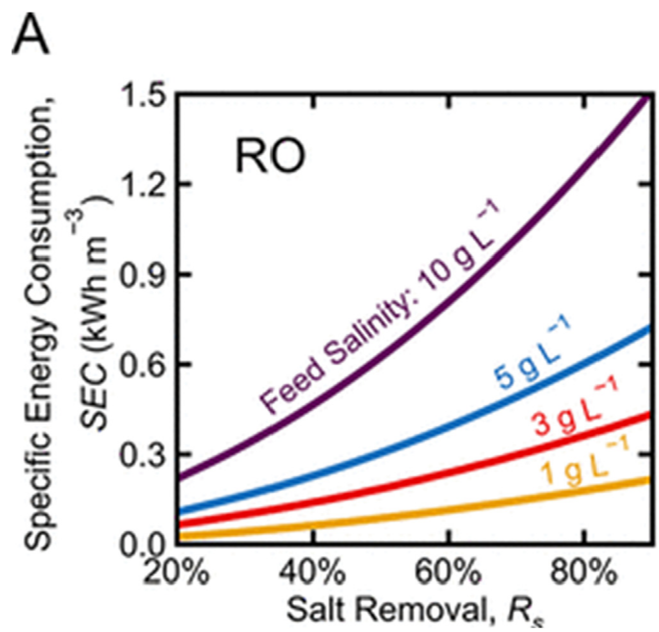

Fig. 3. Energy consumption for RO ([30]).

$$FE = 40.3 \times N + 8.6 \times P + 6.4 \times K \tag{12}$$

The value of the N, P, and K included in a database is specific for each proposed crop in the study area. Due to the lack of available structured data sets, soil type and other parameters (like farming method – eg. no tillage) that determine fertiliser requirements can currently not be considered in the model.
2 Transportation Energy (TE).
It represents the energy needed to go back and forth from the farm (TF) to the market (TM).

$$TE = 2 \times Fuel\,consumption \times HHV \times TF + TM\,FieldArea \tag{13}$$

Fuel consumption: According to Lubbe and Archer [25], for a truck size of 8 t, the fuel consumption rate is assumed at 30.0 L diesel/100 km.
HHV: the higher heating value of diesel fuel (41.24 MJ/kg).
TF: present the farm location, entered by the user.
TM: the nearest market for the selected crop, entered by the user.
Due to the lack of structured data on truck type and size, loading capacity, road quality, permissible and realizable speeds etc, actual fuel consumption can not be estimated more precisely.
3 Crop protection energy (CPE).
The crop protection energy is the energy needed to produce fungicides, insecticides, and herbicides (I, H, F). The energy conversion factors of insecticides, herbicides, and fungicides are 200 MJ/ kg, 240 and 96 MJ/kg respectively [16]. Hence, the CPE (in MJ/ha) is calculated as shown in Table 2.
4 Total indirect energy consumption IE.
Consumption comprises of energy consumed to refine oil into diesel, transport and distribution of processed fuels, energy consumed for manufacturing and maintaining (including lubrication) the machines used, production, storage and transport of seeding materials, production, storage and transport of fertiliser (chemical or natural), production, storage waste disposal and transport of chemicals used.IE can be calculated by (Eq. (14))

$$IE = FE + TE + CPE \tag{14}$$

Table 2
Energy content for Crop Protection input [15].

Input	Typical rate of application (kg/ha)	Sequestered energy (MJ/kg)	Energy content of crop produce (MJ/ha)
Insecticide	0.14	200	28
Herbicide	5	240	1,200
Fungicide	3	92	276

FE: Fertiliser production energy (MJ/ha).
TE: Transportation Energy of consumable inputs (MJ/ha).
CPE: Crop protection energy (MJ/ha).

3.4.1. Food yield

The FAOSTAT database is considered the primary source of the database of the food production for each crop. It is based on official and estimated, FAOSTAT offers a useful preliminary assessment of country-specific agricultural activity. However, currently, the FAOSTAT database cannot be used to estimate crop yield at local scales or to get more accurate, site-specific data. Recent research efforts [19] indicate that in the future, monthly physical area data on production, yield, and harvested area might become available.

3.5. Model assumptions

Historical data on solar irradiation and precipitation are considered sufficiently predictive for future events. Evapotranspiration is considered representative of a large variety of crop varieties [18]. Similarly, fertilization requirements and the use of crop protection agents assumes conventional agricultural methods. However, breeding efforts concentrate on better water management in plants, and organic agriculture significantly impacts fertilization requirements, the use of crop protection agents, and crop yield, but might also influence the water storage capacity of the soil and yield. Hence the inclusion of further parameters and correction factors for water requirements might become pertinent once validated structured datasets become available.

Similarly, the model assumes an off-grid scenario, with PV-supplied electricity, and diesel-driven machinery. It also assumes the average efficacy of PV panels to remain constant, necessitating regular cleaning in dusty environments, the availability of sufficient energy and water storage and/or the alignment of solar energy provision with energy needs although advances have been mad recently to model photovoltaic system performance under varying condition [10]. Since irrigation is most effective between dusk and dawn, suitable correction factors remain to be determined and implemented. Other energy-related assumptions include the aforementioned fertiliser production, but also factors for harvesting and transportation. Currently, no suitable structured data are available to differentiate between different storage and transportation requirements, for example for vegetables, grains or fodder crops.

Last, but not least, crop yield is currently determined by FAOSTAT data and area size, assuming that water and fertiliser availability allow for predictable growth. However, soil type, water quality, solar irradiation, cultivation method, are also likely to have an impact thus providing the opportunity to refine the model, once suitable datasets become available. Thus, the current use of average values that might improve by adding further complexity to the model.

4. Model implementation

4.1. Data entry

Specific data are entered in a simple mask as shown in Fig. 4. It requires essential data including inputs on location and area, used irrigation system, salinity and crop, targeted market or retailer, spacing and density, the month of planting and harvesting. It thus allows the comparison, of different scenarios, or changes of one or more parameters.

4.2. Study area

Several regions were considered in the areas of the 1.5 million feddan desert reclamation project implemented by the Egyptian Government, for initial evaluation of the model. They encompassed different climate zones, groundwater levels, water quality

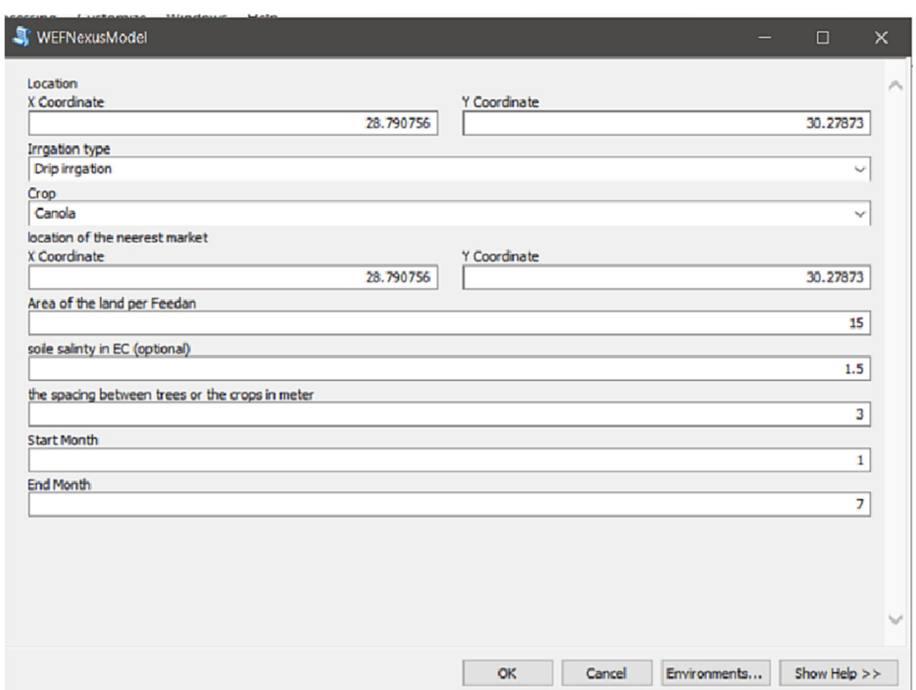

Fig. 4. Model data entry.

scenarios, etc. They were identified on the basis of being as diverse as possible, by being connected to different aquifers, in different climatic zones, with different levels of solar radiation. Variation in soil quality was also considered but with less priority, because it is quite heterogeneous within each region. Based on these initial considerations and the availability of local data, the Moghra region was identified as best suited for initial characterisation of the model.

Moghra region is located between longitudes 28° 10′ and 29° 10′ E and latitudes 29° 50′ and 30° 41′ N in the northeastern extension of the Qattara Depression, about 250 Km from Cairo city. It has a total area of about 245,000 feddans (approx 103.000 ha) [40]. The highest average temperature in Moghra Oasis is 41.4 °C in August and the lowest is 10.7 °C in December. The humidity varies from 39.5 % in December to 19 % in June. Wind speed is at its highest point in September (3.7 m/s) and at its lowest point in January and February (2.8 m/s). The yearly precipitation in this region fluctuates between 25 and 50 mm, which is insufficient for normal plant growth or rain fed agriculture [28,39]. Due to saline lakes to the east, seepage of saltwater from the Mediterranean Sea in the north, limited groundwater recharge, and leaching of clay and shale layers, the Moghra groundwater is brackish with TDS generally reported to vary from 3090 ppm to 5350 ppm with an average of 4220 ppm. To the north-west, ion and TDS concentrations rise. Due to the alkaline chemical makeup of the aquifer rocks and the influence of the ocean, the Moghra aquifer has pH values that vary from 7.2 to 8.7 with an average of 8.0 [35]. Previous studies on sustainable groundwater management in Moghra indicate that using 1000 wells to harvest 1.2 Mm^3/d of water for a total area of 85,714 acres is the optimal management scenario (360 km^2). The project requirement that allows a maximum drawdown of less than 1 m/year is satisfied by this scenario [33,32].

4.3. Scenario and location descriptions

There are three scenarios investigated in this study to show the developed model capabilities. Scenario one is designed to show the effect of the change in the size of the farm. Scenario two is designed to show the effect of change of the crops type at the same site and finally scenario 3 is designed to show the impact of change the location of the farm on the water and energy consumption.

Table 3 summaries the components of each scenario: location of the farm, irrigation system, crops, location of the market and area. Five locations for farms have been selected and two locations as a market as shown in Fig. 5.

Table 3
The three scenarios inputs on the model.

Scenarios	Location of the Farm	Irrigation system	Crops	Location of the Market	Area (Hectare)
Scenario 1	Location 2	Sprinkler irrigation	Canola	Market 1	Changeable
Scenario 2	Location 2	Drip irrigation	Sorghum Sunflower Olives Wheat Canola Bean (green)	Market 1	8.4
Scenario 3	Location 1 Location 2 Location 3 Location 4 Location 5	Drip irrigation	Canola	Market 2	8.4

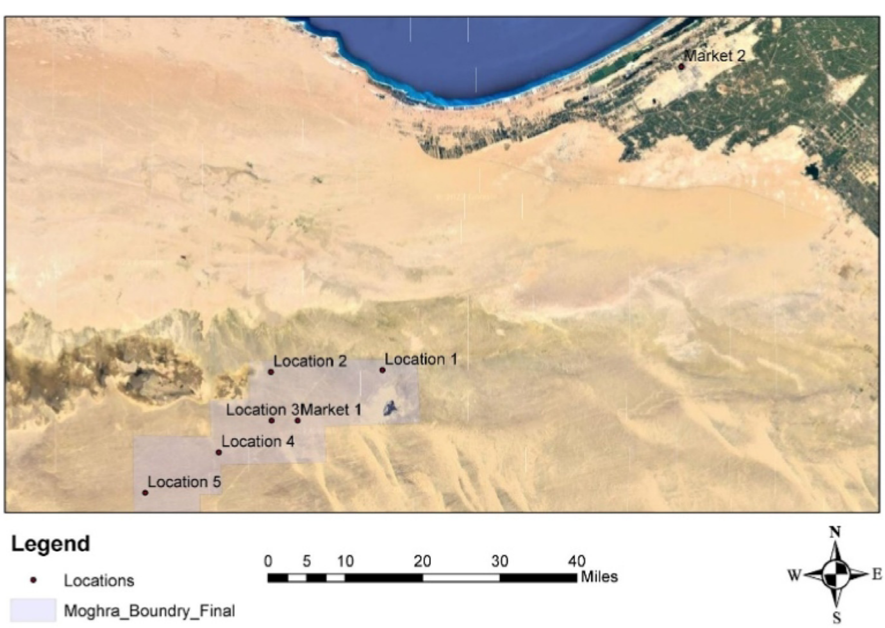

Fig. 5. Locations of the different Scenario on the case study area.

4.4. Results and discussion of model outputs

4.4.1. Scenario one

Scenario one is designed to show the effect of the change in the size of the farm on the results of the model. Therefore, the input data like sprinkler irrigation system, canola crop, location one and location of the market are fixed for eight different farm area values. As would be predicted, increasing the area used at any location increases the other values. As shown in Fig. 6 present the relation between the water consumption (m^3) and area (Ha) are correlated. The increase in the area affects the increase in water consumption in a linear manner.

Fig. 7 presents the relation between the energy consumption (MJ) and the area (Hectare) it shows the effect of the area increasing on energy consumption, like the desalination energy requirements, energy requirements for planting and harvesting, as well as fertilizer use and crop protection in a linear manner. The water salinty on this location is around 4000 ppm, which has impact on the energy concumed on the desalination process.

However, the calculation of the water head and the related water pumping energy take into account differences in topography within the area and hence adjusts for water supply requirements to irrigate the highest point identified, as shown in Fig. 8, which present the relation between the area, the difference on elevation and irrigation head.

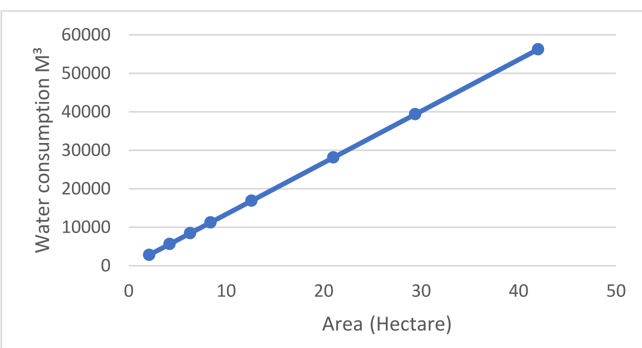

Fig. 6. Scenario one, the impact of change in the size of the farm on the water consumption.

Fig. 9 which presents the relation between the area (hectare) and the energy consumption (MJ). This is one factor that influences the total direct energy consumption, which scales in a non-linear manner. since the volume or weight of the yield and assumed truck size do not perfectly match, and hence efficiency savings can be factored in at scale. Interestingly, additional slight efficiency effects appear to affect the total indirect energy at scale, although this effect does not seem to reach operational relevance.

Since Food production and water consumption are function of the area, the water productivity, which is water consumed in M^3 to produce a value of kg of the canola crop in the exact location is in a linear manner with the size of the farm, as shown in Fig. 10, which present the relation between the area (hectare) and the water productivity.

4.4.2. Scenario two

Scenario two was designed to show the effect of change of the crops type at the same site. Therefore, the input data like drip irrigation system, location of the farm, area and location of the market are fixed for six different crops types. The results of scenario two shows the effect of different crops, planting date and growth durations on water consumption as shown in Fig. 11.

Regarding energy consumption, fertilizer needs are factored according to the crop plant modelled, and the latter have different growth durations, affecting each crop's water consumption. Therefore, modelling different crops at the same site has major effects on all energy related parameters as shown in Fig. 12. As would be expected, these largely remain between sites with similar groundwater and reference evapotranspiration levels but can be exacerbated by the latter further.

The results of the second scenario show that the model is effective as a decision-support tool for the stakeholder to show the effect of different crops on the water and energy consumption.

4.4.3. Scenario 3

Scenario 3 designed to show the impact of change the location of the farm on the water and energy consumption Therefore, the input data like drip irrigation system, area, canola crop, location one and location of the market are fixed for eight different area values. Fig. 13 showed the water consumption and the water salinity level on different locations, which the total water consumption directly correlated with water salinity, due to the influence of soil

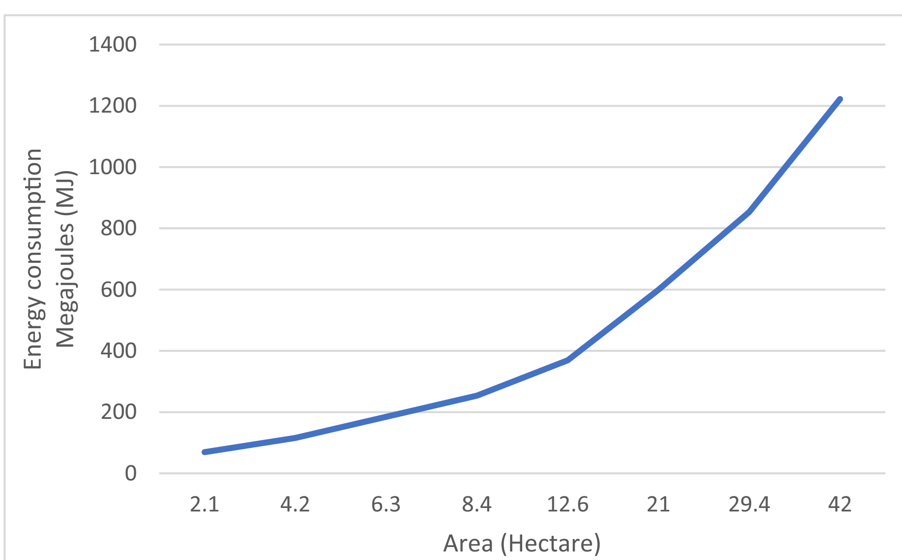

Fig. 7. Scenario one, the impact of change in the size of the farm on energy consumption.

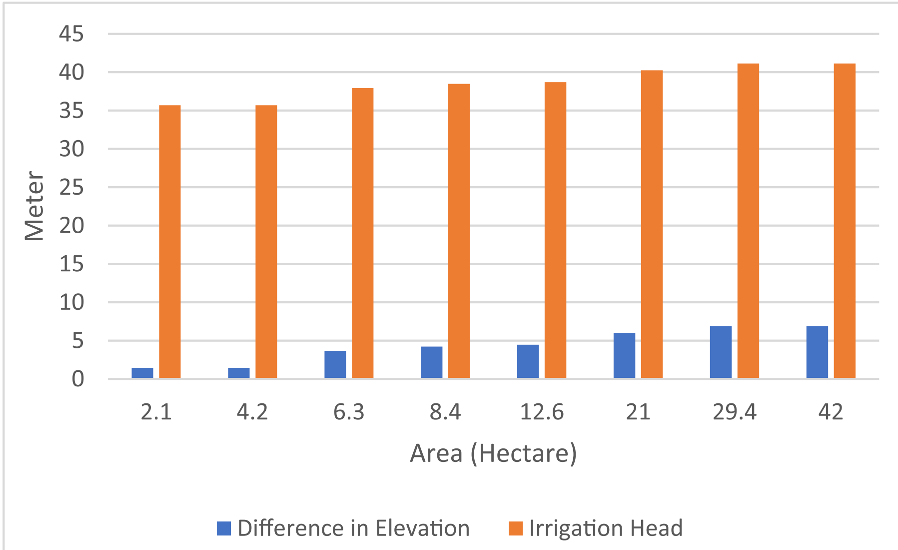

Fig. 8. Scenario one, the impact of change in the size of the farm on elevation and irrigation head.

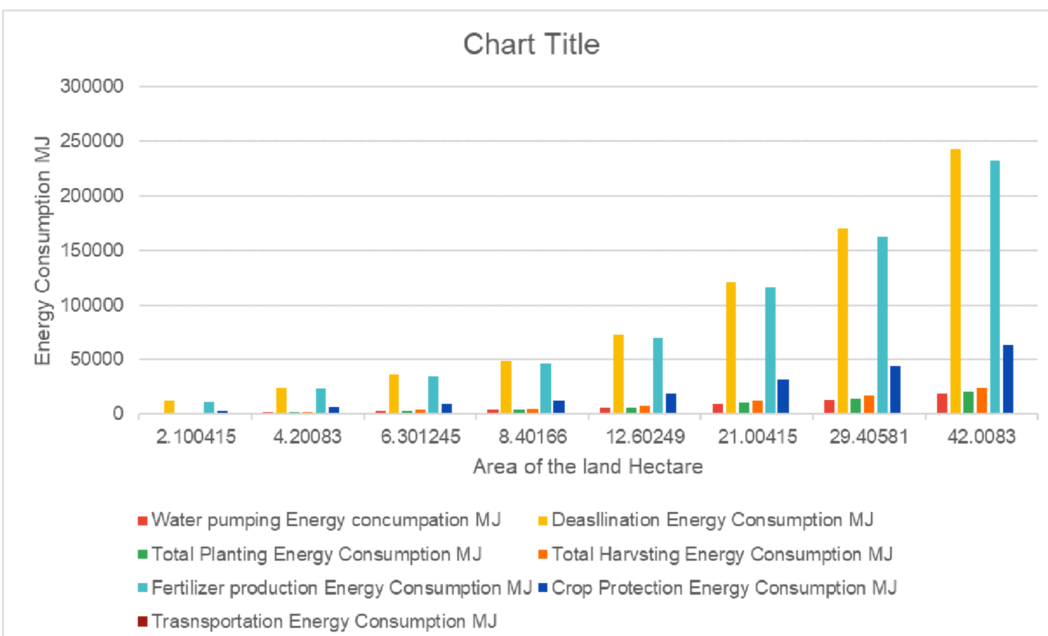

Fig. 9. Scenario one, the impact of change in the size of the farm on Energy Consumption.

salinity, evapotranspiration, and other factors. As mentioned before, salinity below 2000 ppm was not included in the desalination calculations. The effect can be observed in location 3, which has a salinity level of less than 2000 ppm. Water consumption is higher than in other locations, because of the leaching water consumption.

Regarding the energy consumption on scenario 3 as shown in Fig. 14 the indirect energy is fixed because the planting and harvesting as well as fertilizer use and crop protection for a specific crop are the same in any location. The direct energy is variable because the change on groundwater level, elevation, level of water salinity and others.

As shown from the third scenario results, different locations affect the water and energy consumption for a small region in Egypt with approx. 103.000 ha. As a result, the model is effective as a decision-support tool for the stakeholder to show the effect of different locations on water and energy consumption and the advantage of location.

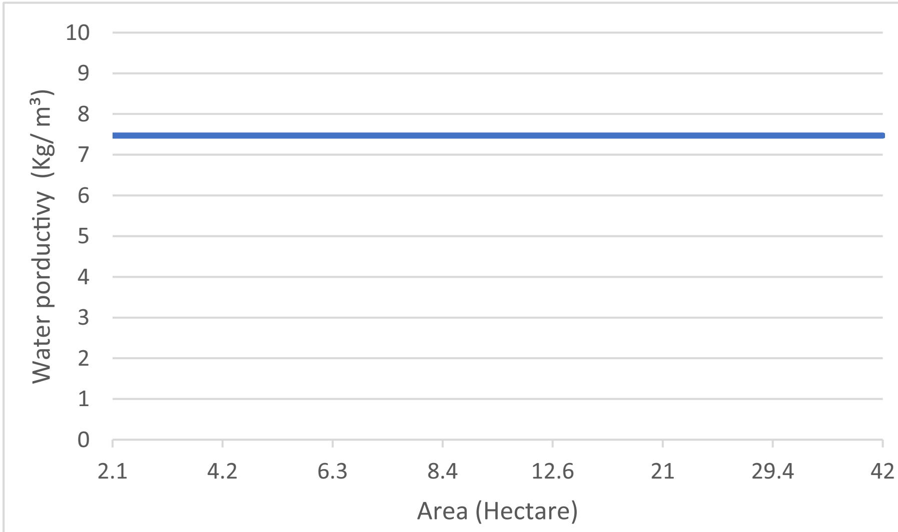

Fig. 10. Scenario one, the impact of change in the size of the farm on water productivity.

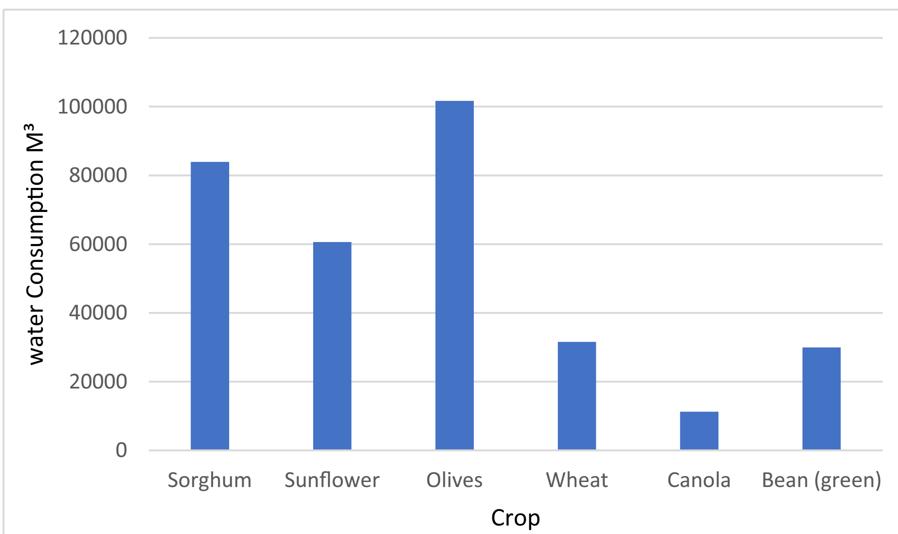

Fig. 11. Scenario two, the impact of change in the type of crop of the farm on water Consumption.

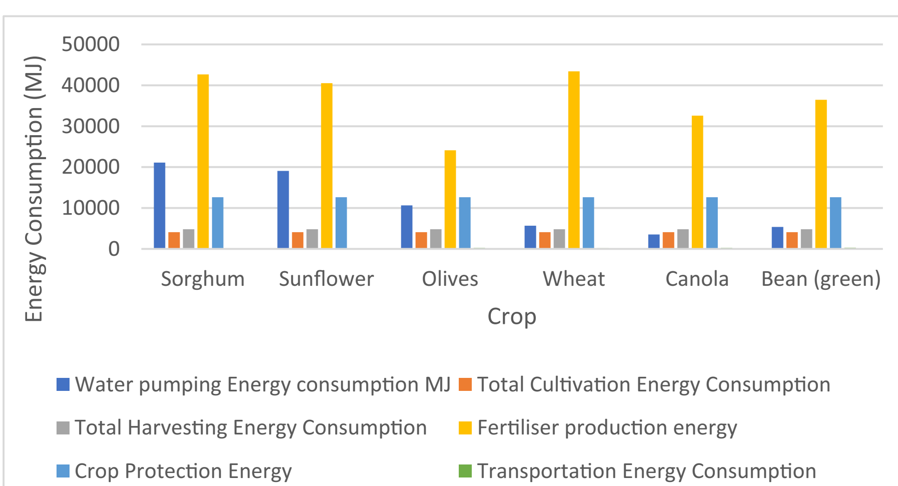

Fig. 12. Scenario two, the impact of change in the type of crop of the farm on Energy Consumption.

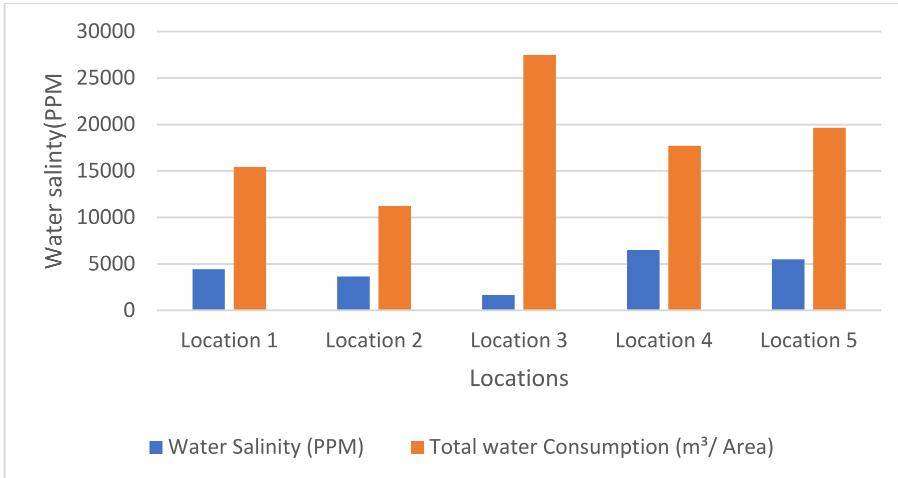

Fig. 13. Scenario three, the impact of change in the locations of the farm on Water consumption.

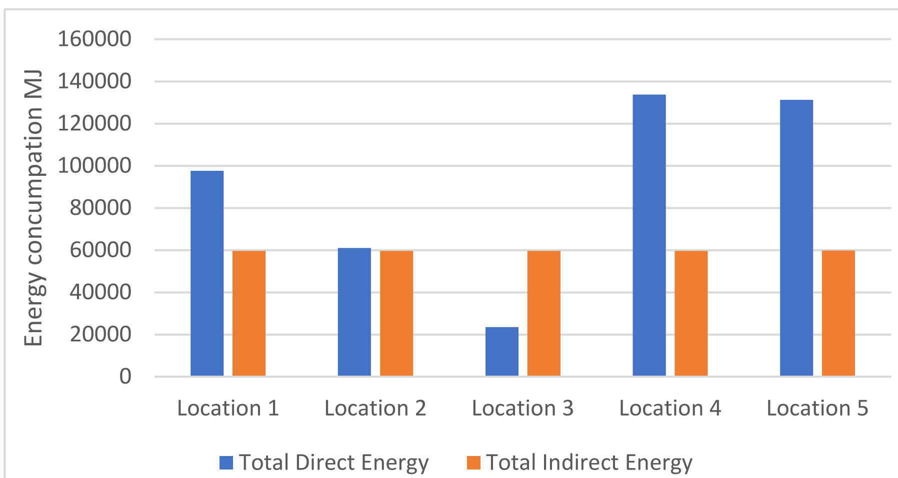

Fig. 14. Scenario three, the impact of change in the locations of the farm on direct and indirect energy consumption.

5. Conclusion

Governments and policymakers need concrete evidence that brings a comprehensive knowledge of the complexity and interconnectivity of factors affecting farm production, water consumption and energy consumption in order to improve evidence-based policy. Constructive intervention techniques could be developed as a result. Additionally, in order to implement a wide range of decisions that lead to more efficient resource usage, a broad spectrum of stakeholders and practitioners in the agriculture sector should be provided with, contribute to and utilize location-specific data The designed tool is the first attempt to connect the WEF nexus through the geographic information system on small-scale farming.to characterise and visualise the complex interactions and dependencies of the Water-Energy-Food nexus. The Model demonstrated that the needs for geospatial capabilities and the dynamic nature of WEF resources are compatible. In addition, the tool enables the user to assess several scenarios and include new data for other regions or even a different country.

As has been observed for other complex systems, it is not feasible to devise models with maximum complexity initially. As has been showcased for climate modelling and predictions about climate change, conceptual models are succeeded by mathematical ones that subsequently incorporate energy balances, developing toward increasingly comprehensive coupled and interlinked representations of the entire system [11]. As argued by [27] using model pluralism can further the study of complex systems that allows the application of a robustness scheme. It is thus not a disadvantage that similar models are being developed elsewhere, based on similar or different assumptions and with a variety of aims. [31] conducted Water-Food-Energy Security Nexus-based dynamic modelling of sustainable groundwater water resources management. Recently [2] used the successfully calibrated and validated Soil and Water Assessment Tool (SWAT) to demonstrated that climate change might in the future reduce potential irrigable areas, due to changes in dependable flow and diversion water requirements. Furthermore, a recent publication by [9] suggests that climate change has a negative impact on food security and has been responsible for the reversal of past improvements. Therefore, additional climate change related parameters related to the FAO food insecurity experience scale (FIES) might impact the WEF-Nexus overall. Similarly, Ma and Ma [26] found that it might become necessary to incorporate mitigation responses for insects into prediction models, to account for climate change related changes in the distribution of invasive crop pests.

The usability of the tool is demonstrated with a case study in Moghar, Egypt. For this purpose, three sets of scenarios were described. S1: The first scenario analyses the effect of area size, S2: the second scenario discusses the effect of different crop types, while S3: the third one addresses the impact of the location of the farm. The results of S1 show the impact of the change in the farm area on water consumption, energy consumption and food production. The effect of the farm area on water consumption was linear. On the other hand, some parameter of the indirect energy consumption was nonlinear. S2 results showed the impact of the change in the crop types on water and energy consumption. Due to different crops, planting dates and growth durations the effect of the results was noteworthy. S3 results showed the effect of the location of the farm when the other inputs were fixed, due to the change of the values connected by the location like evapotranspiration, water quality and groundwater level, etc. The energy and water consumption have different results for the same crop. Based on the results of the three scenarios, the model is a helpful tool for stakeholder to include their data in the model to design their scenarios to get quantitative and spatial information of the WEF nexus.

Further work is required to improve the existing framework, including data for farming methods, offering storage and transportation requirements, and connecting the framework with remote sensing data to calculate the food yield. Modifications to the framework and tool would then be made to include the climate change scenarios data to predict the effect on water and energy consumption on agriculture. Additionally, the development of future scenarios will enable an analysis of the WEF nexus based on a temporal scale.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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For any interested to use the tool or the code, can send an email to the first author and the tool will be sent it.

References

[1] Abdelkhalek, A., King-Okumu, C., 2021. Groundwater Exploitation in Mega Projects: Egypt's 1.5 Million Feddan Project BT - Groundwater in Egypt's Deserts, in: Negm, A., Elkhouly, A. (Eds.), . Springer International Publishing, Cham, pp. 347–372. 10.1007/978-3-030-77622-0_14.

[2] Alejo LA, Alejandro AS. Changes in Irrigation Planning and Development Parameters Due to Climate Change. Water Resour Manag 2022;36:1711–26. doi: https://doi.org/10.1007/s11269-022-03105-4.

[3] Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO Irrigation and Drainage Paper No. 56 - Crop Evapotranspiration.

[4] Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, et al. Considering the energy, water and food nexus: Towards an integrated modelling approach. Energy Policy 2011;39:7896–906. doi: https://doi.org/10.1016/j.enpol.2011.09.039.

[5] Bhaduri A, Ringler C, Dombrowski I, Mohtar R, Scheumann W. Sustainability in the water–energy–food nexus. Water Int 2015;40:723–32. doi: https://doi.org/10.1080/02508060.2015.1096110.

[6] Borge-Diez D, García-Moya FJ, Rosales-Asensio E. Water Energy Food Nexus Analysis and Management Tools: A Review. Energies 2022;15. doi: https://doi.org/10.3390/en15031146.

[7] Choi Y, Suh J. applied sciences GIS-Based Solar Radiation Mapping, Site Evaluation, and Potential Assessment : A. Review 2019.

[8] Dargin J, Daher B, Mohtar RH. Complexity versus simplicity in water energy food nexus (WEF) assessment tools. Sci Total Environ 2019;650:1566–75. doi: https://doi.org/10.1016/j.scitotenv.2018.09.080.

[9] Dasgupta S, Robinson EJZ. Attributing changes in food insecurity to a changing climate. Sci Rep 2022;12:1–11. doi: https://doi.org/10.1038/s41598-022-08696-x.

[10] Ebhota WS, Tabakov PY. Influence of photovoltaic cell technologies and elevated temperature on photovoltaic system performance. Ain Shams Eng J 2023;14:. doi: https://doi.org/10.1016/j.asej.2022.101984101984.

[11] Edwards PN. History of climate modeling. Wiley Interdiscip Rev Clim Chang 2011;2:128–39. doi: https://doi.org/10.1002/wcc.95.

[12] Endo A, Yamada M, Miyashita Y, Sugimoto R, Ishii A, Nishijima J, et al. Dynamics of water–energy–food nexus methodology, methods, and tools. Curr Opin Environ Sci Heal 2020;13:46–60. doi: https://doi.org/10.1016/j.coesh.2019.10.004.

[13] Fao. WaPOR database methodology. WaPOR database methodology 2020. doi: https://doi.org/10.4060/ca9894en.

[14] FAO, 2005. Fertilizer use by crop in Egypt 57.

[15] FAO, 2000a. The Energy and Agriculture Nexus: Environment and Natural Resources No. 4. 10.13140/RG.2.1.2041.4169.

[16] FAO, 2000b. The energy and agricultural nexus. Environment and Natural Resources Working Paper No.4. FAO, Rome.

[17] FAOSTAT, 2021. Food and Agriculture Data. [WWW Document], 2022. URL www.fao.org/faostat/en/#home%0A.

[18] Ghiat I, Mackey HR, Al-ansari T. A Review of Evapotranspiration Measurement Models. Field Applications Water (Switzerland) 2021;13:2523.

[19] Grogan D, Frolking S, Wisser D, Prusevich A, Glidden S. Global gridded crop harvested area, production, yield, and monthly physical area data circa 2015. Sci Data 2022;9:1–16. doi: https://doi.org/10.1038/s41597-021-01115-2.

[20] Jones E, Qadir M, van Vliet MTH, Smakhtin V, Kang S. The state of desalination and brine production: A global outlook. Sci Total Environ 2019;657:1343–56. doi: https://doi.org/10.1016/j.scitotenv.2018.12.076.

[21] Kongshaug, G., 1998. Energy consumption and greenhouse gas emissions in fertilizer production, in: IFA Tech. Conf., Marrakech, Morocco, 1998. Int. Fertilizer Industry Assoc.

[22] Lewis, C.A., 1997. Fuel and energy production emission factors. MEET Proj. Methodol. Estim. Air Pollut. Emiss. from Transp. Retrieved July 28, 2007.

[23] Li M, Fu Q, Singh VP, Ji Y, Liu D, Zhang C, et al. An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty. Sci Total Environ 2019;651:1416–34. doi: https://doi.org/10.1016/j.scitotenv.2018.09.291.

[24] Lubbe PA, Archer CG. Guide for machinery cost 2015–2016, the directorate economic services, national department of agriculture. Pretoria: Republic of South Africa; 2016.

[25] Lubbe PA, Archer CG. Guide to machinery costs 2014/2015, department of agriculture. Pretoria: forestry and fisheries; 2014.

[26] Ma G, Ma C-S. Potential distribution of invasive crop pests under climate change: incorporating mitigation responses of insects into prediction models. Curr Opin Insect Sci 2022;49:15–21. doi: https://doi.org/10.1016/j.cois.2021.10.006.

[27] Mazzocchi F, Pasini A. Climate model pluralism beyond dynamical ensembles. Wiley Interdiscip Rev Clim Chang 2017;8:1–10. doi: https://doi.org/10.1002/wcc.477.

[28] Mohamaden MII, El-Sayed HM, Mansour SA. Combined application of electrical resistivity and GIS for groundwater exploration and subsurface mapping at northeast Qattara Depression, Western Desert. Egypt Egypt J Basic Appl Sci 2017;4:80–8. doi: https://doi.org/10.1016/j.ejbas.2016.10.003.

[29] Muhirwa F, Shen L, Elshkaki A, Velempini K, Hirwa H. Tracing attribute and scope of research and applied projects in Africa's water energy food nexus implementation: A review. Environ Sci Policy 2022;136:33–45. doi: https://doi.org/10.1016/j.envsci.2022.05.012.

[30] Patel SK, Biesheuvel PM, Elimelech M. Energy Consumption of Brackish Water Desalination: Identifying the Sweet Spots for Electrodialysis and Reverse Osmosis. ACS ES&T Eng 2021;1:851–64. doi: https://doi.org/10.1021/acsestengg.0c00192.

[31] Rahmani M, Jahromi SHM, Darvishi HH. SD-DSS model of sustainable groundwater resources management using the water-food-energy security Nexus in Alborz Province. Ain Shams Eng J 2023;14:. doi: https://doi.org/10.1016/j.asej.2022.101812101812.

[32] Sayed E, Riad P, Elbeih S, Hagras M, Hassan AA. Multi criteria analysis for groundwater management using solar energy in Moghra Oasis. Egypt Egypt J Remote Sens Sp Sci 2019;22:227–35. doi: https://doi.org/10.1016/j.ejrs.2019.04.001.

[33] Sayed E, Riad P, Elbeih SF, Hassan AA, Hagras M. Sustainable groundwater management in arid regions considering climate change impacts in Moghra region. Egypt Groundw Sustain Dev 2020;11:. doi: https://doi.org/10.1016/j.gsd.2020.100385100385.

[34] Scott CA, Pierce SA, Pasqualetti MJ, Jones AL, Montz BE, Hoover JH. Policy and institutional dimensions of the water-energy nexus. Energy Policy 2011;39:6622–30. doi: https://doi.org/10.1016/j.enpol.2011.08.013.

[35] Sharaky, A.M., Saleh, N., Farok, O.M., Saadany, E.R., 2021. Groundwater Quality and Potentiality of Moghra Aquifer, Northwestern Desert, Egypt, Springer Water. Springer International Publishing. 10.1007/978-3-030-77622-0_10.

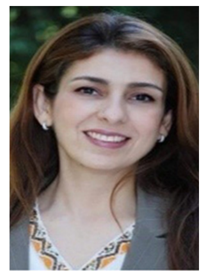
[36] Sims DE. Egypt's Desert Dreams: Development or Disaster? American University in Cairo; 2014.

[37] Taguta C, Senzanje A, Kiala Z, Malota M, Mabhaudhi T. Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. Front Water 2022;4:1–21. doi: https://doi.org/10.3389/frwa.2022.837316.
[38] Earth Explorer, 2022. FS; 083-00; Geological Survey (U.S.). Available online: https://earthexplorer.usgs.gov/ (accessed on 16 December 2022).
[39] Yousf AF, El Fakharany MA, Abu Risha UA, Afifi MM, Al Sayyad MA. Contributions to the geology of the New Valley area, Western Desert. Egypt J Basic Environ Sci 2018;5:1–19.
[40] Youssef T. Assessment of Groundwater Resources Management in Wadi ElFarigh Area Using MODFLOW. IOSR J Eng 2012;02:69–78. doi: https://doi.org/10.9790/3021-021016978.
[41] Yu, Z., Lanre Ridwan, I., Irshad, A. ur R., Tanveer, M., Khan, S.A.R., 2023. Investigating the nexuses between transportation Infrastructure, renewable energy Sources, and economic Growth: Striving towards sustainable development. Ain Shams Eng. J. 14, 101843. 10.1016/j.asej.2022.101843.

Anas Azzam. Eng. Anas is a Projects Manager at Delphy and NuriWEF company. Eng. Anas take part in several research projects funded by local and foreign parties such as FAO, ERASMUS+ and PRIMA. He is also a MS.s candidate at Ain Shams University.

Prof. Ghada Mahmoud Samy. Ghada Mahmoud Samy is Professor of Hydraulics, Irrigation & Hydraulics Department, Ain Shams University, Cairo, Egypt. She got Phd and MSc from Ain Shams University. She is a reviewer of ASEJ journal. Her area of interest is Hydraulics, Hydraulic structures and water resources management. She published many papers in international periodicals and conferences and supervised many post graduate researches

Prof. Mona A. Hagras. Mona A. Hagras is Professor of Hydraulics, Irrigation& Hydraulics Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt. She received PhD and MSc from Ain Shams University. She supervised many theses and published many papers in referred national and international journals. She is a reviewer of ASEJ journals. Her area of interest is Water Resources Management, Hydrology, Hydraulics, and Groundwater modeling.



Prof. Rasha El-Kholy. Prof.Rasha El-Kholy has 25 years of experience in the fields of water resources engineering, sustainable development, Water Energy Food WEF nexus, environmental protection, entrepreneurship and community service. Currently Prof. El-Kholy is holding the position of the President of the National Water Research Center in Egypt. El-Kholy is a Senate of the EuroMediterranean University EMUNI and member of the students' Affairs', strategies and new programs committees. With her wide exposure to Egyptian and European education and research she has formulated and presented curricula, bylaws, developmental programs, for both undergraduate and post graduate and policies for the consideration of many engineering faculties of private universities based on innovative approaches with relevance to real life cases.