Integrated framework model for water productivity calculations "WP-Calc": theoretical basics and evaluation

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1. Introduction

Improving agriculture and irrigation management needs to be based on more efficient and profitable use of water to produce more crops. "Water productivity" is a simple concept reflects the objectives of producing more food, income, livelihood and ecological benefits with less social and environmental cost per unit of water consumed (Molden et al., 2010). Water productivity could be determined for spatial levels; single crop, farms, irrigation zones, agricultural districts, national level, and global level. Increasing water productivity, as essential objective for irrigated agriculture in arid regions, could be achieved by applying less water to produce the same yield, or applying the same amount of the water to have higher yield (Descheemaeker et al., 2013). Water productivity analysis helps to understand and identify where and when water can be saved in an irrigation zone or system, by understanding water and salts movement and balance (Pedras and Pereira, 2006), which could give good implications of the sustainability of the irrigation practices, by investigating the short and/or long term impacts on soil and water resources. For a given watershed, irrigation requires an integrated planning including both crop level and watershed level, to avoid the planning and management gaps between the two levels. It should consider the different biophysical and hydraulic parameters of the system, under different spatial and temporal levels of analysis. This integrated concept of irrigation planning is no longer a difficult challenge, that at the recent decades the integrated irrigation management is improved as a result of the improvement in data collection and analysis tools, decision support tools, digital technology, communication tools, and communities' awareness (Rinaldi and Ubaldo, 2007).
Crop simulation models are valuable tools for evaluating the potential effects of environmental, biological and management factors on crop growth and development. They have been evaluated and used for many soil and environmental conditions across the world and have in the past, been successfully used in yield predictions (Jagtap and Jones, 2002), irrigation planning for crops (Behera and Panda, 2009), optimization of irrigation water use (Bulatewicz et al., 2009, Attaher et al., 2010), and understanding the climate change impacts on various crops (Eid and EL-Marsafawy, 2002; You et al., 2009; Hassanein and Medany, 2009; Reidsma et al., 2010;). Crop simulation models need to be applied at larger scales to be economically useful to analyze the effects of various alternate management strategies across the watershed or the region (Naresh Kumar et al., 2013; Mishra et al., 2013), by the inclusion of biophysical crop growth algorithms within hydrology models. Furthermore, global studies on linking crop models with a Geographical Information System (GIS) have demonstrated the strong feasibility of crop modeling applications at a spatial scale (Kadiyala et al., 2015). However, the majority of the available irrigation management models are focusing on a limited domain of the water balance, missing important interactions between on-farm level and irrigation distributary network level within the irrigation project, which limits the needed support to water planners and policy-makers who are concerned with the integrated scale management (Roost, 2002 and Drastig et al., 2012).
Irrigated agriculture in Egypt could be a clear example for the irrigated agriculture struggle to improve water productivity. Egypt has one of the most complicated irrigation systems covering almost all the agricultural areas along the nation. Where, the irrigated agriculture in Egypt is under serious pressures due to the imbalance between the water resources and demands, poor management, and the weak institutional and infrastructure frameworks (Allam et al., 2005). The irrigation system in Egypt is strongly changed at the recent decades as a result of several emerging key issues, such as land fragmentation, free

cropping pattern policy, poor maintenance of the irrigation network, soil salinity problems, water table logging, water logging, excessive water wasting, and energy considerations, which strongly affect the poorer farmers and decrease their production and income potential (Soliman et al., 2010 and El-Agha et al., 2011). Past experience in showed that when irrigation action or a strategy is planned and implemented in isolation from other system components, disruptive impacts are perceived (MWRI, 2004). Several models have been used to describe, simulate, and optimize the planning and management process of the irrigated agriculture system in Egypt (Nardini and Fahmy, 2005). These models included those related to water demand and requirement calculation for on-farm system or irrigation distribution network, water allocation and distribution among various water users, derivation and analysis of the operating policy for the national irrigation network, simulation of pollutant loads in the waterways, etc. (Progea, 2003, and Nardini and Fahmy, 2005). The use of these models in actual planning and management has been limited because most of these trials focused only on one aspect of the irrigation system and neglected the integration of the other aspects (Attaher et al., 2013). Progea (2003) reported different trials to use modeling coupled with GIS tools in the contest of decision support systems, to support irrigation management planning in Egypt. The majority of these trials did not include the on-farm level, with appropriate resolution of application, on the analysis, which produces a gap between the irrigation distributary network application and on-farm actual demands in practical application. On the other hand, several crop models were tested, calibrated, and evaluated the impact of several on-farm irrigation applications on the crop yield and water use efficiency (e.g.; Eid, 1993, El Marsafaway and Eid, 1999, Medany, 2001, Hassanien et al., 1999, Eid and EL-Marsafawy, 2002, Hassanein and Medany, 2007, and Attaher et al., 2010). Almost all these studies focused on simulations for single crops of single fields. Recent national reports and studies highlighted the strong need to conduct integrated spatial analysis to evaluate more practical and applicable irrigation options to improve water productivity starting from farm level, and going up to the national irrigation network level (Attaher et al., 2013 and ICARDA, 2012).

Accordingly, this paper presents an integrated framework model, titled "WP-Calc", aiming to analyze water productivity and environmental impacts of irrigation practices, starting from field scale to tertiary/branch canal irrigation zone scale. The paper gives a detailed background about the theoretical principles of the framework model. Furthermore, it presents a validation case study of the model under Egyptian conditions.

2. The principles of "WP-Calc"

"WP-Calc", as "Water Productivity Calculator", is a computer modeling framework that allows a numerical and spatial analysis of a given irrigation scheme, and provides an integrated analysis of water and salt balance, water productivity, irrigation efficiencies, and irrigation adequacy. It has two connected routines, one for on-farm irrigation management and another routine for irrigation distributary network. Both routines are linked together in an integrated modeling framework by using VB. NET (*ver.11.0*) programing language (Included in the Microsoft's® integrated development environment; Visual Studio 2013), and attached with simple GIS environment.

The current paper presents the "Beta" version of "WP-Calc", which covers a hierarchical structure of simulation of three distinct levels, namely the "field level", "fields-distributary canal level" which called in Egypt "Mesqa", and "tertiary/branch canal level". "Mesqa" level is the smallest level of the analysis that is showing a spatial representation and real field data. The data of the "field level" is included in the analysis as "pilot points". Each one of these points is representing one crop of one sowing date, using the same on-farm irrigation system and management practices. These pilot points are assembled and normalized to represent the spatial average of the water and salt balance conditions at the Mesqa command area. This is mainly performed based on the percentages of the cultivated areas of the crops inside the command area of the Mesqa. The summarized and normalized analysis process of the fields, inside the Mesqa command area, is designed to overcome the lack of the detailed data at the field level, which is commonly observed in Egypt.

"WP_Calc" is providing a water and salt balance analysis starting from root-zone system water balance, moving to water-balance at the irrigation distributary network. Figure (1) shows the conceptual representation of the main irrigation system components– including the groundwater and drainage systems – and their interactions, which are addressed in WP-Calc water and salt balance analysis. The time step of the WP-Calc water and salt balance simulation is fifteen days, in order to match actual national irrigation rotations system. Furthermore, the irrigation scheme under study is analyzed within a spatial grid-box, with a predefined cell size based on the unit of land "area". In case of using "Feddan" as the unit of the land area, the cell size of the grid-box will be 4200 m^2 [64.81 m X 64.81 m], while it will be 10000 m^2 [100 m X 100 m] for the land area unit "Hectare". For the both cases the depth of the cell will be equal to the depth of the soil layer provided by the soil profile data.

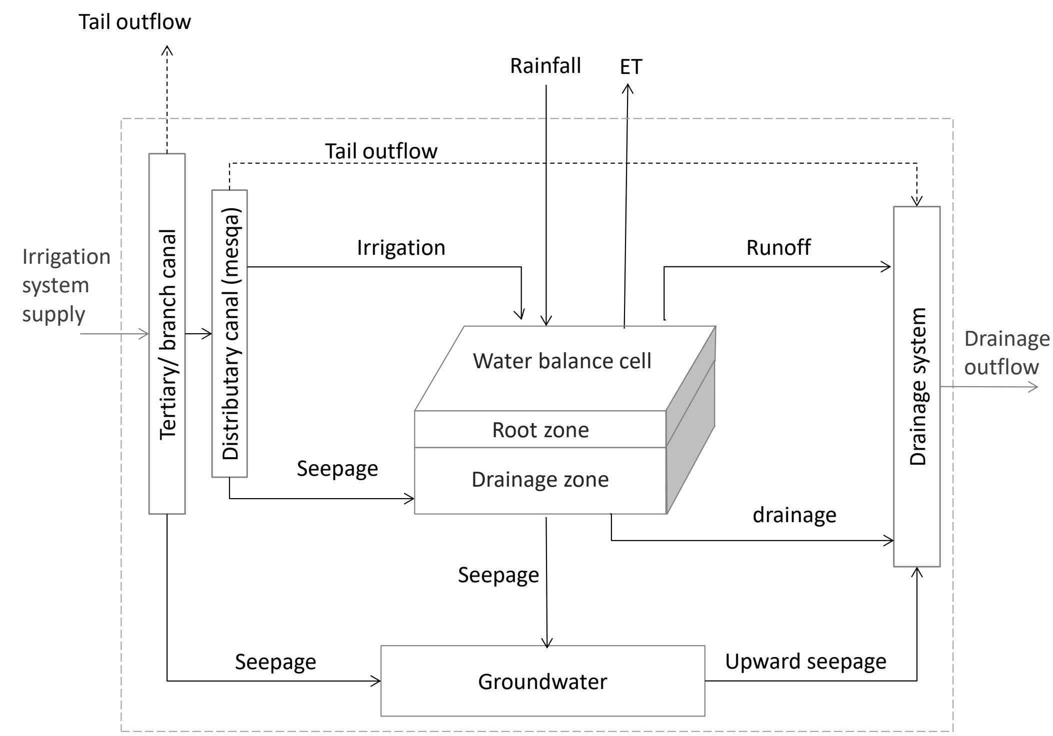


Figure (1): System boundaries and water inflows and outflows for the calculation of the water and salt balance

2.1 On-farm irrigation management routine:

The on-farm irrigation routine in WP-Calc is designed to predict yield response to water of the simulated crops at a given Mesqas. WP-Calc utilize the FAO AquaCrop model (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009), as the basic modeling core of the on-farm routine, via attaching the "AquaCrop" plugin "ACsaV40.EXE" (Version 4.0) with the other modules of WP-Calc. AquaCrop is a crop-water management dynamic model, has a significantly smaller number of parameters and a better balance between simplicity, accuracy and robustness (Steduto et al., 2009). By tracking the incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) water and salt fluxes at the boundaries of the root zone, the amount of water and salt retained in the root zone can be calculated at any moment of the season. Infiltration and internal drainage are estimated by an exponential drainage function that takes into account the initial wetness and the drainage characteristics of the various soil layers. Evapotranspiration is simulated as crop transpiration and soil evaporation, and the daily

transpiration is used to derive the daily biomass gain via the normalized biomass water productivity of the crop, considering key physiological characteristics of the crop. AquaCrop uses canopy ground cover. Canopy development, stomatal conductance, canopy senescence and harvest index are the key physiological crop responses to water stress, which are are expressed through indicators vary from 0 to 1. The model reproduces the canopy cover from daily transpiration taking into account some important physiological characteristics of the crop such as leaf expansion growth and canopy development and senescence (Steduto et al., 2009). The conservative water productivity parameter in the model is normalized in order to make the model applicable to diverse location and seasons including future climate scenario (Steduto et al., 2006, 2009; Hsiao et al., 2009). AquaCrop accommodates different water management systems, including rainfed agriculture and supplemental, deficit, and full irrigation.
A detailed AquaCrop model description is available in Steduto et al. (2009) and Raes et al. (2009). Since the year 2009, the model has been evaluated and calibrated in a wide number of studies covered a wide range of crops and strategies for arid and semi-arid conditions, and other water scarcity case studies (e.g. ; Therese et al., 2009, Araya et al., 2010, Salemi et al., 2011, Stricevic et al., 2011, Katerji et al., 2013, Vanuytrecht et al., 2014, Bird et al., 2015, Toumi et al., 2016). Lorite et al., (2013) developed and evaluated two tools for managing the inputs and outputs of AquaCrop, named AquaData and AquaGIS respectively. AquaData, in combination with the AquaCrop plug-in program, facilitates in multiple runs of the pre-defined projects. AquaGIS enhances the interpretation of simulation outputs by linking them to a geospatial module to permit spatial analysis and improve visualization through mapping.

2.2 irrigation distributary network routine

In the irrigation-distributary network routine, the outputs of the on-farm routine are normalized, as inputs for the out-scaling calculations for Mesqa command area and upper level of distributing canals. Those calculations are arranged in four modules of, (i) water balance analysis module, (ii) salt balance module, (iii) water-productivity module, and (iv) irrigation efficiencies and adequacy module.

2.2.1 Water balance analysis

The basics of the water balance in "WP-Calc" are based on the principle of the conservation of mass for boundaries defined in space and time. These boundaries are identified based on the "reservoir concept" which is addressed in several water balance models (etc. Oosterbaan, 2002, Van Dam et. al., 2008, and Raes et. al., 2012). As shown in figure (2), the main assumption of the analysis is that the system is consisted of three consecutive horizontal reservoirs; the "root zone" reservoir, "drainage zone" reservoir and the "groundwater zone" reservoir. All balance factors are uniformly distributed over the area and that the water table remains within the groundwater zone, as an artificial drainage system is controlling the water table level below the drainage zone.
The water balance at the root zone for a certain period could be represented by the following equation:

$$I_g + P_r + R_r = ET + L_r + R_o + \Delta W_f \qquad [1]$$

Where: "I_g" is the gross irrigation inflow, "P_r" is the precipitation, "R_r" is the amount of capillary rise into the root zone, "ET" is the crop evapotranspiration, "L_r" is the amount of percolation loss from the root zone, "R_o" is the surface runoff, "ΔW_f" is the storage of moisture in the root zone between field capacity and wilting point.
The drainage zone water balance is represented by the following equation:

$$L_r r + R_g + L_m = R_r + G_f + V_g + \Delta W_x \qquad [2]$$

Where: "R_g" is the amount of capillary rise from groundwater zone to drainage zone, "L_m" is percolation loss (seepage) from mesqa, "G_f" the amount of horizontal drainage outflow from drainage zone, "V_g" is the amount of vertical percolation loss from drainage zone, "ΔW_x" the water storage in the drainage zone between field capacity and wilting point.

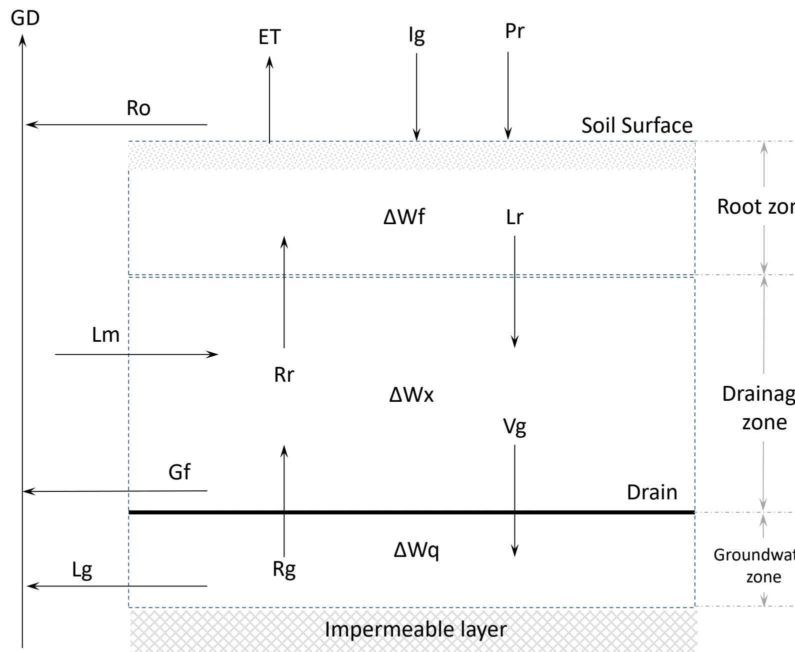


Figure (2): The system assumed zones and the water balance inflow and outflow factors.

The overall water balance is represented by the following equation:

$$I_g + P_r + L_m = ET + R_o + G_f + V_g + \Delta W_f + \Delta W_x \qquad [3]$$

Whereas, the gross drainage outflow:

$$G_d = R_o + G_f + L_g \qquad [4]$$

Where: "G_d" is the gross drainage outflow, and "L_g" is the amount horizontal water outflow through the groundwater zone.

The water balance module divides the irrigation scheme into small fractions, in a mesh grid boxes, each box has a predefined cell size as mentioned before, as one-dimensional vertical water flow and root water uptake, that can be solved by applying a finite difference technique (Carnahan et al., 1969; Bear, 1972). The root zone water balance for each pilot crop is determined by using the AquaCrop water balance modules. In case the single cell of simulation contained more than one pilot crop, the inputs and the outputs from the each crop are normalized at the cell level in order to represent the overall root-zone water balance.

The estimation of R_o is based on the curve number method developed by the US Soil Conservation Service (USDA, 1964; Rallison, 1980; Steenhuis et al., 1995). The drainage paramters are calculated by using drainage function that described by Raes (1982); Raes et al. (1988); Oosterbaan (2002) and Raes et al. (2006). The capillary rise parameters for the different reservoir layers were calculated according to the calculation method used in the AquaCrop water balance modules described by Raes et al. (2012).

Canals seepage is a main source of water losses in canals, and one of the important factors affecting ground water fluctuation. For improved mesqas, the seepage values are very limited. For tertiary canal, the seepage can be quantified reference to the conveyance efficiency (Ec). For both mesqa and tertiary canal, "WP-Calc" estimating the seepage values as a percent from the canal flow referenced to the maintenance level of the canal as an estimated percentage, which is included at the water balance inputs.

2.2.2 Salt balance analysis

Salt balance analysis in "WP-Calc" was conducted based the same assumption for the horizontal reservoirs used in water balance. Those calculations were conducted for each reservoir separately, based on their water balances, using the salt concentrations of the incoming and outgoing water. The initial salt

concentrations of the water in the different soil reservoirs are given as inputs, of the irrigation water and of the incoming ground water in the aquifer, in terms of electric conductivity (EC in dS/m). The simulation of salt balance in "WP-Calc" uses the calculation procedure presented in "SALTMOD" model (Oosterbaan, 2002) and BUDGET model (Raes et al., 2001; Raes, 2002; Raes et al., 2006).
For both water and salt balance analysis the overall results are accumulated from daily bases to represent the simulation time-step of 15 days.

2.2.3 Water productivity

The general equation for calculating water productivity [WP] under "WP-Calc" is the following:

$$\mathrm{WP} = \frac{\text{Yield per unit area}}{\text{Water volume used to produce yield}} \quad [5]$$

The volumes of water [m^3] delivered to the field per feddan for a given crop (V_f), and the water delivered from mesqa (V_m) and tertiary canal (V_t) are main inputs of "WP- Calc" calculation of water productivity for the three levels of the analysis, as follows:

$$WP_c = \frac{Y}{V_f} \quad [6]$$

$$WP_m = \frac{Y_m}{V_m} \quad [7] \qquad \text{Where,} \qquad Y_m = \sum_{i=1}^{m} Y \times a_c \quad [8]$$

$$WP_t = \frac{Y_t}{V_t} \quad [9] \qquad \text{Where,} \qquad Y_t = \sum_{i=1}^{n} Y_m = \sum_{i=1}^{n} \sum_{i=1}^{m} Y \times a_c \quad [10]$$

Where, "Y" is the crop yield per feddan [kg or calories], "Y_m" is the crop yield per the total command area of mesqa [calories], "Y_t" is the crop yield per the total command area of the tertiary [calories], "a_c" is the total area of a given crop at a mesqa command area [feddan], "m" is the number of the crops at the mesqa command area, and "n" is the number of mesqas at the tertiary canal. Water productivity could be calculated for each crop using kg units to indicate the yield, whereas, at the higher levels of mesqa and tertiary, the yields of different crops are converted to calories in order to calculate spatial average values of WP at mesqa and tertiary levels.

2.2.4 Irrigation efficiencies and adequacy

Irrigation network efficiencies are used to indicate the performance of the irrigation system in "WP-Calc" simulations. The usual efficiencies in irrigation networks are conveyance, distribution and application efficiencies defined as (Tehrani et al., 2011):

$$E_i = E_c \times E_d \times E_a \quad [11]$$

where E_i is total efficiency, E_c, E_d and E_a are conveyance, distribution and application efficiencies respectively. The three efficiencies are defined as:

$$E_c = \frac{V_m}{V_t} \quad [12] \qquad E_d = \frac{V_f}{V_m} \quad [13] \qquad E_a = \frac{V_a}{V_f} \quad [14]$$

The delivery adequacy (A_{de}) is one of the performance indicators reflecting the ability of the system to deliver the actual water demands. In "WP-Calc", A_{de} is the volume of water delivered to fields from mesqa (V_m) related to total irrigation demands of the mesqa command area (V_{req-m}) (Clemmens, 2006):

$$A_{de} = \begin{cases} \dfrac{V_m}{V_{\mathrm{Req}-m}} & V_m < V_{\mathrm{Req}-m} \\ & or \\ & V_m > V_{\mathrm{Req}-m} \\ 1 & V_m = V_{\mathrm{Req}-m} \end{cases} \qquad [15]$$

Where, $$V_{req-m} = \sum_{i=1}^{m} V_a \times a_c \qquad [16]$$

When the value of A_{de} is less than 1, it reflects a shortage in irrigation application, whereas, the value of A_{de} more than 1 reflects an excessive use of water in irrigation.

2.3 Inputs, databases and outputs

The current version of WP-Calc, can perform a simulations for ten crops (wheat, cotton, rice, faba bean, sugar beet, sugar cane, potato, tomato, and vegetables), that occupy the majority of the crop area in Egypt according to the national statistics. For each crop the crop response parameters should be calibrated, by using AquaCrop under windows version, before using the crop file by “WP_Calc”. Table (1) show a list the inputs of the WP-Calc. While the model outputs are given as text reports and/or maps for water balance parameters at mesqa level, and water productivity and adequacy between mesqas. The structure of “WP-Calc” include a database consisting of seven sections; (i) climate data, (ii) crop data, (iii) soil data, (iv) irrigation network, (v) drainage network, (vi) groundwater, and (vii) Processing, result, and quality control. In addition to the database contain some simulation default and reference data for soil types, reference crop yield, reference crop-water productivity, number of calories for the crop per kg, and partial surface wetted percent for the different irrigation systems.

Table (1): “WP-Calc” inputs

Data Group	Item
climate	▪ Minimum and Maximum air temperature ▪ ETo ▪ Rainfall
Soil	▪ soil texture data ▪ Soil water content at saturation, field capacity, and at permanent wilting point. ▪ hydraulic conductivity at saturation ▪ Bulk density
Irrigation zone	▪ Shape file of the mesqas and canals ▪ Shape file of mesqas command areas
Crop/ mesqa data	▪ Crop ▪ The percent of cultivated area at the mesqa command area [%] ▪ Crop-sowing and harvesting dates ▪ Irrigation system type
Applied water parameters	▪ Crop irrigation events and depth ▪ Irrigation water salinity at each irrigation event ▪ Total applied water at each mesqa (seasonal) ▪ Total applied water at each canal (seasonal)
Water and salt balance parameters	▪ Maintenance level of the mesqa [%] ▪ Maintenance level of the canal [%] ▪ Drainage systems types ▪ On-farm drain level ▪ Distance between laterals ▪ Laterals level ▪ Drained water depth and salinity

	▪ Initial water table level and salinity ▪ Change in water table level and salinity

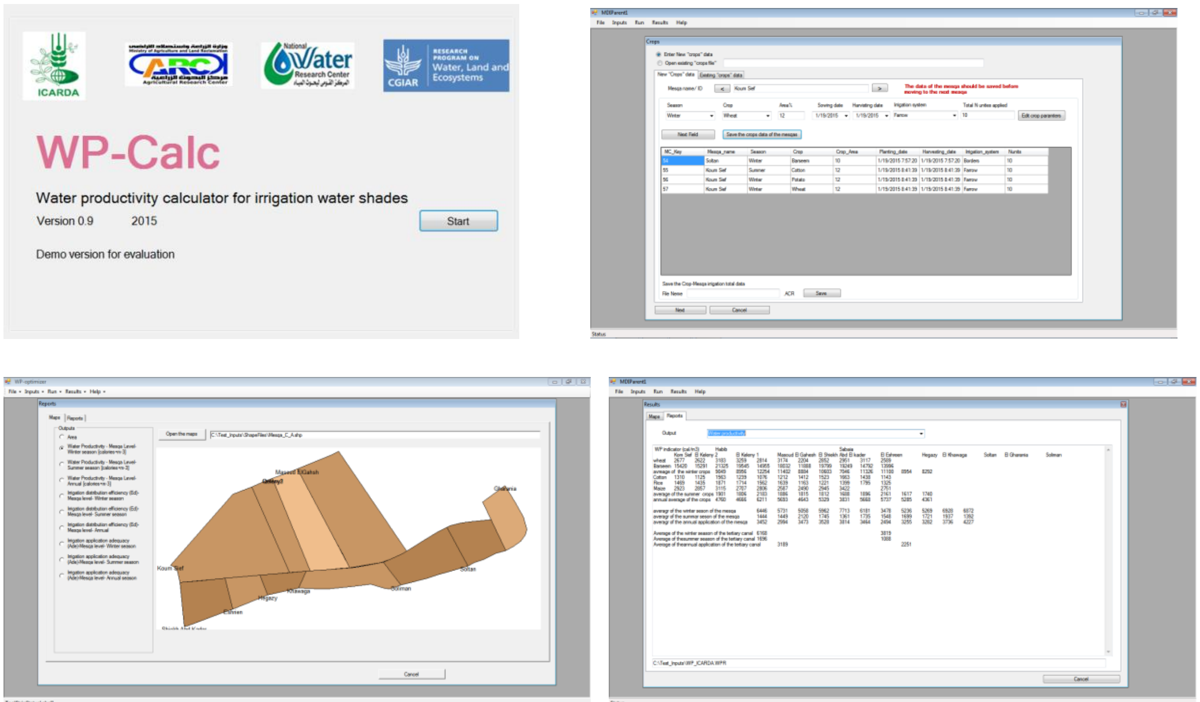


Figure (3) shows some examples of “WP-Calc screens”

3. WP-Calc validation case study:

In this paper a validation case study was conducted in order to evaluate “WP-Calc”, under the conditions of traditional irrigated agriculture in the Nile Delta region, at the winter and summer seasons of 2011/2012.

3.1 Description and the inputs of the case study

A pilot location in Behaira Governorate (very close to Damanhour city) was selected to represent irrigated agriculture in old land (Figure 4), for data collection and case study evaluation. The water source of the location is originally from El Nasery Canal then Sabya and Habib tertiary canals. The location has only one main drain of Nasr Allah drain. The study total area is 596 Feddan, with 201 and 410 Feddan in Sabia and Habib respectively. The studied command area had eleven Mesqas, the command area, and the total water supplied by each Mesqa for agricultural seasons of 2011/2012, are listed in in table (4).
The major soil texture in the study area is ranged between “clay” to “sandy clay loam”. The climate of the northern delta is categorized as typically Mediterranean, with dry, mild summers and cool, wet winters.

A set of performance indicators have been employed for water balance analysis of the canal system, such as water level, routine discharges and cropping patterns of tertiary canals, pump operations for Mesqas, irrigation events at selected portable pumps, water use index, application adequacy, distribution efficiency, and dependability. The measured data presented the spatial and temporal water distribution pattern among the system, reflect the main characters and weakness points of water management within the system, and identify the existing gap between water management at the level of irrigation delivery system and on-farm system. The data for evaluation collected through the summer and winter seasons of the years 2011 and 2012. Table (1) shows the command area of each Mesqa at the study area. The dominated crop pattern (Figure 5) had rice and cotton as the major crops at the summer, remaining small areas of maize and vegetables. While, wheat and barseem (short clover) was the major dominated crops at the winter season, with very small areas for vegetables.

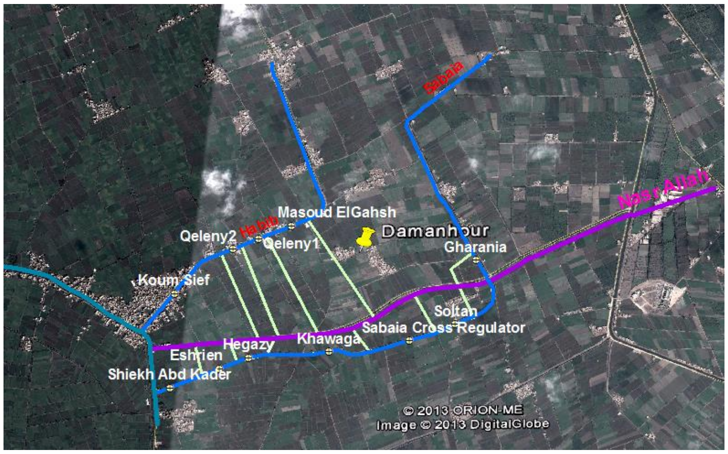


Figure (4): The location of the evaluation case study (at Behaira Governorate)

Table (2) The command area and the total water supplied by each Mesqa at the study area (agricultural seasons of 2011/2012).

canal	Mesqa	Command area (Fed)	Total water supplied (m^3/year)
Habib	Kom Sief	85	743920
	El Keleny 2	45	433170
	El Keleny 1	59	418192
	Masoud El Gahesh	77	569107
	El Shiekh Abd El kader	50	417550
	El Eshreen	85	704905
Sabaia	Heqazy	35	425635
	El Khawaga	45	365040
	Soltan	35	285110
	El Gharania	40	372240
	Soliman	40	288080

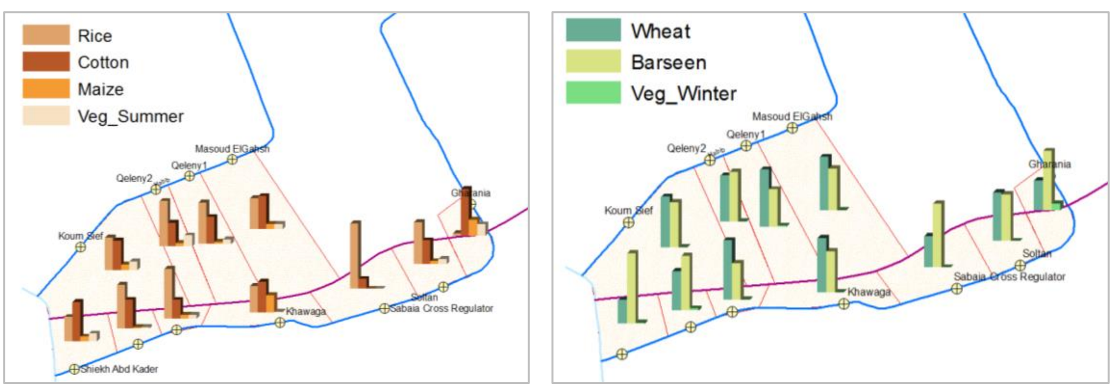


Figure (5): the crop pattern of summer and winter seasons of the study area.

A daily climatic data of two years (2011 &2012) from the nearest meteorological station in Behaira Governorate was used in the simulation. The station is located at 30.65 ºN latitude, 30.70 ºE longitude, and 16 m altitude. The data included the main climate parameters, of (i) maximum and minimum temperature [°C], (ii) maximum and minimum relative humidity [%], and (iii) precipitation [mm]

The average soil classes and texture of the study area are presented in table (3). Based on the classification the hydraulic properties of each layer were calculated.

The size of the grid boxes is defined based on using the feddan as the measuring unit of the land area, therefore the cell size in this case study was 4200 m^2 [64.81m X 64.81m], with a cell depth: 0.25 m (equal to the depth of the soil profile layers). Accordingly, the grid of this case have 2940 cell.

A set of performance indicators have been employed for water balance analysis of the canal system, such as water level, routine discharges and cropping patterns of tertiary canals, pump operations for mesqas, irrigation events, water salinity, drained water depths and salinity, ,crop yield, application adequacy, and distribution efficiency. The measured data presented the spatial and temporal water distribution pattern among the system, reflect the main characters and weakness points of water management within the system, and identify the existing gap between water management at the level of irrigation delivery system and on-farm system.

Tables (4) listed the planting and harvesting dates of the dominated crops in the study area. Those values and parameters were used in the calibration of the crop files of the AquaCrop model. Table (5) shows the average values of the actual crop yields from some pilot fields at each mesqa of the case study, which were used to evaluate the crop response simulation. Whereas, table (6) presents theguidelines of the national values of the studied crops water productivity ($kg \cdot m^{-3}$), and the equivalent calories per kg of the primary crop yield of the studied crops.

Table (3): the average soil texture, classification and the average hydraulic properties of the study area

Depth [cm]	Soil Texture			Classification	PWP	FC	SAT	Sat Hydraulic conductivity [mm/day]	Matric bulk density [g/cm3]
	Clay %	Silt %	Sand %		% volume				
0-25	42	30	28	Clay	25.4	39.3	49.9	71.28	1.33
25-50	41	35	24	Clay	25	38.4	48.5	61.68	1.37
50-75	36	28	36	Clay loam	22.4	35.5	46.8	85.44	1.41
75-100	27	23	50	Sandy clay loam	17.6	29.4	44.6	209.04	1.47

Table (4): Planting and harvesting dates and growth duration of the studied crops

Season	Crop	Planting [month]	Harvesting [month]	Duration [days]
Winter	Wheat	11	5	180
	Clover (Barseem)	10	3	100
Summer	Cotton	3	9	180
	Rice	6	9	100
	Maize	5	8	120

Table (5): Average crop yield [ton/ ha] of the studied crops, from pilot fields at the studied mesqas.

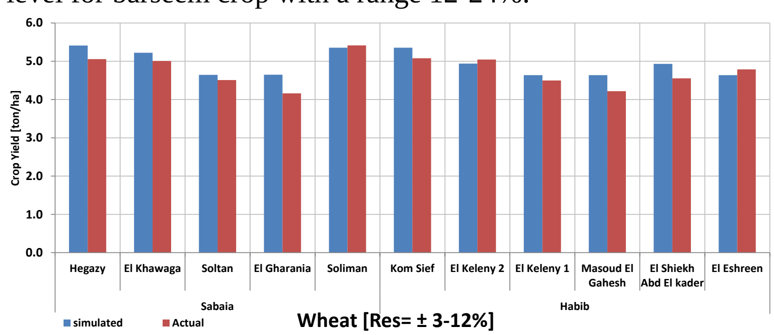
Canal	Mesqa	Yield [ton/ha]				
		Wheat	**Barseem**	**Cotton**	**Rice**	**Maize**
Sabaia	Hegazy	5.06	80.41	2.01	9.32	5.46
	El Khawaga	5.01	75.63	2.10	9.49	5.01
	Soltan	4.51	68.31	2.45	9.23	5.50
	El Gharania	4.16	67.50	2.63	9.15	
	Soliman	5.41	78.37	2.02	9.16	5.41
	Average	**4.83**	**74.04**	**2.24**	**9.27**	**5.34**
Habib	Kom Sief	5.08	79.80	2.00	9.79	5.08
	El Keleny 2	5.04	68.23	2.99	9.02	5.54
	El Keleny 1	4.50	63.11	2.05	9.29	5.25
	Masoud El Gahesh	4.22	67.40	2.09	9.46	5.61
	El Shiekh Abd El kader	4.55	67.01	2.66	9.13	5.55
	El Eshreen	4.79	62.00	2.79	9.49	5.79
	Average	**4.70**	**67.92**	**2.43**	**9.36**	**5.47**
Average		**4.76**	**70.71**	**2.34**	**9.32**	**5.42**

Table (6): guidelines of the national values of the studied crops water productivity (kg·m^{-3}), and the equivalent calories per kg of the primary crop yield of the studied crops

	wheat	Barseem	Cotton (fibers)	Rice	Maize
WP_c [kg·m^{-3}]	0.9-1.4	17-29	0.1-0.2	0.7-0.8	0.7-1.2
Calories per kg	3509	1080	5600	3439	3615

3.2 Crop yield responses:

The crop yield of the simulated crops is one of the important parameters used in the evaluation case study. The results of this parmater are illustrated in Figure (6). The indicated residuals between the actual and simulated crop yields was at the lowest values for maize crop (less than ±7%), and around the range of ± 3-12% for rice and wheat. For the cotton the indicated residuals was around the range of ± 6-20%, and it recorded the highest level for barseem crop with a range 12-24%.



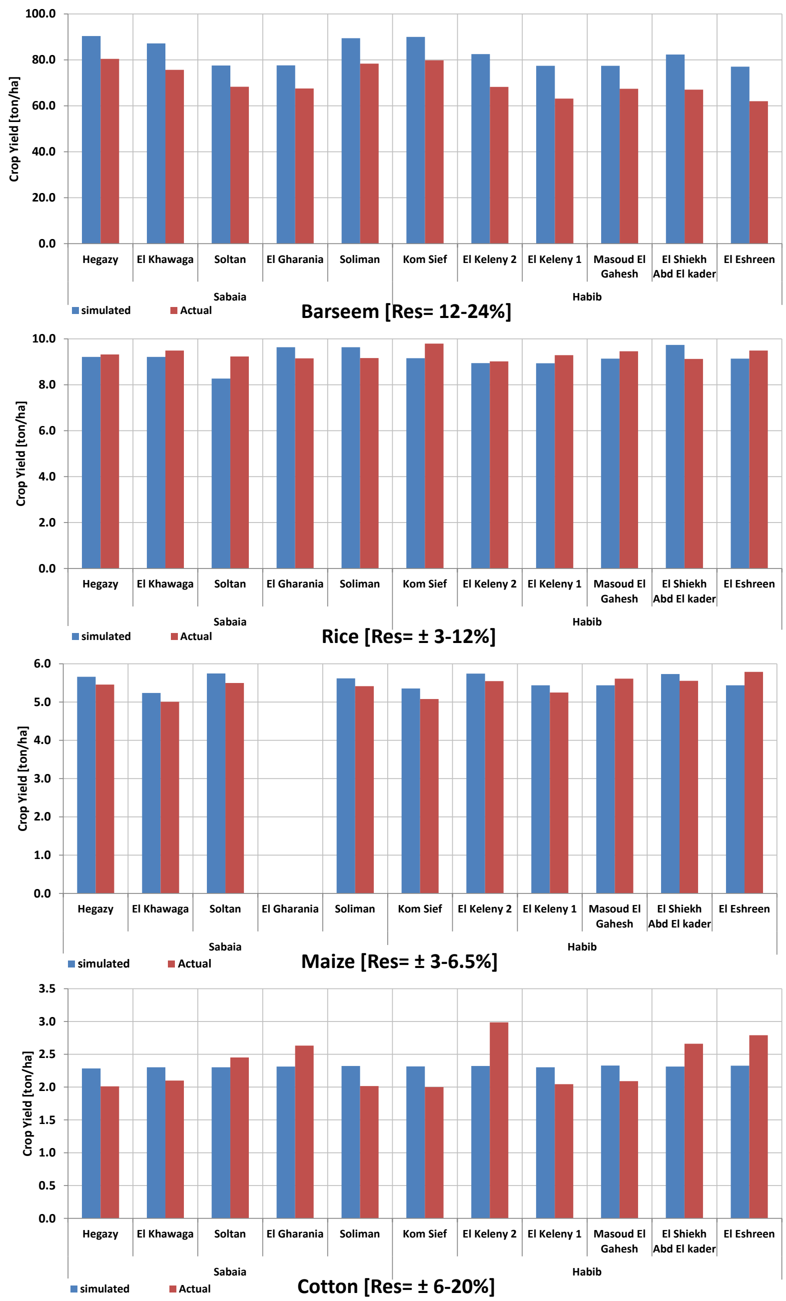


Figure (6): The simulated crop yield with AquaCrop vs. the actual crop yields of the pilot fields at the mesqas under evaluation [Res: residuals between the actual and simulated crop yield]

3.3 Water and salt balance

The water balance at the mesqa command area is the second level of the water balance analysis given by WP-Calc. The results did not indicate major differences between the values of water balance parameters of the studied mesqas, except for "Hegazy" mesqa (Figure 7). Regarding to the actual data of the case study, "Hegazy" mesqa experience a quite high amounts of applied irrigation, which induced an increase in runoff and drained water values. The overall water balance analysis of the two tertiary canals "Habib" and "Sabaia" (Figuer 8), revealed that "Sabaia" canal experience a kind of over irrigation practices, which cause a losing of the excess water as drained water.

Figure (7): The mesqa level water balance of the mesqas under study (at winter season, summer season, annual)

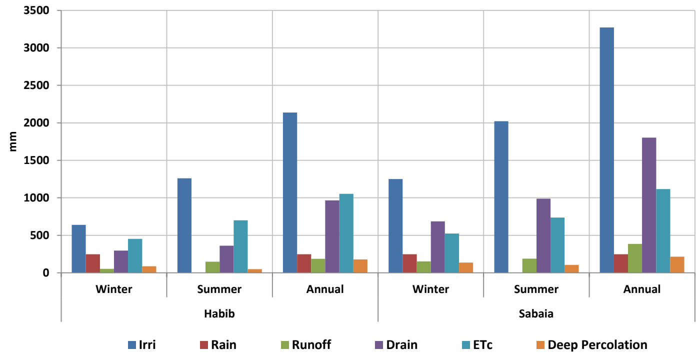


Figure (8): The tertiary canals “Habib” and “Sabaia” water balance analysis for summer, winter annual irrigation.

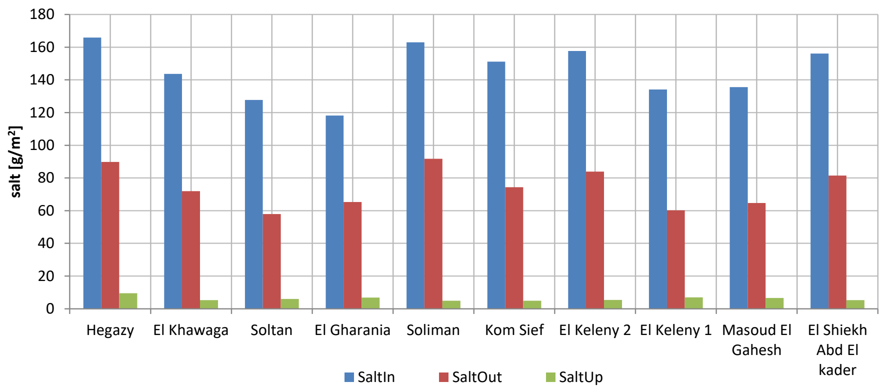


Figure ( ): annual soil salt balance at for the studied mesqas, calculated by WP-Calc

3.4 Irrigation Efficiencies and Adequacy:

Figure (9) shows the variation between the application efficacy values (E_a) for the irrigated crops, at the studied mesqas. E_a was a quit high and ranged from 0.63 to 90 for wheat, from 0.75 to 1.0 for cotton, and from 0.59 to 0.83 for maize. Whereas, barseem and rice indicated a lower E_a values, ranged from 0.26 to 0.67 for barseem, and from 0.22 to 0.36 for rice. Those noticeable differences between the crops could be attributed to the different types of the on-farm surface irrigation system applied for each crop (farrow, basin, borders), and/ or the common on-farm irrigation practices related to the crop water sensitivity.
The distribution efficiency (E_d) revealed a fair to good water distribution uniformity from the mesqa to the fields (Figure 10), with a general average of 0.83. The mesqas of Habib canal indicated higher values of E_d (0.9- 1.0), than the mesqas of Sabaia canal (0.5 – 1.0). The differences between Ed values of winter, summer, and annual were very small (or not observed) for the same the mesqa. “Soliman” mesqa had the lowest E_d of 0.6 and 0.5 for winter and summer seasons, and an average annual of 0.5. The values of the distribution efficiency are a quit high than the national records of the old lands (less than 0.6), that the mesqas at the case study area are developed.
Habib canal indicated higher conveyance efficiency (E_c) than Sabaia, with an annual average of 0.9 for Habib, and 0.7 for Sabia. There was no indicated difference in the Ec values of the two tertiary canals through the winter and summer seasons.
The ability of the mesqas to deliver the actual water demands was tested in “WP-Calc” by calculating the delivery adequacy (A_{de}). This indicator reflects the water shortage or over-irrigation situations. Figure (11) shows the A_{de} for the studied mesqas at annual values, and winter and summer seasons values. All values of A_{de} for the eleven mesqas were above 1 with an overall annual average of 1.8. A_{de} values for the

summer season were higher than the winter season, with a range from 1.8 to 2.3 and from 1.3 to 1.7 for summer and winter seasons, respectively. The high values of A_{de} could be understood within the location of the study area at the head of the two tertiary canals Habib and Sabia; water delivered at the head of a branch canal is typically larger than actual crop water and soil leaching requirements in order to account for conveyance and field application losses at the downstream mesqas. These results could reflect a good potential of water distribution improvement between canals upstream and downstream mesqas.

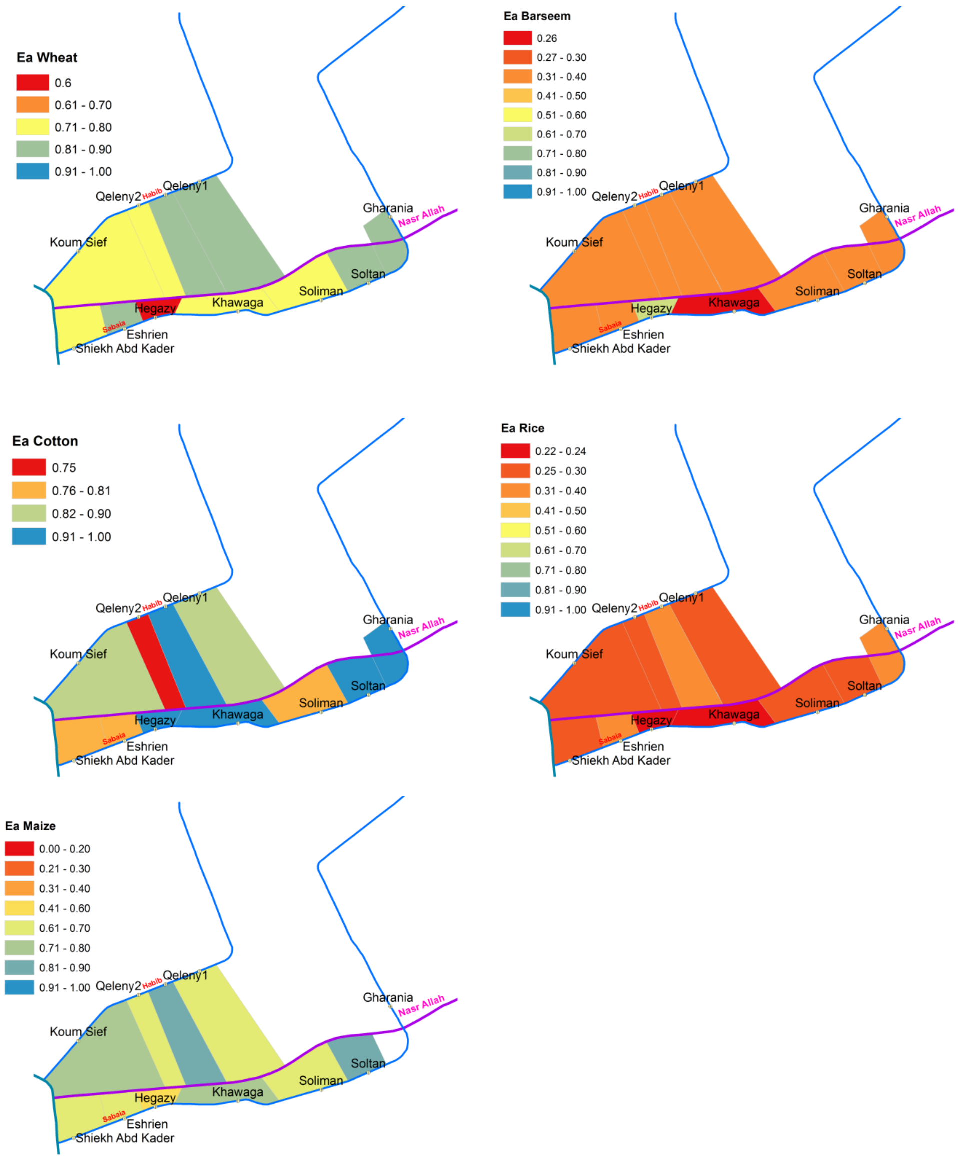


Figure (9): the spatial distribution of the irrigation application efficiency (E_a) of the five studied crops at the eleven mesqas command zones.

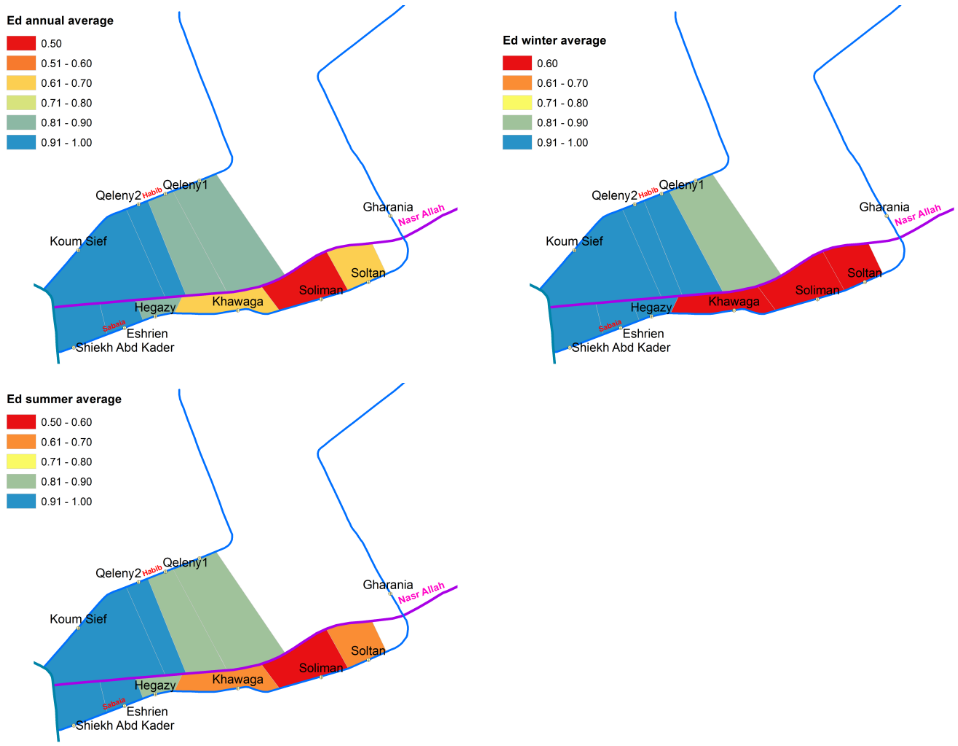


Figure (10): the spatial distribution of the winter, summer and annual irrigation distribution efficiency (E_d) of the eleven mesqas.

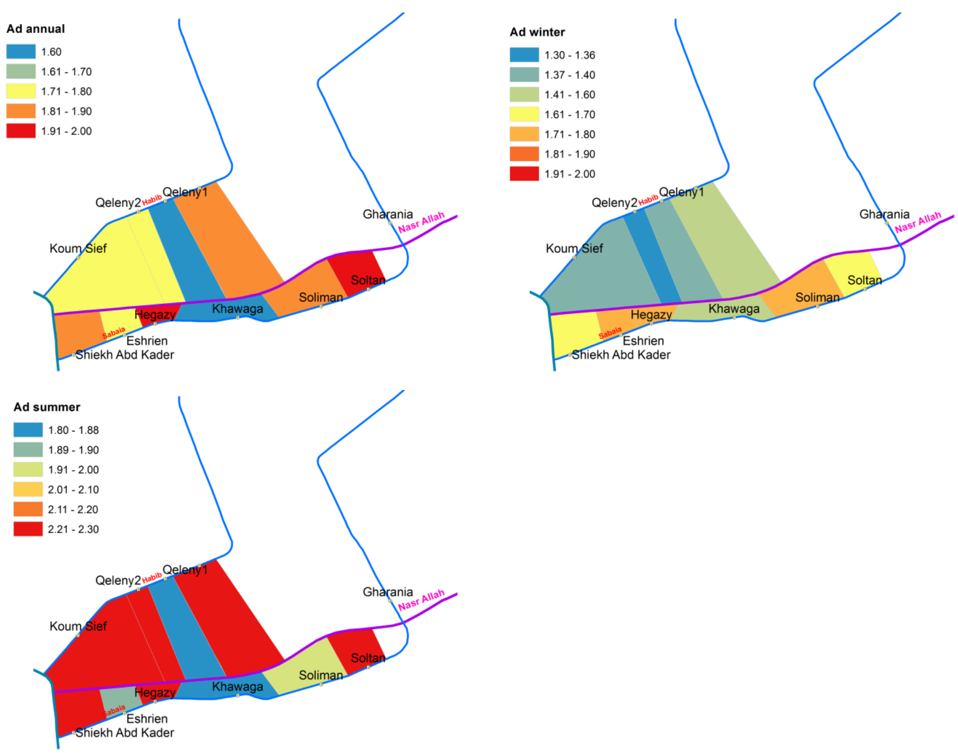


Figure (11): the spatial distribution of the winter, summer and annual irrigation application adequacy (A_{de}) of the eleven mesqas.

3.5 Water productivity

At the evaluation case study, the WP_c calculated values for the studied crops (figure 12) were lower than or closer to the minimum national levels (table 6). WP_c average ranges were 0.36- 0.93 kg·m^{-3} for wheat, 15-20 kg·m^{-3} for barseem, 0.34- 0.54 kg·m^{-3} for rice, and 0.69-0.95 kg·m^{-3} for maize. WP_c of cotton crop indicated range was 0.19-0.30 kg·m^{-3}, which is higher than the national range. The indicated lower values of the WP_c revealed good potentials for water productivity development at the studied irrigation zone.

Figure (13) shows the WP_m calculated values of the eleven mesqas under the evaluation. For all mesqas, WP_m of winter season was two or three times higher than the value of summer for the same mesqa. The average annual range of the WP_m was 2494-4227 calories·m^{-3}. Whereas the indicated WP_m range of the winter season was 3478-7713 calories·m^{-3}, and it was 1361- 2120 calories·m^{-3} for summer season. WP_t calculated values for Habib and Sabia tertiary canals are listed in table (7), which is giving a summary of the results of the water productivity in the three levels of the analysis. The results show noticeable differences between the WP_t of two canals, that overall water productivity of Habib canal is recognizably higher than Sabia. Also, WP_t of winter season is three times higher than the values of the summer season for the two canals.

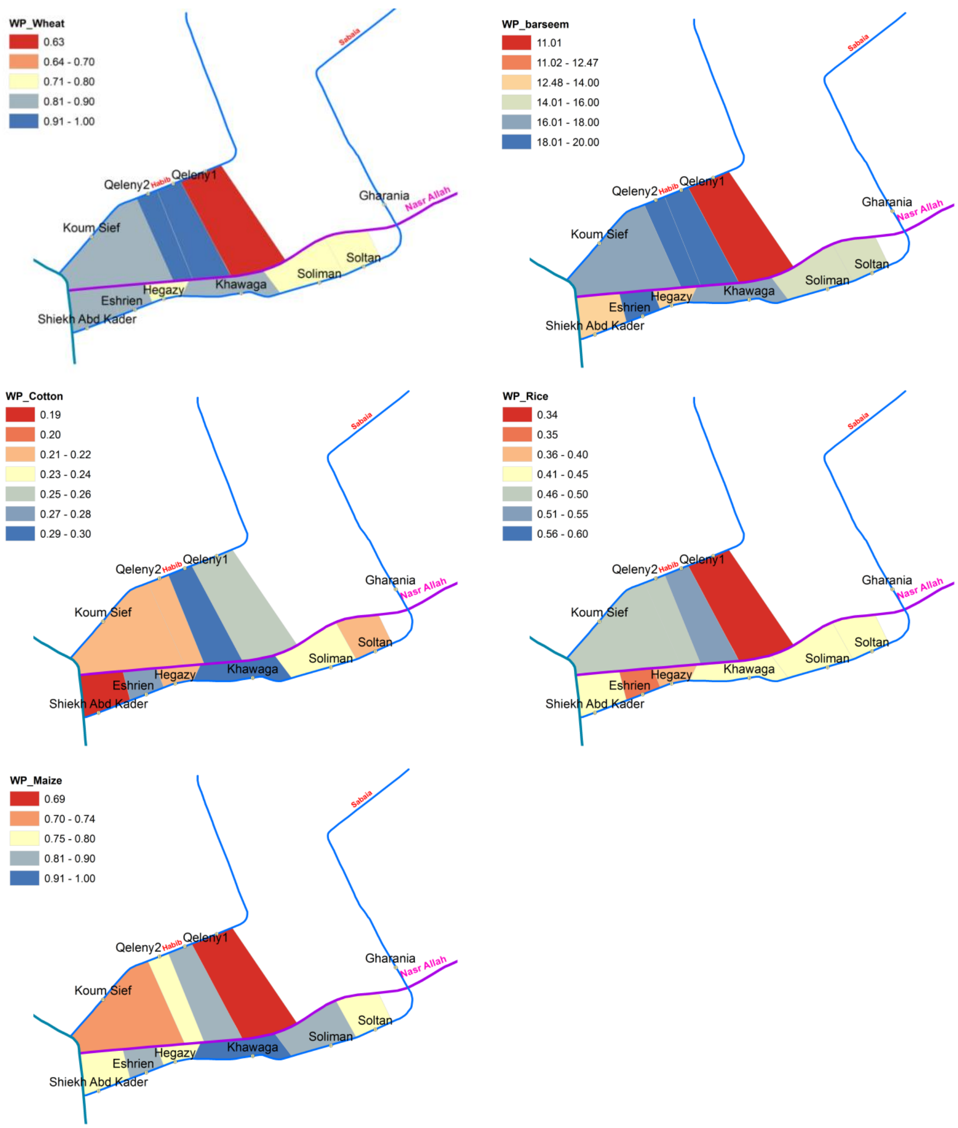


Figure (12): The spatial distribution of the WP_c (kg·m^{-3}) of the five studied crops at the eleven mesqas command zones.

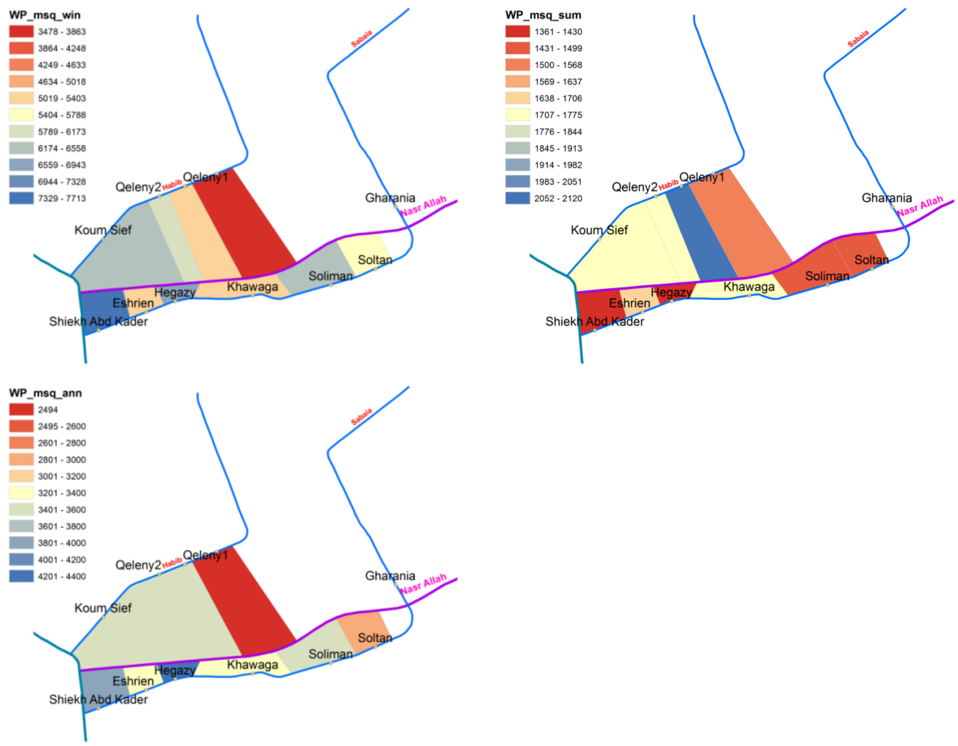


Figure (13): The spatial distribution of the winter, summer and annual WP_m (calories·m^{-3}) of the eleven mesqas.

Table (7): summery of the WP-Optimizer water productivity (WP) analysis of the studied irrigation zone starting from field to the tertiary level (calories·m^{-3})

WP indicator (calories·m^{-3})	**Habib**						**Sabaia**				
	Kom Sief	**El Keleny 2**	**El Keleny 1**	**Masoud El Gahesh**	**El Shiekh Abd El kader**	**El Eshreen**	**Hegazy**	**El Khawaga**	**Soltan**	**El Gharania**	**Soliman**
WP_c [crop]											
Wheat	2677	2622	3183	3259	2814	3174	2204	2852	2951	3117	2589
Barseem	15420	15291	21325	19545	14955	18032	11888	19799	19249	14792	13996
average of the winter crops	**9049**	**8956**	**12254**	**11402**	**8884**	**10603**	**7046**	**11326**	**11100**	**8954**	**8292**
Cotton	1310	1125	1563	1239	1076	1212	1412	1523	1663	1438	1143
Rice	1469	1435	1871	1714	1562	1639	1163	1221	1399	1795	1325
Maize	2923	2857	3115	2707	2806	2587	2490	2945	3422		2751
average of the summer crops	**1901**	**1806**	**2183**	**1886**	**1815**	**1812**	**1688**	**1896**	**2161**	**1617**	**1740**
annual average of the crops	**4760**	**4666**	**6211**	**5693**	**4643**	**5329**	**3831**	**5668**	**5737**	**5285**	**4361**

WP_m [mesqa]											
Winter season	6446	5731	5058	5962	7713	6181	3478	5236	5269	6928	6872
Summer season	1444	1449	2120	1745	1361	1735	1548	1699	1721	1937	1392
annual average	**3452**	**2994**	**3473**	**3528**	**3814**	**3464**	**2494**	**3255**	**3282**	**3736**	**4227**
WP_t [tertiary canal]											
Winter season	6168						3819				
Summer season	1696						1088				
annual average	**3189**						**2251**				

4. Conclusions

Improving agriculture and irrigation management based on water productivity concept needs technical efficient tools to help the researches and planners in the evaluation and finding out the gaps and the potentials in the current production systems, and study new possible development options as well. Simulation models are proved as a strong tool for evaluation and development of improvement options for a wide range of case studies, regarding to irrigation management. "WP-Calc" is an integrated framework model, designed and developed to analyze water productivity and environmental impacts of irrigation practices, starting from field scale to tertiary/branch canal irrigation zone scale. In this paper the "WP-Calc" structure and the theoretical basics were described in details. Furthermore, the paper presents a complete validation case study of the model under Egyptian conditions. The design of "WP-Calc" allow to conducted an integrated analysis for a given irrigation scheme, in order limit the current gap between the on-farm and water-distributary network levels planning and management. It can provide different levels of water productivity analysis, water balance analysis and irrigation network efficiency analysis, with acceptable levels of accuracy. This version of WP-Calc is the beta version, and it's still has wide potentials for improvement, relevant to improve the salt balance analysis quality, develop a standalone crop-response sub-model, and improve the GIS database flexibility to cover more complicated irrigation zones.

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