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Allocation of Irrigation Water under Conditions of Limited Water Supply Using Precision Agriculture Techniques

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LIST OF ABBREVIATIONS

Symbol	Description
Ab	Albedo
ALL	Full Growth Season
B	Biomass (kg)
BCM	Billion cubic meter
BREBS	Bowen-Ratio Energy Balance System
CWSI	Crop Water Stress Index (.)
DEM	Digital Elevation Model (m)
DI	Deficit Irrigation
DOY	Day of Season
D_{sat}	Soil water content at saturation (mm)
E_a	Field application efficiency (%)
e_a	Actual vapour pressure (kPa)
EEFLUX	Earth Engine Evapotranspiration Flux
ERF	Effective rainfall (mm),
e_s	Saturation vapour pressure (kPa)
ET	Evapotranspiration (mm)
ET_a	Actual Evapotranspiration (mm)
ET_a/ET_m	Relative Evapotranspiration (.)
ET_m	Maximum Evapotranspiration (mm)
ETM+	Enhanced Thematic Mapper
ET_0	Reference evapotranspiration (mm/day)
ET_oF	Fraction of grass-based reference crop evapotranspiration (.)
ETr	Alfalfa Reference Evapotranspiration (mm)
ETrF	Fraction of Alfalfa -based reference crop evapotranspiration (.)
ETWP	Evapotranspiration Water Productivity (kg/m^3)
$ET_{\lambda E}$	Estimated actual evapotranspiration using BREBS data (mm)
F_g	Grains Filling Ratio (%)
F_v	Fraction of soil surface (.)

G	Soil heat flux density (MJ m^{-2} day^{-1})
GEE	Google Earth Engine,
G_f	Filled grains weight (gm)
G_W	Grains weight (gm)
h	The Plant height for each growth stage [m] (0.1 m < h < 10 m).
H	Sensible Heat Flux (W m^{-2})
HI	Harvest Index (%)
IWR	Irrigation water requirements (m^3)
K_C	Crop coefficient (.)
$K_{C\ end}$	Crop coefficient at end of the late season growth stage (.)
$K_{C\ mid}$	Crop coefficient during the mid.season growth stage (.)
K_r	Saturated hydraulic conductivity (mm/day)
K_s	Water Stress Coefficient (.)
K_y	Yield Response Factor to Water Stress (.)
LSD	Least Significant Difference (.)
LE	Latent Energy Consumed by ET_a (W m^{-2})
LST	Land Surface Temperature (°K)
LST_{cold}	The temperature of well-irrigated pixel which is almost covered fully by vegetation (Cold pixel)
LST_{hot}	The temperature of the crop covered pixel with maximum value of water stress (Hot pixel).
METRIC	Mapping Evapotranspiration at High Resolution with Internalized Calibration
MODIS	Moderate-resolution Imaging Spectroradiometer
NDVI	Normalized Distribution Vegetation Index
NIR	Net irrigation requirement (mm),
OLI	Operational Land Imager
P	Daily percolation rate out of the root zone (mm)
p	Evapotranspiration depletion factor (%)
PA	Precision Agriculture
PRO	Reproductive Stage
Q	Irrigation water amount (m^3)

R^2	Coefficient of Determination (.)
RAW	Readily available water (mm)
RH_{min}	Daily minimum relative humidity (%)
RIP	Ripening Stage
RP	Required ponding depth (saturation depth) (mm),
R_n	Net Radiation (W m^{-2})
RS	Remote sensing technology
SAT	Amount of water added to saturate the soil (mm)
SEBAL	Surface Energy Balance Algorithm for Land
SLC	Scan Line Corrector
SMC	Soil moisture content in the effective root zone (mm)
SP	Seepage and percolation (mm),
St	Straw weight (gm)
SVM	Support Vector Machine Algorithm.
T_a	The Air Temperature (◦C)
T_c	The Leaf Temperature (◦C)
$T_c - T_a$	The Leaf-Air Temperature Difference
$(T_c - T_a)_{ll}$	The Non-Water-Stressed Baseline
$(T_c - T_a)_{ul}$	The Non-Transpiring Baseline
T_{cold}	Cold pixel, LST of the well-irrigated pixel which is almost covered fully by vegetation.
T_{hot}	Hot pixel, the temperature of the crop covered pixel with maximum value of water stress
TIRS	Thermal Infrared Sensor
TIN	Triangulated Irregular Network
TM	Thematic Mapper
T_s	(Land Surface Temperature) LST, Canopy Temperature in Cropped Land, (◦C)
TVDI	Temperature Vegetation Dryness Index (.)
u_2	Wind speed at 2 m height (m/s)
VEG	Vegetative Stage
WD	Water depth in the field (mm)

W_g	1000 grains weight (gm)
WP	Water productivity (kg/m^3)
WRS-2	Worldwide Reference System-2
W_P	Soil water content at wilting point in percentage of volume (%)
Y_a	Actual yield (kg/ha)
Y_m	Maximum Yield (kg/ha)
Z_r	Measured root zone depth (mm)
Δ	Slope vapour pressure curve (kPa /°C)
$\Delta h/\Delta z$	head gradient (.)
ρ_R	Reflectance in the visible red (Band 4 at Landsat 8 and Band 3 at Landsat 7)
ρ_{NIR}	Reflectance in the Near-infrared (Band 5 at Landsat 8 and Band 4 at Landsat 7)
γ	Psychometric constant (kPa /°C)

5- SUMMARY AND CONCLUSION

Allocation of Irrigation Water under Conditions of Limited Water Supply Using Precision Agriculture Techniques

Agriculture is the biggest consumer of the freshwater on the earth (70% of global fresh water). Since the fresh available water in the world is limited, the biggest challenge all over the world is how to satisfy the crops water requirements.

Egypt is suffering from limited water conditions in the recent years. there is a gap between supply and demand for water that is estimated 20 BCM/yr. Egypt is predicted to exceed the threshold of absolute water scarcity (500 m^3 /ca/yr) by 2025 in addition to the concerns of reducing surface water levels due to the fast filling of The Grand Ethiopian Renaissance Dam (GERD). Many challenges in water management procedures are found on Egypt including the un sufficiency of surface water particularly during the periods of maximum demand in the summer. In many parts of the Nile Delta due to the wide cultivated area of rice in addition to the high-water consumption

This study was conducted to assess the impact of allocating irrigation water under limited water conditions, in an effort to support attempts to increase water productivity by relying on improving planning and allocating irrigation water, with integration of precision agriculture techniques. The objectives of the study were planned to be realized through the following steps:

1. Studying of factors and tools based on the data and available resources, where it ensures the allocation of a crop, variety, study area and describe the details of the theoretical framework to ensure the optimal representation of the problem of study towards achieving its main goal.
2. Preparing and process all the necessary data that can be applied to the crop and study area, with all available strategies as (calculated by reliable models - field experiments - remote sensing)
3. Conducting a limited field experiment for estimating rice yield response to water stress under different water stress levels and during various growth stages
4. Studying and evaluating of deficit irrigation scenarios over the growth stages of rice for yield production and water use through the field experiment.

5. Developing and implementation a GIS-based model in terms of evaluating irrigation water consumption and water productivity, as an easy-to-use approach to the water balance in the agricultural ecosystem and through the model outputs are applied to the field experiment canal as a case study of water allocation to find real solutions for the agricultural sector under conditions of water scarcity.

All necessary data was prepared and organized through various procedures including Calculation of ETo using FAO Cropwat model, downloading and processing the Remote sensing images for summer season of 2019 from Landsat 7 and 8 and EEFLUX. EEFLUX raster datasets includes: were actual evapotranspiration, reference evapotranspiration, grass reference evapotranspiration fraction, Normalized difference vegetation index, land surface temperature, and Cloud masks. Then, the study was carried out in three main parts:

First part: A limited field experiment was conducted on two consecutive seasons during summer seasons 2018 and 2019 to determine the rice yield response factor to water stress in addition to evaluating the influence of deficit irrigation scenarios. The experiment outline was set up as Randomized Complete-blocks Design under factorial scheme (3 × 4 + 1): four randomized test blocks for the full growth period (ALL) and the main growth stages of rice: vegetative (VEG.), reproduction (PRO.), and ripening (RIP.) which divided into three different treatment plots representing water stress levels that determined as 90, 75, and 60 % of Readily Available Water (RAW). In addition, the additional treatment plot (CONTROL) representing the full irrigation at 100% of RAW.

The main measurements throughout the seasons carried out before irrigation directly are the effective root zone depth and the soil water content measurements in order to calculate the irrigation water requirements and ensure reaching the required water stress level.

By the end of each season, the total water requirements were calculated and harvesting measurements are conducted as follows: Grain yield weight (gm), Straw yield weight (gm), Water content in grains (%), Water content in straw (%), 1000 grains weight (gm), and Grains filling ratio (%) to estimate yield response factor to water stress and calculate DI indicators like harvest index, water productivity and evapotranspiration water productivity. The data were analyzed by one way analysis of variance (ANOVA) in randomized blocks and means were compared based on the least significant difference (LSD) test at the 5% probability level using Costat 6.311. in addition to, compare means analysis for multiple comparison of means' tests to compare several means and organize in groups of significance levels.

Second part: A simple ArcGIS toolbox was created for assessment irrigation water allocation using ArcGIS Pro 2.7. The toolbox includes three toolsets, the first toolset is to create the required parameters for calculations, second toolset to produce raster datasets representing the calculations, and the third toolset to complete and editing the parameters raster datasets.

1. Parameters Creation Toolset: includes three successive tools. The aim of the toolset is obtaining daily required parameters for the calculations by estimating the parameters from the image includes Crop Water Stress Index (CWSI), Crop Coefficient (Kc), water stress coefficient (Ks), and Actual Evapotranspiration (ETa).
2. Water Productivity Estimation Toolset: includes six tools for producing maps for water consumption represented at each growth stage and seasonal actual evapotranspiration, and zones that suffered from water stress during the season. In addition to the impact of water stress that represented at seasonal yield production, irrigation water amounts and water productivity.
3. Data Editing and Completing Toolset: The function of the toolset is preparing, editing and completing the raster datasets of the daily parameters. The toolset includes 6 tools for rice crop identification, cloud masking the raster datasets, masking raster datasets by rice fields raster, completing uncompleted rasters that masked and generating daily raster datasets for the parameters.

Third part: A case study was conducted to the study area to reallocate irrigation water based on the experiment results and the GIS based model for irrigation water allocation assessment using Genetic Algorithms.

The most significant results that obtained from the study could be summarized as follows:

Results of first Part: The limited field experiment for estimate rice yield response to water stress:

1. The average (Ky) to water stress for paddy rice during seasons 2018 and 2019 are: as 1.016, 1.16, 0.65, and 1.04, in addition, regression coefficient (R^2) values are found as 0.99, 0.98, 0.99, and 0.97 for vegetative, reproduction, ripening growth stages, and full growth period respectively.

2. There is a high correlation between yield production and relative evapotranspiration ($\frac{ET_a}{ET_m}$). Furthermore, the correlation is very high among yield production, 1000 grains weight and grain filling ratio. Moreover, these parameters and relative evapotranspiration have high correlation with harvest index, water productivity, and evapotranspiration productivity.

3. Yield production and harvest index at ripening stage treatments have the less reduction compared to control treatments then, vegetatiave stage, full growth season, and finally reproductive stage treatments. The data analysis shows the high positive effect of water stress levels on yield production and harvest index.

4. Grain filling indicatiors: weight of 1000 grains (gm) anf grain filling ration have an agreements with the yield production (ton/ha) in impact of deficit irrigation scenrios thoguout the growth stages. The results indicate that increasing relative evapotranspiration produces increasing in grains filling.

5. The highest average water productivity (WP) obtained from the control treatments with 0.74 Kg/m^3, while the lowest average WP was obtained from reproductive stage treatments with 0.51 kg/m^3. The average WP recorded from vegetative, ripening stages and full season treatments were: 0.57, 0.61 and 0.65 kg/m^3. The average values of evapotranspiration water productivity. (ETWP) throughout the treatments have agreement with average values of WP. The highest average ETWP produced by control stage then ripening growth stage, full season, vegetative, and finally reproductive growth stage treatments with 1.49, 1.22, 1.18, 1.11, and 0.99 kg/m^3 respectively.

6. compare mean test indicates the high agreement among the results of 1000 grains weight (gm) and grain filling ratio (%), and yield production (ton/ha), water productivity and evapotranspiration water productivity.

To conclude the previous results, the growth stage that suffered the least impact of water stress is ripening stage, on the other hand, the highest impact occurred during the reproductive stage. The best results obtained from the treatment RIP90: applying 90% water deficit level during the ripening growth stage, in opposite to the treatment PRO 60: applying 60% deficit irrigation level during the reproductive growth stage.

Results of second Part: GIS Based Model for Assessment of Irrigation Water Allocation:

The toolbox was conducted to the study area at summer season of 2019 based on the obtained Ky values from the previous experiment. The important obtained results are as follows:

1. The map of study area classification based on the LANDSAT 8 image in 11 August, shows that, the area of rice fields was 73.3662 km^2 which represented 45% of the total area. However, the area of buildings, bare soil, and other crops were 16.044, 16.460, 57.988 km^2 represented 10,10,35% of the total area.

2. The average NDVI values for vegetative reproductive, and ripening stages range from (0.18 to 0.85), (0.85 to 0.89), and (0.89 to 0.3). the results indicated that the highest value of NDVI is during the reproductive stage.

3.Values of Kc for vegetative reproductive, and ripening stages range from (0.65 to 1.07), (1.07 to 1.09), and (1.09 to 0.8). Kc value for the reproductive stage is the highest values during the season likewise NDVI. The duration of each growth stage is approximately 73 ,24, and 32 for Vegetative, reproductive, and Ripening. The longest growth stage is vegetative stage.

4. The obtained Kc values are validated compared to the adjusted FAO Kc values to the local climatic condition for the growth stages, vegetative, reproductive, and ripening. The validation of the simple regression equation yielded a coefficient of determination (R^2) = 0.9552 and Root Mean Square Error (RMSE) = 0.08 which indicates to the high accuracy of the estimation.

5. The seasonal summation of ETo for the area ranged between 985.299 to 980.625 mm with average 983.061 mm. The highest ETo summation is approximately 216.722 mm during July, however, the lowest summation is approximately 153.175 mm during September.

6. The highest levels of water stress occurred during the vegetative stage of the rice crop fields, whereas the highest average of CWSI is 0.39 and 16.15% of the area suffered from CWSI values higher than 0.5 when the lowest average of Ks throughout the season is 0.74 with the largest area proportion which suffered from Ks values lower than 0.7. Otherwise, the lowest level of water stress occurs during the reproductive stage, because of the value of average CWSI is 0.27 and only 4.47% of the area recorded CWSI values higher than 0.5, on the other hand, the lowest level of water stress occurs during the reproductive stage, since the value of average is 0.91 and only 0.1 % of the area recorded Ks values lower than 0.7.

7. The agreement between CWSI and Ks for evaluating water stress throughout individual growth stages. On the other hand, CWSI is not an accurate index for water stress throughout the season because it is based on land surface temperature which affected by the growth stage of the plant.

8. The highest value of average daily actual evapotranspiration values (ETa, mm) throughout the season is 6.74 mm at the 72nd day, however the lowest value is 2.12 mm at the 7th day. Although, the lowest average values of ETo occurred during the vegetative growth stage, this stage contributed the largest proportion of the seasonal ETa summation due to the long duration of this stage compared to other stages and the opposite is true for the reproductive stage.

9. The spatial distribution of yield production(ton/ha) indicates that, fields which produced the largest grain yield (8 to 10.7 ton/ha) represented 3% of the total rice fields area. The estimated total yield production of the study area for 2019 season is 27588 ton.

10. The spatial distribution of the consumed irrigation water amounts indicated that, fields which consumed more than 1.1 $m^3 \backslash m^2$ represented 18% of the total area. The total estimated water consumption for the study area was 50,658,900 m^3.

11. The spatial distribution of water productivity (WP) and evapotranspiration water productivity (ETWP) in (kg/m^3) indicates that, the highest values of WP and ETWP are 0.9 and 1.81 kg/m^3.

12. The outputs of the ArcToolbox were validated by the corresponding output from the limited experiment to estimate rice yield response to water stress. the output values of model-based WP and ETWP for ripening stage were used for the validation compared to the similar experiment- based values. The root means square error (RMSE)= 0.0178 and 0.0547 for WP and ETWP respectively, which indicates to the high accuracy. The statistical analysis illustrated the convergence between the model-based and experiment-based outputs, which proved the accuracy of the toolbox for estimating water consumption, water stress level, yield production, water productivity, and evapotranspiration water productivity.

Results of third part: Spatial irrigation water allocation using genetic algorithms:

1. The new distribution of growth stages which could be concluded as follows: 7.95%, 6.55%, and 85.49% for the vegetative, ripening growth stages and full season water stress. reproductive growth stage didn't distribute due to the high sensitivity to water stress.
2. The total proposed irrigation water was 4.99×10^{7} m^3. The spatial irrigation water distribution (m^3\$m^2$) varied from 0.92 to 1.35 m^3\$m^2$.
3. The new predicted spatial yield production varied from 0.514 to 0.785 kg/m^2. The total new potential yield production is 28383 ton, which higher than the real production by 11.88% (3014 ton).

The recommendations

- It is recommended to use the rice yield response factors to water stress for various growth stages for accurate estimation of actual yield production.
- The most tolerant growth stage of rice which is recommended to apply water stress is ripening stage, on the other hand, the highest impact of water stress occurs during the reproductive stage.
- Applying 90% of readily available water during the ripening growth stage is recommended under water stress conditions while, applying 60% deficit of RAW during the reproductive growth stage causes a reduction in yield production.
- It is recommended to use the (ArcGIS Toolbox for irrigation water allocation assessment) to estimate water stress, yield production and water productivity accurately, using daily data throughout the season.
- Using genetic algorithms is recommended to reallocate irrigation water based on deficit irrigation methods, which predicted 11.88% production higher than the actual production under the same amount of available water.