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Evaluation of Irrigation Uniformity and Equity Under Center Pivot Using Remote Sensing

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ABSTRACT

Due to fresh water being rare, especially in the arid regions, the need to produce more food, and facing the climate change effects on agricultural production, so, enhancing irrigation systems and raising their efficiency become urgent necessity. The good evaluation of irrigation systems leads to better water management and sustainable agricultural development. This study proposed a framework for evaluating the center pivot irrigation systems based on remotely sensed data and field measurements. Irrigation uniformity distribution (CU and DUlq) were assessed from field data using catch cans method. Irrigation equity was evaluated by estimating actual evapotranspiration (ETa) based on the triangle method from satellite data. The spatial variation of ETa was assessed from the coefficient of variation (CV), and ETa maps were produced for better interpretation. Irrigation equity assessed at different two scales, the whole cultivated area and different placements of the center pivot irrigation system. The results showed that the irrigation system water distribution uniformity was "poor" as the CU value was between 70%-79% and the DUlq was 61%. The results also indicated the absence of irrigation equity (i.e., fairness of irrigation distribution) especially in the early and late stages of the crop life cycle, as the STDV of ETa and the CV values were high during the monitoring dates. Also the irrigation equity did not exist along the center pivot irrigation system radius at different 4 placement of irrigation.

KEYWORDS: Remote sensing, Irrigation performance indicators, Uniformity, Adequacy.

1. INTRODUCTION

Irrigated agriculture stands for 20 percent of total cultivated land and 40 percent of total food production worldwide. Competition for water resources is predicted to increase due to population expansion, urbanization, and climate change, with a particular impact on agriculture. It is anticipated that agricultural production will need to increase by 70% by 2050 to meet the increasing food and fiber demands (World Bank). At the same time, climate change is expected to reduce water supplies and, consequently, irrigation water availability. Arid regions, in particular, confront significant challenges due to restricted water resources. Egypt, for example, faces a significant issue due to its limited water supplies. Furthermore, a decrease in Nile River water is predicted following the completion of the Grand Ethiopian Renaissance Dam (Elnmer, et al. 2018). Better irrigation management is required to efficiently utilize valuable fresh-water resources. A key factor in improving water management in irrigated agriculture is the assessment of irrigation performance in order to maximize water use efficiency (Ashour, et al. 2021). Accordingly, Irrigation Performance Indicators (IPIs) have been developed to assess the process of irrigation performance in several irrigation schemes. Irrigation performance assessment (IPA) for multiple levels of irrigation (i.e., field, irrigation system, and basin) carried out by systematic observation, documentation, and interpretation of irrigated agriculture activities, so, it provides data for the efficient design, implementation, operation, and management of irrigation schemes (Elnmer, et al. 2018 and Ashour, et al. 2021). The IPA is classified into two types: external (EIPA) and internal (IIPA) performance assessments. (Elnmer, et al. 2018 and Hollanders, et al. 2005). Concerned with the overall state of the irrigation system is the external irrigation performance assessment, (EIPA). It places a strong emphasis on the irrigation system's water productivity, environmental effect, and water efficiency. The irrigation system's (IP) can be tracked over time, and the (IPs) of other irrigation systems can be compared. (Akhtar, et al. 2018). The IIPA compares delivered water supply and water needs, even though it describes the internal irrigation operations and water allocation of an irrigation system. It uses adequacy, equity, efficiency, and dependability metrics to assess the temporal and spatial performance changes of the irrigation system (Bos, et al. 1993 and Elnmer, et al. 2018). A full ground survey may be necessary for the most accurate evaluation and monitoring of any operation, but doing so frequently and over a big region is typically expensive and time-consuming. The most prevalent issues in evaluating and monitoring irrigation are a lack and unreliability data, which makes the use of remotely sensed data crucial. (Aman, 2003). High spatial and temporal resolutions of remote sensing are useful for analyzing agricultural performance. With greater access to satellite imagery and retrieval methods, remote sensing now offers efficient yet spatially and temporally comprehensive options for estimating agricultural indicators. These options are particularly helpful for assessing irrigation effectiveness in data-scarce locations like Africa. (Blatchford, et al. 2020). To estimate and evaluate various indicators for irrigation performance at the irrigation scheme level (i.e., the irrigation perimeter), remote sensing has been verified and evaluated at various temporal and spatial resolutions (e.g., spatial resolution refers to the pixel size, and temporal resolution refers to the satellite revisit time). Adequacy, sustainability, and water productivity are all included in these studies (Elnmer, et al. 2018, Taghvaeian, et al. 2018 and Karimi, et al. 2019).

The center pivot irrigation system (CPIS) is the most widely used sprinkler irrigation system in achieving sustainable irrigated agricultural projects around the world, particularly in Egypt. The individual center pivot device can irrigate an area of about tens of hectares, different crops, and challenging operation conditions (mostly arid conditions). As a result, there is an urgent need to develop a detailed framework for assessing the irrigation performance of the Center Pivot Irrigation System (CPIS).

This study aims to set a detailed framework for evaluating the center pivot irrigation system (CPIS) internal performance using remote sensing. This framework consists of irrigation distribution uniformity calibration and irrigation equity (i.e., Fair distribution in irrigation).

2. MATERIALS AND METHODS

2.1. Study area

The 6th of October Company is located in the eastern part of the Nile Delta as shown in Fig. 1. The total area of the project is approximately 13,800 ha. The project makes use of two irrigation systems: center pivots and drip irrigation. There are approximately 100 pivot irrigation units in the project. A total of 63.6 hectares is irrigated by each pivot unit with standard pivot length about 450 meters.

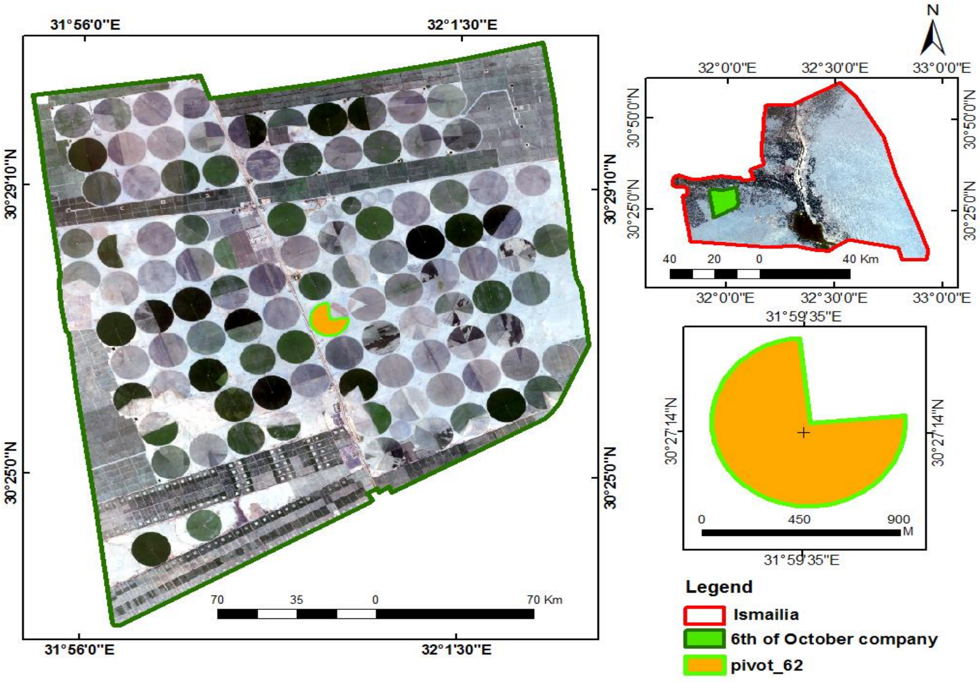

Figure 1. study area

According to the Köppen Climate Classification System, the climate in the study area is dry and arid, with precipitation accounting for less than 50% of potential evapotranspiration. The average annual temperature exceeds 18°C. The average annual rainfall is about 20 mm. The highest rainfall totals are recorded in January, with an average of 6.9 (mm). The average of maximum temperature in June is 34.6°C, with January being the coldest month at 19.0°C. Minimum temperatures range from 8.0 °C in January to 21.5 °C in August.

2.2. Data

There are many satellites sensors that provide a variety of scenes as remote sensing data. Each sensor has its specifications of spatial, temporal, spectral, and radiometric resolution. So the data of each sensor is different from another. Here, a hybrid of Landsat 7 and Landsat 8 sensors data were chosen (Row = 39 and Path = 176) to be used in this study to cover the summer season crops of 2021. These time series data were acquired in the 6th of June, 22nd of June, 8th of Jul, 9th of Aug, 25th of Aug and 18th of Sep of 2021 and also were used to investigate irrigation equity by estimating of the actual evapotranspiration (ETa) and producing the ETa maps. On the other hand, field tests using the catch cans technique occurred to evaluate the center pivot irrigation system performance, which resulted in the determination of irrigation water applied depth, water distribution uniformity and irrigation equity.

2.3. Methods

Evaluation of distribution uniformity and irrigation equity model needs to integrate different data sources like field data, climatic data, and satellites data to enhance the evaluation accuracy. The following flowchart (figure 2) explains the evaluation framework steps, and types of integrated data.

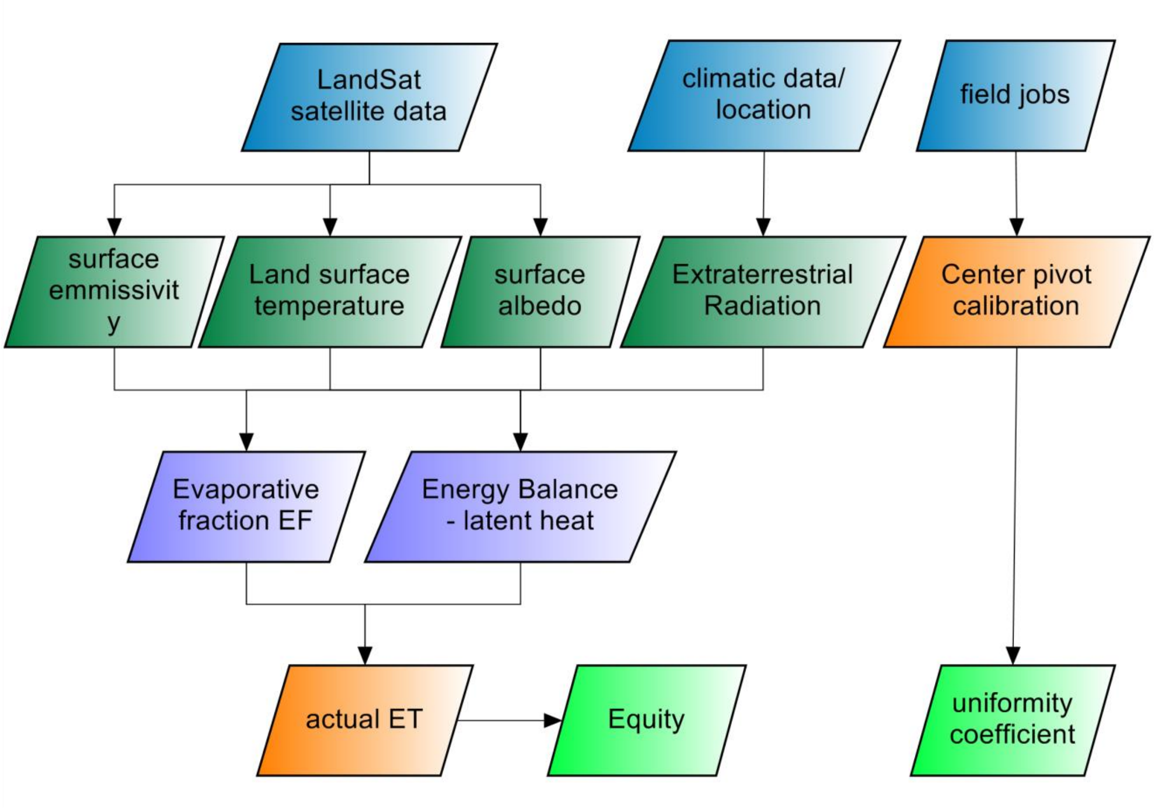

Figure 2. Evaluation framework flowchart and integrated data

2.4. Distribution uniformity calibration

Center pivot sprinkler irrigation system unit No. 62 of area 115 acre was chosen to conduct field evaluation measurements. The evaluation was to determine water distribution uniformity coefficient (CU) and (DU_{lq}) from field measurements from an array of water collecting cans spaced 8 meter apart (catch cans experimental method). The measurements were repeated 3 times and the average values were represented in (figure 4) and analysis to obtain Christiansen uniformity coefficient (CU) and (DU_{lq}) as follows:

$$CU = 100\left[1-\frac{\sum|xi-x*|}{nx*}\right] \qquad \text{eq. } 1$$

(Christiansen, 1942)

CU: Christiansen uniformity coefficient (%).

Xi: the individual water depth collected by each catch cans (mm).

X*: the average of all measurements in catch cans (mm)

N: number of catch cans.

According to the CU values, the uniformity of the irrigation water distribution under sprinkler irrigation systems was categorized as very good (CU > 90%), good (CU between 89% and 80%), mediocre (CU between 79% and 70%), and worse (CU 70%). (Little, et al. 1993).

2.5. Low Quarter Distribution Uniformity (DUlq)

A further indicator of application uniformity is low quarter distribution uniformity (DUlq). James (1988) defined it as the percentage difference between the mean low quarter amount

(Xlq) in mm and the typical quantity caught in catch cans. (Xa) in mm.

$DUlq = 100\,(\frac{Xlq}{Xa})$ eq. (2)

Based on DUlq, DU was categorized as excellent if it was between 80% and 79%, very good if it was between 79% and 70%, decent if it was between 70% and 65%, fair if it was between 65% and 60%, and poor if it was between 60% and 50% Mecham (2004).

2.6.Equity

The equity indicator expresses the irrigation system's spatial distribution uniformity and fairness in delivering the required irrigation water. (Fan, et al. 2018). Soil variation properties may cause spatial variation in water requirement, and also cultivate different crops, and crop bio properties do that. The irrigation system should face this variation to achieve fairness in irrigation. Equity is calculated by calculating the coefficient of variation (CV) between ETa values. (Dejen, et al. 2015and Karatas, et al. 2009).

CV of evapotranspiration= STDV **ETa**/ Mean **ETa** eq.3

Where:

CV: is the coefficient of variation between ETa values.

STDV **ETa**: is the standard deviation of ETa values.

Mean **ETa**: is the average of ETa values**.**

2.7. ETa Estimation

Actual ET by plants can differ greatly from potential ET rates due to the influences of drought, disease, insects, vegetation quantity, phenology, soil texture, fertility, and salinity. The triangle method is one of the different methods proposed for measuring ETa using remote sensing based on the energy balance equation and showed high accuracy and correlation under Egyptian conditions for different crops (Baioumy et al. 2016).

The daily component of the energy balance equation (eq.4) is used by the Triangle method to determine daily ETa;

$Rn = G + H + \lambda E$ eq.4

Where: net radiation expressed by Rn in (Wm^{-2}), soil heat flux expressed by G in (Wm^{-2}), sensible heat flux expressed by H in (Wm^{-2}), and latent heat flux expressed by E associated with actual ET (Wm^{-2}). The energy balance can be changed;

$\lambda E = EF \cdot (Rn - G)$ eq.5

Where; Evaporative fraction (EF) is a dimensionless number and (Rn − G) reflects the net energy available for ET. G is frequently neglected over time periods of one day or more, so λE is totally a function of Rn and EF.

The ratio of actual ET to available energy is another definition for the EF (dimensionless).

$EF = \frac{\lambda E}{Rn-G}$ eq.6

According to the (Priestley-Taylor) equation, the conventional formula, which reflects the Triangle approach, was applied in this study:

$\lambda E = \phi.(Rn - G).\frac{\Delta}{\Delta+\gamma}$

eq.7

Where

ϕ Is a substituted for (P–T) parameter, and its values also range from ($\phi_{min} = 0$) at dry bare soil pixels to (ϕ max =1.26) at none stressed with full vegetation cover pixels.

γ is the psychometric constant (kPa/K) and Δ is the slope of saturated vapor pressure at the air temperature (kPa/K).

Daily ETa was calculated by using eq.7 for each pixel (pixel area 900 m2) of the pivot area of about 157 acres during the cultivation season for peanuts crop and daily ETa maps were created for all monitoring dates. Actual evapotranspiration (ETa) values were extracted from the ETa map in different 4 placements of irrigation system (figure 3) to represent the variation of the ETa values on the same placement and also irrigation equity side by side to the (CV) which represents the ETa variation and equity in the whole pivot.

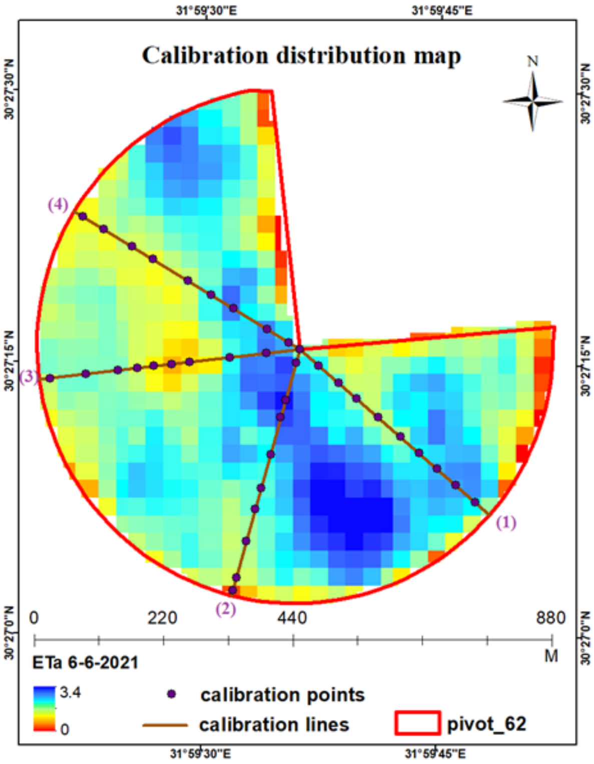

Figure 3. Different placements of the irrigation system and extracted ETa values locations.

3. RESULTS AND DISCUSSIONS

3.1. Irrigation system uniformity

Uniformity coefficients were determined from field measurements by using an array of water-collecting catch cans. Figure 4 shows water depths collected by the catch cans distributed along the radius of the center pivot.

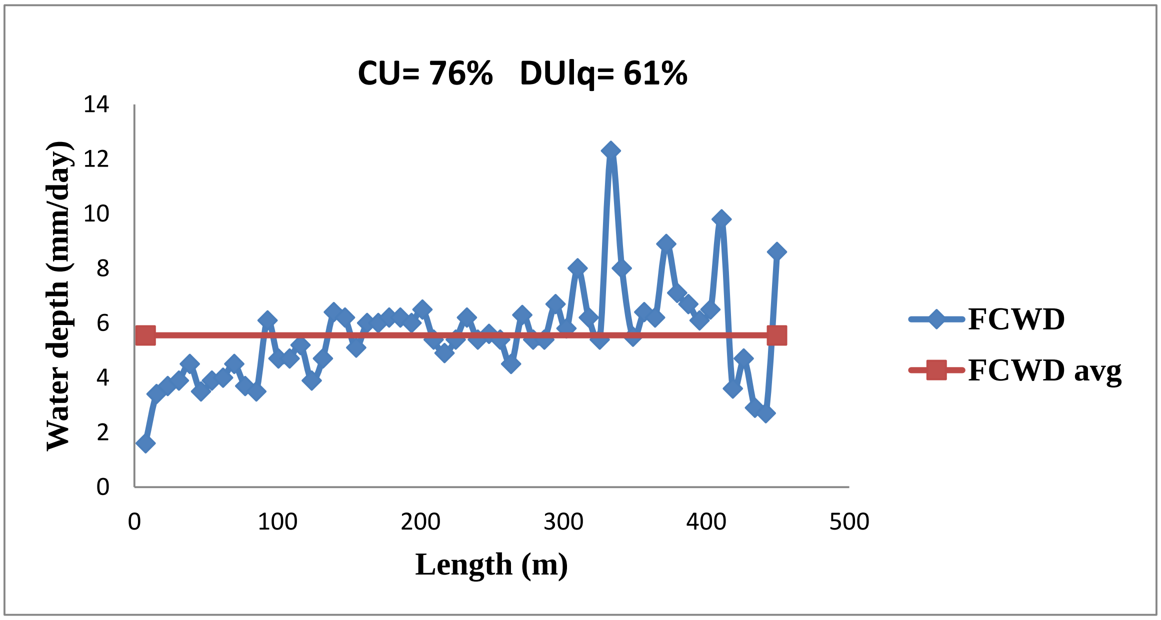

Figure 4. Water applied distribution graph along the center pivot radius

By using the Christiansen's uniformity (CU) equation (eq. 1) and (DU_{lq}) eq. (2) and according to the classification of uniformity (Little, G.E., et al. 1993) the result of the calibration was:

Table 1 Classification of the irrigation system efficiency.

Pivot no.	value	dependability	reference
CU	71 %	poor	70%-79%
DU_{lq}	61%	fair	60%-65%

3.2.Equity

Daily ETa (mm/day) as calculated by using eq.7 for each pixel of the pivot area during the different monitoring dates throughout the cultivation season for peanuts crop were Statistical analyzed as shown in table 3.

Table 2 Threshold of ETa (mm/day) for pivot 62 during the different monitoring dates.

Date	min	max	mean	STDV	CU% satellite
06-Jun-21	2.3	3.4	3.0	0.2	94
22-Jun-21	3.2	6	5.4	0.4	92
08-Jul-21	3.8	7.2	6.2	0.8	88
09-Aug-21	5.4	8	7.4	0.4	94
25-Aug-21	4.6	7.5	6.9	0.5	92
18-Sep-21	3.7	6.9	6.3	0.4	94

Results shown in (table 2) and (figure 5), which were based on satellite maps in (fig 8),could be interpreted as follows: on the 6th of Jun, beginning of germination, the ETa values ranged from 2.3 mm/day as a minimal value to 3.4 mm/day as a maximum value of ETa with an average value 3 mm/day. Although the percentage of the difference between the min and the max is 68%, the standard deviation of ETa at this date is 0.2, and the majority ranged around the average which means that there is no significant variation from the mean. On the 22nd of Jun, with an increase in the biomass, the ETa values ranged from 3.2 mm/day as a minimum value to 6 mm/day as a maximum value of ETa with an average value of 5.4 mm/day. By increasing biomass, the spread of values around the mean began to increase the standard deviation value at this date was 0.4 while, the difference between the minimum and the maximum decreased, and its percentage became 53%. On the 8th of Jul, the biomass was continually developing, so the ETa values also became higher in almost the entire pivot and ranged from 3.8 mm/day as a minimal value to 7.2 mm/day as a maximum value of ETa with an average value 6.2 mm/day. The difference between the min and the max is about 53%; the standard deviation of ETa at this date was 0.8, which means that there is, to some extent, significant variation from the mean. Although the ETa seems consistent in almost the pivot (about 70 % of the area), there was a very decline in the ETa values in the residual area (about 30%) (Figure 8). The interpretation of this phenomenon back to irrigation management as the center pivot cannot work in a complete circle. For some reason, center pivot equipment needs to move in the reverse direction, so it duplicates irrigation in some covered areas and create a deficit in another area. The 9th and the 25th of Aug represent the peak of the crop growth and by extension, the highest values of the ETa during the season. The ETa values on the 9th of Aug ranged from 5.4 mm/day as a minimal value to 8 mm/day as a maximum value of ETa with an average value of 7.4 mm/day that shows the average is close to the max ETa value the thing which means the majority of values is close to max and minority close to min. The percentage of the difference between the min and the max of ETa was 68% but

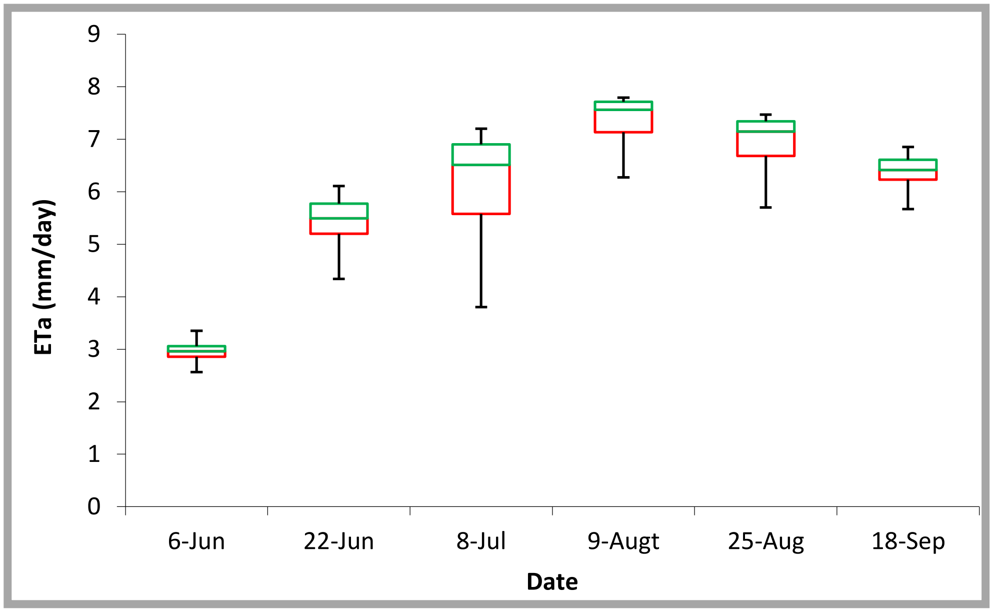

Figure 5 Actual ET stats. for each monitoring day.

it represents minority values and the standard deviation was 0.4. The ETa values on 25th of Aug ranged from 4.6 mm/day as a minimal value to 7.5 mm/day as a maximum value of ETa with an average value of 6.9 mm/day. The percentage difference between the min and the max of ETa was 61%, and the standard deviation was 0.5, so, we find that this observation date is the begging of ETa rates decreasing, and more variation will appear following dates. As predicted, the following observation date 18th of Sep showed an increase in the difference between min and max ETa (3.7 and 6.8 mm/day, respectively), where the average was 6.3 mm/day. The average still close to the max ETa value but it is consistent with the decline track and is lower than the previous averages (Figure 5).

Extracted ETa values from the ETa map represented in (figure 6) shows the behavior of ETa values along the center pivot radius in different 4 placements. ETa map of 6th of June at germination stage chosen to reflect the inter action between soil properties, weather condition and ETa rates. It shows swings in values and varying curves up and down, the thing which mean absence of equity in the same placement. Although the user deliberately added large amounts of water more than required to overcome the variation in soil properties (i.e. soil holding capacity and available water), the results showed absence of irrigation equity and disability of the irrigation system to achieve it.

The coefficient of variation (CV) between ETa values was estimated using eq.3 and the values listed in table 3 below for different dates. The CV showed some responsible variation for the equity and also showed variance from one day to another. Looking to (figure 5) and table 3 we find that there is a positive relation between CV and the difference between min and max ET for each day. Whenever the variation between min and max ET increased, CV increased, and vice versa.

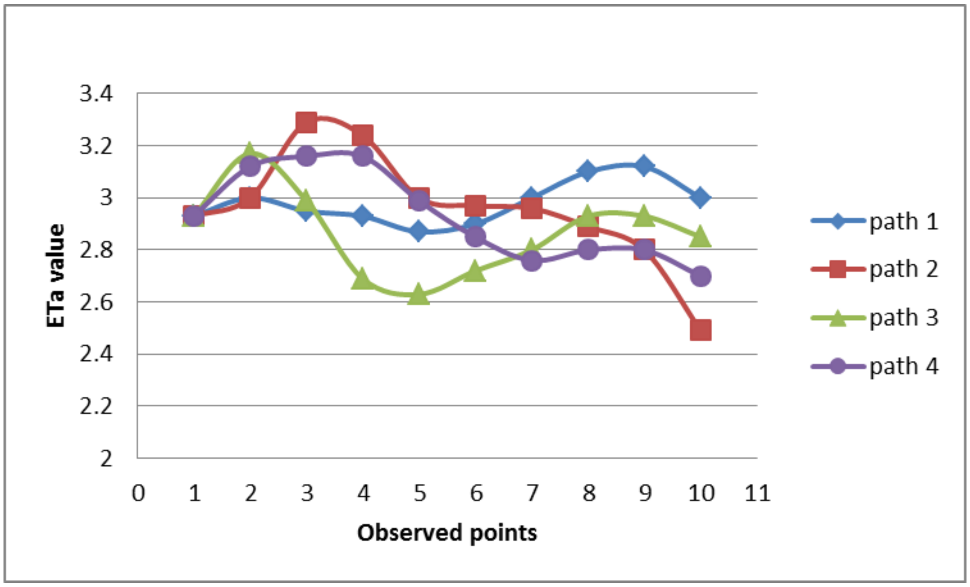

Figure 6. ETa trends of the 4 placements of the irrigation system.

Table 3 Coefficient of variation of actual daily ET:

Date	6-Jun	22-Jun	8-Jul	9-Aug	25-Aug	18-Sep
CV	0.05	0.08	0.12	0.06	0.08	0.07

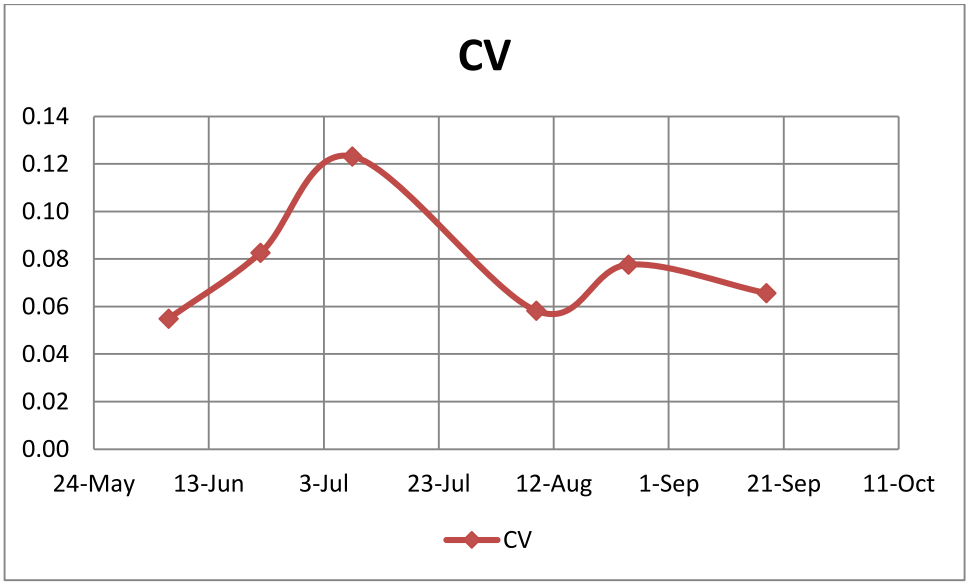

Figure 7. shows the behavior of CV during the monitoring dates.

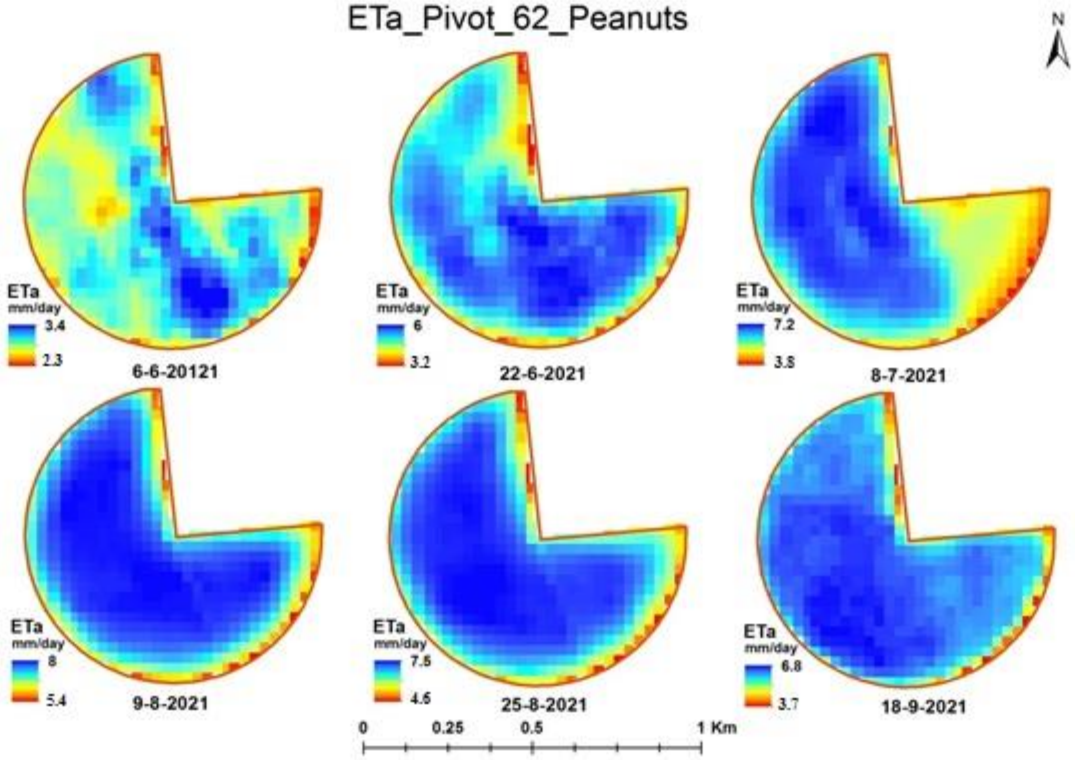

Figure 8. ETa mapping for pivot 62, summer season, peanuts in each monitoring date.

Daily actual evapotranspiration (ETa) is produced for each day (figure 8) for better visualizing interpretation and to show deficit and optimized places of water consumption. The maps show that there is a variation in the ETa values at the beginning of the season due to the variation in the germination rate on dates 6th and 22nd of Jun and this variation decreased gradually by increasing of the germination rate and crop coverage on dates 9th and 25th of Aug. when the crop reached to the end of the season, the variation come back again and have a recognizable value. The presence of ETa variation between the beginning and the end of the cropping season may be back to the interaction between the crop and non-uniformity of soil properties as well as the climate changes during cop growth stages. On the other hand, the privation of ETa variation in the mid-season back to adding more over the amount of water by the users to overcome the soil properties variation, plant canopy increase and losing water from transpiration basically.

4. CONCLUSIONS

An internal framework for evaluating the center pivot irrigation system (CPIS) performance using remote sensing is proposed in this study. This framework consists of irrigation distribution uniformity calibration and irrigation equity (i.e., fairness of irrigation distribution). The irrigation uniformity distribution is continuously assessed by using the uniformity coefficient (CU) developed by Christiansen and low quarter distribution uniformity (DU_{lq}) defined by James (1988). According to the classification of uniformity (Little, G.E., et al. 1993), the result of the calibration was “poor”. The second index was the irrigation equity responsible for the fairness of irrigation distribution. Actual evapotranspiration (ETa) is estimated for each monitoring day during the season based on the energy balance “triangle method”. The ETa values were used for estimating the irrigation equity which assessed at different two scales, entire the pivot and four different placement of the irrigation system. The results showed that there was a responsible variation in the equity values at the beginning and at the end of the crop season, and it can be explained basically to the weakness of the irrigation uniformity distribution and the interaction between the crop growth stages and the non-uniformity of soil properties. Also he results showed the absence of irrigation fairness at the same placement and along the center pivot radius. This variation decreases when the crop cover becomes higher and near to similarity in the whole area. Finally, this research recommends doing some enhancement to the center pivot to raise its uniformity and if possible applying the precision irrigation system. Other recommendation related to the soil, some of soil enhancement materials like organic matter should be added to the soil in order to raise its capability of catching irrigation water.

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الملخص العربي

تقييم إنتظامية وعدالة توزيع مياه الرى تحت نظام الرى المحورى بإستخدام الإستشعار عن البعد

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[٢]قسم هندسة النظم الزراعية والحيويه –كلية الزراعة– جامعة بنها

نظراً لندرة المياه العذبة، خاصة في المناطق القاحلة و الحاجة إلى إنتاج المزيد من الغذاء، ومواجهة تأثيرات تغير المناخ على الإنتاج الزراعي، أصبح تعزيز أنظمة الري ورفع كفاءتها ضرورة ملحة. إن التقييم الجيد لأنظمة الري يؤدي إلى إدارة أفضل للمياه وتنمية زراعية مستدامة. اقترحت هذه الدراسة إطارا لتقييم أنظمة الري المحوري إعتمادا على بيانات الاستشعار عن بعد والقياسات الحقلية. تم تقييم توزيع الري (DUlq –CU) من البيانات الحقلية باستخدام طريقة علب تجميع المياه. تم تقييم عدالة الري من خلال تقدير البخرنتح الفعلى (ETa) بناءً على طريقة المثلث من بيانات الأقمار الصناعية. تم تقييم التباين المكاني لـ ETa من معامل التباين(CV) ، وتم إنتاج خرائط ETa لتفسير أفضل لتوزيع المياه. تم تقييم عدالة الري على نطاقين مختلفين، المساحة المزروعة بأكملها والمواضع المختلفة لنظام الري المحوري. أظهرت النتائج أن انتظام توزيع المياه في نظام الري كان "ضعيفاً" حيث كانت قيمة CU تتراوح بين ٧٠%-٧٩% و كانت الـ DUlq 61%. كما أشارت النتائج إلى غياب عدالة الري (أي عدالة توزيع مياه الري) خاصة في المراحل المبكرة والمتأخرة من دورة حياة المحصول، حيث كانت قيم STDV لـ ETa وقيم ال CVعالية خلال مواعيد الرصد. كما أن عدالة توزيع مياه الري لم تتحقق أيضا على طول نصف قطر نظام الري المحوري عند ٤ مواضع مختلفة للري.

الكلمات المفتاحية: الإستشعار عن بعد، مؤشرات تقييم الرى، إنتظامية التوزيع، عدالة توزيع مياه الرى.