A Developed Simple Spreadsheet for Center Pivot Irrigation System Design

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Abstract - Centre pivot irrigation system is a promising and precise system, for increasing the utilization efficiency of unit water. However, Egyptian agricultural-water uses policies for reclaiming and cultivation 1.5 million feddan (625000 ha) had stated center pivot irrigation system as a major irrigation system. Hence, a developed simple-spread sheet module for center pivot irrigation system design has been developed and validated. However, the developed spread sheet is based on different design criteria, as, crop type, weather data, and soil characteristics. The module comprises five sub-models for: (a) main sub-model; (b) data entry sub-model; (c) weather sub-model; (d) irrigation sub-model; and (e) results sub-model. The most important outputs include nozzle flow rate (m³/h), application rate (mm/h), and throw diameter (m). These outputs (outputs of 9 scenarios) were compared with observed/manufactured data for the calibration and validation of the model.

Results of this comparison show that differences in model accuracy owing to different variables affecting the design and management of the center pivot were not significant. The relationships between the observed/manufactured and simulated results have a good correlation with high value of coefficient of determination and the best models are as follows:

1. Nozzle flow rate (m³/h) was in scenario 5 with R² = 0.967 and explained by an exponential model: Q simulator = 0.1067e^{0.3133 (Q observed)}.
2. Throw diameter (m) was in scenario 1 with R² = 0.942 and explained by a power model: Dw simulator = 3.9064 (Dw measured)^0.4361.

Keywords: Modeling; Application rate; Nozzle flow rate; Throw diameter.

1. INTRODUCTION

Center pivot is a promising method of irrigation, became very popular in Egypt, in which water is dispersed through a long segmented arm that revolves a water source (deep well for example) and covers a circular area. A wide diffusion of the center pivot irrigation systems [8 and 15] is due to two reasons: (I) automation is built into the center pivot device allowing for irrigation with minimal labor input; and (II) center pivot systems can be one of the most efficient and uniform methods of applying irrigation water. Currently, an objective of irrigation planners is to obtain a high level of irrigation management as general and center pivot irrigation management in specific. Attempts to apply and manage center pivot irrigation systems have been started in the 1960s. Reference [7] had developed center pivot irrigation model software for water and/or water-nitrate distribution analyses from center pivots. Reference [2] developed a model for simulating of water application under center pivots, focusing on irrigation uniformity. A sophisticated software package for center pivot evaluation and design (CPED) was introduced by [9].

Generally, several attempts on design and watering management of center pivot irrigation systems based on different modeling techniques, had been considered. Reference [5] stated that modelling remains a valuable tool to address a variety of engineering problems (such as irrigation management), at the design, planning, and operations levels. Accordingly, the application of simulation models in irrigation water management reduces water and energy consumption which, leads to increase the efficiency of utilization of these resources [11].

In practical, there are many simulation models that have proved a great success in the design and management of pressurized irrigation systems such as: the SpacePro model [3], for the purpose of selecting nozzle size and spacing for a given application; the SIRIAS model for sprinkler droplet simulation [4]; the TRAVGUN model for sprinkler application depth [14].

Due to the design requirements of center pivot irrigation systems and attributed watering-management criteria, that needs a highly qualified data and designer’s background. Therefore, the aim of this study was to open a new era of spread-sheets modeling in design of center irrigation system under arid conditions.

2. MATERIAL AND METHODS

2.1. Modeling Conceptualization of the Developed Spreadsheet

The appropriate development of a simulation model begins with understanding and interpretation of the real system through one of the methods of system analysis. Thus the waterfall model is used in the model building which gives the possibility to programmers to follow phases of development of the program in a certain order, as presented in Fig. 1. However, database contains information such as station information, weather information, and crop water data information. Consequently, the mathematical model consists of five sub-modules was developed. A detailed description of the sub-modules could be summarized as following:

2.2. Main Sub-module:

Main sub-module is the way to interact with a computer using pictures and other visual elements displayed on a computer screen. This sub-module directs the running of the model by offering the user ability to select subsequent sub-
available discharge of water source; reference evapotranspiration ETo (whether entered manually by the user or retrieved from the database incorporated in the program for three cities); wind speed; soil characteristics retrieved from the database; and crop coefficient and root zone depth for each crop retrieved from the database.

2.4. Sub-module Requirements of Center Pivot Irrigation System Design

Fig. 2 represents all related calculations to crop water requirements, irrigation requirements, and center pivot irrigation system design had been considered. However, these related parameters could be described as:

2.4.1.1. Center Pivot System Capacity (Qs, m³/h)

Center pivot system capacity design followed the methodology recommended by [10] as follows:

\[ Q_s = K \times A \times I_s / T_i \times T \]  

Where:
- \( K \) is conversion factor = 0.001;
- \( A \) is total irrigated area, m²;
- \( I_s \) irrigation requirement;
- \( T_i \) is operating time, h/day
- \( T \) is irrigation interval

2.4.1.2. Center Pivot Hydraulic Analysis

Hydraulic of center pivot irrigation system includes determination of friction losses (\( H_f \), m) along the sprinkler line, sprinklers operating pressure head (\( H_{op} \), m), nozzle size (\( d_{np} \), mm), nozzle discharge (\( Q_{np} \), m³/h) and Sprinkler throw diameter (\( D_w \), m). The hydraulic characteristics design followed the approaches proposed by (10 and 1) as the following equations:

Friction head losses, m
\[ H_f = 1.22 \times 10^{-2} \times f \times (R/100) \times (Q_{np}/C)^{1.852} \times D^{-4.87} \]  

where:
- \( f \) : outlet friction coefficient (0.548)
- \( R \) : pipe length, m
- \( C \) : Roughness coefficient (for galvanized steel = 120)
- \( D \) : pipe inside diameter, mm

Operating pressure head in the pivot point, m
\[ H_c = H_z + 1.1H_f - \Delta H_c + H_{op} + H_r \]  

where:
- \( H_z \) : Pressure head required in the end of the sprinkler line, m
- \( \Delta H_c \) : Height difference between pivot and the end of lateral, m
- \( H_{op} \) : Head losses in pressure regulator, m
- \( H_r \) : Height of Sprinkler, m

Sprinklers operating pressure head, m
\[ H_{op} = H_i (1-1.875(X^2/3) + (X^4/5)) + H_c \]  

where:
- \( X = r_{np}/R \)

Nozzle size, mm
\[ d_{np} = 30.46 \times (Q_{np}/P_{sp})^{15} \]  

Nozzle discharge, m³/h
\[ Q_{np} = (2 r_{np} S_{np} x Q_s) / R^2 \]  

Sprinkler throw diameter, m
\[ D_w = 2.59 + 0.56 d_{np} + 0.023 P_{sp} \]  

where: Psp is sprinkler operating pressure in kPa

2.4.1.3. Application rate (\( R_m \) mm/h):

The application rate of sprinkler, as described in the following equation, depends on distance to sprinkler at lateral (\( r_{np} \), m), system capacity (\( Q_s \), m³/h), radius of center pivot (\( R \), m) and throw diameter of sprinkler (\( D_w \), m).
\[ R_m = (2 \times 1000 \times r_{np} \times Q_s) / (R^2 \times D_w) \]  

2.4.2. Sub-module Output

One of the most important objectives of this study was creating good output sub-module that allows users generating and handling clear outputs easily. Reports of the output can be printed or saved in spreadsheets such as Microsoft Excel according to users' specific needs, as shown in Fig. 3 and Fig. 4.

2.4.3. Validation Case Study

Field experiment on a single span center pivot irrigation system was used for validation process. The technical configuration of the evaluated center pivot irrigation system was: a span length of 56.7 m with flow rate of 4.2 m³/h. Sprinklers were manufactured by Nelson Irrigation Corporation with pressure regulators of 1.03 bars. The distance from the sprinkler to the ground surface was
1.8 m. Sprinklers throw diameter were varied in a range of 14 to 16 m from the beginning at the center pivot to the end of the center pivot radial line. Nozzle flow rate was measured for each nozzle along the radial line of the center pivot, meanwhile, the application rate (mm/h) and throw diameter (m) data of sprinklers were downloaded from the official web site of center pivot provider for the same center pivot model used in the experiment (Nelson Irrigation Corporation).

The analyzed output variables include Nozzle flow rate (m$^3$/h), application rate (mm/h), and throw diameter (m). All scenarios have two types of boundary conditions. Firstly, are related to soil-plant-water relationship, while the second are related to center pivot irrigation management. Data of boundary conditions and limitations of the different scenarios of the validation case studies are shown in Table (1).

2.4.4. Statistical Analysis

To achieve the objectives of the research, hypothesis testing was performed through the use of statistical analysis. Descriptive statistics, tests of normality, and test of homogeneity of variances were initially used for analyzing the data using IBM SPSS Statistics version 20.0. An analysis of variance between groups (ANOVA) for both simulated and observed/manufactured data was performed. Nozzle flow rate (m$^3$/h), application rate (mm/h), and throw diameter (m) were included in the statistical analysis and tested for statistically significant differences at 5% confidence level, [13, 6 and 12].

![Fig. 2: Input data and required design equations of center pivot irrigation system](image)

**TABLE 1: Boundary conditions of studied variables at different design scenarios.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Span length, m</th>
<th>Equivalent output length, m</th>
<th>No. of Sprinklers</th>
<th>Distance between sprinklers, m</th>
<th>Flow rate, m$^3$/h</th>
<th>Soil</th>
<th>Crop</th>
<th>ET$_{o}$, mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario.1</td>
<td>30</td>
<td>56.3</td>
<td>7</td>
<td>7.5</td>
<td>7</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.2</td>
<td>30</td>
<td>57.5</td>
<td>11</td>
<td>5</td>
<td>6.2</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.3</td>
<td>30</td>
<td>56.3</td>
<td>18</td>
<td>2.5</td>
<td>5.5</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.4</td>
<td>40</td>
<td>55</td>
<td>6</td>
<td>10</td>
<td>6.3</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.5</td>
<td>40</td>
<td>56.7</td>
<td>8</td>
<td>6.67</td>
<td>6.2</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.6</td>
<td>40</td>
<td>55</td>
<td>14</td>
<td>3.33</td>
<td>5.4</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.7</td>
<td>50</td>
<td>56.3</td>
<td>5</td>
<td>12.5</td>
<td>6.8</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.8</td>
<td>50</td>
<td>54.2</td>
<td>7</td>
<td>8.33</td>
<td>5.94</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
<tr>
<td>Scenario.9</td>
<td>50</td>
<td>56.3</td>
<td>12</td>
<td>4.17</td>
<td>5.8</td>
<td>Sand</td>
<td>Alfalfa</td>
<td>8</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

3.1. Nozzle Flow Rate

Fig. 5 shows the average flow rate of the nozzle for different designed scenarios and observed data. Average nozzle flow rates do not differ significantly across scenarios and observed data at the \( p<0.05 \) level (sig. 0.211). However, the highest rate of convergence was in scenarios 2, 3, 6, and 9. With a deeper analysis of this comparison, there is a notable declination of the mean of nozzle flow rate in scenarios 3 and 6 by 36.17%, 17.02%, respectively. While the mean of nozzle flow rate has a slight increasing in scenarios 2 and 9 by 19.15%, 4.26%, respectively. On the contrary, there is a diverging the mean of nozzle flow rate in scenarios 5 and 8 by a large margin of 65.96%, 80.85%, respectively. Scenarios 1, 4, and 7 have abnormal results from the mean of nozzle flow rate that are increasing by more than 90%.

On the other hands, unlike the Nozzle flow rate and application flow rate, there is a significant difference between means of throw diameter of the scenarios and manufactured data at the \( p<0.05 \) level (sig. 0.012).
3.2. Application rate

Fig. 6 indicated that, the absence of any significant difference between means of the scenarios and manufactured data at the p<0.05 level (sig. 0.905). By comparing these curves, we found that the highest rate of convergence between simulated and manufactured data was in scenarios 4, 7, and 8 with an increasing percentage of 5.83%, 7.50%, and 4.17 respectively, then scenarios 1, 2, and 5 by 22.64%, 21.53%, and 20.83 respectively. Whereas, the farthest mean of water application rate was in scenario 3 by 34.44%.

3.3. Throw diameter

Fig. 7 shows the mean throw diameter for different scenarios and manufactured data. Therefore, the post-hoc comparison was applied using the multiple comparisons (Tamhane test) to test the difference between each pair of means. Results of Tamhane test indicate that the mean of scenarios 2, 3, 6, and 9 were significantly different with the manufactured data.
However, scenarios 1, 4, 5, 7, and 8 did not significantly differ from the manufactured throw diameter.

3.4. Validations of the developed simple spread-sheet

Regression analysis is done in order to estimate the relation between the independent variable (observed/manufactured) and the dependent variable (simulated). $R^2$ is the proportion of the total variation in predicted values that can be accounted by the relationship with measured or manufactured values. $R^2$ values near to 1 indicate that the data points fall in a well-defined equation, as shown in Table 2.

Table (2): The developed equations based on regression analysis under different design scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Nozzle flow rate, m$^3$/h</th>
<th>Application rate, mm/h</th>
<th>Throw diameter, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>$R^2$</td>
<td>Model</td>
</tr>
<tr>
<td>1</td>
<td>$Q_{SIM} = 0.1383e^{4.0428(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 1.798$ (Ra $MFD$) - 2.194</td>
</tr>
<tr>
<td>2</td>
<td>$Q_{SIM} = 0.0574e^{2.2448(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 1.2472$ (Ra $MFD$) - 1.5135</td>
</tr>
<tr>
<td>3</td>
<td>$Q_{SIM} = 0.0254e^{2.0831(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 0.649$ (Ra $MFD$) + 1.962</td>
</tr>
<tr>
<td>4</td>
<td>$Q_{SIM} = 0.0534e^{6.803(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 2.2664$ (Ra $MFD$) - 5.1754</td>
</tr>
<tr>
<td>5</td>
<td>$Q_{SIM} = 0.1067e^{4.1131(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 1.5587$ (Ra $MFD$) - 1.7341</td>
</tr>
<tr>
<td>6</td>
<td>$Q_{SIM} = 0.0754e^{2.7614(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 0.8492$ (Ra $MFD$) + 0.771</td>
</tr>
<tr>
<td>7</td>
<td>$Q_{SIM} = 0.0911e^{4.923(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 2.7596$ (Ra $MFD$) - 6.3291</td>
</tr>
<tr>
<td>8</td>
<td>$Q_{SIM} = 0.0441e^{6.2973(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 1.9854$ (Ra $MFD$) - 4.6628</td>
</tr>
<tr>
<td>9</td>
<td>$Q_{SIM} = 0.0761e^{3.325(Q_{obs})}$</td>
<td>0.9</td>
<td>Ra $SIM = 1.0428$ (Ra $MFD$) - 0.1537</td>
</tr>
</tbody>
</table>

3.4. Validations of the developed simple spread-sheet

Regression analysis is done in order to estimate the relation between the independent variable (observed/manufactured) and the dependent variable (simulated). $R^2$ is the proportion of the total variation in predicted values that can be accounted by the relationship with measured or manufactured values. $R^2$ values near to 1 indicate that the data points fall in a well-defined equation, as shown in Table 2.
However, results obtained from the regression analysis with $R^2$ are indicated that there are three groups of models that could explain the relation between the observed/manufactured data and simulated data. Firstly, exponential models that interpret the relationship between the observed and simulated for nozzle flow rate (m$^3$/h). The best model that explains the relationship between observed and simulated for nozzle flow rate (m$^3$/h) among scenarios was obtained from the scenario no. 5 with $R^2 = 0.967$. Secondly, linear models that interpret the relationship between manufactured and simulated application rate (mm/h) with a very high $R^2$ (more than 0.99) for all scenarios. Finally, power models that interpret the relationship between manufactured and simulated throw diameter (m). The best model that could explain the relationship between manufactured and simulated for throw diameter (m) among scenarios was obtained from the scenario no. 1 with $R^2 = 0.942$.

### 4. REFERENCE


