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COMPUTATION MODEL OF SPRINKLER SPACING AND LAYOUT

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ABSTRACT

This paper presents the formulation of a computational model for overlapping multiple sprinklers. Input data required by the model are the water application profile, desired geometrical layout and degree of spacing. A two step process of interpolation and superimposition were employed to convert the water application depths on radial lines onto square grid. The approach considers the observation pattern from a single leg sprinkler system as a multidimensional array. Necessary zero arrays are inserted where no water was applied. This leads to a modified array of data which contains the original data set. Overlapped elements were computed by adding corresponding elements for desirable sprinkler spacing. The model applies to the three main layouts of sprinklers. Coefficients of uniformity for four overlapped sprinklers simulated by the model were compared with that from measured data under low wind conditions at the same operating conditions. They gave a mean absolute error of 1.60 %.

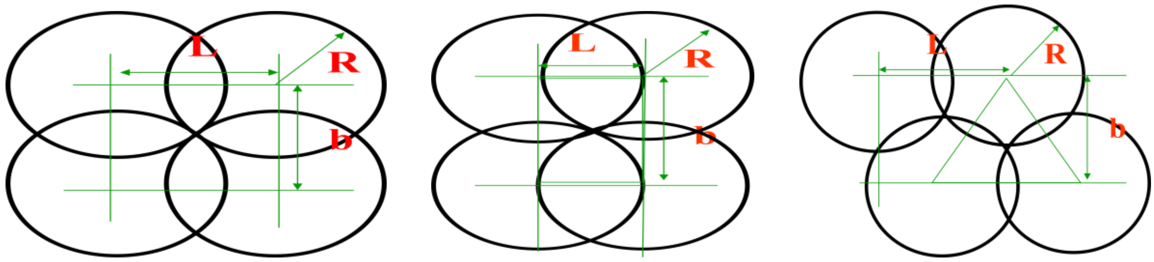
KEYWORDS: *Sprinkler Spacing, computational model, uniformity, interpolation, Matlab*

I. INTRODUCTION

The basic objective of sprinkler irrigation systems is to distribute water to the field efficiently and uniformly. The primary factors controlling these objectives are equipment selection, system design, installation and maintenance. One of the most important questions to be asked is how the sprinkler head should be spaced to ensure optimum results. DeBoer et al.[1] emphasized that sprinkler spacing can have big influence on water application uniformities, especially for application patterns that exhibit large variations in application rates.

Proper spacing of sprinkler heads is a key component of uniformity and leads to a more efficient system. Once installed, if a solid set system performs inefficiently, changing the nozzles or even the sprinkler heads may not be enough to correct the problem. And changing the sprinkler spacing after installation requires a great deal of additional time and money. However, most of the time problems with sprinkler spacing and geometry are not identified until it is too late [2]. It is therefore necessary to simulate options of sprinkler placement for the desired uniformities before installation on the field. Many studies have been carried out concerning uniformity and spacing in sprinkler irrigation, however, differing conclusions have been drawn. The geometrical shape of the sprinkler layout and spacing are usually issues that have resulted in diverse conclusions [3]. Generally, three basic types of sprinkler spacing patterns can be distinguished, namely, square, rectangular and triangular geometric shape [2-4] (Figure 1). Some studies recommend triangular spacing while others show no clear advantages between them but that it depends on the sprinkler water distribution pattern [3, 5, 6].

The coefficient of uniformity of a sprinkler irrigation system is a measure of the characteristic effect of the individual sprinkler type, the spacing, operating pressure and prevailing wind conditions. Another characteristic measure of the quality of performance of a sprinkler system is the water application profile. Unlike coefficient of uniformity, the water application profile depends more on the make and the dynamics of the individual sprinkler with operating pressure [7].



(a) Square (b) Rectangular (c) Triangular

Figure 1 Different geometrical layout of sprinklers

Critical to the design of sprinkler irrigation systems is the knowledge of the relation between the water application patterns from a single sprinkler with operating pressure and nozzle characteristics. The shape of the water application profile influences sprinkler spacing and lateral spacing on the field, which also has economic implications.

Several analytical tools that accord irrigation designers the ability to analyze sprinkler designs have been developed already. Most of these developments occurred in the last few decades [8-12]. However, data interpolation and representation and other features need to be utilized to widen the capabilities, improve the quality of the analysis and output of the models. Provision for overlap of two or more distinct distribution patterns as well as one pattern generalized for all overlapping sprinklers should be in cooperated.

The objective of this study was to develop a model to compute and simulate the water distribution pattern of overlapping sprinklers at varying spacing for different geometrical layouts. The proposed model incorporates data interpolation and superimposition techniques coupled with visualization features in Matlab for analysis to improve on the model's output. This model can serve as a support tool for sprinkler irrigation layout design to ascertain optimum spacing for uniform water distribution pattern as well as aid decision on sprinkler selection.

II. METHODS AND MATERIALS

2.1. Model Description

The computational model for overlapping of sprinkler patterns employed for this study is that of Hart [8], that was utilized by Dingre [13] which considers all observation patterns as one dimensional matrix and water application depths collected in catch cans considered as elements. Dingre [13] on the other hand considered observations patterns as three dimensional arrays. Their methods were limited to only square and rectangular layouts of sprinklers with a single generalized pattern for all sprinklers.

The proposed computational model extends the application to square, rectangular and triangular layouts of sprinklers. In addition to one identical observation pattern the approach also integrates multiple observation patterns from overlapping sprinklers as a multidimensional array. Necessary zero arrays are inserted in rows and columns where no water was applied. This leads to a modified array of data which contains the original data set. Overlapped pattern elements are computed by adding corresponding elements of the same or different distribution pattern for desirable sprinkler spacing. The model developed for the computation is described below.

Mathematically, $a_{i\,j} = b_{m\,n} + b_{m\,l}$ (1)

Where $b_{m\,n}$ and $b_{m\,l}$ values are elements in the original patterns to overlap. $a_{i\,j}$ values are elements in the resultant overlapped pattern.

$i = 1,2,3, \ldots\ldots, h \quad m = 1,2,3, \ldots., h \quad l = (v), (v-1), \ldots\ldots, 1 \quad j = 1,2,, \ldots\ldots, v \;\; n = 1,2,, \ldots\ldots, v$

h and v are the number of observation points in the rows and columns of the patterns to overlap respectively. The original data pattern from the single sprinkler experiment is considered to be a matrix of order h by v containing h*v data values denoted as $a_{h\,v}$. The matrix $a_{h\,v}$ is then modified by inserting necessary zero arrays in the corners to form a modified matrix with elements denoted as $b_{i\,j}$. To simulate overlapping of two adjacent sprinklers on a lateral, the matrix $b_{i\,j}$ is transformed by reflection in the necessary axis. The reflected matrix is denoted as $b_{i\,k}$ where k= v, v-1... 1.

$C_{i\,l=}b_{i\,j} + b_{i\,k}$ (2)

Where, $C_{i\,j}$ values are elements in the resultant overlapped pattern for the two sprinklers. For overlapping of sprinklers on adjacent laterals, layouts of more $C_{i\,j}$are modified by reflecting in the relevant axis and necessary zero arrays are inserted as:

$$C_{m\,n} = \begin{bmatrix} C_{i\,l} \\ O_{i\,l} \end{bmatrix}, \;\; d_{m\,n} = \begin{bmatrix} O_{i\,l} \\ C_{i\,l} \end{bmatrix} \quad (3)$$

$$E_{m\,n=}C_{m\,n} + d_{m\,n} \quad (4)$$

$d_{m\,n}$ is the reflection of $C_{m\,n}$ in the relevant axis and $E_{m\,n}$ is the overlaped pattern, $m = 2i \;\; n = l$

The model calculates the degree of overlap required and then shifts the modified input matrix forward from right to left or upward from the bottom as the case may be and sums the corresponding elements for overlaps on the laterals and adjacent laterals respectively. For overlap of more than two sprinklers (they may have distinct water distribution patterns) along a lateral, necessary numbers of $C_{i\,l}$, $b_{i\,j}$ *and* $b_{i\,k}$ are modified by inserting zeros. The modified matrixes are then added as follows;

$$F = [C_{i\,l} \quad O_{i\,j} \quad O_{i\,k} \;\, O_{i\,l},,,,] + [O_{i\,l} \quad b_{i\,j} \quad O_{i\,l} \;,,,,] + [O_{i\,l} \quad O_{i\,j} \quad b_{i\,k}, \;\; O_{i\,l},,,,] + \quad (5)$$

For overlap of more than two sprinklers on adjacent laterals, the resultant pattern is as follows;

$$G = \begin{bmatrix} C_{i\,l} \\ O_{i\,l} \\ O_{i\,l} \\ O_{i\,l} \end{bmatrix} + \begin{bmatrix} O_{i\,j} \\ b_{i\,j} \\ O_{i\,j} \\ O_{i\,j} \end{bmatrix} + \begin{bmatrix} O_{i\,k} \\ O_{i\,k} \\ b_{i\,k} \\ O_{i\,k} \end{bmatrix} +,,+ \quad (6)$$

Equations (5) and (6) enables the overlap of two or more distinct distribution patterns as well as one pattern generalized for all overlapping sprinklers, in which case $C_{i\,l}$, $b_{i\,j}$ *and* $b_{i\,k}$ will have the same pattern (elements), a feature that is useful for evaluation of existing solid set systems. The coefficient of overlap which relates the degree of overlap indicates the number of shifts necessary for overlap. It is determined by the expression:

$$t = {}^{r}/_{s}\left(\frac{x}{100}\right) \quad (7)$$

Where,

x = percentage of overlap (%); r = radius of throw (m);

t = coefficient of overlaps ; s = spacing of catch cans

2.2. Input profile for the computational model

The primary data required as input by the model are the application rates measured around a single sprinkler, desired geometrical layout and degree of spacing. For accuracy and simplicity of computation it is advisable to place the cans closely and at equal distance from each other. The methodology supports a single leg sprinkler data points or grid of data points to overlap the observation patterns. This presupposes that catch cans should be placed in the form of a network to form grid data sets. However cans could be placed according to any convenient pattern and later converted to a grid data points. In the experiments used for the analysis, cans were placed in orthogonal shape pattern around the sprinkler (Figure 2) and then converted to a square grid pattern (Figure 3). 1. A two step process of interpolation and superimposition were employed to convert the water application depths on the radial lines onto square grid. The first step is to convert the web grid into a square grid by employing equation (8) and (9)

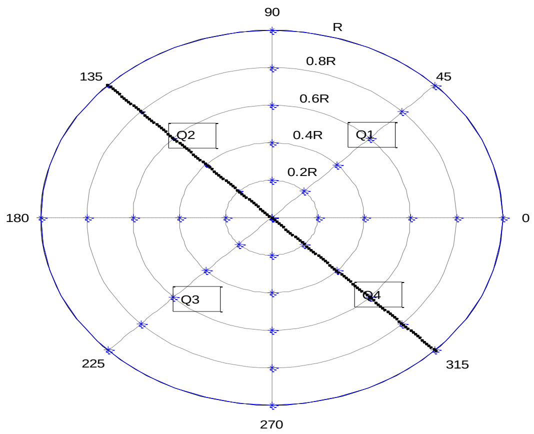


Figure 2. Orthogonal arrangement

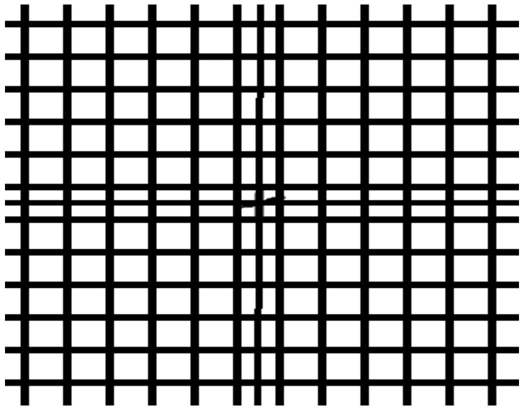


Figure 3. Grid distribution of data points

$$p = f(x, y) = f(r, \theta) \quad (8)$$

$$x_i = r_i cos\theta_j \ and \ \ y_i = r_i cos\theta_j \quad (9)$$

Where r = distance from the sprinkler to the i^{th} catch can on the radial line, θ is the angle subtended by the radial line to the horizontal, x_i and y_i are the coordinates of the i^{th} catch can. Finer grid is subsequently obtained by interpolation using cubic spline. The next step is to superimpose the water distribution depth values on the generated grid after subsequent interpolation of the water distribution values to fit the finer grid generated. The program was coded using Matlab software (The Math works Inc, MA, USA) to convert the observed orthogonal data sets to a two-dimensional interpolated grid data points and for overlaps. Matlab presents high capabilities for matrix calculation, interpolation, transformation and representation.

2.3 Catch can experiment

To validate the computational model, field experiments were carried out under low stable wind speed conditions less than 1.0 m/s. The following standards were adopted for the experimental procedure: ASAE S.330.1 [14], ASAE S.398.1 [15]. Two categories of experiments were carried out at the same operating pressure concurrently. The first category consisted of four sprinklers with an array of catch cans equally spaced and placed between the sprinklers constituted the experimental area (Figure 4). The second category consisted of isolated sprinkler experiments with catch cans placed along eight radii at equal distance from each other within the radius of throw of the sprinkler forming an orthogonal pattern (Figure 2). Same operating pressure conditions were ensured with the aid of pressure gages and valves. This ensured that the distribution pattern of the isolated sprinkler experiments were as much as possible similar to each of the four overlapping sprinklers. This is a necessary requirement for comparison with the simulated overlaps with the measured pattern for similarity of the contributing sprinklers.

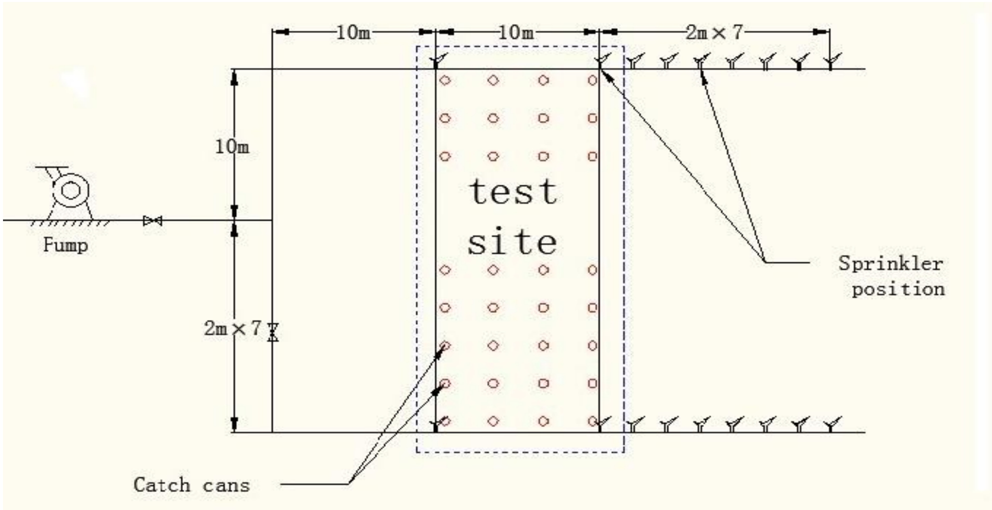


Figure 4. Layout of Overlapping Sprinkler in the first category experiment

The performance evaluation of sprinkler irrigation is often based on water uniformity coefficients, calculated from the water application depths collected in catch can experiments [16-18]. Several uniformity formulae have been developed over the past few decades [19-21]. The most commonly used uniformity coefficient is that of Christensen [22]. It is defined as

$$CU = 100\left[1 - \frac{\sum|h_i - \bar{h}|}{n\bar{h}}\right], \quad (10)$$

where CU is the coefficient of uniformity (%); h_i the water depth collected in each catch can (mm); $\bar{h}$ is the mean water depth collected (mm) and n the total number of catch cans. CU values were calculated for both measured and simulated geometrical overlaps using equation (10)

2.4. Model Validation

The validation of the proposed computation model is through comparison between measured and simulated overlapped patterns under similar working conditions. This was done through the Mean Absolute Error (MAE) statistical formula below.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n}|e_i| \quad (11)$$

Where, $e_i = |f_i - y_i| =$ absolute error;

$f_i =$ the simulated value; $y_i =$ the experimental value

The MAE is a statistical quantity used to measure how close simulations are to the eventual field situations.

III. RESULTS AND DISCUSSION

3.1 Comparison of Computed with Measured coefficients of uniformity (CU) values

Table 1 shows the coefficient of uniformity for the computed and measured overlap of four identical sprinklers in three different layouts; square, triangular and rectangular. The measured coefficients of uniformity values were determined from field experiment under low wind speed of less than 1.2 ms^{-1}. A regression analysis between the computed and measured values gave $y = 0.8613x + 12.208$, with a coefficient of determination $r^2 = 0.6189$, where y and x are the measured and computed values. For a given distribution profile, these computations could be done for different layouts and spacing for best design options as well as for different profiles of sprinklers to aid selection of best sprinkler for desired uniformity and application intensity.

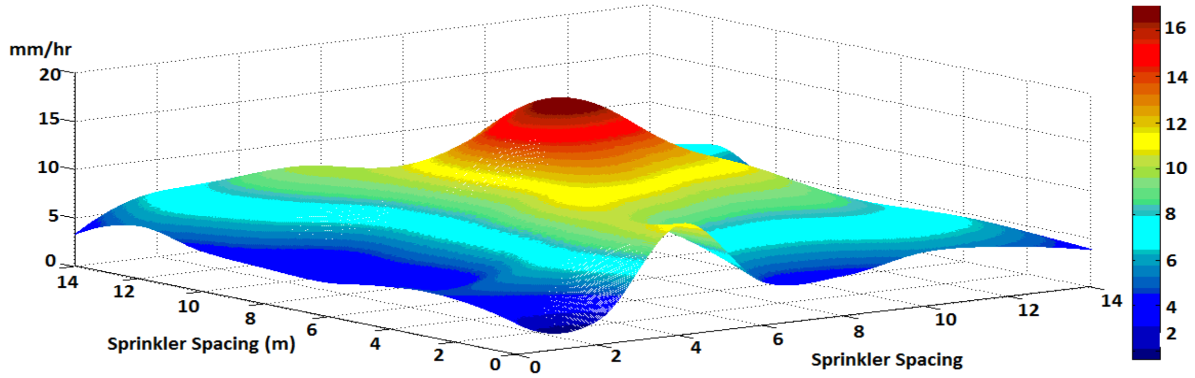
Table 1 Coefficient of Uniformity for Computed and Measured overlapped geometrical layouts

	Layout	Computed CU (%)	Measured CU (%)	Absolute Error (%)
Square	14 x 14	85.00	83.45	1.82
	15 x 15	84.00	83.00	1.19
	16 x 16	83.25	82.45	0.96
Triangular	17 x 17	82.79	81.85	1.14
	18 x 18	80.25	81.39	1.05
	14 x 16	82.00	80.95	1.28
Rectangular	15 x 17	81.85	80.91	1.15
	17 x 18	81.55	80.95	0.74
	16 x 18	81.34	79.00	2.88
		Mean Absolute Error		1.60

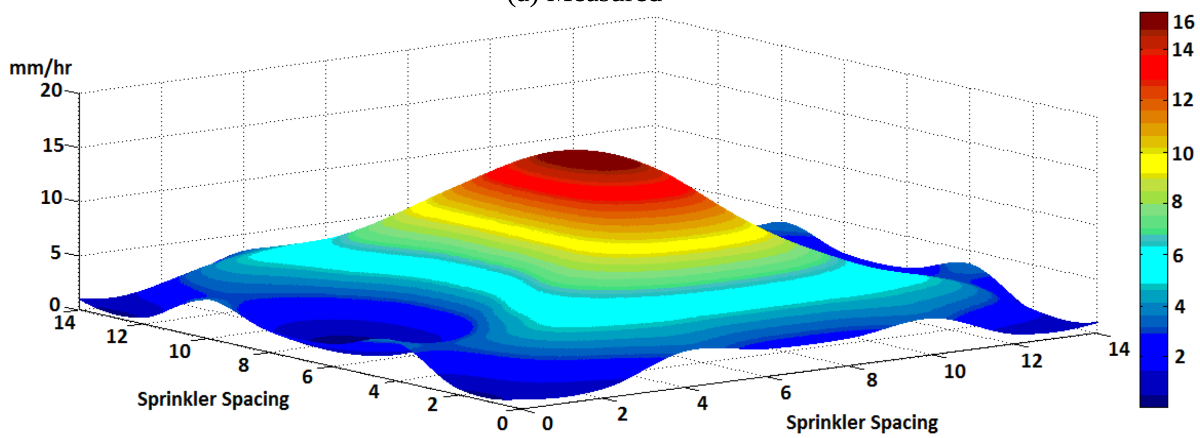
From the generated application intensities other comparative performance indices such as distribution uniformity, scheduling coefficient, Hermann and Heins uniformity coefficient, standard deviation and statistical uniformity could be evaluated to support decision making [23].

3.2 Comparison of Computed with Measured Application Intensities

Sample simulated and measured 3D plots for four overlapping sprinklers are shown in Figure 5 and Figure 6 for square and triangular layouts. The vertices of the plots are the locations of the sprinkler positions.

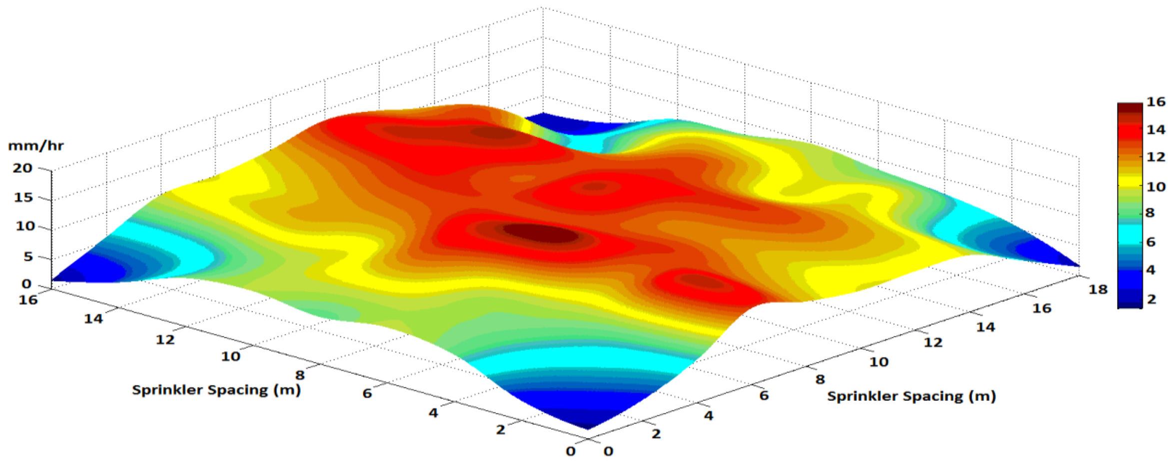


(a) Measured

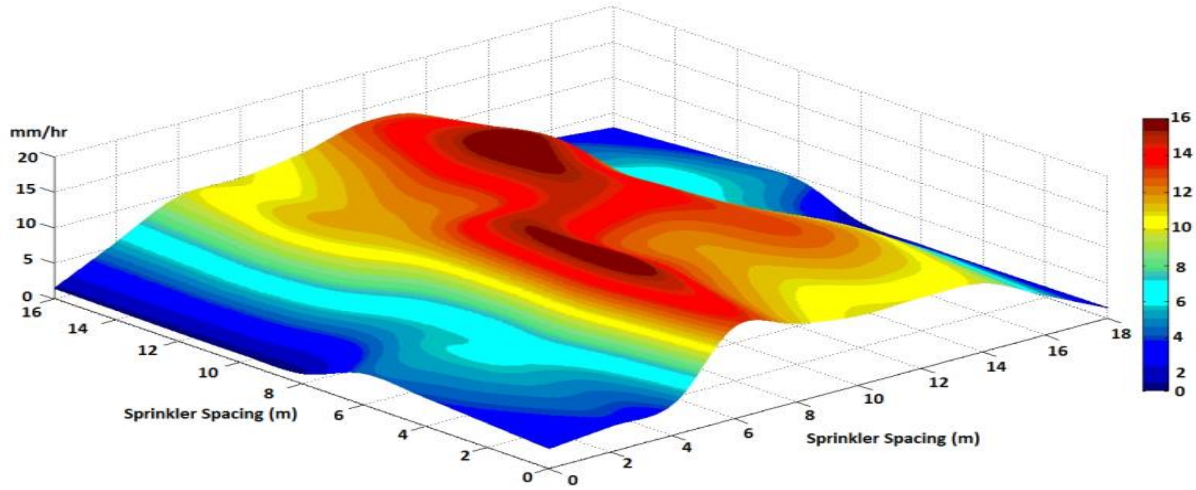


(b) Simulated

Figure 5. Measured and Simulated Overlapped Square Layout (14 x 14)



(a) Measured



(b) Simulated

Figure 6. Measured and Simulated Triangular Layout (18 x 16))

Contour plots could also be generated for analysis. They indicate the water application intensities on the field at different spacing. Water application rates at any point along the laterals could be indicated. By varying the spacing at specified operating conditions several plots could be simulated to obtain best spacing for highest performance parameters. The Polynomial regression of the simulated coefficient of uniformity as a function of degree of sprinkler spacing gave $y = 0.0001x^3 - 0.0252x^2 + 1.901x + 33.352$ with r^2 value of 0.9954. Similarly the Polynomial regression of the measured coefficient of uniformity as a function of degree of sprinkler spacing was $y = 0.0001x^3 - 0.0239x^2 + 1.9245x + 28.485$ with r^2 value of 0.9707.

Previous computational methodologies considered all overlapping sprinklers as having only one identical observation pattern and do not make room for overlap of multiple distinct distribution patterns. The proposed methodology is capable of incorporating distinctive water distribution pattern of individual sprinklers that are to be overlapped instead of only one general pattern for all the sprinklers. Equation (5) and equation (6) makes provision for this feature. This feature becomes very relevant when precision evaluation of the water distribution intensities and uniformities of individual sprinklers in an already existing solid set system is required.

IV. CONCLUSION

A computational model for overlapping multiple sprinklers on the field has been described. It is capable of simulating spacing of sprinklers with three main geometrical layouts, namely rectangular, square and triangular. Input data required by the model are the water application profile, desired geometrical layout and degree of spacing. It has been compared with measured field data under low wind conditions and has been found to be good with a mean absolute error of 1.60 %. The model is capable of estimating sprinkler pattern profiles, sprinkler irrigation performance indices for sprinkler selection and evaluation for improvement as well as plots for 3D, contour and plan view plots of the distribution pattern. It also has the feature of incorporating water distribution patterns of individual sprinklers that are to be overlapped instead of one general pattern for all the sprinklers. The model can serve as a decision support tool for sprinkler irrigation layout design for optimum spacing and layout for uniform water distribution.

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