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Assessment of Surface and Subsurface Water Uniformities for Center Pivot

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Abstract. The water uniformity for a center pivot system has been investigated. The uniformity of above and below soil surface was evaluated along the main line and in the direction of the system movement. Three sprinklers' heights, which were 50, 100 and 130 cm, have been considered during the field experiment. The catch container depths were used to assess the above soil surface uniformity. The average volumetric soil moisture contents were measured at three soil depths, 10, 20, 30 and 40 cm, to assess the below soil surface uniformity. The measurements were taken after 24, 48, and 72 hours from the time of irrigation. The results revealed that the below surface uniformity is higher than the above soil surface uniformity. On the average, there was a noticeable decrease in the surface soil uniformity measured along the main line (68.4 %) compared to that measured in the direction of system movement (80.5 %). On the other hand, there wasn't much difference in the subsurface uniformity measured in both directions (88.2 % along the system movement and 89.1 % along the system line). The results also was revealed that the subsurface uniformity is less affected by the sprinkler height compared to the surface uniformity. Relationships between subsurface and surface uniformities have been uniquely developed. The presented equations can be used to predict subsurface uniformity from surface uniformity with insignificant errors.

Introduction

The expectantly continuous growth of the word population increases the amount of water needed to produce more food and fiber. The ultimately increased water demand would lead to water shortage, which likely causes a world wide water crisis. For long time, it has become certain that the agricultural sector is the most water consumer, particularly irrigation. To help conserve the irrigation water, efficient irrigation systems have been existed for decades. The sprinkle irrigation system is widely and universally spread. Abo-Ghobar and Mohammed reported that there were about 20,000 center pivots in Saudi Arabia [1].

An efficient center pivot system is usually reflected by how the water is evenly distributed above the soil surface. This may not be an appropriate reflector of the actual water distribution in the root zone. Davis raised the importance of the water distribution inside the soil and stated that the evaluation of water distribution above the soil is not a good indicator of crop yield [2]. For a solid sprinkle system, Hart assessed the evaluation of the water distribution above and below the soil surface [3,4]. He noticed some differences between both methods of evaluation and emphasized on the consideration of water distribution below the soil surface when designing a sprinkle irrigation system. Rao conducted a field experiment to study the influence of canopy on the coefficient uniformity and found that the CU below wheat canopy is higher than CU above the canopy [5]. This study has a similar result to that reported by Ayars et al. for cotton crop [6]. These studies imply that the traditional measurement of CU above the soil surface has to be reconsidered.

The increased agricultural water use, the universal spread of the center pivot irrigation systems, and the continuously spatial and temporal changes of the field characteristics, along with other factors, encouraged the current study. The study objectives included mainly the determination of the below soil surface uniformity and secondly the effect of sprinkler height on surface and subsurface water distribution.

Materials and Methods

Experiment site

The experiment was conducted at the Agricultural Researches and Experiments Station that belongs to College of Agriculture, King Saud University, Riyadh. The field of experiment has an area of 6.63 hectares. The mechanical soil analysis revealed that the soil texture is sandy loam with 82 % sand, 8 % silt, and 10 % clay. It was also found from the analysis that the soil has an average bulk density equal to 1.48 gm/cm^3. The water arrives to the filed from the municipal treated wastewater plant. The chemical characteristics of the soil and the treated wastewater are shown in Table 1.

Table 1. Chemical analysis of field soil and irrigation water

				Cations (meq/l)				Anions (meq/l)		
	SP (%)	**pH**	**EC(ds/m)**	**Ca^{++}**	**Mg^{++}**	**Na^{+}**	**K^{+}**	**Hco_3^-**	**CL^-**	**So_4^{--}**
Soil	2.40	7.92	1.45	6.62	2.45	3.62	1.84	4.00	4.03	6.50
Water	-	7.09	1.50	6.57	2.83	3.67	1.93	4.46	4.71	5.83

System characteristics

The length of the center pivot irrigation system used in the experiment was 145.3 m with an inside diameter of 102 mm. The lengths of the first, second, and third towers were 42.7, 49.4, and 49.4 m, respectively. Although the system consisted of three towers, the last tower, which is away from the pivot, was considered for this study. Fixed spray type sprinklers were utilized with constant sprinklers spacing that was equal to 2.4 m. The system was operated at a speed equal to 50 % of its maximum speed that is 3.9 m/min. The flow rate of the pivot was kept constant during the run of the experiment and equal to 22 L/s (79.2 m^3/h) [7].

Determination of surface and subsurface water distribution

The determination of surface and subsurface water distribution was accomplished along the system main line (perpendicular or normal to the pivot) and along the system movement (parallel to the pivot). The surface water distribution was assessed by considering the amount of water collected in the cans, which are 15 cm in height and 10 cm in diameter. For measurement along the along the system main line, two lines of cans were placed with an angle of 20 degree and distance equal to 3 m between each two successive cans. The distance from the pivot to the first can was 99 m. For measurement in the direction of system movement, two lines of cans were also used. The distances between the lines and the cans were 3 m and the distance from the pivot to the first line was 111 m. The layout of the experiment is shown in Fig. 1.

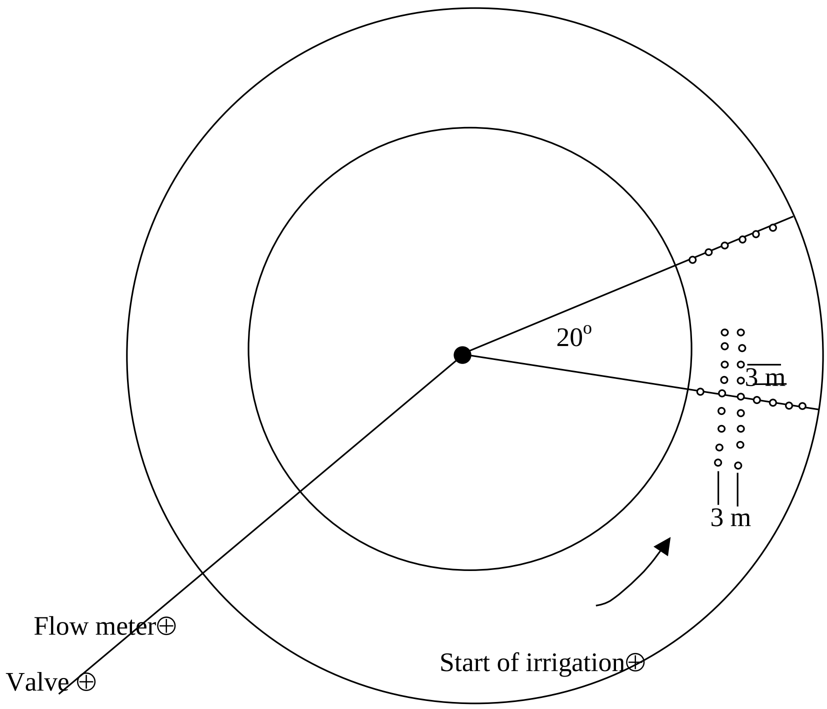

Fig. 1. Layout of the field experiment.

For the subsurface water distribution assessment, the soil moisture contents were determined. The gravimetric method was utilized to measure the soil moisture contents at four soil depths (10, 20, 30 and 40 cm). The measurements were taken after 24, 48 and 72 hours. At the later, the irrigation started again. It should be noted that the mean of the measurements was considered for the determination of CU beneath the soil surface.

Computation of surface and subsurface water distribution

How water is evenly distributed over an irrigated filed is usually presented by uniformity terms such as coefficient of uniformity, CU. Several equations have been proposed to compute the uniformity coefficient CU. The modified Heermann and Hein equation [8]:

$$CU_H = 100\left[1 - \left(\frac{\sum_{\eta} S_s \left| D_s - \frac{\sum_{\eta} D_s S_s}{\sum_{\eta} S_s} \right|}{\sum_{\eta} D_s S_s}\right)\right] \quad (1)$$

was used to compute the above soil surface CU along the system main line. The below soil surface CU in both directions and the above soil surface CU in the direction of system movement were calculated based on the Christiansen equation [9]:

$$CU_C = 100\left(1 - \frac{\sum_{\eta} \left| D_s - \overline{D} \right|}{\sum_{\eta} D_s}\right) \quad (2)$$

where

CU_H = Heermann and Hein uniformity coefficient,
D_s = Collected depth of water (or soil water contents) at a distance S from the pivot,
S = Distance of the collector to the pivot,
s = Subscript denoting a point at S distance,
η = Number of catch containers,
CU_C = Christiansen uniformity coefficient, and
$\overline{D}$ = Mean of collected depths (or soil water contents).

Results and Discussion

Figure 2 shows the relationship between the above soil surface CU and the sprinkler height. The figure depicts that the CU, along the sprinkle main line and along the system movement, increases with the increase of the sprinkler height. It could also be seen from the figure that the variation of CU along the sprinkle main line is much higher than the variation of CU in the direction of the system movement. As shown in Table 2, the values of surface CU normal to the pivot were found to be 83.9, 69.5 and 51.8 % for sprinkler heights 130, 100 and 50 cm, respectively. On the other hands, the values of the surface CU parallel to the pivot were 86.8, 82.7 and 71.9 % for sprinkler heights 130, 100 and 50 cm, respectively.

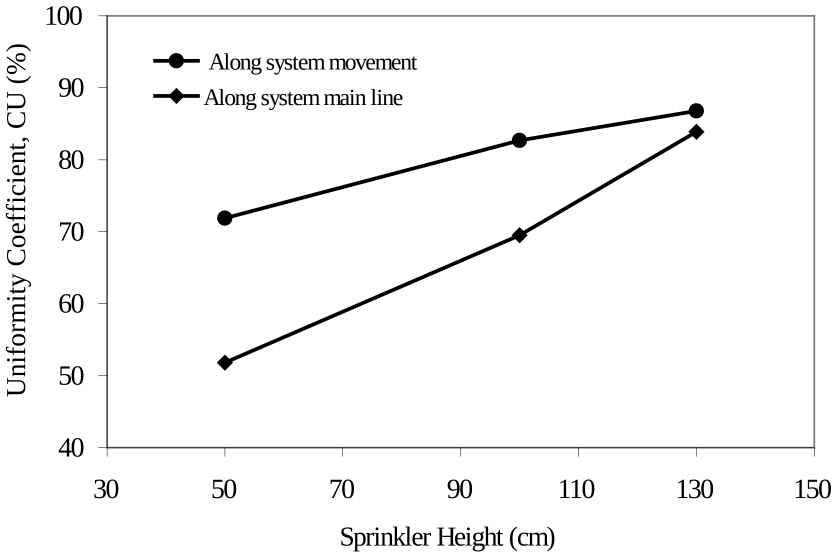

Fig. 2. Relationship between surface CU and sprinkler height.

Figure 3 shows the variation of the below soil surface CU in both directions with the sprinkler height. As can be seen from the figure, the CU gets better when the sprinkler height increases. Unlike the surface CU, the subsurface CU values are almost identical for both directions. In other words, the values of CU along the sprinkle main line and in the direction of system movement are about the same. The insignificant variation of subsurface CU values is apparently attributed to the redistribution of water within the soil media. This result supports and emphasizes the reconsideration of evaluating the sprinkle systems in general and the center pivot systems in particular.

Table 2. Values of surface and subsurface CU and errors in predicting subsurface CU from surface CU

Sprinkler height (cm)	**Observed CU_{sur}(%)**		**Observed CU_{sub} (%)**			**Predicted CU_{sub} (%)**		**Errors in predicted CU_{sub} (%)**	
	Normal to pivot	**Parallel to pivot**	**Normal to pivot**	**Parallel to pivot**	**Average**	**From Eq. 3**	**From Eq. 4**	**From Eq. 3**	**From Eq. 4**
130	83.9	86.8	90.2	92.5	91.4	91.3	91.4	-0.1	0.0
100	69.5	82.7	89.9	89.8	89.9	87.6	89.6	-2.6	-0.3
50	51.8	71.9	84.5	84.9	84.7	82.2	84.7	-3.0	0.0
Average	68.4	80.5	88.2	89.1	88.6	87.0	88.6	-1.9	-0.1

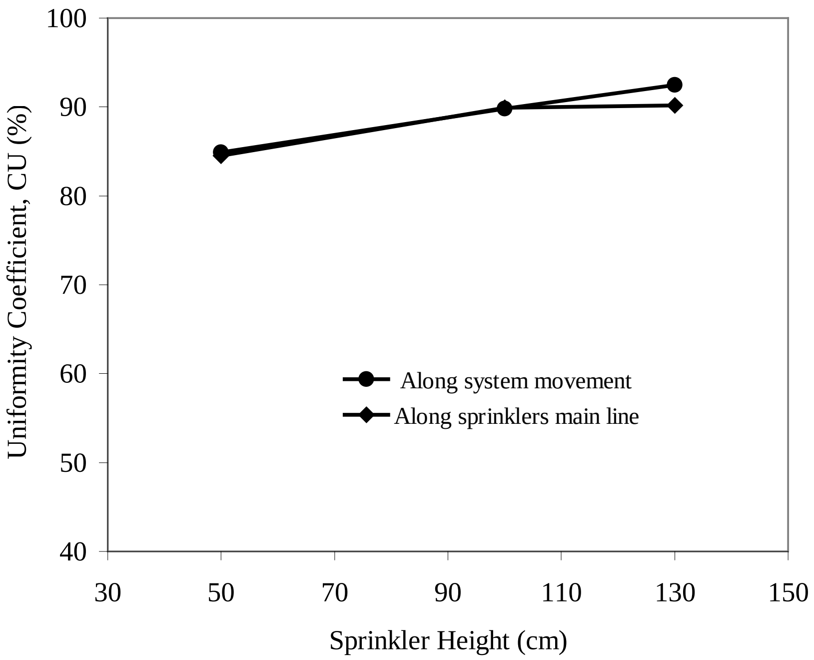

Fig. 3. Relationship between subsurface CU and sprinkler height.

Table 2 shows the average values of the subsurface CU normal to the pivot that were 90.2, 89.9 and 84.5 % for sprinkler heights 130, 100 and 50 cm, respectively. And the average values of the subsurface CU normal to the pivot were 92.5, 89.8 and 84.9 % for sprinkler heights 130, 100 and 50 cm, respectively.

The subsurface evaluation of the center pivot, or even other irrigation systems, would be a difficult task to accomplish. Therefore, it is preferred to have a mathematical relationship between the below soil surface CU and the above soil surface CU. It is revealed from Figures 3 and 4 that the average subsurface CU and the surface CU normal to and parallel to the pivot have relationships of power functions. Thus it was fortunate to possibly relate the subsurface CU to the surface CU. Since there were small differences between the values of the subsurface CU measured along the sprinkle main line and those measured along the system movement, the average values were considered as shown in Table 2.

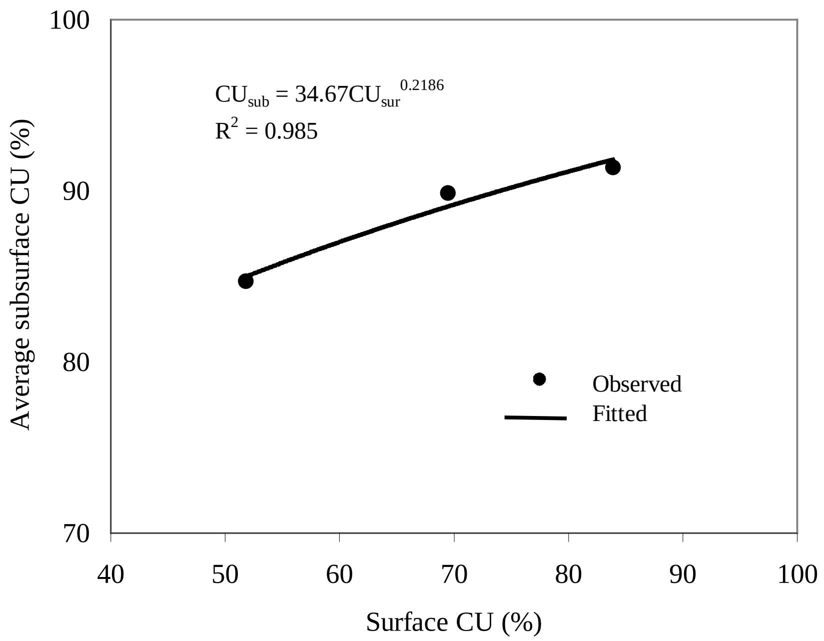

Fig. 4. Average subsurface vs. surface CU normal to pivot.

The equation for predicting the subsurface CU (CU_{sub}) from the surface CU (CU_{sur}) measured along the system or sprinkle main line has the following form

$$CU_{sur} = 34.67 CU_{sub}^{0.2186} \tag{3}$$

And the equation for predicting the subsurface CU (CU_{sub}) from the surface CU (CU_{sur}) measured along the system movement is

$$CU_{sur} = 15.115 CU_{sub}^{0.4031} \tag{4}$$

As can be seen from Table 2, the relative errors in predicting the CU_{sub} using equation 2 or 3 were less than or equal to the absolute value of 3 %. The correlation coefficients R^2 are 0.985 for equation 3 and 0.999 for equation 4. The high R^2 values reflect the good agreement between the computed and the observed CU_{sub}. It turns out that these relations indicate that a certain trend of subsurface CU with surface CU would be attained. It, however, should be noted that the above equations would be of limited field applications due to that the sprinkler height was the only parameter varied during the run of the experiment.

Indeed, the uniformity of a center pivot irrigation system is a complex phenomenon or process and involves interactions of several variables of system specifications, soil characteristics and weather conditions. Nevertheless, further essential researches are encouraged upon the final judgment of the suitability of the above equations. The intensive and expanded study of the evaluation of subsurface uniformity is practically important and encouraged to be conducted. Until then, the above equations may however be used as guidelines for preliminary determination of the subsurface CU from conventionally measured surface CU.

Conclusion

A field evaluation of center-pivot system uniformity was accomplished. The results indicated that the surface and subsurface CU are affected by the sprinkle height with more significance to the surface CU. The results implied that CU increases with the increase of the sprinkle height. The subsurface CU can be obtained from either surface CU, along the system main line or in the direction of system movement with insignificant errors, less than ± 3 %.

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تقييم انتظامية إضافة المياه السطحية والتحت سطحية للري المحوري

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ملخص البحث. أجريت تجربة على نظام الري المحوري لتقييم انتظامية توزيع المياه فوق وتحت سطح التربة، وذلك في اتجاه خط السير وعلى طول خط الرش، وباعتبار ثلاث ارتفاعات للرشاشات (٥٠، ١٠٠ و١٣٠ سم). استخدمت طريقة علب التجميع لتقييم الانتظامية فوق سطح التربة، بينما استخدمت الطريقة الحجمية لتقييم الانتظامية تحت سطح التربة، حيث تم تقدير متوسط المحتوى المائي للتربة عند أربعة أعماق (١٠، ٢٠، ٣٠، ٤٠ سم) وذلك بعد ٢٤، و ٤٨، و ٧٢ ساعة من إضافة مياه الري. بينت النتائج أن انتظامية توزيع المياه تحت سطح التربة أعلى من انتظامية توزيع المياه فوق سطح التربة. كما بينت النتائج أن هناك انخفاضا ملحوظا في انتظامية المياه السطحية المقاسة على طول خط الرش (٦٨,٤ %) مقارنة بالانتظامية في اتجاه خط السير التي كانت تساوي ٨٠,٥ %. في المقابل، وجد أن انتظامية إضافة المياه تحت سطح التربة كانت متقاربة في الاتجاهين، حيث كانت ٨٨,٢ % في اتجاه خط السير، و ٨٩,١ % على طول خط الرش. كما بينت النتائج أن الانتظامية التحت سطحية اقل تأثرا بارتفاع الرشاشات مقارنة بالانتظامية فوق سطح التربة. ونظرا لصعوبة تقدير الانتظامية التحت السطحية، طورت علاقات رياضية يمكن من خلالها تقدير انتظامية إضافة المياه تحت سطح التربة بمعرفة الانتظامية فوق سطح التربة.