The areal distribution of applied water above and below soil surface under center pivot sprinkler irrigation system

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Abstract

In this study an evaluation of the areal distribution of applied water above and below the soil surface for six center pivot systems was conducted under field conditions, to quantify the subsurface distribution of soil water content and water application on the ground surface. The measured application depth of water and water distribution patterns with the distance from the pivot were presented. Field experimental results showed evidence of the importance of redistribution of the applied surface water. The values of the subsurface uniformity coefficients were higher by approximately 12% than the surface values. It was found that the water within the soil is more uniformly distributed than that applied above the soil surface. An experimental relationship between the uniformity coefficients above and below the soil surface was derived under center pivot sprinkler irrigation systems.

Keywords: water distribution, water uniformity coefficients, center pivot, sprinkle irrigation, nonweighted coefficient of uniformity, water application, areal distribution.

1 Introduction

With population growth in the world, the demand of water is increasing. Hence, the necessity for conservation of water resources increases, particularly in countries of limited water supply, where the agricultural irrigation has traditionally been the major water use sector in these areas, usually in the range of 80 to 90%. The sprinkler irrigation system is widely and universally spread. This is because it has flexibility and water application can be controlled
efficiently with it. Center pivot systems are used more than any other irrigation system in the Kingdom of Saudi Arabia due to its high automation level in the wide desert areas. It accounts for more than 80% of the irrigated area and there are more than 20,000 center pivots in the country (Abo-Ghobar and Mohammad, [1]). As the necessity for conservation of water resources increases, the water application uniformity is becoming increasingly important. This increases the need for better-designed and managed sprinkler irrigation systems. Water application uniformity is an important measure of performance used in the design and evaluation of sprinkler irrigation systems. The performance of an irrigation system is described by its uniformity and efficiency. Uniformity refers to the evenness at which water is applied or infiltrated throughout the field and depends on system design and maintenance. Efficiency refers to the amount of water needed for crop production compared with the amount applied to the field and depends on system uniformity and management. It has been demonstrated that the uniformity of irrigation water application has an effect on crop yield (Solomon [14]; Letey [11] and Mantovani et al. [12]).

Numerous investigations and works have been made on the surface distribution of water from sprinklers (Christiansen [4]; Heermann and Hein [9] and Merriam and Keller [13]) and stated the procedures of sprinkler distribution testing above soil surface, e.g. Merriam and Keller [13] and ASAE [3]. A necessary step before calculating an applied water distribution parameter is the accurate measurement of applied water from sprinklers using catch cans or collectors (Fischer and Wallender [6]). Procedures to determine the distribution of water from different sprinkler systems are given in ASAE Standard 5436 [3].

1.1 Uniformity coefficient

Traditionally, center pivot irrigation systems are evaluated by placing a transact of catch cans, uniformly spaced and radially outwards from the pivot point along the lateral. As the machine travels across the transact. The water is caught in the cans, and then the system performance is evaluated from the measured water caught in the cans. Nonuniformity in the center pivot system is assumed to occur more along the lateral than in the direction of travel (Hanson and Wallender [7]). The uniformity of water application could be influenced by many factors. These factors include improper sprinkler nozzling and spacing, wear of sprinklers and pipes, variation in pressure distribution along the lateral, and wind speed and direction during irrigation. Also, the evaluation entailed measuring pressures, system and nozzles flow rates and travel speed of the end tower.

Numerous coefficients of uniformity (CUs) have been developed over the past few decades. These coefficients have been generally accepted as criterion of sprinkler irrigation design. In general, all CUs can be divided into two categories: nonweighted and areal-weighted. Nonweighted CUs are calculated directly from the observations (actual or simulated catch-can data), and each observation is assumed to represent the same land area. The nonweighted coefficient of uniformity (CU) developed by Christiansen [4] is written as:
where:

\( CU = \) Christiansen’s coefficient of uniformity
\( x_i = \) the depth in equally spaced catch cans on grid
\( \bar{x} = \) the mean depth of water caught in the cans, and
\( n = \) number of collectors measured

The above definition required that each catch can represents the depth applied to equal areas could be used to assess the center pivot uniformity along the travel path. But, this is not true for data collected under center pivot irrigation systems where the catch cans are equally spaced along a radial line from the pivot point to the outer end. Heerman and Hein [9] defined the weighted coefficient of uniformity (CU) for center pivot system as:

\[
CU = 100 \left[ 1 - \frac{1}{n} \sum_{i=1}^{n} \left( x_i - \bar{x} \right) \right]
\]

where:

\( CU = \) Heerman and Hein uniformity coefficient
\( D_S = \) Total depth of application at a distance \( S \) from the pivot point
\( S = \) Distance from the pivot point to the collector
\( s = \) subscript denoting a point at a distance \( S \)
\( \eta = \) number of catch containers

1.2 Distributions above and below soil surface:

Most sprinkler irrigation systems are evaluated by determining the uniformity of water as it is applied to the surface of the soil. The irrigation water interception by the plant, however, influences the distribution of water content within the soil. In reality much attention is given to the evaluation of sprinkler irrigation systems above soil surface and ignoring water distribution uniformity below soil surface due to a lack of knowledge. The concern of the designer is mostly associated with achieving uniformity of the spray in the air above the soil surface rather than obtaining a uniform wetting of the root zone or uniformity of water uptake by crop. However, the yield response of the crop is affected by the water within
its root zone and therefore, the distribution of water within the soil is more important than its distribution on the soil surface. Thus, the surface uniformity coefficient may not be an appropriate reflector of the actual water distribution below the soil surface. Davis [5] and Li and Kawano [10] raised the importance of the water distribution inside the soil profile and stated that the evaluation of water distribution above the soil surface is not a good indicator of crop yield. Hart [8] showed examples of uniformity coefficient of 60% of water distribution from conventional sprinkler system at the soil surface becoming 76% and 86% after redistribution in the soil for 1 and 2 days, respectively. Alazba, et al. [2] investigated the uniformity of above and below soil surface under one center pivot system with different nozzle heights. They concluded that there was difference between the Cu values of above and below soil surface. However, The effect of redistribution within the soil, is of course, much dependent upon the spatial distance between above-average and below-average applications (Thooyamani and Norum [15]). Thus, the uniformity of application under the sprinkler irrigation system may be improved considerably if the redistribution within the soil profile is taken into consideration.

The above discussion concerning the prediction of uniformity below the soil surface strongly suggests that the current approach to sprinkler system design has limitations. There is a need to establish a more appropriate design method which takes account of how the water applied was redistributed after irrigation in the root zone, and finding a relationship between uniformity of the water above the soil surface and uniformity below the soil surface. The aim of this work is to evaluate the above and below soil surface uniformity of water application of six center pivot sprinkler irrigation systems operating under field conditions, and to find out a relationship between the above and below soil surface uniformity coefficients.

2 Materials and methods

Six low-pressure center pivot sprinkler irrigation systems were used in this study. Each system is 412 m long with uniform nozzle spacing of 2.54 m. There were a total of 154 different sized nozzles. These nozzles provide increasing discharges with radial distance from the pivot point. System description is given in table 1. The spray nozzles from the pivot point up to number 91 were equipped with pressure regulators to keep the pressures within the recommended operating range of small nozzles. The pivot lateral is a steel pipe with two diameters (table 1), and the drop tubes made of PVC with diameter of 19.05 mm and 3 m long.

The evaluation tests were carried out under normal field conditions in the early morning to minimize the effect of evaporation. Wind speeds ranged from 2 to 7 m/s, the air temperature ranged from 14 to 19°C, and the relative humidity ranged from 13 to 28%. Two rows of catch cans were used for each system to measure the uniformity of water distribution in radial direction. The catch can spacing was 8 m with first can at 11.6 m from the pivot point. The speeds of the systems at time setting of 100% during the tests ranged from 6.36 to 6.88 m/min.
The height of spray nozzle was 1.1 m above the top of the catch cans. There was no end-gun sprinkler at the lateral end in any system and the systems were operated nearly on level grounds.

Table 1: Specifications of center pivot systems used in the study.

<table>
<thead>
<tr>
<th>Manufacturer: Linsay Zimmatic</th>
<th>Pivot height: 4.3 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe diameter: Span 1-6=168.22 mm</td>
<td>Tower height: 3.8 m</td>
</tr>
<tr>
<td>Span 7-8=141.22 mm</td>
<td>Span length: 52 m</td>
</tr>
<tr>
<td>Nozzle type: Senninger (360/cv-m)</td>
<td>Nozzle spacing: 2.54 m</td>
</tr>
<tr>
<td>Regulator model: PMR - 15 LF</td>
<td>System age: 10 years</td>
</tr>
</tbody>
</table>

The evaluation indexes of each center pivot above and below soil surface were determined. The weighted coefficient of uniformity (Cu) was used to determine the water distribution in radial direction above the soil surface for each system. For the subsurface water uniformity assessment, the soil water contents (\(\theta\)) were used and determined gravimetrically at three soil depths (20, 40 and 60 cm). The initial moisture content was determined before the beginning of water application. Soil water content (\(\theta\)) for each depth was measured after 12, 24 and 36 hours after water application ceased. The soil texture was loamy sand (85% sand, 7% silt and 8% clay).

The uniformity of water redistribution below the soil surface was determined by rewriting the nonweighted coefficient of uniformity developed by Christiansen [4] in the following form:

\[
\bar{\theta} = \left( \sum_{i=1}^{N} \theta_i \right) / N
\]

\[
CU_s = 100 \left\{ 1 - \frac{\sum_{i=1}^{N} |\theta_i - \bar{\theta}|}{N \bar{\theta}} \right\}
\]  

(3)

where:

\(CU_s\) = Christiansen’s coefficient of uniformity of soil water content

\(\theta_i\) = the measured soil water content

\(\bar{\theta}\) = the mean soil water contents, and

\(N\) = number of measured points
3 Results and discussion

The water distribution patterns of the tested center pivot systems above soil surface are shown in Fig. 1. The patterns present the average depth of water caught in each can along the lateral of the pivot. It can be seen from the figures that there was a variation in depth of water applied along the lateral from one system to another, and it can be said that the water was distributed non-uniformly in some systems than the others along the lateral. Also, the values of the average depths and the average low quarter depths of application for each system were determined and shown in figure 1. The weighted uniformity coefficients (Cu) were determined for each system above the soil surface. The values of Cu were 71.9%, 69.2%, 74.7%, 70.7%, 71.4% and 69.9% for systems...
A, B, C, D, E and F respectively. The systems were distributing water below the generally accepted level of uniformity (80%). This non-uniformity is attributed to the field operation factors, such as improper nozzling, leakage, and pressure variation along the lateral.

A substantial amount of work has been done to measure and evaluate the uniformity of center pivot systems below the soil surface. The average values of CUs below the soil surface at three different depths and different time of measurements were calculated, and the values were 85.42%, 78.85%, 87.15%, 82.11%, 84.44% and 81.2% respectively for the six systems. It can be noticed that the values of CUs below the soil surface were higher (83.2% an average) than those of Cu above soil surface (71.3% an average). This can be explained by the hydraulic gradients existing within the unevenly wetted soil which causing water movement laterally and vertically within the soil profile, resulting the water within the soil to be more uniformly distributed than the indicated by the surface-measured distribution (Cu). These findings are in agreement with the results of Hart [8] and Li and Kawano [10].

Figure 2: The subsurface uniformity coefficients of water (CUs) as function of soil depth after irrigation from six center pivot systems.

Figure 3: The subsurface uniformity coefficients of water (CUs) as function of time after irrigation from six center pivot systems.
Also, it was found that the values of CUs below soil surface were decreased slightly with the increase of soil depth (Fig. 2) due to the soil water diffusivity, but increase with the time of measurements (Fig. 3) due to the achievement of equilibrium. In general, the water within the soil at any depth and time of measurement was more uniformly distributed than the surfaced-measured distribution of water, and the CUs values were generally above the acceptable uniformity level of design (80%).

\[ CUs = 23.588e^{0.0177Cu} \]
\[ R^2 = 0.9318 \]

Figure 4: The relationship between the surface and subsurface uniformity coefficients for center pivot irrigation systems.

Many researchers have studied the function to represent the distribution of water application above soil surface from sprinkler systems. However, the function to represent the distribution of water at different depths of soil profile after infiltration under center pivot systems has not been reported. However, given the difficulties inherent in the above-mentioned work and the above discussion concerning the prediction of redistribution water strongly suggests that an alternative approach to the subsurface evaluation of center pivot performance is to relate the subsurface evaluation indexes to the surface evaluation indexes. Such relationship describing the sprinkler system performance in relation to the prediction of water redistribution is likely to be useful index to the farmer and system designer. The results depicted in Fig. 4 is revealed the type of the relationship between the surface and subsurface uniformity coefficients (Cu and CUs) which was found to be an exponential type with correlation coefficient \( R^2 = 0.9318 \), which has the following form:

\[ CUs = 23.588e^{0.0177Cu} \]  

This equation can estimate the water distribution uniformity coefficient under soil surface expected from center pivot system instead of the tedious work,
which requires the field measurements of soil water contents. The value of Cu should be substituted in the equation as true value not percentage.

4 Conclusion

It can be concluded that all the six center pivot systems were distributing water above soil surface below the generally accepted level of uniformity. But, the water within the soil was more uniformly distributed than the surface-measured distribution of water. The redistribution of water within the soil profile is a function of many irrigation and soil variables, such as depth of water applied, uniformity above soil surface, initial soil water content and soil water diffusivity.

A system designed using the current design criteria for sprinkler irrigation uniformity, such as $\text{Cu} \geq 75\%$, or $\text{Cu} \geq 80\%$ may not be the most economical if the system is mainly aimed at producing desirable uniform soil water distribution. This conclusion may not necessarily apply for arid regions where the irrigation depth for an irrigation event is larger than in humid regions. Therefore, the level of design of the acceptable uniformity of application under the sprinkler irrigation systems should be re-examined with taking into consideration the redistribution of water within the soil profile.

The results revealed that there is an exponential relationship between the surface ($\text{Cu}$) and the subsurface ($\text{Cus}$) uniformity coefficients. The derived equation may provide a useful guide to potential performance of sprinkler systems in respect to redistribution of water under soil surface, which will lead to the saving of precious resource in areas of limited water supply. Also, the study is expected to draw the attention of sprinkler irrigation system designers and users to consider the previous concept of the evaluation of sprinkler systems above soil surface.

References


