Overview of advances in improving uniformity and water use efficiency of sprinkler irrigation

Ransford Opoku Darko[1,2*], Yuan Shouqi[1], Liu Junping[1], Yan Haofang[1], Zhu Xingye[1]

(1. *Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, China*;
2. *Department of Agricultural Engineering, University of Cape Coast, Central Region, Cape Coast, PMB Ghana*)

Abstract: Water is the scarcest resource and the importance of the judicious use of water in the agricultural sector for sustaining agricultural growth and the retardation of environmental degradation needs no further elaboration. The successes of using sprinkler irrigation to develop new lands, point the way forward to a much greater role for the development of future land reclamation projects. Water use efficiency through a proper improvement of water management techniques and other production factors are essential to boost on-farm productivity. Various factors affecting uniformity and water use efficiency in sprinkler irrigation have been outlined in this research, highlighting possible ways to improve such essential parameters in crop production. The study emphasizes on an irrigation system that works adequately in applying water to stay within the root zone, making the water always available in sufficient quantities to meet the crop water needs. It suggests practical ways of managing irrigation systems within tolerable limits not neglecting the effects of wind which is a major contributing factor to non uniformity in sprinkler irrigation.

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1 Introduction

Efficient use of water in agriculture is a complex subject that involves a broad range of disciplines including agronomy, plant physiology and engineering. In this regard, efficiency to the agronomist relates to irrigation efficiency, to the plant physiologist as transpiration efficiency and to the engineer as water use efficiency[1]. Modern sprinkler irrigation technologies usually convey water through pipes hence resulting in less water wastage. Furthermore the irrigation engineer can control the amount of water applied and its timing more easily which can increase the productivity per the unit of water consumed. Sprinkler irrigation systems seem to have large potential for improving water use efficiency of crops[2]. It is therefore of a paramount interest to evaluate sprinkler irrigation systems based on their ability to establish uniformity in water application to identify run times that minimize dry areas. In order to realize this objective, the uniformity with which an irrigation system applies water will have to be increased which will have an impact on the systems' application efficiency and on the crop yield[3,4]. According to Darko et al.[4], sprinkler irrigation systems with poor uniformity results in reduced yields due to water stress as well as

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Biographies: Yuan Shouqi, Professor, research interests: CFD of pumps, fluid machinery, irrigation systems, Email: shouqiy@ujs.edu.cn; **Liu Junping,** Associate Professor, research interests: CFD of pumps, fluid machinery, irrigation systems, Email: liujunping401@163.com; **Yan Haofang**, Associate Professor, research interests: water saving irrigation theory and technology, agricultural water management. Email: yanhaofang@yahoo.com; **Zhu Xingye**, Associate Professor, research interests: CFD of pumps, fluid machinery, irrigation systems, Email: zhuxy@ujs.edu.cn.
∗**Corresponding author: Darko Ransford Opoku,** Doctoral Research Fellow, research interests: water saving irrigation, agricultural water management, sustainable agriculture. Mailing address: Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, China; Department of Agricultural Engineering, University of Cape Coast, Ghana. Tel: +86-13101925601, Email: chiefrodark@yahoo.com.

water logging which contributes to an increase in the cost of irrigation and other related issues. Considering the many factors affecting the crop production function in addition to evapotranspiration deficits, sprinkler irrigation uniformity also contributes meaningfully[5-10]. Its effect on the crop yield is an important consideration for the design of irrigation systems. Ideally, an irrigation system would apply water in a completely uniform manner so that each part of the irrigated area receives the same amount of water. Unfortunately, there seems to be no way to achieve this. Li and Rao[11], in their research on field evaluation of crop yield as affected by non uniformity of sprinkler-applied water and fertilizers recorded insignificant effect on winter wheat yield for the studied uniformity range. Letey et al.[12] provided a general method for analyzing the effects of infiltration water uniformity on crop yield and concluded that ignoring irrigation uniformity leads to underestimates of the optimum irrigation amounts. Mantovani et al.[13] simulated the effects of sprinkler uniformity on crop yield by assuming a uniform sprinkler water distribution and a linear crop water production function. Li[14] also presented a model that relates yield response to evapotranspiration deficits at special growth stages to evaluate the impacts of the uniformity on the crop yield. It is widely believed that establishing uniformity in sprinkler irrigation is a key approach in enhancing crop yield in sprinkler irrigated fields and also saving water. The success of using sprinkler irrigation to develop new lands point the way forward to a much greater role for the development of future land reclamation projects to increase yields and also to improve water use efficiency (WUE). It is based on these that this paper reviews the advances made so far in improving uniformity and water use efficiency in sprinkler irrigation, highlighting on the various factors which contributes to nonuniformity and water use efficiency to recommend possible ways of improvement in crop production.

2 Irrigation uniformity in sprinkler irrigation

Irrigation uniformity is a central goal of the sprinkler irrigation system design[15]. It is the variation or non-uniformity in the amounts of water applied to locations within the irrigated area and may also be defined as the variation in irrigation depths over an irrigated area. It is an important performance characteristic of the sprinkler irrigation system[16-18]. Sprinklers, properly spaced will respond to a relatively uniform application of water over the irrigated area. Irrigation uniformity may have different perspectives depending on whether it is viewed by an engineer or by an agronomist. To the engineer, it will be geared towards the design and management of the sprinkler irrigation systems. According to Redditt[19] various measures of uniformity are used as indices of the performance by which sprinklers and sprinkler spacing are judged and they may also set hydraulic limitations on the sprinkler pipe network To the agriculturist, perfect uniformity may be perceived as each part of the growing crops receive uniform application of water. If the sprinkler system is operated so that a part of the crop receiving least amount of water has its water requirement met, other parts of the crop field that were sprayed with the most water will be over irrigated and then vice versa. Excess water reduces crop yields below recommended range by way of increased leaching of plant nutrients, incidence of diseases or failure to stimulate growth of the commercially valuable parts of the plants. Limited amounts of water given to crops may result in weaker plants and reduced crop yields[20,21]. Extensive research has been made on the surface distribution of water from sprinklers[10,15,17,22]. However, little work has been carried out to investigate their effect on crop yield which is an important consideration for the design of sprinkler systems. Dechimi et al.[10] mentioned in their research work that sprinkler uniformity directly affects the crop production function. Sezen and Yazar[23] also revealed that the effects of the applied amount of sprinkler irrigation water, irrigation frequency and water use efficiency are particularly important in order to obtain higher yields. Their research showed that evapotranspiration, crop yield, water use efficiency (WUE) and crop harvest index are all being affected by controlled soil water content during the growth seasons.

Christiansen's CU[24] identifies the evenness of an irrigation system's water distribution by comparing the average difference in the amount of water collected in each catch can to the mean amount of water collected by all catch cans. The degree of uniformity of water distribution depends on the water distribution styles and features of sprinkler nozzles. The basic function of sprinkler nozzles is to distribute water uniformly, without causing surface flow and excessive drainage from the root zone. For this reason, sprinkler nozzle is considered to be the most important element of the system. The performance of the sprinkler nozzle determines the productivity and efficiency of the whole system[25,26]. It is necessary that the determined water distribution be at an acceptable level. Earlier periods reveals that several coefficients that indicate the uniform application of the sprinkler irrigation system have been formulated with Christiansen leading the way. He brought up the specific quantitative investigation of sprinkler uniformity which he determined by the equal distribution coefficient. Christiansen's coefficient of uniformity[24] is expressed as a measure of the absolute difference from the mean divided by the mean expressed as a percentage below:

$$CU = 100\left(1 - \frac{\sum_{i=1}^{n}(X_i - \bar{X})}{n\bar{X}}\right) \tag{1}$$

where, X_i is water depth collected from the i^{th} catch can, mm/h; $\bar{X}$ is mean water depth collected in all catch cans within the area, mm/h; n is the total number of catch cans in the area under consideration.

Wicox and Swailes[27] used squares of the deviation from the mean instead of the deviations themselves, contrarrily to that of Christiansen[24,28]. Their coefficient is as follows:

$$CU = 100\left(1 - \frac{\sigma}{\mu}\right) \tag{2}$$

where, U is uniformity coefficient, %; σ is standard deviation of total depth of water, mm; μ is mean application depth, mm.

Hart and Reynolds[29] proposed the distribution efficiency, which is based on the numerical integrations of the normal distribution function[28]. The approach requires that you have to first select a target CU and target percentage area which will be adequately irrigated. They proposed:

$$\sum_{i=1}^{n}|X_i - \mu| \cong \frac{n\sigma\sqrt{2}}{\pi} \tag{3}$$

$$CU = 100\left(1 - \frac{0.798\sigma}{\mu}\right) \tag{4}$$

where, σ is standard deviation of all depth measurements, mm.

Criddle et al.[30] and Beale and Howell[31] also formulated their coefficient just as that of the Christiansen[24], however Criddle et al.[30] limited their equation to the lower quarter depths of water application while Beale and Howell[31] limited the equation to the highest quarter depths of water apllication.

Criddle et al.[30] $$CU = 100\left(1 - \frac{\sum_{i=1}^{\frac{n}{4}}|Xi - \mu|}{\mu \times \frac{n}{4}}\right) \tag{5}$$

Beale and Howel[31] $$CU = 100\left(1 - \frac{\sum_{i=\frac{3}{4}n+1}^{\frac{n}{4}}|Xi - \mu|}{\mu \times \frac{n}{4}}\right) \tag{6}$$

The distribution uniformity coefficient (DU), proposed by Merriam and Keller[32] is also computed by dividing the mean low quarter caught in the cans by the average depth caught in all the cans expressed as a percentage[33]. Their coefficient is as follows:

$$DU = 100\left(\frac{Dlq}{\mu}\right) \tag{7}$$

where, DU is distribution uniformity, %; Dlq is mean of the lowest one-quarter of the measured depths, mm.

The scheduling coefficient (Sc) also represents the ratio of area receiving the least amount of water to the average amount of water applied through the irrigation area. This value as cited by Solomon[34] enables us to find the critical area in the water application pattern. Matemathically, Sc is defined as:

$$Sc = 100\left(\frac{1}{DU}\right) \tag{8}$$

Karmeli[35], Benami and Hore[36] as well as Heermann and Hein[37] also did research to propose equations on expressing the coefficient of uniformity[38]. All the above mentioned uniformity coeefficients are based on some measures of deviation of water distribution. Of the above coefficients, Christenson's Coefficient of uniformity is the most widely used and accepted criterion to define uniformity[18,35,39]. In sprinkler irrigation, CU is the measure of the characteristic effect of the individual sprinkler type, the spacing, operating pressure and the prevailing wind conditions[38]. A CU coefficient of above 80% must be desired. Arrangement styles that have the results less than this value should not be used[25]. A threshold value of CU for a sprinkler irrigation system must fall within the acceptable range recommended by some researchers. A CU value of less than 85% representing "low" and 85% or above representing high was recommended by Merriam and Keller[32]; Kay[40]; Keller and Bliesner[25] as desirable. A low coefficient of uniformity indicates that the application rates from the delivery devices are very different, while a high coefficient of uniformity indicates that the application rates from the delivery devices are very similar in value. It must however be emphasized that the coefficient of uniformity by itself is not a measure of how well the system is distributing water within the root zone.

Currently, there is only little report on field test which discussed the irrigation uniformity using sprinkler systems especially, movable irrigation systems. Guo et al.[41] researched into the calculation method of irrigation uniformity of centre-pivot sprinkler systems in the 1980s. Lan et al.[42], Jin et al.[43] and Yan[44] conducted a research on the nozzle configuration method of centre-pivot irrigation system. Asough and Kiker[45] also used the Herman-Hein uniformity coefficient (C_{UH}) to evaluate the uniformity of irrigation water distribution. Dukes and Perry[46] also published few dissertations on ASABE academic journal. Duke[47] and Duomoh et al.[48] focused their uniformity test on the influence of wind. Many studies have been conducted to determine the factors affecting sprinkler irrigation uniformity; however there have been a limited number of studies regarding the systems effect on growth and yield of crops; hence, issues on uniformity distribution, system efficiency and the application rates still remain and needs to be researched[39,49].

3 Water use efficiency in sprinkler irrigation

Water use efficiency (WUE) may be defined as the ratio of the quantity of water effectively put into the crop root zone and utilized by growing crops to the quantity delivered to the field expressed as percentage. The concept of efficiency is related to the distribution of water within the root zone. Efficiency is always less than 100% mainly because of the limited control in the way in which water is applied and how it distributes itself in the soil. Low efficiency in sprinkler irrigation is usually due to a combination of the following factors:

a) Evaporation losses by sprinkler nozzle spray;

b) Losses due to deep percolation;

c) Direct evaporation from soil surfaces;

d) Runoff from the field.

Soil water availability to crops is affected by infiltrated irrigation water and rainfall, drainage and evapotranspiration (ET). The single most important factor influencing plant growth and crop yields is soil water availability. According to Hill and Barnhill[50], it takes 120 pounds of water (ET only) to produce 1 pound of potatoes, 560 pounds of water for 1 pound of alfalfa hay and 790 pounds of water for 1 pound of wheat. A best approach in achieving good water management program is to know the actual consumptive use of the crop (ETc). English and Raja[51] mentioned in their studies that the effects of irrigation on crop production are usually quantified using crop water production functions that relate crop yield to the amount of water applied. The utilization of techniques to management of evapotranspiration (ET) as a major driving force in crop yields could be a major step in increasing production in the future[52]. In recent years, global agriculture has been met with the new challenge, of increasing food production for the growing population under increasing scarce water resources[53]. This could be achieved by improving water use efficiency[54] and the sooner the mitigation activities begin, the lower the likely impacts. Adaptation will be needed to protect livelihoods and food security in many developing countries that are expected to be the most vulnerable, even under moderate climate change[55]. This indicates that the overall challenge of climate policy will be to find the efficient mix of mitigation and adaptation solutions that limit the overall impacts of climate change. Many studies have shown a linear relationship between wheat/sunflower yields and seasonal evapotranspiration[56,57]. According to Zhang et al.[58], the crop yield and WUE in wheat sprinkler irrigated fields was higher than in surface irrigated fields. They also pointed out that the WUE for wheat decreased with increasing seasonal evapotranspiration. However, some researchers showed the curvilinear relationship with increasing evapotranspiration[59]. WUE decreases with increases in irrigation duration and amount applied over the growing season[60]. Liu et al.[61] revealed that WUE under improved cat swarm optimization (ICSO) aided in optimization of channel trapezoidal section. They mentioned that performance of ICSO optimization in channel cross section with minimum loss of water results in a promising computational efficiency and search ability when compared with conventional cat swarm optimization (CSO), particle swarm optimization (PSO) and genetic algorithm (GA). Smart irrigation technologies evaluated in Egypt and Dookie also resulted in saving 38% of water over conventional irrigation[62]. The use of frequent but low water application volumes was seen to be superior to the more traditional scheduling method of using fewer applications of large volumes[63,64]. Water management for agricultural production is a critical component that needs to adapt in the face of both climate and socio-economic pressures in the coming decades. According to Bates et al.[65], changes in water use will be driven by the combined effects of (i) changes in water availability, (ii) changes in water demand for agriculture, as well as from competing sectors including urban development and industrialization, and (iii) changes in water management. One approach for improving water use efficiency is to replace surface irrigation systems with more efficient pressurized sprinkler systems[66] to significantly reduce water application on the farm scale, thereby increasing water land productivity, but also increasing energy and investment requirements. Water use efficiency (WUE) has been studied with crop growth models by using parameters from different climate models. The changes in crop production related climatic variables will possibly have major influences on regional as well as global food production[67].

Increasing water productivity is related to the production of the same yield with less water resources or to obtain higher crop yields with the same water resources[68]. Although Bouman[53] suggested that just "increasing water productivity" may not solve the dual challenge, it is also necessary to understand the latent mechanism of increased water productivity. The existing studies show that climate is the single most important determinant of agricultural productivity, basically through its effects on temperature and water regimes[69]. Crop water productivity inversely related with vapor pressure and is an important index to evaluate water saving and water investments for farmers and scientists[68]. Water use efficiency can be increased significantly if irrigation is reduced and the crop water deficit is widely induced[70]. In the decreased precipitation regions, the irrigation amount will increase for optimal crop growth and production, but this may decrease crop water output. Therefore, it will be a big challenge to increase water use efficiency at all levels. Kijine et al.[54] reported that water productivity can be improved by increasing investments in agricultural infrastructure and research rather than investments in the irrigation system. Khan et al.[71] presented an approach of combining GIS with groundwater modeling MODFLOW (Modular Three-dimensional Finite- difference Ground-water Flow Model) to enhance water productivity in the Liuyuankou Irrigation Area, China and concluded that the reduction in non-beneficial evapotranspiration can make the extra water be used in other areas, thus improving water productivity. Li and Barker[72] found that the AWD (alternate wetting and drying) irrigation technique can increase water productivity for paddy irrigation in China. Lecina et al.[73] analyzed modernization in the Alto Aragon irrigable area. They highlighted some advantages and disadvantages of migrating from surface to sprinkler irrigation systems and quantified water savings and some of the associated economic and social impacts. Morena et al.[74] analyzed energy efficiency in more than 20 water user associations in Castilla-La Mancha and proposed measures to increase energy efficiency.

4 Hydraulic factors affecting uniformity in sprinkler irrigation

There are many factors that affect the uniformity of sprinkler irrigation, including the sprinkler system, climatic conditions and field management practices[22]. The spatial distribution of irrigation may affect the water distribution in the root zone, with significant effects on crop yield. As farmers throughout the world become conservation minded, there is a need to probe more into uniformity which can serve as water saving tool in irrigation and increasing crop yield. The factors may include:

4.1 Intake rate of the soil

Sprinkler irrigation systems, as opposed to furrow irrigation, transmit water to the field independently of topography. Spacing and discharge of sprinkler determine the application rate which should be less than infiltration rate in order not for surface runoff to occur. Determination of safe intake rates for soils is one of the most important considerations in planning sprinkler irrigation system. The intake rate of the soil is the soils ability to take in water during a normal water application period. This rate is governed by the conditions of the soil surface, together with the inherent physical characteristics of the soil profile. The intake rate of the soil should not be exceeded by the precipitation rate of the sprinklers. This precipitation rate is governed by pressure and nozzle size selected for given spacing. Sprinkler capacities for various pressure and nozzle size combinations are given in performance tables supplied by the sprinkler manufacturer. In general, the intake rate of lighter-textured (sandy) soils is higher than that of heavier- textured (clay) soils. However, sprinkler irrigation with very high quality water can lead to surface run-off even on sandy soils[75,76]. Matching the sprinkler application rate to the soil intake rate is difficult because the rate at which water infiltrates the soil is complex. First, the intake rate varies with time; it is high when the water is initially applied and decreases with time (Figure 1). Runoff is therefore more likely to occur if the irrigation lasts longer. On soils with low intake rates and a greater runoff potential, growers often irrigate more frequently with shorter set times to minimize water runoff. Considering Figure 1 below, fields with different soil textural properties will result in varied rate of infiltration of irrigated water into the soil thereby causing non-uniformity. At the beginning of an irrigation turn, the irrigation flow is usually lower than the infiltration rate and all the water applied infiltrates into the soil[77]. With time, the infiltration rate decreases and becomes lower than the irrigation rate[78]. When irrigation continues after this point, superficial water flow and runoff-run-on (overland flow and infiltration thereof) occur[78]. The rate of overland flow on a sloping field depends on the amount of water that can accumulate on the rough soil surface or its depressions. Runoff–run-on and surface depression storages imply additional areas of water infiltration that remain active for sometime after the pass of the irrigation machine. Time is also relevant to irrigation efficiency. If irrigation is completed in a short time, operation and maintenance costs decrease[77] and water would be saved due to the reduction in evaporation. Efficient irrigation planning involves achieving maximum infiltration rates in minimum operation times.

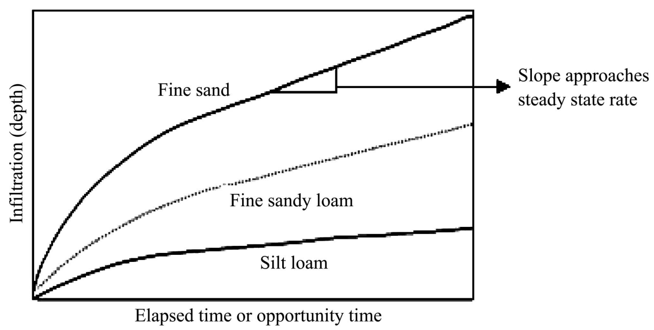

Figure 1 Basic infiltration rate versus time

4.2 Spacing of sprinklers and laterals

The uniformity in water distribution depends on the distance between the sprinkler nozzles as well[38,48,79-81]. As sprinklers are spaced further apart, uniformities usually decrease[82,83]. Clark et al.[84] mentioned in their research that no sprinkler nozzle should be operated without providing the desired over-lateral and inter-lateral overlap. They reiterated that the desired degree of overlap is achieved by the sprinkler pattern of nozzles and wind conditions. Spacing should be closer in windy weather and lateral and nozzle spacing should be determined according to different speeds and directions of wind and different nozzle pressures[85]. Since windy conditions negatively affect the distribution of water, the spaces between nozzles should be decreased. It is generally suggested that irrigation should be carried out when wind speed is lower than 2.5 m/s[47]. If wind speed increases, the uniformity coefficient decreases[47].

4.3 Riser height

Another factor affecting efficiency is sprinkler height which has a great effect on sprinkler uniformity, especially in windy weathers[86]. Sprinkler should be at the same height and able to move freely for dispersal of the water droplets. Sprinkler nozzles should also be vertical to the surface of land. According to Mateos[87], the equipment and design factors which include the nozzle characteristics (composed of nozzle size, nozzle type, discharge angle, jet straightening vane inside the main nozzle and the number of nozzle), determine the single-sprinkler distribution patterns under indoor conditions. In a study conducted by Bishaw and Olumana[86], they observed that an increase in riser height leads to increase in sprinkler water uniformity. Much work will be needed in this area to evaluate the effect of riser height in sprinkler irrigation since only little research is available in this direction.

4.4 Pressure

Every irrigation system experiences pressure variations which affect overall performance. Poor uniformity caused by pressure fluctuations can alter flow and sprinkler uniformity, affecting crop quality and yield[80]. Fluctuations can be caused by changes in field elevation, zones cycling on and off, and activation of pivot end guns. The use of preset pressure regulators overcomes these variations. If you have a low pressure irrigation system, pressure variations are of even greater concern. In a 20 psi (1.4 bars) system, a 4 psi (0.28 bars) variation means a 10% flow variation. That makes a big difference to sprinkler performance and directly impacts on overall system uniformity. The use of pressure regulators in irrigation design is like an insurance to keep the sprinklers and system performing at peak distribution uniformity. A sprinkler will not work well when made to operate outside of its recommended pressure range. High pressure causes overwatering near the sprinkler head and produces small droplets susceptible to wind drift and evaporation. According to Zoldoske[26], high pressures can also damage sprinklers whereas low pressure effects may result in the sprinkler rotational speed[88]. This creates dry spots near the head and overwaters in a donut shaped pattern. The use of pressure regulators helps ensure that sprinklers perform well. Without pressure regulators, one will need to irrigate longer to water the drier areas, causing over-watering of the other areas. In addition to wasting water, this directly increases pumping costs, and energy consumption. Over-watered areas are at risk for disease, leaching, runoff, and soil damage. Leaching and runoff increases costs for fertilizers and can lead to pollution of ground water. Pressure regulators may also be required if the pressure produced by the pump is too high/low due to irrigation zones that vary in size or zones with different elevations. When a system is introduced with low pressure sprinklers, the pump must be modified to match the pressure needs of the new components. Pressure regulators must be used in low volume systems to provide the optimal pressure required for lateral lines and other low pressure system components. Pressure compensating emitters and mini sprinklers perform better and last longer when operating with a balanced system pressure.

4.5 Wind

The distribution uniformity and application efficiency of sprinkler irrigation systems are potentially high, but these parameters are highly dependent on the weather conditions, especially on wind[15]. According to Bishaw and Olumana[86] higher sprinkler water uniformity and low application water loss have been encountered in low wind speed conditions. Wind strongly affects the sprinkler irrigation performance since it lowers the uniformity and the efficiency of the water distribution[10,38,47,81]. Consequently, it is necessary to increase technical knowledge and develop tools that can improve sprinkler irrigation performance in windy conditions. For a given wind condition, the primary factors affecting uniformity are nozzle type and size, operating pressure, and spacing. For a fixed grid system, there are two spacing dimensions, the distance between sprinklers on a lateral, and the distance between laterals.

Rough rules of thumb for maximum spacings given by Solomon[89] are summarized in Table 1 where he defined low wind to be 0-7 km/h, a moderate wind to be 7-14 km/h, and a high wind to be 14 km/h or more. The spacings are given as a percentage of the sprinkler's wetted diameter.

Table 1 Maximum recommended sprinkler spacings[89]

Wind Conditions	Spacing
Low	60%-65% of wetted diameter
Moderate	50% of wetted diameter
High	30%-50% of wetted diameter

Wind monitoring is essential to manage sprinkler irrigation districts where moderate or high winds are frequent and extensive. Usually a single reference weather station, located close to the irrigation district, is used to assess the water needs of crops for the whole of the area. The information provided by these stations is useful to assess the water needs of crops and to schedule irrigation. However, both can be improved by accounting for the spatial variability of the wind within the irrigation environment. The estimation of the wind conditions at sites with no or few records can be performed by linking a location to a nearby place for which a wind series is available. According to Landberg and Mortensen[90], it should be based on the idea that within a certain distance, given by the local meso-scale conditions, overall wind conditions are the same. The suitability of the data provided by a meteorological station may vary since its representativeness depends on the complexity of the terrain and nearby obstacles[47]. Wind exposure can vary within an irrigation district, and specific irrigation management may be advisable depending on the degree of exposure. Nevertheless, the problem is complex and scale-dependent[47,81,91]. Among the methods used to predict the wind resources at target sites, empirical methods are based on statistical correlations between the time series from different sites. However, these methods are usually applied to describe general and average conditions rather than to find relationships for short periods such as irrigation events. Achberger et al.[91] emphasized that the knowledge of the local wind conditions is an important topic in many applications such as setting up of wind turbines and estimating the environmental impact of air pollution from a point. They present a great opportunity to improve the quantification of the crop water needs and scheduling of sprinkler irrigation towards a more efficient use of water. When farmers are forced to irrigate under unfavorable and prolonged windy conditions and when the period with low wind is not sufficient to irrigate the whole irrigation region, then average irrigation performance of the region can be improved by including the wind exposure of each zone as a management factor. In addition, crop rotation schedule needs to be improved by observing the sensitivity of the crops to the irrigation uniformity together with the local wind exposure. The spatial variability of the wind is also a criterion to be included in designing the sprinkler spacing and arrangements adopted in new sprinkler installations.

4.6 Management issues

Nozzles and risers are significant source of sprinkler non-uniformity. Nozzles wear as water with grit is pumped through them. Also wires used to unplug nozzles can abrade the opening and thus allow more water to exit than the original design specifies. To check the nozzle opening for wear, use the shank of a drill bit of the same size as the nozzle opening. Movement of the drill bit shank should be less than 5°-10°. If the bit can move more than this then the nozzle should be replaced. Different types of nozzles developed include the constant-diameter, constant-discharge, and diffuse-jet nozzles[91]. A good management practice would be to replace all nozzles every 2-3 years. Risers must be perfectly plumb so that water is sprayed at the same elevation across the bed. Each year, as lines are put back into the bed each riser should be checked to ensure that it is plumb and then carefully staked. This is easy to check with a short magnetic bubble level. Riser height can also affect uniformity[86]. According to Loule and Selker[93], taller risers up to two feet will provide greater uniformity than shorter risers. Inadequate selection of pipe diameters, inadequate selection of sprinkler head and nozzle as well as inadequate sprinkler overlap are all management issues that has to be dealt with in order to achieve minimum variation of water distribution on the field.

5 Discussion

The importance of sprinkler irrigation uniformity has been recognized as early as 1942[24]. Widespread research has been conducted on the factors affecting sprinkler irrigation uniformity. The main factors affecting water application (water distribution uniformity) are sprinkler nozzle type, operating pressure, nozzle diameters, nozzle elevation, heat and damp[3,9,16,18,22,25]. Such factors include wind speed and direction and the sprinkler nozzle characteristics[33,38,48,61,81]. In addition to nozzle size and pressure, the type of diffuser device, sprinkler spacing[81], riser height[86], field topography[94], and jet straightening vane inside the main nozzle, discharge angle, the alternation of day and night irrigation, number and configuration of the sprinklers, and wind speed and direction[81] can influence water application uniformity. There is an interesting relationship between recommended spacings and soil characteristics in sprinkler design. One of the tenants of sprinkler system design is that the application rate should not exceed the basic infiltration rate of the soil. Application rate is proportional to the flow rate and inversely proportional to the product of the two spacing dimensions. For a given pressure, increasing the nozzle size will increase both sprinkler flow rate and wetted diameter, but flow rate will increase considerably more than diameter. The increase in wetted diameter will permit slightly larger spacings, but the increase in flow rate overshadows this, so that for a fixed uniformity, increasing the nozzle size generally means an increased application rate as well. Within the range of small to medium sized sprinklers, it is generally more economical to design the system with the largest sprinkler and spacings permissible. So the two factors that often determine sprinkler nozzle size and spacing are the desired uniformity and the infiltration rate of the soil. When growing high value crops, where high uniformity is normally desirable, on fine textured soils, successful designs invariably employ small nozzles (3 mm diameter) and close spacings (9 m × 12 m). On coarser textured soils with a higher infiltration rate, or where lower uniformities are acceptable, larger nozzle and wider spacings may be used.

Common operating pressures for these size sprinklers used to be in the range of $3\frac{1}{2}$ to $4\frac{1}{2}$ Bars, but with the high cost of energy, there has been a tendency to reduce the operating pressure. A variety of new nozzles, generally with non-circular orifices, have been specially designed for low pressure use. These nozzles use mechanical means to provide extra breakup of the water jet at low pressures[95-97]. With such nozzles, operating pressures are often 1 Bar lower than with traditional nozzles. Rapid rotation of a sprinkler may considerably affect the breakup of the stream, and to this extent, it determines how wind will affect the pattern. A jet of water in the air tends to carry with it an envelope of air moving at a velocity approaching that of the jet. When this condition is achieved, air drag on the jet is at a minimum. If the jet is made to change position, it encounters a new mass of air that is essentially at rest, thereby providing resistance to the water. A rapidly rotating jet has no chance to develop an envelope of moving air, so it always encounters maximum drag and undergoes the most breakups. Thus, rapidly rotating sprinklers are affected by wind more than sprinklers with lower rotation speeds.

The trajectory angle of the sprinkler (the angle above horizontal at which the water jet leaves the sprinkler) can influence the water pattern, and hence uniformity[16]. In the absence of air drag, a 45º trajectory would give the maximum wetted diameter for a given nozzle and pressure. Due to the air resistance encountered by the water jet, the trajectory angle for maximum throw is actually less, perhaps just over 30º. In the presence of wind, however, high trajectory angles suffer the disadvantage that the water is in the air longer and hence more susceptible to the wind[81]. In an empirically derived compromise, many sprinkler manufacturers have settled on a trajectory angle of about 27º as "standard". It achieves near maximum throw in the absence of wind, yet does not suffer pattern distortion in wind to the extent that a 30º trajectory would. For sprinklers to be used in moderate to high wind conditions lower trajectory angles are advised; 23º, 21º and even 18º trajectory angles are available for use in successively higher wind conditions.

Lower trajectory angles are available for special purpose uses. An important question in sprinkler selection is whether to use sprinklers with a single nozzle or with dual nozzles. In most agricultural applications, the single nozzle is preferred, for the following reasons. For a given spacing, the application rate is determined by the sprinkler flow rate. It is usually most economical to design for an application rate near the limit dictated by the soil type, so that spacings can be maximized. When selecting nozzles, it is presumed that the desired sprinkler flow rate is known. The nozzle choice becomes a question of whether one should put all the available water through a single nozzle, or use a slightly smaller main nozzle accompanied by a secondary or "spreader" nozzle. Water from the spray nozzle is usually much finer and more diffuse than the spray from the main nozzle, so it is much more affected by the wind. Using the largest possible main nozzle will maximize wetted diameter and minimize wind distortion. Thus, unless the wind conditions are unusually calm, the single nozzle sprinkler will generally have the better coverage, the higher uniformity, and the superior resistance to wind. In some sprinklers a special stream straightening device, or "vane" is placed behind (upstream of) the main nozzle. The purpose of the vane is to reduce turbulence in the water stream introduced during its passage through the sprinkler body. Less turbulence means that the stream is not broken up as much or as soon; hence more water is thrown farther. Any wind effects are reduced because the entire stream is more cohesive. Fewer drops are broken up and/or slowed by the wind, so the drop size distribution of a vaned sprinkler is affected less by the wind than that of a vaneless sprinkler. Uniformity test procedures, testing conditions, and the required equipment for linear move sprinkler irrigation systems are clearly explained in ASAE test standards[98]. Prior to a uniformity test, the system nozzle package should be confirmed according to design specifications. The irrigation application depth should at least be 15 mm, and the system should pass over the catch devices entirely before the measurements are recorded. Many types and sizes of collectors have been tested by other researchers to measure irrigation application depths and coefficients of uniformity. Due to non-uniform nature of sprinkler irrigation, some areas in irrigated fields receive less while other parts receive more water. Lamm et al.[99] reported that wheat yields might be reduced by as much as 140 kg/hm^2 for each 10 mm reduction in irrigation water. Conversely, over irrigation may cause leaching of nutrients, slow down plant growth, and could possibly reduce yield[4]. Non-uniform irrigations might also waste energy and chemicals. Increasing irrigation uniformity can improve irrigation efficiency by preventing deep percolation and surface runoff due to over irrigation. Von Bernuth[100] claimed that if yield response to water amount is linear, then if any spot in a field receives less water than the mean will produce lower yield compared to fully irrigated areas. Bralts et al.[101] stated that a 5%-12% increase in irrigation uniformity might result in 3%-17% more wheat grain yield. Clark et al.[102] conducted a series of studies to determine the effect of collector diameter on sprinkler irrigation depth and CU measurements and reported that depending on the sprinkler irrigation system, the opening diameter of collector would make difference in measurements and they indicated that in addition to collector diameter, the height of collector and sprinkler irrigation system speed might be factors that influence measurements. The length of the irrigation time can affect uniformity. Variations in wind speed and direction can improve uniformity relative to the case of a constant wind[103]. Longer irrigation times create more change for this wind variation to occur, and hence generally have higher uniformities than systems using short irrigation sets. The time of day of the irrigation can also have an effect, particularly in areas with prevailing winds. It is best to plan your irrigation so that the same parts of the field are not irrigated at the same time of day each time they are irrigated. This will give an opportunity for natural changes in wind speed and direction to balance out, improving the uniformity of application over consecutive irrigation events.

6 Improving irrigation uniformity and water use efficiency in sprinkler irrigation

Major water-saving improvements from irrigation in the future will be realized largely through the management and innovative design of integrated water delivery and field irrigation systems for both agrarian and urban settings. Managing and developing infrastructure and policies for water security to equitably satisfy the demands of all users of this limited resource will be a challenging and lengthy task. Changes in policy and incentives will clearly become necessary. However, water and land resources and their many complex and competing uses must be considered in a comprehensive regional and international framework. Improvements should be systematic, not concentrated on only one or two components of the hydrologic system. It will therefore be necessary for rural and urban irrigators to improve productivity per unit of water consumed. However, doing so will require major systematic, cultural, managerial, engineering and institutional changes. This must be supported by system-wide enhancement of water delivery systems, advanced site-specific irrigation technologies that include self-propelled sprinklers and micro irrigation systems, and other supporting monitoring, modeling and control technologies. Decision support tools will be needed to assist growers and managers in optimizing the allocation of limited water among crops, selection of crops by regions and adoption of appropriate alternative crops in drought years. Hence the following recommendations are made for efficient use of water in sprinkler irrigation.

a) Sound judgment is required in selecting a rate of application which will not be exceeded regardless of the surface conditions of the soil. Understanding how soil properties affect water storage before designing an adequate irrigation system can help optimizing water use by plants. Soil moisture depends on climate, topography and other soil characteristics. Some plant species are highly adaptable and can tolerate a range of moisture conditions. Others have very specific moisture requirements.

b) To avoid irrigating during times when the wind is blowing you can use a control system that detects wind. One method of doing this is to install a wind speed monitor nearby. It detects high wind speeds and shuts off the irrigation. It does this in a non-smart way; it just shuts off the power to the valves and irrigation stops. This is a really effective method but there is a drawback-the irrigation gets skipped and the landscape may dry up if the wind blows for several days! So if you use a wind detector like this you need to keep an eye on it, wind can make the landscape dry out fast. Some high-end irrigation controllers are smart enough to know that the irrigation was shut down and will attempt to reschedule it at a wind free time. Finally, some irrigation controllers have a remote programming feature where the irrigation schedule is calculated and controlled.

c) A minimum variation in pressure at individual sprinklers is necessary if high water application efficiencies and good uniformities of application are to be attained. Where slow turning, large capacity sprinklers (giant type) are considered, it must be remembered that high instantaneous application rates may be applied to the soil as the sprinkler revolves. Increasing pressure increases the design diameter of sprinklers. This also tends to give more uniform sprinkler patterns.

d) Improvement in sprinkler uniformity can also be achieved through the replacement of worn out nozzles and the sprinkler precipitation pattern on the farm should be periodically checked. Droplet size, determined by a combination of nozzle size and pressure is an important consideration to be made to achieve the desired result.

e) An understanding of the molecular basis and physiological mechanisms regulating WUE in stressed and non-stressed plants needs to be critically surveyed. Also improving the techniques used in irrigation can directly affect WUE by increasing the yield per unit of water applied and reducing the amount in water loss.

7 Conclusions

Irrigation uniformity is a key component in overall sprinkler irrigation efficiency, and hence plays an important role in scheduling irrigations to meet crop moisture requirements. High uniformity of the discharge devices is required for efficient irrigation. However, high uniformity by itself does not lead to a system that is efficient. In order for the system to work adequately, water must be applied in such a way that it stays within the root zone, it is always present in sufficient quantity to supply crop needs, and the variation from the different outflow devices is maintained within tolerable limits. In practice, it is not possible to obtain 100% of uniformity on the irrigated area, (that is to say having equal water distribution on the areas that are being irrigated but closeness to uniformity must be very much desired. The use of modern irrigation technologies is necessary in several ways towards ensuring significant improvements in the efficiency of the irrigation system. A good way of managing water use and pollution is to establish a comprehensive Water Management Plan (WMP) for the farm that identify water use and sources of pollution, water footprints of the crops and water use efficiency plans. Management of the system as well as wind effects should not be neglected as they contribute greatly to uniformity in sprinkler irrigation. Maximizing the cultivated area during periods of low environmental demand for ET and/or period when rainfall events are likely to occur should be encouraged.

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