Water-smart sprinkler irrigation, prerequisite to climate change adaptation: a review

Zakaria Issaka, Hong Li, Jiang Yue, Pan Tang and Ransford Opoku Darko

ABSTRACT

The world is increasingly experiencing water scarcity due to the impact of climate change, a phenomenon that is affecting agricultural production, particularly in tropical regions. An effective response system is required to adapt and reduce the impact on agricultural production. There have been calls on the role agriculture can play to reduce the impact without compromising food security. Hence, the present article discusses some of the major difficulties in water-smart sprinkler irrigation to adapt to the impact of climate change on agricultural production. In order to meet investment cost with water-smart sprinkler irrigation, the fixed water dispersion device for an impact sprinkler needs to be optimized to improve its performance under low pressure conditions. This is necessary to produce the desirable droplets sizes for minimising evaporation losses and distortion by wind, whilst maintaining the large distance of throw. Further research should be backed by strong institutional support towards a wide-scale adoption of water-smart sprinkler irrigation technologies. This could be of significant benefit to better water management in the artificially drained catchments and lessen the impact of climate change on agricultural production.

Key words | agriculture, climate change, sprinkler irrigation, uniformity, water-smart technology

INTRODUCTION

The impact of climate change on water resources raises a major global concern. It is expected to affect the hydrological cycle, leading to a significant decline in agricultural production (Yinhong et al. 2009; Liu et al. 2010; Guoyong et al. 2016; Xing-Guo et al. 2017). For example, a 5–20% increase in crop yields of rain-fed agriculture is expected in parts of North America. A study in Brazil shows that higher temperatures have resulted in a reduction in crop yields (Mendelsohn 2009; Rosenzweig et al. 2015; IPCC 2015; Liang et al. 2016). The impact of climate change on crop yields in sub-Saharan Africa indicates significant reductions in crop yields by 22, 17, 17, 18 and 8% for maize, sorghum, groundnuts and cassava, respectively (Schlenker & Lobell 2010; Blanc 2012). This will stimulate variations in trade, prices and net food imports between countries around the world. In order to sustain future population growth, agricultural production has to increase by 60% by 2050 (FAO 2010, 2013, 2015; Alexandratos & Bruinsma 2012). Although the impact of climate change is already evident in many parts of the world, it presents an opportunity for improvement in irrigation systems to sustain agricultural production.

In most parts of the world, the lack of efficient irrigation methods leads to wastage or excessive use of irrigation water. Studies show that many of the irrigation systems are inefficient, with less than half of the irrigated water on average actually reaching the crop (FAO 2011, 2013, 2015). Hence, installation of water-smart sprinkler irrigation systems can prove useful for saving water, time and cost. In sprinkler irrigation, water is sprayed into the air and allowed...
to fall on the ground surface. The spray is developed by the flow of water under pressure through small orifices or nozzles. With careful selection of nozzle sizes, operating pressure and sprinkler spacing, the amount of irrigation water required to refill the crop root zone can be applied at a near-uniform rate to meet crop water requirements. Users are able to customise and schedule irrigation based on the soil and plant type, sun exposure, and nozzles when sprinkler irrigation systems are automated and integrated with other applications. Uniformity is an important parameter for evaluating the performance of sprinkler irrigation systems (Tarjuelo et al. 1999; Yacoubi et al. 2012; Yan et al. 2010; Liu et al. 2011; FAO 2015). It is influenced by factors such as sprinkler and nozzle types, spacing and layout, weather conditions, soil and crop data (Schwankl & Hanson 2007; Sanchez et al. 2010; Xiang-yu & Hai-yan 2016). Variations in these factors lead to differences in the water distribution patterns. For instance, the slightest wind distorts the trajectory of droplets and induces evaporation losses (Ptacek 1973; Lima et al. 2002; Sinha et al. 2015; Sinha & Ravikrishna 2017). Hence, it is important that these factors are considered when an irrigation system is designed and managed in order to ensure an application of water that is as uniform as possible. Christiansen’s uniformity coefficient appears to be the most widely used by researchers on the global scale. However, more uniformity coefficients have also been proposed by other researchers.

A major challenge in water-smart sprinkler irrigation is how to achieve high uniformity under low pressure conditions, particularly for high pressure sprinklers such as impact sprinklers. Low pressure sprinkler irrigation is gaining momentum, and the sustainability of pressurized irrigation is being compromised. This is particularly important in the case of impact sprinklers as their pressure requirements are higher than the R33 rotator and pivoted sprinklers. The fixed water dispersion device can be optimized and installed on the impact sprinkler to facilitate jet breakup, providing a conducive microclimate for crop production through temperature reduction and increase in humidity around the agricultural land. The present article highlights the key difficulties in water-smart sprinkler irrigation. Optimization of the fixed water dispersion device for the impact sprinkler and comparing its performance characteristics with the R33 rotator is necessary from a future perspective. This could be of significant benefit to better water management in the artificially drained catchments and could lessen the impact of climate change on agricultural production.

**WATER-SMART SPRINKLER IRRIGATION**

Many studies have described sprinkler irrigation as water-smart technology which can adapt to the negative impact of climate change and overcome the constraint of water scarcity by saving water for crop production (Loe et al. 2001; Belder et al. 2005; Tuong et al. 2005; Mushtaq et al. 2006; Kato et al. 2009). Kato et al. (2009) found that sprinkler irrigation can reduce water consumption and increase grain production. The adoption of sprinkler irrigation technologies can improve crop yields, increase input use efficiency, increase net income and reduce gas emissions (Gathala et al. 2011; Khatri-Chhetri et al. 2016). A sprinkler distributes water in the cropped field, imitating a form of rainfall. It eliminates water conveyance channels, thereby reducing water losses through evaporation and leakages. Sprinkler irrigation technology is adapted to a wide-range of topographies and is suitable in all types of soil, except heavy clay. It provides a relatively uniform application of water to agricultural land, promoting steady crop growth. Sprinklers are also used for applying fertilizers and soil amendments with the irrigation water, and applying herbicides and pesticides (NRC 2012; Han et al. 2013; Fan et al. 2016). Soluble fertilizers can be injected and channeled through the pipe network for easy and even application. The risk of soil erosion is also reduced because the sprinkler system limits soil disturbance. Sprinkler irrigation increases evaporation from airborne droplets, canopy interception, and the wet soil surface. Hence, the crop microclimate is significantly influenced by an irrigation event. Tolk et al. (1995) indicated that vapour pressure deficit and air temperature decreased significantly during a sprinkler irrigation event. Other studies have also found that air temperature and air vapour pressure deficit decreased due to sprinkler irrigation (Liu & Kang 2007; Urrego-Pereira et al. 2015). Similarly, Liu & Kang (2007) reported a decrease in canopy temperature of wheat of 0.3 to 2.8°C in a sprinkler-irrigated field compared with a non-sprinkled field. Tolk
et al. (1995) compared the microclimate of maize under centre pivot sprinkler and surface irrigation, and found that the daily average canopy and air temperatures of the sprinkler irrigation field were cooler than those of the surface irrigation field. The cooling effect of sprinkler irrigation is higher during days of high evaporative demand, and the condition lasted for about 1.3 hours after an irrigation event, which is similar to the findings of other studies.

Water-smart sprinkler irrigation has proven to be one of the most effective means of protecting a variety of crops against frost damage. A properly designed system can protect crops to temperatures as low as −6 °C (Sonsteb y & Heide 2008; Liu et al. 2011b). As long as water is supplied at an adequate rate, the temperature of the plant will remain at or near 0 °C. Frost damage can cause severe crop losses for fruits, vegetables and nursery crops. Severe damage usually occurs when frost takes place after buds and blossoms have begun to open. According to Hatfield & Prueger (2015), frost protection by irrigation sprinklers can make the difference between a 90% crop and one that is 20% or less, or the difference between profit and failure. As presented in Table 1, Liu et al. (2003) and Kundu et al. (1998) showed that sprinkler irrigation is a major contributor to crop yield and water use efficiency.

Several solutions exist to design an automated sprinkler irrigation system. High-tech solutions, in combination with GIS and satellites, can automatically measure the crop water requirement and operate the irrigation system from any location. For example, Genghuang et al. (2010) designed an automatic irrigation system using GSM and radio communication technology for command, control and monitoring of irrigation work. Anil et al. (2012) also developed a fully automated system which optimizes the use of energy and water for the daily needs of a small garden. Further, Venkata & Rohit (2013) developed an automatic system for irrigating plants. Recently, Chaitali et al. (2014) proposed a microcontroller and soil moisture sensor based on an irrigation system which proves to be a real time response control system which monitors all the activities of an irrigation system. Automation can also be achieved with simple, mechanical appliances such as clay pots, porous capsule irrigation networks or bottle irrigation. The automatic closed circuit of a mini-sprinkler irrigation system is an available tool for accurate soil moisture control in highly specialized greenhouse vegetable production and is a simple and precise method for irrigation (Mansour et al. 2015). Automated sprinkler irrigation systems can be connected to Wi-Fi and accessed from remote locations through smartphones or laptops. The smart sprinkler irrigation systems dispense the correct amount of water for the time of the year, climate, and weather of a location. Users can also start, stop, and change the sprinklers from their cell phones or computers. They can also check the detailed report on water usage. For example, the systems allow users to customize each zone and schedule water sprinkling based on the soil and plant type, sun exposure, and nozzles. These irrigation systems operate after taking an automatic reading of the past, present, and future weather. These devices can be integrated with Amazon Alexa, The Google Assistant, Nest, Wink, IFTTT, Control4, Nexia, and others. An adjustable time panel can also be rescheduled to operate during early mornings instead of midday, to avoid water loss due to evaporation. A rain shutoff device ensures the equipment remains turned off during or immediately after rainfall. Market vendors are focusing on tapping the hidden potential of smart sprinkler irrigation systems to ensure optimum water usage.

**Table 1** | Crop response to sprinkler irrigation

<table>
<thead>
<tr>
<th>Crop</th>
<th>Water saved (%)</th>
<th>Yield increase (%)</th>
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<tbody>
<tr>
<td>Barley</td>
<td>56</td>
<td>16</td>
</tr>
<tr>
<td>Cabbage</td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>35</td>
<td>12</td>
</tr>
<tr>
<td>Chilies</td>
<td>33</td>
<td>24</td>
</tr>
<tr>
<td>Cotton</td>
<td>36</td>
<td>50</td>
</tr>
<tr>
<td>Groundnut</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Maize</td>
<td>41</td>
<td>36</td>
</tr>
<tr>
<td>Onion</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>Potato</td>
<td>46</td>
<td>4</td>
</tr>
<tr>
<td>Wheat</td>
<td>35</td>
<td>24</td>
</tr>
</tbody>
</table>
water moves under pressure before being delivered to the crop via sprinkler nozzles as shown in Figure 1. It is equipped with an air release valve, meter, and check valve; a shut-off valve between the two outlets and the pump delivers water into the mainline and the laterals (Brouwer et al. 2001). A sprinkler system is operated using valves to turn the system on and off. The opening and closure of the valves can be automated by using controllers and solenoids. The system basically simulates rainfall in that water is applied through overhead spraying. The ultimate goal of a sprinkler irrigation system design is to obtain a system with optimum nozzle capacity, sprinkler head spacing, lateral spacing, lateral size, main pipe size, and power requirements such that the irrigation system performs effectively and efficiently. During its operation, a stream of water is discharged into the air at high velocity and friction between the air and the water stream causes the stream to break up into water droplets that fall to the surface.

**Types of irrigation sprinklers**

Impact and fluidic sprinklers are high pressure sprinklers that produce moving streams of water at a large distance of throw. Impact sprinklers provide either a full or half circle application pattern with 12 m head-to-head spacing (Phocaides 2007). High-pressure sprinklers disperse water into the air in a concerted stream, which tends to create small water droplets that are easily dispersed by wind and rapidly evaporate in dry atmospheric conditions. A sprinkler designed for higher operating pressures cannot be used at lower pressures, and every sprinkler is designed to operate within a specific range of flows and pressures. For example, operating the impact sprinklers with 0.70–1.0 bar will result in distortion of the application pattern with lower efficiency (Phocaides 2007; Speir 2009; NRC 2012). This can also make them distribute water in excessively large droplets that can cause runoff or soil sealing. Inadequate break-up from an impact sprinkler occurs when operated under low pressure, resulting in poor water distribution. However, as pressure is reduced, the water distribution pattern becomes annular or doughnut-shaped. Operating the impact sprinkler under low pressure conditions leads to uneven water distribution, and waste of irrigation water. For this reason, it is imperative to mechanically break up the water jet with a fixed dispersion device to improve water distribution at a low pressure. There are several ways to improve the water distribution of sprinklers under low pressure. For example, an orifice nozzle, non-circular nozzles, vanes and fluidic devices can be installed on these sprinklers (Han et al. 2013; Zhu et al. 2013). Li et al. (2007) developed a new fluidic sprinkler which operates with the principle of ‘coanda effect’, performing the function of rotation which can eject water from the nozzle of the main tube into the fluidic component to form a region of low pressure on both sides at the entry into the main jet flow. When the fluidic component is optimized, it can lead to improvement in the rotation stability and minimize variability in the water application rate of the fluidic sprinkler. Impact and fluidic sprinklers can be used in a solid set configuration where sufficient nozzles are installed to cover all parts of the desired area. They can be used in a set-move configuration where lateral lines are operated and then moved at 12 or 24-hour intervals. Although the solid set systems cost more to install, they can be automated to give lower labour requirements.

The centre pivot sprinkler system is self-propelled, rotating around a pivot point, and has low labour requirements. It is constructed using pipes attached to moveable towers. The amount of water applied is controlled by the speed of rotation. Centre pivots can be adjusted to any crop height and are particularly suited for lighter soils. Since centre pivots cover a circular area, they are best adapted to fields that are round or square (Smajstrla et al. 2005; Speir 2009). When the system is computerized the operator is able to
programme many features for the irrigation process. It is also possible to install a corner attachment system (end-gun) that allows the irrigation of corner areas missed out by conventional centre pivot systems. The linear move irrigation system is built in the same way as a centre pivot; that is, with moving towers and pipes interconnecting the towers (Allen et al. 2004; Speir 2009). The main difference is that all the towers move at the same speed and in the same direction. Water is pumped into one of the ends or into the centre. They are used on high-value crops such as potatoes, vegetables and turf. The travelling big gun system uses a large-capacity nozzle and high pressure to throw water over the crop as it is pulled through an alley in the field. Travelling big guns come in two main configurations: hard-hose or flexible-hose feed. With the hard-hose system, a hard polyethylene hose is wrapped on a reel mounted on a trailer. The trailer is anchored at the end or centre of the field. The gun is connected to the end of the hose and is pulled towards the trailer. The gun is pulled across the field by the hose winding up on the reel. With the flexible-hose system, the gun is mounted on a four-wheel cart. Water is supplied to the gun by a flexible hose from the main line. A cable winch pulls the cart through the field towards the cart. A side or wheel roll system consists of lateral aluminium pipes, usually a quarter of a mile long, mounted on 1–3 m-diameter wheels with the pipe serving as an axle. When the desired amount of water has been applied to an area, a gasoline engine at the centre is used to move the side roll to the next. Such sprinklers are generally mounted on weighted, swivelling connectors so that no matter where the side roll is stopped, the sprinklers will always be on top. This type of system is not recommended for gradients greater than 5% and should be used mainly on flat ground (Merkley & Allen 2004; NRC 2012). Side roll systems are adapted only to low growing crops, have medium labour requirements and moderate initial cost.

Low pressure sprinklers such as the R33 Rotator from Nelson Irrigation Company (Walla Walla, USA) is an innovation that saves money and time and performs better than the 3/4” (19.05 mm) brass impact sprinklers, which are no longer produced (Phocaides 2007; Nelson 2016). The R33 represents a modern and high performing sprinkler which produces a longer throw distance, fighting the wind better and delivering uniform coverage. With new advancements in speed control, the breakthrough design allows the sprinkler to move from a slow mode back to a fast mode throughout its rotation. Reducing the speed of rotation intermittently, the R33 produces a wind-fighting pattern with maximum throw distance. The fast mode also assists in filling out the water pattern for greater uniformity. The R33 is easy to clean, easy to repair and costs less to replace. Without a drive arm, the sprinkler creates no riser vibration. It also has a long wear life because no seals or bearings are exposed to water pressure. Low-cost systems attempt to retain the benefits of conventional systems whilst removing the factors preventing their uptake by poor smallholders, i.e. purchase cost, the requirement of a pressurized supply, the associated pumping costs and complexity of operation and maintenance.

Cost implications

In order to meet investment costs with a water-smart sprinkler irrigation system, sprinklers need to be optimized for operating under low pressure. The cost of installing a suitable sprinkler system is between US$600 and 2500/ha, depending on the type of materials used, local conditions, and size of the farm (Savva & Frenken 2002; FAO 2015). These conditions determine regional trends and allow for the estimation of average regional unit costs, which is of particular interest to regional planning. Except for small sprinkler irrigation systems, large systems such as the linear move or centre pivot irrigation systems incur high capital costs. The requirement for the implementation of sprinkler irrigation systems is relatively higher due to energy demand. For instance, mechanized sprinkler irrigation systems have a relatively high energy demand. Affordable sprinkler irrigation technologies are available at low cost, and operate under low pressure systems with the same technical advantages. With newly bought sprinklers, farmers must be certain of their design specifications before reducing pressures and pump sizes. However, most manufacturers agree that anything over 2 bars is a mid-range to high-range sprinkler (Phocaides 2007; Nelson 2016). Energy savings vary depending on the specific irrigation system, hours of operation, flow, and pressure used. However, farmers can expect to see energy savings of about 50% just by adopting low pressure sprinklers (Merkley...
Some irrigation sprinkler manufacturers have chosen to use simple equipment parts and this results in inaccuracies. For example, large variations in application rates along a lateral occur due to differences in the sizes of sprinkler equipment parts. Some manufacturers supply their normal sprinkler equipment, which tends to be more costly for farmers. Increased investment costs of sprinkler equipment makes it unaffordable for adoption by farmers, especially in sub-Saharan Africa. To this end, appropriate financial and technical support is necessary to ensure adoption of sprinkler irrigation systems. Low-cost systems have equal potential to reduce the impact of climate change and raise productivity and enhance rural livelihoods.

**FACTORS AFFECTING SPRINKLER UNIFORMITY**

Water losses in sprinkler irrigation systems have been attributed to equipment and design parameters, and management practices (Topak et al. 2005; Liu et al. 2010). Other water losses include; evaporation from wet soil surfaces, transpiration from unwanted vegetation and field border losses (Keller & Bliesner 1990). From Table 2 below, it is obvious that the major water loss in sprinkler irrigation is mostly due to uniformity of application. Hence, studying the uniformity of water application is imperative for the effectiveness and efficient operation of sprinkler irrigation systems.

**Wind drift and evaporation losses**

A major factor that affects sprinkler irrigation systems is the distortion of the water application pattern by the wind and evaporation. Wind and evaporation losses are uncontrollable factors, and their effect on irrigation uniformity is significant, hence they must be considered in every sprinkler irrigation design. Wind and evaporation are the most important uncontrollable factors affecting sprinkler irrigation systems (Topak et al. 2005; Moazed et al. 2010). High wind velocities can jeopardize the effectiveness of sprinkler irrigation or limit farm operations to times of relatively low winds, such as night. The range is the distance across a water application pattern from dry soil in front of the system to dry soil behind the system. The water jet may have different velocities, from approximately zero close to the outside to a maximum velocity near the centre of the stream. The difference in velocities creates the initial breakup of the stream. The breakup is supported by sprinkler rotation and interruption of the jet by the sprinkler arm. The surface tension of the water jet holds the droplets intact and in a spherical shape. Wind distorts the spherical shape of a droplet by flattening the leading end of the droplet (Cuenca 1988; Xiaoxia et al. 2012). When the distortion exceeds the cohesive force of surface tension, the droplet disintegrates into smaller droplets.

Wind also reduces the velocity of droplets as they fall to the ground. For this reason, a sprinkler jet does not follow the parabolic trajectory of ballistic projectiles (Solomon 1990; Dwomoh et al. 2014a, 2014b). Trajectory angle is the path taken by a projectile when it is launched, neglecting all forces. This means that in no-wind conditions the sprinkler jet will follow the parabolic profile of ballistic projectiles. The ballistic profile of projectiles serves as a guide to designing sprinklers to achieve higher performance. The inertia of a droplet is a function of its mass, while the resistance of the air is a function of its cross-sectional area, and the smaller droplets are slowed much more rapidly than the larger ones. Smaller droplets fall near the sprinkler, while the larger ones fall farther away. For the same reason, wind causes the breakup and distribution processes to change in two ways: (1) it affects the breakup of the water due to air resistance; and (2) it blows all the resulting drops around (Okasha & Sabreen 2016). For example, when the nozzle is directed into the wind, air resistance is increased and larger droplets become unstable and break up into pieces. Smaller droplets resulting from this disintegration are slowed rapidly by air resistance, tending to decrease the

<table>
<thead>
<tr>
<th>Water loss component</th>
<th>Range (%)</th>
<th>Values (%)</th>
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<tbody>
<tr>
<td>Leakage in pipes</td>
<td>0–10</td>
<td>0–1</td>
</tr>
<tr>
<td>Evaporation in air</td>
<td>0–10</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Wind drift</td>
<td>0–20</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Interception</td>
<td>0–10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Surface runoff</td>
<td>0–10</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Application depth and rates</td>
<td>5–80</td>
<td>5–30</td>
</tr>
</tbody>
</table>

Adapted from Davoren (1995).
upwind radius of throw and, as the drops are falling, the wind blows them back toward the sprinkler. The same kind of interaction causes a small decrease in the cross wind radius of throw as well. Conversely, when the nozzle is pointing downwind, air resistance is lower than normal, and fewer large drops break up, and the all droplets are blown by the wind resulting in longer downwind radius (Okasha & Sabreen 2016). For high wind conditions, the difference is the droplet sizes, which shortens the upwind radius more than it lengthens the downwind radius. The magnitude of wind and evaporation losses can be very relevant under certain environmental conditions. Losses range between 5 and 10% under moderate evaporative demand (Keller & Bliesner 1990); other studies have also reported maximum losses of 30% (Yazar 1984) or up to 50% (Frost & Schwalen 1955; Faci et al. 2001).

**Equipment design**

For a specific wind condition, the factors affecting uniformity include nozzle type and size, operating pressure, and spacing (Robert et al. 2013). There are two spacing dimensions for a fixed grid system; the distance between sprinklers on a lateral, and the distance between laterals. A guideline for sprinkler spacing is presented in Table 3 below. The spacings are given as a percentage of the sprinkler’s wetted diameter.

There is a remarkable relationship between the recommended spacing and soil characteristics in sprinkler design. A common rule is that the application rate should not exceed the basic infiltration rate of the soil. The application rate of a sprinkler is proportional to the flow rate and is inversely proportional to the product of the two spacing dimensions (Suliman 2015; Phocaides 2007; Robert et al. 2013). 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. An increase in wetted diameter will allow slightly larger spacing, but the increase in flow rate for a fixed uniformity with increase in nozzle size will generally increase the application rate. Within the range of small- to medium-sized sprinklers, it is more economical to design the system with the largest sprinkler and spacing permissible. Factors that determine sprinkler nozzle size and spacing are the desired uniformity, and the infiltration rate of the soil (Kincaid et al. 2000; Isiguzo & Ahaneku 2010). When growing high value crops on fine textured soils, where high uniformity is normally desirable, successful designs invariably employ small nozzles (3 mm diameter) and close spacing (9 × 12 m). Lower uniformities are acceptable in coarse soils with a higher infiltration rate, and larger nozzle and wider spacing are used. Common operating pressures for these size sprinklers used to be in the range of 3.5–4.5 bars, but with the high cost of energy there has been a tendency to reduce the operating pressure (Solomon 1990; Bartels et al. 2003). 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 additional breakup of the water jet at lower pressures. Such nozzles are operated at pressures usually 1.0 bar lower than with traditional nozzles (Isiguzo & Ahaneku 2010; Robert et al. 2013).

Factors affecting uniformity of sprinkler irrigation are related to the specific sprinkler being used. Rapid rotation of a sprinkler may affect the breakup of the stream, and to this extent it determines how wind will affect the pattern. A water jet in the air carries with it an envelope of air moving at a velocity close to that of the jet. When this condition is achieved, air drag on the jet is at a minimum. When the water 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, and it encounters maximum drag and undergoes the most breakups (Solomon 1990). Thus, rapidly rotating sprinklers are affected by wind more than sprinklers with lower rotation speeds. The big debate in the sprinkler manufacturing industry is whether metal-made sprinklers perform better than plastic ones and vice versa. Conventionally, metal is more durable than plastic. In the late 1970s most sprinklers were made

<table>
<thead>
<tr>
<th>Wind condition</th>
<th>Spacing</th>
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<tbody>
<tr>
<td>Low</td>
<td>50–65% of wetted diameter</td>
</tr>
<tr>
<td>Moderate</td>
<td>50% of wetted diameter</td>
</tr>
<tr>
<td>High</td>
<td>35–50% of wetted diameter</td>
</tr>
</tbody>
</table>

Adapted from Solomon (1990).
from brass, and sometimes zinc (Xiaoxia et al. 2012). However, the common material used by manufacturers for most sprinklers is plastic. The common reason for the shift lies in the cost of materials; metal parts are extremely expensive compared to plastic. Fortunately, most of the plastic sprinkler heads are properly designed with optimum performance. A few companies still manufacture plastic sprinklers with brass nozzles, which they claim results in a better water pattern. Other manufacturers argue that plastic nozzles perform equally well as brass-made nozzles. In terms of performance, there is no considerable disparity between most brass and plastic nozzles, although brass nozzles will obviously last longer (Xiaoxia et al. 2012). Generally, poor performing nozzles come pre-installed on sprinklers without recommended features, sprinklers with recommended features result in acceptable quality nozzles.

The effectiveness of a sprinkler is reduced by operation at either excessively high or low pressures. Pressures that are too high produce fogging and irregular turning of water. Fogging produces too many small droplets that fall too close to the sprinkler (Isiguzo & Ahaneku 2010). Under low pressure, the water stream is not sufficiently broken up and a doughnut-shaped application pattern results. Water from the nozzle settles in a ring distance away from the sprinkler. Under optimum pressure, water distribution is balanced around the sprinkler. Under high pressure, water from the nozzle breaks into fine drops and concentrates around the sprinkler. The fineness of the droplets makes them liable to wind influence. Single nozzle sprinklers tend to perform better in high wind conditions than double nozzle sprinklers. Therefore, under either condition, water is not uniformly distributed. The discharge rate of a sprinkler head is determined by the size of the sprinkler nozzle and the operating pressure. Reducing the operating pressure of the sprinklers reduces the sprinkler discharge rate. For a particular nozzle size, the discharge rate is not significantly changed by small changes in operating pressure. Operating a sprinkler below its recommended pressure range results in unacceptable breakup of the sprinkler spray pattern and poor irrigation uniformity (Schwankl & Hanson 2007; Elfath 2015). Caution should be taken to reduce the sprinkler pressure since it can affect the sprinkler application uniformity. A high uniformity is desirable since it helps ensure all areas receive the same amount of water.

The trajectory angle is the angle above horizontal at which the water jet leaves the sprinkler, which can influence the uniformity of application. In the absence of air drag, a 45° trajectory leads to maximum wetted diameter for a given nozzle and pressure. Due to the air resistance encountered by the water jet, the trajectory angle for a large range is about 30° (Xiaoxia et al. 2012; Rahman & Singh 2014). In the presence of wind, high trajectory angles suffer the disadvantage that the water is in the air for a longer time and is more susceptible to the effect of wind. Many sprinkler manufacturers have settled on the trajectory angle of 27° as standard. This angle has a relatively larger range in the absence of wind, and does not suffer from wind distortion. For sprinklers to be used in moderate wind conditions, lower trajectory angles of 23, 21 and even 18° are advised (Solomon 1990). Even lower trajectory angles are available for special purposes. An important question that arises in the selection of sprinkler nozzles is whether to use sprinklers with a single nozzle or with dual nozzles. The single nozzle is preferred in most sprinkler applications because, for a given spacing, the application rate is determined by the sprinkler flow rate. Also, it is economical to design for an application rate near the limit set by the soil type, so that spacing can be maximized. When selecting nozzles, it is assumed that the desired sprinkler flow rate is known. Water from the spreader nozzle is usually much finer and more diffuse than the spray from the main nozzle, so it is much more affected by the wind (Schwankl & Hanson 2007; Xiaoxia et al. 2012). Using the largest main nozzle maximizes the wetted diameter and minimizes wind distortion. When wind conditions are calm the single nozzle sprinkler will have improved coverage, higher uniformity, and greater resistance to wind.

Management practices

Sprinkler irrigation uniformity can be influenced not only by the irrigation equipment in the system, but also how the system is operated and managed. The length of irrigation time can affect uniformity (Ayman 2008). Longer irrigation times create more change for wind variation to occur, resulting in higher uniformities than systems using short irrigation sets (Grant et al. 2007; Dereje 2012). The time of day of irrigation also has an effect, particularly in areas with
prevailing winds. The timing of irrigation can affect the overall water distribution pattern. It is recommended to plan the irrigation so that the same parts of the field are irrigated at different times of the day each time they are irrigated. This gives the opportunity for natural changes in wind speed and direction to balance out, improving the uniformity of application over consecutive irrigation events. Alternate sets improve uniformity because the light and heavy application areas of one set tend to fall on the heavy and light areas, respectively (Solomon 1990). Moreover, the practice of irrigating blocks of adjacent laterals has the advantage of developing a micro-climate within the farm, minimizing losses caused by wind and evaporation.

**METHODS OF DETERMINING SPRINKLER UNIFORMITY**

The uniformity of water application in a sprinkler irrigation system is an important evaluation index for sprinkler performance (Solomon 1988). The performance is often evaluated based on water uniformity coefficients collected in an array of rain gauges (Topak et al. 2005). Such a system requires a minimum value of uniformity to be considered as acceptable by the end users. Sprinkler uniformity is related to crop yield and profitability. As such, uniformity is an important parameter for the design and evaluation of sprinkler irrigation systems (Derrel & Ronald 2007). Under-irrigation may result in high soil moisture tension, plant stress and a decline in crop yield. Conversely, over-irrigation may also decrease the crop yield below optimum levels through leaching of plant nutrients, increased disease incidence or stunted growth. In non-uniform water distribution, some parts of the crop will receive more water than others. The irrigation system is operated in such a way that part of the crop receiving a large portion of the water has its requirements met. In addition, when the system is operated so that the part of the crop receiving the least amount of water has its requirements met, then the remainder of the crop will be over-irrigated. But a non-uniform irrigation unavoidably results in some degree of under- or over-irrigation (Solomon 1990; Siosomarde & Byzedi 2002). A non-uniformity of water distribution results in the application of excess water, with loss of several water-related resources. The losses include energy for pumping excess water, chemicals, and capital losses due to the extra capacity designed into the irrigation and drainage systems to carry the excess water. Hence, uniformity is a key component in overall sprinkler irrigation efficiency, hence playing an important role in the scheduling of irrigations to meet crop water requirements.

Methods for evaluating sprinkler uniformity began with Wadsworth (1926) using catch cans or funnels of uniform cross-section placed at equal distances along one radius of a circle. Staebner (1933) tested the ability of sprinklers to distribute water so that the maximum depth was not more than twice the minimum. However, the optimum spacing and overlap of sprinklers was not researched. In order to close the gap, Christiansen (1942) carried out tests on portable sprinklers, and developed the uniformity coefficient ($C_U$) equation as shown below:

$$C_U = \left[ 1 - \frac{\sum d}{nm} \right] \times 100\%$$

where $m$ = mean of observations, $n$ = number of observations and $d$ = deviation of observations from the mean.

According to Christiansen (1942), a sprinkler with a high percentage means that the same amount of water was applied in all directions of the area irrigated, and low percentage represents non-uniform application. Christiansen further defined six cross-sectional patterns for water distribution in irrigation sprinklers (Figure 2). Patterns A–F are divided into A, B, and C, for which the application decreases gradually toward the edge of the area wetted; and D, E, and F, for which the application is fairly uniform over most of the area covered.

![Figure 2](http://iwaponline.com/jwcc/article-pdf/9/2/383/735257/jwc0090383.pdf) Geometrical sprinkler patterns (Christiansen 1942).
The results were summarized as follows:

- Factors that affect uniformity include pressure, wind, and spacing of sprinklers.
- Uniformity is achieved with appropriate sprinkler spacing.
- Conical patterns occur near the sprinkler and decrease gradually to the edges of the area covered.
- Larger sprinkler spacing produces uniformity for some distances from the sprinkler and tapers off gradually.
- Uniformity for portable sprinklers is achieved when the lateral is moved ≥ 50–70% of the wetted diameter covered by a single sprinkler, and when the sprinkler spacing along the lateral was ≥ 35% of the diameter covered.

Schoenleber (1944) found that oscillation of sprinkler line equipped with small nozzles consistently showed the highest uniformity for the pressure used. Wilcox & Swailes (1947) used a modified procedure to determine the uniformity coefficient in Equation (2). The formula is used in evaluating the effects of pressure, wind, spacing, and nozzle size on the uniformity of distribution:

\[
U = \left[ 100 - \frac{SD}{M} \right]
\]

(2)

where \( U \) = modified uniformity coefficient, \( SD \) = standard deviation of depths of water in cans and \( M \) = mean of depths of water.

Wiersma (1952) concluded that the uniformity of application is affected by the influence of wind velocity, type of sprinkler, height of sprinkler above the ground, operating pressure and sprinkler spacing. Similarly, Molenaar (1954) used a uniformity coefficient to compare the relative distribution performance for sprinklers under actual field conditions as shown below:

\[
U = \left[ 1 - \frac{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}}{X} \right] 100
\]

(3)

where \( x_i \) = volumes of water accounted for in cans within a sprinkler spacing area; \( x \) = mean value of \( x_i \); \( n \) = number of grid points within the wetted area.

McDougald & Wilcox (1955) suggested a range coefficient (\( R \)) and a spacing coefficient (\( S \)) for the evaluation of the uniformity of distribution. The range coefficient is represented by the formula:

\[
R = \frac{200 (H - L)}{H + L}
\]

(4)

where \( H \) = highest value of catch can and \( L \) = lowest value of catch can. When \( R \) is 200 the lowest value is zero and the range is at its maximum. However, when \( R = 0 \) there is perfect uniformity of distribution. The spacing coefficient, \( S \), is expressed by the formula:

\[
S = \frac{100 \sqrt{\text{area included in spacing}}}{\text{diameter of throw}}
\]

(5)

The Soil Conservation Service used a step-by-step procedure for evaluating sprinkler system performances. This expression is called pattern efficiency, and is expressed by the formula:

\[
S = \frac{\text{Average of 25\% catch can}}{\text{Average of all catch can}} \times 100
\]

(6)

Criddle et al. (1956) and Beale & Howell (1966) also used the concepts of the deviations of the mean, as did Christiansen (1942); however, Criddle et al. (1956) limited their equation to the lowest quarter depths of water while Beale & Howell (1966) limited the equation to the highest ones. Criddle et al. (1956) proposed their equation as follows:

\[
CU = \left[ 1 - \frac{\sum_{i=1}^{n} |x_i - \mu|}{\mu \times \frac{n}{4}} \right] 100
\]

(7)

Hansen (1960) proposed a distribution efficiency which is defined by the expression:

\[
E_d = \left[ 1 - \frac{y'}{d} \right] 100
\]

(8)

where \( E_d \) = water distribution efficiency, \( y' \) = average numerical deviation in depth of water stored from average depth stored during the irrigation and \( d \) = average depth of water stored during the irrigation.
According to Hart (1961), the relationship between Christiansen’s uniformity coefficient and the uniformity coefficient of a normally distributed population is as follows:

$$U_{ch} = 1 - 0.78\frac{a}{x}$$

(9)

where $U_{ch}$ = HSPA uniformity coefficient, $a$ = standard deviation of sample and $x$ = average observations.

Christiansen’s uniformity coefficient was compared to the HSPA uniformity coefficient using 2,024 superimposed patterns. A linear regression analysis resulted in the following:

$$CU = 0.0300 + 0.958CU_h R^2 = 0.888$$

(10)

where $R$ = correlation coefficient.

Hart (1961) also established a theoretical relationship to the uniformity coefficient of a normally distributed population:

$$PE_H = 1 - 1.15\frac{a}{x}$$

(11)

The SCS pattern efficiency was compared to the HSPA pattern efficiency using 1,558 superimposed patterns. A linear regression analysis resulted in the following equation:

$$PE = 0.0782 + 0.0935PE_H R^2 = 0.914$$

(12)

where $R$ = correlation coefficient and $PE$ = SCS pattern efficiency.

The high correlation coefficients indicated that $PE$ and $CU$ were reliably estimated by FEH and UCH.

Keller (1962) stated that higher application efficiencies can be obtained through alternate sets than through standard sets using the equation below.

$$C_U = 10\sqrt{CU}$$

(13)

where $C_U$ is uniformity coefficient of a single-alternate set.

Benami & Hore (1964) introduced their uniformity coefficient expressed as:

$$A = 166\left(\frac{N_a}{N_b}\right)\left(\frac{2T_b + D_bM_b}{2T_a + D_aM_a}\right)$$

where $A$ is uniformity coefficient (%); $M_a$ and $M_b$ are mean values of the measured application depths, greater and smaller than the overall mean application depths, respectively; $n_a$ and $n_b$ are number of measured application depths greater and smaller than the overall mean values of the overall mean application depths, respectively; $T_a$ and $T_b$ are sum of the measured application depths which are greater and smaller than the overall mean values of application depths; and $D_a$ and $D_b$ are the differences between the number of measured application depths which are greater and smaller than the overall mean application depths, respectively.

Beale & Howell (1966) also proposed a uniformity equation as follows:

$$CU = \left[1 - \frac{\sum_{i=1}^{n}\left|x_i - \mu\right|}{\mu \times n} \right] 100$$

(14)

Karmeli (1978) reported that the uniform distribution was an acceptable form to represent the sprinkler water distribution for stationary systems. This equation is only valid for the values of $CU$ higher than 50%.

The equation is expressed as:

$$CU = [1 - 0.5(x_{max} - \mu)]$$

(15)

Merriam & Keller (1978) defined their ‘distribution uniformity coefficient’ as follows:

$$CU = \left(\frac{D_{iq}}{\mu}\right) 100$$

(16)

where $D_u$ = distribution uniformity (%), and $D_{iq}$ = mean of the lowest one-quarter of the measured depths ($L$).

In the same year Hawaiian Cane Society Specialists cited by Merriam & Keller (1978) also proposed their uniformity coefficient as follows:

$$CU = \left[1 - \left(\frac{2}{\pi}\right)^{0.5}\left(\frac{\sigma}{\mu}\right)\right] 100$$

(17)
Recently, the Matrix Laboratory (MATLAB) program has been widely used to simulate uniformity according to the radial water distribution for different spacing and layouts (Zhu et al. 2015; Liu et al. 2016). Radial data of water distribution from a single sprinkler can be modified into net data. The available data points are distributed in a manner similar to a spider web. A grid of data points can be converted to calculate the $CU$. The depth of the net point depends on the distance away from the sprinkler. The water depth of every interpolating point, assumed to be a continuous variable value, was calculated using a mathematical model of interpolating cubic splines (Han et al. 2010; Zhu et al. 2013).

A value of $\geq70\%$ for the modified uniformity coefficient is desirable (Wilcox & Swailes 1947). When the $CU$ value is approximately $70\%$ or higher, the approximation depths from a rain-gauge evaluation tend to follow a normal distribution. In this case, when the mean application depth, $\mu$, is equal to the required net application depth, $d_n$, $50\%$ of the irrigated area will be under-irrigated while the remaining $50\%$ will be over-irrigated. This is due to the fact that the normal distribution is symmetrical about the mean value (Merkley 2004). Uniformity coefficients, using Christiansen’s expression $\geq85\%$ or greater, are suggested as being acceptable by the Soil Conservation Service. The US Sprinkler Irrigation Association suggested a uniformity coefficient of $84\%$, according to the Christiansen formula. The American Soil Conservation Service recommended a distribution curve with a steadily decreasing rate of water application from the sprinkler outward as being the most satisfactory type. The American Society of Agricultural Engineers (1951) recommended minimum requirements for the design, installation, and performance of sprinkler irrigation equipment. Uniformity is determined by pressure and spacing, recommendations for desirable pressures and spacing for different types of sprinklers and nozzle sizes are obtained from the manufacturers chart. The rule of thumb is to limit the pressure difference to $20\%$ of the designed operating pressure. Different researchers have used various concepts to express the coefficients of uniformity, hence the equations lead to different results in the expression of the distributed water uniformity in the same fields.

**LIMITATIONS OF SPRINKLER IRRIGATION**

Specifications for newly designed sprinklers are obtained under average operating laboratory conditions and are provided in the manufacturers’ charts (Ascough & Kiker 2002). After a period of operation, the discharge rate of the sprinkler decreases due to wear and tear, resulting in low performance.

Wind drift and evaporation losses constitute a major concern for the design and management of sprinkler irrigation systems, which is particularly true under subtropical and tropical conditions (Yacoubi et al. 2012). The slightest wind can jeopardize the effectiveness of sprinkler irrigation or limit farm operations for days, whilst evaporation losses occur from the water streams in the air, which increases in the case of fine droplets.

The operating costs of impact sprinklers are high compared with low pressure sprinklers such as the R35 and centre pivot sprinklers because their pressure requirements are higher. The rising cost of energy required for operating the impact sprinkler already puts a heavy burden on the farmer. Low pressure irrigation is gaining momentum, and the need to optimize the impact sprinkler is important for reducing the cost of operation.

In the past few decades, different researchers have proposed various theories to evaluate sprinkler uniformity. These equations usually lead to differences in results when used under the same operating conditions.

Inadequate technical skills on the part of the farmer are a major constraint to effectively operate and manage sprinkler irrigation systems. The design and management of sprinkler irrigation systems is location specific. Hence, any change in the irrigation equipment for a different location leads to poor system performance.

**CONCLUSION AND FUTURE PERSPECTIVES**

Water-smart sprinkler irrigation systems can play a significant role in adapting to the worsening impact of climate change on agricultural production. However, to meet investment cost with the technology, optimization of the fixed water dispersion devices for the impact sprinkler to operate
under low pressure conditions is necessary. Such devices are useful for producing droplets of sizes that are desirable under low pressure conditions, which is important for increasing humidity while reducing temperature at the same time. For countries to reap the potential benefits, it is also imperative to implement sprinkler irrigation systems on a wide scale to fit new sprinkler irrigation technologies in farm situations. To save water and adapt to the impact of climate change on agricultural production through water-smart sprinkler irrigation will require the following:

1. Sprinkler equipment should be field calibrated regularly to ensure that application rates and uniformity are consistent with values used during the system design and those given in the manufacturers’ chart. Regulations to urge sprinkler manufacturers to be responsible for the appropriateness of installed sprinkler irrigation systems and to offer after-sales and after-setting service.

2. An impact sprinkler is commonly used because it is inexpensive and more reliable compared with a low pressure sprinkler such as the R33 and centre pivot sprinklers. Due to its large distance of throw, the impact sprinkler is efficient for irrigating large areas. Hence, optimization of the fixed water dispersion devices for the impact sprinkler has great potential to improve its performance under low pressure conditions. Water dispersion devices facilitate jet breakup under low pressure, producing a mist of droplets in mid-air, resulting in higher humidity and lower temperatures. The water dispersion devices will help to determine the optimum droplet sizes produced. This is particularly important for minimizing wind and evaporation losses, thus promoting the water-smart sprinkler irrigation technology.

3. Although the upfront cost of the sprinkler system may seem daunting, the correct sprinkler system can actually save costs over a period of time. Optimization of water dispersion devices to improve water distribution under low pressure has the potential to significantly lower the cost required for impact sprinklers, and maintain the large distance of throw.

4. Christiansen’s CU appears to be the most popular uniformity coefficient used by researchers on a global scale. However, more coefficients have also been proposed by other researchers. Research is needed to investigate the different uniformity coefficients proposed and their effects under different field conditions. This will help to develop a new model for evaluating the uniformity of a sprinkler, and identify the rain-gauges with maximum and minimum depths of application.

5. Farmer involvement in the development stages of a sprinkler irrigation project is recommended to help ensure social acceptance. In line with this, farmers need a certain degree of skill to operate and maintain an irrigation system. The irrigation sprinkler equipment dealers, after installing the system, must follow up with the farmer.

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REFERENCES


Christiansen, J. E. 1942 Irrigation by Sprinkling. California Agricultural Experiment Station, Bulletin 670, San Francisco, USA.


Davoren, A. 1995 Spray Irrigation: Is Your System up to Scratch, Schools of Isolated and Distance Education. Schools of Isolated and Distance Education, New Zealand.


FAO 2013 Climate-Smart Agriculture Sourcebook. FAO, Rome, Italy.

FAO 2005 Coping with Climate Change – The Roles of Genetic Resources for Food and Agriculture. FAO, Rome, Italy.


Merkley, G. P. & Allen, R. G. 2004 *Sprinkle and Trickles Irrigation Lecture Notes*. Utah State University, USA.


Molenaar, A. 1954 *Factors Affecting Distribution of Water from Rotating Sprinklers*. Washington Agricultural Experiment Station, Circular 244, Pullman, USA.


Schwankl, L. & Hanson, T. B. 2007 Managing Existing Sprinkler Irrigation Systems. Reducing Runoff From Irrigated Lands. Publication 8215, University of California, Division of Agriculture and Natural Resources, USA.


Solomon, K. H. 1990 Sprinkler irrigation uniformity. Centre for Irrigation Technology, California State University, Fresno, USA.


Yazar, A. 1984 Evaporation and drift loss irrigation systems under various operating conditions. Agric. Water Manage. 8 (4), 439–449.


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