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Analyzing Water Application Uniformity of Hose-Move Sprinkler Irrigation System

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Abstract: This study was basically intended to analyze the infield water application uniformity of sprinkler irrigation system by catch can test method as it is normally practiced at Finchaa Sugar Estate Irrigation Project. Field experiments were conducted to measure sprinkler head rotation speed, discharge, application rate (discharge) and distribution of water in the field for the operating hydrant pressure of 3.5, 4.0, 4.5 and 5.0 bar. For the assessment and analysis of the uniformity of applied water, uniformity coefficient (CU) and distribution uniformity (DU) were determined as indicators. The obtained CU (DU) values were 86.67% (80.33%), 89.33% (83.67%), 91.67% (88.67%) and 92.67% (89.67%) at the respective operating hydrant pressure of 3.5, 4.0, 4.5 and 5.0 bar. The result shows that applying irrigation water at 3.5 bar operating pressure causes non-uniform in-field water distribution and may cause water stress to the crop. Coefficient of uniformity increased by 7% when the operating pressure was increased from 3.5 to 5 bar for 18 m × 18 m sprinkler spacing. It is suggested that the estate should use the best combination of the hydrant operating pressure, set time, sprinkler spacing and soil type and to be successful and work as planned.

Key words: Water Application · Sprinkler Irrigation · Uniformity · Hydrant Pressure · Catch Can Test

INTRODUCTION

A key purpose of every irrigation method is to apply irrigation water as uniform as possible to the root zone of the crop, till they grow up completely. It must also be noted that, irrigation is needed for a continuous and reliable water supply to the different crops in agreement with their different needs. When water supply is not adequate (neither too much nor too less) and timely, crop yield declined and consequently famines and disasters [1]. It is also used to apply fertilizer (fertigation) and increase water use efficiency [2-4]; for sustainable use of available agricultural water [5]; to optimize water application cost [6] and to enhance the growth, yield and quality of crops [4, 7]. Thus, irrigation may be either supplementary irrigation or total irrigation based on rainfall availability. Irrigation water application techniques broadly classified as surface and pressurized irrigation methods [1].

The sprinkler irrigation method, one of the pressurized irrigation systems, takes water from a source and sprays it to the atmosphere as droplets by means of an enclosed system and under pressure. The water is transmitted to the surface of the soil in equal distribution with the sprinkler irrigation system to obtain uniform distribution in the crop root zone [8]. In this method, the correct amount of irrigation water required to refill the crop root zone that can neither cause runoff nor damage the crop and also provide the best possible uniformity under the prevailing wind and management conditions can be applied by careful selection of nozzle diameters, operating pressure, riser height and sprinkler spacing [8-9]. The selection of the particular combination of sprinkler nozzles, operating pressure and spacing that can compromise the basic determining factors (i.e. soils, climate and crops) requires special consideration of costs, uniformity of watering required and the effects of operating pressure and drop size [9, 10].

In-field water application performance can be characterized either water losses or uniformity of application. Even though both components are influenced by system design and management practices, the losses are predominantly a function of management while the uniformity is predominantly a function of the system

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design characteristics [11]. The principal purpose of sprinkler irrigation design is to apply irrigation water uniformly [8]. Irrigation uniformity is an important indicator to characterize the performance of sprinkler irrigation system and it is a key component of sprinkler irrigation [9, 12, 13]. Reduction in application efficiency, water productivity and crop yield and height are due to less uniformity coefficient of a sprinkler irrigation system [14-18].

Furthermore, it has been found that higher water distribution uniformity and irrigation efficiency values indicates best performance and vice versa. In the recent times uniformity and efficiency become important tools for the modern day irrigation performance evaluation throughout the world [19]. At Finchaa Sugar estate, it was observed that in different fields there is a wide difference in growth/height, poor stand and patchy drying and yellowing of planted cane which may be due to the non-uniformity of water application in the field. In light of this, it is vital to analyze the actual water application uniformity to express the uniformity of water distribution for different sprinkler irrigation systems [20]. It is important to improve soil moisture uniformity; reduce energy and water demand; reduce water losses in the form of surface runoff and deep percolation and optimize the yield of crop through healthier plant growth [21]. Therefore, the objective of this study is to analyze the infield water application uniformity of sprinkler irrigation system at Finchaa Sugar Estate irrigation project.

MATERIALS AND METHODS

Description of the Study Area: The Finchaa valley is located in the Oromia administrative regional state, Horro Guduru Wollega Zone, at a distance of 350 km West-North of the Addis Ababa, which is the capital city of Ethiopia. It is found at the downstream part of Lake Finchaa catchment and positioned at coordinates of 9°30' to 10°00' North and 37°15' to 37°30' [22]. East in Blue Nile basin. It covers five districts (called woredas) of Horro Guduru Wollega Zone, namely, Horro, Abbay Chommen, Jimma Genneti, Guduru and Hababo Guduru woreda (Fig. 1).

Major part of the land has slopes between 2 and 5%, there is no land with slopes less than 2%. Due to the topographic features of the project area, distribution of rain is very smooth and regular, easy to manage and adjust water distribution to crop requirement during cropping cycle. The average annual rainfall at 1400 m a.s.l altitude within the valley is about 1300 mm while at a weather station nearby plateau of altitude 2200 m a.s.l is about 1600 mm. The rains are more intensive during the four rainy months of June to September such that more than 80% of the rain falls during this period (Fig. 2).

Maximum air temperatures range from 26°C to 34°C, the lowest prevailing between July and October. Minimum air temperatures begin to decline around September and reach their lowest levels in December and January (about 11.5°C). The annual average relative humidity is

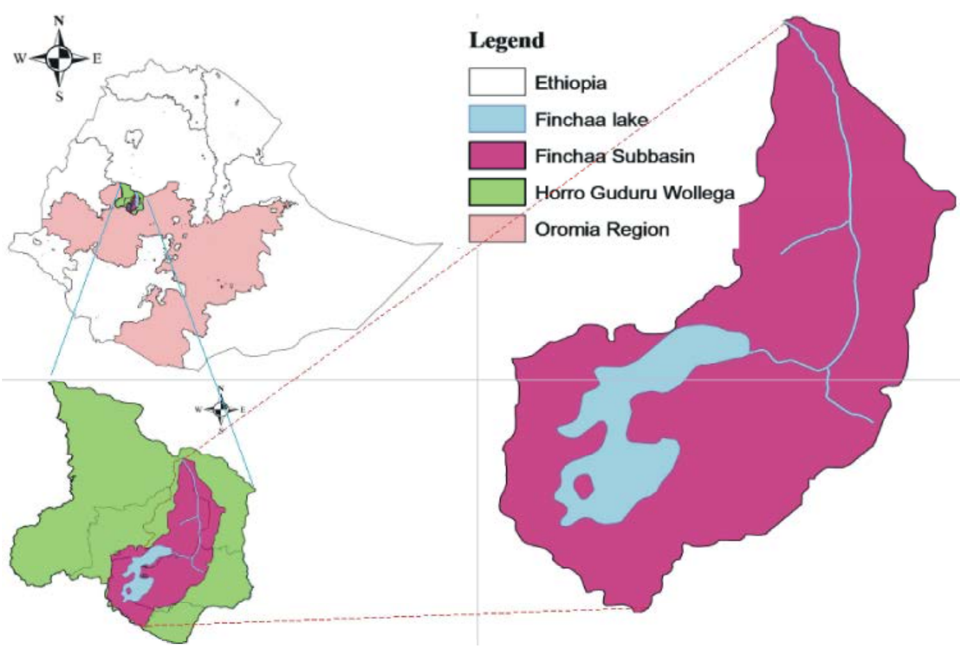

Fig. 1: Location of Finchaa Sugar Estate

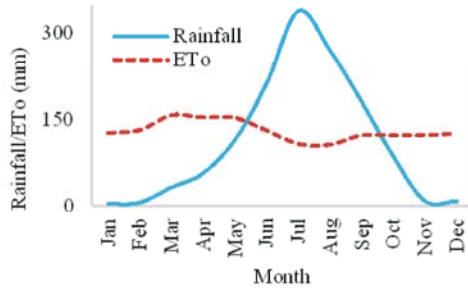

Fig. 2: Climatic Water Balance (Rainfall and Reference Evapotranspiration (ETo)) of Finchaa valley

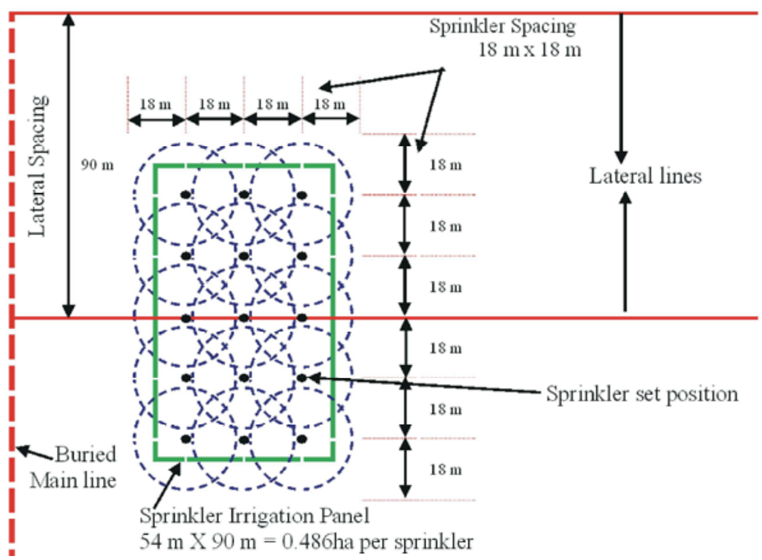

Fig. 3: A typical layout of hose-move sprinkler system

around 84%. Monthly maximum average humidity varies from June to September (94 – 96%) to February to March (62 – 65%). The minimum relative humidity observed from December to April [22].

Description of Fichaa Sugar Estate Irrigation Project: Finchaa Sugar Estate Factory was placed at East bank of the Finchaa River whereas the developed land lies on both West and East bank. Fichaa River was regulated by a Finchaa hydro-electric power dam and source irrigation water for Fichaa Sugar The estate supports a fully irrigated scheme utilizing a drag-line/Hose-Move sprinkler system of irrigation.

Finchaa Sugar Estate Irrigation system is designed to give a gross application of 134.5 mm per cycle. The infield efficiency is estimated at 75% giving a net application of 100 mm. The system is designed to operate on a 15 day cycle with a 24 hour set time, for all types of soil and plant growth stages/conditions, even though the two major soil types (Chromic Luvisols and Eutrophic Vertisols) prevailing in Finchaa Valley have completely different physical and chemical properties, such as water holding capacity and infiltration rate. The system is, therefore, designed to apply a maximum of 269 mm (200 mm) of gross and net irrigation water per month.

The lengths of the lateral lines were 90 m, whereas the spacing between the sprinklers was 18 m. The sprinkler assembly comprises 36 m length and 25 mm diameter plastic hose connected to a galvanized steel tripod with four meter high riser valve and a brass sprinkler. The sprinkler type is a VYR35 impact type designed to operate at a hydrant pressure of 4.76 bar and at a sprinkler nozzle pressure 3.17 bar discharging water through two nozzles having 2.4 mm (Auxiliary) and 4.8 mm (Main) sizes to give a nominal flow of 1.8 m^3/h or 0.5 l/sec. A single sprinkler assembly is irrigating at fifteen (15) set points for twenty four (24) hour at each point. A total 0.486 ha area of land can be irrigated by one sprinkler per irrigation cycle (Fig. 3).

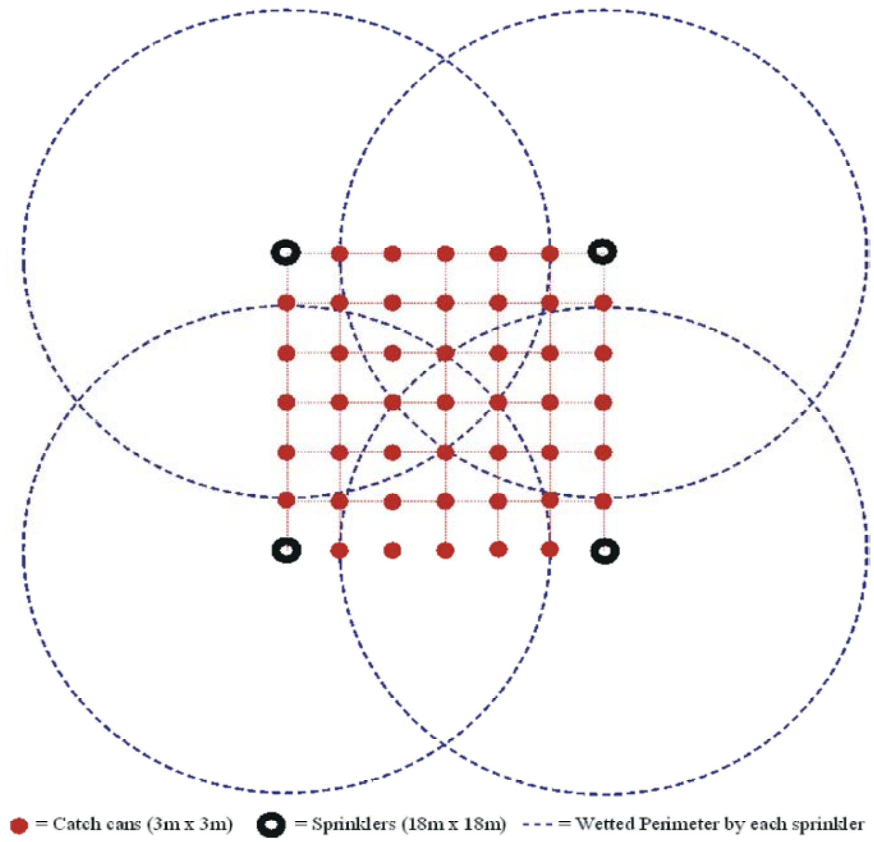

Fig. 4: Schematic representation Catch Can test

Materials: The equipment that were used for the field experiments: Pressure gauge with pitot tube attached, stopwatch, a large container of known volume clearly marked, a hose having a diameter appreciably larger than the outside diameter of nozzles, catch containers, 100 ml graduated cylinder to measure volume of water caught in containers, tape meter, wind velocity gauge, rain coat, rubber boots and manufacturer's sprinkler performance charts.

Field Experiments

Sprinkler Head Rotation Speed Measurements: The sprinkler head rotating speed influences the water distribution pattern by affecting the spray range. A low rotating velocity of sprinkler head decreased the spray range, the wetted area, produces larger drop size and reduced the speed of sprinkler head. In this study the speed of sprinkler head revolution was determined during uniformity test was carried out. The time taken to complete a revolution is recorded for each of overlapped four sprinklers that are operating at the same time. It was noted that the speed of sprinkler head varied under different hydrant operating pressure. In addition, number of beats of sprinklers head per revolution was counted.

Sprinkler Application Rate Measurements: The actual sprinkler discharge rate was measured at field condition on two fields (namely P513 and G204) for four hydrant pressure (3.5 bar, 4.0 bar, 4.5 bar and 5.0 bar) with four replicates. Totally sixteen (16) tests was carried out across the lateral pipes to measure discharge of sprinkler by connecting flexible hose to each of sprinkler nozzles and allowing the water to fill a known volume of bucket (10 liters). The discharge from the two nozzles were collected separately and finally added together.

Water Application Uniformity Measurements: In order to analyze the infield water application uniformity, a total of twelve (12) field experiments were conducted in the period of January to March 2016. Field tests were conducted adopting the methodology of Merriam and Keller [23] and Merriam *et al.* [24]. The tests sites are spread over two sections/villages, namely, village C and village Hora and three fields, P513, EPS-705 and G204. The crops grown on all experiment field plots were sugarcane. Fig. 4 shows the schematic representation layout of catch can test.

During the tests sprinkler spacing (18 m x 18 m) kept as practiced by the estate. The catch cans were placed in a grid of 3m x 3m. A total of 45 (Fourty five) cans

(15 cm height and 14 cm diameter) were used to collect water sprayed by four sprinklers during each test. Operating pressure is measured with pressure gauge fixed on a pitot tube.

Uniformity Indicators: The uniformity coefficient (CU) [25], the distribution uniformity (DU) [23], the system uniformity (System CU) and the system distribution uniformity (System DU) were used to analyze of the systems infield water application uniformity as indicators. In this study both the Christiansen's Coefficient of Uniformity (CU) and the Distribution Uniformity (DU) parameter, as defined by Keller and Bliesner [8] and Meriam and Keller [23] were used and calculated using equation below.

$$CU = 100 \times \left(1 - \frac{\sum_{i=1}^{N} |X_i - X_m|}{NX_m} \right)$$

and

$$DU = 100 \times \frac{X_{lq}}{X_m}$$

where

X_i: The individual depth of catch observations from uniformity test, mm

X_m: The mean depth of observations, mm

X_{lq}: The average low quarter water depth of water received, mm

N: The number of observations.

In order to take in the assessment of the performance account of the pressure variation in the system; the system uniformity (System CU) and the system distribution uniformity (System DU) were determined. These coefficients were, according to calculated with the following equations;

$$System\ CU = CU \times \frac{1 + \sqrt{\frac{Pn}{Pa}}}{2}$$

and

$$System\ DU = DU \times \frac{1 + \sqrt[3]{\frac{Pn}{Pa}}}{4}$$

where:

Pn: The minimum sprinkler pressure, kPa

Pa: The average sprinkler pressure, kPa

Data Analysis: Descriptive statistics such mean, standard deviation, minimum, maximum and variance of the catch cans collected water depth were analyzed. Correlation between operating hydrant pressure and speed of sprinkler head rotation, application rate of sprinkler and uniformity of irrigation were determined. In addition, to represent the relationships between the uniformity indicators in linear equations the general linear model regressions were determined, with INSTAT software version 3.36 for window. MS-Excel 2016 was used to draw different graphs and charts throughout the paper.

RESULTS

Speed of Sprinkler Head Rotation: The test of sprinkler head rotation speed revealed that, on average, at 3.5, 4.0, 4.5 and 5.0 bars, 1.45 RPM, (ranging from 1.4 to 1.5 RPM), 1.72 RPM (ranging from 1.67 to 1.76 RPM), 2 RPM (ranging from 1.93 to 2.14 RPM) and 2.4 RPM (ranging from 2.3 to 2.6 RPM) respectively. The obtained results at hydrant pressure of 3.5 bar was less than the recommended sprinkler rotation, while at 4.0, 4.5 and 5.0 bar the speed of sprinkler head rotation were within the allowable range (2 RPM, based on the design pressure of sprinkler). Therefore, to make the speed of sprinkler rotation within the recommended range, the use of 3.5 bar hydrant pressure should be neglected. Maintaining a constant speed of revolution and number of beats is critical for efficient irrigation system. Otherwise some portion of the wetted area receive more water than others which may leads to non-uniformity of applied water. Fig. 5 shows the relation between the speeds of sprinkler head with the hydrant operating pressure.

There was a significant positive correlation (r=0.995) between hydrant pressure and speed of sprinkler head rotation. In addition to the speed of sprinkler head revolution, the number of beats of sprinkler head per revolution also counted at different hydrant operating pressure. The result shows that the average numbers of beats of sprinkler head were 52, 58, 65 and 72 beats per revolution of sprinkler heads at 3.5, 4.0, 4.5 and 5.0 bars of hydrant pressure respectively.

Actual Sprinkler Application Rate: The results of the sprinkler discharge rate and application rate at different hydrant operating pressure are given in Table 1.

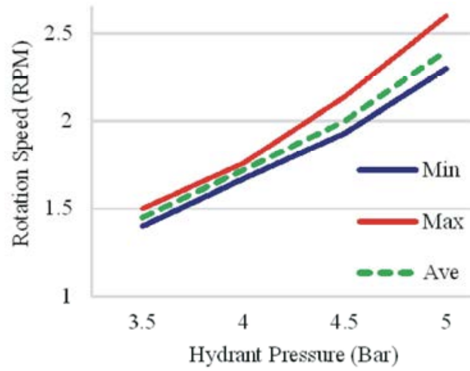

Fig. 5: Hydrant pressure and speed of sprinkler head rotation

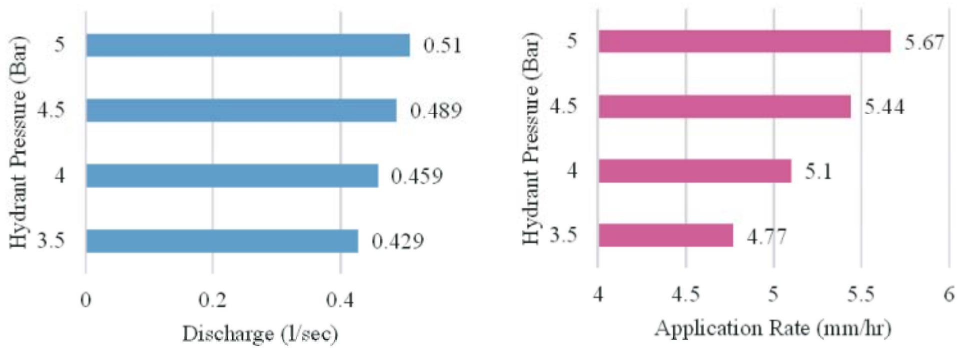

Fig. 6: Hydrant pressure and Discharge (left) and Application rate (right) of sprinkler

Table 1: Sprinkler discharge rate and application rate at different hydrant operating pressure

	Discharge of nozzles (l/sec)			
Hydrant pressure (bar)	2.4 mm nozzle	4.4 mm nozzle	Total Discharge (l/sec)	Application rate (mm/h)
3.5	0.081	0.348	0.429	4.77
4.0	0.088	0.37	0.459	5.1
4.5	0.097	0.392	0.489	5.44
5.0	0.106	0.404	0.51	5.67

The discharge rates at different operating pressures are illustrated in Fig. 6 indicates more clearly the effects of operating pressure on discharge rate from the sprinkler nozzles. They have strong positive correlation with R^2 of 0.993. This is in good agreement with Tekin *et al*. [26] finding.

The variation of the measured discharge from the design discharge were within the acceptable range (± 10%) for 4.0, 4.5 and 5.0 bar of hydrant pressure, 8%, 2% and 2% respectively. However, for 3.5 bar of hydrant pressure the variation was unacceptable, 14%.

Uniformity of Individual Test: As indicated in the methods and materials section the performance parameters were calculated on the basis of the volume of water collected in a large number of catch cans (45 catch cans). The obtained average CU and DU for the selected operating hydrant pressure were given in Table 2 and Fig. 7.

The obtained average Christiansen's Uniformity coefficient, CU, were 86.67% (range from 83% to 89%), 89.33% (range from 88% to 91%), 91.67% (range from 91% to 92%) and 92.67% (range from 91% to 94%) at the respective operating hydrant pressure of 3.5, 4.0, 4.5 and 5.0 bar. It looks important to note that the obtained CU values ranges between 83% and 94% for the twelve field tests at all hydrant pressure, which is greater than 80%. Table 2 shows the summary of the result of uniformity indicators.

Similarly, the obtained distribution uniformity, DU, values from the field experiment analysis of sprinkler irrigation were 80.33%, 83.67%, 88.67% and 89.67% at the

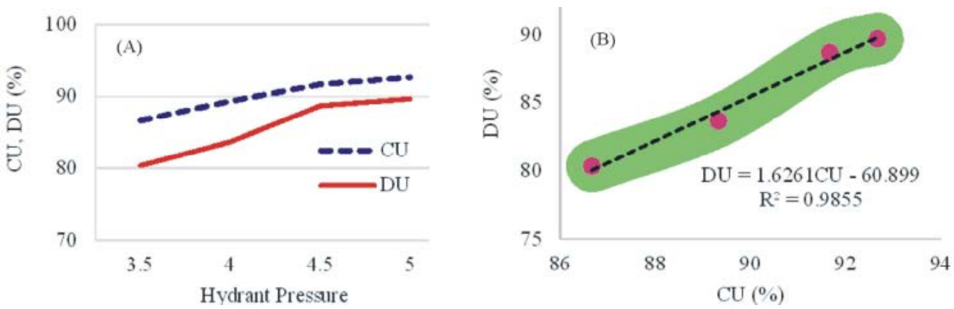

Fig. 7: Illustration of (A) CU and DU and Hydrant Pressure and CU and DU Correlation

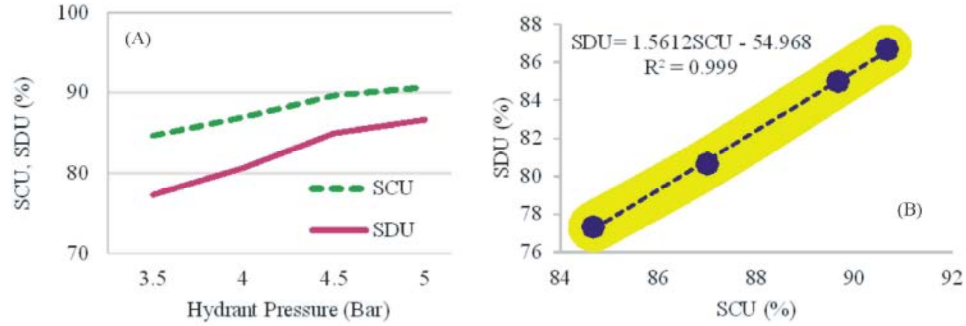

Fig. 8: Illustration of (A) The relationship SCU and SDU with Hydrant Pressure (B) SCU and SDU Correlation

Table. 2: Uniformity of water application for individual tests

Exp't no.	Hydrant pressure, bar	Mean of collected water, mm	Lower quarter mean, mm	CU, %	DU,%
Exp't-1		3.72	2.8	83	75
Exp't-2	3.5	3.58	2.9	89	81
Exp't-3		3.83	3.25	88	85
Exp't-4		4.45	3.7	89	83
Exp't-5	4	4.52	3.7	88	82
Exp't-6		4.42	3.8	91	86
Exp't-7		4.71	4	91	85
Exp't-8	4.5	4.8	4.3	92	90
Exp't-9		4.87	4.42	92	91
Ex't-10		4.9	4.29	91	88
Ex't-11	5	4.91	4.44	93	90
Ex't-12		4.86	4.43	94	91

CU: Coefficient of Uniformity; DU: Distribution Uniformity

operating hydrant pressure of 3.5 bar, 4.0 bar, 4.5 bar and 5.0 bar respectively. From the graph above we can see that similar pattern of CU and DU under different operating pressure. That is to say good CU is an indicator of good distribution uniformity and vice versa. A linear relationship was noted between CU and DU values and the equation was given in Fig. 7B. It shows that CU and DU have strong positive correlation (R^2= 0.985).

Uniformity of the Whole System: The application uniformity of the whole irrigation system was also approximated from the uniformity of individual tests using the empirical equations developed by Keller and Bliesner [8] based on the average and the minimum riser pressure across the lateral assuming a linear distribution of pressure variation between the average and minimum pressures. The results of the system CU and DU are indicated in Fig. 8A.

These tests highlighted that the system uniformity was less than the uniformity obtained from individual tests. The reason, as stated by Keller and Bliesner [8] may be due to the pressure and discharge variations throughout the whole irrigated field. The values of the System CU and System DU were very closely to the calculated CU and DU values of individual tests, indicating that the pressure variations within the system was small. Likewise the individual tests CU and DU results, there was a significant positive correlation between system CU and system DU (Fig. 8B).

Generally, it is not enough to have uniform application if the average depth is not enough to refill the root zone to field capacity. Similarly, it is not enough to have a correct average application depth if the uniformity is poor. Uniformity is mainly a function of design and subsequent system maintenance, but application depth is a function of management (i.e. a function of the set time). Application depth reflects adequacy of the irrigation system.

DISCUSSION

The finding of the current study indicated that, increasing the hydrant pressure increases the discharge rate (Application rate) of sprinklers. As a result, the sprinkler discharge rate and the operating hydrant pressure has a strong positive correlation with a correlation coefficient of 0.998 (r=1). This result is justifying an argument that states the rate of increase in water delivery as the direct function of pressure as forwarded by Cuenca [27] and Keller and Bliesner [8].

The application rate obtained in this study at 3.5 bar was less than the allowable variation (10%). To solve this problem, change in factors which affects application rate should be required. These factors are the size of sprinkler nozzles, the operating pressure and the sprinklers spacing [9]. Changing the sprinkler spacing in an existing field is not practical, because it extremely time consuming and expensive. Changing the size of nozzles and operating pressure may, however, be feasible. In case of Finchaa Sugar Estate sprinkler nozzle size and sprinkler spacing are constant i.e. similar throughout the system. But, the operating hydrant pressure are varying from field to field and hydrant to hydrant. Increasing the hydrant pressure is critical.

The result of the tests indicates that better (CU>= 90%) uniformity of water application or distribution have obtained at about 4.5 bar and 5.0 bar hydrant pressure, which very near to the design hydrant pressure (4.76 bar). The result also revealed that the uniformity of water distribution increased with operating hydrant pressure. When pressure increased from 3.5 to 4 bar, from 4 to 4.5 bar and from 4.5 to 5 bar the CU increased by 3.2%, 2.6% and 1.1%, respectively. The increments of increases were decreased as pressure increase. Even though these results differ from previous study done by Bishaw and Olumana [28], they are consistent with those of work done by Moazed *et al.* [29] and El-Waled *et al.* [16]. According to Keller and Bliesner [8] recommendations the CU values obtained at Finchaa sugar estate irrigation fields were falls within the recommended range, which states for high value crops CU> 84% is a must, at all selected operating hydrant pressure.

Another important finding was that, the DU values obtained exceed 75% for all tests, at all hydrant operating pressures considered. This indicates DU irrigation system of Fichaa sugar estate was within the allowable range, according to Keller and Bliesner [8] recommendation, which is DU>75% for high value crops. Similarly, according to California State Polytechnic University Irrigation Research and Training Center recommendation an irrigation system having Distribution Uniformity DU of 85% or greater is excellent, 80% is very good, 75% is good, 70% is fair and 65% or less is poor. Therefore, the DU of the current study was fall in the range from good to excellent accordingly.

Further analysis show that hydrant pressure between 4.0 bars and 5.0 bars give better water application. But, the relationship between uniformity and pressure beyond 5 bars needs further study. Previous study by El-Waled *et al*. [16] obtained better uniformity of water application at 3.0 bar hydrant pressure and revealed that working at hydrant pressure of 3 bar has an advantages than 2 and 2.5 bar in application rate and uniformity of water application.

The value of CU and DU obtained indicate the good hydraulic design performance of the irrigation system. That means the uniformity of water application was very high and acceptable at all operating pressure. However, the higher uniformity levels do not indicate the adequacy of water application performance level. Uniformity does not give any physical meaning about the adequacy of irrigation. That means the inadequate water application/delivery performance may result with good uniformity performance and vice versa. Therefore, it is suggested that to analyze the relationship between uniformity and adequacy of irrigation for further representation of the performance of the project.

CONCLUSION

This paper has investigated effects of operating hydrant pressure on water application rate and in field water distribution uniformity of Hose-Move sprinkler system of irrigation. The evidence from this study intimates that maximum application rate and sprinkler head rotation were obtained for operating hydrant pressure of 5 bar, whereas the minimum were resulted at 3.5 bar. The highest CU and DU were obtained at operating hydrant pressure of 5 bar. In general, one can conclude that by increase of the operating hydrant pressure the uniform distribution of applied irrigation water. However, it not guarantees for adequate irrigation because, good uniformity may result with inadequate water application/delivery performance. Therefore, it is recommended that further research should be undertaken to correlate the adequacy irrigation water application with uniformity and operating hydrant pressure.

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