Uluslararası Tarım Araştırmalarında Yenilikçi Yaklaşımlar Dergisi
International Journal of Innovative Approaches in Agricultural Research 2021, Vol. 5 (1), 37-51
https://doi.org/10.29329/ijiaar.2021.339.3

Original article

Performance Evaluation of Hand-Move Sprinkler Irrigation System: A Case Study in Rwanda

Theophile Niragire [a, *], Sinan Süheri [a] & Suresh Kumar Pande [b]

[a] Faculty of Agriculture, Selçuk University, Konya, Turkey
[a] Faculty of Agriculture, College of agriculture, animal science and veterinary Medicine , University of Rwanda, Rwanda

Abstract

This study was carried out with the main objective of evaluating the efficiency of the government-funded irrigation project equipped with hand-moved portable sprinkler irrigation system in the Nyagatare district of eastern Rwanda. The study was performed in maize field irrigated by a sprinkler irrigation system during the 2014 agricultural season. Catch cans experiments were used to assess the efficiency of the current field irrigation sprinkler system. Performance indicators such as coefficient of uniformity (CU), distribution uniformity (DU), Potential application efficiency of the low quarter (PAElq), pressure variation along laterals, delivery performance ratio (DPR), evaporation and wind drifts losses were analysed. The Christiansen equation was used to measure the CU. The results of this study revealed that the coefficient of uniformity, uniformity of distribution and efficiency of water application of the method were 84.7%, 88% and 88% respectively. These experimental findings indicated that the performance of existing hand-move sprinkler irrigation system was satisfactory. The study put forward performance guidelines and advices for the designers and managers of sprinkler irrigation systems to achieve optimum performance.

Keywords: Sprinkler irrigation, Performance evaluation indicators, Irrigation efficiency and uniformity.

Received: 05 October 2020 * **Accepted:** 18 March 2021 * **DOI:** https://doi.org/10.29329/ijiaar.2021.339.3

* **Corresponding author:**

Theophile is a Master Student in the Department of Agricultural Structures and Irrigation at Selcuk University in Konya, Turkey. His research of interest includes the Irrigation and drainage engineering, Agricultural engineering and water management. He has lived and studied in Konya, Turkey.
Email: theophile.niragire@lisansustu.selcuk.edu.tr

INTRODUCTION

Rapid population growth creates a constant need to increase food production while encroaching on agricultural land and accelerating land-fragmentation. In this regard, the only effective solution and practical approach to meet food demand sustainably with scarcity of land resources is to increase agricultural productivity through modernized and skills-based agriculture. According to Mukashema et al. (2014), the estimated total agricultural land occupies 15013km^2, which constitutes 57 % of the total land area while the rest of the country is protected by natural and cultivated forests (26%), water areas (5%), wetlands (6%) and urban areas (6%). Small scale agriculture including seasonal, annual and perennial crops consist majority of Rwandan agriculture.

Irrigated agriculture has been playing a key role in providing food to the rising population for a long time and is going to play a major role in the future in alleviating drought and climate change.

According to FAO Aquastat (2005), Rwanda has internal renewable water resources of 31, 9 x 109 m^3/year (Minagri, 2013). A research released earlier by ICRAF in 2010 on the analysis of the national water balance and irrigation water potential revealed that the country has approximately 28 billion m^3 of water in annual rainfall, taking into account all water resources (rainfall, runoff, surface and groundwater). Approximately 4.3 km^3 overflows, 9.5 km^3 evaporates, 5.3 km^3 is transpired by the vegetation and 4.3 km^3 percolate into the groundwater system.

The 2010 Irrigation Master Plan, revised in 2019, indicated that Rwanda had a potential irrigation area of 600,000 hectares, a figure that put agriculture and irrigation growth at the forefront of the country's development agenda by implementing strategic plans to transform the country's agriculture (IMP, 2019). According to Malesu et al. (2010) The current formal irrigation infrastructure is about 56,000 hectares, which is equivalent to 9.5% of the country's total potential irrigation land. Habineza et al. (2020) estimated 47% of the total irrigation area from the marshland and 53% from the hillside. Investments in irrigation in Rwanda have a tremendous potential to improve the lives of smallholder farmers who otherwise rely on rainfed agriculture, by raising yields, increasing dry season cultivation and maximizing crop and water productivity (Magruder and Ndahimana, 2020).

The ideal irrigation system must apply the right amount of water and reduce losses. Recently, pressurized irrigation systems such as drips, sprinklers and center pivots have been recognized as an important method for boosting in-field water usage efficient. The greatest challenge in managing crop irrigation is to achieve consistent application of water and system productivity while maintaining natural resources— soil and water.

A sprinkler system is a common irrigation system among farmers, known for its considerable efficiency. It’s simple to install and maintain, ideal for all crops and soil types. Portable systems, known for their flexibility and reduction in the cost of installation, are becoming common and widely used around the world. Topak et al. (2005) stressed that the use of the sprinkler irrigation method promotes system operation and automation by raising the capacity to achieve high uniformity and effective irrigation, resulting in water and energy savings that improve farm profitability.

Performance evaluation has been an important part of irrigation design and management since the first man began using water to increase crop production (Bos et al., 1993). Efficiency of irrigation applications is a term that is commonly used in system design and management. It can be divided into two parts, uniformity of application and loss. If either uniformity is weak or losses are high, performance will be low.

According to Keller and Bleisner (2000), a key design objective is the uniformity of sprinkler irrigation. Uniformity indicates if the water is spread uniformly over a given area or not. Owing to the lack of uniformity in the distribution of water, parts of the surface area receive less water, while others may receive more water. Topak et al. (2005) stated that the pattern of distribution of sprinkler water depends on the system network design parameters such as nozzle diameter sprinkler spacing and operating pressure and environmental variables such as wind direction and speed. A research study conducted by Salmerón et al. (2012) on maize yield simulation with respect to sprinkler uniformity variabilities concluded that the simulated yield of maize with a decrease in irrigation CU from 100 to 70% differed from year to year and resulted in a reduction in maize yields ranging from 0.75 to 2.5 mg ha−1.

The two most popular methods for phrasing uniformity are the coefficient of uniformity (CU) and the uniformity of distribution (DU). Keller and Bliesner (1990) stated that a low DU or CU value shows that losses because of deep percolation can be high if aduquate irrigation is applied to all over area. While the principle of low values is subjective, the values of DU < 60% (CU < 75%) are commonly considered to be relatively low, including for general field and forage crops. For higher value crops a DU > 75% (CU > 84%) is recommended. Burt et al. (1997) suggested that the gross irrigation water needed for an irrigation event could be measured using a low-quarter (PAElq) application efficiency capacity.

Evaluating the performance of newly installed and existing sprinkler systems is of great significance area of research and several articles have been published in this regard (Acar et al. 2010; Ahaneku, 2010; Burt et al., 1997; Dabbous, 1962; Dinka, 2016; Howell, 2003; Keller, 1995; Keller and Bliesner, 1990; Li, 1998; Li and Rao, 2001; Salvatian, and Amiri, 2015; Mantovani et al. 1995; Maroufpoor et al. 2010; Martinez et al. 2003; Merriam et al. 1980; Ngasoh, et al. 2018; Topak et al., 2005; Wilson and Zoldoske, 1997). This article provides additional details on the effect of the key factors on the distribution of water in pressurized irrigation systems.

In Rwanda, several studies have been performed to enhance in-field irrigation water management (Geoffrey et al. 2015; Kannan et al. 2011; Majoro et al. 2016; Narayanan, 2014; Urujeni and Ngabitsinze, 2015). To date, however, no research has been conducted on the performance evaluation of pressurized irrigation systems. This research was therefore carried out to evaluate the current performance of hand-move sprinkler irrigation system of Government-funded sprinkler irrigation project installed in the eastern part of the country, Matimba sector of Nyagatare District. In addition, a set of advices will be provided for the designer and operators of these systems for this area and for other areas where agricultural and environmental conditions may be similar.

MATERIAL AND METHODS

Description of the study area

This study was conducted at the Government-funded irrigation project (GFI-Nyagatare) in Nyagatare district, Eastern Province of Rwanda during the 2014 agricultural season. The geographical position of the experimental site is 1º03'55 "latitude and 30º24'07" longitude, with an average altitude of 1513.5 meters above sea level. The soil type of the area under study was sandy loam soil. Small amounts of rain and hot temperatures differ in this district, with an annual average temperature ranging from 25.3°C to 27.7°C and a mean annual rainfall of 827mm and potential evapotranspiration of 1337mm (Malesu et al.,2010), indicating the imperative need for irrigation in this region. Like other regions of Rwanda, the area of study has three agricultural seasons, namely (A, B and C): season A begins at September and ends January of each year. The main crops of A season are maize, beans and soybeans. Season B begins at March and ends July. The main crops of B Season are maize, beans, soybeans, Irish and sweet potatoes and cassava. However, the agricultural season (C) starts in June and end in August and is certainly reserved for vegetable production in marshlands and hillside irrigation. In order to achieve the objectives of this research, materials such as catch cans, stopwatch, measuring cylinder, pressure gauge, container of known volume, plastic pipe, record sheet, pen, scientific calculator, ruler, digital camera and GFI project design map and technical data were used to locate and create the area under study.

The overhead plastic impact sprinklers manufactured by Jain irrigation Ltd, that are installed in the experimental site had the following features:

Total irrigated area	:110Ha
Number of plots	:22 (5ha per plot)
Net irrigated area per plot	:240x192m= 4.6ha
Number of hydrants per plot	:1
Number of laterals per hydrants:	:2(Operating in opposite direction)

Number of sprinklers per lateral:	:10
Provided Jain Plastic Sprinkler Model	:5035 (TWIN NOZZLE)
Sprinkler spacing	:12X12 m
Sprinkler discharge range	:720 to 3540 lph (1950lph=32.5lpm=0.54lps)
Operating Pressure range	:2.5 to 5 Kg/cm² (3.0 kg/cm²)
Wetted Diameter range	:24 to 36 m (30m)
Inlet Connection	:3/4” male Threaded(20mm)
Nozzle size	:4 to 4.5mm
Number of shifts per day	:2

Field experimental procedures

The total area fitted with a sprinkler system is equivalent to 110 ha, divided into 22 plots (5 ha per plot). The net irrigated area per plot has a square shape of 240x192 m roughly equal to 4.6 ha. This means that the total net irrigation area is approximately 101.2 ha. The water used is pumped out directly from the Muvumba River and delivered to the field via a network pipeline system. A series of hydrant boxes are connected to the submain pipes. Each plot has its own hydrant at which two sides laterals are connected and operated in reverse direction. Each single lateral pipe comprises 10 sprinkler heads arranged in a square pattern of 12x12 m with equal spacing between laterals and riser pipes. In this location, the overhead plastic impact sprinklers manufactured by Jain company Ltd-Indian are double nozzles type 4 to 4.5 mm in size and are located 1.8 m above ground level. Irrigation practices is performed in shift-basis and there are two shifts per day per each lateral pipe.

The field assessments were carried out using the Merriam and Keller (1980) approach and the ASABE (2009) standard procedures. The field tests, were carried out in all areas covered by maize crop. The field evaluation measurements were taken while the farmers were performing their normal irrigation practice on clear and sunny day between 9am and 5pm from June to August. In the evaluations, the field tests were performed as single-lateral test. Concerning the field procedures, firstly the experimental site was randomly divided into 4 zones and a sprinkler position on lateral line was chosen in each zone. The test protocol consisted of installing a pattern of similar metallic catch cans container.

For the square spacing of 12x12 m, the Catch cans were located roughly in a square grid of 2 meters inside the space bounded by four sprinklers. The total catch can between adjacent lateral were simulated by overlapping the right-hand and left-hand catch can data. Figure-1 shows the catch-cans arrangement for the block irrigation test. Prior to the beginning of each test, both the discharge rate and sprinkler operating pressure were controlled at both systems pumping station level and at hydrant level.

During the test, the sprinkler head flow rate, inlet and outlet pressure along lateral were recorded. The test duration of 30 minutes for each inspected sprinkler lateral was recorded and the reading process of catch cans took approximately 10 to 15 minutes. After test completion, the water amount accumulated in each catch can was measured with graduated cylinder. These experiment procedures were replicated for each sprinkler lateral tested.

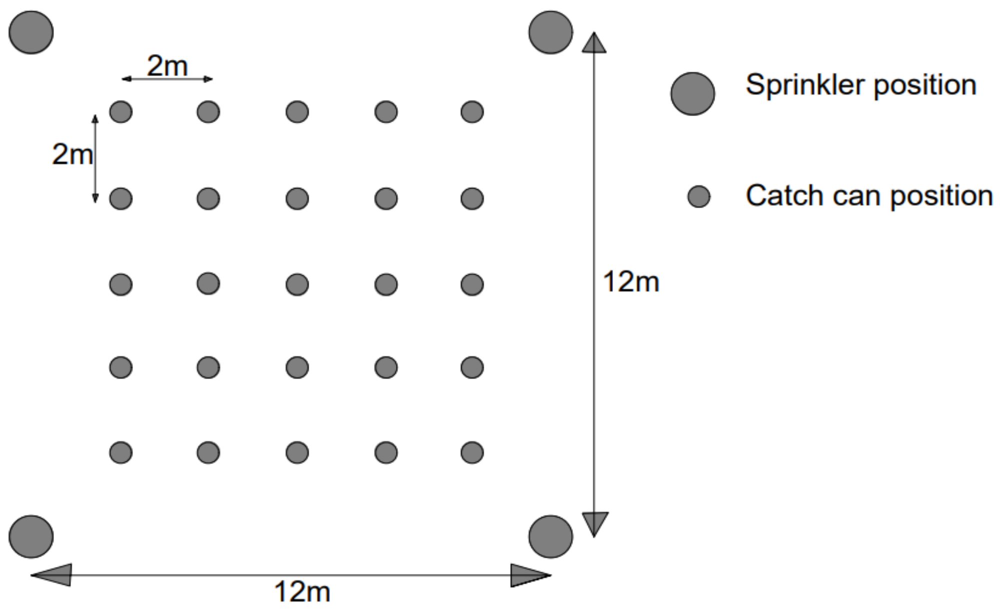

Figure 1. Sprinkler catch-can pattern

Evaluated performance indicators

The performance parameters analysed are shown with the following equations:

Christiansen Coefficient of Uniformity CU (%):

$$CU = 100[1.0 - \frac{\Sigma x}{n.m}] \quad \text{or} \quad CU = 100[1.0 - \frac{\Sigma|z-m|}{n.m}] \quad \text{or } CU=\left[1 - \frac{\sum_{i=1}^{N}|X_i - \bar{X}|}{N \times \bar{X}}\right] \times 100 \tag{1}$$

Where:

x = |z-m|=Numerical deviation of individual observation from average application rate, mm.

m = Average water depth collected in all catch cans (average application rate), mm

z= The individual depth of catch observation from uniformity test(mm)

n= Number of observations

The system coefficient of uniformity CUS has defined by Keller and Bliesner (1990)

As follows:

$$CUS = CU \times \frac{1}{2}\left[1 + \sqrt{\frac{P_n}{P_s}}\ \right] \quad (2)$$

Where:

Pn: The minimum sprinkler pressure (kPa)

Ps: The average sprinkler pressure (kPa)

Distribution uniformity DU, (%)

$$D_U = \frac{d_q}{d} \times 100 \quad (3)$$

Where:

dq= Average low-quarter depth of water depth received (mm)

d= Average depth of water received in the test area (mm)

Merriam and Keller (1978) stressed the similarity and differentiation between the two parameters shown in equations (1) and (3). Christianen 's coefficient (CU) tells us the average deviation across the field, while distribution uniformity (DU) compares the driest quarter of the field to the rest. A CU of 100 per cent is fully standardized, while a CU of 90% shows an average deviation of 10%, etc. They have also demonstrated that, for a typical overhead sprinkler irrigation system with a statistically normal distribution and CU >70%, CU and DU are approximately related by:

$$\mathrm{CU} = 100 - 0.63(100 - \mathrm{DU}) \quad (4)$$

Discharge efficiency E_d:

$$E_d = \frac{d_0}{d_d}\ x\ 100 \quad (5)$$

Where:

d_o= Average water depth observed in catch cans (mm)

d_d=Average water discharged by sprinkler(mm)

Topak et al. (2005) defined discharge efficiency as the relationship between the water collected by the catch cans and the water discharged by the sprinkler. The difference between them indicates the evaporation and wind drift losses during irrigation event mainly due to environmental conditions.

Potential application efficiency of low quarter (PAE_{lq}):

The net water losses were computed as the difference between evaporation and wind drift losses during the test and the water lost by evaporation in catch cans during the test. However, the water loss from the catch cans was not considered as loss. Following (Burt et al., 1997) PAE_{lq} was determined as follows:

$$\text{PAElq} = \frac{d_c}{d_{lq}}\, x\ 100 \qquad (6)$$

Where:

d_c= Average depth of irrigation water contributing to the target(mm)

d_{lq} = The low quarter irrigation water target depth(mm).

Delivery performance ratio (DPR)

The data obtained from the discharge tests were used to determine DPR of the sprinkler system which is a measure of the system performance efficiency. Following the relation elaborated by David et al.(1990), DPR was estimated as:

$$\text{DPR} = \frac{QA}{QR} = \frac{Actual\ discharge}{Required\ dischage} \qquad (7)$$

RESULTS AND DISCUSSION

Analysis of sprinkler system uniformity

The table-1 presents the key results of evaluated uniformity parameters of hand-move sprinkler irrigation system of the same sprinkler spacing 12x12m. From the figure-2 it is evident that CU ranged from 84.2% to 85.5% in all 4 zones (Z1P1 to Z4P4) with mean value of 84.9%. The DU ranged from 88.2% to 89.1% with an average of 88.1%. The evaluated system coefficient of uniformity CUS increased from Z1P1 to Z3P3 and declined in Z4P4 with a mean value of 84.7% in all study zones.

Table 1. Computed uniformity parameters for hand-move sprinkler system evaluation

Zone	Nº of observ.	Sprinkler pressure at hydrant (kPa)			Discharge rate (Lph)	Coefficient of uniformity CU (%)			Distribution of uniformity DU (%)			System coefficient of uniformity CUS (%)
		Max.	Min.	Avg.		Min.	Max.	Avg.	Min.	Max.	Avg.	Avg.
Z1P1	6	292	285	288.5	1862	83.4	85	84.2	85.9	87.5	86.7	83.9
Z2P2	6	276	271	273.5	1783	84.3	85.5	84.9	88.2	90	89.1	84.7
Z3P3	6	264	258	261	1694	84.7	86.3	85.5	87.4	89.6	88.5	85.3
Z4P4	6	253	250	251.5	1570	84.4	86	85.2	88	88.4	88.2	85
Average	**24**	**271.3**	**266**	**268.6**		**84.2**	**85.7**	**84.95**	**87.38**	**88.88**	**88.13**	**84.7**

Z1P1: Zone-1 at Pressure-1, Z1P2: Zone-2 at Pressure-2 Z3P3: Zone-3 at Pressure-3, Z4P4: Zone-4 at Pressure-4

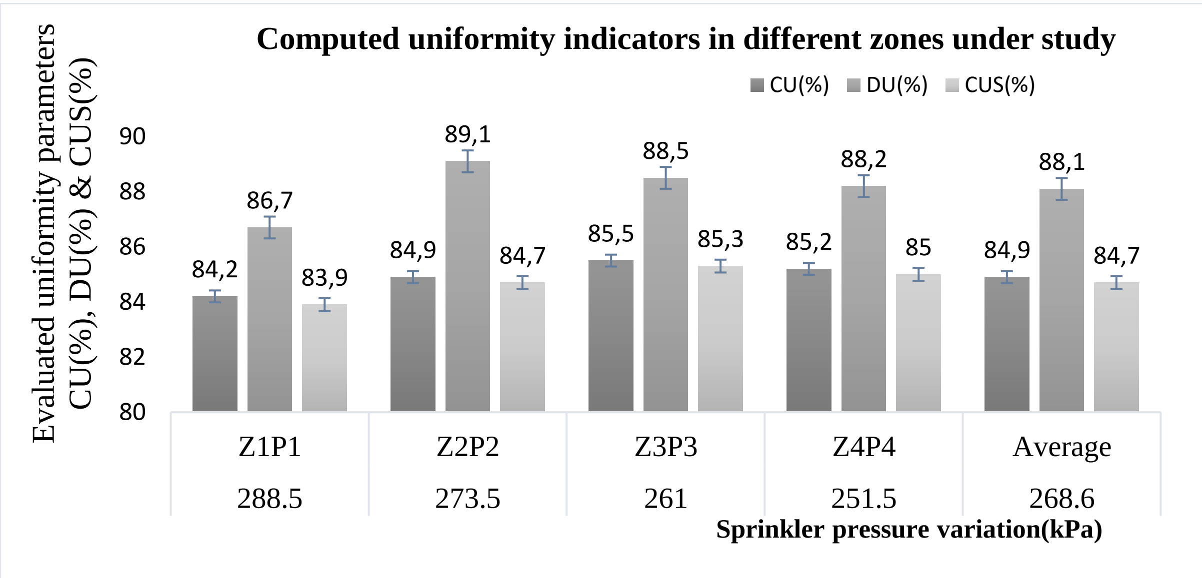

Figure 2. Computed uniformity indicators in different zones under study

These results are in conformity with (Topak et al., 2005) and (Keller and Bliesner, 1990). As shown in fig-2, it is also clear that in zones Z2P2 and Z3P3 both CU and DU values are relatively higher than zones Z1P1 and Z4P4. As the two zones (Z2P2 and Z3P3) are surrounded by zones Z1P4 and Z4P4, they have least wind effect. The lowest value of CU and DU in zone Z1P1 can be justified by the wind direction blowing from this zone. The analysis of climatic data under this particular study area revealed that the wind speed varies from 1m/s to 3m/s with mean value of 1.7m/s which makes this area under study to be categorized under a low wind speed zone. The results of study carried out by Hills and Barragan (1998) showed no significance effect on CU under low wind speed conditions(<2m/s). In general, when sprinkler spacing and wind speed increase CU and DU values decrease.

Inlet pressure and outlet pressure of each sprinkler lateral evaluated in different field zones were measured to determine pressure variation along laterals. Since the sprinkler operating pressure affects the sprinkler discharge rate and amount applied (fig-4), It is widely agreed that, in order to achieve reasonable uniformity, the limit of discharge changing in different points of laterals should not exceed 10% of average discharge. In order to achieve this, the pressure variation limits should not exceed 20% of the average working pressure.

Higher variation in pressure above this limit would affect the uniformity of water distribution (DU) and sections of the surface area may results receiving less water, while others may receive more water. This problem may happen when the hydraulic design of irrigation system is not right, particularly when the selected pipe diameters are lower in relation to the flow to be delivered. The difference between inlet pressure and outlet pressure in each lateral measured in all evaluations gives the lateral pressure variation, which was much less than 20% of operating pressure. Based on the thresholds established by Keller and Bliesner (1990) recommending to keep DU>75% and CU>85% for higher value crops irrigated by overhead sprinkler system, the obtained mean values of CU (84.9%) and DU (88.1%) fit under the category of desirable and show a very good performance of the entire irrigation system.

Analysis of sprinkler system efficiency

Table 2. Computed efficiency indicators for hand- move sprinkler irrigation system.

Zones of study	Nº of observations.	Discharge rate (Lph)		Application-rate (mm/h)	Water collected in catch cans (mm)	Evaporation &wind drift losses (mm)	Discharge efficiency-(%)	DPR	Potential application efficiency of low quarter PAE$_{lq}$ (%)		
		Actual	Required						Min	Max.	Avg.
Z1P1 Spacing 12x12m	6	1862	1950	12.93	10.13	2.8	78.3	0.95	71	85	78
Z2P2 Spacing 12x12m	6	1783	1950	12.38	11.2	1.18	90.5	0.91	87	93	90
Z3P3 Spacing 12x12m	6	1694	1950	11.76	10.4	1.36	88.4	0.87	87	89	88
Z4P4 Spacing 12x12m	6	1570	1950	10.9	10.2	0.64	93.6	0.80	93	95	94
Average		**1727.2**	**1950**	**11.9**	**10.48**	**1.49**	**87.7**	**0.88**	**90.5**	**90.5**	**87.5**

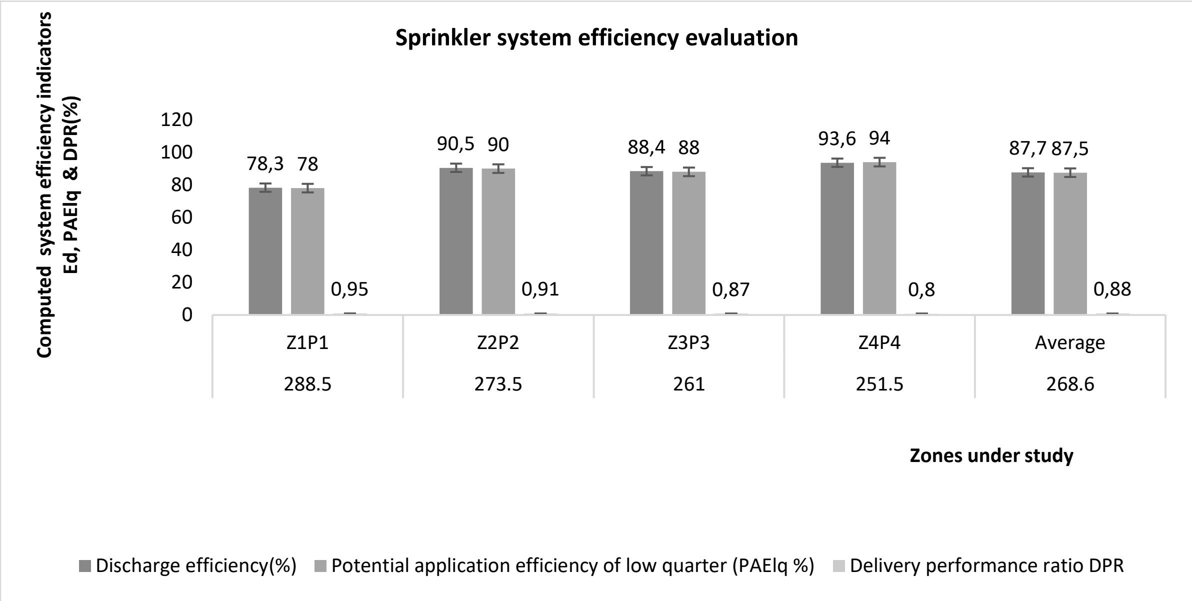

Figure 3. Computed efficiency indicators in different zones under study

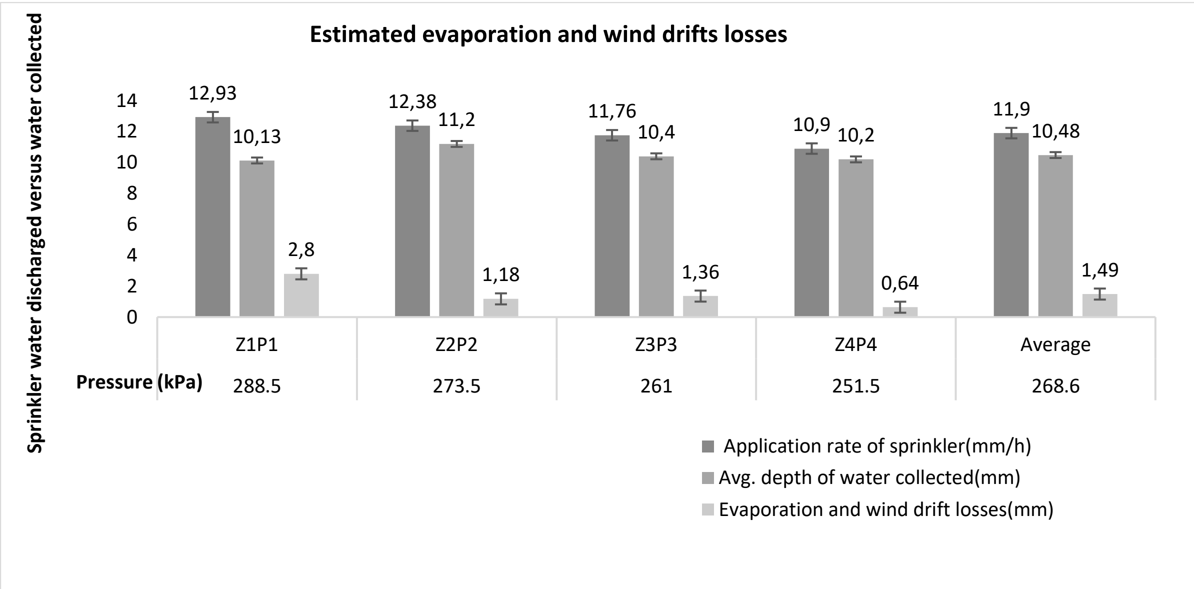

Figure 4. Estimated evaporation and wind drifts losses

Table 3. Results of key evaluated parameters of the sprinkler system

Parameter evaluated	Value obtained	Standard/expected value
CU of the system (%)	84.7	CU>84% is recommended for high value and field crops (Keller and Bliesner, 1990)
DU of the system (%)	88	75% and above (Burt et al., 1997)
Operating pressure (Kg/cm² or bar)	2.68	Design pressure:3bars, Manufacturer operating pressure range 2.5 to 5 Kg/cm²
Average discharge of sprinklers(lph)	1727.3	1950(from sprinkler manufacturer)
Average application rate of sprinkler(mm/h)	11.99	13.54mm/h (Less than soil infiltration rate found in study area (sandy loam soil (20-30mm/hr)
Discharge efficiency (%)	87.1	1
Delivery performance ratio (DPR) of the system	0.88	1

As it is indicated in figure-3, discharge efficiency (Ed) variability was relatively large, ranging from 78.3% to 93.6% compared to the main value of 87.7%. A moderate variability about 2.1% was observed in middle field zones (Z2P2, Z3P3). Contrary, a high level of discharge efficiency variability increased at the border zones (Z1P1, Z4P4) as they were more exposed to wind effect. The same variability was noticed for potential application efficiency of low quarter (PAElq) with respect to the field zones and their locations. The discharge efficiency indicates the relationship between the water discharged by sprinklers and the water collected by catch cans. The variations between two measurements represents evaporation and wind drifts losses (Figure-4). Based on the results of this field experiment, the operating pressure of the system affects the amount of water applied and evaporation and wind drift losses.

The highest PAElq value of 94% was attained in zone Z4P4 while the lowest was tested in Z1P1(78%) with the system average PAElq value of 87.5%. These values are within the limit suggested by Keller and Bliesner (1990) (PAElq>60) for this type of sprinkler. Under the same sprinkler spacing(12x12m), the current environmental characteristics and wind condition of the study area had no great difference with potential application efficiency of low quarter (PAE_{lq}) mainly due to the low-speed wind in this region and endurable variability in water application. Generally, the dependence of PAElq on sprinkler pressure, spacing and wind speed condition is similar to that found for CU.

Table-2 shows that the average sprinkler application rate (11.9 mm / h) obtained was lower than the predicted one (13.5 mm / h) and that both were less soil infiltration rate found in the study area (sandy loam soil [20-30 mm / hr]). The irrigation system application rate as measure of how much water per hour is being applied to the soil, based on the field experiment all water applied was fully infiltrated into the soil profile. Therefore, no runoff was occurred during the irrigation period. It can be concluded that the water application intensity of the sprinkler system is adequate.

The pressure variation analyses showed that, the operating pressure of the system affected the uniformity of sprinkler application and the amount applied since the applied water depth increase proportionally with the working pressure. The decline in the value of the discharge may have resulted from the age, nozzle clogging of the system. In addition, the pressures and discharge imbalances in the laterals were caused by some leakages in the distribution network, mainly at the control valves, pipe junctions, hydrants and connections of the portable irrigation equipment's at the farm.

As denoted in Table-2, the delivery performance ratio, DPR was observed to be 0.88 from the experimented field data which indicated sprinkler system efficiency of 88% and an estimated deviation of 12% from evaporation and wind drifts losses reflecting a good class of system efficiency (Molden and Gates,1990). This obtained efficiency agrees with the experimental results of (Ahaneku, 2010) but disagree with (Ngasoh et al, 2018) which was 0.79. Based on the studies done by Irmak et al. (2011) the sprinkler irrigation system of the research area is effective. This efficiency can be improved if sprinkler equipment's are properly managed and replaced at due time.

Conclusion

Performance evaluation of the irrigation system can be divided into two key components, namely uniformity and efficiency. If either uniformity is poor or losses are high, efficiency will be low, resulting in water and energy waste, which in turn adversely affects water productivity and farm income. The evaluation of the efficiency of sprinkler irrigation in Rwanda is of prime importance for the design and planning of sustainable and economical pressurized irrigation systems. The results of this study revealed that the distribution uniformity, coefficient of uniformity and system application efficiency were 84.7%, 88% and 88% respectively. These experimental findings ensure the performance of the entire sprinkler system to be evaluated as a satisfactory system. However, proper operation and frequent maintenance of the system are recommended in order to achieve optimal system efficiency.

Acknowledgement

This study was supported by university of Rwanda under student research grant. We would like to thank all staffs of Rwanda Agriculture Board, department of irrigation and mechanization for their kind support during this research.

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