DOI: 10.4172/2168-9768.1000227

Irrigation & Drainage Systems Engineering

Research Article Open Access

Evaluation of Overhead Irrigation System Performance at Finchaa, East-Bank Sugar Estate, Ethiopia

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Abstract

The study was done to assess the overhead irrigation system performance of dragline sprinklers at Finchaa, East-bank sugar estate irrigation scheme using water distribution uniformity indicators, sprinkler discharge efficiency and variation of system discharge and operating pressure. The measurements of sprinklers water distribution uniformity were made for overlapped sprinklers at recommended spacing of 18 m × 18 m at head, middle and tail end of lateral lines for selected field at different locations of the command area. The estimated values of uniformity coefficients (CUc) and distribution uniformity (DU) along the laterals from head to tail ends varied from 71.8 to 82.8% and 66.6 to 74.3% respectively. The water distribution uniformity decreased from head end to the tail end of the lateral lines and was not satisfactory at middle and tail ends of the laterals. The sprinklers discharge and pressure along the lateral line from head end to tail end varied from 6.1 to 14.3% and 9.4 to 24.1% respectively. The values were higher for field having longer laterals (360 m to 410 m) as compared to the fields having shorter laterals (260 m to 295 m). The sprinkler discharge efficiencies varied from 87.08 to 92% and the values were slightly lower than the proposed ranges. The sprinkler spray losses were higher due to high evaporation during the test.

Keywords: Overhead irrigation; Water distribution uniformity; Sprinklers; Pressure; Discharge variation; Spray loss

Introduction

The undulating topography and shallow marginal soils in highlands of Ethiopia are most favorable for the adoption of overhead sprinkler irrigation system. However, the use of sprinkler irrigation in Ethiopia is limited mainly due to lack of local manufacturing and economically poor farmers. The extensive use of sprinkler irrigation in Ethiopia started for production of sugar cane crops in large state farms. Presently, sprinkler irrigation is widely practiced at Finchaa, Tana-Beles, and Wonji-Shoa sugar estates in Ethiopia.

The need for irrigation arises from the lack of timely and adequate natural rainfall for extensive productions of annual crops like sugarcane in Ethiopia. Finchaa sugar estate is a large-scale farm where sugar cane crops are grown at three alienated schemes: East-bank, West-bank and Nashie farm for the production of sugar cane. The production potential of sugarcane crop of the estates relies on irrigation during the dry season starting from October to May. Currently, several irrigation problems were observed at East Bank sugar estate. These include non-uniform growth of crops, water stress conditions and stunted plant growths in most fields. The sugarcane crop yields declined in most fields resulting decreased production. Oteng-Darko et al. [1] reported the adverse effects of non-uniform application of water necessary for the plants on crop growth. The non-uniform water application leads to water logging, leaching of plant nutrients, non-uniform and stunted crop growth. The assessment of sprinkler irrigation system performance is very important improvement mechanism of the overhead irrigation system performance. The main challenges of sprinkler irrigation system are associated with poor water application system and low distribution uniformity [2]. The evaluation of overhead sprinkler irrigation system performance should be concerned with the assessment of sprinklers water application efficiency and distribution uniformity in the field [3]. Therefore, the present study was initiated to assess the performance of existing sprinkler irrigation system using different performance indicators related to water application uniformity, efficiency and variation of operating pressure and discharge in the system.

Specific objectives

- To evaluate the sprinklers system discharge and operating pressure variations along the field laterals at prevailing operating system
- To evaluate uniformity of sprinklers water distribution system using distribution uniformity performance indicators.
- To evaluate water application efficiency of sprinklers and spray losses in the field.

Materials and Methods

Study area

The study was conducted at Finchaa, East-bank sugar estate which is located between the geographical boundaries of 9°30' to 10°00' N latitude and 37°15' to 37°30' E longitude. The average altitude of the area is 1,350 m above mean sea level. Its topography is generally described as gradually undulating with an average downslope of 0 to 5% [4]. At Finchaa sugar estate; there are three separate sub-estate sugar cane farms namely: West-bank, East-bank and Nashie. East-bank and West-bank commands are irrigated by water supplied from the same water source of Finchaa River through separate canals. Nashie farm is the late expansion commands of Finchaa sugar estate. The East-bank sugar cane farm is separated from West-bank by the gorge of Finchaa River which is tributary of Blue Nile. The location map of Finchaa sugar estates is shown in Figure 1.

The climate of the area is a warm humid tropical zone with mean annual maximum (T_{max}) and minimum air temperature (T_{min}) equal to 33.2°C and 15°C respectively. The mean annual rainfall of the area is

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Received January 18, 2019; **Accepted** March 01, 2019; **Published** March 08, 2019

Citation: Terefe Y, Singh P (2019) Evaluation of Overhead Irrigation System Performance at Finchaa, East-Bank Sugar Estate, Ethiopia. Irrigat Drainage Sys Eng 8: 227. doi: 10.4172/2168-9768.1000227

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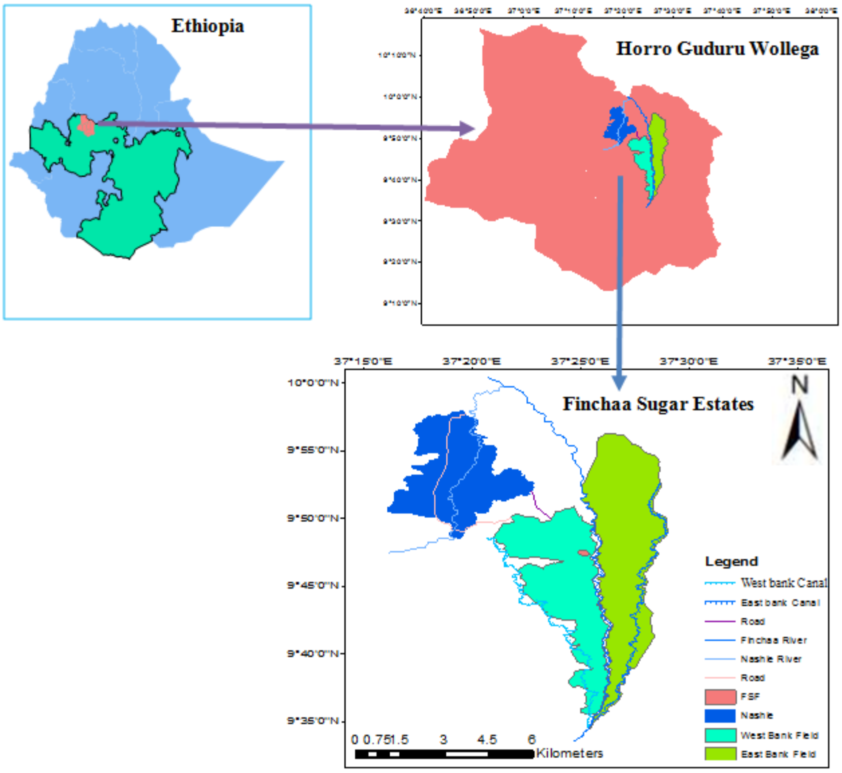

Figure 1: Location map of Finchaa, East-bank Sugar Estate.

1,276.5 mm per year. The long year average of daily recorded maximum wind speed of the estate is less than 3 km h^{-1}. At Finchaa sugar estate, the dry season starts in October and extends up to May. The irrigation of sugarcane crop during this period is crucial for successful crop production.

The Finchaa, East-bank sugar estate water acquisition, and conveyance system includes headwork, lined main canal, closed pipe mainlines, sub-main lines, hydrants and field laterals. Flows into the main canals are regulated manually with a single radial gate at headwork. The gravity fed and pump fed systems are installed at various reaches along the main canal to deliver water to each field from canal off-takes. Water released from canal off-takes reaches the field through closed pipes of main lines, sub-mains, and laterals. The water flows into sub-main lines and laterals are regulated by isolation valves and valves at hydrants respectively. Most of the lateral lines in East Bank fields are HDPE pipes. The length of lateral pipes varies based on the size of the fields. The irrigation water is applied to crop by semi-portable dragline sprinklers fed by 36 m long hoses attached to the sprinklers. The sprinklers are mounted on risers (tripods) made of aluminum pipes. The radius of the wetted area of the sprinklers at recommended operating pressure equal to 3 bar to 3.5 bar was 15 m. The sprinklers have double nozzle head with size of 2.4 mm by 4.4 mm. The irrigation is done by shifting sprinklers manually at recommended lateral line and main line spacing of 18 m × 18 m based on the sprinkler wetted area at recommended operating pressure. The layout of sprinklers installed in the sugar cane fields is shown in Figure 2.

Methodology

Data sampling techniques

Representative Fields were selected to collect sample data at different locations. The field observations were made having transient walk to examine the status of fields before starting data collection. Four representative fields were randomly selected from the entire East-bank Commands at different locations. The two fields were selected from pump fed irrigation commands (irrigation water is supplied to the fields by centrifugal pump) and the other two fields were selected from gravity fed irrigation commands (water supplied by gravity). The pump fed fields were designated as $EP3_{-6}$, and $EP9_{-9,}$ and the gravity fed as $EG6_{-4}$ and $EG12_{-13}$. Three lateral lines at upstream, middle and downstream locations were selected for each of the four selected field to collect data for evaluation of the overhead irrigation system performance of sprinklers. The layout of the selected fields and lateral lines is shown in Figure 3.

Measurement of sprinklers discharge and operating pressure variation

The sprinklers discharge and operating pressure were measured at head and tail ends of each of the 12 selected lateral lines using the method as described by Bishaw [5]. The sprinklers nozzle operating pressures were measured using pressure gauge fitted with a pitot tube. The percentage variation of the sprinklers discharge and operating pressure along the laterals were estimated using eqns. (1) and (2) respectively.

$$q_v = \frac{q_{max} - q_{min}}{q_{max}} * 100 \quad (1)$$

where,

q_v=discharge variation (%)

q_{max}=maximum sprinkler discharge at the head end of lateral (lit s^{-1})

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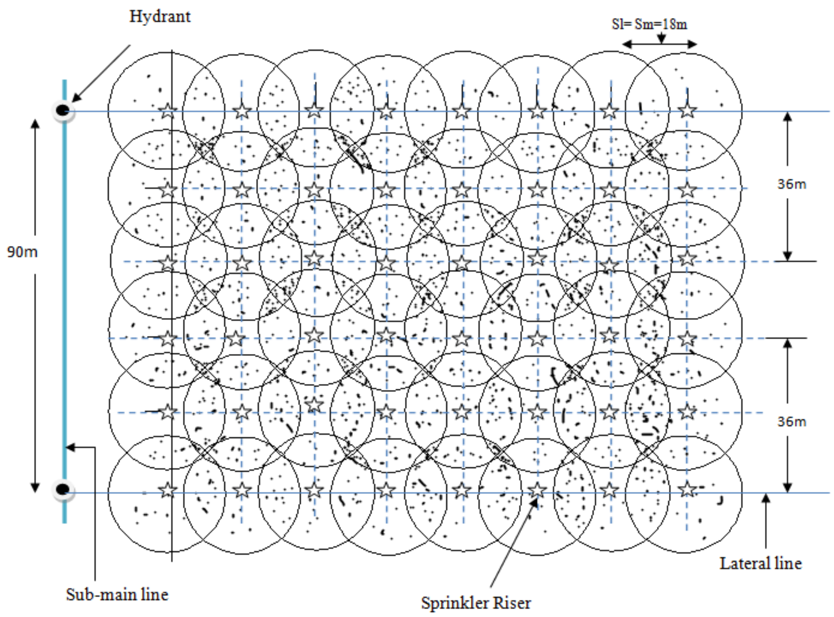

Figure 2: Layout of operating sprinkler irrigation system at Finchaa Sugar Estate.

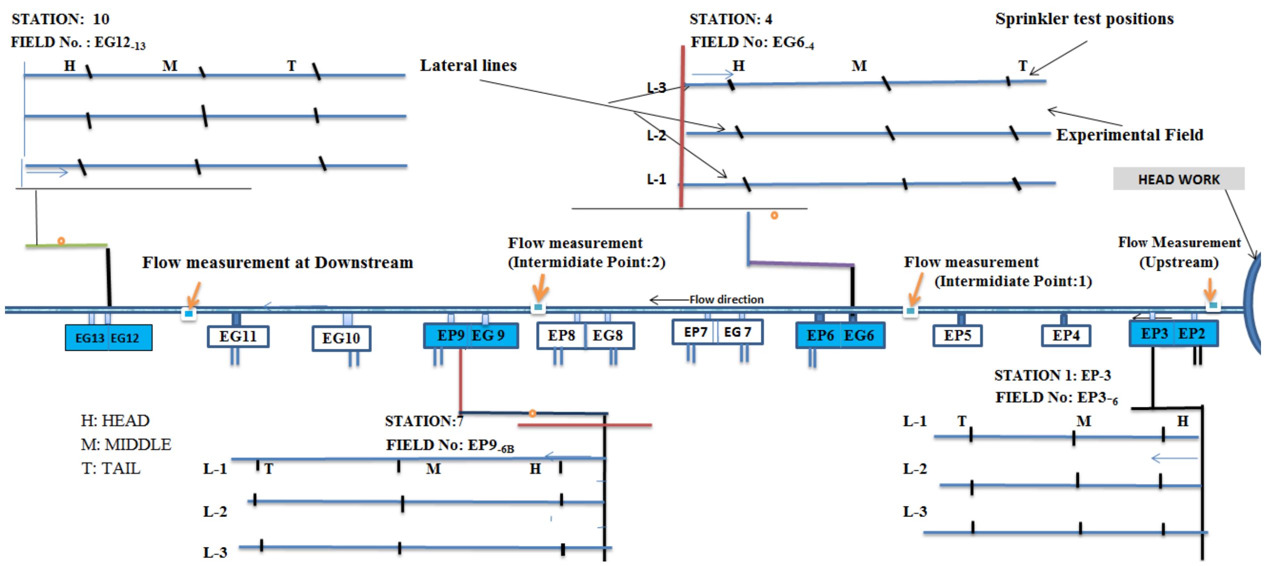

Figure 3: Description of representative field locations for data collection.

q_{min}=minimum sprinkler discharge at the tail end of lateral (lits^{-1})

$$P_v = \frac{P_{max} - P_{min}}{P_{max}} * 100 \qquad (2)$$

where,

P_v=pressure variation (%)

P_{max}=maximum operating pressure along lateral (bar)

P_{min}=minimum operating pressure along lateral (bar).

Measurement of water distribution uniformity indicators

The main objective of sprinkler irrigation is to apply water on the soil surface to appropriate water distribution uniformity at the low operating pressure on wide spacing [6].The data for measurement of overhead sprinklers water distribution uniformity indicators were collected at head, middle and tail ends of each of the 12 selected field laterals by operating the sprinklers at the estate recommended spacing of 18 m × 18 m and operating pressure. The grid points were marked in the 18 m × 18 m area at grid spacing of 3 m × 3 m. The standard catch cans 36 in number, each of 80 mm diameter and 15 cm depth were placed at the grid points as shown in Figure 4. The tests were conducted in fields of short sugar cane crop (height less 0.75 m) to avoid interruption of overhead water droplets by plant leaf as stated by Kelley [7]. The sprinkler water application tests at each location were operated for 2 hr and the depths of water collected in the catch-cans were measured. Additional data collected during the test were sprinkler discharge, operating pressure, evaporation rate and wind speed.

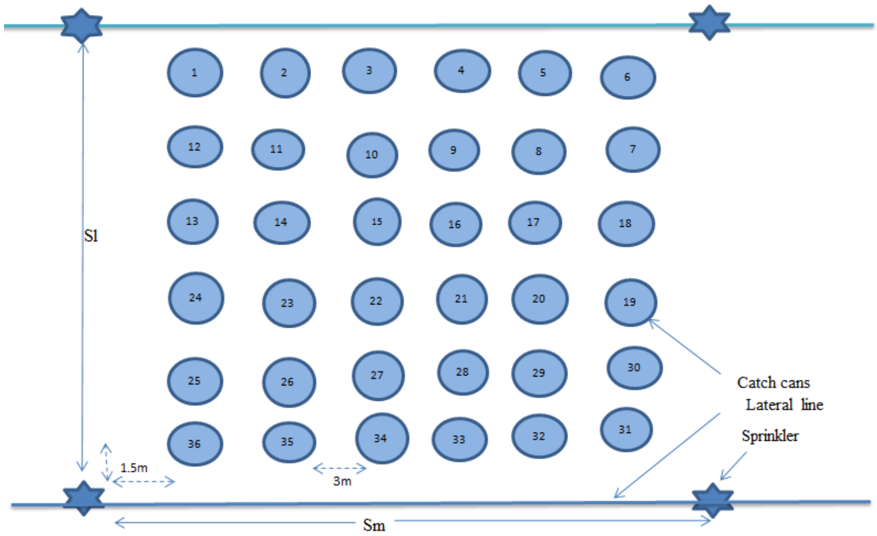

Figure 4: Catch cans layout for block test measurement.

The major water distribution uniformity indicators estimated were: i) Distribution uniformity ii) Christiansen coefficient of uniformity iii) Distribution uniformity absolute low as expressed by eqns. (3)-(5).

i. Distribution uniformity

$$DU = \frac{X_{lq}}{X_a} * 100 \quad (3)$$

where,

DU=distribution uniformity (%)

X_{lq}=average low quarter depth of water collected in the catch can (cm)

X_a=average depth of water collected in the catch can (cm).

ii. Coefficient of uniformity

$$CU_c = 100\left(1 - \frac{\sum |X_i - X_a|}{\sum X_i}\right) \quad (4)$$

where,

CU_c=Christiansen Uniformity Coefficient (%)

X_i=depth of Water collected in each catch can (cm)

X_a=average value of collected water depth (cm).

$\sum |X_i - X_a|$=sum of absolute deviations of each water depth from average.

iii. Distribution uniformity absolute low

$$DU_a = \frac{X_{min}}{X_a} * 100 \quad (5)$$

where,

DU_a=distribution uniformity absolute low (%)

X_{min}=minimum value of water depth collected in the catch can (cm).

Sprinklers discharge efficiency

Sprinklers discharge efficiency is a measure of the fraction of water applied from a sprinkler head that reaches the soil surface. It was calculated from the ratio of water depth collected in the catch cans to the application rate of system discharge as described by Edkins [2]. The measurements of water collected in catch-cans and system discharges were made by operating single sprinklers at the middle of each of the 12 selected field lateral lines. The grid points were marked in the sprinkler wetted area at grid spacing of 3 m × 3 m. The 104 standard catch cans each of 80 mm diameter and 15 cm depth were placed at the grid points as shown in Figure 5. The sprinklers system was operated for 2 h for each test. The layout of catch-cans for sprinkler test was selected based on methods described in past studies of Christiansen [8] and Dabbous [9]. The sprinkler discharge was measured directly from the sprinkler nozzles head using a hose pipe to divert water into a bucket and recording the volume of water collected and time. The water evaporation for the test period was measured by putting four cans filled with100 ml of water in the field at different locations near to the test sites. The sprinkler overhead discharge efficiency was expressed mathematically by eqn. (6).

$$DE = 100 * \frac{1/n\ (\Sigma X_i)}{q_s * t /\ (n * S_x * S_y)} \quad (6)$$

where,

DE=sprinkler discharge efficiency (%)

n=number of catch cans

q_s=sprinkler nozzle discharge ($cm^3 s^{-1}$)

t=duration for nozzle discharge measurement (sec)

X_i=depth of water collected in different catch cans (cm)

$S_y * S_x$=catch cans grid spacing (3 m × 3 m).

Results and Discussion

Sprinklers discharge and operating pressure variation

The system discharge and operating pressure variation along the laterals were estimated from the maximum and minimum sprinkler discharge (q_s) and operating pressure (P_s) measured at head and tail end of the selected field laterals using eqns. (1) and (2) respectively.

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The measured values of operating pressure, sprinkler discharge and the estimated value of the variations are given in Table 1.

It may be observed from Table 1 that the sprinklers operating pressure (p) varied from 3.31 to 3.7 bar and 2.6 to 3.1 bar at the head and tail end of the lateral lines respectively. The operating pressure was higher at the head f lateral lines and lower at the tail end of the lateral. The measured values of sprinklers nozzle discharge varied from 0.32 to 0.35 l s^{-1} and 0.28 to 0.31 l s^{-1} at the head and tail end of the field laterals respectively. The sprinkler discharge and operating pressure varied from 6.1 to 14.3% and from 9.4 to 24.1% respectively. The variations were lower for fields with shorter field laterals ($EP3_{-06}$ and $EG6_{-04}$) as compared to the fields of longer lateral lines ($EP9_{-6}$ and $EG12_{-13}$). However, the type of off-take, whether pump fed or gravity fed had no significant influence on variations of sprinkler discharge and operating pressure along the field laterals. The serious physical problems which affected system discharge variation and pressure loss along the field laterals were leakages from pipes, riser valves, fittings and friction loses. According to Merkley and Allen [10], the optimum values of sprinklers operating pressure and discharge variation are ±20% and ±10%, respectively. Thus the sprinkler discharge and operating pressure variations for fields $EP9-_{6}$ and $EG\ 12-_{13}$ were considerably higher than the permissible value while for those fields $EP3-_{6}$ and $EG6-_{4,}$ the operating pressure and sprinkler discharge variation were within acceptable range.

Water distribution uniformity measurement

The values of water distribution uniformity indicators DU, CUc and DU_a estimated using eqns. (3), (4) and (5) respectively at different selected field locations are given in Table 2.

The values of DU, CUa and DUa varied from 71.2% to 77%, 80.6%

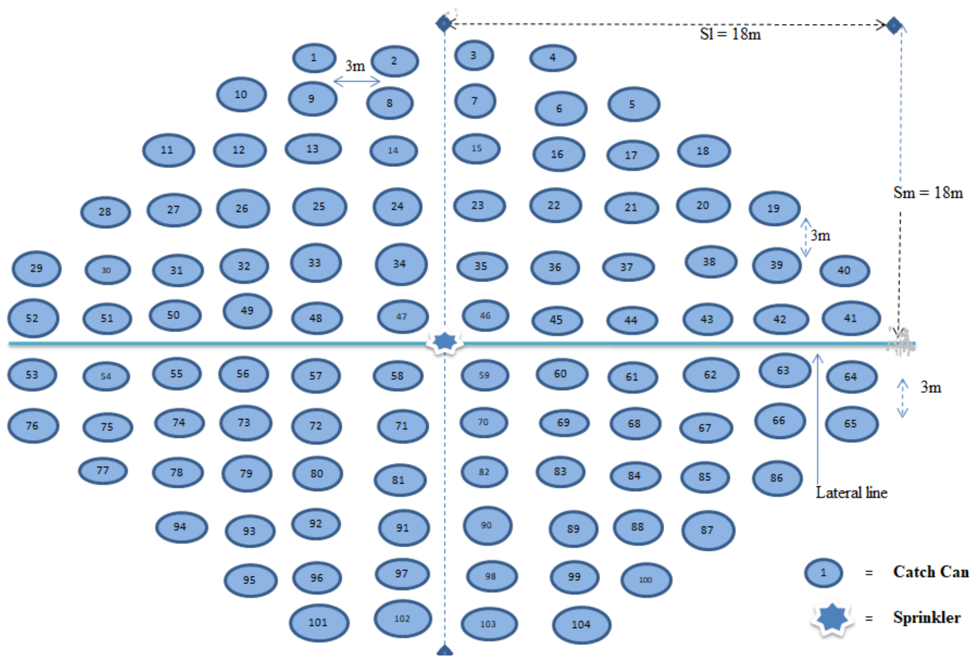

Figure 5: Catch cans layout for point source test measurement.

Off-takes	Field No.	Field area(ha)	Length of laterals (m)	Head end		Tail end		P_v (%)	q_v (%)
				P (bar)	q_s (l s^{-1})	P (bar)	q_s (l s^{-1})		
OT-1 (Pump fed)	$EP3-_{6}$	19.03	260	3.43	0.33	3.1	0.31	9.62	6.1
OT-4 (Gravity fed)	$EG6-_{4}$	19.11	295	3.31	0.32	3.0	0.30	9.4	6.3
OT-7 (Pump fed)	$EP9-_{6}$	29.0	360	3.4	0.33	2.6	0.28	23.5	13.64
OT-10 (Gravity fed)	$EG12-_{13}$	26.6	410	3.7	0.35	2.81	0.30	24.1	14.3
Overall average values		23.4	331	3.5	0.33	2.9	0.30	15.7	10.1

Table 1: Sprinklers discharge and operating pressure variations along the laterals.

Off-takes	Selected Field	Head			Middle			Tail		
		DU (%)	CUc (%)	DUa (%)	DU (%)	CUc (%)	DUa (%)	DU (%)	CUc (%)	DUa (%)
OT-1	EP3-6	73.8	80.6	55.9	68.4	74.5	51.3	67.4	70.9	51.4
OT-4	EG6-4	77	85.6	55.5	72	81.7	52.5	70.8	75.8	53.1
OT-7	EP9-6	71.2	81.1	56.6	68.4	76.9	53.2	65.8	69	48
OT-10	EG12-13	75.1	84	49.7	67.8	74.4	51	62.2	71.5	46
Overall Average		74.3	82.8	54.4	69.2	76.9	52	66.6	71.8	49.6

Table 2: Estimated average values of water distribution uniformity indicators.

to 85.6% and 49.7% to 56.9% at the head, 67.8% to 72%, 74.4% to 81.7%, and 51.0% 53.2% at the middle and 62.2% to70.8%, 69.0% to 75.8%, and 46.0% to 53.1% at the tail end respectively. The overall average values of DU, CU_c and DU_a were 74.3%, 82.8%, 54.5% at the head, 69.2%, 76.9%, 52% at the middle and 66.6%, 71.8%, 49.6% at the tail end of laterals, respectively. The values of DU, CU_c and DU_a were higher for sprinklers operating near to the head end of laterals and lower for sprinklers at the tail ends of the lateral lines. The values of the water distribution uniformity indicators significantly decreased from the head to the tail ends due to the variation of sprinkler discharge and operating pressure along the field laterals (Table 1). Keller and Bliesner [11] recommended the values of DU and CU_c for satisfactory performance of the sprinkler irrigation system to be equal to 75% and 84% respectively. The estimated values of DU and CU_c at the middle and tail ends of field laterals for present study were lower than the values as recommended by Keller and Bliesner for satisfactory performance [11].

Merkley and Allen [10] stated the main factors which affect water distribution uniformity of overhead irrigation system including pressure drop, wind drift losses and sprinklers spacing in the field. But at Finchaa sugar estate condition, the long year average of daily maximum wind velocity was less than 3 km h^{-1} with only slight annual variations indicating less significant effects on water distribution uniformity of sprinklers. Sahoo et al. [12] reported the effects of wind drift on water distribution and spray patterns of sprinklers at different wind speed condition and concluded that the wind velocity below 4 km h^{-1} is not very serious while the wind velocity above 15 km h^{-1} highly distorts the spray patterns of sprinklers in the field. The major reseason for lower values of the water distrubution uniformity at the middle and tail ends in the present study was considerable operating pressure drops along the field laterals.

Effects of sprinklers operating pressure on DU and CU_c

The graphical variations for the estimated values of DU and CU_c with sprinkler operating pressure are shown in Figure 6. It may be observed from Figure 6 that DU and CU_c values increased linearly with the increase in operating pressure of sprinklers. Bishaw [5] conducted water distribution test at different sprinklers operating pressure at Wonji-Shoa sugar estate and observed similar trends of variations of water distribution uniformity with sprinkler operating pressure.

Sprinkler discharge efficiency and spray losses

The sprinkler discharge efficiency (DE) was estimated using eqn. (6). The estimated average values for each of the selected field are given in Table 3.

The sprinkler discharge efficiency varied from 87.08% to 92% with the overall average value of 88%. The result indicated that 12% water was lost from sprinkler spray before reaching ground surface. The estimated losses for the present study were large as compared to the values proposed by Merkley and Allen [10]. Yazar [13] indicated the combined effects of wind drift and evaporation rate as the main factors which affect spray losses of sprinkler irrigation system depending on climatic and operating conditions. Merkley and Allen [10] suggested that the wind drift and evaporation losses for sprinkler irrigation systems may vary from 5-10%. Shamnugam [14] classified wind speed as low (less than 6.4 km h^{-1}), medium (6.4 km h^{-1}-12.8 km h^{-1}), high (above 12.8 km h^{-1}) and he reported that the sprinklers spray loss by wind drift was less significant for low wind speed conditions (less than 6 km h^{-1}). Sahoo et al. [12] also observed that the wind drift losses were highly significant in areas where the maximum wind speed reaches 15 km h^{-1}. The annual average wind speed at Finchaa East-bank sugar estate was within the range of low wind speed and thus had insignificant effect on spray losses. Based on the long term wind speed records of Finchaa sugar estate, it was observed that the daily average wind speed of the area varied from 2.1 to 3.2 km h^{-1} throughout the year. On the other hand, the evaporation rate measured during the test was 0.14 mm h^{-1}, which was considered to be high and had significant effect on water losses from sprinkler spray during the test. This indicates that the overhead discharge efficiency of sprinklers installed at Finchaa, East-bank sugar estate was significantly affected by evaporation rather than by wind velocity.

Conclusion

In this study, the performance of sprinkler irrigation system installed at Finchaa, East-bank sugar estate was evaluated. The sprinkler discharge and operating pressure were higher at the head end of laterals and significantly decreased towards the tail ends. The high variations of sprinkler discharge and operating pressure were observed for field having longer laterals as compared to the fields having shorter laterals. The main reasons for the variation of sprinkler discharge (q_v) and operating pressure (P_v) along the laterals were higher pressure losses

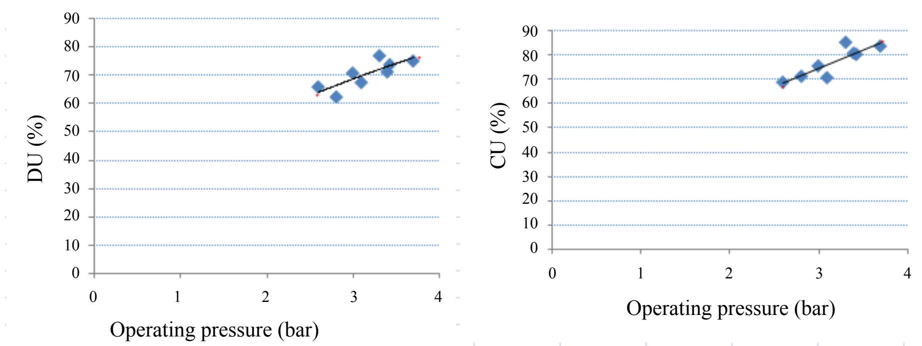

Figure 6: Variation of DU and CU_c value with sprinkler operating pressure.

Field Number	EP3-6	EG6-4	EP9-6	EG12-13
Sprinklers discharge efficiency	92%	87.08%	87.80%	88.70%

Table 3: Measurements of sprinklers discharge efficiency in selected fields.

due to friction and leaky pipe fittings of sprinklers in the field laterals. The water distribution uniformity in the system was also lower than the recommended values. The estimated sprinkler discharge efficiency was slightly lower due to the high evaporation rates during the test period. In general, major problems identified were poor water distribution uniformity, larger variation of operating pressure and sprinkler discharge along the lateral line due to improper functioning of infield water distribution lines, leakages and poor maintenance of irrigation structures. This all resulted in non-uniform plant growth and water logging problems in most fields of Finchaa, East Bank sugar estate.

Recommendations

- Many sprinklers installed on the laterals were not operating at recommended nozzle pressure as it was tested for most field laterals. Therefore, sprinklers operating pressures at isolated valves and at hydrants should be checked regularly and corrected.
- Hydrant valves, field laterals, sprinkler hoses and pipe fittings on lateral line should be regularly maintained and properly managed in order to avoid leakages from the pipes and pressure drops in the field. Unnecessary wastages of water from the leaking pipes result accumulation of water in the field and crop root zone which may also leads to high ground water rising problem in the estate.

Acknowledgment

The authors express sincere thanks to Dr. Santosh Pingale, Scientist-C, NIH, Roorkee, India for his technical supports and valuable guidance in the preparation of this manuscript.

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