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ANALYSIS OF SOIL TEXTURE, FURROW GEOMETRYAND INFILTRATION RATE FOR IMPROVING WATER APPLICATION EFFICIENCY

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ABSTRACT

Soil texture, furrow geometry, and infiltration rate are the main characteristics for improving water application efficiency. Substantial amounts of diverted irrigation water are often lost because of poor water control, inefficient irrigation conveyance systems, poor on-farm water management, or poor application practices. Field experiments were conducted on three farm plots within the command area for water availability and accessibility under the Melka Hida small-scale irrigation scheme in the West Guji Zone of Oromia Region, Ethiopia. The physical characteristics of soil, including depth, particle distribution, textural classification, bulk density, field capacity, and permanent wilting point, were studied and the results are presented. Furrow parameters including slope, width, length, and shape geometry were measured. The cumulative infiltration and infiltration rates were also recorded. The results show that irrigation application efficiency ranged from 57 to 64% with an average of 61%, indicating that about 40% of the applied water was not used by crops. The storage efficiency ranged from 79.6 to 81.6% with an average of 80%. Soil moisture measurements showed that crops were water stressed during the experimental period. Application efficiency decreased with increasingly steep slopes and cutoff times, greater applied depth, and high inflow rate in the study area. Unavailability of irrigation water control structure, weakness of water users' associations, and maintenance of furrows and steep slopes were observed as the major causes of inefficient water management in the Melka Hida irrigation scheme.

Contribution/Originality: This study contributes original research work carried out to solve the real problems of marginal farmers in the West Guji Zone of Oromia, Ethiopia. This study uses new estimation methodology for improvement of field irrigation effeiciency in the Melka Hida small-scale irrigation scheme, through soil moisture monitoring and water mangement.

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1. INTRODUCTION

Water is the most important resource for life, since it is a basic need. With increased population growth and the erratic nature of rainfall, competition for water resources has increased. Due to water scarcity and drought, efficient application of irrigation water is expected in the context of increasing competition for water resources. Reliable and suitable use of irrigation water with appropriate system management can result in improvements in irrigation performance and ensure economic development (Mancosu, Snyder, Kyriakakis, & Spano, 2015). The main purpose of irrigation is to restore water to the plant root zone, making it available to the crop as a whole. This may be accomplished by means of several procedures that can be grouped thus: overhead, surface, and subsurface.

Ethiopia has an irrigation potential of 5.3 million ha, of which 3.7 million ha can be developed using surface water sources and 1.6 million ha using groundwater and rainwater. Currently a number of irrigation projects are being implemented with huge resources to help overcome human struggle and the hardship of poverty. Despite their promise as engines of agricultural growth, the efficiency of irrigation schemes in this country has not reached full potential (Awulachew & Ayana, 2011). According to the Food and Agriculture Organization (2011), 60% of the fresh water diverted for agriculture globally does not contribute directly to food production. This amount of water is lost because of poor water control, inefficient irrigation systems with leaking conveyance and distribution, and poor on-farm water management and application practices. The FAO maintains that only about 40% of fresh water abstracted globally for irrigation is being used effectively for consumption in agriculture. Part of the water discharged in these systems is lost to saline groundwater. According to Beshir and Bekele (2006), Ethiopia's irrigation efficiency is generally low – around 25–50% – and problems with rising water tables and soil salinization are now emerging. It is crucially important to measure application efficiency as a performance parameter in the use of irrigation water, to minimize wastage. Pearse (1973) suggested that improvement in surface irrigation efficiency is limited to the understanding of key factors such as soil type, topography, furrow shape, flow rate, and crop age that affect the performance of such systems. In the case of furrow irrigation, Holzapfel, Pannunzio, Lorite, Silva, and Farkas (2010) suggested that the correct selection of furrow irrigation variables – length, time of cutoff and discharges – improves irrigation scheduling and field water management. This may potentially reduce over-irrigation and deep percolation of applied irrigation water. Furrow length, width, shape, spacing, topography, and flow rate are among the parameters that were considered for evaluation of performance measures in the Melka Hida irrigation scheme. The efficient use of irrigation water is highly important due to the rapid increase in the world's population, particularly in developing countries where great potential for increasing food production and rural incomes is often found in areas under irrigation. This has become a very serious challenge in recent years and, despite the very high costs involved; the performance of many irrigation schemes has fallen far short of expectations (Food and Agriculture Organization, 1989).

To fill this knowledge gap, the present study was carried out on the Melka Hida surface irrigation scheme, constructed in 1999 by the government. It has an irrigation potential of 80 ha, and around 200 households are currently benefiting from it. Despite deterioration in its biophysical appearance, no evaluation of water application efficiency has been carried out to identify constraints and improve efficiency. Hence, it was deemed necessary to evaluate water application efficiency and devise the required improvements. The Melka Hida small-scale irrigation system is located in the Oromia Regional State of Ethiopia, West Guji Administrative Zone.

Irrigation development constitutes a major requirement and benefit for agricultural development and food security strategies. On the down side, irrigation schemes have the potential to degrade soil and waste valuable water resources if they are mismanaged. In recognition of both the benefits and disadvantages, assessment and evaluation of irrigation scheme efficiency has now become of paramount importance, not only to determine where the problems lie, but also to identify alternatives that may be both effective and feasible in improving efficiency (Abebe, 2015). This paper reports the results of recent research on soil physical properties, furrow geometry, and infiltration rate with the aim of improving water application efficiency.

2. MATERIALS AND METHODS

The field experiments were conducted on three farm plots within the command area, with water availability and accessibility being key for selection of plots. These plots were selected through communication and discussion with irrigation users, with input from kebele administrations and Gelana district irrigation office experts. The three selected plots are situated at the head (Feleke farm, H1), middle (Geremew farm, M1), and tail (Wako farm, T1) of the irrigation scheme. A detailed description of the experimental plots and crops grown in the study area is shown in Table 1.

Table 1. Description of the experimental plots and crops grown.

Field ID	Area (m^2)	Crop	Growing stage at start of experiment (days)	Planting date	Harvesting date
Head (H_1)	510	Tomato	45	4/1/2017	5/5/2017
Middle (M_1)	672	Tomato	40	9/1/2017	10/5/2017
Tail (T_1)	375	Tomato	48	1/1/2017	2/5/2017
Head (H_1)	510	Tomato	45	4/1/2017	5/5/2017
Middle (M_1)	672	Tomato	40	9/1/2017	10/5/2017
Tail (T_1)	375	Tomato	48	1/1/2017	2/5/2017

Source: Field data, 2017.

The experiments were conducted with three replications (furrows) in each of the experimental blocks; the selected replications in each plot were separated by a distance of 8–11 m. Immediately after selection of replications from each plot, wooden marker posts were installed to identify the selected replications from other furrows, as shown in Figure 1.

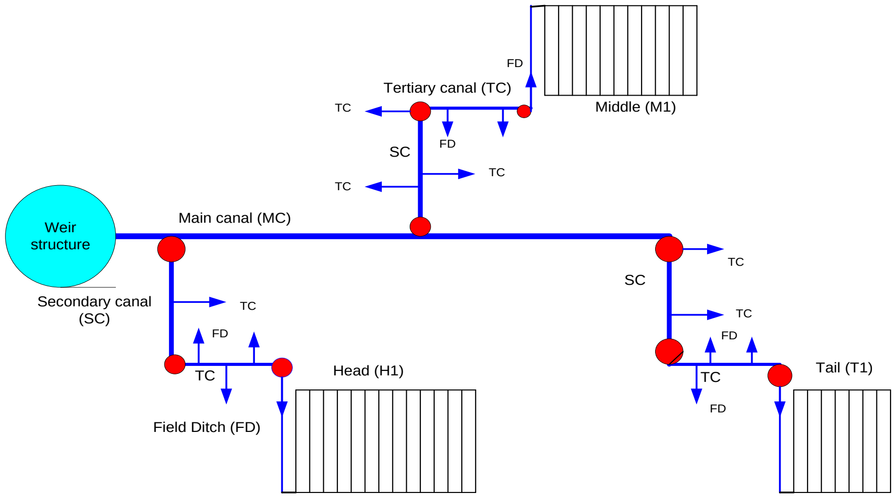

Figure 1. Schematic diagram of experimental plots.

2.1. Fieldwork for Primary Data Collection

Soil texture, field capacity (FC), permanent wilting point (PWP), and bulk density of the experimental fields were determined in the laboratory. Soil samples were collected from the three experimental plots at depths of 0–30, 30–60, and 60–90 cm using a core sampler. Locations of soil sampling in the experimental plot are shown in Figure 2. Soil samples were collected using a diagonal technique and mixed thoroughly according to recommendations (Thakur, Baghel, Sharma, Sahu, & Amule, 2012). In the process of sampling, the core sampler was inserted into the soil without disturbing the arrangement and structure of the soil using hammered metal. A sampling code was given to each soil sample based on pit, replication, and farm plots, to identify and analyze soil data without confusion.

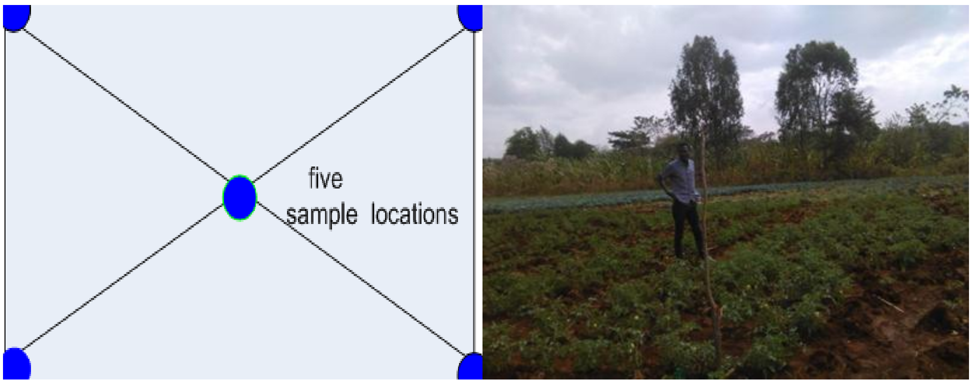

Figure 2. Location of sampling sites in the experimental plot.

In the laboratory, hydrometry was used to determine soil particle distribution while the USDA SCS soil textural triangle method was used to establish soil textural classification.The laboratory testing procedure on soil samples is presented in Figure 3. Bulk density of the soil was computed using Equation 1:

$$\rho b = \frac{M_s}{V_t} \quad (1)$$

where ρ_b is the bulk density of soil (cm^{-3}), M_s is the weight of oven-dried soil (g), and V_t is the total volume of soil (cm^3).

Soil FC and PWP were determined using a pressure plate apparatus at 1/3 and 15 bar, respectively. Moisture content was computed gravimetrically, by applying Equation 2:

$$\theta_m = \frac{M_w}{M_s} \times 100 \qquad (2)$$

where θ_m is soil moisture content expressed on a mass basis (%), *Mw* is mass of water (g), and *Ms* is mass of oven-dried soil (g). Volumetric water content was determined from the gravimetric content using Equation 3:

$$\theta_v = \theta_m \frac{(\rho_b)}{(\rho_w)} \qquad (3)$$

where θ_v is volumetric water content (%) and ρ_w is water density (g/cm^{-3}).

Figure 3. Laboratory test of soil samples.

Soil infiltration rate was determined in the field using a double-ring infiltrometer (Figure 4).

Total available soil water was computed using Equation 4:

$$TAW = 10(\theta_{fc} - \theta_{pwp}) \times Z_r \qquad (4)$$

where *TAW* is total available water (mm), θ_{fc} is moisture content at FC (vol %), θ_{pwp} is moisture content at PWP (vol %), and Z_r is rooting depth (m).

In this study, furrow length, width, depth, and spacing were measured for each replicate at all three farm plots using measuring tape, spirit level, ropes, and stakes (Kulapongse, 1966).

Furrow slope was measured at two locations along each replicate using Equation 5:

$$S = \frac{V}{H} \qquad (5)$$

where *S* denotes furrow slope (–), *V* is vertical distance (m), and *H* is horizontal distance (m).

Figure 4. Measurement of soil infiltration rate.

2.2. Field Application Efficiency

As reported by the Food and Agriculture Organization (2002), furrow application efficiencies of 50–70% are commonly reported, 85–90% are periodically reported from studies incorporating careful soil moisture monitoring, and performance may be acceptable if water application efficiency is >70%. Application efficiency is computed using Equation 6, and the depth of water stored in the root zone was calculated by Equation 7:

$$Ea = \frac{D_s}{D_f} \times 100 \qquad (6)$$

where E_a is application efficiency (%), D_s is the actual volume of irrigation water stored in the root zone (mm), and D_f is water delivered to the field or farm (mm). Ds was estimated thus:

$$D_s = M_c \times Asg \times Z_r \qquad (7)$$

Where D_s is the depth of water stored in the root zone (mm), M_c is the moisture content of soil (%), *Asg* is the apparent specific gravity of soil, and Z_r is the depth of the root zone (m).

3. RESULTS AND DISCUSSION

3.1. Analysis of Physical Characteristics of Soil

The soil texture in the experimental field is dominated by clay loam and loam, which is red in color. Soil particle distribution and textural classification of the topmost 90 cm are presented in Table 2. Percentage particle size distribution across the experimental plots showed no significant variation. The topmost 30 cm is dominated by clay loam in all experimental plots; the middle 30–60 cm is predominantly clay loam near H1 and T1 but is loam in M1. The topmost 90 cm of T1 is clay loam while the bottom 60–90 cm is loam; a higher percentage of sand is present in both H1 and M1. The average soil texture is dominated by clay loam and, in general, shows no significant variation across the experimental field.

Soil texture is one of the most basic soil characteristics influencing infiltration, moisture, and drainage. According to the Food and Agriculture Organization (1992), a clay loam soil with a depth of 90 cm is often chosen as optimal for crop production under average management. The proximity of our experimental plots to each other is one of the reasons for the uniformity of soil texture across the site. The soil texture in the study area is good in regard to water-storage capacity and crop production. For this soil type, good irrigation performance should be expected under effective irrigation system management.

Table 2. Results of soil particle distribution and textural classification.

Experimental plot	Soil depth (cm)	Soil particle distribution (%)			Textural classification
		Sand	Silt	Clay	
Head (H_1)	0-30	37	24	39	Clay loam
	30-60	31	29	40	Clay loam
	60-90	40	35	25	Loam
Middle (M_1)	0-30	29	34	37	Clay loam
	30-60	34	41	25	Loam
	60-90	34	39	27	Loam
Tail (T_1)	0-30	26	38	36	Clay loam
	30-60	21	39.5	39	Clay loam
	60-90	27	33	40	Clay loam
Average		29	34	37	Clay loam

3.2. Bulk Density, FC, and PWP

Bulk density, FC and PWP of the experimental plots were determined in the laboratory for the topmost 90 cm of soil, and are presented in Table 3. Bulk density is a key soil property because it is used to estimate water-holding capacity. The bulk density of soil in the study area was 1.25 and 1.36 g/cm^{-3} for clay loam and loam, respectively. This is in agreement with results found in the literature, which describe a range of 1.2–1.5 g/cm^{-3} for medium soil (Ministry of Agriculture, 2011). Bulk density increased with soil depth in our experimental plots except for M1, which was low at a depth of 60–90 cm. This shows that soil compaction increases from top-down. This bulk density value demonstrates that both soil aeration and water-holding capacity are high across the plot. Therefore, under gentle slopes, soil erosion would not expected with such a level of bulk density.

Table 3. Results for bulk density, FC, and PWP.

Plot	Soil depth (cm)			
Head (H_1)	0–30	30–60	60–90	Average
ρ_bg/cm^{-3}	1.25	1.31	1.36	1.3
FC (vol. %)	29.2	29.5	28.1	29
PWP (vol. %)	13.3	14.5	13	13.6
TAW (mm/m)	159	150	151	155
Middle (M_1)	0-30	30-60	60-90	Average
ρ_bg/cm^{-3}	1.29	1.35	1.27	1.31
FC (vol. %)	30.5	29	29.2	29.6
PWP (vol. %)	13.6	13.2	11.4	12.7
TAW (mm/m)	169	158	178	169
Tail (T_1)	0–30	30–60	60–90	Average
ρ_bg/cm^{-3}	1.27	1.33	1.34	1.33
FC (vol. %)	30.7	28.7	29.8	29.8
PWP (vol. %)	14.2	13.8	13.1	13.7
TAW (mm/m)	165	149	167	163

Note: *FC, field capacity; PWP, permanent wilting point; ρ_b, bulk density; TAW, total available soil water.

Based on volumetric method, the average FC of the topmost 90 cm soil layer was 29, 29.6, and 29.8% at H1, M1, and T1, respectively. This shows that the FC of the Melka Hida irrigation scheme is almost uniform across the area.

The recommended values for soil FC range from 15–30% and 12–18% for clay loam and loam, respectively. The FC values of the study area are higher than those recommended in the literature for medium soil texture.

The average PWP of the topmost 90 cm soil layer was 13.6, 12.7, and 13.7% at H1, M1, and T1, respectively. The recommended range for PWP is 7–16 and 6–10% for clay loam and loam, respectively (Michael et al., 1972). As such, the PWP of the study area is marginally within the values recommended in the literature. The uniformity of FC and PWP across the experimental field is due to the uniformity of the soil texture in the study area. The available soil water of the topmost 90-cm layer ranged between 155 and 169 mm/m; the water-holding capacity of medium soils is expected to be 100–180mm/m (Michael et al., 1972). The soil moisture available is also virtually uniform across the plots, i.e., the moisture-holding capacity of the Melka Hida irrigation scheme is within the range of values described in the literature. This implies that the field has high water-storage capacity that will be beneficial in yielding enhanced agricultural production.

3.3. Furrow Slope and Dimensions

Furrow slope was estimated for the experimental plots (Figure 6) using Equation 5; slope varied between 1 and 2%: the average at H1, M1, and T1 was 1.45, 1.1, and 1.7%, respectively. In the experimental plots, average maximum (1.7%) and minimum (1.1%) slopes were at T1 and M1, respectively. Slope showed significant variation even between replicates in the same experimental plot. Maximum slope variation was 0.5%, at T1,. These values are outside the limits recommended in the literature – 0.2–0.4% for medium soil (Michael et al., 1972).

Our results show that the study area was dominated by a marginally suitable degree of slope in regard to surface irrigation, which has certain limitations. Slope is among the major topographic criteria regarding the suitability of surface irrigation as it is largely responsible for runoff and soil erosion, and the findings from our study area imply a potential erosion problem. It was observed that the challenge of soil erosion was of major consideration in the irrigation scheme. To deal with the soil erosion problem in yhe study area, permissive stream size should be applied (Figure 5). Farmers had constructed their furrows almost horizontally to reduce soil erosion and water wastage, especially at T1. Despite the best efforts of users, due to the gap in scientific knowledge, soil erosion and water losses remain of great concern in the irrigation scheme. Losses of this precious resource were due to the steep slopes, which were identified as the key factor affecting performance in the study area.

Figure 5. Measurement of slope and furrow dimensions in the field.

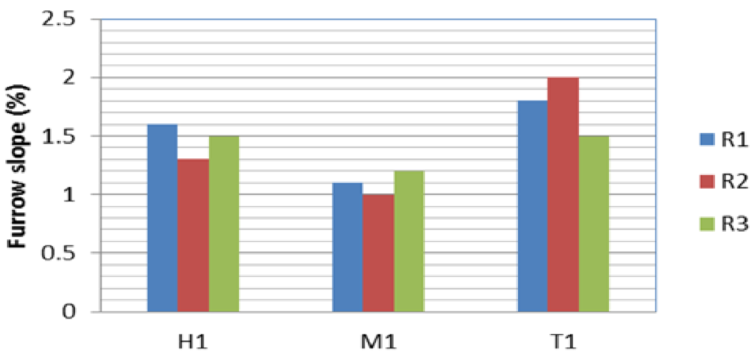

Figure 6. Influence of furrow slope in experimental plots.

Note: R1,R2,R3 :Replications of H1,M1,T1 for irrigations events 1,2 and 3.

3.4. Soil Infiltration Rate

The infiltration rate of soil in the irrigation scheme was determined for the three experimental plots by field measurement (Figure 7). The initial infiltration rate rapidly decreased as the soil was wetted, and infiltration reached the basic rate almost after 3 h. Basic infiltration rate determined for H1, M1, and T1 was 8.5, 9.0, and 11.25 mm/h, respectively. According to the Food and Agriculture Organization (2002), the recommended optimum infiltration rate for gravity irrigation is between 7 and 35 mm/h; for clay loam and loam this ranges between 5 and 10 mm/h, respectively. Hence, the basic infiltration rate for H1 and M1 was within the recommended range, while for T1 it was slightly higher. This may be due to land management conditions, because infiltration rate is markedly influenced by the condition of the soil surface. In regard to the ideal infiltration rate, the time for which irrigation water is applied must be properly managed to avoid deep percolation. At T1, due to furrow alignment, severe deep percolation was a problem that farmers did not take into account. The efficiency of irrigation application can be increased by using an appropriate inflow rate no greater than the soil infiltration rate. In general, the basic soil infiltration rate in the study area was within the optimum infiltration rate range for the gravity irrigation method (Tables 4–6).

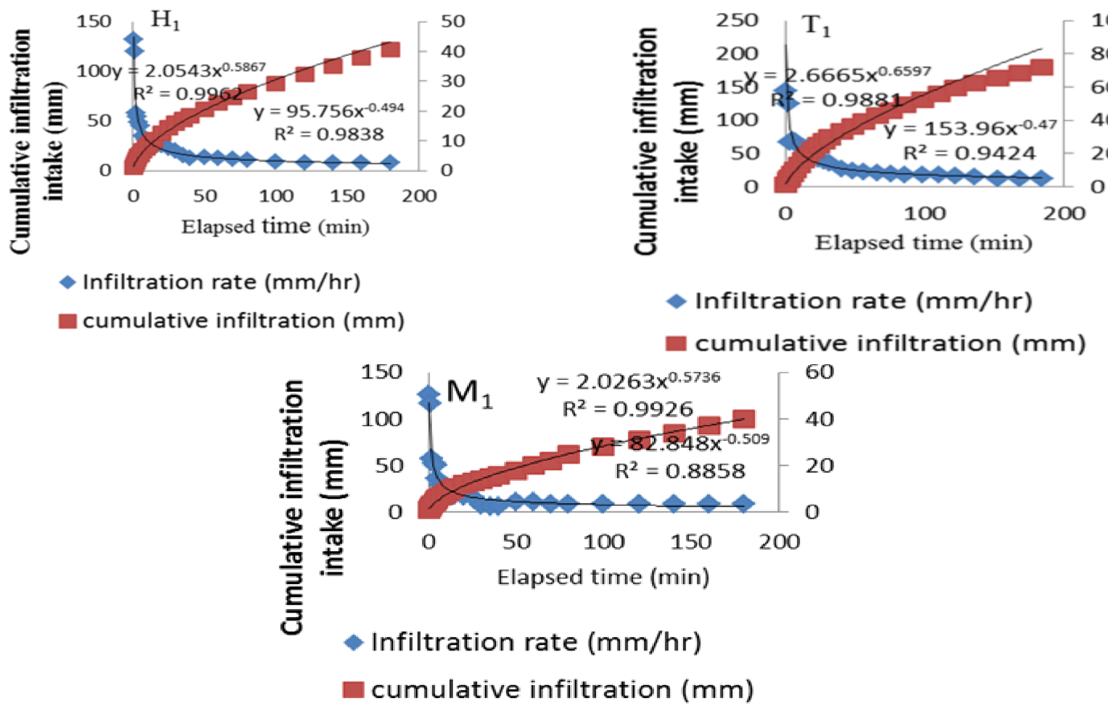

Figure 7. Cumulative infiltration (mm) and infiltration rate (mm/h) in the experimental plots.

Table 4. Infiltration rate and cumulative infiltration at H1.

Elapsed time (min)	Time interval (min)	Time (h)	Average intake (mm)	Average infiltration rate (mm/min)	Average infiltration rate (mm/h)	Average cumulative infiltration (mm)
0	0	0	0	0		
0.5	0.5	0.00833333	1.1	2.2	132	1.1
1	0.5	0.00833333	1	2	120	2.1
2	1	0.01666666	0.97	0.97	58.2	3.07
3	1	0.01666666	0.91	0.91	54.6	3.98
4	1	0.01666666	0.81	0.81	48.6	4.79
5	1	0.01666666	0.75	0.75	45	5.54
7	2	0.03333333	1.15	0.575	34.5	6.69
9	2	0.03333333	1.05	0.525	31.5	7.74
11	2	0.03333333	0.96	0.48	28.8	8.7
13	2	0.03333333	0.84	0.42	25.2	9.54
15	2	0.03333333	0.75	0.375	22.5	10.29
20	5	0.08333333	2.15	0.43	25.8	12.44
25	5	0.08333333	1.9	0.38	22.8	14.34
30	5	0.08333333	1.65	0.33	19.8	15.99
35	5	0.08333333	1.3	0.26	15.6	17.29
40	5	0.08333333	1.05	0.21	12.6	18.34
50	10	0.16666666	2.32	0.232	13.92	20.66
60	10	0.16666666	2.1	0.21	12.6	22.76
70	10	0.16666666	1.9	0.19	11.4	24.66
80	10	0.16666666	1.75	0.175	10.5	26.41
100	20	0.33333333	2.96	0.148	8.88	29.37
120	20	0.33333333	2.85	0.142	8.55	32.22
140	20	0.33333333	2.85	0.142	8.55	35.07
160	20	0.33333333	2.85	0.142	8.55	37.92
180	20	0.33333333	2.85	0.142	8.55	40.77

Table 5. Infiltration rate and cumulative infiltration at M1.

Elapsed time (min)	Time interval (min)	Time (h)	Intake (mm)	Infiltration rate (mm/min)	Infiltration rate (mm/h)	Cumulative infiltration (mm)
0	0	0	0	0		
0.5	0.5	0.008333333	1.05	2.1	126	1.05
1	0.5	0.008333333	0.97	1.94	116.4	2.02
2	1	0.016666667	0.95	0.95	57	2.97
3	1	0.016666667	0.88	0.88	52.8	3.85
4	1	0.016666667	0.83	0.83	49.8	4.68
6	2	0.033333333	1.2	0.6	36	5.88
8	2	0.033333333	0.97	0.485	29.1	6.85
10	2	.0333	0.92	0.46	27.6	7.77
12	2	0.033333333	0.89	0.445	26.7	8.66
14	2	0.033333333	0.82	0.41	24.6	9.48
18	4	0.066666667	1.25	0.3125	18.75	10.73
22	4	0.066666667	1.15	0.2875	17.25	11.88
26	4	0.066666667	1.05	0.2625	15.75	12.93
34	8	0.133333333	0.95	0.11875	7.125	13.88
42	8	0.133333333	0.92	0.115	6.9	14.8
50	8	0.133333333	0.85	0.10625	6.375	15.65
62	12	0.2	2.15	0.179167	10.75	17.8
74	12	0.2	2.1	0.175	10.5	19.9
86	12	0.2	1.85	0.154167	9.25	21.75
106	20	0.333333333	3.1	0.155	9.3	24.85
126	20	0.333333333	3.05	0.1525	9.15	27.9
146	20	0.333333333	3	0.15	9	30.9
166	20	0.333333333	3	0.15	9	33.9
186	20	0.333333333	3	0.15	9	36.9
206	20	0.333333333	3	0.15	9	39.9

Table 6. Infiltration rate and cumulative infiltration at T1.

Elapsed time (min)	Time interval (min)	Time (h)	Intake (mm)	Infiltration rate (mm/min)	Infiltration rate (mm/h)	Cumulative infiltration (mm)
0	0	0	0	0		
0.5	0.5	0.008333333	1.2	2.2	144	1.2
2	1.5	0.025	3.12	2	124.8	4.32
3	1	0.016666667	1.1	0.97	66	5.42
5	2	0.033333333	2.3	0.91	69	7.72
7	2	0.033333333	2.26	0.81	67.8	9.98
10	3	0.05	3	0.75	60	12.98
13	3	0.05	2.96	0.575	59.2	15.94
16	3	0.05	2.91	0.525	58.2	18.85
20	4	0.066666667	3.1	0.48	46.5	21.95
24	4	0.066666667	2.75	0.42	41.25	24.7
28	4	0.066666667	2.55	0.375	38.25	27.25
32	4	0.066666667	2.4	0.43	36	29.65
40	8	0.133333333	3.5	0.38	26.25	33.15
48	8	0.133333333	3.2	0.33	24	36.35
56	8	0.133333333	3	0.26	22.5	39.35
66	10	0.166666667	3.4	0.21	20.4	42.75
76	10	0.166666667	3.2	0.232	19.2	45.95
86	10	0.166666667	3	0.21	18	48.95
98	12	0.2	3.55	0.19	17.75	52.5
110	12	0.2	3.45	0.175	17.25	55.95
122	12	0.2	3.25	0.148	16.25	59.2
136	14	0.233333333	3.35	0.1425	14.36	62.55
152	16	0.266666667	3	0.1425	11.25	65.55
168	16	0.266666667	3	0.1425	11.25	68.55
184	16	0.266666667	3	0.1425	11.25	71.55

4. CONCLUSION

In this research, performance measures for the Melka Hida community-managed furrow irrigation scheme were evaluated. The performance measures used were the efficiency of application, distribution uniformity, and water storage, deep percolation ratio, and tail water runoff ratio. These parameters were evaluated at H1, M1, and T1 in the irrigation scheme.

Performance showed variation based on plot and irrigation event variation in the system. Water application efficiency ranged between 57 and 64%, with an average of 61% across the scheme.

Excess wastage of irrigation water was found, resulting from deep percolation and tail water runoff. Steep slopes, long cutoff times, and inflow rate greater than soil infiltration rate were revealed as the key factors. Other factors identified included lack of attention during irrigation application, absence of a water control structure, and irregular furrow construction by farmers. In addition, the effectiveness of the water users' association was poor in regard to irrigation system management due to a knowledge gap and financial constraints. The efficiency of application of irrigation water at the farm level was poor, particularly in T1. In conclusion, the need for further improvements in irrigation is required in this scheme.

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