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On-farm performance evaluation of improved traditional small-scale irrigation practices: A case study from Dire Dawa area, Ethiopia

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Abstract. Field evaluation of surface irrigation systems play a fundamental role to determine the efficiency of the system as it is being used and to identify management practices and system configurations that can be implemented to improve the irrigation efficiency. This study evaluated the performance of an 'improved' traditional small-scale irrigation practice at Adada, a representative small-scale irrigation practice in Dire Dawa Administrative Council, Eastern Ethiopia. In order to determine numerical values of performance measures, certain parameters were measured/observed before, during and after an irrigation event while farmers are performing their normal irrigation practice. These parameters include: irrigated crop, irrigation method, stream size, cutoff time, soil moisture deficiency, and field size, shape and spacing. The results showed that the irrigation water applied to a farmer's plot during an irrigation event/turn was generally higher than the required depth to be applied per event. Since the irrigation method used was end-dyked, the major cause of water loss was due to deep percolation. The deep percolation loss was 32% in sorghum, 57% in maize, and 70% in tomato and potato fields. The type of irrigation system used, the ridged irrigation practice and the poor irrigation scheduling in the study sites were the main problems identified in the management and operations of the schemes. The following corrective measures are recommended to improve the system: (1) farmers should regulate the depth of irrigation water they apply according to the type of crop and its growth stage, change the field irrigation system and/or configuration especially for shallow rooted row crops, to furrow system, (2) guidance and support to farmers in developing and introduction of appropriate irrigation scheduling, and (3) future development interventions towards improvement of traditional irrigation practices should also focus in improving the on farm irrigation systems in addition to improving physical infrastructure of the scheme.

Key words: Ethiopia, irrigation scheduling, performance evaluation, traditional irrigation

Introduction

Farmers around-the-world evolve their own system of management for their irrigation systems. Their management criteria result in a variety of performance levels depending upon the field conditions and the resources available to farmers. A traditional concept is that when water is scarce, because it is either physically, economically or legally limited, water will be used efficiently. One of the most difficult concepts to accept in Pakistan was that farmers with an inadequate supply of water could be using more water than was needed (Reddy & Clyma, 1993). The assumption that the water supply was inadequate was grossly invalid for some areas, but still farmers typically apply water according to traditional practices and the effectiveness of water use is accidental.

Traditional irrigation is very old in Ethiopia although modern irrigation was started only at the beginning of 1960s by private investors in the Middle Awash Valley. According to the Ministry of Water Resource's sector report, the area under irrigation is only about 197,250 ha (3% of the potential irrigable); of which small-scale irrigation accounts about 85,000 ha (MoWR, 1998). According to the Dire Dawa Administrative Council Water Mines and Energy Office water sector review report, total irrigated area in the Dire Dawa area is about 2039 ha (DDAC, 2000).

Technically the small-scale irrigation schemes in the Dire Dawa Administration can be categorized as *traditional irrigation schemes and improved community irrigation schemes.* The traditional schemes are those constructed by farmers with their own resource and initiative. They are characterized by temporary headwork, unlined canals and with or without unlined storage pond. The 'improved' community irrigation schemes are upgraded or newly constructed by government and/or non-governmental organization with some participation of the farmers. These schemes are characterized by permanent headwork, partially lined canals and with or without lined storage pond. Most of the small-scale irrigation in the region can be categorized as single-source multiple-user gravity system in which single water source, stream or colony of springs, is shared by a community.

The interventions so far made in the region towards the development of small-scale irrigation are mainly focused on upgrading the physical structure of the existing traditional small-scale irrigation schemes. Very limited or no effort has been made in improving the on-farm water management and operation. Traditional on-farm water management and operation continued to dominate irrigated small-holder production. Locally elected individuals called '*melaqa*' undertake the management; the beneficiaries of the schemes are responsible for maintenance of both types of schemes with some support from the Regional Water, Mines and Energy Office to maintain the 'improved' irrigation schemes. In almost all the irrigated areas in the region, surface irrigation (uncontrolled flooding) methods supplied from collective canal system are used. Fixed delivery schedule, poor/no on-farm land leveling, small plots and no or few structure to manage water in the field characterize the irrigation practice of the study area. These problems usually result in poor irrigation performance and low water use efficiencies especially in areas dominated by soils with high infiltration rate and low water retention characteristics. Poor irrigation management results in important social, economical and environmental problems (Pereiera, 1996). Therefore, ensuring the sustainability of irrigated agriculture requires an improvement in the performance of irrigation practices (Faci et al. 2000).

Field evaluation of surface irrigation systems plays a fundamental role to determine the efficiency of the system as it is being used and to identify management practices and system configurations that can be easily and efficiently implemented to improve the irrigation efficiency (Merriam et al. 1983; Walker, 1989). Farm irrigation systems are designed and operated to supply the individual irrigation requirement of each field on the farm while controlling deep percolation, runoff, and operational losses (Hart et al. 1983). The field evaluation should at least identify problems such as applying too much or too little water, the poor distribution of infiltrated water over the field, excess tail water runoff or significant deep percolation losses.

In view of the above background, the specific objectives of this study were: (1) to evaluate the adequacy of irrigation in terms of the perceived requirements; (2) to identify the type and magnitude of irrigation water losses in the farmers' plots; and (3) to identify problems encountered in the management and operation of the scheme and recommend appropriate measures to improve the performance of the system.

Materials and methods

Description of the study area

Dire Dawa Administrative Council is located between 9°27′N and 9°49′N latitude and 41°38′E and 42°19′E longitude at a distance of 515 km from the capital, Addis Ababa. The climate of the region is characterized mainly by warm and dry climate with mean monthly temperature of 25 °C and annual rainfall of 657 mm. The soil texture of the area is sandy loam. The study site is *Adada* small-scale irrigation scheme located 14 km southeast of Dire Dawa town.

The major irrigated crops grown in the area are tomato, maize, potato, and sorghum. Net scheme size is about 16 ha and the number of plot holders is 99 with average family size of 7. More than 82% of the farmers in the study area own rainfed plots other than their irrigated plots and generally rainfed plot sizes are larger than the irrigated ones. Average plot size per farmer (both rainfed and irrigated) is about 0.46 ha, of this irrigated plot accounts for about 0.16 ha and it ranges from 0.05 to 0.5 ha. Irrigated farmers' plots in the study area are generally rectangular in shape, and relatively flat in topography.

The most common type of irrigation unit is an end-dyked border with mean dimension of length 15.5 m, width 2.8 m and area of 34.3 m^2. Farmers in the study area use the same types of irrigation unit and method of irrigation irrespective of the type of crop they grow.

The irrigation water sources for the scheme are three perennial springs with cumulative average discharge of about 10 l/s. The discharge from each spring is between 2.2 and 5.6 l/s. Irrigation water from the source is first delivered to and stored in ponds before it is distributed to the farmers' plots. This is so because the discharge rate from the sources is so small and direct irrigation from the sources will result in high conveyance loss and poor on-farm irrigation efficiency. Therefore, the pond is the most important element in the water distribution system of the study area and its main purpose is to augment the flow delivered to a farmer's plot, rather than serve as night storage.

The irrigation water delivery and distribution system consists of 382 m long lined canal that delivers water from the sources to the storage pond, 40 cm diameter concrete pipe, two lined ponds of capacity 101 and 156 m^3, respectively, and field water distribution earthen ditch network of 4.6 km. The field distribution ditches are parabolic in shape and have top width between 30 and 50 cm and an average depth, including free board, of 30 cm. They have a capacity to deliver between 20 and 40 l/s, although the discharge delivered to the farmers usually range between 5.8 and 9.4 l/s.

Field data measurement

Soil samples were taken for the analysis of the following parameters: bulk density, moisture content at field capacity and permanent wilting points and moisture contents just before and about 36 h after irrigation events. To determine soil moisture deficit (SMD) and adequacy of an irrigation event, the soil moisture content just before and about 36 h after irrigation event were determined using gravimetric method. For this purpose, soil samples were collected per irrigation using soil auger at two to three sampling points (with two replicates per sampling point) which are located at the head, middle, and tail ends of the test unit. The soil moisture deficit, defined as the depth of water required to bring a specific depth of soil to field capacity at a particular time (Merriam et al. 1983), was computed using the relation:

$$\mathrm{SMD} = \sum_{i=1}^{n} (\theta_{\mathrm{FC}\,i} - \theta_i) D_{\mathrm{s}i} \tag{1}$$

where $\theta_{\mathrm{FC}i}$ is the field capacity moisture content in the ith layer of the soil, θ_i the existing moisture content in the ith layer of the soil, n the number of soil layers in the root zone, and $D_{\mathrm{s}i}$ the depth of the ith soil layer within the root zone (m).

To determine numerical values of performance measures, certain parameters were measured/observed before, during and after an irrigation event while farmers perform their normal irrigation practice. These include stream size, cutoff time, and soil moisture deficiency. In addition, data was collected about type of irrigated crops, irrigation method, field size, shape and spacing. For this purpose 8 farmer's plots and 16 irrigation units (2 units per plot) were selected among the irrigated plots. The selected plots were spatially distributed over the irrigated areas so that various (in terms of dimension, inflow rate and slope) irrigated plots located towards the head end, tail end and in between were reasonably represented. The plots were composed of a number of uncontrolled flooded end-dyked border or rows of series of basins that have relatively higher length dimension than their width dimension.

Irrigation evaluation

Discharge rate available for irrigation and inflow rates to farmers' plot or lower unit during an irrigation event were measured using Parshal flume. In order to note the irrigation phases conveniently, depending on the field lengths, three to five stakes were placed uniformly along the flow direction in the test unit. Two important measurements were noted during advance phase; the discharge rate into the test unit and the time the advance front arrives at each of the stakes. The measurements taken during ponding phase were the elapsed time between the time at which water reaches the end of the test unit and time of cutoff. The recession time was found difficult to be noted, as there were not discernable receding edge and pattern. Nevertheless, as the water drains from the test unit the time of recession at the stakes was noted.

The following elements to be used in the performance evaluation were obtained from the field measurements: (1) the amount of inflow or irrigation depth (D_{in}) per test unit computed as

$$D_{\text{in}} = \frac{Q_{\text{av}} T_{\text{ap}}}{A} \tag{2}$$

where D_{in} is the depth of water applied, A the area over which water is applied, T_{ap} the application time, Q_{av} the average discharge rate; (2) the infiltration opportunity time at each stake placed along the test unit computed as a difference in time between the irrigation water advance and recession from that particular point; and (3) depth of water the irrigation system should apply or the required irrigation depth (Z_{r}) computed for each major irrigated annual crop of the study area (Allen et al. 1998) as:

$$Z_{\text{r}i} = P \,\text{TAW}\, D_i \tag{3}$$

where Z_{ri} is the required depth to be applied for crop i, P the average depletion fraction for crop i, TAW the total available water of the soil, D_i the effective root depth of crop i.

Performance measures of irrigation event

The following on-farm irrigation performance and water loss measures or indicators were employed to characterize the performance of the on-farm irrigation systems during each irrigation event.

1. *Application efficiency* is the ratio of the amount of water stored in the subject region to the amount diverted into the subject region. The volume of water admitted into the subject region was computed as a product of the average inflow rate measured at the head end of the test unit and the average application time noted for that test unit. As all the irrigation units in the study area were end-dyked borders or series of interconnected check basins, there were no run off losses; thus the volume of water admitted equals total volume of water infiltrated over the entire reach of the test unit length. Volume of water infiltrated over the entire reach of the test unit was calculated by integrating the depth infiltrated versus distance curve equation developed for that test unit over the entire reach of the test unit. The total volume of water infiltrated over part of the test unit, which received irrigation amounts at least equal to the perceived requirement (Z_{ri}) was computed using the same equation but integrating over the length under consideration. The length of the test unit that receives irrigation water at least equal to Z_r was computed by combining depth infiltrated versus distance curve equation and the required depth (Z_r) to be applied to a particular crop. The volume of water retained in the subject region over the reach that receives excess irrigation was computed as the product of over irrigated length of the test unit (L_{ov}) and Z_r. The water application efficiency E_a was then calculated as (Zerihun & Feyen, 1996).

$$E_a = \frac{\int_0^L Z\,dx - \int_0^{L_{ov}} Z\,dx + Z_r L_{ov}}{\sum_{i=1}^{I} Q_{oi}\,\Delta t_i} \times 100 \tag{4}$$

where Z is the cumulative infiltration expressed as a function of distance (m^3/m), L the channel length (m), L_{ov} the length over which the infiltrated amount equals or exceed the requirement (m), Z_r the net irrigation requirement or perceived requirement (m^3/m), Q_{oi} the inflow rate during time period Δ_{ti}, Δ_{ti} the ith time interval during which the inflow rate is set at Q_{oi}, i the time index, I the total number of time interval.

2. *Adequacy or storage efficiency* is the measure of how close the applied amount is to the perceived requirement (the right amount) over the entire subject region and defined as the ratio between the amounts actually stored in the subject region to the required amount (Walker & Skogerboe 1987; Zerihun & Feyen 1996). The general form of storage efficiency E_s (Zerihun & Feyen, 1996) is

$$E_s = \frac{\int_0^L Z\,dx - \int_0^{L_{ov}} Z\,dx + Z_r L_{ov}}{Z_r L} \times 100 \tag{5}$$

3. *Distribution uniformity* is the minimum infiltrated amount (Z_{min}) divided by the average infiltrated amount (Z_{av}). The minimum infiltrated amount was taken equal to the minimum of the depth infiltrated computed for observation points (stakes) over the test unit under consideration. Average infiltrated amount was computed by dividing the volume of water infiltrated over the test unit length.
4. *Deep percolation fraction* is the ratio of the volume of water percolated below the bottom boundary of the subject region to the total volume admitted into the subject region (Karmeli et al. 1978). It is calculated as:

$$D_f = \frac{\int_0^{L_{ov}} Z\,dx - Z_r L_{ov}}{\sum_{i=1}^{I} Q_{oi}\,\Delta t_i} \times 100 \tag{6}$$

Results and discussion

The bulk density of the soil of the scheme under consideration shows variation with depth following the presence of a stratified material. It varies between 1.20 and 1.52 g/cm^3 and generally the top surface soil has lower bulk density than the subsurface. The field capacity and permanent wilting point moisture contents also vary with depth. The top 30–60 cm thick surface soils have larger average FC value of 32% while the subsurface soils have average FC value of 22%. The permanent wilting point moisture content is 18% at the surface and 13% for the subsurface. Mean value of total available water (TAW) was 136 mm/m depth of soil at the top and 100 mm/m depth of soil in the subsurface soil. The weighted mean TAW for the soil of the study site was found to be 115 mm/m depth of soil.

Field irrigation management

Irrigators do not pay for irrigation water and the schemes are managed by, in decreasing order of magnitude, locally elected person(s) called '*melaqua*', elders in the community and peasant association officials. Basically, each irrigator is free to grow a crop he wants and he is entitled to get a fixed amount (full pond, half full pond, etc.) of irrigation water based on a 'fixed interval of time' (days) during a particular period of growing season. The amount of water an irrigator could get during his turn mainly depends upon his irrigated plot size. His turn varies with the total number and size of plots under the scheme irrigated during that particular period of the growing season. However, the amount and interval during the particular period is subject to change depending upon the condition of the plant, availability of irrigation water and agreement between irrigators. The '*melaqua*' is mandated to fairly administer the scheme deciding which plot to irrigate, when, and how much irrigation water a plot holder should get during his turn. Elders and peasant association officials interfere with the management of the scheme only when there is a disagreement between the '*melaqua*' and other irrigators.

The usual trend in the area is that irrigation water from the sources is first diverted to and stored in pond (s) before it is distributed to a farmer's plot. This is so because the discharge from the sources is so small that direct irrigation from the sources will result in high conveyance loss. Therefore, pond is the most important element in the water distribution system of the study area. The method of operating the supply system is rotational, in which a fixed supply that equals to pond outlet discharge is used to irrigate a farmer plot. Each pond holder is responsible to operate the scheme during his turn. He checks all the distribution field ditch starting from his plot to the pond outlet for leakage and/or breakage, open the pond when it is full and then manage the irrigation water on his plot.

The total irrigation hours in the study area is divided into day and night shifts and vary between 10 and 12 h. The mean irrigation duration per farmer's plot is between 30 min and 1.5 h. Number of farmers' plot managed in a day ranges between 7 and 18 with mean value of 12. Farmers usually irrigate every 5–10 days. The method of operating the supply system is rotational, in which a fixed supply that equal to pond outlet discharge is used to irrigate a farmer plot with supply duration and supply interval varying according to plot size, type, condition, stage of cop grown and availability of water. Each plot holder is responsible to operate the scheme during his turn. He checks all the distribution field ditch for leakage and/or breakage starting from his plot to the pond outlet, open the pond when it is full, and then manage the irrigation water on his plot.

Field measurement of parameters

Average depth of water infiltrated per test unit was computed using the derived infiltration equations and the observed opportunity times at observation points in a test unit, and compared with measured inflow depths to each test unit. Three infiltration tests were conducted and the following infiltration equations were derived: Test 1: $Z = 1.7\,t^{0.648}$ ($R^2 = 0.94$), Test 2: $Z = 2.2\,t^{0.654}$ ($R^2 = 0.99$), and Test 3: $Z = 1.5\,t^{0.411}$ ($R^2 = 0.92$) with average: $Z = 1.8\,t^{0.571}$. The average difference between the computed average infiltrated depth and the measured inflow depth per test unit was 15% and varies between 0.9 and 34%. Since there was no runoff loss from the test units, the variation indicates failure of the infiltration equations to characterize infiltration over the entire study areas. Nevertheless, it was assumed that the computed infiltration values over the observation points on a test unit can at least show the relative distribution of depth of irrigation water infiltrated over the observation points. Thus, the difference between the mean computed infiltrated depth and the measured depth of water admitted to a test unit was equally distributed over the observation points and can approximate the actual field condition. The resulting values of depth infiltrated over the observation points are then used to quantify the performance measures used in this study.

Table 1 presents results of irrigation variables/parameters measured at the study area. The number of test units (plots) used in the determination of the variables was 16. The discharge rate mainly depends on the pond outlet capacity and the relative distance of a plot from the pond. Generally, the rate delivered to the tail enders is less than that of the head enders due to conveyance loss. The whole discharge delivered to a plot is directly admitted

Table 1. Measured irrigation variables/parameters.

No.	Irrigation variable/parameter	Measured magnitude		
		Minimum	Maximum	Mean
1	Irrigation unit length (m)	5.7	26.9	15.5
2	Irrigation unit width (m)	1.7	2.8	2.1
3	Irrigation unit area (m^2)	9.9	74.4	34.3
4	Slope (%)	−0.3	0.5	0
5	Inflow rate (l/s)	5.8	9.4	7.7
6	Application time (min)	1.3	12.0	5.9
7	Advance time (min)	1.2	11.1	5.3
8	Storage time (min)	0.0	1.9	0.7
9	Depletion time (min)	1.3	12.6	6.6
10	Recession time (min)	2.3	13.5	6.2
11	Opportunity time (min)	6.9	15.3	10.9
12	Depth applied (mm)	54.6	106.4	77.8
13	Soil moisture deficit SMD (mm/m)	34.0	85.0	61.5
14	Variation between computed infiltrated depth and measured inflow depth to a test unit (%)	0.9	34.0	15.3

into its lower units (border or series of check basins) turn by turn until all the area under the plot is irrigated or the stored water in the pond is drained out.

From Table 1 it can be observed that the applied depth was 28% larger than the SMD. The mean time required for the admitted irrigation water to complete the flow path (advance time) ranges from 1 to 11 min with average value of 5.3 min. Correlation analysis of the irrigation variables shows that advance time has significant positive linear correlation with irrigation unit length, width and area. Thus, it increases with the increase in length, width and/or areas of the irrigation unit. Ponding phase (interval between end of advance and inflow cutoff) was very small with mean value of 0.7 min. This was due to the fact that irrigators in the study area cutoff the inflow as soon as the water reach the end of the irrigation unit. Mean depletion phase (vertical recession) was 6.2 min. It has a significant positive correlation with length and area of the field, application time, advance time and distribution uniformity.

A total of 16 plots of infiltrated depth versus distance curves and their corresponding equations were derived and used to quantify the performance measures. For this purpose trend lines were fitted to the infiltrated depth computed over each observation points along a test unit (Table 2). The variation in the pattern of the equations was mainly attributed to the imprecise land leveling practice in the study area and the resulting rough surface (micro-topographical effect) and variation in magnitude and direction of the slope

Table 2. Summary of the pattern of depth infiltrated over test unit lengths and the corresponding trend line equation.

Test ID	Trend line equation
F1/TU1	$Y = -0.0011X^2 - 0.059X + 9.31$ (1)
F1/TU2	$Y = -0.0011X^2 - 0.059X + 9.2$ (2)
F2/TU1	$Y = -0.0225X^2 + 0.0354X + 11$ (3)
F2/TU2	$Y = -0.0048X^2 - 0.0262X + 12.7$ (4)
F3/TU1	$Y = -0.6992X^2 + 9.78$ (5)
F3/TU2	$Y = -0.0083X^2 - 0.70X + 7.6$ (6)
F4/TU1	$Y = -0.0434X^2 + 0.66X + 6.2$ (7)
F4/TU2	$Y = -0.0447X^2 + 0.64X + 8.3$ (8)
F5/TU1	$Y = -0.2389X^2 + 8.81$ (9)
F5/TU2	$Y = -0.0359X^2 + 0.199X + 9.9$ (10)
F6/TU1	$Y = -0.0006X^2 + 0.0162X + 9.4$ (11)
F6/TU2	$Y = -0.0027X^2 + 0.058X + 10.5$ (12)
F7/TU1	$Y = -0.002X^2 - 0.172X + 7.3$ (13)
F7/TU2	$Y = -0.0041X^2 - 0.156X + 8.1$ (14)
F8/TU1	$Y = -0.0352X^2 + 0.477X + 4.7$ (15)
F8/TU2	$Y = -0.0326X^2 + 0.489X + 5.0$ (16)

Table 3. Required irrigation depths to be applied for fully grown annual irrigated crops.

No.	Crop	Rooting depth (m)	Depletion fraction	Total available water (mm)	Required depth (mm)
1	Maize	1.20	0.55	138.0	75.9
2	Potato	0.45	0.35	51.8	18.1
3	Sorghum	1.35	0.55	155.3	85.4
4	Tomato	1.00	0.40	115.0	46.0

over the length of the irrigation units. Some of the test units have more depth of irrigation water infiltrated towards its tail end than the head end, some of the test units have the inverse of this pattern, while some have more water infiltrated in the middle area than the tail and head ends.

The required depth of water the irrigation system should apply during irrigation (or the perceived requirement) varies with the type of crop and the total available water holding capacity of a soil. Thus, in this study the required depth (Z_r) was computed for each of fully grown major irrigated crops of the study sites to sustain normal crop growth and obtain satisfactory yield. The calculation was based on Equation (3) and the result is presented in Table 3. From Table 3 it can be observed that the average depth of irrigation water actually applied (78 mm) was greater than Z_r for most crops in the area except sorghum.

The soil moisture deficit (SMD) of the study site just before irrigation was determined gravimetrically using Equation (1) and compared with the computed perceived requirement Z_r (Table 3). The SMD varies from place to place and ranges from 34 to 85 mm/m with average value of 62 mm/m. The mean SMD (62 mm/m) was less than the perceived requirement computed for maize and sorghum. Irrigation water actually applied by the irrigators per irrigation event (78 mm) was generally greater than the average SMD.

Performance of the scheme

Although various authors have suggested many performance measures, the type of measures or indicators chosen depends on the purpose of the performance assessment. In this study, application efficiency, storage efficacy, distribution efficiency and deep percolation fraction were used as measures of performance.

Application efficiency

Table 4 presents summary of the results of application efficiency (E_a) determined for each crop. It can be seen that E_a varies with the type of crop grown. Generally, the application efficiency of plots grown with deep rooted crops

Table 4. Summary of the calculated application efficiency.

No	Crop	Application efficiency (E_a) (%)		
		Minimum	Maximum	Mean
1	Maize	70.8	100.0	89.1
2	Potato	16.7	34.5	23.8
3	Sorghum	79.2	100.0	94.0
4	Tomato	42.9	81.6	60.4

was much better than that planted with shallow rooted crops. Accordingly, plots grown with sorghum have the highest application efficiency that varies between 79 and 100% with mean value of about 94%; maize plots have the second highest application efficiency that varies between 71 and 100% with mean value of 89%; plots planted with tomato have E_a value between 43 and 82% with mean value of 60%; and plots planted with the third major irrigated crop potato, have the lowest application efficiency with mean value of 24%, with range of 16–35%. Potato has also the highest yield reduction as calculated using CROPWAT (Smith, 1992).

From Table 4 it can be seen that the major portion of irrigation water admitted into potato fields was lost and the minimum loss occurred in fields planted with sorghum. The main reason for the variation of E_a with the type of crop grown was due to the variation in the effective root depth and depletion fraction, thus the required depth to be applied (Table 3). The ridged irrigation practice, field layout and configuration, water application method, rate of water delivered and applied to a plot (or a lower unit), and depth applied, irrespective of the type of crop grown, also contributes for variation of E_a with the type of crop grown.

Water requirement efficiency

The adequacy of an irrigation event expressed in terms of water requirement (storage) efficiency (E_s) is summarized in Table 5. Plots grown with potato were found to have the highest storage efficiency of 100% followed by tomato with mean E_s value of 99%. Sorghum fields that have the highest E_a have

Table 5. Summary of the calculated storage efficiency.

No.	Crop	Storage efficiency (E_s) (%)		
		Minimum	Maximum	Mean
1	Maize	68.5	100.0	90.9
2	Potato	100.0	100.0	100.0
3	Sorghum	61.3	100.0	74.9
4	Tomato	92.4	100.0	99.4

scored the lowest storage efficiency with mean value of 86% and plots planted with maize have mean E_s value of 91%. High E_s value for potato and tomato indicate that most of the plots planted with these crops (100% of potato plots and 70% of tomato) receive the perceived or the required amount of irrigation over its entire length during an irrigation event, thus E_s index is no more a spatially variable term for these crops. The relatively low E_s value for sorghum and maize fields indicate that most of sorghum or maize fields/plots (87% of sorghum and 81% of maize plots) were under irrigated over their entire length or partially under irrigated.

Distribution uniformity

To get a complete picture of an irrigation event performance we need to know more than just the indicators above, because these are averages taken over the entire length of the field. The spatial uniformity (evenness) of irrigation water application provides a vital clue as to how good the corresponding E_s index is as representative measure of adequacy over the entire irrigation unit. Distribution uniformity (DU) is the most commonly used uniformity index in surface irrigation application. DU was not varying with the type of crop grown. The DU observed varies between 47 and 99% with mean value of 75%.

Deep percolation fraction

The two principal types of losses in surface irrigation practice are runoff loss and deep percolation loss. Irrigators in the area use end-dyked borders and/or series of interconnected basins, thus there is no runoff loss and the only type of loss was deep percolation. The magnitude of the deep percolation loss varies with the type of crop grown and negatively linearly correlated with application efficiency. Thus, crops with high application efficiencies have lowest deep percolation ratio values and *vice versa*. Accordingly, irrigation water loss due to deep percolation was highest in potato fields/plots and varies between 65 and 83% (Table 6) with average value of 76%. Deep percolation fraction (D_f) in tomato field was between 18 and 57% with mean value of

Table 6. Summary of the calculated deep percolation fraction.

		Deep percolation (D_f) (%)		
No.	Crop	Minimum	Maximum	Mean
1	Maize	0.0	29.1	10.4
2	Potato	65.4	83.2	76.2
3	Sorghum	0.0	20.7	5.6
4	Tomato	18.4	57.1	39.5

39%. D_f value for maize plot was between zero and 20% with mean value of 10%. Fraction of irrigation water lost due to deep percolation was minimum in sorghum field with mean value of 6% and total varies between 0 and 21%.

Proposed irrigation water management strategy

To characterize the seasonal irrigation management practice in the study area, the existing irrigation schedule practiced by the farmers in the study site was assessed. Mean application depth per irrigation turn, measured at the field, was 78 mm, irrespective of the type of crop grown in the area. It is evident that optimal use of irrigation water at farm level requires monitoring and measuring soil moisture in the field to decide when to irrigate and how much to apply. In addition, it requires having the necessary infrastructure and technology to measure the amount of water to be applied. However, the facility to measure soil moisture and the amount of irrigation water to be applied do not exist in such a traditional irrigation system under consideration and it is also beyond the farmers' capacity to have and manage them.

The following factors were considered to come up with a practical irrigation water management under the given conditions: (i) the irrigation plot size per family is small (an average of 0.16 ha), (ii) the family size is large (an average of seven persons per family), and (iii) the major problem in the area is low water application efficiency at the farm level. Considering these facts the following irrigation water management strategy was proposed. Rather than constructing one large size pond to be shared by the farmers in the irrigation command area, it would be better to construct a number of small tanks for small group of neighboring plots. Then, the direct flow of irrigation water is scheduled to fill the small tanks rotationally and farmers apply water from the tank to their fields not by flooding but manually using watering cans. Since the human labor is not a problem in the area, due to large family size, a family can use the amount of irrigation water allotted to it efficiently and increase the size of plots under irrigation.

Summary and conclusions

For all crops except potato, the irrigators schedule irrigation before the readily available soil moisture is depleted. The soil moisture deficit determined just before irrigation also indicates this case. Irrigation water applied to a farmer's plot during an irrigation event/turn was greater than the perceived requirement or the required depth to be applied (Z_r) calculated for fully grown crops under consideration. Exception to this conclusion is sorghum plots which receive about 14% less than Z_r.

Farmers in the study area use end-dyked borders or series of interconnected basins to irrigate their plots. Therefore, there is no runoff loss and thus deep percolation is the principal type of loss in the farmers' plots of the study area. Amount of irrigation water lost through deep percolation varied with the type of crop and generally it was higher in plots planted with shallow rooted crops. Seasonal deep percolated irrigation water loss during crop growing period was 32% in sorghum, about 57% in maize, and 70% in tomato and potato fields. The irrigation scheduling at the study area is generally poor and the problem of poor irrigation scheduling is more severe in farmers plots planted with shallow rooted crops, which had high amount of water loss and at the same time high amount of yield reduction.

The major problems identified in the management and operations of the schemes that attribute to high amount of irrigation water loss, especially in farmers' plots planted with shallow rooted crops were as follows.

- Inappropriate type of surface irrigation system: Farmers in the area use end-dyked border and series of interconnected basins. However, in surface irrigation systems like in this study where fields have bidirectional slope, and land leveling is imprecise, row crops, small discharge, furrow systems are favored than borders and basins.
- Ridged irrigation practice: Farmers use the same irrigation system, field layout and configuration, water application method, rate of water delivered and thus depth of water applied to their plots irrespective of the type of crop and growth stage.
- Poor irrigation scheduling: The main problem as a result of poor irrigation scheduling is too much water loss.

The strategy of constructing a number of small tanks, rather than one large sized pond, and direct manual irrigation was proposed to increase the water application efficiency.

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