OPEN ACCESS

International Journal of **Water Resources and Environmental Engineering**

September 2018
ISSN 2141-6613
DOI: 10.5897/IJWREE
www.academicjournals.org

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International Journal of Water Resources and Environmental Engineering

Table of Contents: Volume 10 Number 8 September 2018

ARTICLES

Vol. 10(8), pp. 100-110, September 2018
DOI: 10.5897/IJWREE2018.0800
Article Number: 142667058629
ISSN: 2141-6613

http://www.academicjournals.org/IJWREE

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International Journal of Water Resources and Environmental Engineering

Full Length Research Paper

Evaluation of canal water conveyance and on-farm water application for a small-scale irrigation scheme in Ethiopia

Alebachew Shumye[1*] and Ing Pratap Singh[2]

[1]Department of Water Resources and Irrigation Management, Debre Brihan University, Debre Brihan, Ethiopia.
[2]Department of Water Resources and Irrigation Engineering, Arba Minch Water Technology Institute, Arba Minch University, Arba Minch, Ethiopia.

Received 27 February, 2018; Accepted 4 April, 2018

This study was conducted to identify and understand the current level of canal water conveyance and on-farm water application efficiency of Lemchek-Sewur small-scale irrigation scheme in Ethiopia. The water conveyance efficiency of canals was determined by estimating discharge at different segments. On-farm water application efficiency was evaluated from the amount of water actually applied and from soil moisture measurements. Primary data were collected through flow measurement, transect walk, household surveys and group discussions, whereas secondary data were collected from different sources. Microsoft Excels and Geographic Information System software were used to analyze the data. The mean values of water conveyance efficiency of main, secondary and tertiary canals were 86.17, 86.26 and 55.97%, respectively. Mean value of the overall on-field water application efficiency was 53.13%. Generally, the performance of the irrigation scheme was poor mainly due to illegal water abstraction, sedimentation of canals and inadequate operation and maintenance provisions. Therefore, adequate maintenance and suitable management approaches are required to improve the irrigation system performance.

Key words: Lemchek-Sewur SSI scheme, conveyance efficiency, application efficiency, evaluation, Ethiopia.

INTRODUCTION

Water is a valuable resource for agricultural production. Scarcity or misuse of water resources poses serious and growing threats to life and sustainable development. The irrigated agriculture faces number of difficult problems. One of the major concerns is poor efficiency pertaining to misuse of water resources in irrigation practices. To make irrigation projects economically and environmentally sustainable, water users need to improve agricultural productivity, which requires change in their institutional structures, water use management systems and policies, improve service delivery systems, and proper farmland management (Gebremeskel and Mekonen, 2014).

*Corresponding author. E-mail: alexshum21@gmail.com.

Most of the expansion in irrigated area in the past occurred through capital investments in infrastructure for capture, storage and distribution of water. The increased availability of irrigation and less dependency on rain fed agriculture is one of the means to increase food production.

Performance of many irrigation schemes is significantly below their potential due to a number of shortcomings, including poor design, construction, operation, maintenance, and ineffective water control and measurement structure (Degirmenci et al., 2003). Water is a natural resource of strategic importance, which directly affects economic and social development. As competition for water increases, the irrigation sector is often blamed for high and inefficient use of water and commonly held responsible for urban water shortages.

The efficient, equitable and dependable delivery of water and the efficient and uniform application of water to the fields are as important as increasing irrigated area. Therefore, it is necessary to determine water conveyance loss in irrigation canals and in field water application so that economic and operational performance of the systems may be improved.

The competition for irrigation water use among the upstream and downstream irrigation units in Lemcheck-Sewur Small Scale Irrigation (SSI) scheme is very high due to on-farm and off-farm water distribution problems. The irrigation system infrastructure in the scheme lacks the capacity to deliver irrigation water, has problems of operating gates and maintenance of canals, management gaps, water scarcity, poor water management, siltation, flooding and erosion. The critical problem is frequent water related conflicts resulting from unregulated and incorrect allocation of irrigation water. Water User Association (WUA) of the scheme is too weak to manage the system in a sustainable manner. The evaluation of the irrigation scheme performance is of paramount importance not only to point out where the problem lies, but also to identify alternative management options that may be effective and feasible in improving irrigation scheme performance. Therefore, the present study was conducted for Lemechek-Sewer SSI scheme with the following objectives.

Objectives

The objectives of the performance study for Lemechek-Sewer SSI scheme are:

(1) To investigate the situation of existing irrigation practices
(2) To assess canals conveyance and on-farm water application efficiency
(3) To identify the performance gaps and suggest remedial measures.

LITERATURE REVIEW

Ethiopia has abundant rainfall and water resources, but its agricultural system does not yet fully benefit from the technologies of water management and irrigation (Awulachew et al., 2010). The country is presently committing huge investments to develop irrigation infrastructure with the aim to enhance agricultural production but little attention is given to the existing performance of the irrigation schemes. Ayana and Awulachew (2009) and Awulachew and Ayana (2011) studied the performance of different irrigation schemes in Ethiopia and observed that the performance of the existing irrigation schemes are low due to poor operation and maintenance services, problems related to improper planning and design, and lack of incentive for proper management of water in state-run projects. The small-scale irrigation schemes are operated and managed by the water users themselves with little involvement of government agencies. According to Bos et al. (1994), the performance assessment evaluates the existing situation of irrigation performance, identifies the constraints to proper performance, and implements management interventions to improve the performance. Jureins et al. (2001) proposed common efficiency terms for irrigation system evaluation such as application efficiency, conveyance efficiency, distribution uniformity, storage efficiency, runoff ratio, and deep percolation ratio. However, most of the water losses in seepage, deep percolation and runoff are considered by water conveyance and water application efficiencies. Walker (1989) proposed guidelines for design and evaluation of surface irrigation systems. The proposed value of water conveyance efficiency for lined canal was 95%. Whereas, the value for unlined canals varied from 60 to 90% depending on the soil and canal length. Sisay et al. (2009) studied the effect of water management practices on crop productivity for SSI schemes in Blue Nile command in Ethiopia and reported water conveyance losses as 2.58 l/s/100 m for average water flow rate of 43 l/s. The water application efficiency for design and evaluation of surface irrigation system varied from 55 to 70% (Walker, 1989).

The water conveyance losses in different canal and water application efficiency in field water application were studied by different workers in different conditions and different conclusions were drawn. However, such studies for Lemchek-Sewur SSI scheme are yet to be conducted.

MATERIALS AND METHODS

Description of study areas

Lemchek-Sewursmall-SSI scheme is an intake irrigation project, located in Yelen-Wacho Kebele, Kewet Woreda in North Shewa Zone of the Amhara region, Ethiopia. The study area is located at 10° 4' 51.6" N Latitude and 39° 53' 13.2" E longitude at about 1245 m.a.s.l. The total commend area of the project is 180 ha. In

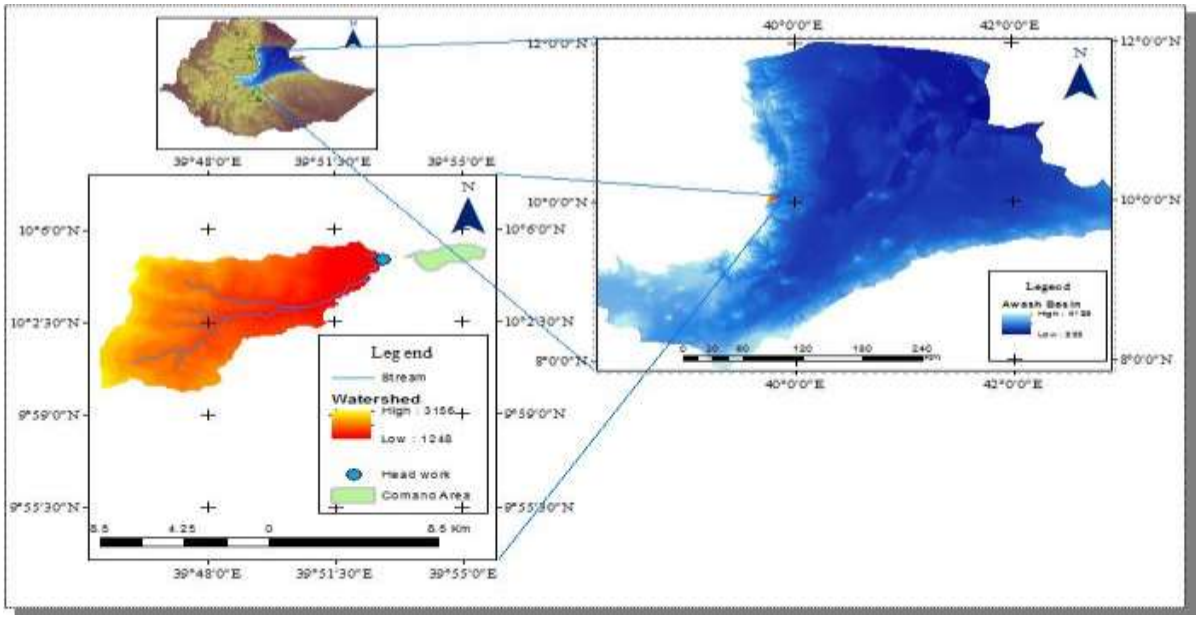

Figure 1. Map of study area.

traditional agro ecological classification system, the project area is located in Kolaagro ecologic zone. The map of the study area is as shown in Figure 1.

Water for the scheme is supplied from an intake structure on the Sewer River. The primary contour canal on the right side of the river course is 1.6 km long. The secondary canal is 1.761 km long and leads water from the main canal into the command area, running down the slope. Nine tertiary canals of total length of 5.516 km run on contours, serve standard size irrigated plots by means of field ditches. Surface drains remove surplus irrigation water and runoff from rainfall. The slope of the main canal ranges from 0.29 to 0.49%, whereas that of the command area slope ranges from 2 to 4%. The irrigation scheme was constructed in 2012 by Bureau of Water Resource Development (BoWRD), with a total investment cost of 7.1 million ETB for its life span of about 20 years. The irrigation scheme has total of 720 household beneficiaries. Farmers are organized in compulsory WUA, which collect fees for maintenance of the canals and formulate bylaws. The layout of Lemchek-Sewur SSI scheme is as shown in Figure 2.

Climate of study area

The mean monthly minimum temperature (Tmin) in the study area varies from 9.6°C in December to 16.9°C in July with yearly average value of 13.5°C. Similarly, the mean monthly maximum temperature (Tmax) varies from 24.3°C in December to 31.0°C in June with yearly average value of 27.7°C. The rainfall distribution in the study areas is ‘unimodal’ rainfall pattern. The main rainy season is from July to early September. The mean annual rainfall (RF) in the study area is 712 mm. The graphical variation of mean monthly climatic data is as shown in Figure 3.

Crops grown in study area

Lemchek-Sewur SSI project is one of the modern irrigation projects in north Shewa zone of Ethiopia dominated by annual food crops. Cereal crops such as teff, sorghum, and maize cover the major part of the area followed by vegetable crops such as onion, cabbage, pepper and tomato and pulse crops such as mung bean.

Method of data collection

The research was carried out from October to December 2016 as large numbers of fields are irrigated during the period. The data collection was done with the Development Agent assigned by the Agricultural Office. The primary data were collected by direct field measurements. Such data were discharge measurements, filed observations, and measurement of soil physical properties. The secondary data were collected from agricultural and rural development office and National Meteorological Service Agency. Such data were climatic data, crop data, actual command areas and designed features of the scheme.

Discharge measurement

Synthetic propeller type current meter and Parshall flume (3” size) were used for discharge measurement of main, secondary and tertiary canals and field off takes. The current meter was used for measurement of water flow for main and secondary canals. The main and secondary canals were rectangular and lined with masonry. The tertiary canals were trapezoidal and unlined. The current meter measured the velocity of water flow using Equation 1.

$$V=k \times n + \triangle \qquad (1)$$

where n = number of propeller rotation per second, V = the flow velocity of the water, in cm/s, and
k and $\triangle$ = coefficient of synthetic propeller type current meter.

The values of k and $\triangle$ depend on number of propeller rotation per second (n). Substituting corresponding values of k and $\triangle$ for different range of n, Equation 1 may be expressed by Equations 2 to 4.

$$V = 31.17 \times n + 1.93, \text{ if } 0.00 < n < 1.98 \qquad (2)$$

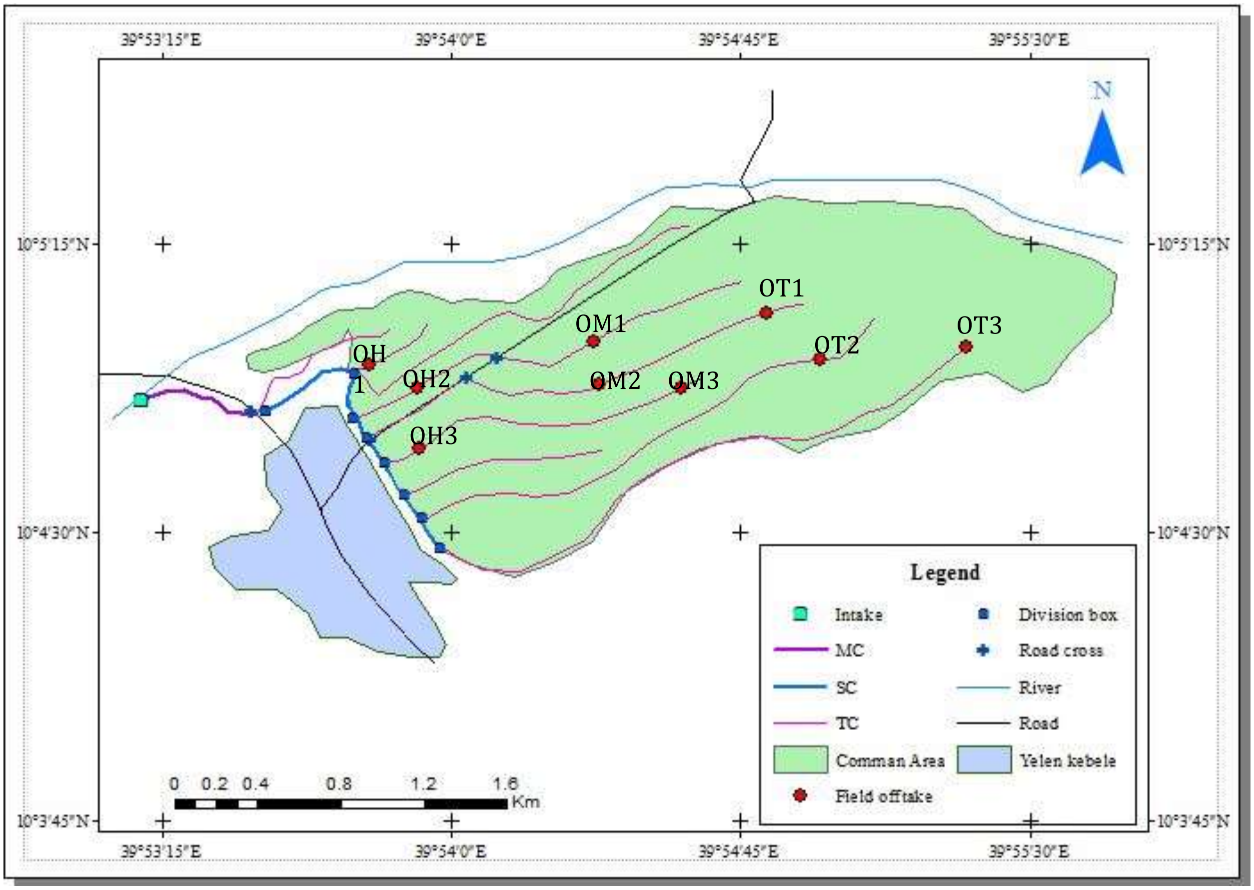

Figure 2. Layout of Lemchek-Sewur SSI scheme.

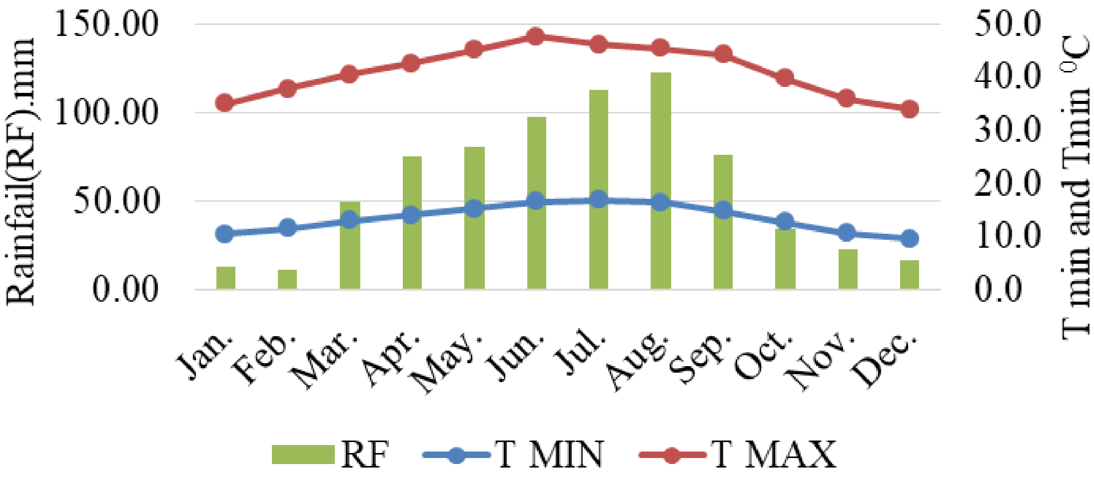

Figure 3. Variation of mean monthly climatic data.

$$V = 32.05 \times n + 0.19, \text{ if } 1.98 < n < 10.27 \quad (3)$$

$$V = 33.44 \times n - 14.09, \text{ if } 10.27 < n < 15. \quad (4)$$

The depths of the water flow in the main and secondary canals were less than 60 cm. Therefore, the water flow velocity in these canals with current meter was measured at depth equal to 0.6 d, where d was depth of water flow in the canal. The discharge for the main and secondary canal was calculated as the multiple of cross-sectional area and water flow velocity.

Parshall flume was used to measure discharge from tertiary canal and field offtakes using Equation 5 for free flow condition.

$$Q = k\, h_1^n \qquad (5)$$

where Q = flow rate in m^3/s, h_1 = upstream water flow depth in the converging inlet section, in m, k = free flow coefficient, and n = free flow exponent.

The value of the constant of k and exponent n for Parshall flume (3” size) and for metric units were 0.1771 and 1.55, respectively (Gertrudys, 2006).

Method of data analysis

Soil analysis

Soil samples were collected from different locations at 0-30 and 30-60 cm soil depths to determine particle size distribution (soil texture), bulk density and soil moisture content before and 24 h after irrigation. Bulk density was determined using the core sampler. Particle size distribution was determined using mechanical analysis and the soil texture was determined using the USDA Soil Textural Triangle. The soil moisture content was estimated using gravimetric method.

Estimation of water conveyance efficiency

The water conveyance efficiency and water losses main secondary and tertiary canals were estimated by measuring inflow and outflow for the selected canal reaches. The inflow and outflow were measured at nine points at an interval of 200 m for main canal and at eight points at an interval of 250 m for secondary canal. The measurements for tertiary canals were made at initial and final points at head, middle and tail reaches. The discharge measurements were made twice a day for 30 min each time for four irrigation events. The average values of inflow and out flows for all measurements for each of the selected canal segment were used for the estimation of water conveyance losses and water conveyance efficiency using Equation 6.

$$Ec = \frac{Q\ \text{outflow}}{Q\ \text{inflow}} \times 100 \qquad (6)$$

where Ec = water conveyance efficiency (%), Q outflow = amount of water outflow, and Q inflow = amount of water inflow.

Estimation of on-farm water application efficiency

The required data for the estimation of on-farm water application efficiency were collected from nine farmers’ fields in the command area of the scheme, three each from the head reach (FH1, FH2 and FH3), middle reach (FM1, FM2 and FM3), and tail reach (FT1, FT2 and FT3). The crop grown in selected fields was onion at full development stage of crop growth. There were 21 numbers of furrows in each field. Three representative furrows were selected from each of the nine selected fields at the head, middle and tail reaches using systematic sampling method. Soil samples were taken before and 24 h after irrigation from 0-30 and 30-60 cm soil depths from each of the selected furrow. The actual amount of the water applied into each furrows was measured using Parshall flume (3” size). The on-farm water application efficiency was calculated using Equation 7.

$$Ea = \frac{ws}{wn} \times 100 \qquad (7)$$

where Ea = water application efficiency (%), ws = depth of water stored in crop root zone soil profile, and wn = depth of water applied to the field.

The depth of water stored in crop root zone soil profile (ws) was estimated using Equation 8.

$$ws = \sum_{i=1}^{n} \rho i \times Di \times (Wf - Wi) / 100 \qquad (8)$$

where ws = depth of water stored in crop root zone soil profile (cm), Wf = moisture content of i^{th} soil layer 24 h after irrigation on oven dry weight basis (%), Wi = moisture content of i^{th} soil layer before irrigation on oven dry weight basis (%), ρi = apparent specific gravity of the i^{th} soil layer (g/cm^3), Di = depth of i^{th} soil layer (cm), i = integer, 1 to n and n =number of soil layers in the crop root zone.

The moisture content of the collected soil samples before and after irrigation was determined using gravimetric method as expressed by Equation 9.

$$W = \frac{Ww - Wd}{Wd} \times 100 \qquad (9)$$

Where W = soil moisture content on oven dry weight basis (%), Ww = wet weight of the soil (g), and Wd = oven dry weight of the soil (g)

RESULTS AND DISCUSSION

Water conveyance efficiency

The water conveyance efficiency was estimated using Equation 6 for each measurement at each selected location along the main canal, tertiary canal and offtake.

Main canal water conveyance efficiency

The estimated average value of inflow, outflow, water conveyance efficiency and water conveyance losses for different sections of the main canal are shown in Table 1. The water conveyance efficiency for main canal varied from 77 to 96.6% with average value of 86.2%. The values of conveyance efficiency were different for each canal section. The measurements for replication 2 were made after the maintenance of the main canal. Therefore, the values of water conveyance efficiency for replication 2 in some of the reaches were higher as compared to the values for replication 1. The water conveyance losses per 100 m length varied from 1.43 l/s/100 m to 20.35 l/s/100 m with average value equal to 10.57 l/s/100 m.

The water conveyance efficiency was the lowest for canal section at 600 to 800 m. The water conveyance losses per 100 m canal length were also the highest equal to 19.16 l/s/100 m for this canal section. This indicates the priority of maintenance in this section as

Table 1. Estimated Water Conveyance Efficiency and Conveyance Loss in Main Canal.

Canal section (m)	Replication	Q inflow (m^3/s)	Q outflow (m^3/s)	Conveyance loss (l/s/100 m)	Ec (%)
0-200	Rep1	0.27	0.23	20.35	85.0
	Rep2	0.207	0.185	11.23	89.2
	mean	0.239	0.207	15.79	87.1
200-400	Rep1	0.23	0.192	18.64	83.8
	Rep2	0.185	0.158	13.61	85.3
	mean	0.207	0.175	16.12	84.5
400-600	Rep1	0.192	0.161	15.82	83.6
	Rep2	0.158	0.143	7.329	90.7
	mean	0.175	0.152	11.57	87.1
600-800	Rep1	0.167	0.129	19.16	77.0
	Rep2	0.143	0.112	15.32	78.6
	mean	0.155	0.121	17.24	77.8
800-1000	Rep1	0.129	0.112	8.168	87.3
	Rep2	0.112	0.092	10.01	82.2
	mean	0.121	0.102	9.087	84.8
1000-1200	Rep1	0.112	0.096	7.918	85.9
	Rep2	0.092	0.084	4.422	90.4
	mean	0.102	0.09	6.17	88.2
1200-1400	Rep1	0.096	0.09	3.231	93.3
	Rep2	0.084	0.081	1.43	96.6
	mean	0.09	0.085	2.331	94.9
1400-1600	Rep1	0.09	0.081	4.645	89.7
	Rep2	0.081	0.065	7.971	80.3
	mean	0.085	0.073	6.308	84.9
	Overall Average	-	-	10.57	86.2

compared to other sections of the main canal. The reasons for high water conveyance losses were nonfunction of flow control gates, unauthorized water turnouts, breaching of main canals and illegal water abstractions for domestic purpose. This inefficient conveyance affected the equity of water distribution throughout the systems, particularly, the tail users did not get their equitable share of water.

Secondary canal water conveyance efficiency

The estimated average values of inflow, outflow, water conveyance efficiency and water conveyance losses for different section of the secondary canal are shown in Table 2. The water conveyance efficiency for secondary canal varied from 52.49 to 96.02% with average value equal to 86.26%. The water conveyance losses per 100 m length of secondary canal varied from 0.731 l/s/100 m to 7.858 l/s/100 m with average value equal to 2.617 l/s/100 m. The lowest values of water conveyance efficiency was observed for canal section at 1500 to 1750 m. Reason being this section was highly cracked which caused high seepage and leakage losses. It was observed during the field visit that the water was leaking from different locations, wherever, canal was breached. The measurements for replication 2 were done after the maintenance of the secondary canal. Therefore, the values of conveyance efficiency for second replication in some of the cases were higher as compared to replication 1. The major reasons for high water conveyance losses in the secondary canal of the scheme were generally improper construction, canals silting with weeds and soils, cracked sections and broken parts at

Table 2. Water conveyance efficiency and conveyance loss in secondary canal.

Canal section (m)	Replication	Q inflow (m^3/s)	Q outflow (m^3/s)	Conveyance loss (l/s/100 m)	Ec (%)
0-250	Rep1	0.054	0.0506	1.886	93.07
	Rep2	0.055	0.0493	2.927	89.38
	mean	0.055	0.05	2.407	91.22
250-500	Rep1	0.051	0.045	2.801	88.93
	Rep2	0.049	0.0444	2.466	90.00
	mean	0.05	0.0447	2.633	89.46
500-750	Rep1	0.045	0.0418	1.612	92.84
	Rep2	0.044	0.0373	3.553	83.98
	mean	0.045	0.0395	2.583	88.41
750-1000	Rep1	0.042	0.0367	2.554	87.78
	Rep2	0.037	0.0343	1.464	92.14
	mean	0.04	0.0355	2.009	89.96
1000-1250	Rep1	0.037	0.0352	0.731	96.02
	Rep2	0.034	0.0313	1.492	91.31
	mean	0.036	0.0333	1.111	93.66
1250-1500	Rep1	0.035	0.0331	1.073	93.91
	Rep2	0.031	0.0264	2.462	84.29
	mean	0.033	0.0298	1.767	89.1
1500-1750	Rep1	0.033	0.0174	7.858	52.49
	Rep2	0.026	0.0189	3.77	71.46
	mean	0.03	0.0181	5.814	61.98
	Overall average	-	-	2.617	86.26

Figure 4. Canals covered by weeds and mud.

different places, canals under design with smaller cross sectional area which resulted in water overflow, sides and beds of the canal were greatly damaged by scouring due to steep bed slope, absence of drop structures and flow control structures (Figure 4).

Tertiary canals water conveyance efficiency

The tertiary canals in the study area received water from secondary canal through offtakes and delivered the irrigation water to the field ditches. The following

Figure 5. Silt deposition in tertiary canal.

problems were observed in tertiary canals before and during the actual evaluation activities.

(1) The physical conditions of some of the tertiary canal structures were not as per designed specifications. The sidewalls were eroded (width was widened) and plants/grasses were growing in the canals. The canal bed slope was also causing backflow when sufficient water was not supplied in the canals. In some of the tertiary canals, there was siltation problem, which decreased water flow depth and widened canal widths (Figure 5).
(2) Seepage from canal sidewalls along the canal length and leakage from offtake points were predominant in the area and it was difficult to be measured.
(3) Operational losses were also observed.
(4) Dead storage was formed at different points inside the canals along the length of the canal, which facilitated irrigation water loss via evaporation and deep percolation.
(5) Overtopping from canals due to releasing of excess water which caused damage to field crops.

Tertiary canal dimensions: The designed and actual field measured values of different dimensions of the tertiary canals are shown in Table 3. The measured value of canal depth varied from 28 to 40 cm, whereas the designed values varied from 40 to 45 cm. The actually measured values of the depth of tertiary canals were smaller than the designed values. It might be due to siltation problems which resulted from canals side erosion and from sediment particles brought into canals with irrigation water (Figure 5). The measured values for bottom width and top width varied from 105 cm to 120 and 124 to 140 cm, respectively. Whereas the design values were 30 and 110 to 120 cm, respectively. The actual values of bottom width and top width were more than the designed values. Similarly, the actual canal cross-section area was also more than the design values. This might have occurred because of unsafe canal cleaning, canal erosions due to repeated excess water flow above free board level, damage by domestic animals and overtopping at some canal banks.

Tertiary canals water conveyance efficiency: The estimated values of inflow, outflow, water conveyance efficiency and water losses for different selected tertiary canals are shown in Table 4. The estimated value of water conveyance efficiency for the tertiary canals varied from 45.3 to 62.7% with average value of 56%. The water conveyance losses for different tertiary canals varied from 1.48 to 2.97 l/s/100 m with average value equal to 2.12 l/s/100 m. The highest mean conveyance efficiency of the tertiary canal for both replication was 60.7% for tertiary canal-2 and the lower mean efficiency was 50.6% for the tertiary canal-7. This indicates that the tertiary canal TC-7 had priority of maintenance. Tertiary canal TC-2 having the highest mean value for both replications equal to 60.7% can be considered as better canal as compared to other tertiary canals. The measurements for replication 2 were taken after canal cleaning and maintenances. The water conveyance efficiency was comparatively lower and thus water seepage losses were comparatively higher for the tertiary canals as compared to main and secondary canals. Efficient water saving can be achieved by keeping the conveyance losses to minimum. In this study, large amount of water was lost in conveyance during its route up to the farms. The main reasons for these conveyance losses in watercourses were leakages from turnouts, high density of vegetation in the unlined watercourses, turns in the watercourse, weak banks broken by domestic animals, siltation, holes

Table 3. Actual field measured and design dimensions of representative tertiary canals.

Tertiary canal	Dimension	Measured values (m)	Measured cross-sectional area (m^2)	Design values (m)	Designed cross-Sectional area (m^2)
TC-2 1:1 canal side slope	Top width	1.35	0.37	1.1	0.28
	Bottom width	1.1		0.3	
	Depth	0.3		0.4	
TC-3 1:1 canal side slope	Top width	1.24	0.32	1.1	0.28
	Bottom width	1.07		0.3	
	Depth	0.28		0.4	
TC-4 1:1 canal side slope	Top width	1.40	0.49	1.20	0.34
	Bottom width	1.05		0.3	
	Depth	0.40		0.45	
TC-6 1:1 canal side slope	Top width	1.30	0.48	1.1	0.28
	Bottom width	1.1		0.3	
	Depth	0.40		0.4	
TC-7 1:1 canal side slope	Top width	1.35	0.45	1.1	0.28
	Bottom width	1.2		0.3	
	Depth	0.35		0.4	
TC-8 1:1 canal side slope	Top width	1.25	0.46	1.1	0.28
	Bottom width	1.15		0.3	
	Depth	0.38		0.4	

made by rodents or boars and lack of maintenance.

On-farm water application efficiency (Ea)

The on-farm water application efficiency for the nine-selected farmers fields, three each at head, middle and tail reach were estimated by the measured water application depth and soil moisture content before and 24 h after irrigation for each of the selected furrow using Equations 6 to 8. The estimated average values of the water application efficiency at different location are shown in Table 5. The water application efficiency varied from 43.76 to 68.60% with over-all average value equal to 53.12%. The lowest application efficiency equal to 43.76% was for field FM_2. Reason being that the furrows at location FM_2 were not blocked at lower end which resulted in huge runoff loss. The furrows at other locations were blocked at lower ends and thus no runoff at lower ends of the furrows was allowed. Generally, farmers in Ethiopia used blocked furrows. The reach wise mean values of the application efficiency were 49.22, 49.42, and 60.72% for head, middle, and tail reach, respectively. The reach-wise mean value of application efficiency increased from head reach to tail reach. Thus, the farmers at head and middle reach were getting more water and applying the water less efficiently as compared to the farmers at tail reach. The deep percolation losses at head and middle reach were higher as compared to tail reach. The farmers at tail reach were getting less water and thus most of the applied irrigation water was stored in the crop root zone. The other factor of low application efficiency at the head and middle reach was high soil moisture contents in the soil as compared to the tail water users. The main factors which contributed to the low application efficiency in the irrigation systems were poor irrigation system design, poor irrigation system management, non-existent of water measuring and control structures, inadequate maintenance of schedules and non-existent of scientific irrigation scheduling.

RECOMMEDATIONS

The following recommendations weredrawn from the performance evaluation studies of the Lemchek-Sewur SSI scheme:

(1) The water allocation should be planned based on predetermined and designed cropping pattern and

Table 4. Water conveyance efficiency and conveyance loss in tertiary canals.

Canal code	Replication	Q inflow (l/s)	Q outflow (l/s)	Conveyance loss (l/s/100 m)	Ec (%)
TC-2	Rep1	20.7	12.40	1.51	59.9
	Rep2	21.95	13.50	1.54	61.5
	Mean	21.33	12.95	1.53	60.7
TC-3	Rep1	19.4	11.40	1.92	58.8
	Rep2	18.2	10.34	1.89	56.8
	Mean	18.8	10.87	1.91	57.8
TC-4	Rep1	26	13.50	2.22	51.9
	Rep2	24.6	13.50	1.97	54.9
	Mean	25.3	13.50	2.09	53.4
TC-6	Rep1	23.3	12.40	1.86	53.2
	Rep2	23.3	14.62	1.48	62.7
	Mean	23.3	13.51	1.67	58
TC-7	Rep1	27.4	12.40	2.73	45.3
	Rep2	30.3	16.94	2.43	55.9
	Mean	28.85	14.67	2.58	50.6
TC-8	Rep1	30.28	16.94	2.97	55.9
	Rep2	28.83	15.80	2.9	54.8
	Mean	29.56	16.37	2.93	55.4
	Overall average	-	-	2.12	56

Table 5. Water application efficiency at different locations in the study area.

Filed code	Depth of moisture stored in crop root zone (mm)	Depth of applied water depth (mm)	Ea (%)
FH1	20.831	41.62	50.05
FH2	21.11	42.09	50.15
FH3	21.188	44.64	47.46
Mean	21.043	42.78	49.22
FM1	20.883	35.64	58.6
FM2	20.998	47.98	43.76
FM3	20.838	45.4	45.9
Mean	20.906	43.01	49.42
FT1	20.785	32.77	63.43
FT2	20.68	30.15	68.6
FT3	20.931	41.74	50.14
Mean	20.799	34.89	60.72
Over-all mean	20.916	40.23	53.12

irrigation scheduling. Water delivered to the fields should be measured and systems should be established to estimate crop evapotranspiration to determine the amount of irrigation water to be applied. Farmers may be provided trainings on water management and irrigation practices to avoid any undesirable impacts of irrigation such as water logging and salt accumulation.

(2) Water User Association (WUA) of the scheme was not

well organized and it has management target gaps. Reforming and training WUA is important for ensuring better management of the irrigation scheme. The organization needs to improve irrigation water use, distribute water equitably, resolve conflicts between users and manage system sustainability. Introducing and adopting the new proclamations IWUAs No. 84/2014 of Irrigation Water Users Associations (IWUAs), for beneficiaries and related stakeholders is very important.

(3) Canals, especially tertiary canals require continuous maintenance to keep them free from weeds and reduce the deposition of silt. Continuous removal of sedimentation, preventing large logs and debris throwing into the canal, constructing water control structure across the canal and canal bank protection are some of the necessary activities. Therefore, WUA and the beneficiaries' farmers should work together in coordination with each other.

(4) Putting formal way of fee collection and utilizing the collected money for maintenance work are relevant to increase farmers participation. Charging the farmers as per amount of water supplied may be examined.

(5) The farmers in Ethiopia generally use furrow irrigation blocked at lower ends. The technology for proper design and operation for the irrigation system especially suitable for Ethiopian conditions may be developed to minimize deep percolation losses and improve on-farm water application efficiency.

(6) Providing water storage structures and enhancing diversion capacity of the scheme might be vital for improving an adequate and reliable supply of irrigation water. The hydraulic characteristics of flow control structures at offtakes play a vital role in water distribution and delivery. Therefore, installation of proportional division structures at offtakes will improve water delivery equity.

(7) Providing water balancing reservoirs in the canal command area to stabilize canal water supply may be examined.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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Vol. 10(8), pp. 111-119, September 2018
DOI: 10.5897/IJWREE2017.0711
Article Number: 3B848E958699
ISSN: 2141-6613

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International Journal of Water Resources and Environmental Engineering

Full Length Research Paper

Performance evaluation and economic analysis of solar photo-voltaic water pumping systems: Case of Abakore borehole water supply system in Kenya

James Origa Otieno*, Christian Thine Omuto and Antony Ayub Gitau

Department of Environmental and Biosystems Engineering, University of Nairobi, P.O.Box 3019 Nairobi, Kenya.

Received 23 January, 2017; Accepted 16 March, 2017

A solar photovoltaic (PV) water pumping system was investigated to determine performance and economic viability. An in-built data logger was used to collect real time data on key performance parameters. Performance indicators were defined and determined, while economic viability was analyzed using life-cycle cost (LCC) method and these costs were compared with a diesel generator pumping system. Solar irradiance varied from 63 W/m^2 to a peak of 857 W/m^2, corresponding to a maximum power output of 11.75 kW. PV array efficiency of 12.1%, sub-system efficiency of 91.82% and overall efficiency of 5.14% were obtained, which are well comparable to the efficiencies reported elsewhere for similar systems. The LCC analysis showed a 20 year average unit water cost of 0.25 US \$/m^3 for solar PV system and 0.6 US \$/m^3 for diesel genset system. Solar PV system is found to be more cost effective and suitable for use over conventional sources.

Key words: Photovoltaics, water pumping, life-cycle cost analysis, efficiency, unit water costs, diesel generator.

INTRODUCTION

Evidence suggests that developing more water harnessing infrastructures as a solution to the global water scarcity crisis will result in an increased demand for energy, especially for pumping applications since water infrastructure largely relies on energy throughout its value chain (United Nations Education and Science Commission (UNESCO, 2012). It is also expected that groundwater will become increasingly energy intensive as water tables fall in several regions; therefore, making sustainable renewable energy supplies options such as wind and solar key components of water security debate (UNESCO, 2012). This expected shift towards renewable energy sources is further evidenced by the fact that 69% of Africans lack connection to an existing electricity grid

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*Corresponding author. E-mail: james.origa@gmail.com.

Table 1. Description of pumping system components.

Open circuit voltage, V	45.4
Voltage at MPP (V_{mpp} (Volts,V)	36.7
Shortcircuit current, A	5.65
Current at MPP (I_{mpp} (Ampres,A)	5.32
Dimensions (Length, L/Width, W/Height, H	1310 mm/990 mm/40 mm
Module efficiency	14.70%
Pump controller	Lorentz PS15k2 with integrated maximum power point tracking (MPPT)
Inverter power in put	15 kW
Pump-motor power	11 kW
Inverter/controller Input voltage	850 Vmax
Maximum power point voltage	575 V
Pump Motor current	24 Amax
Inverter/controller efficiency	98%
Maximum pump head	140 m
Maximum flow rate	25 m^3/h

PV Module: Yingli JS 195, multicrystalline silicon (Standard Test Conditions (STC): 1000W/m^2, 25°C cell temperature).

system (International Energy Agency, 2015). Solar PV water pumping systems are increasingly being promoted as an attractive alternative to pumping water vis-à-vis conventional diesel generator sets. Kenya is increasingly facing the twin challenge of water scarcity and decreasing energy generation as the capacity of the traditionally used hydro dams are rapidly dwindling due to climate change effects.The water-energy nexus arises from the interconnectedness of the critical role water plays in energy production and the need for energy in the water production chain mainly in abstraction and conveyance. As Kenya seeks to fastrack the realization of a prosperous middle income economy stautus by year 20130 as envisioned in her *Kenya Vision 2030* blueprint (Kenya Ministry of Planning and National development & National Economic and social council, 2007), a succesful management of the Water-Energy nexus is envisioned as a key ingredient for success. As it is, Kenya's position lying along the equator endows it with significant amounts of renewable energy in the form of solar radiation that calls for delibarate efforts to intergrate water and energy infrustructure planning so as to harness these resources within a nexus approach. Just recently in 2013, a UNESCO spearheaded exploration of groundwater resources in the drought stricken northern Kenya discovered huge reserves of groundwater aquifers estimated to yield a total renewable output of 3.442 billion cubic meters of water per year (Radar Technologies Internationa and UNESCO, 2013). Stressing Kenya's vulnerability to climate change effects, water scarcity and low energy production, the Kenyan Ministry for Environment recognizes the need for more research and investment in groundwater exploration and renewable energy sources in order to identify, understand and sustainably exploit these groundwater aquifers.

MATERIALS AND METHODS

Study set up

The experimental set-up was a 150 m deep borehole already installed and operational at Abakore village to the south of Wajir County at co-ordinates 0°37'41.98"N,39°42'26.47"E. The directly coupled PV water pumping system comprised of:

1. PV generator Array- 96 number 195W_p Yingly JS 195 solar panels arranged in paralel columns of 24 modules connected in 4 series totalying to 18.72 kW
2. Motor-pump assembly- a 3 phase submersible centrifugal pump, LORENTZ PS15k2 C-SJ17-18 pumping with a design total dynamic head of 100 m.
3. Water storage tank-one 50 m^3 masonry constructed tank. The PV characteristics and pump specifications as given by the manufacturer's specifications are in Table 1.

Data acquisition

Data was collected using PS DataModule, an integral data logger and remote monitoring device built-in on the Pump Inveter/Controller. The data was retrieved using an application called PumpScaner.The data logger and PumpScaner have been developed by LORENTZ, a German solar pumps manufacturer, and was purchased together with the pump controller. The PS DataModule uses Bluetooth^{TM} technology to communicate with the LORENTZ PumpScaner Andriod^{TM} APP allowing secure real time data to be viewed and historical data to be collected without physical connections. Using this data logger and retrieval mechanisms, performance of the system was monitored for 30 days. The operating hours of the system were limited to 12 h per day. The following data relevant to operational parameters of solar PV water pumping installations were recorded every 30 min daily during the operating hours (1) Array

Table 2. Costs of the various system components.

System component	Quantity	Unit costs (Ksh.)	Total costs (Ksh.)
Solar panels	96	19,337.5	1,856,400
Motor-Pump	1	325,600	325,600
Pump controller Unit	1	374,000	374,000
Balance of System(cables,accessories)	1	1,901,250	1,901,250
Modular support structure	1	476,000	476,000
Transport and Labor for installation	1	371,617	371,617
Total cost of solar PV water pumping system			5,304,867
30 KVA PERKINS Diesel Generator set	1	1,200,000	1,327,440
Motor-Pump and accessories	1	372,560	372,560
Transport and installation costs	1	1,031,500	1,031,500
Total cost of generating set			2,731,500
Generator Fuels costs (Ksh/year)	4 L/h at Ksh.125/Assume genset works from 630am to 6pm (same time for solar pump)		2,160,000
Operations and maintenance costs (Ksh/year)	Lubricants (oil, grease)-changed monthly by operator		72,000.00
	Spare parts(Fuel and oil filters)-changed monthly by operator		96,000.00
	Regular service, annual service mechanic fees. Done 2 times a year after rains one-time cost of Ksh.30,000 spread monthly)		60,000.00
Total maintenance and operations costs			2,388,000

in-plane Solar irradiation (W/m^2); (2) water discharge rate, m^3/h; (3) pump input voltage (V) and (4) pump input current (A). The pumping system was designed to operate at a fixed total dynamic head of 100 m.

Economic analysis data

Life-cycle cost (LCC) analysis method which calculates the present worth of all costs, capital, operation and maintenance, and replacement parts over the lifetime of the system was used to perform an economic evaluation of the solar PV water pumping system in comparison with diesel generator water pumping set. Financial data as detailed in Table 2 was provide by Abakore Water Users Association. In the life-cycle cost analysis, the following assumptions and data sources were used:

1. The expected lifetime of the solar system as 20 years and diesel system 10 years.
2. Operation and maintenance costs per year are assumed constant for the systems.
3. The solar pump and diesel pump is replaced every 10 years.
4. The storage tank and distribution line costs are not included in the analysis because, it is considered as the same for both cases.
5. The interest rates and inflation rates used were 16.56 and 6.88%, respectively, while the Kenya shillings to US dollar conversion rate was 1 US $ to Kenya shilling 98.6. All values were averages for the preceding year of analysis as extracted from the Central Bank of Kenya.

RESULTS

System performance analysis

The data obtained from Abakore installation have been analysed and treated in order to evaluate the performances and the characteristic parameters of the system. Figure 1 shows the observed solar irradiance in the plane of the PV array (W/m^2) and the power output of the PV array (kW). It was observed that the system generated a maximum power output of 11.75 kW from the panels against a solar irradiance input of 778.06 W/m^2 at about mid-day.

Figure 2 shows that the solar pumping system pump discharge started at irradiance level of between 101 and 200 W/m^2, increasing gradually as solar irradiance increased while the diurnal variation in pump output as shown in Figure 3 indicated on average, production of 16.7m^3/hr and a total daily production of 156m^3/day as shown by Figure 4.

Figure 5 shows the scatter plot of the pumping system characteristic curve installed at Abakore generated using measured solar irradiance and pump flow rate data. The Pearson coefficient of correlation was 0.925, and the significant difference by the statistical significant test was meaningful with 1% of levels of significance.

The results indicate an average of discharge of 156 m^3/day. Figure 6 shows the relationship between nominal power output of the PV Array, the PV array actual power output at field conditions and the hydraulic power generated by the pump. The nominal power is determined as the irradiation received on the array plane multiplied by the standard test conditions efficiency provided by the manufacturer as 14.7%. The nominal power is the ideal power the PV array generator should generate as determined by the manufacturer at standard test

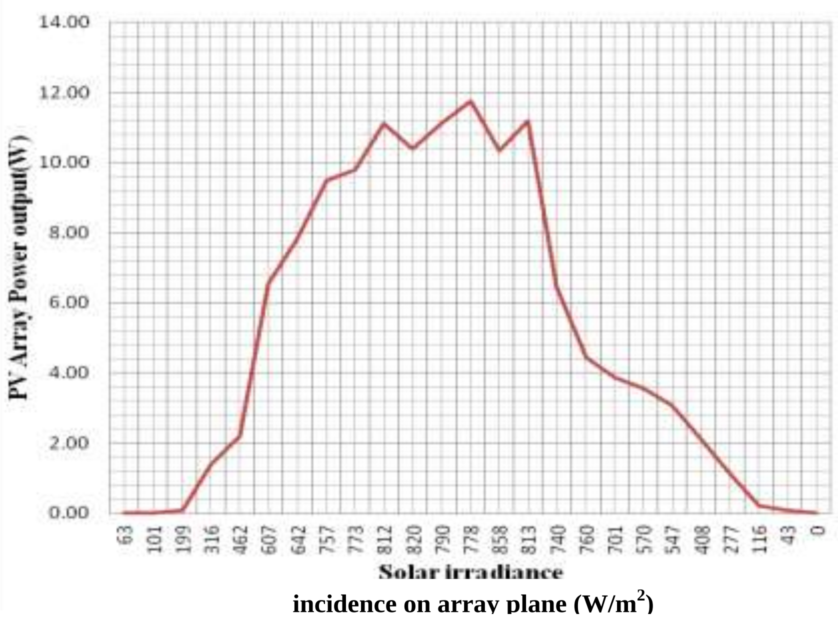

Figure 1. Variation of PV power output and the incident solar irradiance received on PV array plane.

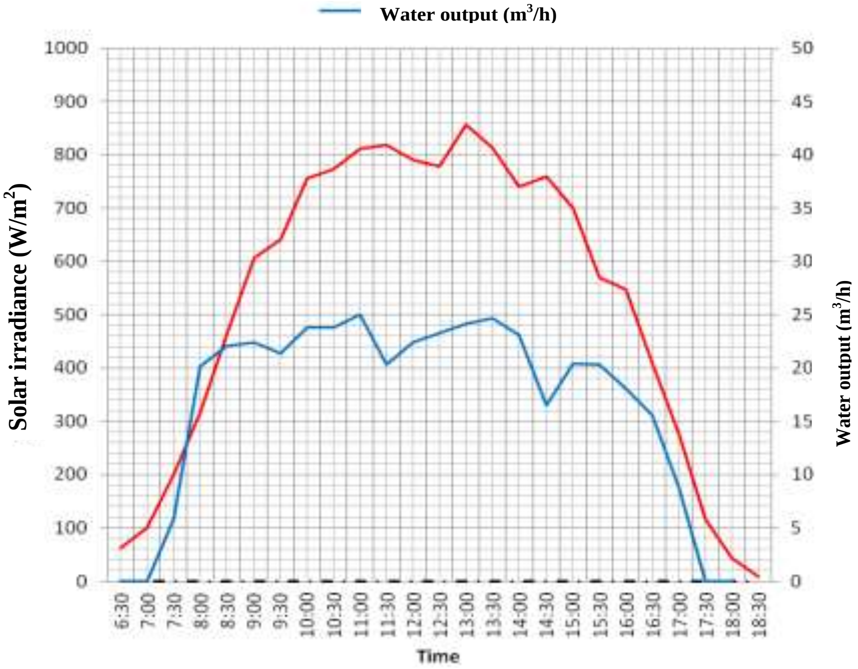

Figure 2. Relation between incident solar irradiance and water output.

conditions. The results showed that the power generated by the PV array is clearly below the ideal power at standard test conditions. Figure 7 shows comparison of the array, sub-system and overal system efficiencies obtained.

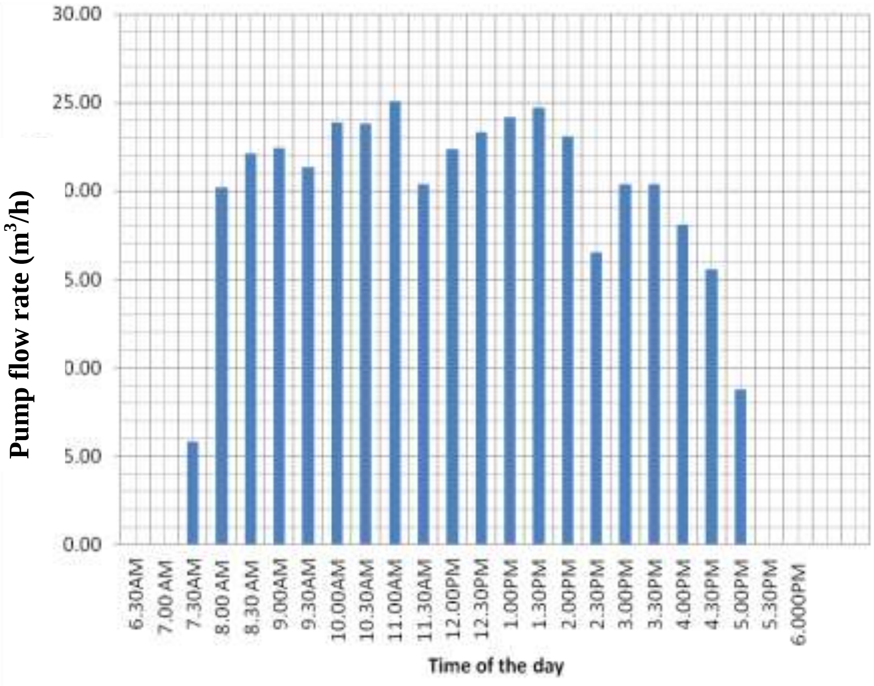

Figure 3. Diurnal variation of flow rate of the pumping system.

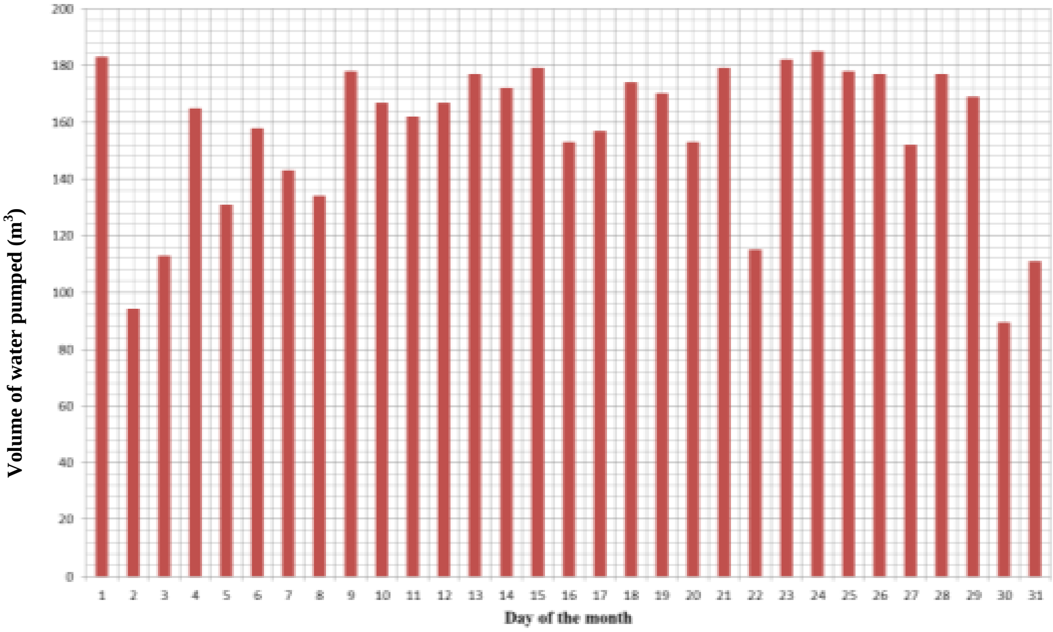

Figure 4. Measured daily volume of water pumped by the system of solar PV pumping at Abakore.

Life-cycle cost analysis

Figure 8 compares the life cycle costs for the photovoltaic and diesel powered water pumping systems installed at Abakore. The analysis was caried at an average interest rate of 16.56% and inflation rate of 6.88%.

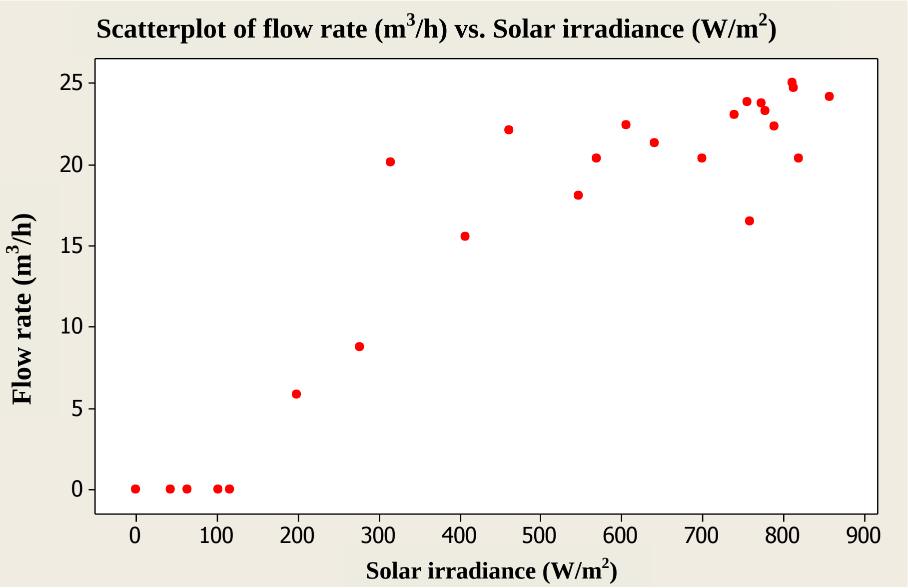

Figure 5. Scatter plot of the Abakore system characteristic curve.

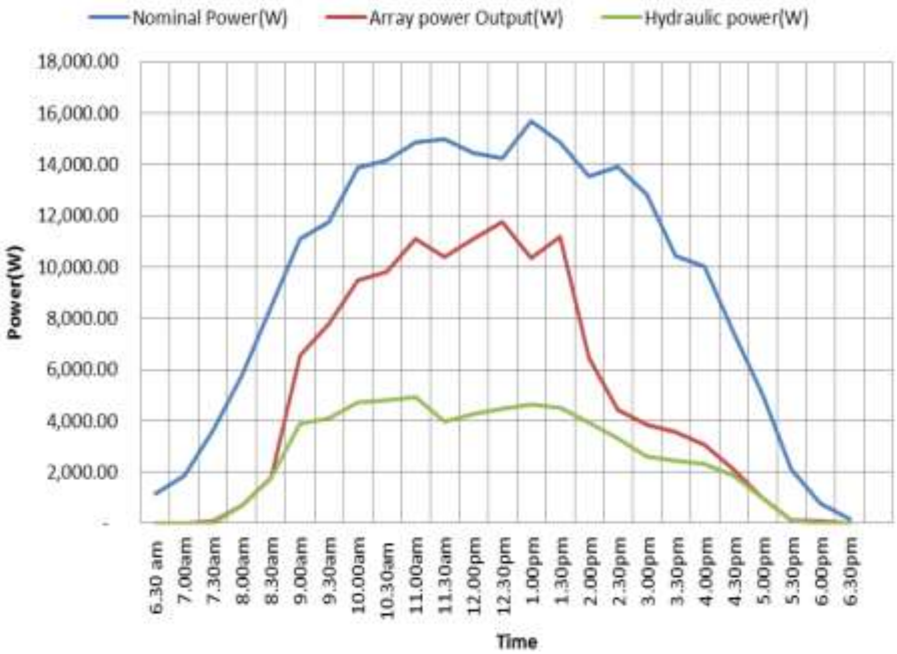

Figure 6. Relationship between nominal power, PV array output power and the hydraulic power generated by the pump.

The breakeven point between PV water pumping system and diesel pumping system was found to be in the third year of operation. The results indicate that the life cycle costs of diesel pumping system will increase significantly over the years, while the life cycle costs of solar photovoltaic system is expected to remain fairly constant over the years. While the unit water cost in Ksh/m^3 using photovoltaic pumping system is expected to decrease

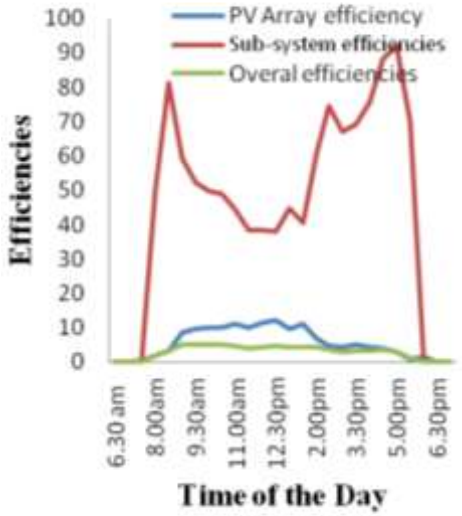

Figure 7. Comparison of array, sub-system and overall system efficiencies.

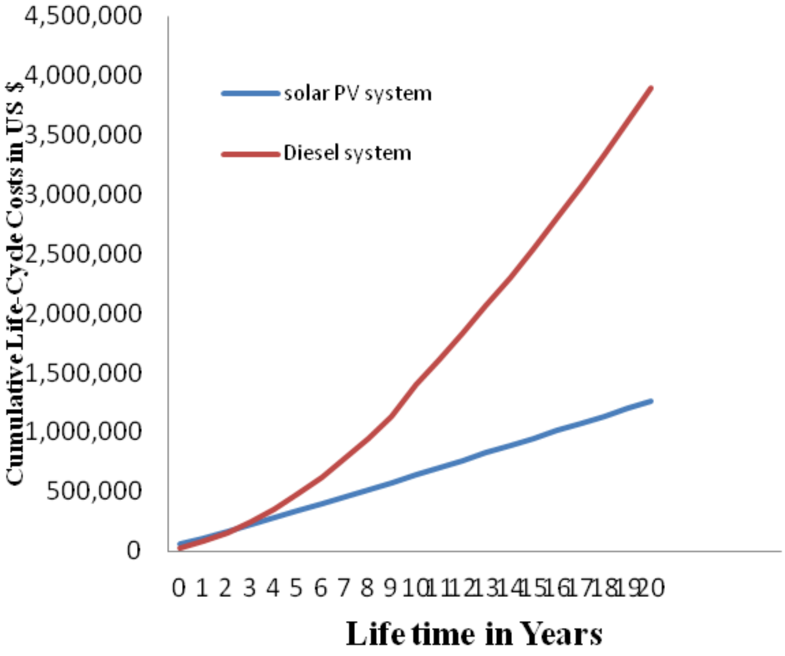

Figure 8. Comparison of 25 year PV and diesel systems life cycle costs.

over the years, the unit water cost for diesel pumping system will increase significantly. In a similar pattern as the unit water cost, the energy cost in Ksh/m^4 which is the equivalent hydraulic energy for the PV pumping system decreases with years while that of diesel pumping system is expected to increase. The unit cost of water provided by the photovoltaic pump was found to be 104.05 Ksh (1.06 $)/m^3 in year one then reduced in the following years to an average of 24.75 Ksh (0.25 $)/m^3 for the 20 year period, while the unit cost using the diesel genset system showed an initial result of 95.58 Ksh (0.96 $)/m^3 in year one and an average of 59.92 Ksh (0.6 $)/m^3 over the 20 year period of analysis.

DISCUSSION

The system obtained a highest PV array conversion efficiency of 12.1%. This is slightly less than the manufacturer provided efficiency of Yingly J195 solar modules of 14.7%. This array efficiency compares well with most literature which cites the achievable efficiency in the conversion of solar radiation to electricity by solar cells in practice to be about 9 to 15.1% under field conditions (Dapkus and Hummel, 1993). This slightly lower efficiency observed at Abakore can be attributed to variations in cell temperature from the standard test conditions. This study did not analyse the effects of temperature variation on PV output but other researchers have shown that the efficiency decreases with increasing temperature (Green, 1982). Other parameters that led to this lower efficiency include changes in the quantity of solar irradiance received on the array plane and incidence angle which varied through the day. Losses in wirings of PV modules into PV arrays and inverter losses are also attributable to the lower PV conversion efficiency.

The sub-system efficiency and overall system efficiency exhibited a three-phase changing pattern within a day. Phase 1 occurs between 6 to 9 am, phase 2 from 9 am to 4.30 pm, and phase 3 from 4.30 to 6:30 pm. During phase 1, the sub-system and overall system efficiency starts from zero and increases to a relatively high value, the efficiency remains relatively constant during phase 2 varying from a range of 5.14 to 3.7% for the overall system efficiency. It can be seen that the subsystem efficiency showed the highest value of 81.36% during phase 1 in the early morning and 91.82% at the end of phase 2 in the late hours of the day. This can be attributed to the fact that as the flow rate increases at higher irradiation conditions, the efficiency goes down due to the decrease in the pump efficiency. Even though the efficiencies of inverter and motor normally increase by higher flow rates (higher frequencies), this cannot compensate for the decrease of the pump efficiency. The most important consideration in system design is the match between the motor-pump sub-system and the PV array. The sub-system efficiency is an indicator of the match between the motor-pump sub-system and the PV array. It is obtained as the ration between hydraulic power and the electrical power of the sub-system. The range of 49 to 91% sub-system efficiencies obtained at Abakore shows a good match between the motor-pump and the PV array. The optimum load matching factor for the Abakore PV water pumping system was obtained as an average of 0.66. This value was obtained from the radiation threshold of 200 W/m^2 and from the daily average, hourly solar irradiance curve. This value is comparatively average showing that the system components were averagely well matched and adequately configured.

Conclusions

The key significance of this study was to present the performance results of a system operating under real variable field conditions and not in a controlled laboratory environment. The overall system efficiency obtained for the Abakore installation was 5.14%. This shows good result in comparison with current practice where PV-pumping overall efficiency has considerably improved from 1-3% in 1980s to 3.5-5% in 2016. While the installed capacity was 18.72 kW and the maximum power generated by the PV array was found to be 11.1 kW, the maximum discharged obtained was 25.05 m^3/h at a power input of 9 kW which is half of the installed capacity. This demonstrates that while improvements in photovoltaic module manufacturing techniques are continuously researched, there still remains a clear need for development towards both improved reliability, efficiency values and components matching of solar pumping sub-systems in order to extract the maximum power capability of the solar generator at all times. The results of the economic analysis demonstrates that the higher initial cost of photovoltaic pumping systems can be justified by the savings in the lower operation and maintenance as well as the increased reliability throughout the useful longer life of the PV system as compared to diesel generator pumping system.

ACKNOWDEGEMENTS

The authors are grateful to Nicholas Odera of Davis and Shirtliff and Abdirizak Kontoma of Oxfam for providing the resources and materials to study the solar installations in Wajir County. They are also grateful to Dr. Omuto and Prof Giatu, both of the Department of Bio systems and Environmental Engineering, University of Nairobi for their technical support and supervision in collecting and analyzing the data for this study.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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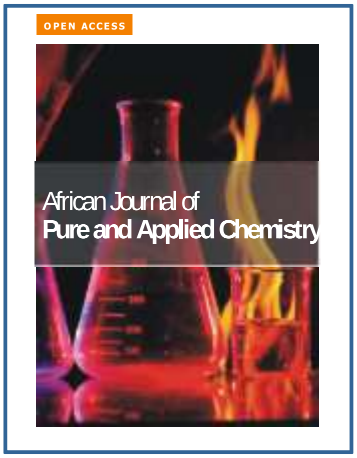
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