Scientific Research Publishing

Computational Water, Energy, and Environmental Engineering, 2021, 10, 95-107
https://www.scirp.org/journal/cweee
ISSN Online: 2168-1570
ISSN Print: 2168-1562

Evaluation of Water Delivery Performance of Nkhafi Irrigation Scheme in Dowa District, Malawi, Africa

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How to cite this paper: Sibale, D., Mwenelupembe, G., Chikabvumbwa, S. and Chisale, S. (2021) Evaluation of Water Delivery Performance of Nkhafi Irrigation Scheme in Dowa District, Malawi, Africa. *Computational Water, Energy, and Environmental Engineering*, **10**, 95-107.
https://doi.org/10.4236/cweee.2021.103007

Received: April 13, 2021
Accepted: May 31, 2021
Published: June 3, 2021

Abstract

This study evaluated the water delivery performance of Nkhafi irrigation scheme based on adequacy, water delivery efficiency, equity, dependability and irrigation efficiency. Primary data were collected from field measurements, scheduled interviews, group discussions and use of a structured questionnaire. CROPWAT 8.0 computer model was used to determine crop water requirements and irrigation requirements. The results revealed that adequacy, water delivery efficiency, equity, dependability and overall water delivery performance were (0.74; 0.82), (0.70; 0.80), (0.15; 0.20), (0.11; 0.21) and (0.80; 0.80) for 2017 and 2018 seasons respectively. The scheme overall irrigation efficiencies were 20% and 25% for 2017 and 2018 respectively. These findings revealed that scheme users failed to deliver adequate and dependable water in an effective manner in both growing seasons. This occurred due to insufficient water supply, poor irrigation scheduling, lack of adequate knowledge and skills in operating and rehabilitating hydraulic structures, siltation and water losses through seepage in canals. Therefore, it is recommended that major maintenance works need to be done along the whole canal network in order to achieve good overall water delivery performance. Furthermore, farmers need to be trained in water management, sustainable agricultural production practices, operation and maintenance of irrigation structures. The study has provided an insight on the status of the scheme hence encouraging scheme users to improve water delivery performance.

Keywords

Adequacy, Water Delivery Efficiency, Equity, Dependability, Irrigation Efficiency

1. Introduction

In Malawi, dwindling of water resources due to climate change impacts has resulted into increasing water scarcity in most areas. Rainy seasons have become unpredictable and droughts have been more frequent in the last decades due to climate change and variability [1]. Water users in agriculture sector are facing challenges to access adequate water due to increasing drought frequency and erratic rainfall. The changing climate with greater rainfall uncertainty has created severe problems in managing and supplying freshwater supplies [2]. Climate change has also increased hydrological variability in most areas, making it more difficult to satisfy the increasing water demands. It poses a threat to sustainability of water resources [3] [4]. More emphasis has now been drawn into efficient use of irrigation water in order to maximise economic return and water resources sustainability. This calls for effective ways of managing water resources in irrigated agriculture in Malawi.

Erratic rains due to climate change have affected effective production of food crops. Irrigation development is a viable option for increasing agricultural production in the country. Irrigated agriculture is a major water user; however, there is low performance in water delivery in most irrigation schemes. Water management activities are performed by farmers themselves; furthermore, they also lack technical capacity to manage water properly. Other factors contributing to low performance of many irrigation schemes include: poor system's design and construction, poor water management approaches, poor operation and maintenance of irrigation infrastructure. These drawbacks further contribute to poor water delivery performance in irrigation schemes [5].

In irrigated agriculture, transferring water with minimum losses can help to increase irrigation efficiency, hence saving large quantities of water resources. The conveyance, distribution and application systems need to be in good condition in order to minimise water losses. One of the possible approaches is to improve water delivery performance of existing irrigation schemes. In most Malawian smallholder irrigation schemes, much attention focuses on production and outputs from the scheme and little attention is given to the water delivery performance in the schemes. As a case study, Nkhafi irrigation scheme was chosen for an evaluation of water delivery performance. The study was conducted to analyze the performance of the surface irrigation system in relation to water delivery performance indicators which included: adequacy, water delivery efficiency, dependability, equity and irrigation efficiency. Fan *et al.* [6] reported that assessing the performance of an irrigation system is an imperative step in enhancing sustainable agriculture water management. The findings from the study would help to point out where problems exist in the system and provide proper guidance to scheme managers and users on effective operation, maintenance and management of the scheme.

Previous Studies

Gomo *et al.* [7] conducted a research study on technical performance of the Mooi River irrigation scheme. It was discovered that poor water management practices contributed to a situation of having shortage of water in the scheme. Farmers knew the causes of the water shortage but needed external support in order to ensure water is equitably distributed. Vandersypen *et al.* [8] evaluated the irrigation performance of the Office du Niger (Mali) in 1995 and 2004 using equity, dependability, adequacy and efficiency. They found that irrigation delivery service was excellent due to timely physical rehabilitation of the irrigation network. Mohammadi *et al.* [9] conducted an assessment of Varamin irrigation scheme in Iran. The results of their research showed that most of the structures were poorly being operated, leading to unfair delivery and wastage of much water during water distribution. Ortiz [10] conducted a research study in Tumbaco irrigation system, located in the province of Pichincha, Republic of Ecuador, to determine conveyance, distribution, application and overall irrigation efficiencies. The results showed that the conveyance, distribution, application and overall irrigation efficiencies were 78.82% (regular), 37.95% (poor), 60.72% (good) and 18.17% (poor) respectively. The poor overall irrigation efficiency was affected by the disparity in water distribution to the users. The timing of water delivery assigned by water user association did not take into account the real discharge delivered to the users neither to the crop water requirements, creating inequity, conflicts between users as well as over and under irrigation.

2. Materials and Methods

2.1. Study Area

The study was conducted at Nkhafi irrigation scheme (Longitude: 33.6˚, Latitude: 13.4˚, 1115 m above sea level), about 68 km north of Lilongwe, the capital city of Malawi. The mean rainfall per year in the study area is 62.5 mm with the maximum of 104.5 mm and minimum of 20.4 mm. The average temperatures range from 19.4˚C and 21.3˚C. **Figure 1** shows location of the irrigation scheme.

2.2. Data Collection

Primary data were collected from field measurements carried out within the scheme. Such measurements included: flow velocity, canal dimensions, and actual water surface elevation in canals and volume of water supplied to each block of the scheme. Measurement of canal water flow was done by applying the velocity-area method. CROPWAT 8.0 Computer model was used to determine crop water requirements and irrigation requirements (IR). The input data for CROPWAT model included; climatic data of the study area, soil texture, type of crops, crop coefficient, root depth, depletion factor, available soil moisture, basic infiltration rate, and irrigation efficiency. Daily and monthly reference Crop Evapo-transpiration (ETO) was estimated based on FAO Penman-Monteith method. The volume of water required to feed the main and branch canals were

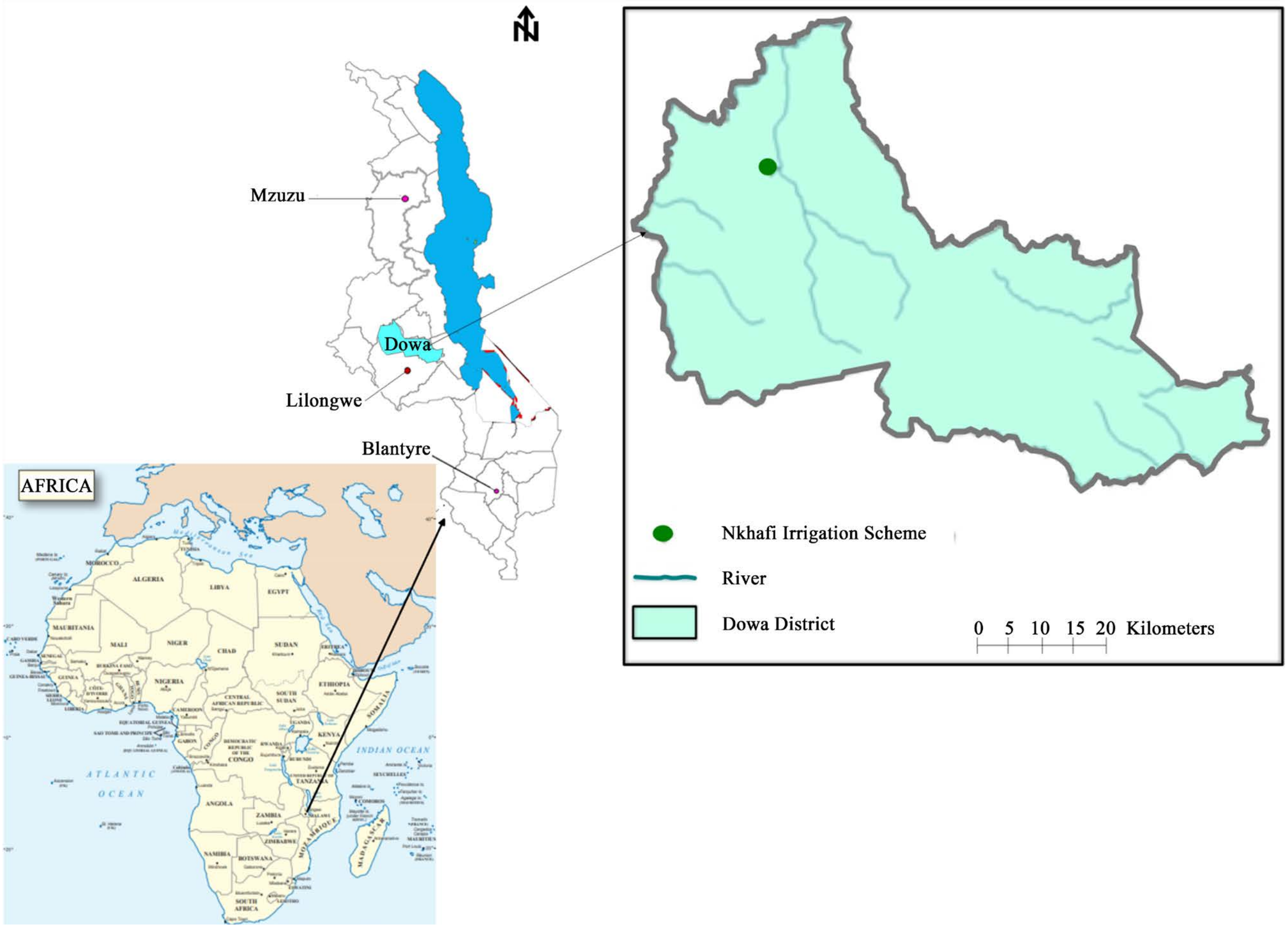


Figure 1. Location of Nkhafi Irrigation scheme.

estimated based on gross irrigation requirement and the command area served.

Data collection was carried out in collaboration with scheme users (farmers), WUA executive members, Agricultural extension development officers, irrigation officers and chiefs. To get information from targeted respondents, a structured questionnaire containing both open and closed-ended questions was used. This approach was incorporated in the study in order to assess the perceptions of water users regarding the irrigation service delivery and identify factors that affect water delivery at the study area. Data on climate, crops under irrigation, actual command areas, canal discharge, and features of hydraulic structures, were fully utilized in the study.

2.3. Water Delivery Performance Indicators

Adequacy, water delivery efficiency, equity, dependability and irrigation efficiency were the key internal water delivery performance indicators in this study.

2.3.1. Adequacy

According to Molden and Gates [11], adequacy is a measure that reveals if the required amount of water is adequately supplied to crops under irrigation. It is a measure of the ability of an irrigation system to meet targeted deliveries in terms of quantity [12]. Adequacy was determined using Equation (1):

$$P_A = \frac{1}{T}\sum\frac{1}{R}\left(\sum pA\right) \tag{1}$$

$$\text{and} \quad pA = \frac{Q_D}{Q_R}$$

where, P_A is performance measure relative to adequacy at subsystem or system level, pA is adequacy for a single point (delivery performance ratio), Q_D is the actual amount of water delivered per block, Q_R is the required amount of water, R is the region served by the system and T is the irrigation time.

2.3.2. Water Delivery Efficiency

This clearly shows the amount of water wasted by checking the amount of water delivered and the amount of water required per block. The water delivery efficiency was determined using Equation (2):

$$P_F = \frac{1}{T}\sum\frac{1}{R}\left(pF\right) \tag{2}$$

$$\text{and} \quad pF = \frac{Q_R}{Q_D}$$

where, P_F is the performance measure of water delivery efficiency, pF is the adequacy for a single point (delivery performance ratio), Q_D is the actual amount of water delivered per block, Q_R is the required amount of water, and R is the region served by the system, and T is the time period.

2.3.3. Equity

Equity is a measure of water delivery fairness among water users and is given by a coefficient CV_R which measures spatial variation of the ratio of the amount of water delivered to the required amount of water. Equity was determined using Equation (3):

$$P_E = \frac{1}{T}\sum CV_R\left(\frac{Q_D}{Q_R}\right) \tag{3}$$

where, P_E is the performance measure relative to equity, $CV_R\left(\frac{Q_D}{Q_R}\right)$ is the spatial coefficient of variation of the ratio (Q_D/Q_R) over the region (R), R is the region served by the system, and T is the irrigation time.

2.3.4. Dependability or Reliability

This is an important indicator because it shows the reliability of the system to meet the expected water deliveries. Dependability was determined using Equation (4):

$$P_D = \frac{1}{R}\sum CV_T\left(\frac{Q_D}{Q_R}\right) \tag{4}$$

where, P_D is the performance measure relative to dependability or reliability,

$CV_T\left(\frac{Q_D}{Q_R}\right)$ is the temporal coefficient of variation, R is the region served by the system, and T is the irrigation time.

2.3.5. Overall Performance Indicator (OPI)

The overall performance indicator varies from 0 to 1. After determining the adequacy, water delivery efficiency, equity and dependability, the OPI was measured and evaluated using Equation (5) below:

$$\text{OPI} = \frac{P_A + P_F + (1 - P_E) + (1 - P_D)}{4} \quad (5)$$

where, OPI is the overall performance indicator, P_A is the performance measure relative to adequacy, P_F is the performance measure of water delivery efficiency, P_E is the performance measure relative to equity, and P_D is the performance measure relative to dependability or reliability.

For effective decision making, the water delivery indicators were compared with acceptable standard indicators presented in Table 1.

Table 1. Standard water delivery indicators (Molden and Gates, [11]).

Water delivery indicator	Performance class		
	Good	Fair	Poor
Adequacy (P_A)	0.90 - 1.00	0.80 - 0.89	<0.80
Water delivery efficiency (P_F)	0.85 - 1.00	0.70 - 0.84	<0.70
Equity (P_E)	0.00 - 0.10	0.11 - 0.25	>0.25
Dependability (P_D)	0.00 - 0.10	0.11 - 0.20	>0.20
Overall performance indicator (OPI)	0.89–1.00	0.76 - 0.89	<0.76

2.3.6. Irrigation Efficiency

Performance assessment using irrigation efficiencies both involved infield application efficiencies and overall scheme efficiency. To determine these efficiencies, flow measurement was carried out on strategic points along conveyance, distribution and application systems. The canals were divided into sections such that each section covered a particular block. The water velocity was measured on various sections of the canals. Canal design parameters were checked and verified with existing parameters which included: flow depth, top water width, canal top width, bed width, side slope, bed slope and wetted perimeter.

After knowing the flow rate at the inlet and outlet of each conveyance and distribution system, the conveyance and distribution efficiencies were determined. As for application efficiency, the amount of water supplied to a particular field was measured and soil water content on representative points throughout the field was determined before and after the irrigation. After gathering the much-needed data, the following formulae were used to calculate the required irrigation efficiencies:

1) Conveyance Efficiency

$$E_c = \frac{W_o}{W_s} \times 100 \quad (6)$$

where, E_c is water conveyance efficiency, W_o is the volume of water released from the conveyance system, and W_s is the volume of water delivered into the system from the source.

2) Distribution Efficiency

$$E_d = \frac{W_f}{W_b} \times 100 \quad (7)$$

where, E_d is distribution efficiency, W_f is the volume of water applied to the actual field, and W_b is the volume of water supplied to the block of the field.

3) Application Efficiency

$$E_a = \frac{W_c}{W_f} \times 100 \quad (8)$$

where, E_a is the application efficiency, W_c is the amount of water available for use by the crop in the root zone, and W_f is the volume of water applied to the actual field.

4) Overall Irrigation Efficiency

$$E_p = \frac{W_c}{W_s} \times 100 \quad (9)$$

where, E_p is overall irrigation efficiency, W_c is the amount of water available for use by the crop, and W_s is the volume of water delivered into the system from the source.

Conveyance, distribution and water application efficiencies were checked as guided by Reddi and Reddy [13].

3. Results and Discussion

Water Delivery Performance Indicators

The results for adequacy, water delivery efficiency, equity, dependability and overall water delivery performance are presented in Table 2.

According to the results in Table 2, the overall adequacy was "poor" in 2017

Table 2. Water delivery performance indicators.

Water delivery performance indicators	2017		2018	
	Value	Decision	Value	Decision
Adequacy (P_A)	0.74	poor	0.82	Fair
Water delivery efficiency (P_F)	0.70	Fair	0.80	Fair
Equity (P_E)	0.15	Fair	0.20	Fair
Dependability (P_D)	0.11	Fair	0.21	Poor
Overall water delivery performance (OPI)	0.80	Fair	0.80	Fair

season and "fair" in 2018 season. The findings revealed a gradual trend in terms of supplying the required volume of water in irrigation blocks. In both seasons, it showed that water delivery did not meet crop water requirement. Water supply was not adequate to satisfy water demand due to the decline of water levels from the source and excessive water losses in the conveyance and distribution systems. Lack of capacity to repair water supply systems contributed to an increase in water losses along the supply systems.

In the same process of water delivery in the irrigation scheme, the overall water delivery efficiency was "fair" for both 2017 and 2018 growing seasons. Though there was fair water delivery efficiency, siltation and water losses during delivery process were in existence at the irrigation scheme. This was attributed to poor water management, poor operation and maintenance of the system. It was further noted that there was malfunctioning of flow control structures and poor monitoring of water distribution systems.

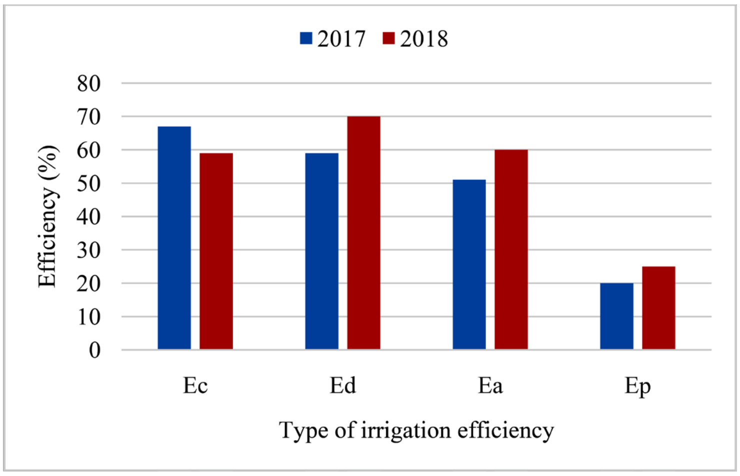
Overall equity was "fair" for both 2017 and 2018 growing seasons. The findings revealed that water delivery was not uniform as expected in the system. Overtime, it was discovered that there was a great disparity in water distribution on each outlet. The results reveal that additional efforts are required to improve water delivery and distribution in the fields with respect to time, quantity and crop water demand. Proper irrigation scheduling and restoration of flow control structures can help to improve the overall equity in the scheme.

Further confirmation was observed on system's dependability where the overall dependability was "fair" in 2017 season and "poor" in 2018. The findings revealed that water was distributed fairly on time in 2017 season and distributed poorly in 2018 season. Some gated structures were in poor condition hence failed to function properly. There was uncontrolled flow of water. This contributed to attainment of poor trend of dependability or reliability (P_D).

Upon considering adequacy, water delivery efficiency, equity, and dependability, the overall water delivery performance (OPI) was fair for both seasons (2017 and 2018). Even though the overall water delivery was fair, the required water was not delivered to field blocks as expected. This occurred due to lack of water measuring devices, insufficient water supply, and lack of competency in operating hydraulic structures. The wasted water through seepage in canals also affected the overall water delivery performance. Therefore, major maintenance works need to be done along the whole canal network in order to achieve good overall water delivery performance. The results align with the findings of Agide *et al.* [14] which emphasized on the need of scheme rehabilitation in order to improve water supply, distribution and application.

In assessing the performance of Nkhafi irrigation scheme in terms of water delivery, the results on conveyance, distribution, application and overall irrigation efficiencies were also helpful. The results are presented in **Figure 2**.

According to [15], the attainable application efficiency ranges from 55% - 70%. Based on the results, the application efficiency was below the required



E_c is the Conveyance efficiency, E_d is the distribution efficiency, E_a is the application efficiency and E_p is the overall irrigation efficiency.

Figure 2. Irrigation efficiencies at the scheme.

range in 2017 season and improved to 60% in 2018 season. According to the study conducted by [16], the distribution efficiency should be ≥60%. The results from this study revealed that the distribution efficiency was below 60% in 2017 season and improved to 70% in 2018 season. According to [17], the acceptable conveyance efficiency is 90% and 70% for lined and unlined canals respectively. In reference to **Figure 2**, the conveyance efficiencies at the scheme were below the acceptable limit in both seasons. This clearly shows that there is laxity in managing water in the conveyance system.

In a surface irrigation scheme, overall irrigation efficiency of 50% - 60% is considered to be good; 40% is considered to be reasonable, while overall irrigation efficiency of less 40% is poor [18]. Though there was an improvement in distribution and application efficiency from 2017 season to 2018 season, the overall irrigation efficiency was poor in both seasons. In reference to **Figure 2**, the results show that the scheme overall irrigation efficiency was 20% and 25% for 2017 and 2018 growing seasons respectively. This revealed that more water was wasted in the scheme due to poor water management practices. It was also noted that water was being delivered to field blocks without knowing the quantity of water to apply and the exact time of water application. Therefore, to improve water management, irrigation scheduling would help in matching the right quantity of water to apply based crop water requirement. Proper field leveling is also required at the scheme. Desilting and effective lining need to be intensified in the distribution network in order to minimize the seepage losses. Trainings in water management should also be targeted to all farmers participating in scheme activities. The study has also revealed the need for high level technical knowledge as indicated in **Table 3**. Absence of supportive training on best irrigation practices to guide sustainable water management and irrigation scheduling further result into low performance of water delivery in an irrigation scheme.

In reference to **Table 3**, majority of the farmers revealed that there are no local technical experts to offer support services to the irrigation scheme. Unavailability of qualified local technical experts to repair irrigation structures implies that there is a technical gap which influences negatively to sustainability of the scheme.

From **Table 4**, it is evident that majority of the farmers revealed that there are no trained committees to handle water management systems. Lack of skills to handle water management systems also led to inefficiency in managing water distribution and application. This study noted that limited abilities, skills and knowledge of farmers in operation and maintenance of the scheme affected the efficiencies at the scheme. These results concur with the findings of Dejen *et al.* [19] and Ulsido [20] who found out that limited trainings on irrigation water management leads to low performance of an irrigation scheme. Yami and Snyder [21] extended that farmers' trainings in irrigation water management are crucial in ensuring sustainable irrigation development.

Performance and sustainability of the scheme also relies on availability of materials for maintenance work. It is evident from **Table 5** that majority of the farmers agreed that materials for maintenance are available within the study area. The availability of materials for maintenance work is an indication that water system's structures can be fixed whenever a breakdown occur without delays. This greatly influences sustainability positively.

Table 3. Availability of local technical experts to provide support services.

Local technical experts	Frequency (F)	Percentage (%)
Yes	7	14
No	43	86
Total	**50**	**100**

Table 4. Availability of trained committees to handle water management systems.

Trained committees	Frequency (F)	Percentage (%)
Yes	5	10
No	45	90
Total	**50**	**10**

Table 5. Availability of materials for maintenance work.

Materials for maintenance work	Frequency (F)	Percentage (%)
Yes	35	70
No	15	30
Total	**50**	**100**

4. Conclusion

An evaluation of water delivery performance of Nkhafi irrigation scheme was a practical exercise that provided a better understanding on how water is conveyed, distributed and applied in the scheme. The water delivery performance of Nkhafi irrigation scheme was evaluated using adequacy, water delivery efficiency, equity, dependability and irrigation efficiency. The results revealed that there was fair overall water delivery performance at the scheme. Furthermore, the study revealed that the overall irrigation efficiency was poor. This confirms that there was a disparity in water distribution at the scheme. Though the overall water delivery performance of Nkhafi irrigation scheme was classified as "fair", much work needs to be done in order to improve its performance. The system can become more dependable by carrying out major maintenance works along the whole canal network and implementing effective irrigation scheduling. With the current impact of climate change on water resources, farmers at the scheme need to be trained in water management, sustainable agricultural production practices, operation and maintenance of irrigation structures. The study has provided an insight on the status of the scheme hence encouraging scheme users and other stakeholders involved to improve water delivery performance.

Acknowledgements

Authors would like to extend great thanks to Nkhafi irrigation scheme users, WUA executive members, agricultural extension development officers, irrigation officers and chiefs for spending their time to provide required information that was very helpful in the study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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