International Journal of Industrial and Manufacturing Systems Engineering
2024, Vol. 9, No. 1, pp. 10-24
https://doi.org/10.11648/j.ijimse.20240901.12

SciencePG
Science Publishing Group

Research Article

Irrigation Performance of a Water Distribution System: The Case of Kigugu Irrigation Scheme-Mvomero District Morogoro Region-Tanzania

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Abstract

This study assessed the performance of the Kigugu Irrigation Scheme's water distribution system in Tanzania with an emphasis on its impact on crop yields. We used a combination of participatory tools and direct observation to gather comprehensive data, including weather patterns, water discharge rates, and farmer input levels. Descriptive statistical analysis revealed significant variations in water distribution across canals, with Relative Water Supply (RWS) values ranging from 0.7 to 5.9, indicating instances of both over- and under-supply. Despite these variations, satisfactory performance was demonstrated by the irrigation system, with high Water Delivery Performance Ratio (WDPR) values consistently recorded above 0.65, indicating that water demands were largely met across the system. Furthermore, the study found that equity in water distribution improved significantly during the growing season, with the equity index dropping from 0.2 to 0.1. This underscores the critical need for fair water allocation practices, particularly during low-flow periods, to ensure that all farmers receive an adequate supply. Based on these findings, several recommendations for irrigation system modifications were proposed to further improve water distribution and equity. In terms of productivity, a notable correlation between water distribution and crop yield was observed. A canal with a design discharge of 0.0228 m^2/s produced a yield of 552.18 metric tonnes, demonstrating efficient water utilization. In contrast, canal SC.4-2, with a lower discharge of 0.0185 m2/s, achieved a smaller yield of 274.31 metric tonnes, further highlighting the importance of optimal water distribution for enhancing agricultural productivity. Overall, the Kigugu Irrigation Scheme maintains a reliable water supply, contributing positively to sustainable water resource management and agricultural productivity. This, in turn, supports local economic growth, enhances food security, and improves community well-being. The study's findings provide critical insights for future improvements in irrigation management and resource allocation.

Keywords

Irrigation Performance, Water Distribution System, Crop Yields, Relative Water Supply, Water Delivery Performance Ratio

1. Introduction

Water distribution systems are critical for effective irrigation scheme management, ensuring optimal water delivery to fields [1]. Assessing system performance is vital for identifying areas for improvement and increasing agricultural

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Received: 9 September 2024; **Accepted:** 4 October 2024; **Published:** 25 December 2024

productivity [2]. Assessing the performance of water distribution systems allows for the identification of inefficiencies and the implementation of targeted interventions to optimise water usage [3]. Evaluating water distribution efficiency and effectiveness requires considering various performance indicators and socio-economic factors [5, 7]. Equitable water allocation is essential, ensuring fair shares for all farmers, regardless of location within the system [6]. Tanzania, with a potential irrigable area of 29.4 million ha, faces challenges with low water-use efficiency (WUE) in many irrigation projects [7, 8]. Improved schemes, like Kigugu (800ha), lack performance evaluation, hindering understanding of their impact on production despite substantial investments [4, 5]. This study focuses on the Kigugu Irrigation Scheme's water distribution system, analysing its efficiency, impact on crop yields, and challenges faced by farmers and the scheme. Recommendations aim to enhance system efficiency and effectiveness, contributing valuable insights to irrigation management.

2. Materials and Methods

1. Description of the Study Area: The research focused on the recently rehabilitated Kigugu farmers-managed irrigation scheme in Mvomero district, Morogoro, Tanzania, covering an area of 800ha. Situated near Kigugu village, the region has two major rivers, Chazi and Kigugu, with rice cultivation occurring in the dry (October–December) and wet (March–May) seasons. Soil conditions are conducive to rice growth. The study area's mean temperature is 24.95 ℃, and rainfall ranges from 700 to 1600 mm annually.
2. Experimental Design and Layout: Upper, middle, and tail sections of streams were analysed, incorporating 62 farmers in the upper and middle blocks and 61 in the lower block. Dominant secondary canals and structures such as water distribution boxes (DBs) and secondary canals (SCs) were key components. Cochran's formula determined a sample size of 184 farmers.

2.1. Data Collection

(i) Assessing Water Distribution Efficiency: Various methods, including infrastructure surveys, discharge measurements, and farmer perceptions, were employed to evaluate the efficiency of water distribution. Field observations identified irregularities. Daily water discharge data were collected using measuring weirs and supplemented with meteorological data.

(ii) Analysing Impact on Crop Yields: Data from registered farmers, including water discharge measurements and crop yields, were analysed to understand the irrigation system's impact on crop productivity.

(iii) Challenges Faced by Farmers and Scheme Management: Stakeholder interviews, focus group discussions, and incident reports were utilised to identify challenges such as water availability, infrastructure maintenance, communication, and administrative hurdles, promoting open dialogue among farmers [9]. The study combines quantitative and qualitative approaches, leveraging a diverse range of data sources and methodologies to comprehensively assess the irrigation water distribution system in the Kigugu scheme.

2.2. Data Analysis

Assessment of Water Distribution Efficiency: The Kigugu irrigation scheme's water distribution efficiency was comprehensively assessed using a diverse range of data sources and methodologies. Discrepancies were identified through water discharge data, surveys, and questionnaires. Field observations and canal inspections were conducted to detect potential leaks and physical factors contributing to inefficiencies [10].

Indicators of Water Supply

(i) Delivery Performance Ratio (DPR):
DPR, representing the ratio of actual measured discharge to design discharge (Equation 1), was crucial in evaluating the system's performance.

$$DPR = \frac{\text{Actual discharge in cumecs}}{\text{Design discharge in cumecs}} \quad (1)$$

Coefficients of Temporal Variation (CV) are linked to DPR to assess discharge variation, with defined criteria for performance levels [6, 11].

(ii) Reliability and Equity Analysis:
Reliability, measured by the Delivery Performance Ratio (DPR), gauged the consistency and dependability of the water supply. Equity in water distribution, assessed by the spatial coefficient of variation (CVR) (Equation 2) and proportional equity (PE) (Equation 3), is aimed at achieving a fair distribution of water among users [11, 12].

$$\text{CV} = \frac{\text{Standard Deviation of Discharge}}{\text{Average Dsicharge}} \quad (2)$$

$$P_E = \frac{1}{\text{T}} \sum \text{CV}_R \left[\frac{Q_D}{Q_R}\right] \quad (3)$$

(iii) Adequacy of Irrigation Water Supply (AIWS):
Adequacy (PA) was evaluated to determine if the water quantity supplied met the agricultural needs. Classes defined by [11] were employed for categorising performance in terms of adequacy and equity (Table 1).

Table 1. Performance classes for Equity (PE) and Adequacy (PA).

Measure	Performance classes		
	Good	Fair	Poor
PE	0-0.11	0.11-0.25	>0.25
PA	0.9-1.00	0.80-0.89	<0.80

Source: Molden and Gates (1990)

(iv) Relative Water Supply (RWS) and Relative Irrigation Supply (RIS):

RWS indicates the relationship between water supply and crop demand, and RIS assesses the balance between irrigation supply and demand, providing a comprehensive understanding of sufficiency in water provision [13, 14].

$$RWS = \frac{Total\ Water\ Supply}{Total\ Crop\ Demand} \quad (4)$$

$$\text{RIS} = \frac{\text{Supplied Irrigation water}}{\text{Crop according to Design Specifications}} \quad (5)$$

The irrigation distribution system design [14] imposed restrictions on agricultural productivity, with water delivery capacity (%) and irrigation ratio (Equations 6 and 7) serving as essential indicators for assessment.

$$\text{Water delivery capacity}(\%) = \frac{\text{Actual capacity to delivery at system head}}{\text{Peak consumptive demand}} \text{ x } 100 \quad (6)$$

$$\text{Irrigation ratio} = \frac{\text{Irrigated crop area}}{\text{Command area}} \quad (7)$$

Water Usage Efficiency (WUE): WUE, calculated as the ratio of water consumed to crop yield (Equation 8), was crucial for evaluating the effectiveness of water use in crop production [15]

$$\text{WUE} = \frac{\text{Water consumed}}{\text{Crop yield}} \quad (8)$$

Crop Water Requirement: CROPWAT 8.0 software was employed to calculate crop water requirements and evapotranspiration, following established guidelines [16].

Analysing the Impact on Crop Yields: The study examined the impact of the water distribution system on rice yields, utilising crop yield data from registered farmers and considering water distribution practices [17]. It also explored seasonal patterns and potential improvements in the water distribution system. Water productivity, as [18] measured it by dividing the economic output (crop yield) by the total water used (Equation 9), offered insights into the efficiency and effectiveness of water use in crop production.

$$\text{Water Productivity} = \frac{\text{Yield (Tons)}}{\text{Water used } (m^3)} \quad (9)$$

Assessing Water Distribution Challenges: Through stakeholder interviews, focus group discussions, incident reports, and quantitative survey data analysis, the study identified challenges faced by farmers and irrigation scheme management. Water scarcity, infrastructure maintenance issues, administrative hurdles, and disruptions in the irrigation system were key concerns. The analysis facilitated the development of targeted solutions and the prioritisation of intervention efforts.

3. Results and Discussion

3.1. Performance of Water Distribution Within the Irrigation Scheme

3.1.1. Water Delivery Performance Ratio (DPR)

The results in Table 2 suggest that all four secondary canals (SC.1, SC.2, SC.3, and SC.4) exhibit DPR values well above the satisfactory threshold of 0.65. This indicates that the irrigation system is performing well and meeting the targeted water supply for crop irrigation in these areas. Although the DPR values suggest satisfactory performance, the system might still face challenges during irrigation water peaks since DPR values are below 1.0, as suggested by [19].

Table 2. Average Discharge Measured at Head of Secondary Canals.

Canal name	Weekly Target irrigation water supply (m^3/s)	Weekly irrigation water supply m^3/s	Water Delivery Performance Ratio	Irrigated Area(ha)
SC.1	0.16	0.13	0.81	3.89
SC.2	0.03	0.02	0.67	11.22
SC.3	0.18	0.14	0.78	13.95
SC.4	0.09	0.07	0.78	114.73

Table 2 displays additional pertinent factors in conjunction with the average discharge assessed at the head of secondary canals. In SC.1, although the weekly target irrigation water supply stood at 0.16 m^3/s, the actual weekly irrigation water supply measured only 0.13 m^3/s, yielding a water delivery performance ratio of 0.81. Despite the marginally lower irrigation water supply compared to the target, the water delivery performance ratio suggests relatively efficient water delivery. The irrigated area for SC.1 is 3.89 hectares. In the case of SC.2, the weekly target irrigation water supply was 0.03 m^3/s, and the actual weekly irrigation water supply measured was 0.02 m^3/s. The water delivery performance ratio was 0.67, suggesting some inefficiency in water delivery. The irrigated area for SC.2 is notably larger at 11.22 hectares. Similarly, for SC.3, the weekly target irrigation water supply was 0.18 m^3/s, and the actual weekly irrigation water supply measured was 0.14 m^3/s. The water delivery performance ratio was 0.78, indicating reasonably efficient water delivery. The irrigated area for SC.3 is 13.95 hectares. For SC.4, the weekly target irrigation water supply was 0.09 m^3/s, and the actual weekly irrigation water supply measured was 0.07 m^3/s. The water delivery performance ratio was 0.78, consistent with SC.3. Despite the larger target irrigation water supply, the actual supply was lower, possibly indicating some limitations in water delivery infrastructure. The irrigated area for SC.4 is significantly larger at 114.73 hectares, with some achieving relatively efficient water delivery while others exhibit lower performance. The irrigated areas also vary, with some canals serving larger areas than others, highlighting the importance of effective water management strategies to optimise agricultural productivity.

3.1.2. Coefficient of Variation (CV) in Discharges of Secondary Canals

Researchers also utilised the RWS concept of unequal water supply [20] to analyse fluctuations in irrigation water supply within an irrigation project. Molden and Gates' three levels of variability—good, fair, and reliable—defined in 1990 served as measures of the irrigation system's performance. In Table 3, it shows that the CV is good if it is less than 0.1, fair if it is between 0.10 and 0.20, and poor if it is larger than 0.3 [11].

Table 3. *Weekly coefficient of variation in discharges of secondary canals.*

May, 2023	Week.1	0.08	Good
	Week.2	0.05	Good
	Week.3	0.09	Good
	Week.4	0.07	Good
June, 2023	Week.5	0.06	Good
	Week.6	0.08	Good
	Week.7	0.05	Good
	Week.8	0.09	Good
July, 2023	Week.9	0.12	Fair
	Week.10	0.15	Fair
	Week.11	0.25	Fair
	Week.12	0.28	Fair
August, 2023	Week.13	0.32	Fair
	Week.14	0.35	Fair
	Week.15	0.45	Poor
	Week.16	0.5	Poor

The CV values range from "good" to "poor" for different weeks from May to August 2023. During the first two weeks, the CV values were low, indicating a stable and predictable flow. However, during the third week, the CV values increased, indicating a moderate increase in variability. The fourth week saw a significant increase, indicating less predictable fluctuations. The sixth week saw a high CV value, indicating substantial variability and potentially impacting water delivery effectiveness. The diminishing trend from "good" to "poor" in the qualitative assessments suggests an escalation in the variability of discharges over time. Possible explanations for this trend could include water loss by seepage, changes in water availability, and operational issues within the irrigation system. Factors such as increased demand, maintenance issues, or variations in water sources may contribute to the observed increase in discharge variability.

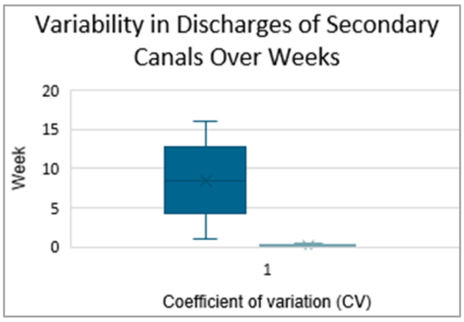

Figure 1. *Variability in Discharges of Secondary Canals.*

1) The median (line inside the box) seems to be relatively consistent, indicating a stable central tendency in CV values.
2) The interquartile range (IQR) (box) appears to be relatively consistent from Week 1 to Week 8, suggesting a stable range of variation during this period.
3) Weeks 9 to 14 show an expansion of the IQR, suggesting increased variability in CV values during this period.
4) Weeks 15 and 16, indicated by the longer whiskers and potential outliers, demonstrate a significant increase in variability, especially in Week 15.

The analysis of the coefficient of variation (CV) values for irrigation indicates the stability or consistency of the variability of certain parameters critical to irrigation efficiency. The consistent central tendency in CV values suggests a stable pattern in certain irrigation metrics over time. However, the expansion of the interquartile range (IQR) and the increase in variability observed in later weeks, particularly in Weeks 15 and 16, indicate potential challenges or fluctuations in the irrigation system.

3.1.3. Reliability and Equity Analysis

The evaluation of reliability and fairness, using guidelines from [6, 11], provided valuable insights into how well the secondary canals (SCs) performed in the irrigation scheme. SC.1 showed strong reliability, with a high Delivery Performance Ratio (DPR) of 0.8125, which means it consistently met the intended discharge [6, 11],

The low coefficient of variation (CV) of 0.08, indicating minimal temporal variation, further strengthens the stability of water supply [6, 11]. To evaluate equity in water allocation, a calculation of irrigation water supply equity (PE) is essential, accounting for both spatial and temporal factors. In SC.2, while the DPR of 0.6667 indicates a departure from the design discharge, the low CV of 0.05 suggests little temporal variation, which helps maintain stable water distribution [6, 11]. To thoroughly evaluate fairness in water allocation, calculating PE is essential, taking into account both spatial distribution and temporal uniformity.

SC.3 and SC.4 both exhibited robust reliability, indicated by high DPR values of 0.7778, akin to SC.1 [6, 11]. Despite slightly higher CVs than SC.1, both SC.3 and SC.4 maintained reliable water supplies, warranting further evaluation of equity through PE calculation [6, 11].

Fairness Assessment: In assessing the fairness of water distribution, high PE values would indicate a more equitable distribution, suggesting that water is consistently and fairly allocated across both space and time. Conversely, low PE values would suggest less equitable water distribution, indicating potential disparities in the allocation of water resources.

The equity of water distribution during the growing season was fair, improving from a hypothetical fair value of 0.2 to 0.1 to 0.1 by the end of the irrigation season. Farmers blocked downstream flows to gain water. However, low flows in October caused competition for water, necessitating the need for rigid guidelines for water sharing among users.

3.1.4. Water Performance Ratio for the Plots

Table 4 shows the Water Performance ratio for the plots (Q_D/Q_R) measure for irrigation systems computed from water management data for secondary canals, specifying monthly water requirements in mm and actual deliveries in mm across canal plots, respectively, in May, June, July, and August.

Table 1. *Water Performance ratio for the plots.*

Months	Water required (Q_D)	Water delivered (Q_R)	$\frac{Q_D}{Q_R}$
May	390	369	1.05
June	130	117	1.11
July	410	393	1.04
August	390	352	1.1

The significance of the Irrigation Water Performance Ratio (IWPR) in evaluating irrigation water supply systems was emphasized, highlighting that a high IWPR value indicates efficient water utilization [21]. Conversely, it was suggested that a low IWPR may signal shortcomings in system performance [22]. The results presented in Table 4 demonstrate variations in the Water Performance Ratio across different months for paddy plots. For instance, while June showed efficient water delivery with a ratio of 1.11, August indicated a shortfall in delivered water compared to requirements, with a ratio of 1.1.

Overall, the results show variations in water performance ratios across the different months, with some months demonstrating efficient water delivery (such as June and July), while others experienced deficits in the delivered water compared to requirements (such as May and August). These findings underscore the importance of closely monitoring water delivery to ensure it meets the demands of agricultural production throughout the growing season.

3.1.5. Adequacy of Irrigation Water Supply (AIWS)

The adequacy of irrigation water supply (AIWS) was evaluated through the application of the Relative Water Supply (RWS) formula, where RWS defined as the ratio of total water supply to total crop demand. The RWS values In Table 5 for various canal subdivisions, including SC.1, SC.2, SC.3-1, SC.3-2, SC.3-3, SC.4-1, and SC.4-2, serve as a quantitative measure to assess the sufficiency or insufficiency of meeting crop water demand. Notably, SC.2 exhibits an exceptionally high RWS of 5.9, indicating a substantial surplus in water supply. Similarly, SC.3-1 and SC.3-2 demonstrate RWS values of 1.8 and 2, respectively, signifying surplus conditions. On the other hand, SC.4-1 and SC.4-2 present RWS values below 1, suggesting inadequacy and potential deficits in water supply for irrigation. The RWS values offer valuable insights into the efficiency of water distribution across canal subdivisions, guiding strategies for optimised water management practices to enhance agricultural productivity.

The value for adequacy, ranging from 0.9 to 1.00, was discussed, indicating complete satisfaction when the requirements for the delivered water quantity are exceeded within a specific timeframe [23].

Table 5. Relative water supply (RWS) a measure of Adequacy of Irrigation Water Supply.

Canal's name	Crop irrigation area (ha)	Total water demand (m^3)	Water supply (m^3/s)	RWS
SC.1	3.89	0.000167	0.02	1.2
SC.2	11.22	0.000997	0.018	5.9
SC. 3-1	4.65	0.000446	0.014	1.8
SC. 3-2	4.65	0.00036	0.012	2
SC. 3-3	4.65	0.000384	0.012	1
SC. 4-1	57.36	0.000705	0.011	0.592
SC. 4-2	57.36	0.00724	0.010	0.366

Table 5 provides insights into the relative water supply (RWS), which serves as a measure of the adequacy of irrigation water supply across different canals. In SC.1, with a crop irrigation area of 3.89 hectares, the total water demand is 0.000167 m^3, while the water supply stands at 0.02 m^3/s. This results in an RWS of 1.2, indicating that the water supply is adequate relative to the demand for irrigation in this canal [13, 14, 24].

Moving to SC.2, which has a larger crop irrigation area of 11.22 hectares, the total water demand is 0.000997 m^3, and the water supply is 0.018 m^3/s, resulting in a notably higher RWS of 5.9. This indicates a more than sufficient water supply compared to the demand, suggesting efficient irrigation practices in this canal.

For SC. 3-1, SC. 3-2, and SC. 3-3, with similar crop irrigation areas of 4.65 hectares each, the RWS values are 1.8, 2, and 1, respectively. These RWS values suggest that the water supply meets or exceeds the demand. In contrast, SC. 4-1 and SC. 4-2, with crop irrigation areas of 57.36 hectares each, exhibit lower RWS values of 0.592 and 0.366, respectively. These lower RWS values indicate that the water supply falls short of meeting the irrigation water demand in these canals, highlighting potential inadequacies in water supply management or infrastructure.

The two most important factors in the planning, design, and operation of irrigation systems are the available water supply and the water demand. Relative Water Supply (RWS), introduced as a crucial concept that describes the relationship between supply and demand [13]. RWS, as presented in Equation (4), is an all-encompassing metric for sufficiency, which has been endorsed by several studies [14, 24].

The findings in Table 5 highlight the need to check if irrigation water supply meets crop needs in various canals for better farming results and water management. Canals with higher RWS values demonstrate more efficient water supply management, while those with lower RWS values may require further attention to improve irrigation water supply adequacy.

RWS is suggested as the all-inclusive adequacy measure, connecting rainfall, pumped groundwater, and surface water supply to the amount of water required by crops [14, 24].

Table 6. Relative Irrigation Supply (RIS) and Relative water supply (RWS).

Canal's name	Crop irrigation area (ha)	Design discharge (mm^3/s)	Water supply in m^3/s	Water supplied in (mm^3/s)	RIS	RWS
SC.1	3.89	390	0.02	369	0.9	1.2
SC.2	11.22	130	0.018	117	0.9	5.9
SC.3	13.95	410	0.014	393	1	1.8
SC.4	114.73	390	0.012	352	0.9	2

Table 6 presents data on both relative irrigation supply (RIS) and relative water supply (RWS) for different canals, providing insights into the adequacy of irrigation water supply and its impact on agricultural productivity. Secondary canal (SC.1) has a relatively small crop irrigation area of 3.89 hectares. Despite the design discharge of 390 mm^3/s, the actual water supply is only 0.02 m^3/s, resulting in an actual supplied water volume of 369 mm^3/s. The RIS value of 0.9 indicates that the actual water supplied falls short of the design discharge, potentially affecting crop performance. However, the RWS value of 1.2 suggests that the water supply, relative to the crop irrigation demand, is adequate [25, 14].

As we move to SC.2, we observe similar trends despite its larger crop irrigation area of 11.22 hectares. Despite the design discharge of 130 mm^3/s, the actual water supply is 0.018 m^3/s, resulting in an actual supplied water volume of 117 mm^3/s. The RIS value of 0.9 indicates a shortfall in the actual water supplied compared to the design discharge. However, the RWS value of 5.9 suggests that the water supply meets or exceeds the crop irrigation demand, indicating efficient water management practices. SC.3, with a crop irrigation area of 13.95 hectares, demonstrates a different scenario. Here, the design discharge of 410 mm^3/s results in an actual water supply of 0.014 m^3/s, providing an actual supplied water volume of 393 mm^3/s. The RIS value of 1 indicates that the actual water supplied matches the design discharge, suggesting efficient water delivery. The RWS value of 1.8, indicates adequate water supply relative to crop irrigation demands.

In contrast, SC.4, with a significantly larger crop irrigation area of 114.73 hectares, experiences challenges. Despite the design discharge of 390 mm^3//s, the actual water supply is only 0.012 m^3/s, resulting in an actual supplied water volume of 352 mm^3/s. The RIS value of 0.9 indicates a shortfall in the actual water supplied compared to the design discharge. However, the RWS value of 2 suggests that the water supply meets the crop irrigation demand to some extent, albeit with room for improvement. Relative Irrigation Supply (RIS) [25] emphasized that the relative irrigation supply (RIS) indicates how well irrigation supply and demand are balanced. When the value exceeds one, it implies an excessive supply of water, which could lead to waterlogging and reduce yields, whereas a value below one signifies an insufficient amount of water for the crops, potentially impacting their growth negatively. In contrast to RWS, which additionally considers rainfall, relative irrigation supply focuses solely on the provision of irrigation water [14]. Equation (5) was utilized to compute it [26].

In summary, Table 6 highlights variations in both RIS and RWS values across different canals, indicating disparities in irrigation water supply adequacy and its impact on agricultural productivity. Canals with lower RIS values may require improvements in water delivery infrastructure to meet design discharge targets, while RWS values provide insights into the relative sufficiency of water supply for crop irrigation, emphasising the importance of efficient water management practices for optimal agricultural performance.

3.1.6. Water Delivery Capacity and Irrigation Ratio

Table 7 shows data on average discharge at the head of secondary canals, including the weekly target irrigation water supply, water delivery performance ratio, and irrigated area in hectares. Equation 7 was used to calculate the irrigation ratio.

Table 7. *Water delivery capacity and Irrigation ratio.*

Subdivision	Weekly Target irrigation water supply (m^3/s)	Weekly irrigation water supply m^3/s	Water Delivery Performance Ratio	Command area (ha)	Irrigated Area (ha)	Irrigation ratio
SC.1	0.16	0.13	0.81	80	3.89	0.53
SC.2	0.03	0.02	0.67	150	11.22	0.04
SC.3	0.18	0.14	0.78	210	13.95	0.11
SC.4	0.09	0.07	0.78	160	114.73	0.97

Table 7 presents enlightening data on water delivery capacity and irrigation ratios across four subdivisions. Canal SC.1 demonstrates commendable water delivery performance, with a ratio of 0.81, delivering 0.13 m^3/s against a weekly target of 0.16 m^3/s, resulting in an irrigation ratio of 0.53 for its 80-hectare command area. Conversely, Canal SC.2 achieves a lower water delivery performance ratio of 0.67, providing 0.02 m^3/s compared to a target of 0.03 m^3/s, resulting in a modest irrigation ratio of 0.04 for its 150-hectare command area. Canal SC.3 maintains a water delivery performance ratio of 0.78, supplying 0.14 m^3/s against a target of 0.18 m^3/s, resulting in an irrigation ratio of 0.11 across its 210-hectare command area. Canal SC.4 stands out for its remarkable consistency, maintaining a steady water delivery performance ratio of 0.78. Although designed to discharge 0.09 m^3/s of water, it consistently delivers 0.07 m^3/s, resulting in an irrigation ratio nearly reaching 1 for its extensive 160-hectare command area. These findings highlight varying efficiencies in water delivery and utilisation across subdivisions, underscoring the importance of tailored irrigation management strategies to maximise agricultural output while conserving water resources [14].

3.1.7. Water Usage Efficiency

Results in Table 8 show that SC. 1 had the highest Water Use Efficiency (WUE), indicating efficient water use for a significant yield. SC. 3-1, SC. 3-2, and SC. 3-3 had similar design water supplies and command areas but varying yields, leading to differences in WUE. SC. 4-1 and SC. 4-2 showed relatively lower WUE, suggesting potential areas for improvement in water use efficiency. The study highlights the need for improved water use efficiency in agricultural production. Water use efficiency is a key component of environmentally sustainable irrigation. Efficient water management practices contribute to reduced environmental impact, resource conservation, and the overall resilience of irrigation systems [27].

Table 8. Command area, water use efficiency and yield.

Discharge point	Design Q (m^3/)	Command Area (ha)	Number of outlets	Yields (tons)	Water supply in m^3/s	Water use efficiency (WUE)
SC.1	0.0231	80	2	500	0.02	0.000148
SC.2	0.0228	150	5	937.5	0.018	0.00033
SC. 3-1	0.0223	70	2	437.5	0.018	0.000091
SC. 3-2	0.0205	70	2	437.5	0.014	0.00007
SC. 3-3	0.0201	70	3	437.5	0.013	0.000065
SC. 4-1	0.019	80	2	500	0.013	0.000047
SC. 4-2	0.0185	80	3	500	0.012	0.000044

Table 8 presents data on command area, water use efficiency (WUE), and yield for various discharge points. Canal SC.1 boasts a design discharge of 0.0231 m^3/s, covering a vast command area of 80 hectares with 2 outlets to meet agricultural demands. This canal yields an impressive 500 tonnes of produce with an actual water supply of 0.02 m^3/s, resulting in a calculated water use efficiency of approximately 0.000148. Similarly, Canal SC.2, with a design discharge of 0.0228 m^3/s, serves a larger command area of 150 hectares with 5 outlets, yielding 937.5 tons. The recorded water supply is 0.018 m^3/s, resulting in a water use efficiency of about 0.00033. Canals SC.3-1, SC.3-2, and SC.3-3, as well as Canals SC.4-1 and SC.4-2, exhibit varying command areas, outlet numbers, yields, and water supply levels, leading to different water use efficiencies. These results underscore the importance of optimising irrigation practices to enhance water use efficiency and maximise agricultural productivity across different canal systems [15].

3.2. Crop Water Requirement

The software CROPWAT 8.0 was utilised to calculate crop water requirements and evapotranspiration, following the guidelines provided by [16]. Overall, Table 9 serves as a valuable tool for farmers and agricultural professionals to plan irrigation schedules and manage water resources efficiently, taking into account the specific growth stages and water requirements of the crop in question. It gives room for decision-making to optimize crop yield while conserving water resources. The cropwat software was used calculate crop water requirement.

Table 9. Crop water requirement.

Month	Decade	Stage	Kc	ETc (mm/day)	ETc (mm/decade)	Eff Rain (mm/dec)	Irr. Req. (mm/dec)
Apr	1	Nurs/LPr	1.08	3.52	35.2	35.7	35.2
Apr	2	Nurs/LPr	1.06	3.81	38.1	52.1	38.1
Apr	3	Init	1.09	3.85	38.5	40.8	0
May	1	Init	1.1	3.88	38.8	27	11.8

Month	Decade	Stage	Kc	ETc (mm/day)	ETc (mm/decade)	Eff Rain (mm/dec)	Irr. Req. (mm/dec)
May	2	Deve	1.11	3.87	38.7	16.4	22.3
May	3	Deve	1.14	4.02	40.2	11.7	32.6
Jun	1	Deve	1.17	4.19	41.9	0	41.9
Jun	2	Mid	1.19	4.32	43.2	0	43.2
Jun	3	Mid	1.19	4.37	43.7	0	43.7
Jul	1	Mid	1.19	4.42	44.2	0	44.2
Jul	2	Mid	1.19	4.48	44.8	0	44.8
Jul	3	Late	1.17	4.54	45.4	0	45.4
Aug	1	Late	1.13	4.46	44.6	0	44.6
Aug	2	Late	1.08	4.38	43.8	0	43.8
Aug	3	Late	1.05	4.47	44.7	0	44.7
	Total				587.9	184.2	603.7

Results from Table 9 provide data on the crop water requirement for the Kigugu Irrigation Scheme.

1) Monthly and Stage-wise Variation: The table illustrates variations in crop water requirements across different months and stages of crop growth. During the nursery/early planting stages in April, the crop's water requirement ranges from 35.2 to 38.5 mm per decade, reflecting the crucial need for adequate moisture during this critical growth phase.
2) Impact of Crop Development: As the crop progresses through different stages of development, such as initiation, development, mid-season, and late-season, there are fluctuations in water requirements. For example, during the late-season stages in July and August, although no effective rainfall is recorded, the crop's water requirement remains high, reaching up to 45.4 mm per decade. This underscores the importance of irrigation during critical growth phases to meet the crop's water needs.
3) Influence of Effective Rainfall: With no rainfall in June, July, and August, the effective rainfall per decade for these months is zero. This highlights the dependence on irrigation to meet the crop's water requirements during these periods. Effective rainfall in other months, such as April and May, contributes to reducing irrigation requirements but may not suffice to meet the crop's full water needs, necessitating supplemental irrigation.
4) Irrigation Requirement: The irrigation requirement per decade reflects the additional water needed to supplement natural precipitation and meet the crop's full water requirements. In some cases, such as during the late-season stages in July and August, the irrigation requirement exceeds the crop's water requirement, emphasizing the crucial role of irrigation in ensuring optimal crop growth and yield, especially in the absence of rainfall.

The total amount of water required for the command area of 600 hectares per season is 362.22 cubic metres.

It was reported that the Igomelo irrigation scheme requires a net irrigation of approximately 366.98 mm, indicating the amount of water needed to adequately irrigate crops throughout the growing season [28]. In contrast, the Dakawa irrigation scheme has a reported crop water requirement of 19.9 mm/day, suggesting the need for a consistent daily water supply for crops to thrive [12]. Additionally, the crop water requirement for the Kigugu irrigation scheme is reported as 362.22 cubic metres for the entire season, representing the total volume of water necessary to support crop growth from planting to harvest.

Comparing these values, we can observe variations in the water requirements among the different schemes. The Dakawa scheme seems to have a relatively lower daily water requirement compared to Igomelo and Kigugu. However, the total seasonal water requirement for Kigugu is comparable to that of Igomelo, indicating similar overall water needs despite differences in irrigation system design and crop types.

3.3. The Impact of the Water Distribution System on Crop Yields

According to Table 10 The water distribution system's impact on crop yields is discernible through variations in yield outcomes across different discharge points.

Table 2. *Discharge measurement points in secondary canals and yield.*

Canal name	Design Discharge (m^3/s)	Command Area (ha)	Number of outlets	Water supply in (m^3/s)	Yields (tons)	Yield ton per ha
SC. 1	0.0231	80	2	0.02	500	6.25
SC. 2	0.0228	150	5	0.018	937.5	6.24
SC. 3-1	0.0223	70	2	0.018	437.5	6.25
SC. 3-2	0.0205	70	2	0.014	437.5	6.25
SC. 3-3	0.0201	70	3	0.013	437.5	6.25
SC. 4-1	0.019	80	2	0.013	500	6.24
SC. 4-2	0.0185	80	3	0.012	500	6.24

Table 10 provides discharge measurement points in secondary canals and their corresponding yields. Canal SC.1, with a design discharge of 0.0231 m^3/s, covers a command area of 80 hectares with 2 outlets, resulting in a water supply of 0.02 m^3/s and a commendable yield of 500 tons. This translates to a yield of 6.25 tonnes per hectare, indicating efficient irrigation practices. Similarly, Canal SC.2 demonstrates a design discharge of 0.0228 m^3/s, serving a larger command area of 150 hectares with 5 outlets, yielding 937.5 tonnes, and maintaining a yield per hectare close to that of SC.1. Canals SC.3-1, SC.3-2, and SC.3-3 exhibit consistent yields of 437.5 metric tonnes per hectare, despite slight variations in their design discharges and outlet numbers. Canals SC.4-1 and SC.4-2 also maintain similar yields per hectare, demonstrating the effectiveness of irrigation management practices across these secondary canals. Overall, these results underscore the importance of efficient water management in achieving consistent and high yields in agricultural production [17].

(i). Water Productivity

The results from Table 11, which represents the water productivity for a specific crop (paddy) across different canals, provide valuable insights into the efficiency of water utilisation in crop production. Here's a detailed discussion of the findings.

Table 3. *Water Productivity for Specific Crop Grown (Paddy).*

Canal Name	Area Served (ha)	Yield of the Area (Tons)	Water Used (m^3/s)	Water Productivity (Tons/m^3)
SC.1	3.89	24.3	0.02	7
SC.2	11.22	70.1	0.02	31
SC.3-1	4.65	29.1	0.02	11
SC.3-2	4.65	29.1	0.01	14
SC.3-3	4.65	29.1	0.01	15.29
SC.4-1	57.36	358.5	0.01	21.1
SC.4-2	57.36	358.5	0.01	22.86

In Table 11, water productivity data for specific crops, particularly paddy, in different canals is presented. Canals with higher water productivity values are indicative of better crop yields, suggesting efficient water management practices or suitable environmental conditions [18]. Conversely, lower productivity values in canals may suggest potential inefficiencies in water management [29].

For instance, the highest water productivity is demonstrated by the canal denoted as SC.4-2, possibly owing to optimised irrigation practices or favourable environmental conditions [30]. This observation underscores the importance of efficient water management in agricultural practices, particularly in paddy cultivation.

Water productivity evaluates the efficiency and effectiveness of crop production [18]. The calculation involves dividing the economic output (crop yield) by the total water used, encompassing both natural precipitation and supplemental irrigation [29]. Higher water productivity values are indicative of better water use efficiency and resource management in agriculture.

(ii). Land Productivity

(a). Output per unit cropped area and output per unit command

Table 12 provides agricultural indicators for the Kigugu Irrigation Scheme, detailing key metrics such as crop area, output per unit command area, and relative water and irrigation supply for various canals within the scheme.

Table 4. *Agricultural Indicators for Kigugu Irrigation Scheme.*

Name of Canal	Crop area (ha)	SGVP US$	Output per unit command area $ per ha	Relative Water Supply	Relative Irrigation Supply
SC.1	3.89	5,721.57	9.54	1.2	0.9
SC.2	11.22	16,590.57	27.65	5.9	0.9
SC.3	13.95	20,573.28	34.29	1.8	1
SC.4	114.73	169,545.02	282.58	2	0.9

The Table 12 shows that canal system exhibits remarkable economic performance, with each canal showcasing distinct strengths. SC.1 leads the pack by delivering the highest output per unit command area. SC.2 follows closely, boasting a substantial Standard Gross Value of Production (SGVP) of 1 496 737 800 TZS (586,956 US dollars). SC.3 achieves an impressive SGVP of 1,995,650,400 TZS (782,608 US dollars), coupled with a notable output of 142 924 950 TZS (56,049 US dollars) per hectare. SC.4 emerges as a standout performer, covering a substantial area of 114.73 hectares and achieving an SGVP of 2 494 563 000 TZS (978 260 US dollars).

These results underscore the diversity in canal performance, which may arise from differences in soil fertility, water availability, cropping patterns, and management practices. This diversity contributes significantly to the agricultural prosperity of the region. Such insights are invaluable for decision-makers and farmers alike, providing essential guidance for optimising water resources and enhancing agricultural output.

Numerous scholars have looked into how output per unit command is determined in parallel studies carried out in numerous locations throughout the world. Examples include output per unit command values of 105 to 1 800 $ ha-1 in the Alto-Rio Lerma project in Mexico and 308 to 5 771 $ ha-1 in the south-eastern Anatolia Project in Turkey [12, 31, 32]. The scheme shows high productivity, efficient use of inputs, and the positive influence of factors like land ownership and crop management practices. The output per unit command area ranged from 52 286.00 USD/ha to 201,085.00 USD/ha, indicating significant economic output. The data also showed variations in irrigation water supply across different segments, but generally a good match between irrigation water supply and irrigation water requirements. These findings suggest the potential for further optimisation of agricultural practices to enhance productivity.

(b). Output per unit irrigation water supply and output per unit irrigation water consumed

Table 13 indicates the area has a productivity of 7.1 tonnes of agricultural output per hectare of land, indicating efficient crop management. The financial value of the area is 394 403 US dollars, reflecting investment in agricultural activities. The output per hectare of cropped area is 394 403 US dollars, indicating economic performance per unit of cropped land. The output per unit per irrigation water supply and consumption is 1 US dollar per cubic metre, indicating the area effectively converts water resources into agricultural output [33].

Table 5. *Total output per unit of Irrigation Supply and output per unit of water consumed.*

Productivity (ton/ha)	SGVP USD	Output per cropped area USD per ha	Output per unit command area USD per ha	Output per unit per irrigation water supply (USD/ m^3)	Output per unit irrigation water consumed (USD/ m^3)
6.1823	3,130,432	4,774.17	16,293.21	0.041	0.157

Exchange rate: 1 USD= 2550 TZS

Table 13 provides a comprehensive overview of the productivity and economic performance of the irrigation schemes under examination. The canals exhibit an average productivity of 6.1823 tonnes per hectare, indicating the yield of rice per unit area of cultivated land. The total gross value of production (SGVP) amounts to $3,130,432, signifying the total economic value generated by agricultural production in an irrigation scheme.

When considering economic output per hectare of cropped area, the calculation yields $4,774.17 per hectare, obtained by dividing SGVP USD by the total cropped area. In terms of economic output per hectare of command area, the analysis reveals $16,293.21 per hectare, calculated by dividing SGVP USD by the total command area. Additionally, assessing economic output per unit of irrigation water supplied yields a value of 0.041 USD/m^3, indicating the efficiency of water utilisation in generating economic value. The economic output per unit of water consumed for irrigation purposes yields 0.157 USD/m^3, demonstrating the economic value generated for each unit of water consumed.

These findings emphasise the importance of optimising water use and management practices to enhance both agricultural productivity and economic returns across the examined irrigation schemes.

3.4. The Challenges Faced by Farmers and the Irrigation Scheme Management

The irrigation scheme is facing some social and economic problems. Table 14 provides an overview of the problems faced by farmers and suggests solutions with corresponding scores.

Table 6. Problems Faced by Farmers and Suggested Solutions.

		Suggested Solution
Shortage of Water	45	Equitable Water Distribution
Lack of Inputs	28	Provision of Loan
Diseases and Pests	15	No Solution
No Constraints	12	No Specific Problems
Total (%)	100	

Table 14 presents a summary of the problems faced by farmers in an irrigation scheme. The most common issue is water scarcity, which affects crop yields and productivity. The suggested solution is equitable water distribution and a fair and balanced allocation of water resources. The second most common issue is the lack of inputs, which include essential resources for agricultural activities. The suggested solution is the provision of loans, which can facilitate access to resources and empower farmers to enhance their practices. 15% of farmers who do not propose a specific solution for diseases and pests suggest a gap in perceived effective strategies. The remaining 12% of farmers have no specific problems, suggesting no immediate issues requiring attention or intervention.

3.5. Overview of Farmers on the Performance of the Irrigation Water Distribution System

The water distribution plan prepared was rated by 90% of respondents as "good," indicating potential room for improvement. However, water distribution conflicts were reported by 100% of respondents, indicating a prevalent issue. The water distribution equity was rated "good" by 90%, but 10% felt it was "bad." The majority of respondents believed that irrigation water adequacy for the previous year was sufficient, but 10% expressed concerns about localised water scarcity issues. The relative irrigation supply for the previous year was considered adequate, but 9% felt it was insufficient. The survey also revealed that irrigation system design and other factors are constraining agricultural production, with only 2% rating the condition of irrigation infrastructure or cropping patterns as "very good." Despite this, all respondents reported a high farmer willingness to engage in irrigation activities.

The majority of respondents (184 out of 184) identified the Water Distribution Committee as responsible for their irrigation water distribution rotations, indicating a centralized approach to scheduling. They were involved in the formulation of the schedule through general meetings of all irrigators, ensuring their input. The most common factor considered in preparing the schedule was reducing conflicts among irrigators. Most respondents had a fixed irrigation rotation, with a rotation interval of three days. Most respondents expressed satisfaction with the current irrigation scheduling system, describing its dependability as "Very High." However, some respondents noted potential issues with equitable water distribution due to illegal water diverting. Most respondents reported the same amount of water given to all crops during all growth stages, with some flexibility allowed based on growth stages. Information was communicated annually, but infrequent communication may be an improvement. Most respondents used fertilizers for crop cultivation, with more than 50kg per acre used per season. They were aware of the potential harm of fertilizers to soil, and varying frequency of cleaning canals and distribution structures. The survey indicates satisfaction with the irrigation scheduling system, but suggests improvements in communication frequency, cleaning practices, and water distribution, particularly regarding illegal water diversion. It also emphasizes the need for sustainable agriculture.

4. Conclusions

The irrigation scheme indicates an efficient water delivery system, as the Water Delivery Performance Ratio (DPR) consistently exceeds the satisfactory threshold of 0.65 in all four secondary canals. However, challenges may arise during short-term irrigation water peaks, emphasising the need for additional capacity. The analysis of Coefficient of Variation (CV) values demonstrates fair discharge variation but potential issues in maintaining equity during low flow periods. Designed and actual discharges for secondary canals indicate instances of underperformance, necessitating further investigation and corrective measures. Recommendations include mitigating challenges at the head level, implementing water-sharing guidelines, and enhancing water-use efficiency. The assessment of crop water requirements underscores the importance of monitoring irrigation water supply for optimised crop yield and water conservation.

Farmers face challenges, including water shortages and lack of inputs, and the study identifies these issues while proposing potential solutions. The baseline survey tools indicate a generally positive perception of the water distribution plan, though conflicts are prevalent. Satisfaction with the irrigation scheduling system is high among farmers, but there is room for improvement in communication frequency. These findings provide valuable insights for enhancing irrigation practices, addressing challenges, and promoting sustainable agricultural development in the Kigugu Irrigation Scheme.

To improve irrigation efficiency, the suggestions are: expanding the canals capacity during short-term water peaks, investigating underperformance in canals, improving communication, promoting equitable water distribution, monitoring crop water requirements, promoting sustainable practices, and evaluating system design. These measures will enhance flexibility and responsiveness to variable water demands and ensure farmers are well-informed about irrigation schedules and system updates.

Abbreviations

RWS	Relative Water Supply
DPR	Delivery Performance Ratio
WUE	Water-Use Efficiency (WUE)
PA	Adequacy
DBs	Water Distribution Boxes
SC	Secondary Canal
PE	Effective Rainfall
CV	Coefficient of Temporal Variation
CV_B	Spatial Coefficient of Variation
P_E	Equity
Q	Amount of Water Delivered
Q_D	Canal Discharge
Q_R	Amount of Water Required
RIS	Relative Irrigation Supply
AIWS	Adequacy of Irrigation Water Supply
Etc	Crop Water Requirement
Eto	Reference Crop Evapotranspiration
IQR	The Interquartile Range
IWPR	Irrigation Water Performance Ratio
TZS	Tanzanian Shillings
USD	US-Dollar
MOA	Ministry of Agriculture
SGVP	Standardized Gross Value of Product
WUA	Water Users' Association

Acknowledgments

First and foremost, I express my gratitude to the Almighty for His guidance and blessings throughout this endeavour. I extend my heartfelt thanks to my wife, Ajeli Mbonaga, and my children, Hussein, Gift, Salama, and Abdulkarim, for their unwavering support and understanding. I am deeply appreciative of the Ministry of Agriculture in Tanzania, particularly the Training and Research Department, for providing the sponsorship that made this research possible. Their support has been instrumental in the success of this study. I am also indebted to my dedicated supervisors, Professor Andrew Kirumi Paul Rai Tarimo and Dr. Festo R. Silungwe, for their invaluable guidance, expertise, and mentorship. Their contributions have greatly enriched the quality of this research. I extend my sincere appreciation to Mr. James Mbiu, the irrigation technician for the Kigugu Scheme, for his significant assistance in the data collection process. His expertise and cooperation were vital to the successful completion of this study. Last but not least, I would like to express my heartfelt gratitude to the farmers who participated in this research. Their cooperation and valuable insights were indispensable to the study's success.

Author Contributions

Mnega Hussein Chogohe: Conceptualization, Data curation, Study design, Statistical analysis, Writing – original draft, Funding acquisition, Project administration, Resources, Investigation

Festo Richard Silungwe: Data curation, Methodology, Formal analysis, Software, Writing – review & editing, Supervision

Andrew Kirumi Paul Rai Tarimo: Supervision, Validation, Writing – review & editing, Data interpretation

Funding

This work is supported by the Ministry of Agriculture, which has allocated a budget of 4,900,000 Tanzanian shillings (TZS), approximately equivalent to 1,921.57 USD. The budget encompasses various expenses, including proposal writing, laboratory and material acquisition, construction of measuring structures, attendance at a one-week short course on CBP, procurement of stationery, data collection, analysis,

and interpretations, transportation costs, and the final report writing, including typing, printing, and binding.

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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