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Evaluation of Crop Yield Response to Water Use Efficiency in the Chauru Irrigation Scheme, Tanzania

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Abstract

It was reported by this paper that diverse irrigation management strategies, crop yield, and the water use efficiency (WUE) impact of those strategies were outlined in the Chauru Irrigation Scheme, Pwani Region. Additionally, with water scarcity on the rise, the allocation of water in agriculture must be done in a manner that is compatible with the sustainability of food production. This research primarily aims to measure the relation between the amount of irrigation water used, the actual evapotranspiration, and crop yield; at the same time, it looks for the water use efficiency (WUE) that comes out from the different scenarios. Concrete activities were undertaken in the field to perform trials on rice (paddy) in 2024 over the representative blocks of the scheme at full irrigation (100% ETc) and at deficit irrigation (85% ETc and 70% ETc), with both rainfed and farmer practice treatments for certain growth stages besides farmer practices. The field research includes the collection of information on yield, irrigation water used, precipitation, soil water content, and meteorological parameters that are further processed by employing crop simulation models like Aqua Crop. According to the results, the 85% ETc treatment gave a crop yield equivalent to full irrigation (6.2 t/ha) but with 15% less water, resulting in a higher crop WUE (1.18 kg/m^3) compared with full irrigation (1.03 kg/m^3). Treatment 70% ETc achieved the highest crop water use efficiency (1.31 kg/m^3), although it showed a slight decrease in yield (5.5 t/ha). Both rainfed and farmer practice treatments had the lowest yields and crop WUE values; the vulnerability of the system to unmanaged water supply and rainfall variability is evident. In this case, the results of the research at hand confirm that moderate deficit irrigation could keep the yields high and increase water productivity a lot at the same time. Under controlled experiments, the Chauru Irrigation Scheme exhibited technical efficiency in water delivery and yield support capacity. However, the gap between the best treatments and farmer practices seems to reveal the possibility of improving on-farm water management. Incorrect timing, uneven distribution of water, and the absence of an irrigation schedule that is properly followed are the main reasons for sub-optimal WUE under actual farmer plot conditions.

Keywords

Water Use Efficiency, Crop Yield, AquaCrop, Deficit Irrigation, Full Irrigation, Rice Production, Chauru Scheme

1. Introduction

Water Use Efficiency (WUE) is becoming a trendy term in the context of sustainable agriculture, and it is being seen as an essential parameter in the sustainable management of water resources in agriculture. Worldwide, agriculture is responsible for about 70% of the freshwater used, but a large part of it is lost due to inefficient irrigation systems (FAO, 2017). Climate change, population growth, and urbanization are some of the reasons that put a lot of pressure on freshwater; a change in WUE might allow us to save water and still produce food without overusing the water resources (FAO, 2020; Rockström et al., 2010).

The WUE is generally a measure of the proportion between the crop output (either biomass or economic yield) and the water consumed, particularly through evapotranspiration (ET). An increase in this efficiency means that we focus on the "more crop per drop" principle (Molden et al., 2007). The highest demand for WUE occurs in the water-limited areas, where the optimum water allocation, as well as the improvement of technologies for irrigation, is the main focus.

In Sub-Saharan Africa (SSA), the majority of agricultural production is rainfed, and irrigated farming is not developed to the extent that it remains less than 6% of total cultivated land (You et al., 2011). However, SSA is the area that has the biggest changes in rainfall and most frequent droughts; thus, irrigating and utilizing water efficiently is extremely important to food security. Research shows that water utilization efficiency in Africa is still very low because of the occurrence of an old system, the irregularity of irrigation scheduling, and the lack of training of farmers (Van Ittersum et al., 2016).

Watering methods today, such as those in Chauru, are often way beyond inefficient, and this is the main reason that the harvests are lower than they could be, and that waterlogging and water depletion take place. Deficient water use efficiency (WUE) has been recognized as the major problem of irrigation schemes in developing countries, which are responsible for a series of negative effects such as waterlogging, a decrease in the amount of water available, etc. These inefficiencies are due to a mixture of technical, institutional, and socio-economic factors (FAO, 2012).

It is important to note that one of the biggest inefficiencies is over-irrigation, in which farmers give the crops way more water than they actually need. Such situations can arise when water demand for a particular crop is not given, or monitoring tools, like soil moisture sensors, are not available. Besides, over-irrigation leads to waterlogging, a situation in which excessive water makes the soil become water, and hence a lack of oxygen will reach the roots of the plants. Waterlogged conditions reduce the roots' ability to function properly; growth of the crop will be stunted; and these can consequently cause fungal diseases, nutrient leaching, and, finally, crop yield will be lowered (Manik et al., 2019).

The downside of water conveyance is low conveyance efficiency that is a major problem for irrigation infrastructure. In the surface irrigation systems that are traditional, water losses through seepage, evaporation, and unlined canals are significant. For instance, open channels with poor maintenance may lose over 40% of water before it even reaches the field (Mdemu et al., 2020). Siltation and canal damage, as observed in the Chauru Irrigation Scheme, further reduce delivery efficiency and cause unequal water distribution, particularly disadvantaging tail-end users.

Poorly maintained sluice gates and division boxes that are not in good condition have become one of the main factors that have led to the lack of proper water control. As a consequence, there is no way for the water to be distributed evenly and in a timely manner across the plots; thus, some farmers end up receiving too much water and others too little (Mdemu et al., 2020). This inconsistency among the various parts of the distribution network aggravates intra-scheme conflicts and leads to inefficient use of the command area, where some parts of the irrigable land are left uncultivated due to insufficient water or, in the case of areas with water surplus, the land becomes unsuitable for cultivation. Besides, in a good number of schemes, irrigation does not correspond to the crop growth stages. In the case of water not being delivered during the most critical crop development periods (for instance, flowering or grain filling), even the smallest deficits would result in a drastic reduction in yields. On the contrary, surplus irrigation is used during critical periods.

Earlier research aimed at addressing the issue of water use efficiency was carried out in different irrigation schemes across Tanzania which are Chate, Marigat, and Ahero, and have brought out their potential for improved irrigation performance and water management (Habineza, 2018). These studies offer greatly important regional insights but are not targeted at the evaluation of the Chauru Irrigation Scheme in Pwani Region.

This present research is primarily oriented at the Chauru Irrigation Scheme in coastal Tanzania. The scheme is perforated with issues of poor irrigation scheduling, uneven water distribution, and yield variability. Inefficiencies in the smallholder irrigation systems that abide by these accounts are the primary culprits of sub-optimal water productivity and food insecurity. This study tries to narrow the space of knowledge by checking the crop yield response and water use efficiency under different irrigation strategies in Chauru through the running of field trials and AquaCrop simulation modeling. The research supplies a quantitative foundation to the optimization of irrigation scheduling, the improvement of water infrastructure, and sustainable water use in this vital rice-growing region.

The main goal of this research is to assess and enhance water management methods for irrigation in the Chauru Irrigation Scheme, particularly aiming at rice cultivation. Rice is a crop that requires a lot of water, and in places like Tanzania, where water resources are becoming more limited due to climate change, making more efficient use of water is very important for food security and environmentally friendly farming (Bouman et al., 2007). The primary goal of this study is to establish a quantitative relationship between irrigation water input, crop evapotranspiration (ETc), and rice yield in field settings. We can compare the FAO AquaCrop model ETc estimation (Meinzen-Dick, 2012) with actual yield to determine the efficiency of water used for photosynthesis. The relationship thus demonstrated is the basis for the subsequent identification of the points at which the water supply can be decreased without any dramatic fall in yield, and hence is a major consideration in deficit irrigation strategies (Fereres & Soriano, 2007).

The next purpose of this research is to measure WUE resulting from a variety of irrigation methods. Water Utilization Efficiency (WUE) proves to be a very significant performance indicator for irrigated agriculture, particularly in semi-arid areas, and can be evaluated using several criteria such as crop WUE (yield / ETc) and irrigation water use efficiency (yield/irrigation water applied). Implementation of deficit irrigation, where less water than that needed by the crop is supplied, has been found to increase WUE by up to 25% without major loss of yield, especially if the deficit is properly timed during the critical growth stages (Fereres & Soriano, 2007; Zhang et al., 2004). Analyzing these parameters over full, deficit, and traditional farmer irrigation schedules provides the possibility of selecting the most efficient way to manage.

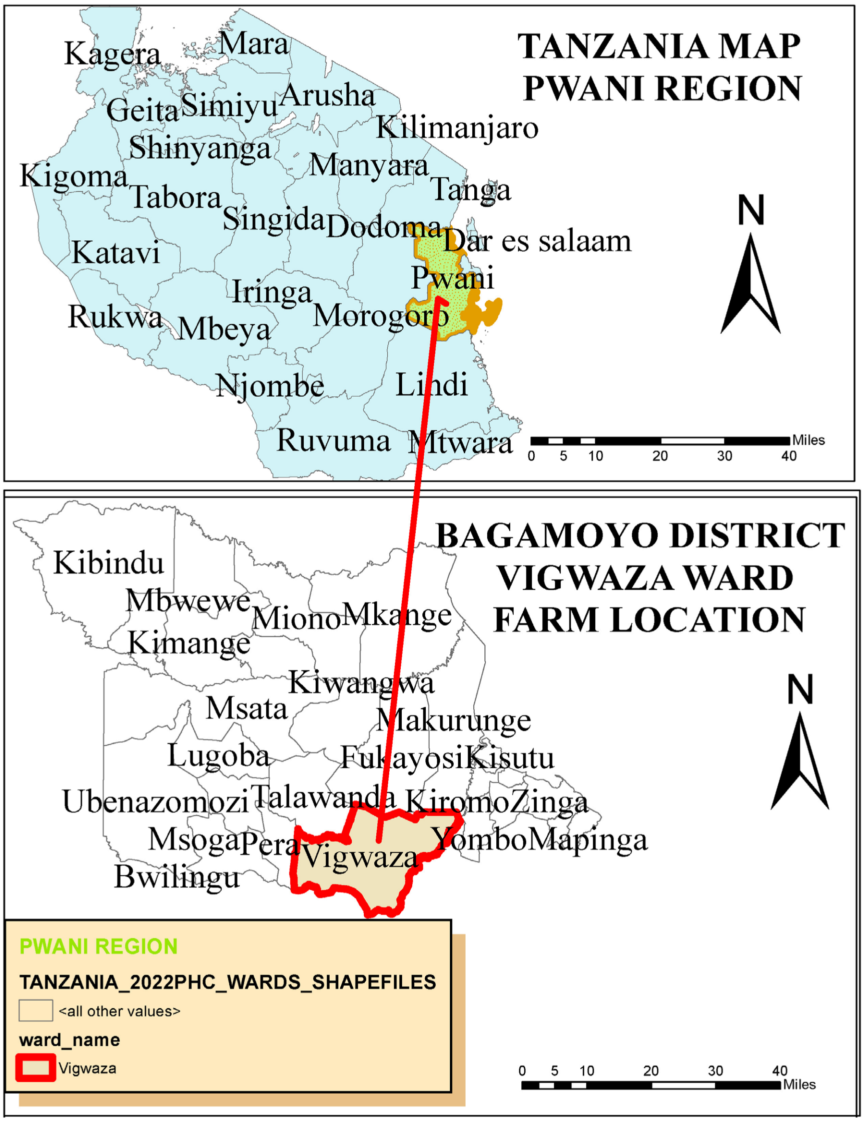
The third goal of this project is to find the best irrigation methods that result in either crop yield or WUE maximization, which is consistent with water conservation in agriculture. Research mimicking irrigation regimes such as regulated deficit irrigation and alternate wetting and drying (AWD) is conducted with the help of AquaCrop to measure their yield and efficiency trade-offs. Experimental results have revealed that techniques such as AWD in rice cultivation can lower repeated irrigation volumes by 30% while retaining or even boosting yields (Tuong & Bouman, 2003). In particular, the identification of such optimized strategies is necessary for places like Chauru, where the competition for water is constantly growing due to the rising population and climate change.

To conclude, the research attempts to find out how evidence-based guidelines relating to water management in the Chauru Irrigation Scheme can be developed. These could include the use of irrigation scheduling based on stages, replacement of canal infrastructure to decrease water losses, educating farmers for efficient water use, and the empowerment of institutional frameworks such as Water User Associations (WUA). Irrigation that is not properly managed frequently experiences inequitable water distribution, high conveyance losses, and issues with accountability, which participatory water governance combined with appropriate monitoring systems can solve (Meinzen-Dick, 2012). By tackling both the technical and institutional aspects of the study, the research can improve water governance, raise agricultural productivity, and ensure the irrigation scheme is sustainable in the future.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted at Chauru Farm, previously known as Ruvu Rice Farm, which has been managed by the Chama cha Wakulima wa Umwagiliaji Ruvu (CHAURU) since 2002. The farm covers 3209 hectares and is located at Visezi Village, Vigwaza Ward, in Bagamoyo District, Pwani Region. The geographical coordinates are Longitude East and 06˚41'24” to 06˚45'36” Latitude South, with an average altitude of 10 - 40 meters above sea level. The map of study area reveal the ward, district, region and the country, as shown in Figure 1 below.



Source: ArcMap 10.4 Software version.

Figure 1. Map of study area locating the ward, district, region, and country.

2.1.1. Climate

The study area experiences a bimodal rainfall pattern, with an average annual rainfall of 950 mm. The long rains, occurring between March and May, contribute 57% of the total rainfall, with April expected to record the highest precipitation. Short rains normally occur from October to December, contributing 25% of the total rainfall. The dry seasons normally extend from June to September and January to February, with average temperatures ranging between 25˚C and 30˚C, making the area suitable for tropical crop production (TMA, 2020).

2.1.2. Scheme Layout

The Chauru Farm irrigation scheme utilizes a pumped water system from the Msua Stream, which is fed by the Ruvu River. The scheme serves 350 farmers, each holding an average of 720 hectares added by 2023/2024. The farm is divided into eight sections, referred to as "Mifereji", further subdivided into 720 blocks for water distribution and land allocation. Figure 2, below shown the scheme layout existed of chauru irrigation scheme. Land preparation is fully mechanized using disploughs and harrows.

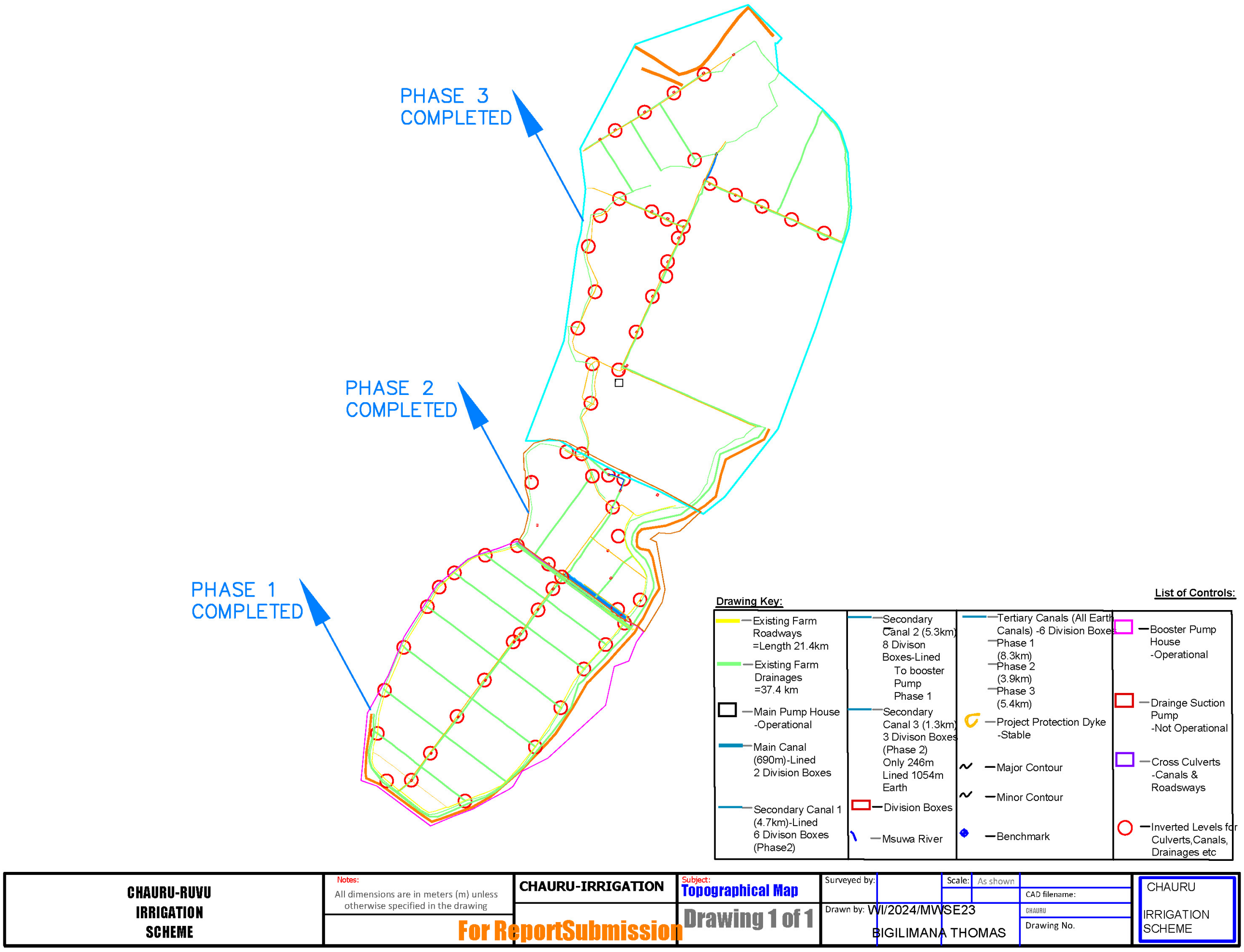


Figure 2. Chauru irrigation scheme layout exists (source: Auto CAD drawing).

2.1.3. Experimental Design

This research was initiated to carry out a thorough investigation of the influence of different irrigation management measures on rice production and water use efficiency (WUE) in the Chauru Irrigation Scheme, Bagamoyo District, Tanzania. The area is a tropical coastal region with very clearly marked wet and dry seasons; this climate is similar to the one found in many East African irrigation schemes. The project has been performed at the field level during the main cropping season in order to produce the necessary conditions for water management and sustainable rice productivity under different water availability scenarios in the locality. The study was initiated in response to the inefficiencies noticed in the scheme in terms of water consumption, which were caused by poor irrigation scheduling, uneven water distribution, and yield gaps, all of which were responsible for water wastage and lower productivity. (Bouman et al., 2007; Tuong & Bouman, 2003).

1) Treatments

The farm experiment evaluated the effect of five different irrigation methods on rice yield and water-use efficiency under controlled field conditions in the Chauru Irrigation Scheme. These treatments were aimed at mimicking different water supply levels and management accuracies, both based on scientific recommendations and local farmer practices. The first treatment (T1), also known as the control or farmer practice, was the basis for irrigation schedules decided by farmers' experience alone, without scientific estimation of crop water requirements. Such irrigation frequently led to non-uniform water application, usually represented by over-watering in early stages and under-supply in critical growth periods. The second treatment (T2) was full irrigation at 100% of the crop evapotranspiration (ETc), where irrigation was applied six (6) days per week based on climatic data calculated by the FAO Penman-Monteith method, using the crop coefficients for rice at the different growth stages. This treatment allowed a maximum yield potential under optimal water availability. The third treatment (T3) was deficit irrigation at 85% of ETc, representing a situation in which water was slightly less than needed. The fourth treatment (T4) went further with the decrease in the water portion to 70% of ETc in order to examine how the crop could adapt under water shortage and still produce acceptable yields while saving water. The fifth and last treatment (T5) was a rainfed condition, in which no additional irrigation was given during the whole growing season. Thus, this treatment was the performance baseline in cases where farmers rely on rainfall alone, for example, during low-water-availability years or in areas where there is no irrigation water supply system (Birhanu et al., 2019). In the Chauru scheme, all irrigated treatments (T1 to T4) were carried out using furrow irrigation, which is the local irrigation method of the scheme. Furrows were made very carefully and kept level to ensure that water flow was uniform and that there was no runoff or waterlogging. Watering was done in the early morning so that water loss by evaporation was as little as possible. The construction of these treatments allowed a detailed study of the effects of the change in the quantity of irrigation on crop performance, soil water balance, and water productivity in the agro-ecological conditions of coastal

Tanzania (Bouman et al., 2007).

2) Crop and Cultivar

The chosen crop for this research was rice (Oryza sativa L.), which is the primary and most profitable crop grown in the Chauru Irrigation Scheme. The exact cultivar used was SARO 5, a semi-dwarf, high-yielding variety launched by Africa Rice and that is still the official one for cultivation in Tanzania. SARO 5 is perfectly adapted to the lowland irrigated environment and therefore is the most convenient for the assessment under the scheme's climatic and soil conditions (Bouman et al., 2007). The crop has a moderate maturity time of 115 to 120 days, which makes it suitable for one cropping season and gives ample time for the next cycle to be prepared. SARO 5 was hence the right choice for the study's goals geared towards water management practice optimization in the irrigation rice system (Tuong & Bouman, 2003).

3) Plot Design

The experimental setup was a Randomized Complete Block Design (RCBD), which aimed at controlling field variability and enhancing the accuracy of treatment comparisons. The research was performed on a flat and even area within the Chauru Irrigation Scheme to ensure minimal natural heterogeneity; however, blocking was still necessary to take into account minor changes in the soil and micro-topography. Each treatment was replicated four (4) times and thus 20 experimental plots in total were used (5 treatments × 4 replicates). The plots were each 3 meters long and 2 meters wide, thus an area of 6 square meters was covered (Gomez & Gomez, 1984). The chosen dimensions represented a compromise between the necessity for a large enough sample size per plot and the aim of keeping irrigation and labor requirements at a reasonable level. This design furthermore enabled not only the analysis of yield and water use data through the analysis of variance (ANOVA) but also the detection of significant differences among irrigation regimes at a 95% confidence level (Steel & Torrie, 1980).

Calculation: 5 treatments × 4 replications = 20 experimental plots.

That means the total number of plots in the experiment is 20. Each of these plots receives a specific irrigation treatment according to the plan, but its location in the field is randomized to avoid bias. This is part of the Randomized Complete Block Design (RCBD). **Table 1**, showing the order of treatments, is randomized in each block to prevent placement bias.

Table 1. The randomized treatment in each block.

Block 1	**T1**	**T2**	**T3**	**T4**	**T5**
Block 2	T2	T3	T5	T1	T4
Block 3	T3	T1	T4	T5	T2
Block 4	T4	T5	T2	T3	T1

4) Agronomic Practices.

In order to be sure that the factors seen during the research were the only ones, caused by the differences in irrigation only, all other crop management practices were normalized and applied equally to all the treatments. The land was prepared with several passes and thorough tillage using tractor-mounted disc ploughs and harrows to get a very fine and well-leveled seedbed that is suitable for rice cultivation as well as uniform irrigation distribution for rice. With manual leveling, the surface was made smooth in order to create shallow furrows, thus minimizing the water runoff and the infiltration being uneven. In June, planting started, and the transplanting was done manually 21 days after the sowing using healthy seedlings, 2 to 3 per hill, which were spaced at 20 cm by 20 cm, which is the best for rice growth in lowland irrigated conditions.

Fertilizer application was in line with agronomic guidelines: a basal dose of 100 kg/ha of NPK (20:10:10) was given at transplanting to provide the necessary nutrients. After this, two split applications of urea (46% N) totaling 90 kg N/ha were given, the first at active tillering (approximately 25 days after transplanting) and the second at panicle initiation (around 50 days after transplanting) to be sure that vegetative and reproductive growth would be at its most vigorous state (Haefele et al., 2020). Weed control was done twice manually, i.e., at 21 and 45 days after transplanting, the latter being the last time. The weed-free conditions thus created would have ensured that the plants did not have to compete with weeds for water and nutrients. To be on the safe side, regular scouting was done to detect the presence of any pests or diseases, and, on the occasion of their being found, chemical control was provided by means of the use of approved pesticides and fungicides (De Datta, 1981).

During the cropping season, soil moisture has been regularly tracked by means of gravimetric sampling and tensiometers to check that irrigation schedules are being followed, and the water used has been accurately determined with calibrated water meters and V-notch weirs (Institute, 2013). Harvesting was done when about 85% to 90% of the rice panicles were at physiological maturity, which is usually 115 days after transplanting (Haefele et al., 2020). These demanding agricultural methods made certain that any change in production and water use efficiency among treatments could be linked with irrigation management differences without any doubt (De Datta, 1981).

2.2. Data Collection Procedures

Data collection in this study was designed to comprehensively capture the variables necessary for evaluating crop yield response and water use efficiency under different irrigation strategies.

2.2.1 Crop Yield Data

Physiological maturity was the stage at which each plot was harvested to obtain crop data. The grain from the middle harvest area of each plot (excluding border rows) was threshed, cleaned, sun-dried, and weighed using a precision digital scale. The yield was converted to 14% moisture content to make the treatments comparable. Besides the grain yield, a subsample of the total aboveground biomass was taken to measure the harvest index and biomass water use efficiency.

2.2.2. Water Applied Measurement

Irrigation water applied was carefully monitored and recorded for each plot. Water was delivered using furrow irrigation, and the volume applied was measured using Parshall flumes installed at the main inlet channels and verified with flow meters at each subplot, if necessary. Flow rates and irrigation duration were registered during each application, and the total seasonal water applied was obtained by integrating the flow rate over time. In the case of motorized pumping, volumetric discharge calculations were confirmed using pump curves and flow measurements.

2.2.3. Soil Moisture Monitoring

To track soil moisture changes, gravimetric sampling was conducted at 10-day intervals during the research period. Soil samples from each treatment plot were taken at various depths (0 - 20 cm, 20 - 40 cm, and 40 - 60 cm) using an auger. The water content was determined by oven drying the samples at 105˚C for 24 hours. TDR (Time Domain Reflectometry) probes were installed in selected plots to obtain real-time trends, and manual observations were also made using this method. The measurements enabled us to determine not only percolation losses but also root zone water availability and the accuracy of the irrigation schedule.

2.2.4. Meteorological Data Collection

Meteorological data were obtained from the Kibaha Meteorological Station, which is located nearby, and also from an automatic weather station (AWS) that was set up in the field at the Chauru farm site. The information consisted of the highest and lowest temperatures recorded daily, the relative humidity, solar radiation, wind speed, and the amount of rain. These weather parameters played a crucial role in the simulation of crop water use and in the evaluation of evapotranspiration under different climatic conditions.

2.2.5. Evapotranspiration (ET) Estimation

Evapotranspiration (ET) was calculated through the FAO Penman–Monteith equation (Food and Agriculture Organization (FAO, 1998), the method most suitable for the estimation of reference evapotranspiration. The reference evapotranspiration (ETo) for the crop was obtained by multiplying ETo with the crop coefficient (Kc), which represented different growth stages, and was adjusted according to local agronomic and climatic conditions. To be consistent, such calculations were carried out with the help of both the FAO CROPWAT 8.0 software and the AquaCrop model, which incorporated local soil, crop, and weather information for the dynamic simulation of ETc and effective rainfall.

Mathematically;

$$\text{ETc} = \text{ETo} \times \text{Kc}$$

2.3. Data Analysis

The purpose of the data analysis in this research was to assess the impact of different irrigation treatments on the output of crops, water use efficiency (WUE), and other agronomic and hydrological parameters. The investigators used the statistical techniques and software applications, which are listed below, to process and explain the gathered data.

2.3.1. Descriptive Statistics

In order to summarize and present an overview of the experimental data, descriptive statistics were computed. The mean, standard deviation (SD), standard error (SE), minimum, and maximum values were obtained for grain yield (t/ha), aboveground biomass (t/ha), water use efficiency (kg/m^3), irrigation water applied (mm), and soil moisture content (%). These statistics permitted a preliminary gauge of the data's variation and tendencies in different irrigation treatments.

2.3.2. Statistical Tools (ANOVA)

One-way analysis of variance (ANOVA) was applied to compare the treatments and establish if there were any statistically significant differences among them at a 5% level of significance ($p < 0.05$). In cases where significant differences were revealed, Tukey's Honest Significant Difference (HSD) test was conducted to identify which treatments differed significantly by performing pairwise comparisons of treatment means (Gomez & Gómez, 1984). **Table 2** shows the meaning of the symbol from the one-way ANOVA mathematical model with one factor (e.g., irrigation treatment) and multiple replicates.

$$Yij = \mu + \tau i + \varepsilon ij$$

Table 2. Showing the meanings of symbols from the linear equation.

Symbol	Meaning
Yij	The observed value of the response variable (yield) for treatment ii and replicate jj.
μ	The overall mean of the observations.
τi	The effect of the ijth treatment.
εij	The random error or residual associated with the ijth observation is assumed to be independently and normally distributed with mean 0 and constant variance σ^2, i.e., $\varepsilon ij \sim N(0, \sigma^2)$.

Source: (Gomez & Gomez, 1984).

2.3.3. Regression Analysis (Water-Yield Relationship)

To quantify the relation between water input and the crop response, a regression analysis was performed. The relationship between the water input and the crop yield production functions was established via regression analysis, that is, the quantitative relationship between water input (either irrigation or evapotranspiration) and the crop yield. A number of models were used for testing to find the best fit. Linear and polynomial models were tested, with grain yield as the dependent variable and either irrigation water applied or crop evapotranspiration (ETc) as the independent variable.

$$Y = a + bX$$

Where;

Y = Crop yield (t/ha)

X = Irrigation water applied (mm) or ETc

a = Intercept

b = slope (yield response per unit of water)

The best-fit models were selected based on the coefficient of determination (R^2), the root mean square error (RMSE), and the p-values of regression coefficients (Team, 2022).

Regression Equation with Polynomial:

a) Yield vs. Irrigation Applied:

$$\text{Irrigation}^2$$

b) Yield vs ETa:

$$\text{ETa}^2$$

These quadratic models capture non-linear relationships between water input and crop yield, which are essential for optimizing irrigation strategies in deficit conditions.

2.3.4. Crop Yield Response to Water-use Efficiency

Crop yield response to water use efficiency (WUE) is a measure of how efficiently water is the driving force of crop production, particularly in water-scarce environments. The unit of this measure is generally the ratio between crop yield (kg/ha) and water consumed (mm or m^3/ha), which is mainly through evapotranspiration. Higher WUE means more efficient water productivity, which is to say that more crop is produced per unit of water applied, an important concept in sustainable agriculture called "more crop per drop" (Molden et al., 2007). In irrigated systems like Chauru, increasing WUE through irrigation scheduling that is carefully planned and using modern methods, for instance deficit irrigation, can not only help sustain yields but also conserve water resources, especially in the case of climate-induced water stress (FAO, 2020; Rockström et al., 2010).

Water Use Efficiency (WUE) is a measure of how effectively water is used to produce crop biomass or yield. It indicates the amount of crop output (biomass or economic yield) obtained per unit of water used (applied or consumed).

Mathematically:

$$\text{WUE} = \frac{\text{Crop yield}\left(\text{kg/ha}\right)}{\text{Evapotranspiration}\left(\text{ETc}\right)\times 10}$$

Or sometimes were computed by.

$$\text{IWUE} = \frac{\text{Grain Yield}\left(\text{kg/ha}\right)}{\text{Irrigation Water Applied}\times 10}$$

OR

$$\text{BWUE} = \frac{\text{Total Biomass}\left(\text{kg/ha}\right)}{\text{Evapotranspiration}\left(\text{ETc}\right)\times 10}$$

These values were analyzed statistically using ANOVA to compare efficiency across treatments.

WUE is used in various ways depending on the level of the observations. At the level of the crop in the field, WUE is usually the ratio of aboveground biomass or economic yield to water use or evapotranspiration (ET) (Mukiza et al., 2014). This study, during the analysis and observation, the way applied to calculate the water use efficiency is aboveground biomass yield to water use. For water use efficiency in the Pwani region for rice crop, WUE less than 3 - 4 kg/m^3 indicates inefficient water use due to Pwani location and its crop growth, around 4 - 7 kg/m^3 indicates moderate WUE, and irrigation practices are improved by alternate wetting and drying, and above 8 - 10 kg/m^3 indicates high WUE with advanced water-saving methods, especially in water-scarce regions. Typically, the WUE for rice in conventional flooded systems is often around 2 - 4 kg/m^3. Efficient systems, such as controlled irrigation or drought-tolerant varieties, can increase WUE toward 8 - 10 kg/m^3, but also achieving WUE above 10 kg/m^3 in rice is challenging yet possible with optimized water management practices (FAO, 2011; Tuong & Bouman, 2003; Zhang et al., 2008). As shown in **Table 3**, the bench mark of the water use efficiency.

Table 3. The WUE benchmark.

Water Use Efficiency (WUE)	Estimated Range	Practical Implication
Low	<3 - 4 kg/m^3	Traditional flooded rice: high water use
Moderate	4 - 7 kg/m^3	Improved practices, water-saving techniques
High	>8 - 10 kg/m^3	Advanced methods like drip or AWD: water-scarce settings

Source: (FAO, 2020).

Water Use Efficiency (WUE) is a vital indicator in our topic, evaluating the impact of irrigation strategies and water management practices to improve the performance of crop production. It is a measure of the amount of crop yield generated from the water used. The most widely used metric for crop WUE is the grain yield (kg/ha) divided by evapotranspiration (ETa, in mm), expressed in kg/m^3 by dividing by 10, since 1 mm of water is equivalent to 10 m^3 per hectare. For irrigated rice, the typical crop WUE range is 1.0 to 2.5 kg/m^3, with values above this band representing very efficient water use, although they could also result from underestimated ET or overestimated yield (Steduto et al., 2012a; Zhang et al., 2004). Another significant parameter is irrigation WUE, which is based on the volume of water used for irrigation rather than on total ETa. It is usually greater if rain plays a major role in ETa or if irrigation is carried out during crucial growth stages with the least losses (Fereres & Soriano, 2007).

2.3.5. Crop Water Response

Water is the most important of all inputs in crop production, especially in irrigated agriculture where rainfall is insufficient or irregular. Water transfer to crops is a necessary but complicated process and yields a relationship with crop growth that is critically important to optimize irrigation management (Zwart & Bastiaanssen, 2004). Crop water use primarily yields a response that refers to the extent to which changes in water availability through rainfall, irrigation, or soil moisture storage affect crop productivity (Kassam et al., 2009). Having a picture of this crop water response capacity allows the formulation of irrigation schemes that are optimally efficient in water use (WUE) and adhere to the principles of sustainable agriculture, especially rice cultivation systems such as the Chauru Irrigation Scheme (Hussain & Bhattarai, 2004).

In this research, the AquaCrop model of the Food and Agriculture Organization of the United Nations (FAO) was opted for to estimate, on a daily basis, under a variety of irrigation situations, water consumption and yield, along with crop growth, while also considering water availability and environmental factors (Doorenbos & Kassam, 1979). The model results gave a full picture of how the rice crop can react to the water provided, thus allowing the allocation of the crop's reaction to water into linear and nonlinear regions.

a) Linear Crop Yield Response to Water

In conditions where water is limiting, rice yield goes up linearly with every extra unit of water that is applied. For instance, during a period of rapid growth or in deficit irrigation conditions, an irrigation of 1 mm may yield 10 kg/ha of rice. Hence, 200 mm of water leads to 2000 kg/ha and 300 mm to 3000 kg/ha, thus keeping a linear response up to the crop's full evapotranspiration demand (ET_m). This activity was found in the Chauru simulation under deficit irrigation, where it was observed that steady increases in yield occurred with the addition of irrigation in the early stages (Steduto et al., 2012b).

b) Nonlinear Crop Yield Response (Diminishing Returns)

Once the water requirement of the crop has been fully satisfied, there is no additional positive effect of irrigation on yield. On the contrary, however, too much water can lead to a decrease in yield caused by waterlogging, lack of oxygen in the root zone, nutrient losses in the soil, fungal infections, or lodging. To give an example, in AquaCrop computer modeling, 700 mm of water gave a yield of 6 t/ha, which was almost optimal; yield was not further increased by irrigation of 900 mm; and at 1100 mm, the yield fell to 5.5 t/ha the beginning of the effects of diminishing returns and the nonlinear response to water (Steduto et al., 2012b).

c) Ky Coefficient and Crop Sensitiveness to Water Stress

To represent yield change with a water shortage, the (FAO, 2020) came up with the Ky factor, which is given by the equation:

$$1-\frac{Y_a}{Y_m}=K_y\left(1-\frac{ET_a}{ET_m}\right)$$

Where:

- Y_a—actual yield
- Y_m—maximum yield under no water stress
- ET_a—actual evapotranspiration

- ET_m—maximum evapotranspiration
- K_y—Crop yield response factor

The more Ky is, the more sensitive the crop is to water deficit. This is in line with the (FAO, 2020) research, which highlights the rice's susceptibility to water shortages during the critical periods of its growth, such as flowering and grain filling.

2.3.6. Irrigation Scheduling and Strategies

This section discusses irrigation scheduling and strategies based on the existing design of the Chauru scheme, which employs rotational surface irrigation every six (6) days. To simulate the conditions for rice (paddy crops), AquaCrop was configured to model basin irrigation with predefined water depths typically ranging from 5 to 8 cm per application. The model incorporated the chosen irrigation method (Surface-Furrow), a fixed interval of six days, consistent timing for irrigation events, and efficiencies that account for conveyance and application losses, resulting in an overall system efficiency of approximately 53.2% for rice cultivation. Besides, two scenarios were analyzed: one where full irrigation meets 100% of the crop's water needs, and another with delayed or deficit irrigation to evaluate how water shortages might impact crop yields.

2.3.7. Crop Yield Model Simulation

This research utilized the AquaCrop model, which was created by the Food and Agriculture Organization (FAO), to investigate how the application of irrigation water, crop yield, and water use efficiency are interrelated under different irrigation regimes. The AquaCrop is a process-based model for the simulation of crop productivity, water use, and soil water balance of herbaceous crops, with special attention to yield response to water (Steduto et al., 2009, 2012a).

The FAO Aqua Crop model was selected to simulate rice yield response to water because it is specifically designed to quantify crop-water productivity under water limited conditions and has been extensively validated across diverse agro-ecological settings, including tropical irrigated systems similar to the Chauru Scheme. Its capability to reliably link irrigation water application, actual evapotranspiration (ETc) and yield makes it particularly suitable for evaluating deficit and full irrigation scenarios and improving on-farm water management for rice in Sub-Saharan Africa contexts (Tuong & Bouman, 2005).

Aqua Crop is a FAO developed, validated tool for simulating rice yield response to water across diverse agro-ecologies, making it well- suited to assess deficit or full irrigation and water use efficiency in the Chauru Scheme (Tuong & Bouman, 2005).

2.3.8. Model Calibration

Calibration is a very important step in determining that the AquaCrop simulations are accurate and dependable. The calibration process is essentially a search for a match between model parameters and observed data from a sample in terms of crop, soil, and management variables.

The effort of finishing the simulation was initiated by matching the AquaCrop model to local observations to make sure the simulated data were as close as possible to the observed ones. The parameters of the crop, which were mainly calibrated, included those that influence the growth of the canopy (cover development), root depth, harvest index (HI), productivity of mass-energy-water, and crop coefficients (Kc). Additionally, soil features such as field capacity, wilting point, and hydraulic conductivity were taken from field and laboratory measurements. Agronomic practices in the field, such as planting date, irrigation schedule, and fertilizer applications, were also considered to mimic and improve the model realism of those that were most likely practiced in the field.

Calibration was mostly done by utilizing the Full Irrigation treatment data, which symbolize the most favorable conditions for rice growth. Canopy development, soil moisture changes, biomass increment, and grain yield are model outputs simulated by the model that are iteratively modified until they converge with the observed data. Validation of the model was next performed for the Deficit Irrigation data after the step of calibration, which is the main stage in a simulation model. This process ensured that the model could accurately reflect the different levels of water supply in crop performance under deficient water.

Following validation, AquaCrop was used to mimic crop performance under four irrigation regimes, namely full irrigation (100% ETc), moderate deficit (85% ETc), severe deficit (70% ETc), and rainfed conditions. The model offered information on crop growth, actual evapotranspiration (ETa), and final grain yield for every case. The simulations were intended to indicate irrigation policies that optimize water productivity and, at the same time, keep the decrease in yields insignificant. The water–yield response functions that AquaCrop generated turned out to be fundamental instruments for designing deficit irrigation protocols, since they supply practical help for the sustainable management of scarce water. The methodological approach is in line with most of the literature (Steduto et al., 2009, 2012a), confirming the model's appropriateness for testing irrigation projects in actual environments.

3. Results and Discussion

3.1 Result

3.1.1. Climate and Water Availability

In the cropping season, a total rainfall of 320 mm was received in the study area, which was unevenly distributed across the growth stages. The average daily temperature was 27.4˚C, which is in the range of thermal optimum for rice growth. The reference evapotranspiration (ETo) for the season, calculated by the FAO Penman-Monteith method, was 850 mm. To make up for the rainfall that fell short and to fulfill the water requirement of the crop, different quantities of irrigation water were applied in treatments: 600 mm for full irrigation, 510 mm for moderate deficit (85% ETc), 420 mm for severe deficit (70% ETc), and 350 mm for farmer practice. The rainfed treatment did not receive any irrigation; thus, it was completely reliant on natural precipitation. These conditions resulted in different water regimes that facilitated a comprehensive analysis of crop response to water availability.

3.1.2. Soil Water Dynamics

Soil moisture content was checked at multiple depths (0 - 60 cm) using gravimetric sampling and TDR sensors throughout the whole growing season. The results showed that there were no explicit differences in soil water profiles across treatments. The full irrigation and 85% ETc treatments were consistently close to the optimal moisture levels during the most important phenological stages, such as panicle initiation and grain filling. On the other hand, the 70% ETc and farmer practice treatments were characterized by the appearance of moisture deficits of medium intensity, particularly during reproductive stages, whereas the rainfed plots suffered acute water shortages throughout the whole season. These changes not only had a great influence on the water character in the root zone but also, consequently, on plant growth and yield formation.

3.1.3. Crop Yield Response

Grain yield was found to vary greatly among the treatments (**Figure 3** and **Table 4**). The maximum yield of 6.2 t/ha was obtained with the full irrigation treatment, followed by a yield of 6.0 t/ha in the 85% ETc treatment, which was very close. The yield dropped more noticeably in the 70% ETc and farmer practice treatments, where yields of 5.5 t/ha and 4.8 t/ha were realized, respectively. The lowest yield, 4.1 t/ha, was produced in the rainfed treatment. The yield differences between treatments at the 5% significance level ($p < 0.05$) were confirmed by the ANOVA method. According to the post hoc Tukey test results, there were no significant differences between the full and 85% ETc treatments, which means that using moderate deficit irrigation can give yields that are close to the best. **Table 4** below shows the treatment corresponding the yield produced and **Figure 3** reveal the Bar graph showing the yield in each treatment.

Table 4. Showing the yield in each treatment

Treatment	Yield (t/ha)
Full Irrigation	6.2
85% ETc	6.0
70% ETc	5.5
Rainfed	4.1
Farmer Practice	4.8

3.1.4. Evapotranspiration (ETa and ETc)

The actual crop evapotranspiration (ETa) has changed across treatments due to varying water availability. The full irrigation treatment recorded the highest ETa of 780 mm, followed by 720 mm for 85% ETc and 680 mm for 70% ETc. The

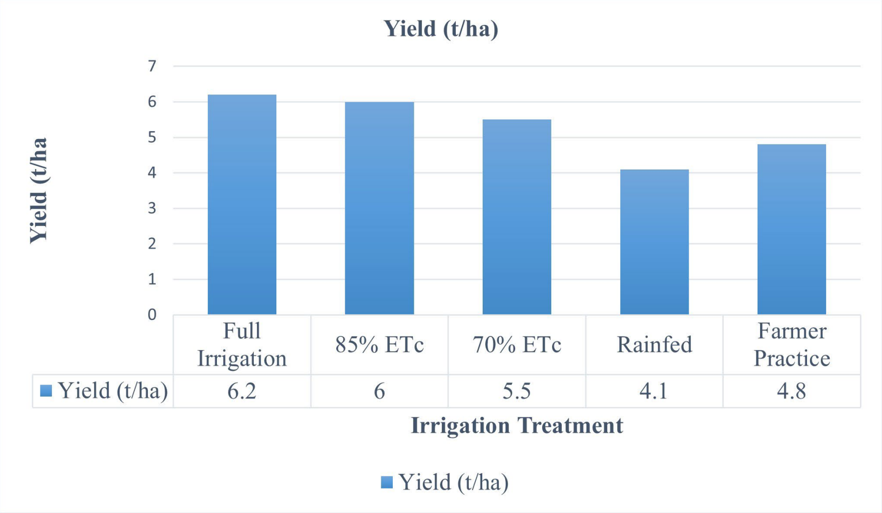


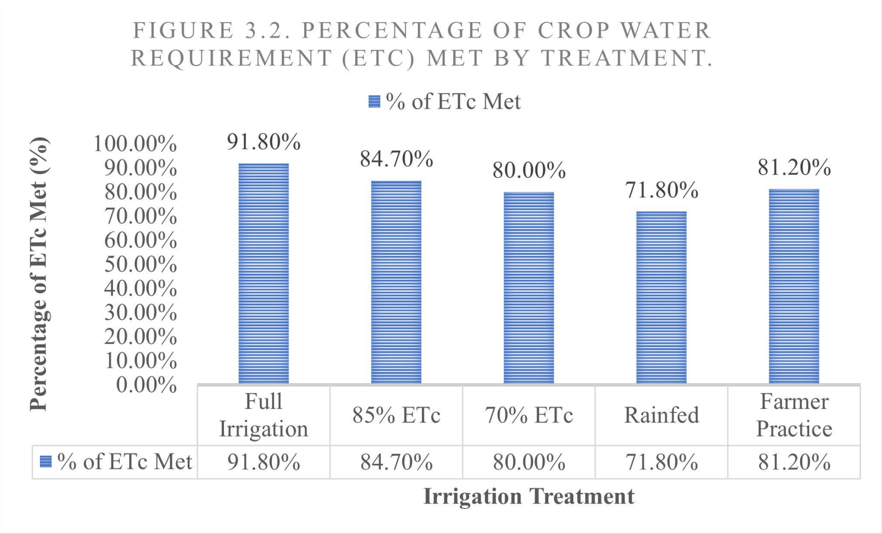
Figure 3. Bar graph shows the yield in each treatment.

farmer practice and rain-fed treatments recorded lower ETa values of 690 mm and 610 mm, respectively. These differences are consistent with the volume of irrigation applied and the corresponding soil moisture levels. When compared to the seasonal ETc requirement (based on Kc-adjusted ETo), treatments with reduced irrigation met a smaller percentage of the total crop water requirement, which partially explains the yield reductions in those treatments. The actual evapotranspiration (ETa) values recorded for each irrigation treatment are presented in **Table 5** and illustrated below:

Table 5. The actual evapotranspiration (Eta) varies in each irrigation treatment.

Treatment	Actual (ETa) (mm)	ETc (Target) (mm)	% of ETc Met
Full Irrigation	780	850	91.8%
85% ETc	720	850	84.7%
70% ETc	680	850	80.0%
Rainfed	610	850	71.8%
Farmer Practice	690	850	81.2%

The table above reveals that the percentage of the crop water requirement (ETc) that was efficiently fulfilled by the actual evapotranspiration (ETa) was significantly different among the irrigation treatments. This difference shows that there were differences in water application and plant water uptake. As shown in **Figure 3**, the Full Irrigation treatment gave about 91.8% of the seasonal ETc (850 mm) (the total amount of water required for the growing season), which means that the crop's water needs were mostly satisfied, although some water losses (such as deep percolation through the conveyance (like lined and unlined canals) may have reduced the total uptake) were still possible. The 85% ETc and 70% ETc treatments accomplished 84.7% and 80.0% of ETc, respectively, which were consistent with the irrigation deficits that were set. These results illustrate that the rice crop has some capacity to cope with water scarcity and still keep evapotranspiration at a relatively high level. The Farmer Practice treatment, which entailed local irrigation schedules and a lower total water input, reached 81.2% of the ETc. This implies that even though traditional methods may not be very scientifically managed, they can still provide a moderate water sufficiency level. However, the Rainfed treatment only got 71.8% of ETc, showing that the crop was under severe water stress due to the limited rainfall, which led to a significant decrease in crop performance. These outcomes pinpoint that moderate deficit irrigation can not only save water but also keep evapotranspiration relatively high; thus, water can be used sustainably without requiring substantial yield reductions. **Figure 4** shows the percentage of water requirement (ETC) met by treatment.



	Full Irrigation	85% ETc	70% ETc	Rainfed	Farmer Practice
% of ETc Met	91.80%	84.70%	80.00%	71.80%	81.20%

Figure 4. The percentage of water requirement (ETC) met by treatment.

This figure visually shows the seasonal water requirement of the crop (ETc = 850 mm) that was fulfilled by actual evapotranspiration (ETa) under the different treatments.

3.1.5. Water Use Efficiency

Water Use Efficiency (WUE) was studied through two parameters: Crop WUE (kg of grain per mm of total ETa) and Irrigation WUE (kg of grain per mm of irrigation water used). The highest crop WUE was found in the 70% ETc treatment (1.31 kg/m^3), trailed by the 85% ETc treatment (1.18 kg/m^3). Interestingly, though, full irrigation resulted in the maximum yield; its crop WUE was still lower (1.03 kg/m^3), signifying that some of the water used may have been more than the crop's optimum water requirement. The rainfed and farmer practice experiments produced the lowest crop WUE numbers, 6.72 and 6.96 kg/ha/mm, respectively. Regarding the irrigation WUE, the farmer practice treatment exhibited a relatively high value (1.37 kg/m^3), probably due to lower irrigation volumes, although the corresponding yield was modest. These results demonstrate that moderate deficit irrigation can improve WUE without yield loss. **Table 6** below shows the calculated WUE in each treatment.

Table 6. The calculated WUE in each treatment.

Treatment	Yield (t/ha)	Irrigation Applied (mm)	CropWUE (kg/m³)	Irrigation WUE (kg/m³)
Full Irrigation	6.2	600	1.03	1.03
85% ETc	6.0	510	1.18	1.18
70% ETc	5.5	420	1.31	1.31
Rainfed	4.1	0	0.67	0
Farmer Practice	4.8	350	0.70	1.37

These results indicate that deficit irrigation methods, especially at 70% - 85% ETc, achieve the right balance between yield and water savings and therefore improve WUE in general. They further confirm the fact that increased irrigation is not necessarily good, particularly when the goal is sustainable water use in areas suffering from water shortage. As shown in **Figure 5**, the comparison of crop WUE and Irrigation WUE by treatment.

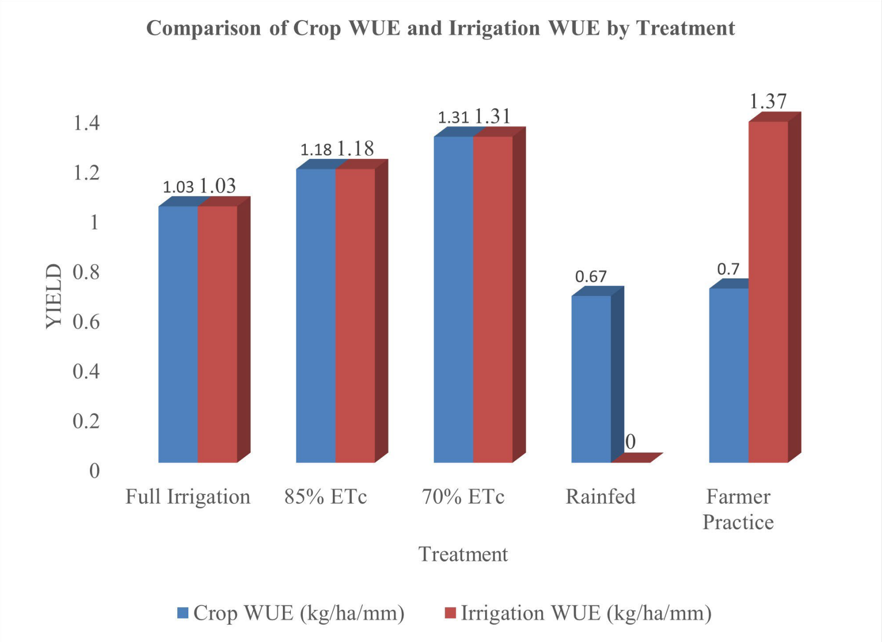


Figure 5. Comparison of crop WUE and irrigation WUE by treatment.

This grouped bar chart represents the efficiency of water use across different treatments, based on crop evapotranspiration and also the volume of irrigation water used. **Figure 5**: WUE of Crop and WUE of Irrigation under different irrigation treatments. The 70% ETc treatment registered the highest crop WUE, whereas the Farmer Practice treatment achieved the highest irrigation WUE as a result of limited water application. The plots that were rainfed, i.e., without irrigation, recorded an irrigation WUE of zero. The findings highlight the suitability of deficit irrigation strategies for utilizing water most efficiently.

3.1.6. Water Production Function

In order to measure the yield response to water, a water production function was established by fitting polynomial regression curves between yield and both irrigation applied and actual evapotranspiration (ETa). The regression exhibited a strong quadratic relation with R^2 values exceeding 0.95, signifying a high correlation between water input and crop output. The graph showed decreasing returns after 85% ETc, which means that full irrigation resulted in a yield that was not proportionally higher than the water used. This is consistent with the fact that when a crop's water requirement has been satisfied, extra irrigation will not significantly increase the yield but can lead to inefficiency (Fereres & Soriano, 2007; Steduto et al., 2009). The fitted water-yield relationships give a valuable decision-support tool for choosing the best irrigation thresholds that not only increase yield but also improve resource-use efficiency. **Figure 6** shows two fitted yield-water response curves: the left panel shows the relationship between irrigation applied (mm) and grain yield (t/ha), and the right panel shows the relationship between actual ETa (mm) and grain yield (t/ha). As shown in **Figure 6**, the relationship of irrigation applied versus grain yield.

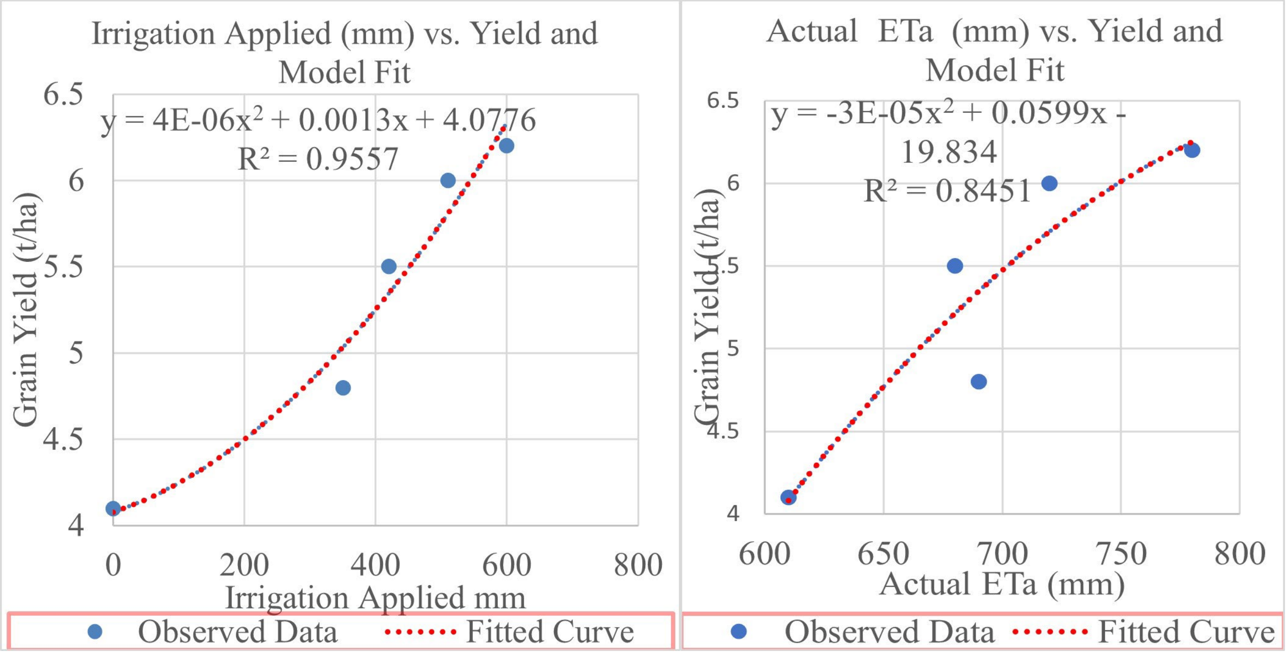


Figure 6. The relationship of irrigation applied (mm) vs. grain yield (t/ha) and Eta (mm).

Figure 6 above states that the fitted polynomial regression curves describe the relationship between grain yield and two water-related variables: irrigation water applied and actual crop evapotranspiration (ETa). The yield response shows a typical diminishing return trend, where increased water beyond a threshold does not proportionally increase yield, affirming the principle of water productivity optimization.

3.2. Discussion

This is a very detailed discussion section, which is specifically designed to address the findings gained from my research on yield, evapotranspiration (ET), irrigation, and water use efficiency (WUE) under various irrigation conditions. The focus is primarily on the rice crop in the Chauru Irrigation.

The findings of the study unveiled a notable yield response to irrigation, typified by a curvilinear, or diminishing returns, pattern. As irrigation was increased from rainfed conditions to full irrigation (600 mm), the grain yield also went up; however, the increment rate of this increase was smaller at higher irrigation levels. For example, while the transition from 350 mm to 510 mm of irrigation resulted in a significant yield increase, the step from 510 mm to 600 mm gave only a small rise. The trend shown here is the law of diminishing returns to irrigation, which states that after a certain level, the water that is added contributes less to the crop and may even cause problems if the water goes very deep or nutrients are washed away. The maximum yield of 6.2 t/ha was observed under full irrigation; however, the 6.0 t/ha yield under the 85% ETc treatment indicated that considerable water savings could be realized with very little effect on performance.

The farmer practice treatment, which got less total irrigation (350 mm) than the scientifically managed 70% ETc deficit treatment (420 mm) definitely reflects unregulated and haphazard watering applications under traditional management. However, it does not mean that they have water-saving behavior. The lower water consumption is caused by the following factors: the irrigation was missed at the important times of the crop stages, the water is distributed unevenly because of the bad infrastructure, and there is no proper irrigation scheduling. On the other hand, the 70% ETc treatment that was irrigated in accordance with the crop water demand always gave the scheduled irrigation that was systematically decided, so its higher total irrigation volume is more effective even if it is a deliberate deficit. This emphasizes the pivotal role of timing and delivery as well as total volume in water use efficiency and yield results.

In terms of water use efficiency (WUE), the 85% ETc treatment provided the best results, which meant that this irrigation level was the most suitable in terms of water applied and crop yield ratio. On the other hand, rainfed and 70% ETc treatments resulted in lower WUE, probably because of water shortage during important growth stages such as panicle initiation and flowering, which are considered the most sensitive rice developmental periods. Moreover, AquaCrop simulation runs, which illustrated the crop's reaction to various irrigation regimes, supported the findings that the physiological behavior was followed. Modeled evapotranspiration (ETa) values also conformed to the data observed in the field, lending additional credence to the model's relevance.

These results are very consistent with the results of previous studies/researchers (Geerts & Raes, 2009) highlighted that deficit irrigation strategies may improve water productivity with no major yield losses, a finding that was also demonstrated in this experiment. In the same way, (Bouman et al., 2007) found that excessive watering in rice systems has no proportional effect on yield and could actually result in a decrease in water use efficiency overall. The curvilinear character of the observed yield response is consistent with the results from (Zhang et al., 2004), who said that plants grown in Mediterranean atmosphere have shown that they are the most water-efficient for that climate when they were irrigated moderately rather than fully. The AquaCrop model used in this study, consistent with (Meinzen-Dick, 2012), effectively simulated crop performance and provided consistent guidance on optimal irrigation levels.

Differences in WUE and yield among treatments were caused by a number of factors. One of the main factors was soil type. Soil's texture and water retention ability were the main things that influenced how water was stored and provided to plants. Soils that were heavier probably kept moisture longer, thus supporting the plants' uptake, while sandy parts of the area might have had very quick drainage and thus lost water. The level of uniformity in the irrigation system also had an influence because small changes in the slope or the way furrows were made might have led to water being distributed in a non-uniform manner across the plots. Besides, the time at which irrigation was carried out in relation to the growth stages of the crop also had an effect on the results; those treatments that got water in time during the most sensitive phases, like the flowering period, performed better in terms of both yield and WUE.

The Chauru Irrigation Scheme is deeply impacted by the study in the practical field of work.

The study indicates that water managers and farmers could use regulated deficit irrigation (for instance, 85% ETc) whereby water will be saved and the yield won't be reduced. It is mostly applicable, among others, in those areas, where the water supply is very restricted or during the drought period when the need is greater than the available water. The scheme can also enhance both productivity and equity among users by implementing efficient irrigation scheduling and upgrading the water distribution infrastructure. Moreover, it can be possible that farmers benefiting from WUE-based practices may lead to water being available for a longer period and sustainability being increased.

The results of this study may be embodied directly in practicing irrigation calendars, seasonal water distribution strategies, and simplified field instructions that can be implemented by Water User Associations (WUAs) and those, who talk to farmers for local extension, can spread this information. Setting milestones for when and how much water a crop should be given at each stage of development, based on the 85% ETc strategy, can help regulate the irrigation practice and avoid wastage. On the other hand, the research has some drawbacks. Due to the low number of treatments ($n = 5$), the statistical power of the analysis was limited, and while the bootstrapping technique gave more reliable estimates, further tests are still needed to verify the results. The experiment was carried out during only one season; hence, the findings could be incomplete, as they may not reflect climate changes over the years. Moreover, inaccuracies in flow meters and soil moisture probes might have resulted in errors in the water balance estimations. In conclusion, because the trial was conducted only within a restricted area, this part of the research may not be representative of the entire Chauru scheme.

4. Conclusion and Recommendation

4.1. Conclusion

The study explores correlations between irrigation water used, evapotranspiration, and crop yield response under various irrigation methods in the Chauru Irrigation Scheme. The primary aim was to assess water use efficiency (WUE) and find out what irrigation methods improve yield and, at the same time save water. In the experiment, five treatments, namely full irrigation (100% ETc), moderate deficit (85% ETc), severe deficit (70% ETc), rainfed, and farmer practice, were considered for analysis of crop yield, actual evapotranspiration (ETa), and irrigation water applied.

The results revealed that the 85% ETc treatment resulted in a yield (6.0 t/ha) practically equal to full irrigation (6.2 t/ha) but with 15% less water, thus enabling a higher crop WUE (1.18 kg/m^3) compared to full irrigation (1.03 kg/m^3). The 70% ETc treatment recorded the highest WUE (1.31 kg/m^3); however, it indicated a minor decrease in yield (5.5 t/ha). The lowest yields and crop WUE values were attained by rainfed and farmer practice treatments, which display the vulnerability of the system to unregulated water supply and rainfall variation. The findings are also consistent with the idea that moderate deficit irrigation can not only sustain high yields but also substantially improve water productivity.

The Chauru Irrigation Scheme that was conducted under controlled conditions showed that it was technically efficient in delivering water and supporting yield capacity. However, the difference between optimal treatments and farmer practice shows that there is still some improvement possible in water management on the farm. WUE that is less than optimal is the result of bad timing, uneven water distribution, and a lack of proper irrigation scheduling, among others, in farmer-managed plots that are under actual conditions.

4.2. Recommendations

4.2.1. Recommendation for Improving Water Use Efficiency

Water productivity and sustainability in the Chauru Irrigation Scheme have been observed under different treatments using yield responses and water use efficiency (WUE) metrics, from which specific and actionable recommendations for improvement are outlined here.

1) Adopting Deficit Irrigation during Non-Critical Growth Stages

Deficit irrigation is a water-saving technique whereby less water is provided than is needed for the crop (ETc), particularly at times when the plants are less sensitive to stress caused by a lack of water. In the experiment, the 85% ETc treatment showed a decrease in yield of only 6.0 t/ha, which is slightly less than that of full irrigation (6.2 t/ha), while water use efficiency improved significantly. This shows that moderate water stress, tactfully imposed, can be a double benefit as it helps to save water and at the same time does not violate the productivity rule.

Plants differ in how much they are affected by water stress, depending on their growth stages. Studies indicate that the vegetative stage and the maturation stage are more tolerant of a water deficit than the flowering stage and the grain-filling stage, which are very important in determining the yield. Thus, using deficit irrigation during the non-critical stages and providing full irrigation during the sensitive stages can lead to water use efficiency over the season.

In the context of the Chauru Irrigation Scheme, the 85% ETc treatment was a very efficient water-saving method that conserved water and, at the same time, gave high yields; thus, it was an ideal solution for regions that were affected by water shortage or had no proper infrastructure. Carrying out this plan necessitates recognition of the crop's phenology and, furthermore, having at least some basic irrigation scheduling aids, such as the growth calendar or soil moisture sensors, available. On condition that farmers get correct training and necessary assistance, they can embrace this method and thus both increase water productivity and be able to face drought or water shortage situations more easily.

In summary, deficit irrigation that is carried out during the period when the crop is not sensitive to stress is a very sustainable and practical choice for irrigating more efficiently in smallholder farming systems.

2) Rehabilitate and Maintain Distribution Infrastructure

Water use efficiency in irrigation schemes such as Chauru is profoundly influenced by the status of the water distribution network. Canals are in bad condition due to a lack of maintenance.

Broken division boxes and malfunctioning turnout structures contribute to water loss, and if the distribution is not equitable, farmers located at the head of the canal receive more water than they need, while those downstream face water shortages. This, in turn, creates uneven yields, inefficient irrigation, and disputes among users. Thus, it is imperative that physical infrastructure problems be solved so that both productivity and fairness may be improved within the scheme.

A proactive infrastructure rehabilitation and maintenance program must also have rescheduled inspections, desilting, repairs to gates and lining, and calibration of division and turnout structures. WUAs that are given the power to carry out such tasks are bound to feel local ownership and, consequently, sustainability. The use of simple flow measurement devices, such as Parshall flumes, can make the process of transparency and control easier. Experiences from similar schemes in East Africa have demonstrated that such interventions could increase water delivery efficiency by 40% at most. Reliable infrastructure is, ultimately, a core condition for the successful implementation of advanced irrigation strategies such as deficit irrigation and it should be at the top of the agenda to upgrade water management in the Chauru Scheme.

4.2.2. Recommendations for Future Research

To deepen sustainability and expand water-efficient irrigation methods in projects such as Chauru, upcoming research ought to focus on extensive, interdisciplinary, and long-duration studies. Firstly, the assessment of the long-term influence of deficit irrigation by means of multi-seasonal field experiments is of the utmost necessity. These experiments would confirm not only yield stability but also soil health, nutrient injection, and overall system resilience. Such data would guarantee that the initial water conservation does not result in soil quality loss or lower production over time.

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Conflict of Interest

The authors would like to state that they have no relevant conflicts of interest to report regarding this study.

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