Investigation into the Effects of Deficit Irrigation on Potato Production in Dedza District-Malawi

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Abstract:- Deficit irrigation strategies in furrow irrigation are important concerns to save irrigation water in areas of poor water management. This study was conducted to establish the strengths and weaknesses of the current irrigation practices in Dedza district, to evaluate the influence of two different types of deficit irrigation on yield strategies on yield, and to establish the profitability of potato production under AFI and FFI. The study was done in Dedza district in Malawi. Farmer plot size in irrigation schemes are limited to 0.22 ha of which 81% use gravity-fed canals to convey water with furrow as a dominant irrigation method due to its many advantages. The Certified potato variety "Violet" seeds were used as study material during the experiment which was laid out as a randomized complete block design. It involved three maximum allowable depletion (MAD) levels of 20, 40, and 60% in which furrow irrigation strategies of (i) conventional furrow irrigation (CFI), (ii) alternate furrow irrigation (AFI), and (iii) fixed furrow irrigation (FFI) were applied. AFI and FFI of a 20% depletion level were concluded to be relatively better in water saving because the crop yields were not significantly different from the control. A total number of 10, 6, and 5 irrigation events were scheduled for the whole season under 20%, 40%, and 60% depletion levels respectively. DI under 20% MAD level show that farmers can still make more than the average national gross margins. The economic water productivity value comes to roughly 4.20 US$/m3 (50% increase) or 3.70 US$/m3 (32% increase) obtained from the AFI and FFI plots respectively under the 20% MAD level. This research has shown that managing the crop under AFI of 20% MAD can allow the farmer to have yields above the national average and at the same time save water.

Keywords:- *Deficit Irrigation, Irrigated Potato Production, Water use Efficiency, Maximum Allowable Depletion, Alternate Furrow Irrigation, Fixed Furrow Irrigation.*

I. INTRODUCTION

Irrigation agriculture is one of the strategies towards increasing food production, hence ensuring food security. Irrigation is defined as the practice of supplying water that has been diverted from rivers or pumped from a well to the land in the provision of support for agricultural production. Irrigation agriculture is vital towards food production at times when rainfall is inadequate (Bakr and Bahnassy, 2018; Modi, 2019). Apart from growing crops more than once a year, irrigation can also help in widening the range of crops that can be grown within a season. However, the success of irrigation agriculture depends on water availability, how the available water is being managed and crops are grown. Currently, about 70% of water withdrawals in the world are a result of irrigation (Sillar, 2021) and with increased pressure to increase food production, the withdrawal is expected to increase. However, with climate change, water resources are dwindling presenting a huge challenge to irrigation agriculture. Irrigation acts as a 'mitigation cushion' against climate change and variability challenges, as it enables farmers to grow crops throughout the year and in so doing, increases the chances for farmers to produce more. Therefore, the desire to produce enough food to feed the population through irrigation agriculture under increasingly favorable environmental conditions has been the driving force to research on irrigation water use and management techniques.

Potato (*Solanum tuberosum L*) is increasingly becoming an important food and cash crop in Malawi (Tione, 2018) which is grown throughout the year. However, just like in many SSA countries, Malawi's irrigated agriculture is facing challenges of limited irrigation water supply owing to climate change, variability, and economic water scarcity (Nhemachena *et al*., 2020; Joshua *et al*., 2020; Sibale *et al*., 2021; Fandika *et al*., 2021). To improve irrigated potato production, water productivity, and land productivity in Malawi, there is a need to address these constraints through research. Therefore, this study aims to investigate the effects of deficit irrigation strategies on potato production under smallholder irrigation schemes available in Malawi.

Several factors such as insufficient rainfall, limited available irrigation water, and poor water management negatively affect potato production in Malawi. This has led to the loss of crop yield and reduced profitability among smallholder farmers. To improve yield, and irrigation water use efficiency, and to save the already dwindling water supply, methods such as drip and sprinkler irrigation are being advocated among smallholder farmers. However, farmers hardly adopt these methods due to their high cost, complexity, and difficult maintenance requirements.

There is a need to explore alternative irrigation strategies that fit well with small-scale farmers' irrigation practices. This is vital because despite having agricultural material resource centres in all the country's extension planning areas (EPAs), there is inadequate information on improved irrigation practices and water management in potato production. The lack of information is due to the fact that studies on potato production in Malawi are mostly focused on rain-fed agriculture with little attention to irrigated agricultural systems. Consequently, with the existing limited water supply conditions faced by many smallholder farmers in Malawi, there is a need to evaluate crop water use, potato yield and potato production profitability under deficit irrigation (DI) strategies as the alternatives.

DI is among the irrigation strategies that are used to save irrigation water and they have been investigated by several authors in terms of their effects on the crop water use efficiency, productivity and profitability of potato production. DI strategies can be used with all irrigation systems and as such, they can fit the Malawian smallholder farmers who dominantly depend on furrow irrigation. Contradictory results in the literature regarding the advantages and disadvantages of DI strategies have been observed. Most of the contradictions have been attributed to experimental implementation errors and in general, the advantages outweigh the disadvantages. The general agreement in the literature on the effects of DI strategies is that their success depends on potato variety, soil type, climate and soil water balance. The variation of these factors implies that for each region and country, there is a knowledge gap that needs to be bridged before the application of DI strategies. And the gap exists in Malawi since no study on DI has been found in the literature so far. Moreover, considering that most of the previous studies applied fixed irrigation intervals that did not consider the fact that crop water use varies with the growth stage, there is a need to investigate DI strategies where irrigation scheduling takes into account changes in crop evapotranspiration. Furthermore, the previous studies seem to imply that the benefits of saving water through the application of DI strategies directly accrue to individuals who can expand their irrigated fields. That may be true for cases where there is no major restriction on the size of the irrigated field. In cases where individuals have fixed land sizes, the benefits of saving water may be complex as individuals may not see the need to save water. Such complexities or realities should be added to the existing body of knowledge so that the correct message is used when talking about the benefits of DI strategies to the farmers.

➢ *Objectives*

The aim of the study is to investigate the effects of deficit irrigation on potato production in smallholder irrigation schemes in Dedza district, Malawi.

- *To guide the study and achieve its aim, three specific objectives were formulated as:*

✓ To establish strengths and weaknesses of the current irrigation practices in Dedza,

✓ To evaluate the influence of alternating deficit, fixed deficit, and conventional furrow irrigation strategies on yield, and

✓ To establish the profitability of potato production under alternating and fixed furrow irrigation in Malawi.

II. METHODOLOGY

The study was done in Dedza district in Malawi. To establish the strengths and weaknesses of the current irrigation practices in the district, the study used data gathered through a questionnaire survey and focus group discussions.

To evaluate the influence of alternating deficit, fixed deficit, and conventional furrow irrigation strategies on yield. A complete randomized block design plots were used where the three furrow irrigation strategies (CFI, AFI, and FFI) were applied for each of the selected MAD levels (20%, 40%, and 60%). Considering the fact that soil moisture values are particularly important for irrigation optimization and the health of a crop, data collection of soil characterization was done prior to the irrigation using the core method to determine the soil bulk density, soil texture and soil moisture content (FC and PWP). The weather data was collected daily from the nearest weather station within Dedza district. Using Class A Pan, the reference evapotranspiration data was corrected and this was used to decide when to irrigate.

The volume of water coming into the field through the calibrated siphon was estimated from the product of the calibrated flow rate of water passing through the siphon during irrigation and the total time taken to finish irrigation. A soil water balance sheet procedure was used to determine the soil moisture content daily during the growth of potatoes and scheduling of irrigation events. Irrigation days were scheduled based on the set different blocks of MAD (20, 40, and 60%). During the experimental potato crop growing season, developmental changes were recorded to establish the main growth stages, from sprouting to senescence. At the end of the experiment, the weight of tubers per plant, marketable yield, and tuber yield of each plot were weighed in kilograms. The least significant difference (LSD) test was used to distinguish between the means of treatment at a 5 percent probability. The ratio of tuber yield and volume of water used for the potato- growing period was used to determine the CWUE.

The final objective of the study was to establish the profitability of potato production under AFI and FFI. It involved doing the gross margin analysis and the determination of the economic water productivity. Gross margins were calculated per unit area where a financial difference between the returns received from assumed sales of potatoes and the variable costs associated with production were calculated. The total revenue was calculated from the product of the physical production and it market value according to Malawi government farm gate price circular during the growing season. The economic water productivity index ($/m3) was calculated as the overall present value of potato divided by the volume of water (m3) consumed by the plant.

III. RESULTS AND DISCUSSION

A. *Strengths and Weaknesses of the Current Irrigation Practices*

- *Descriptive Statistics*

The irrigation practices are considered in terms of land ownership, water lifting/delivery methods and irrigation methods. Based on the information from the focus group discussions, the participants can be regarded as typical of the rural population of Dedza district comprising smallholder farmers. The age range of the smallholder farmers is 39 to 49 years of which 59.1 % are females (Figure 1). Almost all the farmers have an average piece of farmland of 0.22 hectares on which they grow irrigated potatoes. The land is owned through inheritance (11.3%), renting (52.4%) or both inheritance and renting (36.3%). In Dedza, kinship is matrilineal, as such, land is inherited through the women (Fischer *et al*., 2021).

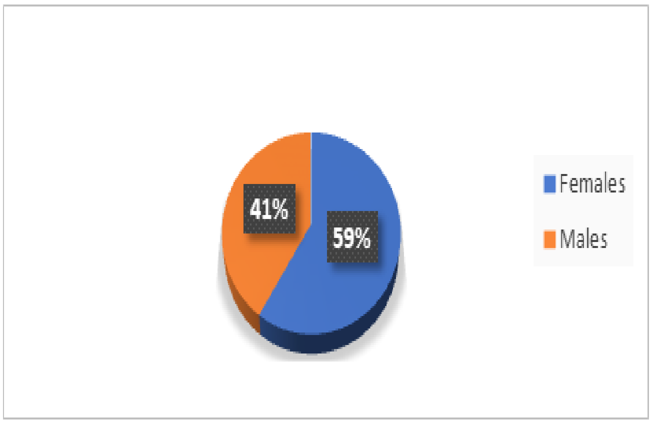

Fig 1 Gender of Participants

The study also established that farmers in Dedza use the furrow irrigation method, basin method and water cans /buckets. The methods used for water lifting and delivery to the irrigated fields are river diversion into gravity-fed canals, watering cans/buckets, treadle pumps, motorized pumps, and solar pumps (Figure 2). The figure shows that the majority of the respondents (80.5%) use gravity-fed canals when irrigating the potato crop. Similar results were also found in other studies in Malawi (Getts, 2018; Frake, 2019; Frake *et al*., 2020). According to the results from the data analyses, almost all the farmers using gravity-fed canals irrigate their fields at least three times a week using furrow irrigation.

The least number of respondents (2%) indicated that they either use motorized or solar pumps. The adoption rates of these improved irrigation technologies are critically low among the smallholder farmers in the study area. This trend is similar to the one among Iranian smallholder farmers as reported in Yazdanpanah *et al*. (2022).

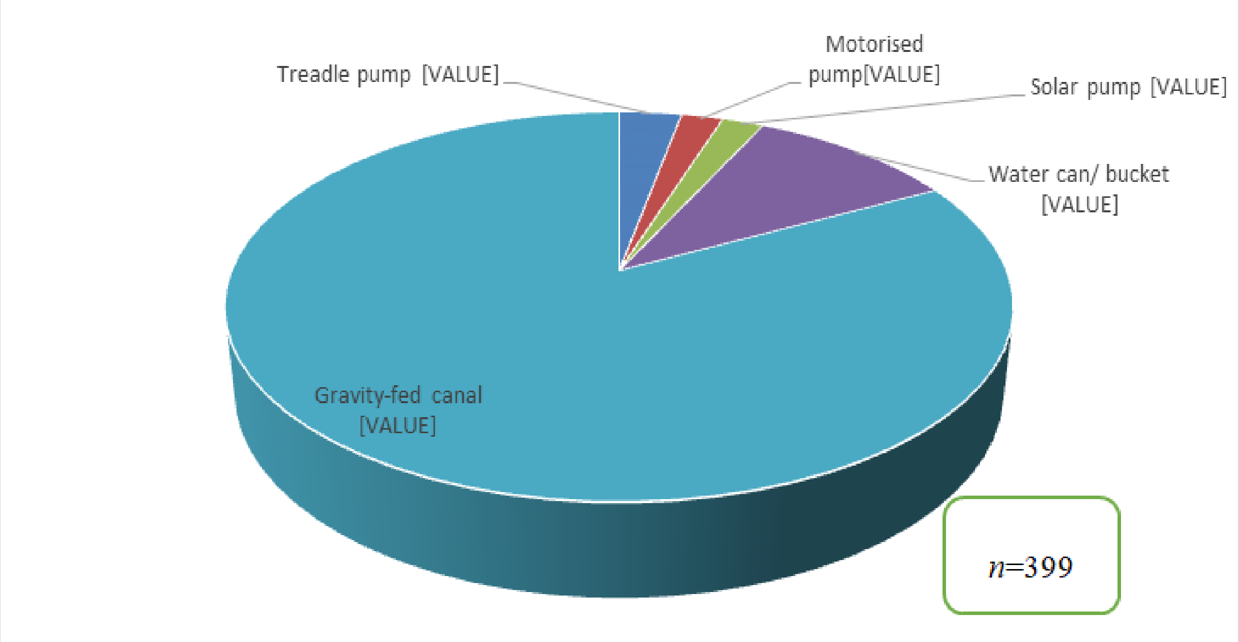

Fig 2 The Current Irrigation Water Lifting and Delivery Method in Dedza District

The current irrigation water delivery methods have their strengths and weaknesses which were established and highlighted in the study.

- *Strengths and Weaknesses of Gravity-Fed Canal Irrigation Water Delivery Method*

Gravity-fed canal irrigation water delivery method is when water flows by gravity from the source to the field. Results from the survey show that irrigation schemes that use gravity have lower operating costs for the conveyance system and they are ease to manage. These were also noted in Aschemann *et al.* (2019), and (Fandika *et al.*, 2020). The canals in the schemes are built using readily accessible and inexpensive materials. They are constructed using earth, except for the main canal. The problem with the earth lined canals is that they need maintenance soon after every irrigation event.

Almost all the small-scale irrigation schemes in the study area use short furrows. Onishi *et al.* (2019) established that using short furrows in irrigation schemes results in uniform water distribution across the field, enabling greater control of water levels. According to Onishi *et al.* (2019), shortening furrow length might be an effective way to save water. The short furrow may have the disadvantage of losing a lot of land to numerous furrow column spacings. This makes furrows that are as long as the field length better as they result in maximising land utilization (Abraham, 2019).

Despite the fact that the study area is hilly, almost all the fields in the irrigation schemes used for data collection are irrigated without extensive levelling or grading. The little levelling that is implemented is done manually using hoes which are also used to make furrows. This is due to the lack of earth moving equipment. Manually, it is difficult for the farmers to ensure uniform slopes. Generally, all the in-field farming activities in the irrigation schemes rely on human labour, making it difficult for one farmer to cultivate a large plot because the it is labour intensive and time-consuming. However, despite these disadvantages, the participants have continued with human labour based farming activities because they are relatively cheap. The present results agree with the works of Sable *et al.* (2019) who reported that furrow irrigation requires less initial capital cost than other irrigation systems.

The results also show that farmers practicing furrow irrigation method requires little technical knowledge. The method has proven to be convenient amongst farmers in the Dedza because there is a lack of a highly skilled labour force in the district.

- *Strengths and Weaknesses of Watering can/Bucket Irrigation Water Delivery Method*

Irrigation by watering cans/buckets is a very basic way that is still widely used in Dedza and other parts of Malawi. Through feedback from the respondents, it was established that the method is practiced both in peri-urban homestead agriculture plots, backyard gardens and rural agriculture for growing vegetables.

The watering can/bucket method serves many purposes. It serves as a way of lifting, conveyance and applying irrigation water. It is also practiced by some small-scale farmers in other countries such as Ghana and Zimbabwe (Scoones *et al.*, 2019; Baldwin and Stwalley III, 2022). The use of watering cans/buckets was shown to enable irrigation of specific locations and only where it is necessary. The method proved to be easy to handle and requires no technical equipment. It is therefore generally cheap in contrast to advanced irrigation water delivery methods. However, results from the study show that the water delivery method creates a lot of work for the farmer especially if it is used on larger plots. This makes the method inefficient and labour-intensive and less desirable (Baldwin and Stwalley III 2022).

➢ *Strengths and Weaknesses of the Treadle, Motorized, and Solar Pump for Irrigation Water Lifting*

According to the current findings, 3% of the farmers are using treadle pumps, and 2% of the farmers are using either motorized or solar pumps. Irrigation using different solar pumping techniques is very environmentally friendly as compared to the use of a motorized pump. However, both motorized and solar pumps proved to be labour-saving as compared to the use of treadle pumps. The findings are in agreement with the observations made by Passarelli *et al.* (2018) in Ethiopia and Tanzania.

Although these pumps (motorized and solar) have been proven to be efficient based on the few adopters in the study area, it was observed that most of the farmers cannot afford them. A similar situation was observed in Ghana by Baldwin and Stwalley III, (2022). Based on the focus group discussions, it was established that most of the pumps that are generally on sale are of sub-standard quality. Poor quality pumps break down quickly and are rapidly scrapped as noted by Baldwin and Stwalley III (2020). The challenge is that the farmers have no opportunity to buy good quality pumps on their own from sources. This absence of the independence of farmers to procure irrigation pumps on their own makes irrigation based on these pumps unsustainable in Malawi as observed by Chiwasa and Kambewa (2018).

B. *Environmental Factors Affecting Irrigation*

➢ *Soil Characteristics*

The soil BD of the experimental area ranges from 1.25g/cm^3 to 1.66g/cm^3 with a mean value of 1.40g/cm^3. This BD is within the range for soils that are good for growing crops according to Patle *et al.* (2019) and Abdelbaki (2016) who reported that the bulk density from 0.8 to 1.43g/cm^3 satisfied the conditions for holding an adequate amount of water and is beneficial for plant root growth. The soil MC at FC varies from 15.6% to 20.7% on mass basis with a mean value of 19.3%. On the other hand, the MC at WP ranges from 4.4% to 7.9% with a mean WP of 6.4%. The relative percentage of sand, silt, and clay spread out from 56 to 80, 18 to 36, and 1 to 8 respectively (Table 1). The table shows that the percentage mean value of sand, silt, and clay is 71.8%, 23.7%, and 4.5%, respectively. Therefore, according to the textural triangle presented by Moreno-Maroto and Alonso-Azcárate (2022), the experimental site has sandy loam soil with a water-holding capacity of 19.3%.

Table 1 Descriptive Statistics of Measured Soil Properties

Soil properties	**Max**	**Min**	**Mean**	**SD**	**CV**
Sand(%)	80	56	71.8	1.3	0.02
Silt (%)	36	18	23.7	2.9	0.12
Clay (%)	8	1	4.5	0.6	0.13
BD (g/cm^3)	1.66	1.25	1.40	0.1	0.07
PD (g/cm^3)	2.77	2.48	2.67	0.1	0.04
FC (%)	20.7	15.6	19.3	1.4	0.07
WP (%)	7.9	4.4	6.4	1.0	0.16

➢ *Weather Condition*

During the field experiments implementation period, the precipitation water was not adequate. There were only three rainfall events (Figure 3). The reference evapotranspiration (ET_0) value of the site ranged between 0.1 mm/day in June (on the 4th and 26th day from planting) to 3.6 mm/day in August (on the 78th and 104th day from planting). The average ET_0 between the 26th day (when the application of strategies started) to the 113th day from planting was 1.9 mm/day (Table 2). The increasing trend in ET_0 towards senescence was mainly caused by an increase in air temperature during the study period. The crop water use in all three irrigation regimes increases as the crop advances during the growing period (Figure 3).

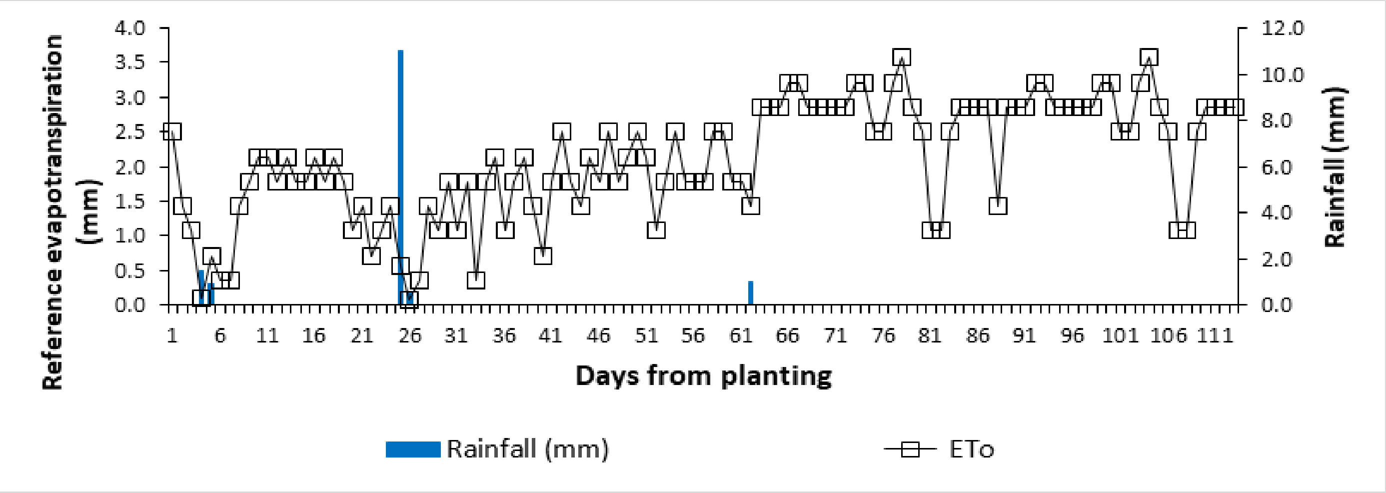

Fig 3 Precipitation Against Reference Evapotranspiration

Table 2 Monthly Average Climatic Data of the Experimental Area During the Cropping Season

DFP	Month	T_{min}° c	T_{max}°c	RH%	Pe $_{mm}$	$ET_{o\ mm/day}$	$ET_{c\ mm/day}$
1-26	May	11.3	22.8	79	13.4	1.4	0.7
27-54	Jun	9.5	21.9	75	0.6	1.6	0.7
55-85	July	9.9	21.6	72	1.0	2.5	2.0
86-113	Aug	10.7	23.8	70	0.0	2.7	3.3
	Mean	10.3	22.6	74		2.3	2
	SD	0.81	1.0	3.9		1.23	1.5
	CV%	0.08	0.04	0.05		0.53	0.8

C. Effects of Deficit Furrow Irrigation as Compared to Conventional Furrow Irrigation Methods

- *Irrigation Water Supply*

Water is a major factor in the successful production of crops. Crops require an adequate supply of moisture for optimum growth. The amount of water that should be supplied to provide the needed soil moisture is affected by the area to be watered, crops grown, weather conditions, time of year, and the environmental factors (solar radiation, wind and relative humidity).

The analysis of variance indicated that the irrigation water supplied for growing potatoes was significantly influenced by the irrigation regimes as well as the irrigation strategies as illustrated in (Table 3). The tables shows that the highest volume of water was supplied in the control (20%MAD-CFI) set-up. This was because under the control, no water-saving strategies were applied. This high irrigation water application is very common in Malawi agriculture. It calls for initiatives to increase the effective use of available water resources to avoid low WUE. The table further shows that the amount of water applied under 40% MAD AFI was half the amount of water applied under 20% MAD CFI. Similar results were presented by Kassaye *et al.* (2020) of Ethiopia whose results revealed that seasonal irrigation water applied in alternate furrows was nearly half of the amount supplied in CFI.

Table 3 Effect of deficit irrigation on the number of scheduled irrigations and volume of irrigation water applied

Treatment	Number of irrigations	Irrigation water applied (m^3/ha)	Water saved (%)
20% MAD-CFI	10	3874.57a	0
20% MAD-AFI	10	2534.17b	35
20% MAD-FFI	10	2648.37b	32
40% MAD-CFI	6	1866.45c	52
40% MAD-AFI	6	1704.91cd	56
40% MAD-FFI	6	1600.28cd	59
60% MAD-CFI	5	1612.79cd	58
60% MAD-AFI	5	1178.18d	70
60% MAD-FFI	5	1381.37cd	64

NB: Mean values within the same columns but with different letters (a-d) are significantly different at the level of 5% ($P \leq 0.05$) within treatments. Values are the mean of three replications of each treatment.

- *Irrigation Scheduling*

- *Irrigation Scheduling Under A 20% MAD*

Irrigation scheduling is an important consideration in cases where water resources seem to be limited with regard to agricultural production. It is an important element in improving water use efficiency. According to the results obtained, the total number of scheduled irrigation events summed up to 10. There were significant differences in the irrigation frequencies (the number of days in between one irrigation event and the next). This was mainly due to the variations in ETc with respect to the weather conditions and the stage of crop development. The conventional, alternate and fixed furrow irrigated plots received almost the same volume of water during the first scheduled irrigation on 13/05/2022 (Figure 4). The volume of water used slightly increased during the second, third, and fourth irrigation events. In general, during the implementation of the scheduled irrigation, the volume of water used in CFI seemed to surpass that of the AFI and FFI plots. This shows that AFI and FFI are water-saving strategies as stated among others in Yactayo *et al.* (2013), and Qin *et al.* (2018). Consequently, deficit irrigation strategies practiced with higher MAD levels beyond 20% could be the best management practice for irrigation to enhance water use efficiency, improve crop quality, and protect water quality.

Figure 4 shows that in July, between the fifth and seventh scheduled irrigation, the actual water supplied was lower than the first scheduled irrigation by about half. Since during irrigation, the furrow inflow was cut off immediately after the waterfront reached the end of the furrow, it implies that during these irrigation events, the advance of the waterfront was faster. This can be attributed to the reduced rate of infiltration. However, the cause of this reduction could not be investigated because it was not anticipated and it was only noticed during data analysis. Moreover, Figure 4 shows that water applied towards the end of the crop growing period is generally slightly less than the application in the beginning. This could be due to the effects of silting of the furrows as more and more silt is deposited by the irrigation water. The silt is picked as the inflow is introduced in the furrow and when it is cut off.

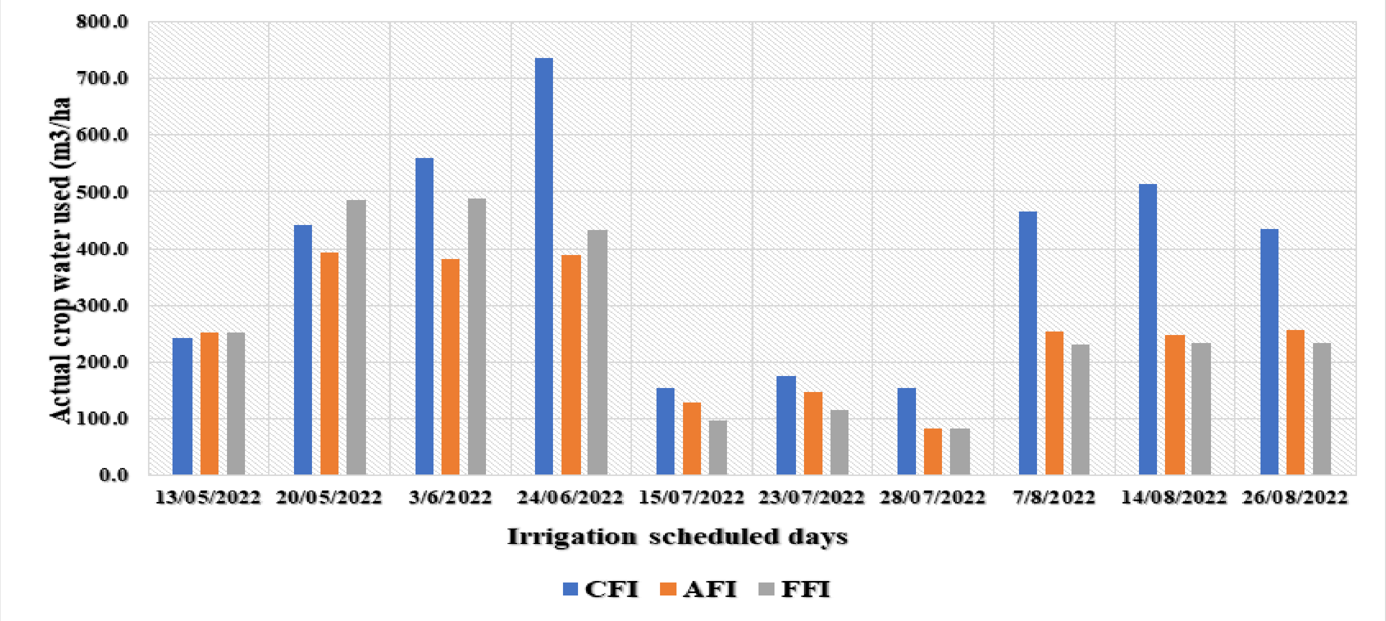

Fig 4 Irrigation Water Distribution within the Irrigation Regime with A 20% Depletion Level

- *Irrigation Scheduling Under A 40% MAD*

In the irrigation regime with a 40% depletion level, the total number of scheduled irrigation events was reduced to 6 with a significant difference in the total number of days before the next irrigation. The volume of water used slightly decreased during the second, fourth, and sixth irrigation events (Figure 6). While the reduction in the applied volume for the second irrigation could be a random event, the 4th and the 5th scheduled irrigation events are within the period when a similar reduction in the applied irrigation water was observed in plots under a 20% depletion level (Figure 4). Figure 5 reflects the actual appearances of the crop at different stages during the application of deficit irrigation.

Statistically, there is a significant difference between the volumes of water used in plots under deficit irrigation and that of CFI. However, the results also show that the volume of water in AFI is almost the same as the volume of water used in FFI.

(a) Crop stand in June

(b) Crop stand in July

(c) Crop stand in August

(d) Tubers in September

Fig 5 Crop Stand Corresponding to an Irrigation Event in Plots with MAD of 40%

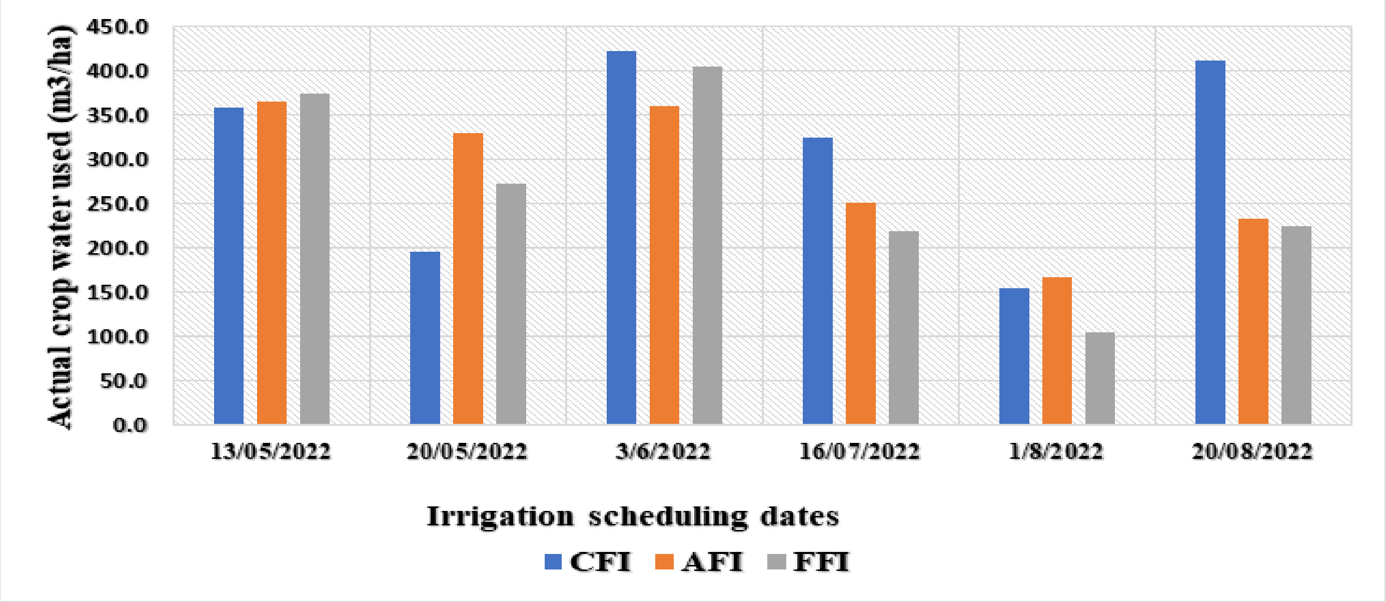

Fig 6 Irrigation Water Distribution within the Irrigation Regime with A 40% Depletion Level

- *Irrigation Scheduling Under A 60% MAD*

The total number of scheduled irrigations was found to be 5 with a significant difference in the number of days in between before the next irrigation. The CFI, AFI and FFI plots received almost the same volume of water during the first and fourth scheduled irrigation. The volume of water applied slightly decreased during the second, third, and fourth schedules of irrigation events. In the fourth scheduled irrigation event, the applied water was lower than the other scheduled irrigation by half because the ponding in the furrows was very quick.

The reason for this is as explained in section 4.4.2.2 since it is within the same period the reduction in the applied irrigation was observed in Figure 4. During the last scheduled irrigation event, the volume of water used in CFI plots was double the volume of water used in AFI and FFI plots (Figure 6). This could suggest that the large duration between the last two irrigation events made the soil very dry and as a result, all the furrows demanded equal amounts of water. But since for the CFI, all furrows are irrigated while for the AFI and FFI half the number of furrows is irrigated during each event, the water applied for the CFI is likely to be twice that of the later strategies. Statistically, there was no significant difference between the total volumes of water irrigated in plots under deficit irrigation and that of CFI.

(a) Crop stand in June

(b) Crop stand in July

(c) Crop stand in August

Fig 6 Crop Stand According to the Date of an Irrigation Event

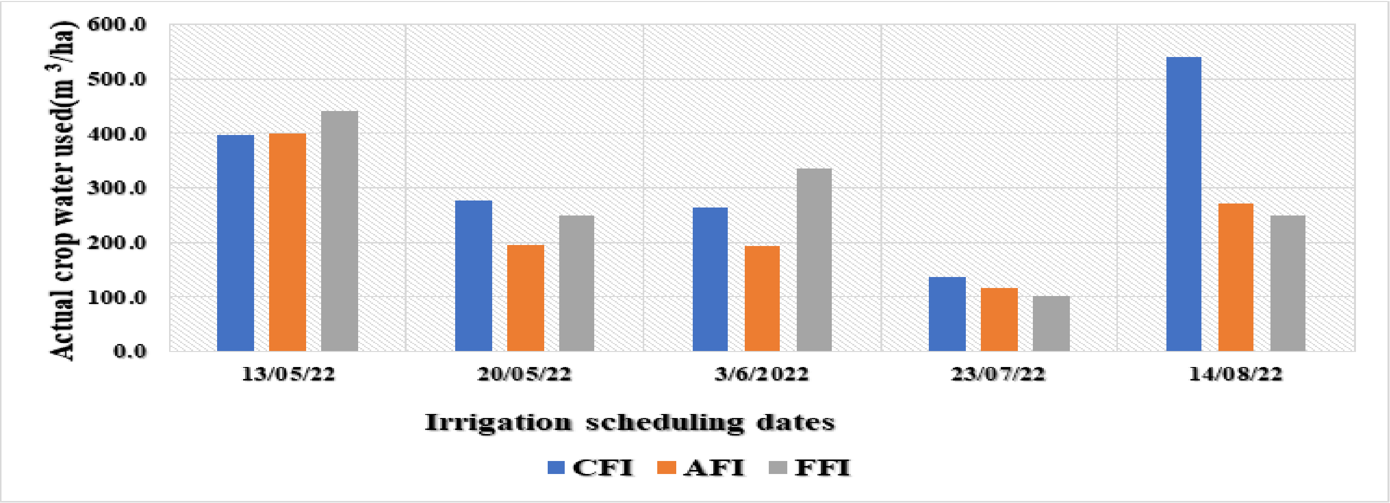

Fig 7 Irrigation Water Distribution within the Irrigation Regime with A 60% Depletion Level

At the end of the growing season, it was noted that all the plots that were subjected to high MAD levels were irrigated with lower amounts of water that were almost half the volume of water applied for the 20% MAD Figure 8. This could have been due to the increased irrigation frequency durations associated with high MAD levels. Moreover, Figure 7 also shows that the same MAD level, CFI used more water than AFI and FFI strategies.

These results show that irrigation water can be save by increasing the MAD levels and by using either AFI and FFI. These water savings give an advantage of irrigating more land with less amount of water in areas where the supply of water is limited (Kassaye *et al*., 2020). As explained in Sarker et al. (2020). The water saving in AFI and FFI strategies due to the reduction of areas of the wetted surfaces leading to less evapotranspiration.

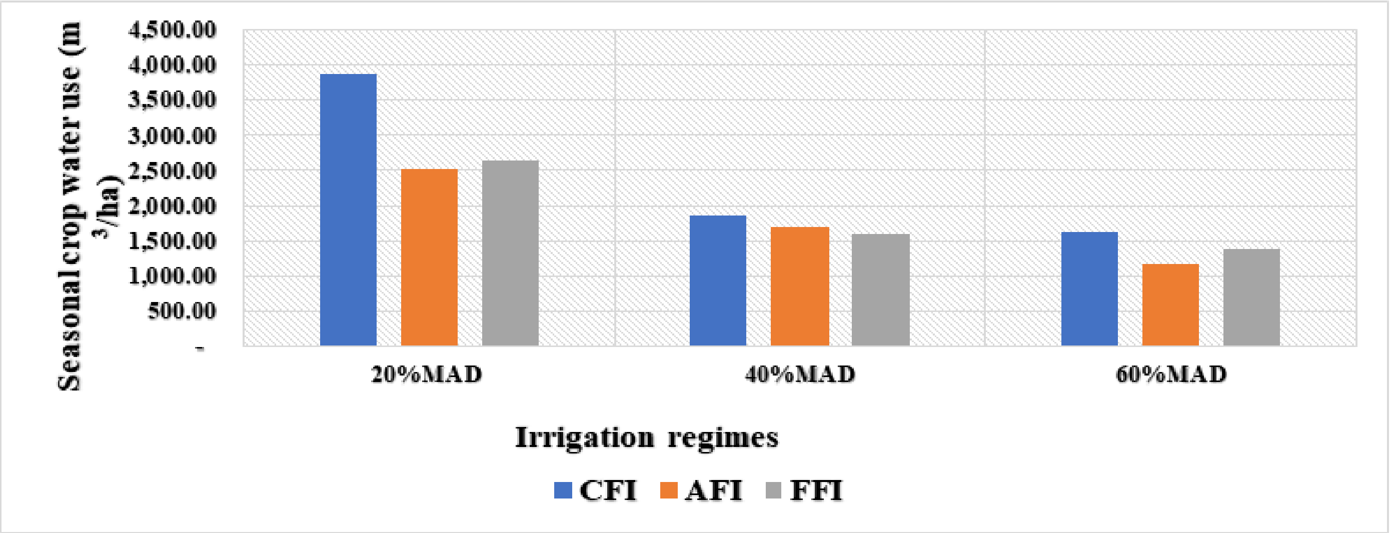

Fig 8 Seasonal Irrigation Water Distribution in All Three Different Irrigation Regimes

The ratio of actual saved water in plots under AFI and FFI with reference to the control (CFI 20% MAD) was calculated by using the following:

$$y = \frac{3875.57 - x_n}{3875.57} * 100 \qquad 1$$

Where: Y is the amount of irrigation water saved expressed as a percentage, 3875.57m^3/ha is the seasonal water used in the control field of 20% MAD-CFI, x is the actual amount of water used per plot under different MAD levels, and n is the number of the plot within the MAD.

Based on Equation 1, the potato producer (smallholder farmer) will be able to save water in the range of 35-70% representing 1,341-2697m^3/ha when the farmer opts to use AFI or FFI strategy. According to Tejero *et al*. (2011), and Liu *et al*. (2022), on average the water saving for sustainable deficit irrigation is roughly between 750-1500m^3/ha. With the maximum water saved in the current results, the water user is able to expand the area of production by 0.7 hectares if grown by the same crop (Table 4.4). However, in the case of Dedza, the saved water would result in the increase of farmers under irrigation. Hence the benefits from the water saved directly accrue to the community by playing a role in poverty reduction through the increased number of farmers under the irrigation scheme and not to an individual farmer.

Table 4 New Area (Ha) of Production from the Saved Water due to Deficit Irrigation

S NO.	Saved water (%)	Actual saved water(m^3/ha)	Equivalent area (ha)
1.	0	-	
2.	35	1,341	0.3
3.	32	1,227	0.3
4.	52	2,009	0.5
5.	56	2,170	0.6
6.	59	2,275	0.6
7.	58	2,264	0.6
8.	70	2,697	0.7
9.	64	2,494	0.6

➢ *Potato Growth Factors*

- *Plant Height*

Plant height is a good indicator for determining stress. It changes at different levels of water deficiency (Bhattacharya, 2021). The results show that plant heights are significantly different ($p \leq 0.001$) within the irrigation regimes. FFI strategy across the different regimes show no significant effect on plant height ($P \leq 0.05$) (Table 5). The plant heights under the CFI strategy with a 40% depletion level, were similar to those of the FFI strategy in all three different regimes and the AFI strategy under 20% MAD. On the other hand, the deficit irrigation strategies (AFI, and FFI) indicate no significant difference from each other in plant height at ($P \leq 0.05$). Plant heights in CFI of 20% maximum depletion level were greater than plant heights recorded in treatments that were replenished when depletion levels were at 40% and 60%.

Table 5 Effects of Deficit Irrigation Strategies and Irrigation Regimes on Plant Height

Maximum allowable depletion level			
Plant heights(cm)			
Irrigation strategy	20% depletion	40% depletion	60% depletion
CFI	38.40a	31.76ab	27.66b
AFI	33.96ab	29.96b	28.96b
FFI	32.30ab	31.40ab	31.90ab

NB: Mean values within the same columns by different letters (a–d) are significantly differe1nt at the level of 5% ($P \leq 0.05$) within treatments. Values are the mean of three replications of each treatment.

The present results show that with increasing soil water supply and less plant moisture-based stress, plant heights were significantly increased (Table 5). This was also reported in Piao *et al.* (2019) and has the implication that deficit irrigation shortens plant height as reported in A *et al.* (2020); Parkash *et al.* (2021) and El-Mageed *et al.* (2022). Moreover, Ostadi *et al.* (2022) and Hazrati *et al.*, (2022) reported that the plant height of Sage (*Salvia Officinalis*) decreased with increased MAD and vice versa. Wang *et al.* (2019) indicated that plant height had a linear correlation with the availability of soil moisture.

- *Number of Stems*

Agronomic attributes such as the number of stems are a causal factor of the potato tuber yield in watertight environments and they are useful indicators in the assessment of drought tolerance (Mthembu *et al.*, 2022). There was no significant difference at the level of 5% ($P \leq 0.05$) within the irrigation strategies (CFI, AFI, and FFI), MAD levels, and the interactions between the strategies and depletion levels (Table 6). A far higher number of stems was recorded in the CFI plots under an irrigation regime of 20% depletion level followed by 40% and 60% irrigation levels respectively. According to Amanturdiyev (2022), the demand for water in the care of crops in agriculture is determined by the irrigation regime (MAD level), climatic conditions (Table 1), and soil type (Table 2) among others. A significantly greater number of stems was recorded in AFI under an irrigation regime of 40% depletion level followed by 20% and 60% irrigation depletion levels. In FFI, a much greater number of stems was recorded in the plots under an irrigation regime of 40% depletion level followed by 60% and 20% irrigation level respectively. Thus, there is no significant difference between CFI, AFI, or FFI across the irrigation regimes.

Table 6 Effects of Deficit Irrigation Strategies and Irrigation Regimes on the Number of Stems

Maximum allowable depletion level			
Irrigation strategy	20% depletion	40% depletion	60% depletion
CFI	1.83a	1.50a	1.46a
AFI	1.56a	1.73a	1.33a
FFI	1.43a	1.66a	1.46a

According to the findings of Barakat *et al*. (2020) in Egypt, potato plants grown under moderate and severe deficit irrigation were negatively affected by having more stems than unstressed plants. From this claim it is possible to conclude that plants under AFI of 40% MAD were as stressed as the plants in FFI of the same MAD. Similar observations were made by Elhani *et al*. (2019) and El Bergui *et al*. (2020) in Morocco who stated that plants grown under deficit irrigation have more stems that are short. Actually, few plants mean less overcrowding which give plant enough room to produce large tubers.

- *Number of Tubers*

The findings show that the number of tubers per plant is significant at the level of 1% (P≤0.01) within the irrigation regimes. On the contrary, the number of tubers per plant show no significant difference between the irrigation strategies. There is also no significant difference of the interactions existing between the MAD and the irrigation strategies. A relatively greater number of tubers per plant was noted in CFI plots under an irrigation regime of a 20% depletion level followed by 40% or 60% MAD levels with the same number of tubers (Figure 9). In AFI, a greater number of tubers per plant was recorded in the plots under an irrigation regime of 20% depletion level followed by a 60% and 40% irrigation depletion level respectively. A significantly greater number of tubers per plant was collected in FFI under an irrigation regime of a 20% depletion level followed by a 40% and 60% irrigation depletion level. Thus, the number of tubers decreases with an increase in MAD level. These results show that from the yield perspective, there is no increase in benefits in stressing the crop in terms of increasing MAD levels together with the application of irrigation strategies (AFI and FFI).

The findings further show that there is a significant difference (P ≤ 0.01) in the number of tubers per unit area within the irrigation regimes. The results also show no significant difference within the irrigation strategies. This implies that the MAD plays a major role in the number of tubers per unit area. These results agree with those found in Turkey by Gultekin and Ertek, (2018). Similar observations were made at Cambridge by Huntenburg *et al*. (2021) who reported that tuber development seemed to respond to systematic moisture stress signals rather than local soil conditions.

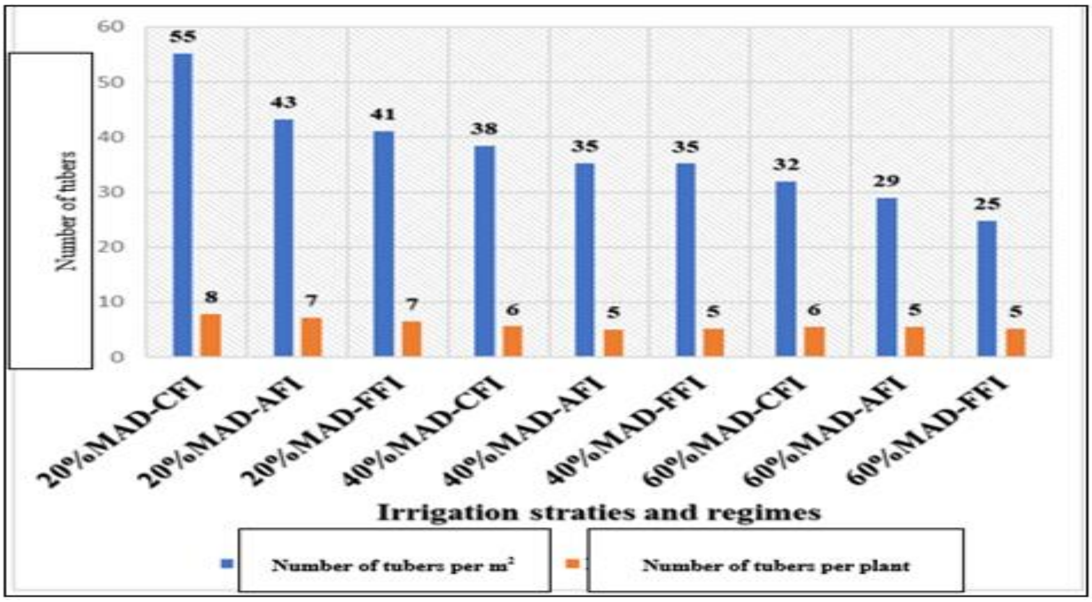

Fig 9 Effects of CFI, AFI, and FFI on the Number of Potato Tubers

- *Tuber Length*

The statistical results show that tuber length is significantly different (P≤0.001) across the irrigation regimes as well as the irrigation strategies. On the other hand, there is a significant difference in tuber length at the level of 5% (P ≤ 0.05) as a result of the interactions between the irrigation regimes and irrigation strategies (Table 7). Thus, the tuber length in FFI of 20% irrigation depletion level show similarities with results found in FFI under 40% irrigation depletion level and AFI under 60% irrigation depletion level. The tuber length in CFI under 60% irrigation depletion level show no significant difference with results found in FFI of the same regime. The tuber length recorded in CFI under individual irrigation regimes is relatively higher than those of AFI and FFI. Based on these results, the tuber length decreases as the depletion level increases. Thus, the length of tubers observed in CFI is not different from AFI of a 20% depletion level.

Table 7 Effects of Deficit Strategies and Allowable Depletion Levels on the Length of Tubers

	Maximum allowable depletion level		
Irrigation strategy	20% depletion	40% depletion	60% depletion
CFI	8.73a	6.36bc	4.16d
AFI	7.30ab	5.20bcd	4.63cd
FFI	5.00cd	4.73cd	3.36d

- *Tuber Diameter*

The findings show that the tuber diameter is significantly different (P≤0.001) across the irrigation regimes. Furthermore, the results show that tuber diameter is significantly different at the level of 5% (P≤0.05) in all the irrigation strategies (Table 8). The tuber diameter recorded in CFI of individual irrigation regimes is relatively greater than that of AFI and FFI. The tuber diameter observed in plots with AFI of 40% and 60% irrigation depletion level turns out to be similar to the results collected in plots that had FFI of 40% and 60% irrigation depletion level. In addition, there is no significant difference between CFI under a 60% irrigation depletion level and that of AFI and FFI which is under a 40% irrigation depletion level. These results suggest that tuber diameter is negatively affected by both the MAD level as well as the application of water-saving strategies.

Table 8 Effects of Deficit Irrigation Strategies on Tuber Diameter

Maximum allowable depletion level			
Tuber diameter(cm)			
Irrigation strategy	20% depletion	40% depletion	60% depletion
CFI	4.16a	2.96bcd	2.30cd
AFI	3.83ab	2.66cd	2.13d
FFI	3.33abc	2.23cd	2.03d

- *Potato Yield*

The statistical results show that the yield exhibits high significant difference (P≤0.001) across the individual irrigation regimes. The magnitude of yield reduction increased with increasing water deficit. On the other hand, the yields in plots with different furrow irrigation strategies show no significant difference. Statistically, there is no significant difference in yields for the interactions between irrigation strategies and irrigation regimes.

It was also observed that more irrigation water was saved as the depletion levels increased with a decrease in yield (Table 9). With respect to the CFI control plots under the 20% depletion, the highest and lowest amount of water saved was observed in FFI under the 20% soil water depletion level and AFI under the 60% soil water depletion level. Furthermore, the results show a minimum of 6% and a maximum of 49% yield reduction in AFI under the 20% soil-water depletion level and FFI under the 60% soil-water depletion level respectively. Despite saving more water in plots under 60% MAD, there is a problem of significant yield decrease due to water stress which was a result of the fewer number of irrigations. Potato plant sensitivity to water stress leads to a decrease in yield (Jefferies, 1993; Stark *et al*., 2013; Ariza *et al*., 2020; Hill *et al*., 2021).

AFI and FFI under 20% depletion level show improved yields which if adopted can improve farmers' income and food security. Thus, the yields realized under AFI and FFI under 20% MAD from this study surpass the current national average potato yield which is 18.4mt/ha (Placide *et al*., 2019). The current results agreed with research done in Tunisia by Ghazouani *et al.* (2019) which concluded that crop yield was affected by either the total amount of irrigation water supplied or the MAD as reflected in Table 9.

With all the factors constant, the amount saved will be enough to produce ≈ 13 tons of potatoes. This tonnage can contribute towards achieving the aim of the government policy of increasing production to meet domestic demand.

Table 9 Effects of Deficit Irrigation Strategies on Potato Yields

Treatment	**Yield (t/ha)**	**Water use (m^3/ha)**	**Water saved (%)**	**Yield reduction (%)**
20%MADCFI	22.68a	3874.57a	0	0
20%MADAFI	21.30ab	2534.17b	35	6
20%MAD-FFI	19.59abc	2648.37b	32	14
40%MADCFI	17.03abcd	1866.45c	52	25
40%MADAFI	15.69bcd	1704.91cd	56	31
40%MADFFI	15.01cd	1600.28cd	59	34
60%MADCFI	13.28d	1612.79cd	58	41
60%MADAFI	12.91d	1178.18d	70	43
60%MADFFI	11.51d	1381.37cd	64	49

D. Profitability of Potato Production Under AFI And FFI

- *Economic Water Productivity*

The recent local average market price for potato tuber was taken as 500,000.00 Malawi kwacha per ton (500 US$/ton). This gave a maximum TR of 10,850 US$ and a minimum of 5,750 US$ for the control plot under 20% MAD and FFI under 60% MAD respectively (Table 10). However, the TR for the CFI under 20% MAD has a smaller difference from the TR for the AFI under the same MAD.

Table 10 Harvested Potato Value based on Local Average Market Price

Treatments	Yield (t/ha)	Revenue (US $/ha)
20% MAD-CFI	21.7	10850
20% MAD-AFI	21.3	10650
20% MAD-FFI	19.6	9800
40%MAD-CFI	17.1	8550
40%MAD-AFI	15.7	7850
40%MAD-FFI	15.0	7500
60%MAD-CFI	13.3	6650
60%MAD-AFI	12.9	6450
60%MAD-FFI	11.5	5750

The ratio of the TR and seasonal water use per hectare gives the picture of economic water productivity (EWP). The highest EWP value was found to be 5.47 US$/m^3 (Figure 9). This gives a 95% increase with respect to the control. This EWP was obtained for the AFI strategy under the 60% depletion level. The control shows the lowest EWP value of 2.80 US$/m^3 (Figure 10). From the results, it is possible to deduce that a highest water profit can be gained per m^3 of irrigation water applied to the field from the AFI with the 60% depletion level. However, if potato yields above the national average (18.4mt/ha) are considered, the economic water productivity value comes to roughly 4.20 US$/m^3 (50% increase) or 3.70 US$/m^3 (32% increase) obtained from the AFI and FFI plots respectively under the 20% MAD regime.

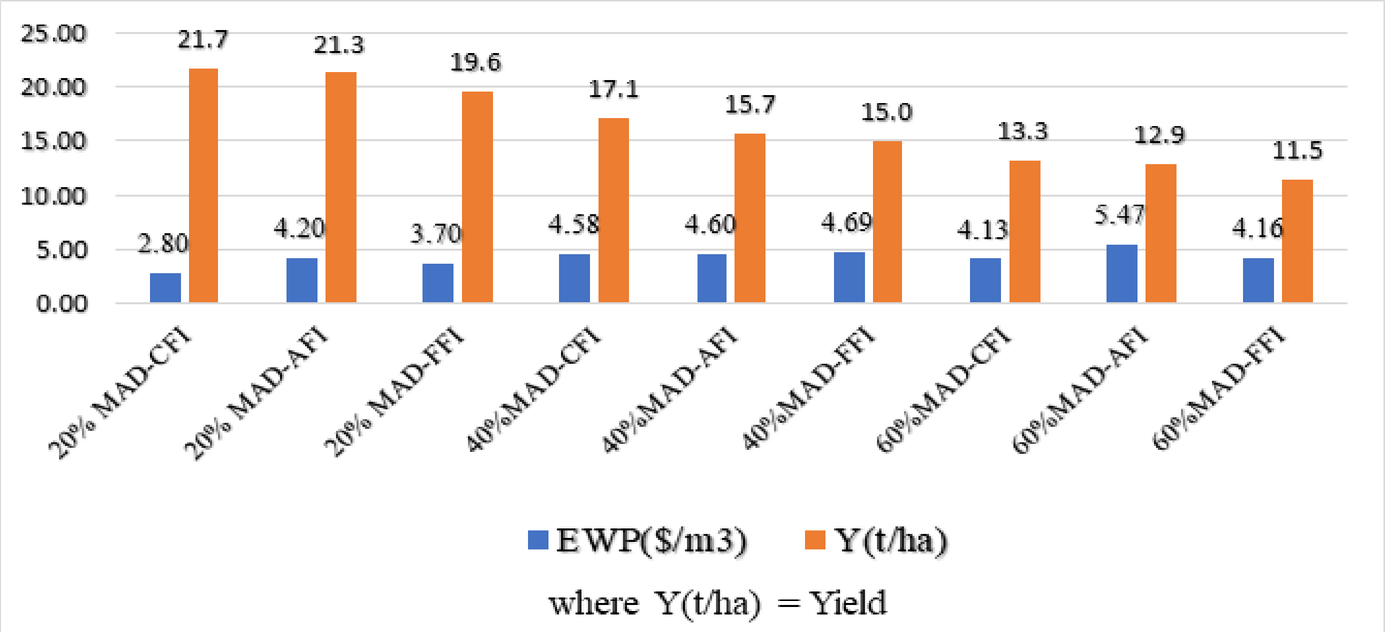

Fig 10 Economic Water Productivity of Potato Production Under Deficit Irrigation

One of the key principles for improving water productivity at the field, farm, and basin levels, which applies regardless of whether the crop is grown under rain-fed or irrigated conditions is to increase the marketable yield of the crop for each unit of water transpired by it (Sharma *et al*., 2018; Mabhaudhi *et al*., 2019; Mabhaudhi *et al* 2021; Patnaik *et al*., 2022). Based on the results, farmers may choose to switch to a different crop or cropping system that will have higher EWP. At the farm level, EWP can help farmers make decisions that will help them increase their income. At the policy level, the EWP can assist decision-makers and water managers in allocating water in an economically optimal way.

- *Profitability of Potato Production*

The profitability of potato production is determined using the gross margin which is the difference between the revenue from the sale of the potato and the cost of producing them. The revenue values from the sale of potatoes for each irrigation strategy and level of soil moisture depletion are shown in Table 10. The total variable cost was derived from the summation of water, labor, fertilizer, seeds, and plant protection costs. Based on the activities undertaken, the total variable cost during the production of potatoes was 1,084.80 US$/ha (Table 11).

Table 11 Variable Costs used During Potato Production Under Irrigation

Variable costs items	**COST (US$/Ha)**
Seed procurement	783.85
Ploughing	21.00
Harrowing+ land levelling	12.00
Ridging+ Plot layout	15.00
Ammonium Sulphate (50kgs)	26.50
Calcium Ammonium nitrate (50kgs)	56.00
Dimethoate 20WP	51.20
Dithane M45	32.00
WUA fee	31.25
Labor	56.00
TOTAL VARIABLE COSTS	**1,084.80**

The gross margins for each MAD level and irrigation strategy (Figure 11) were determined using the values in Tables 10 and 4.11.0, The figure shows that farmers can still be able to make more than the average national gross margins if they implemented DI under 20% MAD regime. Under this level of depletion, AFI and FFI show a significant amount of gross profit that is not significantly different from the profits realized under CFI (Figure 11). The current findings agree with Hilemicael and Tibebe, (2018) who concluded that potato yields can be optimized if the depletion is between 20% and 40%. An equivalent average of 9,137.70 US$ can be realized using the local average market price which was taken at 500US$/ton. In the case of Dedza, while the profitability of AFI and FFI under a 20% depletion level is slightly less than that of CFI, application of these irrigation strategies has more benefits to the communities because it enables more farmers to be under the irrigation scheme. This increase in the number of farmers who are able to access the saved water to irrigate additional land has the community benefit of reducing poverty by enabling more households to have a source of income and assured food security.

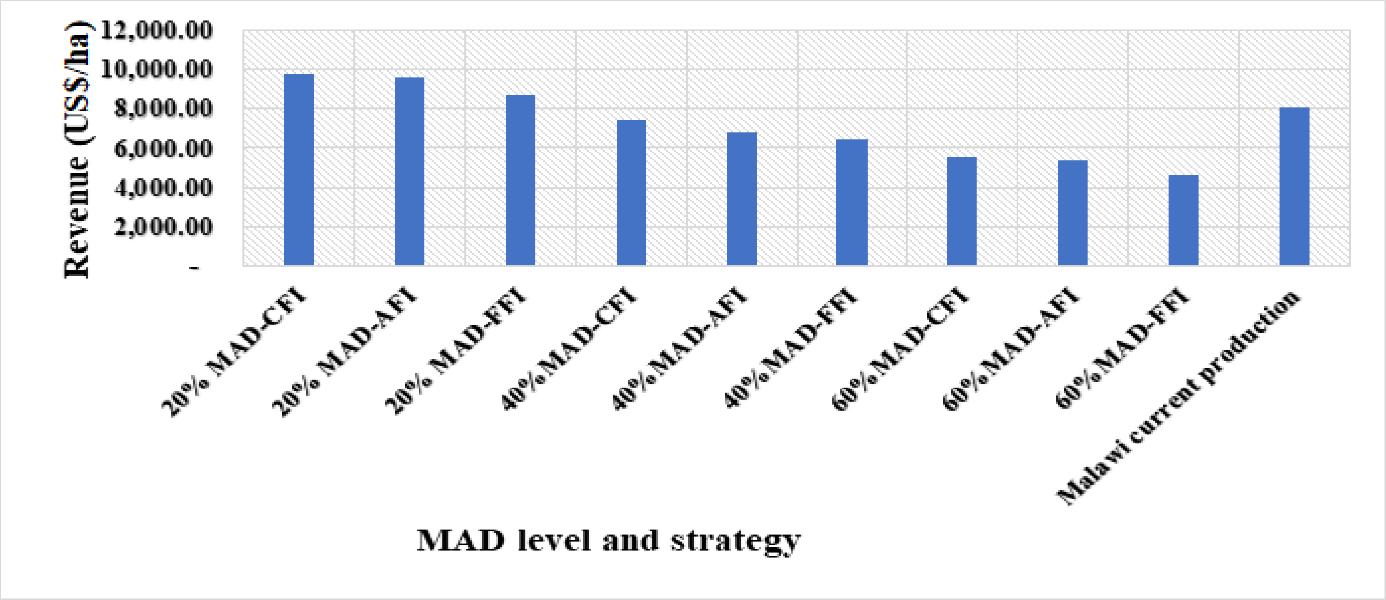

Fig 11 Gross Margin Analysis of Irrigated Potato Under DI

The results disagree with that of Gultekin and Ertek (2018) of Turkey who concluded that deficit irrigation is not suitable for potato cultivation because the profits from the reduced water applications cannot compensate for the income loss from the reduced yield. On the contrary, the results of this study are backed by Cosmas et al, (2019) whose report showed that the reduced yields under deficit irrigation are compensated by increased production from the additional irrigated area with the saved water.

IV. CONCLUSIONS

➢ *The Irrigation Practices were Considered to Comprise Land Ownership, Water Lifting/Conveyance Methods and Irrigation Methods. and the Major Findings were:*

- Farming land is owned through inheritance following the matrilineal kinship, renting, or both. The dominant ownership is through renting. This has implication of limiting the level of investment on the farms by the farmers. Moreover, the farm plots for farmers who are accessing water from the irrigation scheme are limited to 0.22 ha and farmers cannot expand their irrigated farm plots even if they had the capacity to do so.

- For water lifting/and water conveyance, gravity fed canals where irrigation water is lifted by increasing the head using a weir, water cans/buckets, solar pumps, motorised pumps, and treadle pumps are used. Of these, gravity-fed canals are dominant as they are used by about 81% of the farmers. Based on the few farmers using solar and motorised pumps, it was found that they are efficient, but they are relatively too expensive for smallholder farmers.
- The farmers use three irrigation methods; furrow, watering can/bucket and basin. Of these, the dominant method is furrow irrigation. Due to the sloping terrain, short furrows are used. These have the advantage of efficient water application, but they have the disadvantage of land use inefficiency.

➢ *The Study Evaluated the Effects of AFI, FFI and the Different MAD Regimes on Potato Yield, by Considering Plant Height, Number of Stems, Number of Tubers, Length of Tubers, their Diameters and the Weight of Tubers. The Major findings were:*

- DI can be used as a water saving technique that does not reduce the potato yields greatly within the 20% MAD level. In places where the size of irrigated land is not fixed, individual farmers who save water can use it to increase their irrigated area. However, in Dedza, the farm sizes are fixed and as a result, water saved by an individual farmer would benefit the community by enabling other farmers to be included in the irrigation scheme. This can have far-reaching positive effects on the fight against poverty and on ensuring food security.
- There was a total number of 10 scheduled irrigation events in the whole season for the 20% moisture depletion level. For the 40% depletion level, there was a total number of 6 irrigation events for the whole season. While a total number of 5 irrigation events occurred for the whole season under a 60% depletion level. As the depletion level increases, the number of scheduled irrigation events decreases. The deficit irrigation strategies (AFI, and FFI) indicate no significant difference from each other in plant height at ($P \leq 0.05$). Plant heights in CFI of 20% maximum depletion level were greater than plant heights recorded in treatments that were replenished when depletion levels were at 40% and 60%. Thus, with increasing soil water supply and less plant moisture-based stress, plant heights were significantly increased. By using the DI strategies and increasing the MAD levels (regimes), the potato producer will be able to save water amounting to 35-70% representing 1,356.10-2,712.20 m^3/ha which will enable the irrigator to expand the area of production by 0.52 hectares. However, AFI and FFI of a 20% depletion level were found to be relatively better in water saving because the crop yields were not significantly different from the control
- There was no significant difference in the number of stems at the level of 5% ($P \leq 0.05$) within the irrigation strategies (CFI, AFI, and FFI), MAD levels, and the interactions between the strategies and depletion levels.
- The number of tubers decreased with an increase in MAD level. These results show that from the yield perspective, there is no increase in benefits in stressing the crop in terms of increasing MAD levels together with the application of irrigation strategies (AFI and FFI).
- The findings further show that there is a significant difference ($P \leq 0.01$) in the number of tubers per unit area within the MAD levels. The results also show no significant difference within the irrigation strategies.
- The tuber length recorded in CFI under individual MAD level is relatively higher than those of AFI and FFI. Based on these results, the tuber length decreases as the depletion level increases. Thus, the length of tubers observed in CFI is not different from AFI of a 20% depletion level.
- The results show that tuber diameter is significantly different at the level of 5% ($P \leq 0.05$) in all the irrigation strategies.
- Despite plant height being different from each other in all the depletion levels, DI strategies have no effect on the plant height, number of stems and number of tubers within a depletion level. However, DI strategies affected the tuber length and tuber diameter if the MAD increases above 20%.
- The yields under different irrigation strategies (CFI, AFI, and FFI) within the same depletion level were almost the same. The results showed a minimum of 6% and Maximum of 49% yield reduction in AFI under a 20% soil moisture depletion level and FFI under 60% soil moisture depletion level respectively.

➢ *The study also established the profitability of potato production under DI using the gross margins and the major findings were:*

- AFI and FFI show a significant amount of gross profit that is not significantly different from the profits realized under control CFI. Thus, the gross margins for each MAD level and irrigation strategy show that farmers can still make more than the average national gross margins if they use DI under 20% MAD.
- From the results, the highest economic water productivity of 5.47US$/$m^3$ was observed under AFI of a 60% depletion level and the lowest was the CFI of a 20% depletion level. This is explained as; utilizing 1 m^3 of water under the 3 treatments within the three irrigation regimes of irrigation will let one earn a gain of 5.47US$. It is possible to deduce that the highest water profit had been gained per m^3 of irrigation water applied to the field from the AFI with the 60% depletion level. However, the high loss of yield at the 60% depletion outweighs the water productivity.

Considering potato yields above the national average (18.4mt/ha), the economic water productivity value comes to roughly 4.20 US$/m^3 (50% increase) or 3.70 US$/m^3 (32% increase) obtained from the AFI and FFI plots respectively under the 20% MAD level. It is therefore possible to say, more economic water productivity is observed and gained under the deficit irrigation strategies hence higher EWP and profitability compared to the CFI strategy. In short, AFI and FFI under 20% MAD level, if adopted can optimize yields, food security and improve farmers' income. In the case of Dedza, the application of DI strategies will have more benefits to the communities because it will enable more farmers to be under the irrigation scheme, by accessing the saved water. Thus, the reduced yields under DI are compensated by increased production from the additional irrigated area with the saved water.

CONTRIBUTIONS OF THE RESEARCH

- Currently, there is huge knowledge gap on optimal irrigation water management for irrigated potato production in Malawi. The study has shown that with the furrow irrigation under the soil and climate conditions in Dedza, AFI and FFI at 20% MAD level are indeed water-saving irrigation strategies where the farmer does not experience significant crop yield losses. The National Agriculture Investment Plan identifies sustainable irrigation strategies from a farmer's perspective as one of the research needs in the irrigation sub-sector (Government of Malawi, 2018). Thus, these results provide relevant information about the effects of deficit irrigation in potato production and the benefits of adopting such strategies.
- Despite the current increase in the production area, the national average potato yield is still very low (18.4 tons/ha) against the potential of 40 tons/ha. This research has shown that managing the crop under AFI of 20% MAD can allow the farmer to have yields above the national average and at the same time save water that can be used by additional irrigation scheme members. On the other hand, using the water balance sheet and the daily class A Pan data helped in allocating water economically, a thing that is new among the farmers. Scheduling of DI based on crop evapotranspiration is also uncommon in the literature.
- The study has also highlighted the fact that in the case of Dedza, water saving irrigation strategies will not necessarily benefit the individual farmer who applies them. This aspect may make it not necessary for the farmer to use DI strategies unless there are proper packaged awareness messages on the benefits to the large community of employing DI strategies. This can also work better if added in the current irrigation ACT through the influence of policymakers.

RECOMMENDATIONS

- The conclusions in this study are based on results obtained from one season's experimental data. It is recommended that the experiment should be repeated for a minimum of two seasons for the conclusions to be verified and reliable.
- The experiment was done on one site and using one cultivar, it would be more informative if the same experiment was done on different sites in different ecological zones while comparing the performance of different potato cultivars available in the country grown under irrigation. This will provide information on the best performing cultivars in different ecological regions.
- During the experiment, it was observed that the amount of irrigation water reduced around July and August. Though it was suspected that the reduction of irrigation water was due to high moisture content in the soil, it could not be verified because the trend was observed during data analysis. Thus, there is a need for future research that will investigate the moisture contribution from the rise in groundwater levels. The research should combine the use of soil moisture sensors and the water balance sheet in order to provide an explanation for the reduced irrigation water observed in the current study.

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