

**INVESTIGATION INTO THE EFFECTS OF DEFICIT IRRIGATION ON
POTATO PRODUCTION IN DEDZA DISTRICT-MALAWI**

BY

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DECLARATION

I, Aina Tennson Chikankheni, hereby solemnly declare that this dissertation and the work presented in it are my own and has been generated by me as a result of my own original work. I confirm that this work was done wholly while in candidature for the Master of Engineering in Agricultural Engineering at the University of Zambia and has been submitted to the University of Zambia within the framework of the said Master programme.

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ABSTRACT

Deficit irrigation strategies in furrow irrigation are important means of saving irrigation water in areas with poor water management. This study was conducted to establish the strengths and weaknesses of the current irrigation practices in Dedza district, to evaluate effects of alternating deficit, fixed deficit, and conventional furrow irrigation strategies on water saving, potato yield and profitability of potato production under different maximum allowable soil moisture depletion levels. 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. A total of 10, 6, and 5 irrigation events were scheduled for the whole season under 20%, 40%, and 60% depletion levels respectively. Compared to the control (CFI), the results showed that AFI and FFI under 20% MAD, saved 30% and 39% of water with slight crop yield reductions of 6% and 14% respectively. Moreover, under 20% MAD, farmers could achieve 17.8% and 7.3% gross margins above the average national value of US\$8119.20 with AFI and FFI respectively. Compared to 2.8 US\$/m³ for the control, the economic water productivity increased by 39% and 46% for AFI and FFI respectively under the 20% MAD. This research showed that managing the potato crop using AFI or FFI under 20% MAD could allow a farmer in Dedza district to achieve potato tuber yields above the national average while saving water to increase the irrigation scheme membership. The result can be used as the starting point for further research and development of policies that aim at improving potato farmers’ irrigation water and land productivity.

Keywords: alternate furrow irrigation, deficit irrigation, fixed furrow irrigation, irrigated potato production, maximum allowable depletion, water use efficiency

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TABLE OF CONTENT

DECLARATION	II
CERTIFICATE OF APPROVAL	IV
ABSTRACT	IV
ACKNOWLEDGEMENT	V
TABLE OF CONTENT	VI
LIST OF TABLES	IX
LIST OF FIGURES	X
LIST OF ACRONYMS AND ABBREVIATIONS	XII
CHAPTER ONE	1
1 INTRODUCTION	1
1.1 BACKGROUND OF THE STUDY	1
1.1.1 Irrigation agriculture performance in Sub-Saharan Africa and Malawi	2
1.1.2 Irrigation water management practices in Malawi.....	4
1.1.3 Deficit irrigation.....	4
1.1.4 Potato production in Malawi.....	5
1.2 PROBLEM STATEMENT AND JUSTIFICATION	5
1.3 RESEARCH AIM AND SPECIFIC OBJECTIVES.....	7
1.3.1 Research Aim.....	7
1.3.2 Specific objectives	7
1.4 RESEARCH QUESTIONS.....	7
1.5 SIGNIFICANCE OF THE STUDY	8
1.6 SCOPE OF THE STUDY	8
1.7 ETHICAL CONSIDERATIONS	9
1.8 SUMMARY	9
CHAPTER TWO	10
2 LITERATURE REVIEW	10
2.1 INTRODUCTION	10
2.2 IRRIGATION SYSTEMS.....	10
2.2.1 Surface irrigation systems	11
2.2.2 Sprinkler irrigation system.....	15
2.2.3 Localized irrigation systems	17
2.2.4 Subsurface irrigation systems	20
2.3 FACTORS AFFECTING IRRIGATION.....	21
2.3.1 Climatic factors affecting irrigation	21
2.3.2 Soil factors affecting irrigation	22
2.3.3 Crop factors affecting irrigation.....	26

2.3.4	Reference evapotranspiration and crop evapotranspiration	26
2.4	IRRIGATION SCHEDULING	28
2.4.1	Daily crop water requirements	30
2.4.2	Irrigation water requirements	30
2.4.3	Irrigation scheduling methods	30
2.5	DEFICIT IRRIGATION	34
2.5.1	Sustained deficit irrigation	34
2.5.2	Regulated deficit irrigation	34
2.5.3	Partial root-zone drying.....	35
2.5.4	Conventional furrow irrigation strategy.....	36
2.5.5	Similar studies of alternate and fixed irrigation as deficit irrigation strategies 36	
2.6	EVALUATION OF THE CROP IRRIGATION PROJECT	39
2.6.1	Water use efficiency.....	39
2.6.2	Profitability	39
2.7	SUMMARY	42
CHAPTER THREE		44
3	METHODOLOGY.....	44
3.1	INTRODUCTION	44
3.2	STUDY SITE CHARACTERIZATION	44
3.2.1	Field trial site	46
3.2.2	Irrigation scheme profile and water source.....	46
3.2.3	Soil characteristics	46
3.3	DATA COLLECTION FOR ESTABLISHING STRENGTHS AND WEAKNESSES OF THE CURRENT IRRIGATION PRACTICES IN DEDZA.....	48
3.3.1	Household Quantitative survey.....	48
3.3.2	Focus group discussions.....	49
3.4	PROCEDURE FOR DETERMINING DEFICIT IRRIGATION EFFECTS ON POTATO PRODUCTION	50
3.4.1	Soil moisture depletion for the trials.....	50
3.4.2	Plot size	51
3.4.3	Weather data collection.....	51
3.4.4	Crop establishment and management.....	53
3.4.5	Irrigation water supply and Requirement.....	56
3.4.6	Potato crop data.....	62
3.4.7	Analysis of yield and yield traits data.....	62
3.5	POTATO PRODUCTION PROFITABILITY UNDER ALTERNATING AND FIXED DEFICIT FURROW IRRIGATION IN DEDZA DISTRICT.....	63
3.5.1	Gross margin analysis	63
3.5.2	Economic water productivity	64
3.6	SUMMARY	65
CHAPTER FOUR.....		67

4	RESULTS AND DISCUSSION	67
4.1	INTRODUCTION	67
4.2	STRENGTHS AND WEAKNESSES OF THE CURRENT IRRIGATION PRACTICES IN DEDZA DISTRICT	67
4.2.1	Characteristics of respondents.....	67
4.2.2	Strengths and weaknesses of gravity-fed canal irrigation water delivery....	69
4.2.3	Strengths and weaknesses of watering can/bucket irrigation water delivery	70
4.2.4	Strengths and weaknesses of the treadle, motorized, and solar pump for irrigation water lifting	70
4.3	EFFECTS OF DEFICIT FURROW IRRIGATION AS COMPARED TO CONVENTIONAL FURROW IRRIGATION METHODS.....	71
4.3.1	The number of scheduled irrigations and the amount of irrigation water supplied	71
4.3.2	Irrigation scheduling	72
4.3.3	Effects on potato growth and yield factors	78
4.4	PROFITABILITY OF POTATO PRODUCTION UNDER AFI AND FFI	84
4.4.1	Economic water productivity	84
4.4.2	Profitability of potato production.....	86
4.5	SUMMARY	87
	CHAPTER FIVE.....	89
5	CONCLUSIONS AND RECOMMENDATIONS.....	89
5.1	INTRODUCTION	89
5.2	CONCLUSIONS.....	89
5.3	CONTRIBUTIONS OF THE RESEARCH	90
5.4	RECOMMENDATIONS	91
	REFERENCES.....	92
	APPENDIX A1: DATA COLLECTION FOR SOIL CHARACTERIZATION ...	118
	APPENDIX A2: ANOVA MEANS.....	124
	APPENDIX A3: ANOVA MEAN VALUES.....	124
	APPENDIX B1: APPROVAL OF STUDY.....	125
	APPENDIX B2 INDIVIDUAL CONSENT FORM	128
	APPENDIX C1: FARMER INVOLVEMENT QUESTIONNAIRE.....	134
	APPENDIX C2: FOCUS GROUP DISCUSSION GUIDE	136
	APPENDIX D: INVOICE FOR SOIL ANALYSIS.....	138
	APPENDIX E: PUBLISHED PAPER.....	139

LIST OF TABLES

Table 2.1: A guide to available water storage capacities based on textural class	25
Table 3.1: Descriptive statistics of measured soil properties	47
Table 3.2: Dedza district stratified sample	49
Table 3.3: Treatment used for the experiment	51
Table 3.4: Monthly average climatic data of the experimental area during the cropping season	53
Table 3.5: Example of soil water balance sheet for deficit irrigation strategy scheduling (Purdue, 2002).....	61
Table 4.1: Effect of deficit irrigation on the number of scheduled irrigations and volume of irrigation water applied.....	72
Table 4.2: New area (ha) of production from the saved water due to deficit irrigation..	77
Table 4.3: Effects of deficit irrigation strategies and irrigation regimes on plant height	78
Table 4.4: Effects of deficit irrigation strategies and irrigation regimes on the number of stems.....	79
Table 4.5: Effects of deficit strategies and allowable depletion levels on the length of tubers	82
Table 4.6: Effects of deficit irrigation strategies on tuber diameter.....	83
Table 4.7: Effects of deficit irrigation strategies on potato yields	84
Table 4.8: Harvested potato value based on local average market price.....	84
Table 4.9: Variable costs used during potato production under irrigation.....	86

LIST OF FIGURES

Figure 2.1: Furrows and ridges for a furrow irrigation method (Source: El Bergui <i>et al.</i> , 2020)	12
Figure 2.2: Farmer practicing basin irrigation at an irrigation scheme in Malawi (Source: Trust, 2022)	13
Figure 2.3: Layout of border strip (Source: Oke et al., 2022).....	14
Figure 2.4: Components of sprinkler irrigation system (Source: Oke et al., 2022)	15
Figure 2.5: Components of a set sprinkler system (Source: Prestwich and Walker, 2016)	16
Figure 2.6: Center pivot irrigation system (Source: Yan et al., 2021)	17
Figure 2.7: Schematic diagram of drip irrigation system (Source: NETAFIM, 2015) ...	18
Figure 2.8: Micro-spray irrigation (Source: Rashad et al., 2021)	19
Figure 2.9: Bubbler irrigation method (Source: Ame and Shouhua, 2022)	20
Figure 2.10: Artistic view of subsurface irrigation system (Source: Santos and Torres-Quezada, 2018)	21
Figure 2.11: USDA soil textural triangle (Source: Moreno-Maroto and Alonso-Azcárate, 2022)	24
Figure 2.12: Evapotranspiration concept diagram (Source: FAO, 2015)	27
Figure 2.13: The generalized variation of Kc over the crop growth period.....	28
Figure 2.14: Typical partial root zone drying system (Source: Cai et al., 2019)	35
Figure 3.1: The location of Dedza district in Malawi	45
Figure 3.2: The weir on the Chiweta River for Kamgultse irrigation scheme	47
Figure 3.3: Dedza District local weather station	52
Figure 3.4: Precipitation against reference evapotranspiration	52
Figure 3.5: Ploughing of the selected experimental site using hand hoes.....	53
Figure 3.6: The appearance of the field after levelling and harrowing	54

Figure 3.7: The field ridged across the slope	55
Figure 3.8: Water conveyance system within the irrigation scheme.....	57
Figure 3.9: water delivery into the furrows.....	58
Figure 3.10: USDA diagram of the soil water balance of a crop root zone	59
Figure 3.11: Meteorological local weather station in Dedza-Malawi having Class A Pan	60
Figure 4.1: Gender of participants.....	68
Figure 4.2: The current irrigation water lifting and delivery methods in Dedza district	69
Figure 4.3: Irrigation water distribution within the irrigation regime with a 20% depletion level.....	73
Figure 4.4: Crop stand corresponding to an irrigation event in plots with MAD of 40%	74
Figure 4.5: Irrigation water distribution within the irrigation regime with a 40% depletion level.....	74
Figure 4.6: Crop stand according to the date of an irrigation event.....	75
Figure 4.7: Irrigation water distribution within the irrigation regime with a 60% depletion level.....	76
Figure 4.8: Seasonal irrigation water distribution in all three different irrigation regimes	76
Figure 4.9: Effects of CFI, AFI, and FFI on the number of potato tubers	81
Figure 4.10: Economic water productivity of potato production under deficit irrigation	85
Figure 4.11: Gross margin analysis of irrigated potato under DI.....	87

LIST OF ACRONYMS AND ABBREVIATIONS

ABA	Abscisic acid
AFI	Alternate furrow irrigation
BD	Bulk density
CFI	Conventional furrow irrigation
DI	Deficit irrigation
EPA	Extension planning area
ET _c	Crop water
ET _o	Reference crop evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
FFI	Fixed furrow irrigation
GDD	Growing degree- days
IR	Irrigation requirement
MAD	Maximum allowable depletion
MC	Moisture content
PRD	Partial root-zone drying
RAW	Readily available water
RDI	Regulated deficit irrigation
SDI	Sustained deficit irrigation
SI	Surface irrigation system
SMD	Soil moisture deficit
SSA	Sub-Saharan Africa
SWHC	Soil water holding capacity
TA	Traditional authority
WP	Wilting point
WUE	Water use efficiency

CHAPTER ONE

1 INTRODUCTION

This chapter provides a general overview of the study. Firstly, the background in section 1.1 is set by discussing irrigation performance in Sub-Saharan Africa (SSA) and the Malawian context. Thereafter, the chapter discusses irrigation water management practices in Malawi, water management practices, and how deficit irrigation (DI) can be utilized in the production of potato. The chapter also consists of Problem Statement and Justification, Research Aim and Specific Objectives, and Research Questions. Before summary of the chapter, the significance and scope of the study and ethical considerations are presented in sections 1.5, 1.6, and 1.7 respectively.

1.1 BACKGROUND OF THE STUDY

It is anticipated that the world population will increase to 9 billion by 2050 (Ahmad, 2001). The major part of this increase is predicted to occur in developing nations, particularly in sub-Saharan Africa and some Asian countries (Gu *et al.*, 2021). For instance, the current trend shows that the African population has increased by about 624 million people between 1995 and 2020, with an annual growth rate of 2.5% (Klein and Anderegg, 2021). Due to this increase, there are 2.34% more people to feed annually in these regions (Lal, 2020). To ensure food security, for the booming population, food production must increase by 70% between 2005 or 2007 up to 2050 whilst mitigating and adapting to climate change (UN, 2019). Therefore, strategies that will increase food production will be vital towards feeding the increasing population.

Irrigation water supply is amongst 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 (Niswonger, 2020). 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 (Besharat *et al*, 2020) 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. Therefore, the desire to produce enough food to feed the increasing population through irrigation agriculture under increasingly favorable environmental conditions has been the driving force to research on irrigation water use efficiency techniques.

Potato (*Solanum tuberosum L*) is increasingly becoming an important food and cash crop in Malawi (Tione, 2018). The crop is produced both under rainfed and irrigation. However, its yields are continuously reduced due to challenges such as insufficient rainfall, limited available irrigation water, and poor irrigation water management (Wagg, 2021). To improve potato production, irrigation water productivity, and land productivity in Malawi, there is a need to address the constraints. Therefore, this study aims to investigate the effects of deficit irrigation strategies on potato production under smallholder irrigation schemes available in Malawi.

1.1.1 Irrigation agriculture performance in Sub-Saharan Africa and Malawi

Food production in the SSA is mainly dependent on rain-fed smallholder agricultural systems. Approximately 30 percent of agricultural cultivated land lies in arid or semi-arid areas in the region, which are characterized by high evapotranspiration and low, erratic, and unreliable seasonal rainfall (Mafuta, 2019). As such, in the absence of sufficient rainfall, there has been low agricultural production leading to food shortages and food insecurity. In this regard, irrigation has long been considered an option essential for increasing crop water supply (Nikolaou *et al.*, 2020). Improving crop productivity and profitability through irrigation is among the key strategies for reducing poverty and improving rural livelihoods in the SSA where most people depend on agriculture (Berhanu and Wolde, 2019). 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.

Despite the great desire to boost food production and improve people's livelihood through irrigation, irrigation water scarcity is becoming the main constraint for crop production in the region (Dinar *et al.*, 2019). This has made the region experience crop failure repeatedly. As such, irrigation in the SSA has, for the most part, largely failed in its objective to improve crop production for food security and poverty alleviation (Mwamakamba *et al.*, 2017). This is happening when there is a growing demand for food and fibre due to the rapid population growth in the region. Therefore, to ensure that irrigation agriculture achieves its goal of increasing food production to satisfy the increasing demand at a time when water is increasingly becoming scarce, current irrigation practices have to be improved.

Similarly, food production in Malawi heavily depends on rain-fed agricultural systems. Hence, due to erratic and unreliable rainfall, the country is heavily affected by low yields (Chinula, 2019). As such, irrigation development is considered vital and has been given high priority by the Malawi government to deal with food shortages (Chafuwa, 2017). Smallholder irrigation agriculture is considered a tool for increasing Malawi's agricultural production for improved livelihoods and economic development for rural communities. However, just like in many SSA countries, Malawi's irrigated agriculture is facing challenges of limited irrigation water supply owing to climate change and variability (Nhemachena *et al.*, 2020; Joshua *et al.*, 2020; Sibale *et al.*, 2021). Most irrigation schemes in the country experience either physical or economic water scarcity or both (Fandika *et al.*, 2021). Physical water scarcity is defined as a water scarcity indicator that occurs when there is not enough water to meet all demands including the environment (Vanham *et al.*, 2018). Physical water scarcity is caused by natural calamities such as drought and floods, increase food consumption amongst humans, and water overuse and this is exacerbated by climate change and population growth. Economic water scarcity on the other hand is due to institutional and financial constraints over the distribution of water or the poor management of water resources where infrastructure is in place (Gupta, 2021). Therefore, the individual or combined water scarcity phenomenon has led to the loss of crop yield and poor land productivity among smallholder farmers in Malawi.

1.1.2 Irrigation water management practices in Malawi

Most irrigation schemes in Malawi have surface irrigation systems with either furrow or basin irrigation as major water application methods (Fandika *et al.*, 2020). Irrigated farming and water management practices in Malawi are mostly based on traditional knowledge and farmers' experience (Sibale *et al.*, 2021). According to Kamwamba *et al.* (2021), most smallholder irrigation farmers in Malawi are using the least efficient traditional methods of irrigation. Among such traditional methods is the conventional furrow irrigation (CFI) method, which is widely practiced across the country (Fandika *et al.*, 2020).

Practicing the CFI method does not help to improve irrigation water management and crop production in Malawi. For instance, irrigation schemes that use CFI consume a huge amount of water, but their field application efficiencies are very low, usually below 50 percent (Fandika *et al.*, 2020). In response to this challenge, the adoption of the most efficient irrigation methods such as drip and sprinkler irrigation is increasingly being encouraged among farmers for increased yields and crop water use efficiency. However, these methods have not been adopted by smallholder farmers due to their high cost of initial investments, installation, operation, maintenance, and demand for technical knowledge (Abdel-Hamid and Abdelhaleem, 2021).

Hence, smallholder farmers in Malawi are still practicing irrigation methods that demand and consume large volumes of water as they are cheaper and easy to use. This partially explains the inadequacy of irrigation water in many smallholder irrigation schemes in Malawi. The situation calls for low-cost, simple, easy-to-operate but highly efficient, and water-saving strategies to improve yield and irrigation water use efficiency (Fandika *et al.*, 2020).

1.1.3 Deficit irrigation

Deficit irrigation (DI) is one of the strategies for improving water management (Vanham *et al.*, 2018). In this strategy, irrigation water is supplied to crops at a reduced rate below the full crop water requirement (Jensen *et al.*, 2010; Sanchez-Blanco *et al.*, 2019).

Generally, DI can be classified as sustained, partial root-zone drying, and regulated deficit irrigation. DI strategy can improve agricultural production per unit volume of water by increasing irrigable areas per season considering that some water has been saved (Khalili *et al.*, 2020). Therefore, it is essential to develop adaptable water conservation measures and technologies that fit smallholder irrigation farmers' budgets and knowledge and that optimize yield and water profitability.

1.1.4 Potato production in Malawi

Potato (*Solanum tuberosum L.*) is one of the major staple foods and income-generating food for around 1.6 million people in Malawi (Verhage *et al.*, 2018). The crop is the fourth most important crop by volume of production after maize, sweet potato, and cassava. It is the main cash crop and second most important food crop after maize in the major potato-growing districts which include: Dedza, Ntcheu, Neno, Mchinji, Mzimba, and Ntchisi (Kateta *et al.*, 2015) Potato is grown both under rain-fed and irrigated agricultural systems. Under rain-fed agricultural systems potato is grown in areas with rainfall above 750mm while under irrigated agricultural systems, the crop is mostly grown in smallholder irrigation schemes (McNulty *et al.*, 2016). Farmers in Malawi plant their summer crop (rain-fed) between November and December and their winter crop (irrigated) between March and April (Kateta *et al.*, 2015).

1.2 PROBLEM STATEMENT AND JUSTIFICATION

Potato is one of the major staple foods and cash crops among smallholder farmers and plays a crucial role in food security in Malawi (Kateta *et al.*, 2015). The area under potato production expanded from 34299 ha to 66,604 ha between 1990 and 2017 (FAO, 2015; 2019). Despite the 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 (FAO, 2019). 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. Despite some contradictory results in the literature regarding the advantages and disadvantages of DI strategies. 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.

1.3 RESEARCH AIM AND SPECIFIC OBJECTIVES

1.3.1 Research Aim

The study aims to assess the effect of deficit irrigation on potato production in Dedza district-Malawi

1.3.2 Specific objectives

The specific objectives are:

- i. To establish strengths and weaknesses of the current irrigation practices in Dedza district
- ii. To evaluate the effects of alternating deficit, fixed deficit, and conventional furrow irrigation on water saving, potato growth and yield under different maximum allowable soil moisture depletion levels.
- iii. To establish the profitability of potato production under alternating and fixed furrow irrigation in Dedza district.

1.4 RESEARCH QUESTIONS

- i. What are the strengths and weaknesses of the current irrigation practices in Dedza?
- ii. What are the effects of alternate deficit, fixed deficit and conventional furrow irrigation on water saving, potato growth and yield under different maximum allowable soil moisture depletion levels?
- iii. What is the profitability of potato production under alternating and fixed furrow irrigation?

1.5 SIGNIFICANCE OF THE STUDY

The study aimed at contributing toward the understanding of how the available limited water could be put to maximum use in sustaining the already established irrigation schemes. The findings also helped to demonstrate deficit irrigation scheduling as an alternative irrigation approach under situations of shortage of water during irrigation. The findings of the study have relevant information for the potato growers, Agriculture extension development coordinators, policymakers in different ministries, and the community at large on water management in potato production under irrigation. The results of the study has been shared with the public through publication and thus make a valuable contribution to knowledge in the academic world.

1.6 SCOPE OF THE STUDY

In this study, the effects of irrigation strategies (full and deficit irrigation) were investigated to determine the strengths and weaknesses of the current irrigation practices, evaluating the effects of alternating deficit, fixed deficit, and conventional furrow irrigation on water saving potato growth and potato production profitability. Household data collection was done amongst sampled farmers within the eight extension planning areas that grow potato. The experiments were designed with different water levels to be applied to the plots grown with potatoes under different irrigation strategies. A field experiment was carried out under the climatic condition of Dedza district-Malawi using a randomized complete block design (RCBD). The study took four months and an early-maturing local variety of potato known as Violet was used. The experiment consists of nine combinations of treatment and data was collected based on water application strategies and depletion levels as notable variables. Analysis of variance was used to determine if there are significant effects of deficit irrigation on potatoes.

Some of the limitations of this study were conflicts within scheme management which delayed the process of acquiring land through rent for the experiment, funding to support the implementation of the experiment and unavailability of Class A evaporation pan data on the cleaning day every month.

1.7 ETHICAL CONSIDERATIONS

Before the beginning of data collection, approval from the Natural and Applied Sciences Research Ethics Committee (NASREC) of The University of Zambia was obtained. Permission to conduct the study was sought from the Ministry of Agriculture in Malawi through the District commissioner's office of Dedza District Council. All farmers under the water user's association of the Kamgultse irrigation scheme had the right to understand the research protocol and the findings were shared with them through the District Agriculture Office.

1.8 SUMMARY

The chapter provided a general overview of the study. It started with the discussion of irrigation performance in the SSA and the Malawian context. The chapter also discussed irrigation water management practices in Malawi. Problem statement, research aim, objectives, and questions were highlighted. As a strategy to improve irrigation water management, deficit irrigation was also introduced in the chapter.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents relevant research literature on some of the concepts used in this study. The chapter is classified into 7 sections. Following this introduction is section 2.2 which presents a general introduction of irrigation systems. The section discusses types of irrigation systems, namely, surface irrigation systems, sprinkler irrigation systems, and localized irrigation systems. Section 2.3 discusses the major factors that affect irrigation. Irrigation scheduling is discussed in section 2.4. Section 2.5 outlines deficit irrigation and relevant studies that have been conducted under the same. Section 2.6 presents methods for evaluating agricultural irrigation projects such as water use efficiency and profitability. The chapter conclusion is presented in section 2.7.

2.2 IRRIGATION SYSTEMS

Irrigation can be defined in different ways. From the perspective of supplementing precipitation, irrigation is the application of water supplementary to that supplied directly by precipitation for the production of crops (Cai *et al.*, 2021). However, in general, irrigation is the process of artificially applying water to the soil or to the plant's root zone to meet crop water demands (Sowmya *et al.*, 2022; Nikolaou *et al.*, 2020). Irrigation systems range in size and complexity from simple hand home garden watering methods to large and complex sprinkler or furrow irrigation systems found in commercial farms. They can be classified in different ways according to energy or pressure required, method of irrigation water application (placement) and area wetted by irrigation. The methods of irrigation water placement include flooding on the field surface, applying beneath the soil surface, and spraying overhead like rain, (Jha *et al.*, 2019).

Different water application methods are practiced to suit different soil types, water supply, and its quantity, the topography of the land, crops to be irrigated, and costs. Based on the method of applying water to the land, there are four broad classes of irrigation systems: (1) surface irrigation systems, (2) sprinkler irrigation systems, (3) localized irrigation systems, and (4) sub-surface irrigation systems.

2.2.1 Surface irrigation systems

Surface irrigation (SI) systems, are those systems that rely on gravity to convey, distribute, and apply water to the soil surface (Pereira and Gonçalves, 2018). In SI, water is moved over the land surface as it is being wetted or irrigated either partially or completely (Eisenhauer *et al.*, 2021). According to Pereira and Gonçalves (2018), SI systems require proper land grading to facilitate flow of water over the land surface but are simple in layout at the field level and depend on canals for water delivery and drains to carry away excess water from the fields. Some of the major advantages of SI systems over other systems include ease of operation and maintenance with low skilled labour, and they are not affected by windy conditions (Pazouki, 2021). Generally, they are associated with low energy costs or none at all.

Surface irrigation systems do have several disadvantages, however. They are less efficient in water application than sprinkler or localized irrigation systems (Fang *et al.*, 2018; Rkachimov *et al.*, 2020). The spatial and temporal variability of soil characteristics, such as infiltration rate and texture, make water management practices difficult to define and implement (Reyes, 2018). It is also difficult to apply light, frequent irrigations as required early and late in the cropping season (Tasumi, 2019; Minhas *et al.*, 2020). Another disadvantage can be the high labour demand for construction, operation, and maintenance of SI systems, as compared to sprinkler and localized irrigation systems, in situations where labour is not abundant nor cheap (Watson, 2020). Surface irrigation systems can be broadly classified as furrow, basin, and border strip irrigation systems (Pazouki, 2021).

2.2.1.1 Furrow Irrigation method

A furrow irrigation system comprises furrows and ridges that have shapes, spacing and lengths depending on the crops to be grown and the types of soils (Mamatov *et al.*, 2020; Langewitz *et al.*, 2021; Sowmya *et al.*, 2022). The spacing between furrows ranges from 0.75-1.0 m, depending on soil type, crops, and stream size to be applied to the furrow (FAO, 1996). According to FAO (1996), the minimum and maximum slopes for furrows should be 0.05% and 3% respectively in areas of low rainfall intensity. Most field crops that are not closely spaced can be irrigated using furrows

(Figure 2.1). According to Kassaye *et al.* (2020), furrow irrigation is best suited to crops that are grown in rows such as maize, potatoes, onions, and tomatoes.



Figure 2.1: Furrows and ridges for a furrow irrigation method (Source: El Bergui *et al.*, 2020)

Furrow irrigation requires low investment to buy equipment (Sarker *et al.*, 2019). It is a cost-efficient method as it minimizes water loss in gravity irrigation systems (Abdelhafez *et al.*, 2020). Higher crop yield can be ensured through proper furrow irrigation practices (Zaman *et al.*, 2018). Quick mass area irrigation is possible with furrow irrigation (Sable *et al.*, 2019). It is possible to reduce nutrient leaching in furrow irrigation because the water is not applied directly on the ridge where the crop is growing and where fertilizers are applied as compared to the basin and border strip irrigation methods (Yu *et al.*, 2022).

With furrow irrigation, it is possible to recirculate irrigation runoff water with runoff return systems such as pumping (Kandpal, 2018). It is a time and labour-saving method where automatic cutback furrow irrigation systems are used (Abera and Gebeyaw, 2020). Another advantage of furrow irrigation is that the unit cost of pumped water is lower which saves money as compared to sprinkler irrigation (Nur and Ofgea, 2019).

Furrow irrigation, however, does have specific disadvantages. According to Zaman *et al.* (2018), it is not suitable for sandy soils. The method also presents a risk of localized accumulation of salts in ridges (Ali *et al.*, 2019). The movement of farm equipment is difficult in the furrow fields (Yorozu and Ishigami, 2021). The initial field preparation

labour cost is high (Guangyong *et al.*, 2021). It is always difficult to maintain water flow and the method is not suitable for some crops.

2.2.1.2 Basin Irrigation method

According to Abdelhafez *et al.* (2020), basin irrigation is the most common type of surface irrigation method and is particularly used in paddy rice irrigation. A basin is a levelled area of land, surrounded by earth bunds, where the flow of water does not need to be directed and controlled compared to furrow irrigation method (Loiskandl and Nolz, 2021). Figure 2.2 shows an example of basin irrigation practiced by farmers in Malawi. Basin irrigation can be a very useful way of leaching harmful salts (Woldeselassie *et al.*, 2021). However, a good drainage system should also be provided to dispose of the excess water. Basins can be adapted to suit any crop, soil, and farming practices (Uribe *et al.*, 2020).



Figure 2.2: Farmer practicing basin irrigation at an irrigation scheme in Malawi
(Source: Trust, 2022)

The basin irrigation method is more efficient in arid regions where it ensures uniform application of water since the slope is practically zero (Pandey *et al.*, 2021). It allows good control over irrigation water and high water application efficiency (Suryavanshi and Buttar, 2020). The basin irrigation method requires less labour and has low maintenance costs than furrow and border strip methods (Oke *et al.*, 2022).

According to Oke *et al.* (2022), the basin irrigation method brings about too many ridges which occupy a large area of land that could otherwise be used for production. Another disadvantage is that the layout requirement in land preparation and irrigation

is much higher in basin irrigation as compared to other methods. Further, the method impedes surface drainage and requires precise land grading.

2.2.1.3 Border strip irrigation method

According to Oke *et al.* (2022) border strips, are strips of land separated by small earth bunds that guide the water as it flows down the field. According to Loiskandl and Nolz (2021), the strips can have rectangular or contoured shapes, depending on the field. The border strip slopes uniformly away from the source of the irrigation water (Costabile *et al.*, 2023). They have a downward slope but are as horizontal as possible in cross-section to facilitate an even rate of water advance down the longitudinal slope (FAO, 1996). Figure 2.3 exemplifies the layout of border strip irrigation. The size, length, and width of the border strips depend on the soil type, stream size, irrigation depth, slope, field size, and farming practices (FAO, 1996; Birpal *et al.*, 2019).

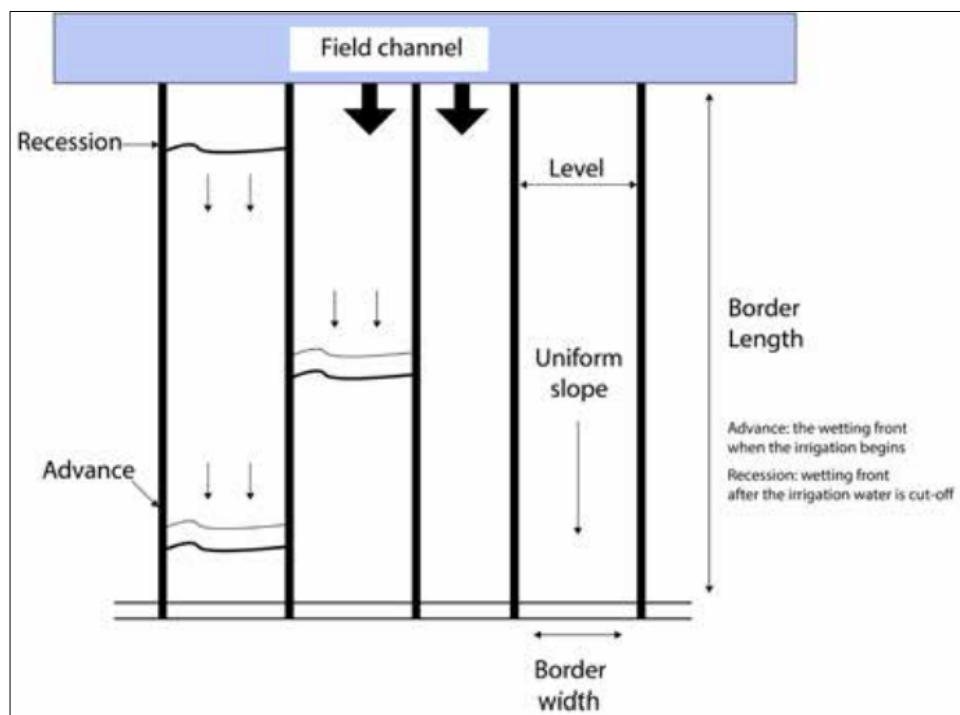


Figure 2.3: Layout of border strip (Source: Oke *et al.*, 2022)

Border strip irrigation method results in uniform distribution of water if the system is properly designed compared to the furrow irrigation method (Nie *et al.*, 2019). According to Nikolaou *et al.* (2020), high water application efficiencies are possible if the system is properly designed. The operation of this irrigation method is simple and

easy (Wojewodzic *et al.*, 2021). With the border strip irrigation method, the labour requirement to irrigate the field is less than for furrow irrigation method (Allen and MacAdam, 2020). Its disadvantage is that it requires larger irrigation streams than furrow irrigation method (Abidalla *et al.*, 2020).

2.2.2 Sprinkler irrigation system

Sprinkler irrigation is an irrigation method where irrigation water is applied in a way similar to natural rainfall (Patel and Prajapati, 2020). In the sprinkler system (Figure 2.4), the irrigation water is conveyed through pipes under pressure (Sidar, 2019). When properly designed and operated, sprinkler irrigation gives better uniformity and could result in higher irrigation efficiency than surface irrigation practices (Sinha, 2022). It is adaptable to small and large farms with the right design (Nakawuka *et al.*, 2018). The system has high irrigation efficiency and a long life span of about 20 years (Singh *et al.*, 2019; Yan *et al.*, 2020).

The use of properly designed, installed and operated sprinkler irrigation saves irrigation water per hectare when compared with surface irrigation while increasing crop yield (Acar and Sevincer, 2020). There are several types of sprinkler irrigation systems, which can be broadly sub-divided into two groups: set systems, which operate with sprinklers in a fixed position, for some time at least, and continuous move systems, which operate while moving.

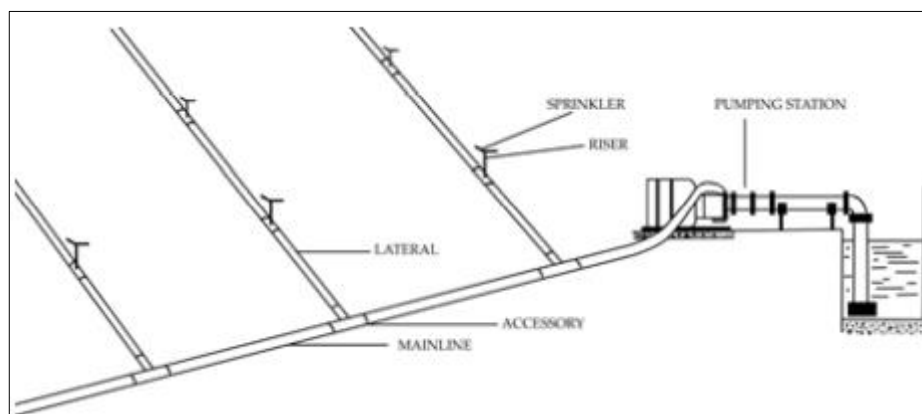


Figure 2.4: Components of sprinkler irrigation system (Source: Oke *et al.*, 2022)

2.2.2.1 Set sprinkler irrigation system

Set systems can be further divided according to whether or not sprinklers should be moved through a series of positions during the course of irrigating a field (Figure 2.5). Those systems that must be moved are called periodic-move systems and those that do not require any movement are called fixed systems (Ravikumar, 2022). Periodic-move systems can be further divided according to the method of movement of sprinklers (Rout *et al.*, 2020) and laterals into hand-move systems (Niragire *et al.*, 2021), where laterals and sprinklers are moved manually (Gan *et al.*, 2018), and mechanically-move systems, where the movement is done by mechanical means.

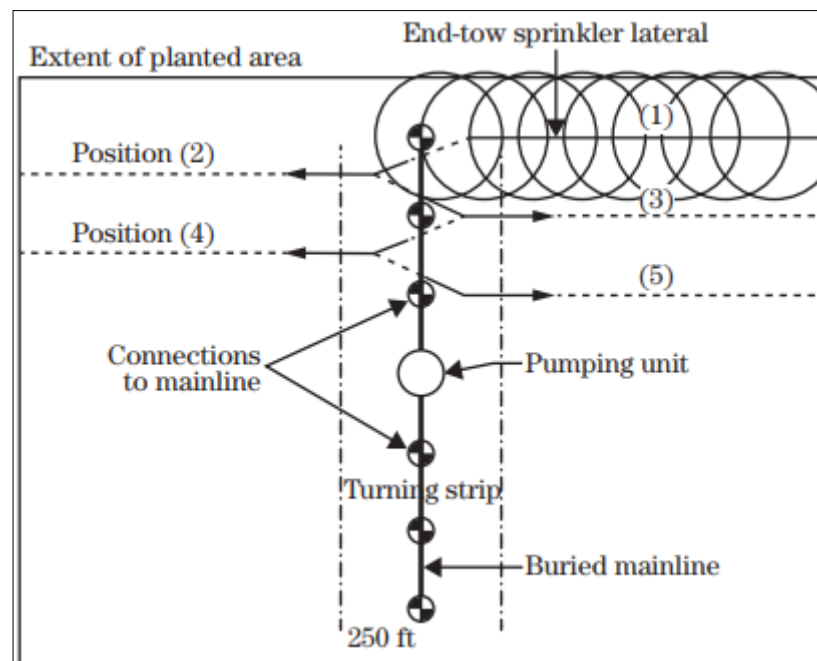


Figure 2.5: Components of a set sprinkler system (Source: Prestwich and Walker, 2016)

2.2.2.2 Continuous move irrigation system

Continuous-move systems have motorized laterals or sprinklers, which irrigate and move continuously at the same time (Peters *et al.*, 2021). Their innovation was prompted by the need to minimize labour inputs. According to Allen *et al.* (2020), continuous move systems include center pivot (Figure 2.6), linear moving laterals, and travelling irrigators.



Figure 2.6: Center pivot irrigation system (Source: Yan *et al.*, 2021)

2.2.3 Localized irrigation systems

Localized irrigation systems are also called Micro-irrigation or trickle irrigation systems. These are pressurized piped systems where filtered irrigation water is delivered to the plants without being spread over the entire area but to a limited soil surface area around the plants (Tayel *et al.*, 2019). The water is distributed under low pressure and the flow rate is low and is applied to each plant or adjacent to it to wet its root zone only (FAO, 1996; Johnbosco, 2022).

Localized irrigation systems are capital-intensive systems with built-in management that require very little but skilled labour (Narayanamoorthy *et al.*, 2020). Among the main advantages of localized irrigation are (i) it reduces water requirements and achieves very high efficiency, while at the same time increasing crop yield and quality (Yan *et al.*, 2021). (ii) it is suitable for most soils, (iii) it can be adapted to virtually any topography (Abraham, 2019), (iv) it reduces weed growth due to the limited wetted area, and (v) it provides the means for very frequent irrigation, daily if needs be (Domínguez-Niño *et al.*, 2020). Hence it is particularly suitable for light shallow soils, irrespective of the slope, and shallow-rooted crops (Ali *et al.*, 2019).

The main disadvantages of localized irrigation systems include: (i) their high capital cost (Alcon *et al.*, 2019), (ii) they are not suitable for crops that are not in rows, (iii) they are susceptible to clogging especially in hot areas with water that has high concentrations of calcium carbonates and they tend to build up localized salinity, especially in low-rainfall areas, they require increased maintenance which may include

periodic injections of sulfuric acid and chlorine or other chemicals to avoid plugging of emitters, and (v) they require higher skills to maintain and operate (Almeida *et al.*, 2022).

Localized irrigation systems are divided into drip, spray, and bubbler irrigation methods (Paredes *et al.*, 2022).

2.2.3.1 Drip irrigation method

Drip irrigation applies water directly to the soil surface and allows the water to dissipate under low pressure in a form of drops (Ravikumar, 2022). Ideally, the area between rows or individual plants remains dry (Tolossa, 2020) and receives moisture only from incidental rainfall (Santosh *et al.*, 2019). In this system (Figure 2.7), the emitters and laterals are laid on the land surface (Ravikumar, 2022). It has been primarily used on widely spaced plants (Singh *et al.*, 2020), but can also be used for row crops (Çetin and Akalp, 2019). Advantages of this system include the ease of installation (Navneet *et al.*, 2021), changing and cleaning the emitters and measuring individual emitter discharge (Sarker *et al.*, 2019). Often the terms drip and trickle irrigation are considered synonymous (Choi and Labhsetwar, 2020).

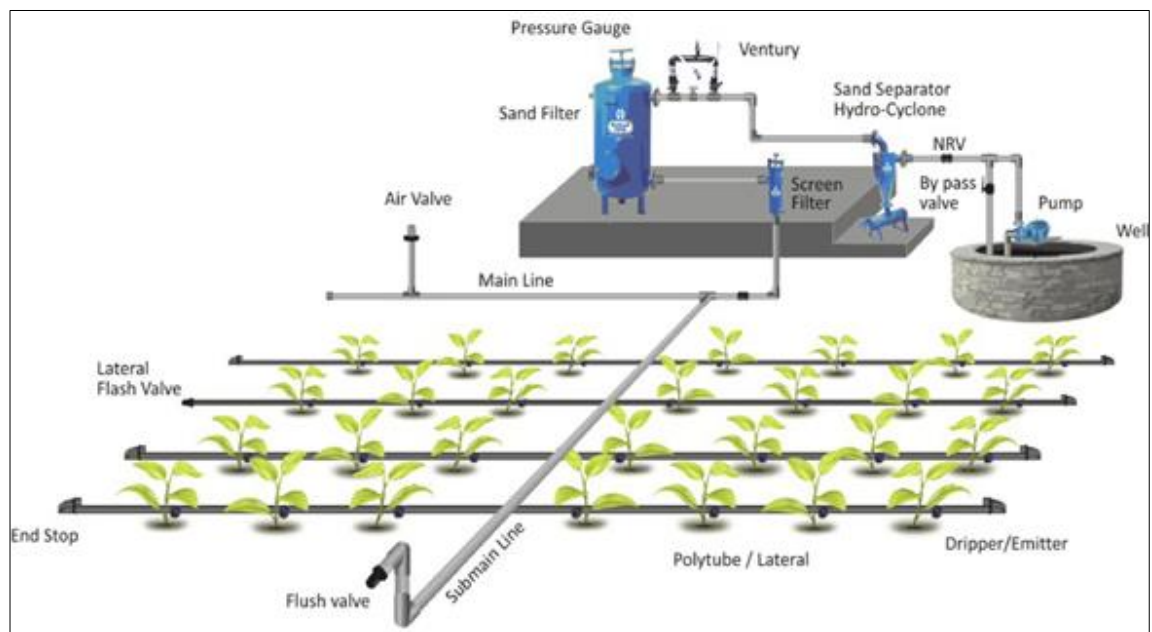


Figure 2.7: Schematic diagram of drip irrigation system (Source: NETAFIM, 2015)

2.2.3.2 Spray irrigation method

Spray irrigation is also known as micro spray or micro-jet irrigation method (Kibuye *et al.*, 2019). Figure 2.8 shows micro-sprayer irrigation. Spray irrigation is a form of irrigation where pressurized water is sprayed on the soil near individual plants (Kibuye *et al.*, 2019). The difference between this method and drip irrigation is that it wets a larger area and it is suitable for coarse soil. If you have a larger area that needs watering, spray irrigation is the best solution (Omran and Negm, 2020). It also allows the irrigator to water the field less frequently (Jobbágy *et al.*, 2022).



Figure 2.8: Micro-spray irrigation (Source: Rashad *et al.*, 2021)

2.2.3.3 Bubbler irrigation method

Bubblers are very similar to the point source online emitters in shape but differ in performance (Tayel *et al.*, 2019). In this method, the water is applied to the soil surface in a small stream or fountain from an opening with a point source (Fayed, 2020). Bubblers (Figure 2.9) are small-sized water emitters designed for localized flood irrigation of small areas. Consequently, a small basin is required to control the distribution of water because the discharge of the bubbler is usually higher than the soil infiltration rate (Fayed, 2020; Rashad *et al.*, 2021). The advantages of bubbler systems are that they have high irrigation application efficiency and low maintenance or repair and energy requirements as compared to other localized irrigation systems (Eisenhauer *et al.*, 2021).



Figure 2.9: Bubbler irrigation method (Source: Ame and Shouhua, 2022)

Bubbler systems use a larger size lateral to reduce the pressure loss associated with a high discharge rate (Ame and Shouhua, 2022). The bubbler heads are used in planter boxes, tree wells, or specialized landscape applications where deep localized watering is preferable (Özocak, 2020). High irrigation application efficiency of up to 75% can be achieved with total control of the irrigation water (Dhehibi *et al.*, 2018). According to Dhehibi *et al.* (2018), the entire piping network is buried, so there are no problems in field operations. According to Ame and Shouhua (2022), this system presents some limitations such as (i) high initial purchase cost; (ii) small water flows cannot be used as in other micro-irrigation systems; and (iii) in sandy soils with high infiltration rates, it is difficult to achieve a uniform water distribution over the crop basins.

2.2.4 Subsurface irrigation systems

The subsurface irrigation system, exemplified in Figure 2.10, is an irrigation system that comes with water emitters connected to a delivery line all installed below the soil surface to distribute water to the soil directly from under the surface (Appels and Karimi, 2021). The delivery line prevents airborne drift and minimizes runoff (Ma *et al.*, 2020). According to Cai *et al.* (2021), it is used to irrigate almost all plants grown in arid areas. The system prefers permeable root zone soil so that the emitters reach every root under the surface (Niragire *et al.*, 2021).

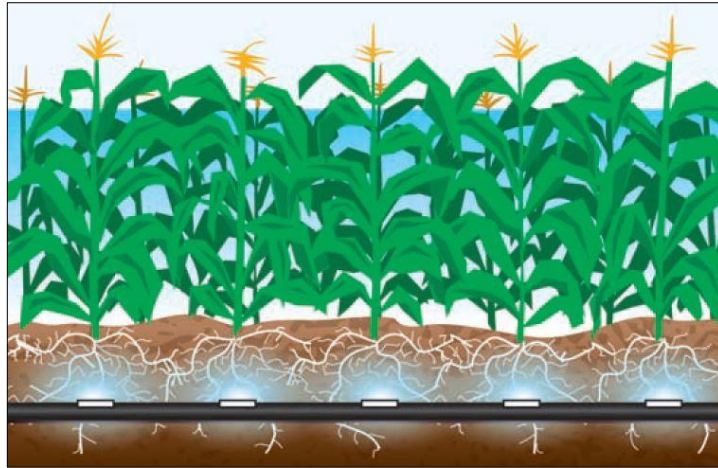


Figure 2.10: Artistic view of subsurface irrigation system (Source: Santos and Torres-Quezada, 2018)

Subsurface irrigation eliminates surface water evaporation and reduces the frequent occurrence of weeds and disease while saving water and improving the yield (Yao *et al.*, 2021). The subsurface irrigation system can render these functions since water is applied directly to the root zone of the plants or crops, which saves it from the soil surface where the seeds of weeds germinate after cultivation (Hussain *et al.*, 2020). This irrigation system enhances the efficiency of water application, especially in a large area (Yang *et al.*, 2020). However, there is a possibility of the emitters getting blocked or damaged by root hairs (Santos and Torres-Quezada, 2018).

2.3 FACTORS AFFECTING IRRIGATION

2.3.1 Climatic factors affecting irrigation

Solar energy is required by the plant to withdraw water from the soil through transpiration. The most important climatic factors affecting transpiration include light, relative humidity, temperature, soil water, wind, and the net radiation available to the plant (Hajickova *et al.*, 2017; Jolliet and Bailey, 2020). Increasing the humidity of the air surrounding the leaf decreases the vapor pressure difference between the leaf and the surrounding air, therefore, reducing the rate of transpiration (Sausa-Gallagher *et al.*, 2013; Wang *et al.*, 2018). Conversely, the wind sweeps away any layer of water vapor accumulated around the leaf thereby increasing the transpiration rate (Ma and Liu, 2019; Schwartz *et al.*, 2022). If the air around the leaf is replaced by warmer and/or dryer air, the transpiration rate increases. According to Ma and Liu (2019) the transpiration rate decreases if the wind brings cooler and/ or humid air. Radiation raises

leaf temperature above that of the surrounding air and hence increases the transpiration rate (Graf *et al.*, 2021; Khuluq *et al.*, 2022). The presence or absence of short-wave radiation in light triggers the opening or closing of stomata respectively. Thus, the stomata of most plants are open during the day and closed at night (Korner *et al.*, 2021; Tarakanov *et al.*, 2022).

2.3.2 Soil factors affecting irrigation

Soil acts as the reservoir for water needed by plants (Peng *et al.*, 2019). Water is actually “held” in the soil as a film coating on soil particles, and in the pore space between particles by combined adsorptive and capillary forces called matric forces (Wallach, 2019). Matric forces have to be overcome to remove water from the soil. As the voids are filled with water and the soil approaches saturation the matric forces holding the water in the soil approach zero (Liu *et al.*, 2019). At saturation, some soil water called gravitational water is drained past the plant root zone and this water is practically not available to plants. The soil water content at which drainage by gravity virtually stops is called field capacity (θ_{fc}) (Wang *et al.*, 2020). The moisture content below which plants are not able to extract water is called the permanent wilting point (θ_{pwp}).

Theoretically, plants are able to obtain water from the soil between θ_{fc} and θ_{pwp} (Seifi *et al.*, 2022). However, the rate of water uptake decreases as more and more water is removed from the soil (Ruth *et al.*, 2019). Towards θ_{pwp} , plants become stressed and that reduces their productivity (Ricci *et al.*, 2020). There exists a moisture content level below which plants start to have stress because of the difficulties in extracting water against the large soil matrix potential (Salimi *et al.*, 2017). This is called the critical moisture content (θ_c). Soil water content between θ_{fc} and θ_c is called readily available water (*RAW*) and is computed by Equation 2.2 (Silla, 2018):

$$RAW = \frac{(\theta_{fc} - \theta_c) * Drz}{100} \quad (2.1)$$

Where:

RAW = readily available water in soil (mm)

- θ_c = critical soil moisture content (%)
 D_{RZ} = effective root zone depth (mm)
 θ_{fc} = soil moisture content at field capacity (%)

(i) Soil characteristics

Soil characteristics can be highly variable much smaller scale that affects irrigation management and decisions (Azami *et al.*, 2020). Irrigation decisions, include: (i) irrigation system choices, (ii) components of system and design and (iii) operation and managements decisions. Plant responses and sensitivity to water, nutrient and salinity management, can significantly be influenced by soil characteristics (Nikolaou *et al.*, 2019). Some of the major soils characteristics that influence irrigation are discussed below:

Solids (mineral and organic matter), water, and air are the three major components of soil (Jia *et al.*, 2019). Other than through changes in organic matter fraction under some environmental/ management conditions, the solids fraction in most soils tends to vary little over time unless subject to erosive processes (Hooshmand *et al.*, 2019). The water plus air portions (pore volume) can also be affected to some extent by management practices (Elmetwalli and Elnemr, 2020). These management practices can reduce the pore volume due to compaction (Jabro *et al.*, 2020). The water fraction is of course highly volatile, affected by evaporation, plant water extraction, drainage etc. (Guangyong, 2021).

(ii) Soil texture

Most managers are well-acquainted with textural classifications (textural triangle) to characterize mineral soils. Soil particles > 2mm in size are separated out, the rest characterized as Clay (< 0.002mm), Silt (0.002-0.05mm), Sand (0.05-2.0mm) (Cai *et al.*, 2021). Once the sand, silt and clay fractions are known, the textural class can be determined using textural triangle (Figure 2.11). According to Seifi *et al.* (2022), soil texture determination is important because many soil properties are influenced by texture including drainage, water-holding capacity, and aeration, susceptibility to erosion, cation exchange capacity, and soil tilth. Since soil texture influences the infiltration rates, it determines the irrigation water application rates. Consequently, as

presented in section 1.2.6.3, soil texture influences the selection of irrigation systems and methods.

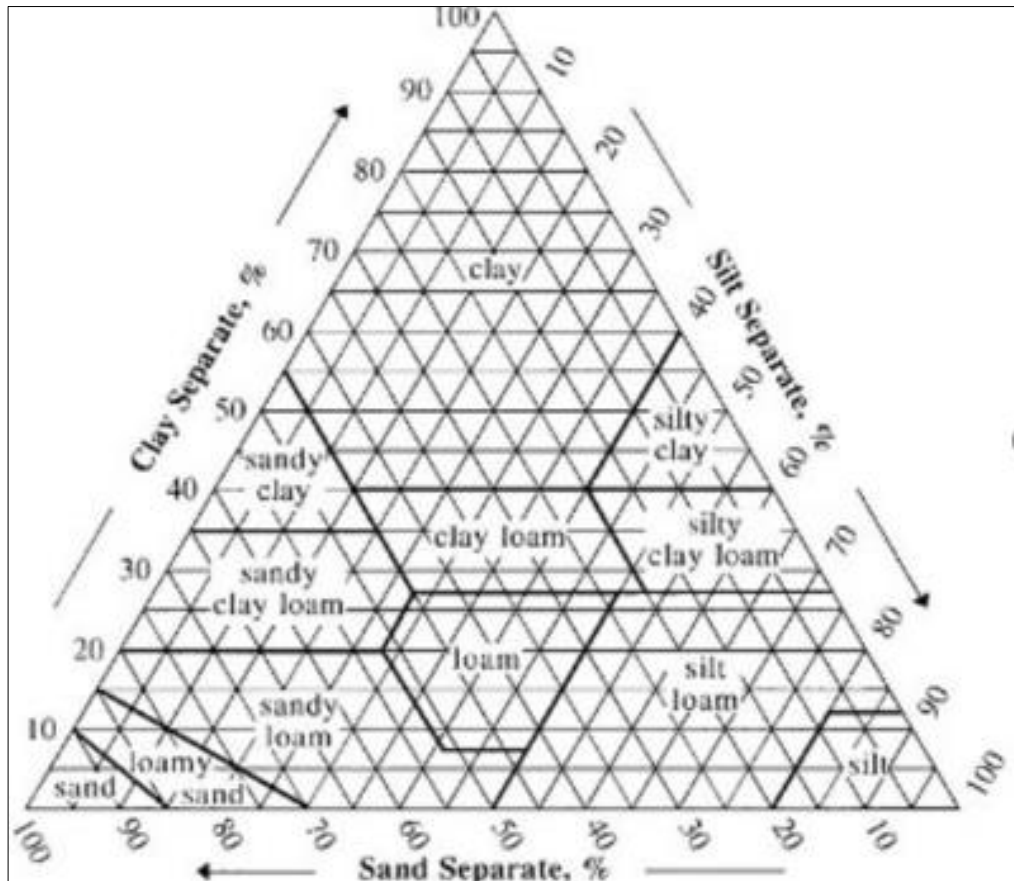


Figure 2.11: USDA soil textural triangle (Source: Moreno-Maroto and Alonso-Azcárate, 2022)

(iii) Soil water holding capacity

Soil water holding capacity (SWHC) is one term used to describe the amount of plant-available water held between field capacity and the permanent wilting point of a soil (Patel and Prajapati, 2020). Some broad generalization are medium textured soils, coarse soils and fine-textured soils. Medium-textured soils have higher water holding capacity than coarser or finer textured soils (Djaman *et al.*, 2021). This is often related to improved structure, resulting in larger pores to hold water. Coarse soils tend to have less aggregation and few small pores to hold water. So, soil water holding capacity is lower (Li *et al.*, 2021). Fine-textured soils with higher clay content, can have less structure/aggregation and many small pores that hold water more tightly, resulting in

less plant-available water (Fantaw *et al.*, 2020). Common ranges of SWHC by soil texture are provided in Table 2.1.

Table 2.1: A guide to available water storage capacities based on textural class

Textural Class	Available water Storage Capacity (AWSC) (mm water / m soil)
Clay	200
Clay Loam	200
Silt loam	208
Loam	175
Fine sandy Loam	142
Sandy loam	125
Loamy sand	100
Sand	83

(Source: Wang *et al.*, 2020)

(iv) Soil structure

Soil structure refers to how soil particles are grouped into larger aggregates (Nair, 2019). It is strongly affected by proportions of soil particles across different textural classes (Schwartz *et al.*, 2022). It can also be affected by environmental occurrences and cultural management practices, at least in the upper soil profile (Li *et al.*, 2020). Soil structure affects the rate at which water and air can move through the soil, root penetration, and the availability of nutrients to plants. Well-structured soils are usually more desirable for agricultural production because structured soils can hold and conduct water and gasses and are also able to support load-bearing activities, such as field traffic. Tillage of some fine-textured soils, particularly when they are wet, can destroy the soil structure, as can irrigation with high sodium (salt) content, which causes dispersion (Birpal *et al.*, 2019).

(v) Soil bulk density

Soil bulk density expresses the ratio of the mass of dry soil to the total volume occupied in the soil (Lafosse and Fernandez-concha, 2013). The total volume includes both the solids and the pore spaces. It is important because it is an indicator of the soil's porosity

(Gu *et al.*, 2020). The porosity of a soil is defined as the volume percentage of pores in a soil (Cai *et al.*, 2019). Within a soil of similar texture, a compacted soil has lower porosity and thus a greater bulk density, while a loose soil has a greater porosity and a lower bulk density (Rout *et al.*, 2020). Bulk density also provides information about the potential for leaching of agrochemicals, erosion, and crop productivity (Seifi *et al.*, 2022). Soils with high bulk density, such as sands, can promote vertical leaching of nutrients and reduce their availability to crops (Scoones *et al.*, 2019). As with soil structure, soil bulk density can be affected by physical management practices, such as tillage. Bulk density is generally measured in a soil sample obtained with a core, which is used to extract undisturbed samples from various depths in the soil profile (Lu *et al.*, 2019).

2.3.3 Crop factors affecting irrigation

Different crops need different quantities of water at various growth stages (Ewaid *et al.*, 2019). For example, in earlier stages, plants need less water whereas more water is required in their growth period (Laxa *et al.*, 2019). The structure of plant roots also affects water demand (Gupta *et al.*, 2020). Water is required by the plant for such processes as metabolism, growth, structural support, photosynthesis, and transport of products of photosynthesis and transpiration (Yoon and Choi, 2020). The largest proportion of water required by plants is used in the process of transpiration (Mwiya *et al.*, 2020). The combined processes of evaporation (evaporating surfaces such as wet soil) and transpiration is called evapotranspiration.

2.3.4 Reference evapotranspiration and crop evapotranspiration

Reference evapotranspiration (ET_o) is a standard measurement of environmental parameters which affect the water use of plants (Sowmya *et al.*, 2022). According to Sowmya *et al.* (2022), ET_o is commonly used as a standard estimate of evapotranspiration (Sowmya *et al.*, 2022). ET_o information enables irrigators to better match irrigations with the requirements of actively growing plants, thereby assisting to achieve higher yields and improve water productivity (Abd El-Mageed *et al.*, 2018). According to Patel and Prajapati (2020), it also helps take the guess-work out of irrigating. A small, but regular improvement in irrigation scheduling can significantly increase over-all plant production and quality (Singh *et al.*, 2020). By regularly

monitoring ET_o data, irrigators can become better informed about plant water requirements and are able to improve their scheduling effectiveness (Kibuye *et al.*, 2019). ET_o can be a very useful learning tool. Another advantage of using ET_o is that local ET_o values are relevant across a whole farm or small district (Tolossa, 2020).

Evapotranspiration is the loss of water from both plants and the soil (Patel and Prajapati, 2020). The main drivers of evapotranspiration are sunlight, wind, humidity and temperature (Liu *et al.*, 2019). Middle illustration of Figure 2.12 shows the process of evapotranspiration and the corners of Figure 2.12 shows the main drivers of evapotranspiration.

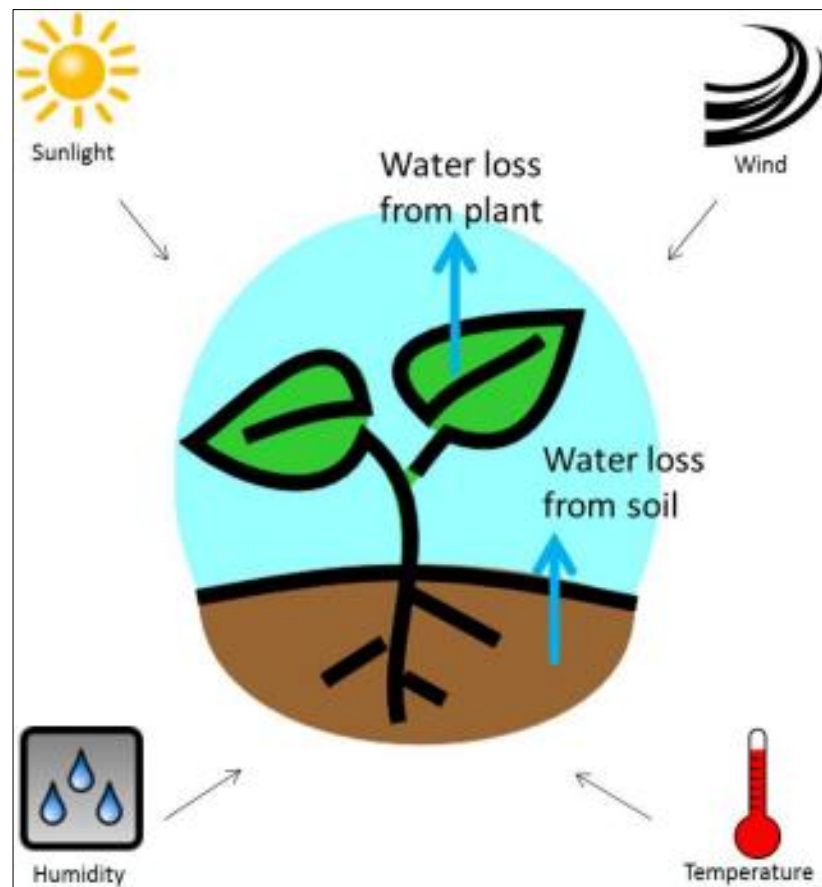


Figure 2.12: Evapotranspiration concept diagram (Source: FAO, 2015)

Crop evapotranspiration (evapotranspiration) (ET_c) is estimated from the reference evapotranspiration by using crop water coefficient (K_c) as shown in Equation 2.3 (Kassaye *et al.*, 2020).

$$ET_c = ET_o * K_c \quad (2.2)$$

The K_c increases in line with plant growth until a full canopy is developed (Frake *et al.*, 2020) then it reduces as the crop matures (Figure 2.13).

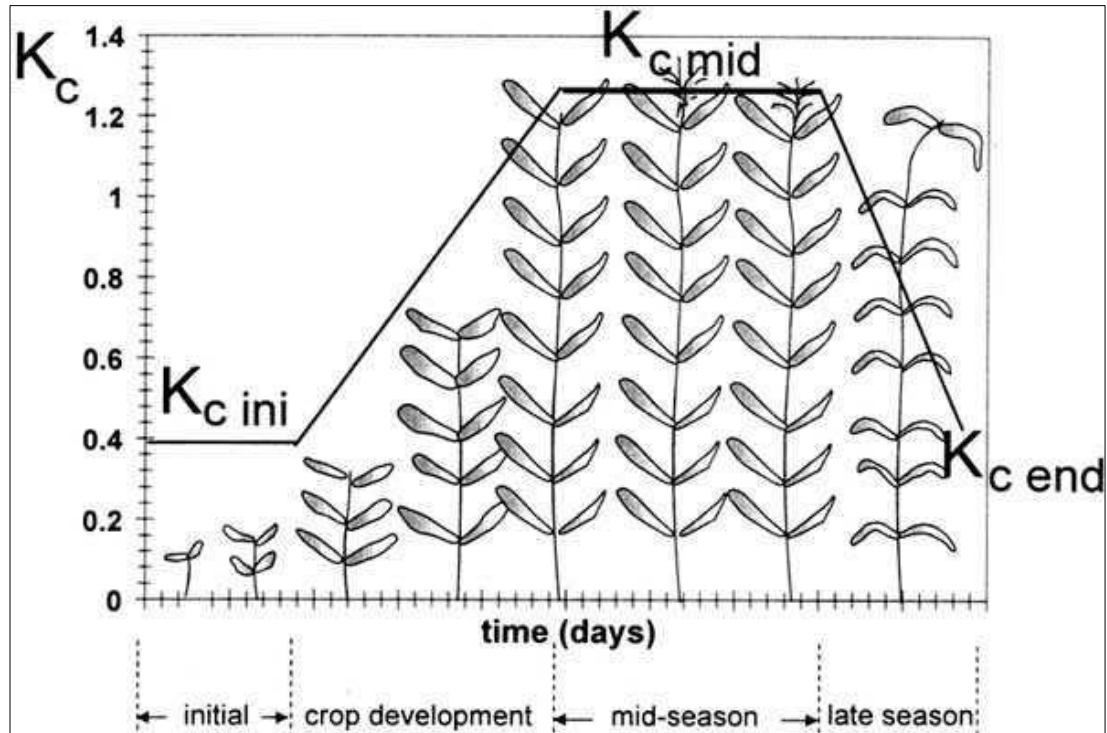


Figure 2.13: The generalized variation of K_c over the crop growth period

According to Patel and Prajapati (2020), evapotranspiration provides a relatively objective and reliable estimate of the water requirements of actively growing plants in a farm situation. Evapotranspiration information can be used by irrigators to more accurately schedule irrigations to help improve water productivity.

2.4 IRRIGATION SCHEDULING

Irrigation scheduling is the technique utilized by irrigation system managers to determine the appropriate frequency and duration of watering (Zinkernagel *et al.*, 2020). The main reason for irrigation scheduling is to enable the application of sufficient water to moisten the root zone of the plant while eliminating the possibility of over or under watering (Lerna, 2023). It also permits the soil to dry out in between watering periods which allows air entry into the soil as well as encourages better root development (Obiechefu and Emerson, 2020).

Irrigation scheduling is mandatory for the efficient management of water because it provides the answers to the questions of when to irrigate, how to irrigate, and how much to irrigate (Alvino and Ferreira, 2021). Irrigation scheduling is important not only for water savings, but also for improved crop yields (Placide *et al.*, 2019). It is used to determine the exact amount of water to be applied to the field and the exact timing for an application that increases irrigation efficiency (Sahoo *et al.*, 2022). A critical element is the accurate measurement of the volume of water applied or the depth of water application. Through irrigation scheduling, uniform water distribution across the field can also be achieved and this accurate water application prevents over or under irrigation (Zinkernagel *et al.*, 2020).

According to Zahoor *et al.* (2019), irrigation scheduling enables farmers to schedule water rotation among the various fields to minimize crop water stress and maximize yields. It also reduces farmers' cost of water and labour through less irrigation, thereby making maximum use of soil moisture storage (Islam *et al.*, 2020). In Crops that rely on fertilizers, irrigation scheduling helps to lower the cost of fertilizer by holding surface runoff and deep percolation or leaching to a minimum extent (Ahmed *et al.*, 2022). Holding other factors constant, it can increase net returns by increasing crop yields and crop quality (Taghvaeian *et al.*, 2020). It also minimizes water logging problems by reducing drainage requirements (Gouthami and Kumar, 2022).

It assists in controlling root zone salinity through controlled leaching (Gallardo *et al.*, 2020). According to Gouthami and Kumar (2022), irrigation scheduling brings additional returns by using the "saved" water to irrigate non-cash crops that otherwise would not be irrigated during water scarce periods. Irrigation scheduling enables the farmer to practice either full or deficit irrigation (Lipan *et al.*, 2021).

Over the years, several irrigation scheduling techniques based on soil-water-plant monitoring and water balance approaches have been developed (Mwiya *et al.*, 2020). For any approach, the three parameters to be considered in preparing an irrigation schedule are the effective root zone depth, the total available moisture, and the daily crop water requirements (Ewaid *et al.*, 2019). The first two parameters are discussed in section 2.3.2 and the last parameter is discussed below.

2.4.1 Daily crop water requirements

Daily crop water requirements (CWR) refer to the amount of water required daily to compensate for evapotranspiration losses from a cropped field during a specified period of time (Minhas *et al.*, 2020). It is used for management purposes in estimation irrigation water requirements, irrigation scheduling, and water delivery scheduling (Bellver *et al.*, 2021). The procedures for the estimate of crop water requirements correspond to those of crop evapotranspiration since both terms refer to the same amount of water. The crop water requirements of one crop variety vary from one location to other due to variations of climatic parameters (Bellver *et al.*, 2021).

2.4.2 Irrigation water requirements

Irrigation requirement includes water used for crop consumptive use, maintaining favorable salt balance within the root zone, and overcoming non-uniformity and inefficiencies of irrigation (Pirmoradian and Davatgar, 2019). Irrigation requirement (IR) can be computed when ET_c is known using the Equation 2.4 (Silla, 2018):

$$IR = \frac{ET_c - P_e + LR + \left[\frac{(\theta_i - \theta_f) * Drz}{100} \right]}{E_s} \quad (2.3)$$

Where:

IR = overall irrigation requirement for time interval under consideration (mm)

ET_c = Crop evapotranspiration for the period under consideration (mm)

P_e = precipitation for the same time interval under consideration (mm)

E_s = overall irrigation system efficiency (%)

LR = Leaching requirement, (amount of water that must flow from the root zone to maintain favorable salt balance in the root zone) in mm.

2.4.3 Irrigation scheduling methods

All irrigation scheduling methods consist of an irrigation criterion that triggers irrigation and an irrigation strategy that determines how much water to apply (Martínez-Romero *et al.*, 2021). Irrigation criteria are indicators used to determine the need for irrigation. Over the years, several methods have been developed for irrigation

scheduling which can broadly be classified into soil indicators, climatological, plant indices, and water balance method (Gu *et al.*, 2020).

Soil indicator methods include feel and appearance, the gravimetric method, neutron probe, TDR, tensiometers and porous blocks soil measurement (Singh *et al.*, 2019). In these methods, the available soil water held between field capacity and permanent wilting point in the effective crop root zone depth is taken as a guide for determining practical irrigation schedules (Mohammed *et al.*, 2021).

The feel and appearance method is one of the oldest and simplest techniques for determining soil moisture content. It is done by visual observation and feeling of the soil by hand (Rowe, 2018). Using this method, the accuracy of judgement improves with experience. The climatological approach for irrigation scheduling is done based on the ratio between the depth of irrigation water and cumulative evaporation from Class A pan (Pachore and Deore, 2022). It depends on the proper installation of the pan evaporimeter and rain gauge and their measurements (de Almeida *et al.*, 2023). Further, the suitability of the method is site specific (Akpoti *et al.*, 2019).

However, despite some of these limitations of the Pan Evaporation method, it is still widely used in some parts of East and Southern Africa (Soroush *et al.*, 2020). This is mainly because the method is very practical and simple, which appeals to many farmers and practitioners (Seifi *et al.*, 2022). In most cases, the Class A evaporation pan is used. The Class A pan is circular, 120.7 cm in diameter and 25 cm deep (Kucserka *et al.*, 2018; Fard *et al.*, 2021; Kumari *et al.*, 2022). It is made of galvanized iron or Monel metal. It is filled with water to 5 cm below the rim, and the water level should not be allowed to drop to more than 7.5 cm below the rim. The water should be regularly renewed, at least weekly, to eliminate extreme turbidity.

The measured evaporation from a pan (E_{pan}) is related to the reference crop evapotranspiration (ET_0) through an empirically derived pan coefficient (K_p) as given in Equation 2.5 (Babakos *et al.* (2020):

$$ET_0 = K_p * E_{pan} \quad (2.5)$$

Where:

ET_0 = Reference crop evapotranspiration (mm/day)

K_p = Pan coefficient

E_{pan} = Pan evaporation (mm/day)

Pan readings (E_{pan}) are taken daily in the early morning, at the same time that precipitation is measured (Mekoya *et al.*, 2019). Measurements are made in a stilling well that is situated in the pan near one edge (Watras *et al.*, 2019). According to Gu *et al.* (2020), by measuring the daily evaporation (E_{pan}), the ETc can be calculated so that the farmer will know within how many days the allowable soil moisture depletion will be reached. Then, if the amount of water available in the root zone depth and the allowable depletion are known, the time that irrigation is due can be calculated (Jabro *et al.*, 2020).

Irrigation scheduling using plant indices can be done by looking at visual plant symptoms, plant water potential, or canopy temperature (Sarkar *et al.*, 2021). Visual plant symptoms are used as an index for scheduling irrigations that include the colour of plants; curling, rolling and wilting of leaves and change of leaf angle (Malo, 2020). Secondly, plant water potential is an in-situ estimate of the energy status of plant water and is analogous to the energy measurements of soil water (Beyer *et al.*, 2020). According to Malo (2020), it is precisely measured either by a pressure bomb or pressure chamber apparatus and serves as a better index of physiological and biochemical phenomena occurring in plants. When the potential values fall below critical limits specific to the crop and growth stage, physiological and growth factors are adversely affected thereby serving as a guideline for irrigation scheduling (Dahal *et al.*, 2019). Thirdly, canopy temperature reflects the internal water balance of the plant which can be used as a potential indicator for scheduling irrigation (Nanda *et al.*, 2018). It is measured by a porometer, infrared thermometer (Gonzalez-Dugo *et al.*, 2019).

Irrigation scheduling based on the water balance approach uses readily available information on weather, crop and soil. It can be expressed in terms of soil moisture depletion (Ali *et al.*, 2022) as follows:

$$SMD_{Current} = SMD_{Previous} - ET_c - DP + I + Pe + GW \quad (2.4)$$

Where:

SMD = total soil moisture depletion in the root zone. It is defined as the difference between total soil moisture stored in the root zone at the field capacity and the current moisture status;

ET_c = crop evapotranspiration;

DP = deep percolation;

I = irrigation amount;

Pe = effective rainfall;

GW = the capillary rise/groundwater contribution.

Irrigation scheduling can be performed based on a fixed interval, fixed depth or maximum allowable depletion (MAD) criteria (Muroyiwa *et al.*, 2022). According to Gu *et al.* (2020), the estimated irrigation requirement under a fixed interval is equal to soil moisture depletion at the end of the interval. In the case of fixed depth, irrigation is required when soil moisture depletion becomes equal to irrigation depth (Lena *et al.*, 2022). According to Lena *et al.* (2022), irrigation scheduling based on MAD is determined as follows:

$$AD = TAW * MAD \quad (2.5)$$

Where:

AD = allowable depletion depth,

MAD = maximum allowable depletion limit. It is defined as the fraction of TAW that can be safely removed from the soil to meet the daily ET demand,

TAW = total available water.

All the irrigation criteria used for scheduling can be used with both full and deficit irrigation (DI). Under full irrigation, crops are not subjected to any moisture-based stress as the crop water requirements are fully met and if water is the only limiting factor, the crop yield is potential yield (Ali, 2007). However, under DI, if only water is the limiting factor, the crop yield is less than potential because the crop is subjected to moisture-based stress. The detailed presentation of the DI concept is in section 2.5.

2.5 DEFICIT IRRIGATION

DI has many definitions. Ali *et al.* (2019) defined it as an optimization technique in which irrigation is applied during drought-sensitive growth stages of a crop thereby concentrating the application of limited seasonal water supplies on drought-sensitive growth stages of a crop. Water restrictions are limited to drought-tolerant stages, often the vegetative stages and late ripening period. According to Liu, *et al.*, (2018) and Begum *et al.* (2018), DI allows economic optimization of water use for crop production where water is limited and Playán *et al.*, (2018) noted that it also involves structural adjustments (e.g., policies that support this kind of measure) in the agricultural system. Furthermore, this watering technique is multifaceted, inducing changes at the technical, socio-economic, and institutional levels and can be practiced with all irrigation systems (surface, sprinkler, localized, and subsurface irrigation systems) (Omran and Negm, 2020).

There are many deficit irrigation strategies which have been used successfully with many crops to improve water use efficiency and crop quality. These deficit irrigation strategies are sustained deficit irrigation (SDI), regulated deficit irrigation (RDI), and partial root zone drying (PRD) (Lipan *et al.*, 2021).

2.5.1 Sustained deficit irrigation

Sustained deficit irrigation (SDI) is one of the DI strategies where a constantly reduced amount of water is applied to a crop and it involves the application of water to meet over 75% to less than 25% of the ET_c (Gonçalves *et al.*, 2019). SDI leads to a gradual increase in water deficit as the season advances, allowing plants to adapt.

2.5.2 Regulated deficit irrigation

Regulated deficit irrigation (RDI) is another DI strategy that provides irrigation water below the full needs for specific development stages (Vivaldi, *et al.*, 2021). It was developed in the 1980s and has been proven suitable for arid and semi-arid areas (Yang *et al.*, 2020). According to Lu *et al.* (2019), RDI has been developed as an irrigation water management approach to control plant growth. This is in contrast to Gonçalves *et al.* (2019), whose findings showed that the strategy does not control vegetative growth. Furthermore, Blanco *et al.* (2020), proposed that RDI could be a promising

mitigation strategy in a scenario of climate change vulnerability. In principle, RDI has the potential to save water without any or with minimal yield and quality reduction (Lu *et al.*, 2019).

2.5.3 Partial root-zone drying

This is a DI strategy that improves crop quality while preventing yield loss (Igbal *et al.*, 2020). It is an improvement over the DI in which irrigation is alternated spatially and temporally to produce wet-dry cycles in many parts of the root system (Qin *et al.*, 2018). PRD alternately lets one part of the root zone be exposed to drying soil while the other part is being irrigated (Figure 2.14). The root growing on the irrigated side can absorb enough water for the maintenance of high shoot water potential (Jensen *et al.*, 2010; El- Abedin *et al.*, 2019). On the other hand, the roots that grow on the other part not exposed to irrigation produce abscisic acid (ABA) which enables the plant to develop a mechanism that optimizes water use (Abyaneh *et al.*, 2017). In Surface irrigation systems PRD is practiced as alternate or fixed furrow irrigation (Mehrabi *et al.*, 2019).

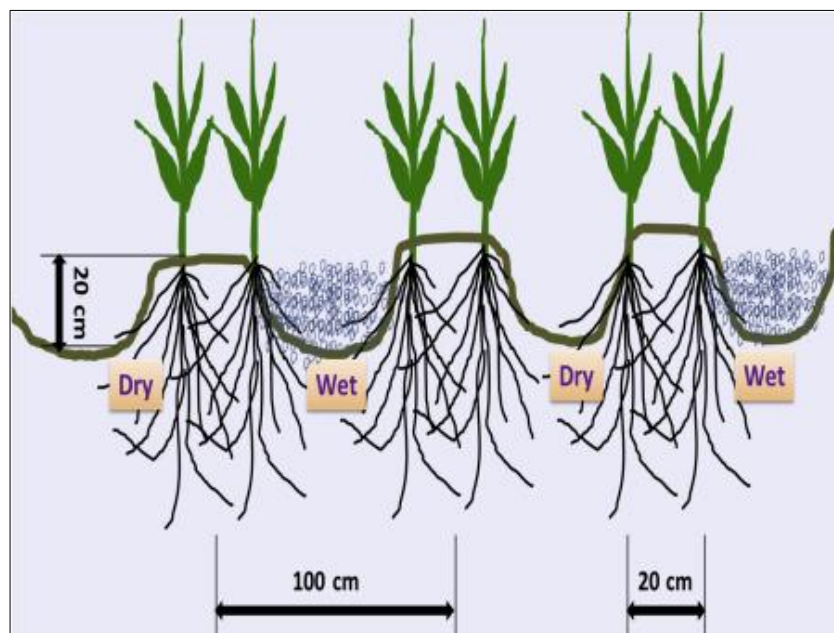


Figure 2.14: Typical partial root zone drying system (Source: Cai *et al.*, 2019)

(i) Alternate furrow irrigation strategy

Alternate furrow irrigation (AFI) strategy is defined as the strategy where one of the two neighboring furrows is alternately irrigated during consecutive watering (Getnet and Molla, 2020). AFI is a way to save water in arid areas where crop production relies heavily on repeated irrigation (Khalili *et al.*, 2020). According to Pereira and Gonçalves (2018), this method reduces water application to the entire field, leading to better on-farm water management flexibility under different surface irrigation conditions.

(ii) Fixed furrow irrigation strategy

Fixed furrow irrigation (FFI) strategy is the irrigation practice where irrigation is fixed to one of the two neighboring furrows (Abera *et al.*, 2020). FFI is recommended in areas where the irrigation water supply is limited. It can also be used if the irrigation water quality is low (Mansuri *et al.*, 2018).

2.5.4 Conventional furrow irrigation strategy

The conventional furrow irrigation (CFI) strategy is the irrigation practice where every furrow is irrigated during each watering (Yang *et al.*, 2020; Torres *et al.*, 2021). CFI is the typical furrow irrigation strategy discussed under surface irrigation methods (section 1.2.1).

2.5.5 Similar studies of alternate and fixed irrigation as deficit irrigation strategies

Alternate and fixed furrow irrigation systems can supply water in a manner that greatly reduces the amount of the soil surface wetted leading to less evapotranspiration and less deep percolation. The reduced evapotranspiration in the AFI and FFI methods is due to a reduction in wet soil surface compared with conventional furrow irrigation.

Abebe *et al.* (2021), in Ethiopia, conducted a study to assess the effects of furrow irrigation methods and intervals on tuber yield, quality of potatoes, and water productivity. The study also sought to determine the optimum irrigation amount for potato production. The treatment consisted of two potato genotypes of Bubu and CIP-

392781.1, two furrow irrigation strategies (FFI and AFI), and three irrigation intervals of 6, 8, and 10 days. The results showed that CIP-392781.1 registered the highest tuber average weight of 158.03g with FFI at a 6-day interval. The genotype of Bubu showed the highest water productivity of 13.20kg/m³ with AFI at 8-day interval where 17.6% of irrigation water was saved, which could irrigate an additional area of 0.25ha. Thus; the effect of deficit irrigation on potato yield, quality and water productivity depends not only on the level of the water stress the potato crop is subjected to as represented by the length of the irrigation interval in this case but also on the genotype of the potato.

Elhani *et al.* (2019), in Morocco, assessed the water saving irrigation techniques, such as FFI and AFI against CFI on potato cultivar Mondial under greenhouse conditions. The results showed that the yield penalty with FFI was similar to that caused by AFI. 20% of water was saved in FFI and AFI. In other words, FFI and AFI produced similar results in terms of yield reduction and water saving ability.

Qin *et al.* (2018), in China, made a comparative study of potato production under FFI, AFI and CFI using similar volumes of water per irrigation and irrigation intervals of 10 days in both strategies (FFI and AFI). The results showed the highest WUE were under both FFI and AFI without a significant yield reduction. FFI produced a 3.1% higher net benefit than AFI. The input and output ratios for FFI and AFI were 10% more profitable than CFI. The effectiveness of different DI strategies on potato productivity is affected by different factors to different extents some of which are known while others are not known. Ahmadi *et al.* (2016) investigated the effects of DI strategies on water productivity, tuber yield and tuber size distribution of two potato varieties of Agria and Ramos subjected to DI strategies in a semi- arid area. They used a fixed irrigation interval of 7 days. Their study found that AFI and FFI decreased yield of Agria potato variety relative to full irrigation. Thus; under non-limiting water conditions, some cultivars produce higher fresh tuber yield.

Among the reasons for the differences in results was that potatoes are drought sensitive crops which close stomata under mild to severe conditions. Hence, the potatoes in the other studies which were done in regions with high relative humidity might not have undergone severe evaporative demands leading to severe stress as compared to the

crop grown in the semi-arid region. The emphasis was that the success of a PRD (AFI/FFI) strategy depends on crop varieties, growing stage, evaporative demand, soil texture and soil water balance.

Furthermore, Igbal *et al.* (2020) did a review of the effects of PRD strategy and its significance in agriculture. The study indicated that the practical significance of the strategy depends on many factors which include soil conditions, crop variety, environmental conditions and method of irrigation. They pointed out that PRD promotes the production of ABA which is moved to the crop shoot and acts as an anti-stress aid which helps the plant to conserve water by reducing stomatal moisture conductance.

Kassaye *et al.* (2020) evaluated the influence of AFI under different irrigation levels (20, 25, and 50%) on growth, yield, water use efficiency and profitability of potato production. The AFI was compared with CFI and FFI. In the study, water was applied according to a predetermined set up which was not described. The study found that the potato yield for the AFI under 25% MAD and the CFI under 20% MAD were practically the same. This was attributed to the fact that the water stress induced by the AFI and reduced level of irrigation water enhanced nutrient use by stimulating plant root growth which made the root system deeper, denser and wider. Furthermore, improved water use efficiency was attributed to the role played by the ABA in reducing the rate of transpiration by partially closing the stomata without hindering photosynthesis, plant growth and yield.

Ahmadi *et al.* (2016) stated that DI strategies are common water-saving irrigation techniques which improve water productivity in irrigation projects. They reported that DI strategies increase potato nitrogen uptake which could be associated with the increased root system.

With reference to the findings above, the success of DI strategies depends on potato variety, soil type, climate and soil water balance. These findings imply that for each region and country there is a need to investigate, where this has not yet been done, the optimal DI strategy that can work in that region or country. No study was found which investigated optimal DI for potato production in Malawi. Consequently, for Malawi

there exists a knowledge gap as regards the best DI strategy for potato production under the existing irrigation scheme setup used by small scale farmers to grow potatoes. In addition, in terms of irrigation scheduling, most of the previous studies applied fixed irrigation intervals. These did not consider the fact that crop water use varies with the growth stage. Therefore, there is also need to investigate DI strategies where irrigation scheduling takes into account changes in crop evapotranspiration.

Further, earlier studies did not highlight the complexities of land ownership as they affect benefits from water savings from DI strategies and their ultimate economic benefits. This knowledge gap should be highlighted in studies that discuss the benefits of DI strategies.

2.6 EVALUATION OF THE CROP IRRIGATION PROJECT

2.6.1 Water use efficiency

Water use efficiency (WUE) has very diverse definitions. It can be defined as the ratio of crop yield (Y , kg ha^{-1}) grown in a known area to the amount of water the crop consumed while growing on the area (ET , $\text{m}^3 \text{ha}^{-1}$) mostly expressed in mm (Mbava *et al.*, 2020; Kassaye *et al.*, 2020). WUE in the field can be improved through better soil fertility management and mulching which reduces soil evaporation (Zhuo and Hoeksta, 2017) thereby reducing the irrigation intervals and quantity of irrigation.

In cases where water is scarce to limit crop production, improvement of the irrigation WUE is particularly relevant and may lead to water savings which may be used to irrigate more land (Koech and Langat, 2018; Ghazouani *et al.*, 2019). WUE is more pronounced in surface irrigation systems (e.g. furrow) whereby irrigation water is conveyed over the soil surface (Koech and Langat, 2018). To increase WUE, it is necessary to adopt irrigation water-saving strategies, like RDI or partial root-zone drying (Ghazouani *et al.*, 2019).

2.6.2 Profitability

Profitability can be considered either as accounting profits or economic profits (Yoon and Choi, 2020). Accounting profit is a type of profit which is earned after various costs and expenses are subtracted from total revenue (Berhanu, 2019). Those costs

include: labor, any inventory needed for production, raw materials, transportation and storage costs, production costs and overhead, sales and marketing costs, and depreciation. Accounting Profits provide an intermediate view of the viability of an enterprise which is also called gross margin analysis. To calculate the accounting profit, the total revenue as well as the explicit costs should be known, and it is calculated using Equation 2.8 (Berhanu, 2019):

$$GM = TR_{ij} - TVC_j \quad (2.8)$$

Where:

GM = gross margin (\$/ha)

TR_{ij} = total (gross) revenue (\$/ha)

TVC_j = total variable Costs (\$/ha)

The total revenue of the outputs (potato tubers) was calculated by applying Equation 2.9:

$$TR_{ij} = Y_{ij} * PY_{ij} \quad (2.9)$$

Where:

TR_{ij} = total (gross) revenue (\$/ha)

Y_{ij} = yield or physical production (Kg/ha)

PY_{ij} = price of outputs (\$/Kg)

i = Crop

j = Scheme management

y = Year or season

Gross margin serves as the unit for evaluating the financial performance of an enterprise and gives an indicator of the feasibility of an enterprise and its potential to contribute to overall income (Mansuri *et al.*, 2018).

Profitability can help the farmer to reduce costs, increase turnover, increase productivity, and increase efficiency (Kucserka *et al.*, 2018). It can also help the farmer to plan for change and growth (Berhanu, 2019; Yoon and Choi, 2020; Liu *et al.*, 2021). According to literature, SI systems have high value of productivity compared to localized and sprinkler irrigation systems which have problems of high salinity levels in the soil (Tayel *et al.*, 2019; Nikolaou *et al.*,

2020; Liu *et al.*, 2021). However, SI systems are not profitable because of high water losses which makes sprinkler and localized systems better hence the need for their use. But, the profitability of converting from surface irrigation system to more efficient irrigation systems depend upon a number of engineering, agronomic, and economic factors (Mwamakamba *et al.*, 2017).

Margin or profitability ratios, break-even analyses, and return on asset assessments are three primary ways to determine whether the enterprise is profitable as according to Equation 2.10 (Kassaye *et al.*, 2020), Equation 2.11 and Equation 2.10 (Waqas *et al.*, 2021):

$$PMR = \frac{[G, O, \text{or } N]P}{s} * 100 \quad (2.6)$$

Where:

PMR = profit margin ratio

[G, O, or N]P = gross, operating, or net profit

S = sales

$$BPUS = \frac{FE}{(USP - UVE)} \quad (2.7)$$

Where:

BPUS = break-even point for unit sold

USP = unit sales price

UVE = unit variable expenses

$$ROA = \frac{NIT}{TA} * 100 \quad (2.8)$$

Where:

ROA = return on assets

NIT = net income taxes

TA = total assets.

A variety of profitability ratios can be used to assess the financial health of an enterprise (Pandey *et al.*, 2021). The profitability ratios include:

- Net farm income from operations,
- Rate of return on farm assets,
- Rate of return on farm equity,
- Operating profit margin ratio, and
- Earnings before interest, taxes, depreciation, and amortization.

2.7 SUMMARY

Irrigation as the process by which water is artificially applied to crops to meet their requirements can be achieved using different systems and method. Based on the methods of water application to the land, there are four broad classes of irrigation systems namely: (1) surface irrigation systems, (2) sprinkler irrigation systems, (3) localized irrigation systems, and (4) sub-surface irrigation systems. These systems have different irrigation efficiencies and even the methods of water application with a give system have different efficiencies. Broadly, localized and surface irrigation systems have the highest and lowest irrigation efficiencies respectively. Thus, from the irrigation efficiency and water saving points of view, localized irrigation systems are the based. However, the actual selection of irrigation systems and methods is based on the consideration of several factors which include; political and economic factors, topography and soil properties, crop characteristics, and social constraints.

The effectiveness of irrigation systems and methods is generally affected by the several factors which include, climatic (temperature and wind), soil (texture), and crop (evapotranspiration) factors. These factors are critical to the irrigation scheduling activities and for any efficient irrigation project there have to be a way in which they are considered.

Irrigation scheduling the backbone of an efficient irrigation project because it provides answers to the questions of when to irrigate, how to irrigate, and how much to irrigate. Irrigation scheduling links crop water demand which is influenced by the stage of crop growth and climatic conditions, soil moisture content which is broadly influenced by soil texture, and water supply which considers the availability of water, irrigation methods and soil type. There are several scheduling methods, but all of them consist of an irrigation criterion that triggers irrigation and an irrigation strategy that determines how much water to apply. Irrigation criteria are indicators used to

determine the need for irrigation and they include soil indicators, climatological, plant indices, and water balance method. Each of these indicators have merits and demerits and the choice is one that is suitable is dependent on the prevailing circumstances. Irrigation scheduling based on any of these indicators is applicable to both full and DI.

DI strategies are used to save irrigation water by improving crop water use efficiency. Adoption of these strategies require changes at the technical, socio-economic, and institutional levels. DI strategies can be practiced with all irrigation systems (surface, sprinkler, localized, and subsurface irrigation systems). There are many DI strategies which include sustained deficit irrigation (SDI), regulated deficit irrigation (RDI), and partial root zone drying (PRD). With respect to furrow irrigation systems, PRD has two variants which are the alternate furrow irrigation (AFI) and the fixed furrow irrigation (FFI) strategy.

Several studies have investigated the effects of DI strategies on water use efficiency, crop productivity and profitability of potato production. The experimental approaches and environments differed from study to study but certain findings were consistent in most of them. Among these findings were that the success of DI strategies depends on potato variety, soil type, climate and soil water balance. These findings imply 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, in terms of irrigation scheduling, most of the previous studies applied fixed irrigation intervals. These did not consider the fact that crop water use varies with the grow stage. Therefore, there is still a need to investigate DI strategies where irrigation scheduling takes into account changes in crop evapotranspiration.

Implementation of DI strategies have different levels of economic benefits. While in some cases, these benefits accrue to individuals, in other cases where individuals may have fixed land sizes, the benefits of saving water may be complex as individuals may not see the need to save water. Earlier studies did not highlight complexities of land ownership as they affect benefits from water savings from DI strategies and their ultimate economic benefits. This knowledge gap should be highlighted in studies that discuss the benefits of DI strategies.

CHAPTER THREE

3 METHODOLOGY

3.1 INTRODUCTION

This chapter highlights the methodology for collecting field data aimed at establishing the strengths and weaknesses of the deficit furrow irrigation strategies. The chapter also highlights steps followed to evaluate the influence of different deficit furrow irrigation strategies on potato production. The data collection involved both qualitative and quantitative methods. The chapter is arranged into 6 sections. Following this introduction is section 3.2 which describes the site where field trials of the irrigation strategies were done. This is followed by section 3.3 which explains the data collection activities aimed at establishing the strengths and weaknesses of the current irrigation practices in Dedza. Section 3.4 presents the activities undertaken to evaluate the effects of deficit irrigation on potato production. Among the aspects considered are the effects of deficit irrigation strategies on growth, yield components and water use efficiency. Establishment of the profitability of potato production under alternating and fixed deficit furrow irrigation in Dedza District is presented in section 3.5. The summary of the chapter is given at the end of section 3.6.

3.2 STUDY SITE CHARACTERIZATION

The study was conducted in Dedza district located in the central region of Malawi (Figure 3.1). The district covers a geographical area of about 362,400 ha (Government of Malawi, 2018).

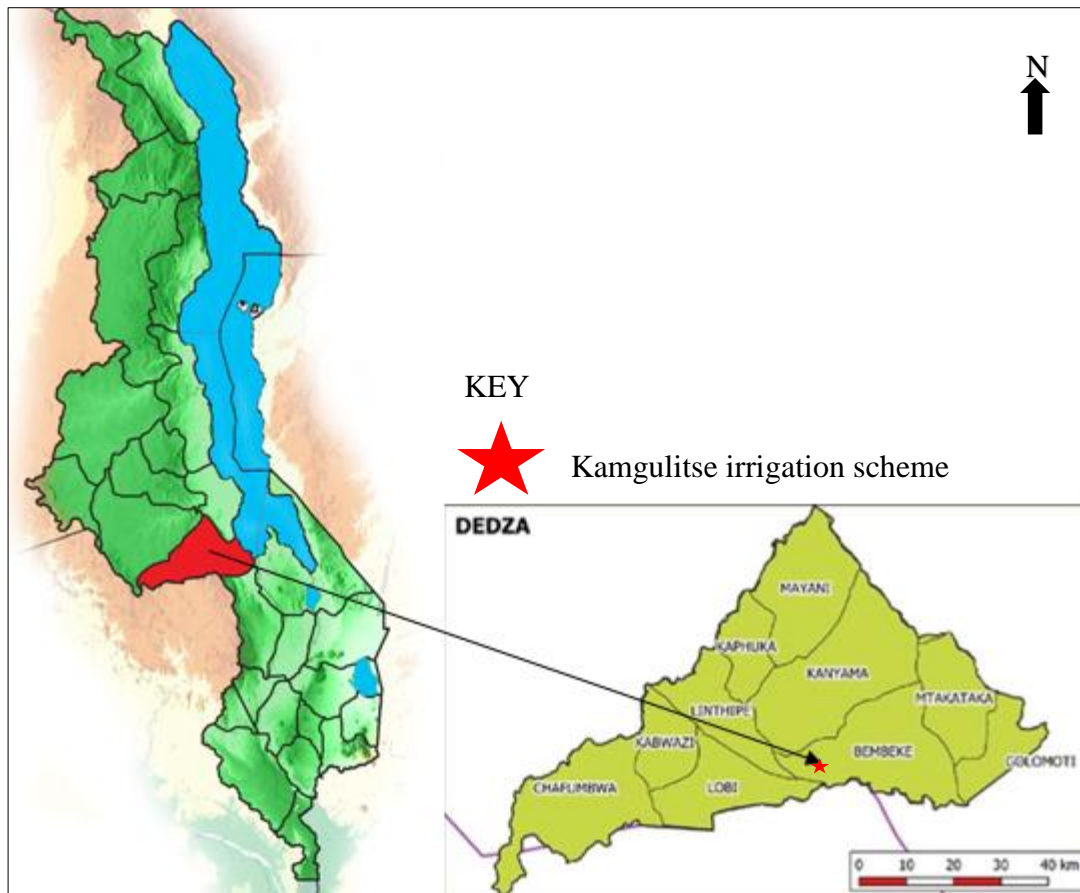


Figure 3.1: The location of Dedza district in Malawi

The physiography of the district is characterized by upland and lowlands with uneven terrain. The district is divided into three topographic zones, namely: The Lilongwe plain with an altitude of 1100 – 1300 m, the Dedza highlands (1200 – 2200 m), and (1000-1500m) for Dedza escarpment (Munthali *et al.*, 2019).

According to Munthali *et al.* (2019), the district has a subtropical highland climate. The mean annual temperatures are relatively low and fluctuate between 14 and 21 °C, with an average temperature of 15.5 °C. The coldest months are June and July, and November is the hottest month. Rainfall occurs between November and March, with a mean annual rainfall ranging from 800 mm to 1200 mm. According to the Government of Malawi (2018), the district is characterized by generally ferruginous soils that are deep and brown to reddish.

3.2.1 Field trial site

The field trials were set in the smallholder irrigation scheme called Kamgultse irrigation scheme. The scheme is located in the extension planning area (EPA) of Bembeke (Figure 3.1) which is under traditional authority (TA) Kamenyagwaza. The scheme is located in Kamgultse and Msesa villages of TA Kamenyagwaza. The site is located at -14.33975 latitudes, 34.41729 longitudes, and 1495.94m altitudes.

3.2.2 Irrigation scheme profile and water source

Kamgultse irrigation scheme was designed by irrigation officers under Dedza district irrigation advisory services unit. It was amongst the gravity-fed irrigation schemes constructed in 2010 with USAID funding to the Malawi government. The scheme was anticipated to improve its member's food security and incomes. The scheme had the potential to irrigate more than 15 ha, however only 6 ha, were developed during the construction phase due to a lack of funds and the technical design aspects of the scheme.

The scheme was designed to allow farmers to achieve three growing seasons. Two seasons with 100% irrigation and one with supplementary irrigation. Kamgultse irrigation scheme is among the places where agriculture production is done using the perennial river called Chiweta (Figure 3.2).

3.2.3 Soil characteristics

The relative percentage of sand, silt, and clay in the soil of the experimental site spread out from 56 to 80, 18 to 36, and 1 to 8 respectively (Table 3.1). According to the textural triangle (Figure 2.11), the experimental site has sandy loam soil. The soil BD ranges from 1.25g/cm³ to 1.66g/cm³ with a mean value of 1.40g/cm³. 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/cm³ 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 detailed procedures for collecting soil samples and their analyses are presented in Appendix A1, A2 and A3.



Figure 3.2: The weir on the Chiweta River for Kamgultse irrigation scheme

Table 3.1: 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/cm³)	1.66	1.25	1.40	0.1	0.07
PD (g/cm³)	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

3.3 DATA COLLECTION FOR ESTABLISHING STRENGTHS AND WEAKNESSES OF THE CURRENT IRRIGATION PRACTICES IN DEDZA

To collect representative data from the communities whose membership is under irrigation schemes, the stratified random sampling approach was used for sampling. This is because this approach enables the capturing of the key attributes of the population (Singh, 2019). It assures the representation of all groups in the population. The data collection process involves two steps, namely: (i) quantitative household survey and (ii) qualitative approach involving focus group discussions.

3.3.1 Household Quantitative survey

This involved the acquisition of an up-to-date register of the farming households in Dedza district from the Ministry of Agriculture and Food Security. From the register, the total number of farming households were by using Slovin's formula in equation 3.1 and the sample size was determined using Equation 3.1.

$$n = \frac{N}{1 + Ne^2} \quad (3.1)$$

Where:

n = Samples size

N = Total population

e = Margin of error.

a It is recommended that researchers come up with their margin of error by subtracting the set confidence level from 1 (Gusen *et al.*, 2017; Asriani, 2018; Masta and Riyanto, 2020).

The sample size (n) was selected using a four-stratum process (Table 3.2). The first stratum consisted of 8 out of the 10 EPAs in Dedza district. The 8 EPAs were chosen because they are potato growers. The second stratum comprised 40 villages that were randomly sampled from the first stratum proportionate to the EPA population. From each of the sampled villages, at least 10 households (third stratum) were randomly selected, and the fourth stratum comprised a member of the household who was involved in irrigation farming. In cases where the whole household was involved, the family selected one representative. The stratified samples are presented in Table 3.2.

Table 3.2: Dedza district stratified sample

Name of EPA	EPA Farmer population	Number of sampled Villages	Number of sampled households
Bembeke	20,457	4	38
Chafumbwa	20,418	4	38
Kabwazi	19,632	4	36
Kanyama	28,764	5	53
Kaphuka	28,964	5	54
Linthipe	50,419	9	93
Lobi	25,730	5	48
Mayani	21,390	4	39
TOTAL	N=215,777	40	N ≈ 399

A household questionnaire survey involving 399 household representatives was conducted from July to September 2022. The aspects covered in the structured survey included: current irrigation strategies, individual farmers' preferred irrigation strategies, strengths, and weaknesses of the current irrigation strategy, and land ownership. Sections of the questionnaire that are important to this dissertation are placed in *Appendix C1 and C2*.

3.3.2 Focus group discussions

Focus groups are especially useful as a complement to the other methods of data collection for providing in-depth information in a relatively short period (Nazari *et al.* 2018; Ruth *et al.*, 2019; Gundumogula, 2020).

In this case, focus group discussions followed the questionnaire survey and the findings from their analysis. Focus group discussions were conducted within the small-scale irrigation schemes to gain additional insights into the strengths and weaknesses of the current irrigation strategies. The discussion focused on the common irrigation strategies of the gravity-fed canal, bucket, treadle pump, motorized pump, and solar pumps. Due to similarities between the schemes in the area and the crop in question, only those irrigation schemes that solely produce potatoes during winter were selected.

One irrigation scheme per EPA was identified. This resulted in a total of 10 schemes. One focus group discussion was conducted within each scheme between July and September 2022. The guiding questions in Appendix D were used.

3.4 PROCEDURE FOR DETERMINING DEFICIT IRRIGATION EFFECTS ON POTATO PRODUCTION

The section has many steps which include the determination of the soil moisture depletion for the field trials, plot sizes, Data collection for soil characterization, weather data collection, crop establishment and management, Irrigation water supply and requirement, determination of the daily soil water storage, potato crop data and the analysis of the potato yield and yield-related traits data.

3.4.1 Soil moisture depletion for the trials

The field trials used three maximum allowable depletion (MAD) levels, according to Gultekin and Ertek, (2012); Hilemical and Tibebe, (2018), were 20%, 40%, and 60% depletion of the total plant available soil moisture content. The irrigation schedule was installed by replenishing water when the soil moisture content is 80, 60, and 40% of the plant's available soil moisture content. The three MAD levels resulted in three fields (MAD) blocks. Three furrow irrigation strategies were applied for each MAD level. The three furrow irrigation strategies were the conventional furrow irrigation (CFI), alternate furrow irrigation (AFI) and the fixed furrow irrigation (FFI).

i) Conventional furrow irrigation

In this strategy, involved water application to every furrow during each irrigation event.

ii) Alternate furrow irrigation

In this strategy, one of the two neighbouring furrows was alternately irrigated during a consecutive irrigation event.

iii) Fixed furrow irrigation

In this strategy, irrigation was fixed to one of the two neighbouring furrows throughout the season.

Each MAD block had three treatment plots for each irrigation strategy (CFI, AFI, and FFI) assigned at random within blocks. The objective of using these blocks is to reduce

the variability of the error term. Each block had nine plots and for the three MAD blocks, there were a total of 27 plots (Table 3.3). Note that the complete randomized block design has no restriction on the number of treatments or replicates (Verdooren, 2020). One advantage of a randomized complete block design is its ability to remove one source of variation from the experimental error and thus increase precision (Petersen, 2017).

Table 3.3: Treatment used for the experiment

REP	MAD1			REP	MAD2			REP	MAD3		
	T1	T2	T3		T1	T2	T3		T1	T2	T3
I	T00	T01	T02	I	T01	T02	T00	I	T02	T00	T01
II	T01	T02	T00	II	T02	T00	T01	II	T00	T01	T02
III	T02	T00	T01	III	T00	T01	T02	III	T01	T02	T00

NB: T00 is the plot with CFI, T01 is the plot with AFI, and T02 is the plot with FFI strategies.

3.4.2 Plot size

Each plot had 10 ridges and resulted in the gross area of each plot of 23.63 m² (3.5 m by 6.75 m). The distance between plots and between replications were 1m and 0.5m respectively. The first and last rows from each side of the plot were regarded as guard rows resulting in a net plot of 2.5m by 5.75m (8 ridges).

3.4.3 Weather data collection

Weather parameters of maximum temperature, minimum temperature, wind speed, sunshine hours, relative humidity, precipitation, and evapotranspiration were recorded daily from the local weather station (Figure 3.3). The weather data was particularly valuable in detecting the amount of rainfall and soil moisture to decide when to irrigate.



Figure 3.3: Dedza District local weather station

3.4.3.1 Weather condition

During the field experiments implementation period, the precipitation water was not adequate. There were only three rainfall events (Figure 3.4). 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 3.4). 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 increased as the crop advanced during the growing period (Figure 4.3).

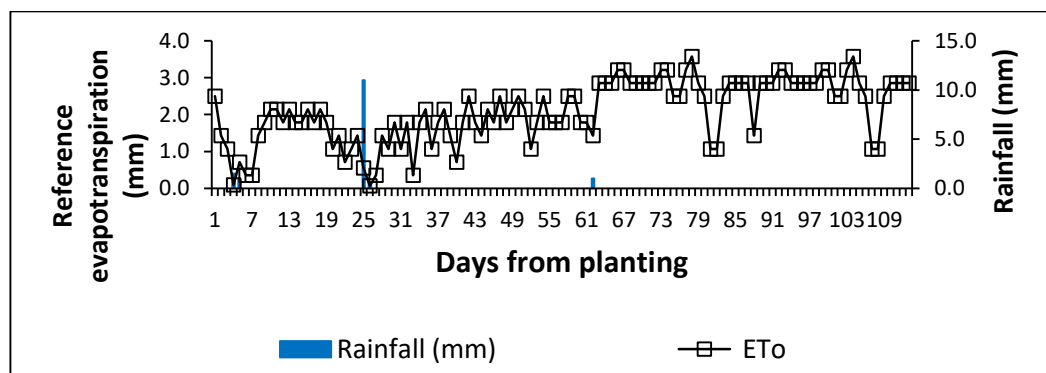


Figure 3.4: Precipitation against reference evapotranspiration

Table 3.4: 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

3.4.4 Crop establishment and management

This involved four sub activities which include land preparation, potato planting, fertilizer application, pest, and weed management.

(i) Land preparation and planting

Land preparation typically involves ploughing, harrowing, and levelling the field to make it suitable for crop establishment.

After collecting soil samples, the whole experimental area was ploughed on the 27th of April to a depth of 25 cm. This activity was done to help to loosen the soil and make it suitable for potato crop development. Figure 3.5 shows how ploughing was done at the irrigation scheme.



Figure 3.5: Ploughing of the selected experimental site using hand hoes

Land levelling was followed by harrowing on 2nd May 2022. Levelling was also done manually. The field where experimental plots were levelled to remove possible water ponding spots that would disturb the uniform distribution of irrigation water on the field. On the other hand, it also ensures the optimal slope for water movement across the plots during irrigation. Similarly, harrowing was done manually by breaking the clods into finer soil structure suitable for planting. All the land preparation activities were done using hand hoes which is the common practice in the area. Figure 3.6 shows how the field looked after levelling and harrowing were done.



Figure 3.6: The appearance of the field after levelling and harrowing

The plot layout and ridge making were concurrently done on 3rd May 2022. Ridging is one of the most common land preparation practices in Malawi. The technique results in irrigation and nutrient management, water saving, better crop stand, and a reduction in lodging (Ali *et al.*, 2018). Figure 3.7 shows part of the field after ridging. The ridges were running across the field slope. This was done because performing tillage along the contour of the land can be an effective conservation measure (Ricci *et al.*, 2020).



Figure 3.7: The field ridged across the slope

(i) Potato planting

The potato variety used was Violet. This variety was used because it was found to be the most popular among potato-growing farmers in the study area and it is resistant to most notable potato diseases such as late blight. The potato was planted on 7th May 2022. Tubers were planted 30 cm apart on ridges spaced 75 cm. After planting, tubers were covered with soil. To create a more favourable environment for plant growth, the potatoes were planted after the first irrigation.

(iii) Fertilizer application

Sulphate Ammonium basal dressing fertilizer was applied at the rate of 100 kg ha⁻¹. This rate of basal dressing fertilizer application is recommended in the area. The fertilizer was applied in the grooves made on top of the ridges. Four weeks after the emergency, the potato was top dressed with 150 kg ha⁻¹ of Calcium Ammonium Nitrate (CAN) fertilizer along the plant rows on the ridge.

(iv) Pest and weed management

Physical removal of weeds was only done occasionally after field scouting. Between the first week and the fourth week after planting, the field was weeded using a Hoe. Aphids were controlled by spraying with 34 grams of Dimethoate 20 WP in 14 litres of water in a knapsack sprayer. In total 6 spraying events were done and a total of 204 grams of Dimethoate 20 WP was used throughout the growing period. At some point, early blight was controlled by applying Dithane M45 at the rate of 20 grams per 10 litres of water. During the study, 60 grams of Dithane M45 was used for the 3 spraying events.

3.4.5 Irrigation water supply and Requirement

(i) Irrigation water supply

Water for irrigation was abstracted from the river (Figure 3.8) via the canal. From the canal (Figure 3.8A), a 63 mm diameter siphon (Figure 3.8B) was used to divert water by gravity to the experimental area (Figure 3.9). The siphon was calibrated at every irrigation event to calculate the flow rate (Q) in litres per second. The siphon calibration was done using the following approach:

- ❖ A 10 litres container and a stopwatch were used.
- ❖ The siphon was positioned to get water from the canal through a water distribution box near the experimental plots.
- ❖ An empty container was placed at the siphon outlet.
- ❖ As soon as the water started dropping into the container, a stopwatch was switched on.
- ❖ When the container was full, the stopwatch was switched off and the time taken was recorded.
- ❖ Steps 3, 4, and 5 were repeated three times to minimize errors by having an average figure.
- ❖ The ratio of the cumulative volume and time recorded were calculated in litres per second.
- ❖ The calculated figure was recorded as the flow rate for that particular irrigation event.

According to FAO (2015), the total time (T in seconds) to irrigate the plots was recorded to estimate the volume of water (V) that entered the field during an irrigation event as:

$$V = Q \times T \quad (3.2)$$

Where:

V = volume of water coming into the field through the siphon in litres

Q = calibrated flow rate of water passing through the siphon during irrigation

T = total time taken to finish irrigation in seconds

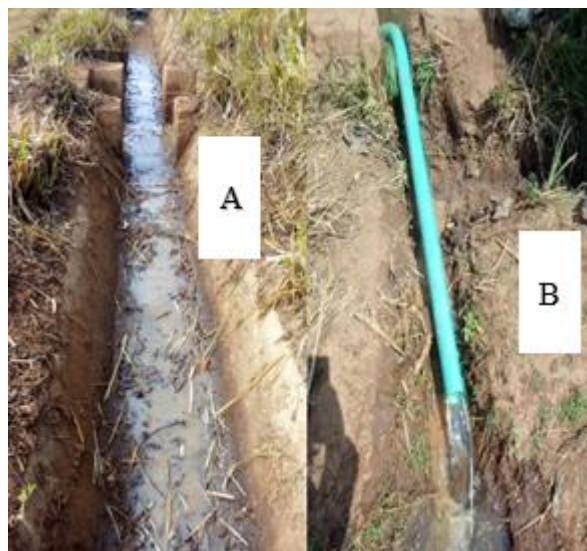


Figure 3.8: Water conveyance system within the irrigation scheme



Figure 3.9: water delivery into the furrows

(ii) Determination of the daily soil water storage

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. The major processes affecting the water balance of a crop root zone were irrigation, rainfall, evapotranspiration, runoff, deep percolation, subsurface flow, capillary rise, and change in soil water storage (Figure 3.10). For design and management purposes, the field water balance was summarised mathematically as:

$$CSWS = PSWS + Pe + IRn + GW - Ro - Dp - ETc \quad (3.3)$$

Where:

$CSWS$ = current soil water storage in millimetres (mm)

$PSWS$ = previous soil water storage in mm

Pe = effective precipitation in mm

IRn = net irrigation in mm of water per meter soil

GW = groundwater contribution to water use during the period

Ro = surface runoff that leaves the area during the period

Dp = deep percolation

ETc = crop water use in mm

The IRn was determined based on the available water storage capacity (field capacity moisture content) of the soils in the experimental field. Irrigation scheduling was done using the guide to the available water storage capacity for various soils (Figure 3.10).

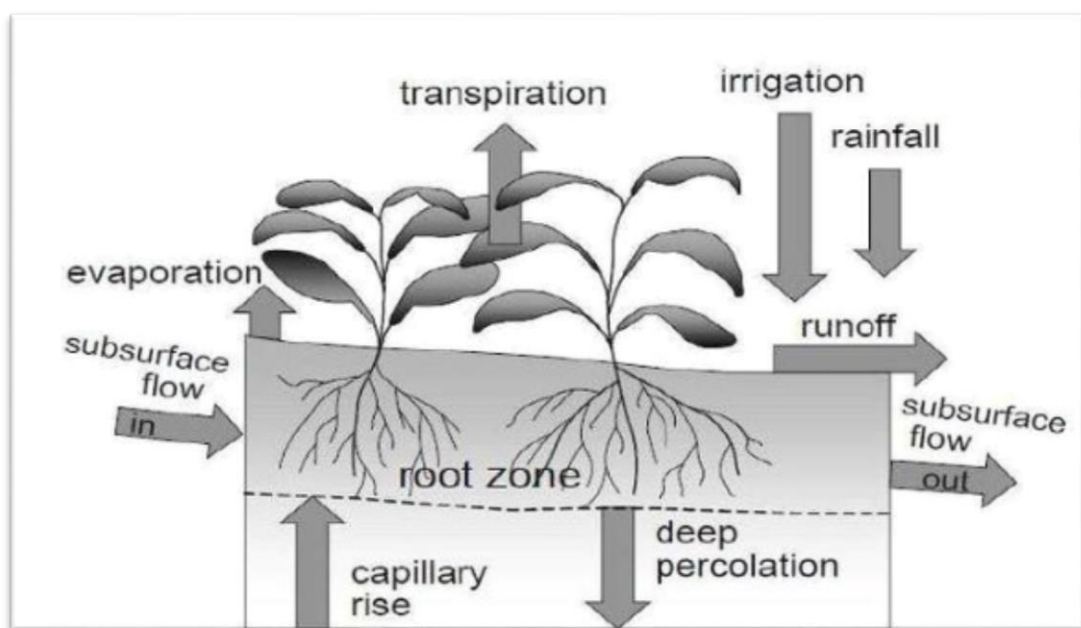


Figure 3.10: USDA diagram of the soil water balance of a crop root zone

After knowing the available water storage capacity of the soil for the experimental area, irrigation days were scheduled based on the set different blocks of MAD (20, 40, and 60%) using Equation 2.4.

(iii) Actual crop water use

Crop water use (ETc), or crop water requirement, is the total amount of water needed for evapotranspiration from planting to harvest. Crop evapotranspiration or crop water use was determined daily by multiplying the reference evapotranspiration (ET_0) by the crop coefficient (Equation 3.4) (Torres *et al.*, 2021):

$$ET_c = ET_0 * K_c \quad (3.4)$$

Where:

ET_c = actual crop water use in mm

ET_0 = reference evapotranspiration in mm

K_c = crop coefficient based on crop development stage

The ET_0 used in Equation 3.5 was determined based on *class A* pan (Figure 3.11) evaporation and its coefficient. The Pan evaporation method is widely used in some parts of Southern Africa including Malawi (km). This is mainly because the method has proved to be both very practical as well as simple, which appeals to many farmers and practitioners.



Figure 3.11: Meteorological local weather station in Dedza-Malawi having Class A Pan

The measured evaporation from a pan (E_p) is related to the ET_0 through an empirically derived pan coefficient (K_p) as given in the following equation from FAO (2015):

$$ET_0 = K_p + E_p \quad (3.5)$$

Where:

Plants are theoretically able to obtain water from the soil whenever the water content exceeds the PWP. However, as the soil water content becomes low, plants need more suction force to extract the water from the soil. Below a critical moisture content which is determined by the MAD, plants get stressed because of the difficulty of getting moisture from the soil. Soil water content between the critical soil moisture content and soil moisture content at FC is the RAW which was computed in Equation 2.2 To calculate the quantity of water that has been lost, the crop water use was subtracted from the actual amount of water applied during irrigation and precipitation for the crop development period.

3.4.6 Potato crop data

(i) Plant growth data

The occurrence of the growth stage was recorded when 50% of the plants reached the specific growth stage: sprouting, leaf development, formation of lateral shoots, stem elongation, tuber formation, inflorescence and flower development, tuber development, and senescence. During the life cycle of the crop, six plants per treatment were observed for the following: the day of sprouting, the number and length of stems, the duration of the tuber bulking stage, and the number of tubers per plant. The number of stems was recorded for ten randomly selected and tagged plants from the net plot at the 50% flowering stage of the plants. The height of the main plant stem was measured from the ground surface to the tip of the apex at physiological maturity.

(ii) Yield and yield-related traits

On the 122nd day (harvesting day), the potential yield was determined with the fresh weight of the tubers from 10 plants per treatment. Tubers per plant were counted from ten randomly selected and pre-tagged plants per net plot area at the physiological maturity of the crop. The weight of tubers per plant, marketable yield, and tuber yield of each plot were weighed in kilograms. Observations were made on disease and insect infestations.

3.4.7 Analysis of yield and yield traits data

The measured yield was converted to yield per hectare in kg/ha using the plot areas.

(i) Statistical data analysis

Using the SPSS, SAS JMP Version 14, and excel, the results were subjected to analysis of variance (ANOVA). The least significant difference (LSD) test was used to distinguish significance differences among the measured parameters between the means of treatment at a 5 percent probability.

(ii) Yield and water use efficiency

The yield and water use efficiency were selected as dependent variables over irrigation water and labour. Crop water use efficiency (CWUE) was calculated as below:

$$CWUE = \frac{Y}{ET} \quad (3.6)$$

Where:

$CWUE$ = crop water use efficiency

Y = yield of tubers in Kilograms per unit square meter (kg ha^{-1})

ET = volume of water used for potato-growing in cubic meters per hectare ($\text{m}^3 \text{ha}^{-1}$)

3.5 POTATO PRODUCTION PROFITABILITY UNDER ALTERNATING AND FIXED DEFICIT FURROW IRRIGATION IN DEDZA DISTRICT

3.5.1 Gross margin analysis

A gross margin analysis was used as a proxy for treatment-level profitability. In this study, gross margin served as the unit for evaluating the financial performance of an enterprise and gives an indicator of the feasibility of an enterprise and its potential to contribute to overall income. Gross margins were calculated per unit area and a financial difference between the returns received from assumed sales of potatoes and the variable costs associated with production was calculated using Equation 3.7.

$$GM = TR_{ij} - TVC_j \quad (3.7)$$

Where:

GM = gross margin (\$/ha)

TR_{ij} = total (gross) revenue (\$/ha)

TVC_j = total variable Costs (\$/ha)

The total revenue of the outputs (potato tubers) was calculated by applying Equation 3.8:

$$TR_{ij} = Y_{ij} * PY_{ij} \quad (3.8)$$

Where:

TR = total (gross) revenue (\$/ha)

Y = yield or physical production (Kg/ha)

P = price of outputs (\$/Kg)

i = Crop

j = Scheme management

The price of potatoes was assumed from the circular obtained from the Ministry of Agriculture, Irrigation, and Water Development (MoAIWD) farm gate price circulars (Government of Malawi, 2022), which are released just before the onset of an agricultural season. The minimum farm gate prices are determined through a consultative process involving key stakeholders in the agriculture sector. Every year, the MoAIWD undertakes a cost-of-production survey in all districts across the country. This survey involves collecting data on production costs from sampled smallholder farmers on selected crop enterprises. The data is then used to compute break-even prices. A markup profit usually set between 10 and 30% on the break-even price is considered to arrive at the minimum farm gate price.

3.5.2 Economic water productivity

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 (Moseki *et al.*, 2019). Farm gate prices circulated by the Malawi government were used. It is used to measure the return to irrigation water as a scarce or limited resource within the irrigation scheme.

3.6 SUMMARY

In this chapter, the methodology for collecting data in line with the study objectives was outlined. The outline included experimental site characterization, the design procedure for the experimental plots, soil and weather data collection, crop establishment and management, crop data collection process, and data analysis procedures. The data collected using outlined procedures were analyzed and the results were presented in chapter four to answer the research questions set at the beginning of the study.

The study was conducted in 8 EPAs of Dedza district. The field trials were set in the smallholder irrigation scheme called Kamgultse irrigation scheme which is in Bembeke EPA. Household quantitative survey and focus group discussions were used to establish strengths and weaknesses of the current irrigation practices in the district. To determine deficit irrigation effects on potato production, a number of steps were followed. The field trials used three MAD levels of 20%, 40%, and 60%. Each plot had a gross area of 23.63 m².

Because of the importance of soil characterization, soil samples were collected from the experimental site before land preparation for determining the bulk density, soil texture, soil moisture content at field capacity, and soil moisture content at wilting point. As an indicator of soil compaction and soil health, soil bulk density was determined using core method. Disturbed soil samples were collected for MC determination at FC and PWP which was significant in water utilization within the irrigation scheme. Soil texture was determined using Bouyoucos or the hydrometer method. By knowing the texture of the soil, the water application rate, and frequency were easily determined.

Weather parameters of maximum temperature, minimum temperature, wind speed, sunshine hours, relative humidity, and precipitation were recorded daily from the local weather station in detecting the amount of soil moisture.

All the land preparation activities on the selected site were done using hand hoes which is the common practice in the area. Violet variety was used because it was found to be

the most popular among potato-growing farmers in the study area and it is resistant to most notable potato diseases such as late blight. Recommended fertilizers (Ammonium Sulphate and Urea) for the areas were applied. Pest and weed management were done using recommended cultural practices of the area.

Water for irrigation was abstracted from the river using gravity via the canal. 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. The ETC was determined based on class A pan evaporation because of its simplicity among farmers as well as practitioners.

Data on Potato growth and yield were captured for analysis to determine the potato yield, water use efficiency and potato production profitability under alternating and fixed deficit furrow irrigation in Dedza District.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter focusses on the discussion of results in line with the research questions. It also highlights the descriptive statistics of the established strengths and weaknesses of current irrigation methods in the study area, soil characterization, weather conditions, and irrigation water supply to the potato crop. The chapter is arranged into 6 major sections. Following this introduction is section 4.2 which discusses the strengths and weaknesses of current irrigation methods in the study area. This is followed by section 4.3 which explains the environmental factors affecting irrigation in general. The next section is 4.4 which evaluates the influence of deficit irrigation as compared to the conventional furrow irrigation methods. Section 4.5 explains the profitability of potato production under deficit irrigation. The summary of the chapter is given at the end of this chapter as section 4.6.

4.2 STRENGTHS AND WEAKNESSES OF THE CURRENT IRRIGATION PRACTICES IN DEDZA DISTRICT

4.2.1 Characteristics of respondents

The irrigation practices were considered in terms of land ownership, water lifting/delivery methods and irrigation methods. Based on the information from the focus group discussions, the participants could be regarded as typical of the rural population of Dedza district comprising smallholder farmers. The age range of the smallholder farmers was 39 to 49 years of which 59% were females and 41% were males (Figure 4.1). Almost all the farmers had an average piece of farmland of about 0.22 hectares on which they grew irrigated potatoes. The land was owned through inheritance (11.3%), renting (52.4%) or both (36.3%). In Dedza, kinship is matrilineal, as such, land is inherited through the women (Fischer *et al.*, 2021).

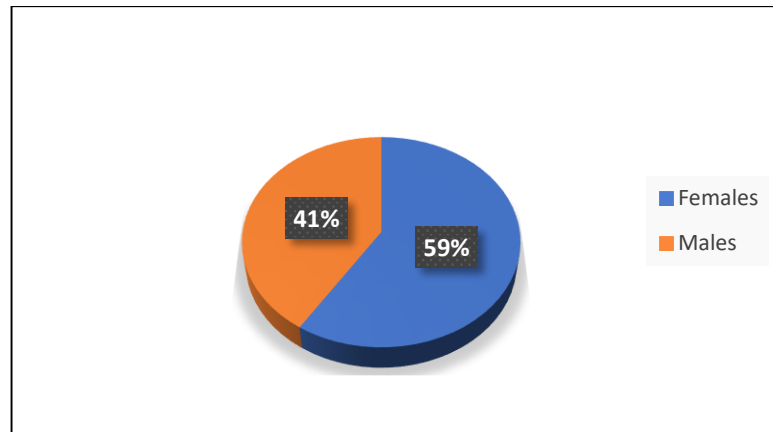


Figure 4.1: Gender of participants

The study also established that farmers in Dedza used furrow irrigation method, basin irrigation method or water cans/buckets to irrigate their potato crop. The methods used for water lifting and delivering it to the irrigated fields included river diversion into gravity-fed canals from which through use of watering cans/buckets, treadle pumps, motorized pumps, or solar pumps (Figure 4.2), delivered water to the fields. Figure 4.2 shows that the majority of the respondents (80.5%) used gravity-fed canals to irrigate their potato crop. Similar results were also found by other studies which were done in Malawi (Getts, 2018; Frake, 2019; Frake *et al.*, 2020). According to the data analyses results, most farmers using gravity-fed canals irrigated 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.

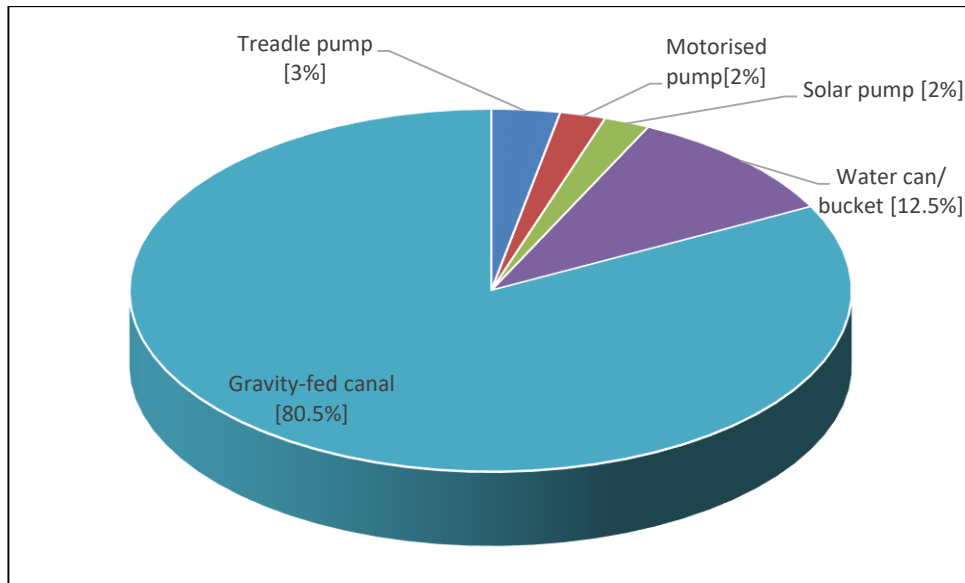


Figure 4.2: The current irrigation water lifting and delivery methods in Dedza district

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

4.2.2 Strengths and weaknesses of gravity-fed canal irrigation water delivery

Gravity-fed canal irrigation water delivery method involves water flowing 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. Similar observations were indicated by Fandika *et al.*, (2020). The canals in the schemes in Dedza were built using locally available and inexpensive materials. The canals were lined with earth, except the main canal. The problem observed with the earth lined canals was that they required maintenance after every irrigation event.

Almost 81% of the small-scale irrigation schemes in the study area used short furrows ranging from 2.5m to 6m. Onishi *et al.* (2019) established that using short furrows in irrigation schemes resulted in uniform water distribution across the field, enabling greater control of water application levels. According to Onishi *et al.* (2019), shortening the furrow length can be an effective way to save water. However, short furrows have the disadvantage of wasting land due to numerous furrow column spacings. This makes furrows that are as long as the field length better as they result in maximum land utilization (Abraham, 2019).

The results also showed that farmers practicing furrow irrigation method required little technical knowledge. The irrigation method has proven to be convenient amongst farmers in Dedza because there was a shortage of a highly skilled labour force in the district.

4.2.3 Strengths and weaknesses of watering can/bucket irrigation water delivery

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 was 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 cheaper in contrast to advanced irrigation water delivery methods. However, results from the study show that the water delivery method created more work for the farmer especially if it was used on larger plots. This makes the method inefficient and labour-intensive and less desirable (Baldwin and Stwalley III 2022).

4.2.4 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 2% 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 could

not 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 suppliers. This absence of the independence of farmers to procure irrigation pumps on their own made irrigation based on these pumps unsustainable in Malawi as observed by Chiwasa and Kambewa (2018).

4.3 EFFECTS OF DEFICIT FURROW IRRIGATION AS COMPARED TO CONVENTIONAL FURROW IRRIGATION METHODS.

4.3.1 The number of scheduled irrigations and the amount of irrigation water supplied

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 environmental factors (solar radiation, wind and relative humidity) (Qin *et al.*, 2018; Ahmedi *et al.*, 2019; Elhani *et al.*, 2019; Igbal *et al.*, 2020; Abebe *et al.*, 2021).

The analysis results indicated that the number of scheduled irrigations reduced as the MAD increased. This is because it takes more days to deplete the soil moisture to a large MAD than to a small MAD level (Table 4.1). The table also shows that irrigation water supplied for growing potatoes was significantly influenced by the MAD level as well as the irrigation technique. This is reflected in the highest volume of water supplied under the control (20% MAD-CFI) set-up in which no water-saving strategies were applied. This high irrigation water application is very common in Malawi agriculture (Chinula, 2019; Fandika *et al.*, 2020). 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) who showed that the seasonal irrigation water applied in alternate furrows was nearly half of the amount supplied in CFI.

Table 4.1: 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)	Net irrigation (mm)	Actual saved water (m ³ /h)	Water saved (%)	Equivalent area for saved water (ha)
20%MAD-CFI	10	3929.9	393	0	0	0
20% MAD.AFI	10	2734.9	273.5	1195	30	0.3
20% MAD.FFI	10	2392.3	239.2	1537.6	39	0.3
40% MAD.CFI	6	2027.8	202.8	1902.1	48	0.4
40% MAD.AFI	6	1681.3	168.1	2248.6	57	0.6
40% MAD.FFI	6	1462.3	146.2	2467.6	63	0.6
60% MAD.CFI	5	4757.7	475.8	(827.8)	(21)	0.6
60% MAD.AFI	5	1304.3	130.4	2625.6	67	0.7
60% MAD.FFI	5	1136.8	113.7	2793.1	71	0.6

4.3.2 Irrigation scheduling

(i) Irrigation scheduling under a 20% MAD

As shown in Table 4.1, the total number of scheduled irrigation events for this MAD level summed up to 10. There were significant differences in the irrigation frequencies (the number of days in between one irrigation event and the next) during the growth period. This was mainly due to the variations in ET_c 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 4.4). 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 was more than 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).

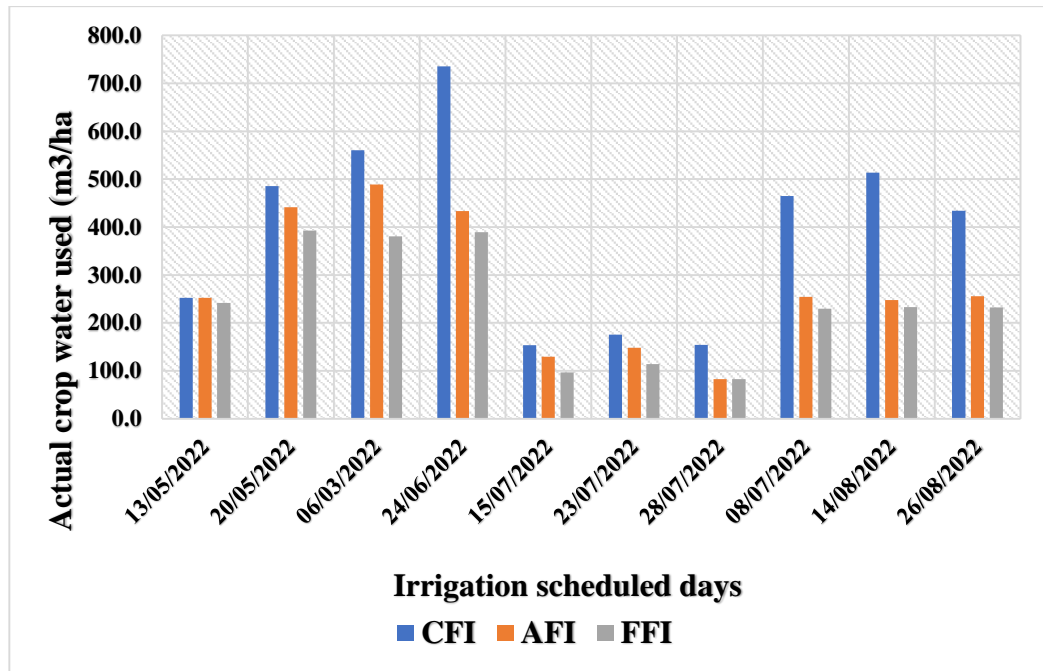


Figure 4.3: Irrigation water distribution within the irrigation regime with a 20% depletion level

(ii) 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 4.5). 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 4.4). Figure 4.5 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.

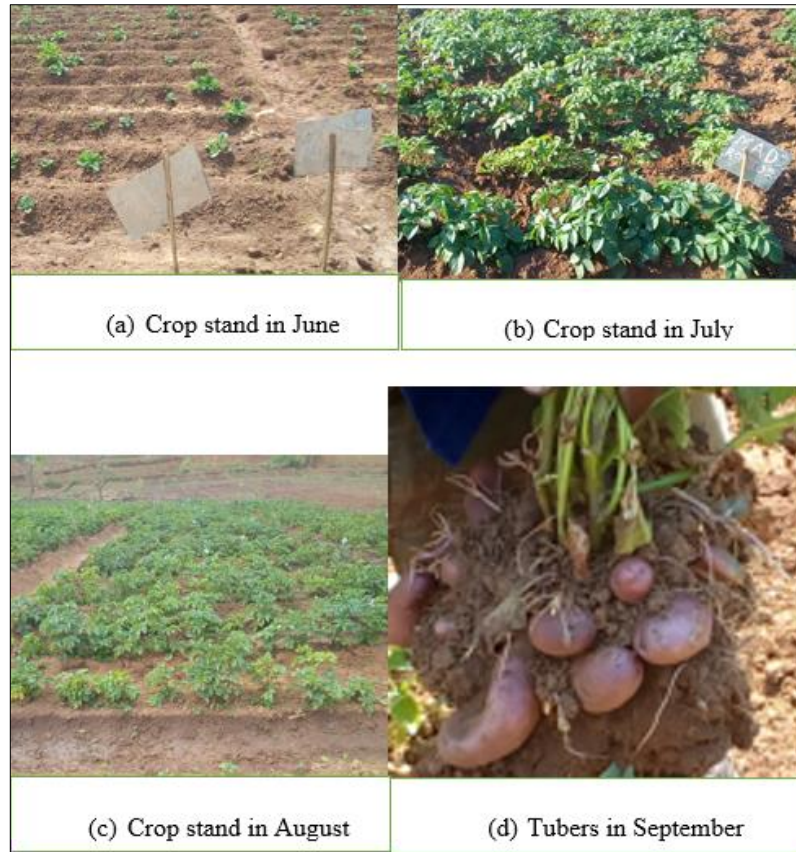


Figure 4.4: Crop stand corresponding to an irrigation event in plots with MAD of 40%

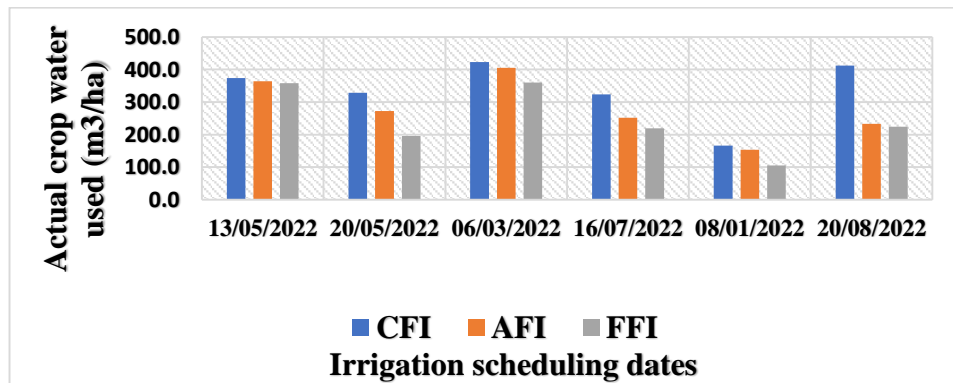


Figure 4.5: Irrigation water distribution within the irrigation regime with a 40% depletion level

(iii) 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 4.4. 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 4.6). 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 which was also reflected in the crop stand as shown in Figure 4.6. Statistically, there was no significant difference between the total volumes of water irrigated in plots under deficit irrigation and that of CFI.

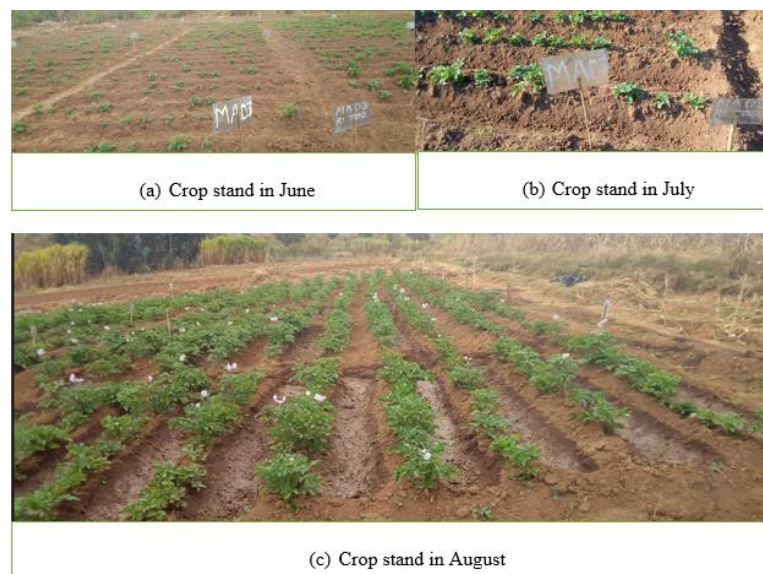


Figure 4.6: Crop stand according to the date of an irrigation event

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 4.8. This could have been due to the increased irrigation frequency durations associated with high MAD levels. Moreover, Figure 4.5 also shows that the same MAD level, CFI used more water than AFI and FFI strategies.

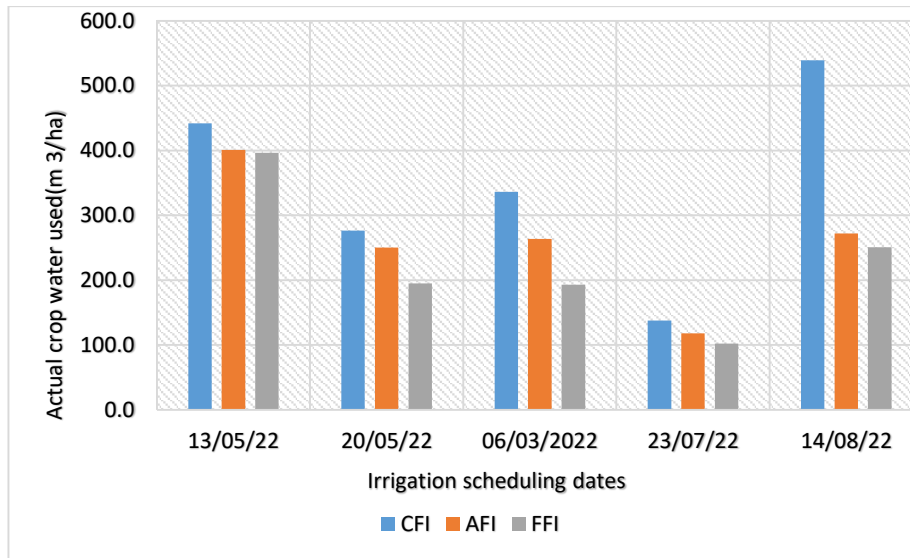


Figure 4.7: Irrigation water distribution within the irrigation regime with a 60% depletion level

These results show that irrigation water can be save by increasing the MAD levels and by using either AFI or/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.

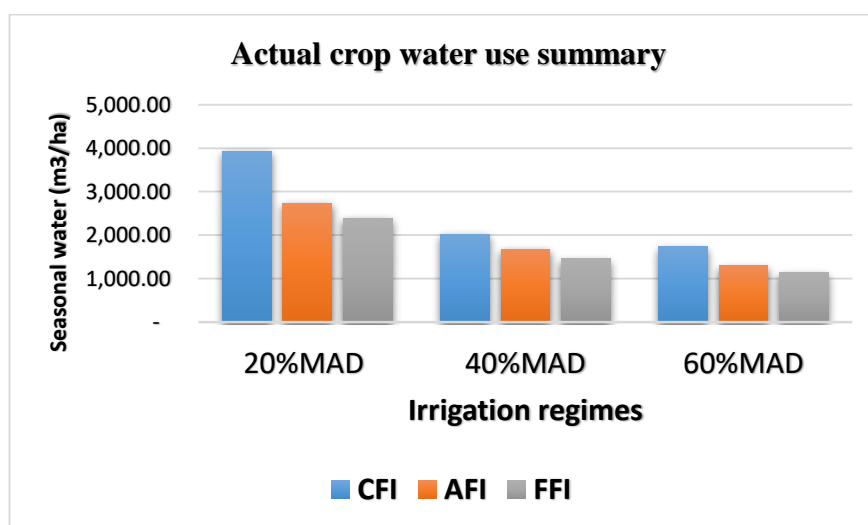


Figure 4.8: Seasonal irrigation water distribution in all three different irrigation regimes

The ratio of actual saved water in plots under AFI and FFI with reference to the control (CFI 20% MAD) was calculated by using Equation 4.1:

$$y = \frac{3929.9 - x_n}{3929.9} * 100 \quad (4.1)$$

Where: y is the amount of irrigation water saved expressed as a percentage, $3875.57\text{m}^3/\text{ha}$ 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 4.1, the potato producer (smallholder farmer) will be able to save water in the range of 35-70% representing $1,341\text{-}2697\text{m}^3/\text{ha}$ 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 $750\text{-}1500\text{m}^3/\text{ha}$. 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 4.2: New area (ha) of production from the saved water due to deficit irrigation

Saved water (%)	Actual saved water(m^3/ha)	Equivalent area (ha)
0	-	
30	1,195	0.3
39	1,537.6	0.3
48	1,902.1	0.4
57	2,248.6	0.6
63	2,467.6	0.6
(21)	(827.8)	0.6
67	2,625.6	0.7
71	2,793.1	0.6

4.3.3 Effects on potato growth and yield factors

(i) Plant height

Plant height is a good indicator for determining stress. It changes at different levels of water deficiency (Bhattacharya, 2021). FFI strategy across the different regimes show no significant effect on plant height ($P \leq 0.05$) (Table 4.5). 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 4.3: 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 different 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 4.5). 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.

(ii) 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 4.6). 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 4.1), and soil type (Table 4.2) 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 4.4: Effects of deficit irrigation strategies and irrigation regimes on the number of stems

Maximum allowable depletion level			
Number of stems			
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.

(iii) Number of tubers

The findings show that the number of tubers per plant is significant at the level of 1% ($P \leq 0.01$) 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 4.9). 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 40% and 60% 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).

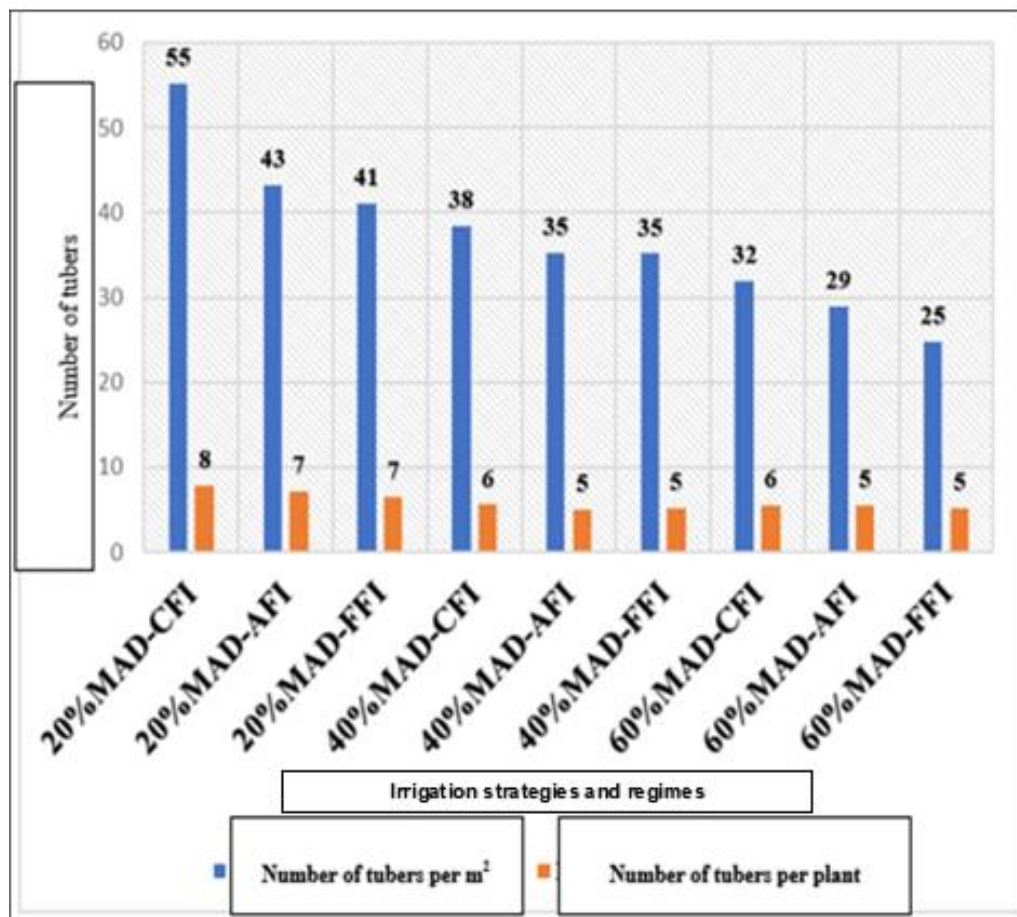


Figure 4.9: Effects of CFI, AFI, and FFI on the number of potato tubers

The findings further show that there is a significant difference ($P \leq 0.01$) 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 Huntensburg *et al.* (2021) who reported that tuber development seemed to respond to systematic moisture stress signals rather than local soil conditions.

(iv) Tuber length

The results showed that tuber length was significantly different ($P \leq 0.001$) across the irrigation regimes as well as the irrigation strategies. On the other hand, there was a significant difference in tuber length at the level of 5% ($P \leq 0.05$) as a result of the interactions between the irrigation regimes and irrigation strategies (Table 4.7). 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 showed 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 4.5: Effects of deficit strategies and allowable depletion levels on the length of tubers

Maximum allowable depletion level			
Tuber Length			
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

(v) Tuber diameter

The findings showed that the tuber diameter was significantly different ($P \leq 0.001$) across the irrigation regimes. Furthermore, the results showed that tuber diameter was significantly different at the level of 5% ($P \leq 0.05$) in all the irrigation strategies (Table 4.8). The tuber diameter recorded in CFI of individual irrigation regimes was 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 under FFI of 40% and 60% irrigation depletion level. In addition, there was no significant difference between CFI under a 60% irrigation depletion level and that of AFI and FFI which was under a 40% irrigation depletion level. These results suggest that tuber diameter was negatively affected by both the MAD level as well as the application of water-saving strategies.

Table 4.6: 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

(vi) Potato yield

The results showed that the yield exhibits high significant difference ($P \leq 0.001$) 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 was 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 4.9). 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 could 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.

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

Table 4.7: Effects of deficit irrigation strategies on potato yields

Treatment	Yield (t/ha)	Yield reduction (%)
20%MADCFI	22.68a	0
20%MADAFI	21.30ab	6
20%MAD-FFI	19.59abc	14
40%MADCFI	17.03abcd	25
40%MADAFI	15.69bcd	31
40%MADFFI	15.01cd	34
60%MADCFI	13.28d	41
60%MADAFI	12.91d	43
60%MADFFI	11.51d	49

4.4 PROFITABILITY OF POTATO PRODUCTION UNDER AFI AND FFI

4.4.1 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 4.9).

Table 4.8: 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 5.10 US\$/m³ (Figure 4.10). 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\$/m³ (Figure 4.10). From the results, it is possible to deduce that a highest water profit can be gained per m³ 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 3.90 US\$/m³ (39% increase) or 4.10 US\$/m³ (46% increase) obtained from the AFI and FFI plots respectively under the 20% MAD regime.

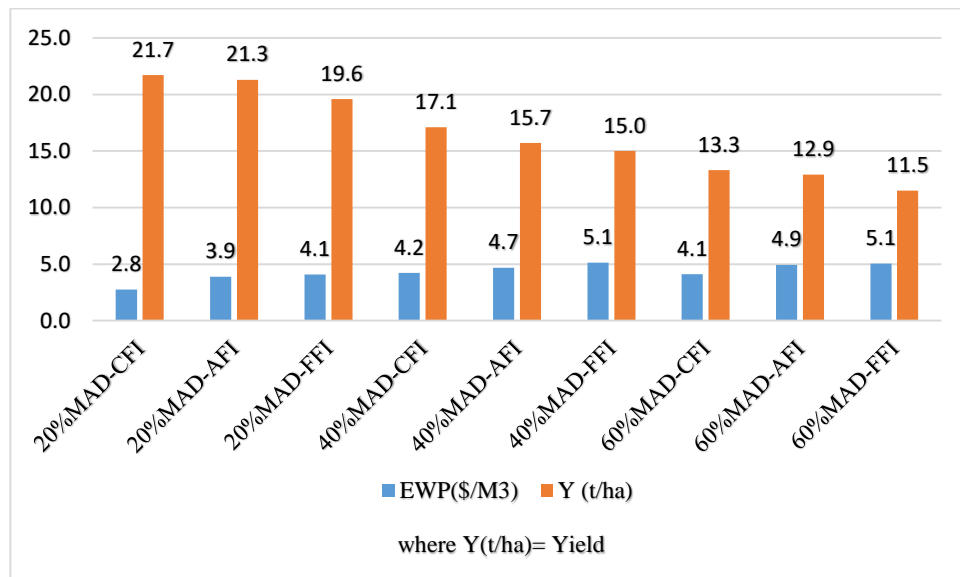


Figure 4.10: Economic water productivity of potato production under deficit irrigation

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.

4.4.2 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 4.10. 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 4.11).

Table 4.9: 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 4.11) were determined using the values in Tables 4.10 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 4.11). The current findings agree with Hilemical 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.

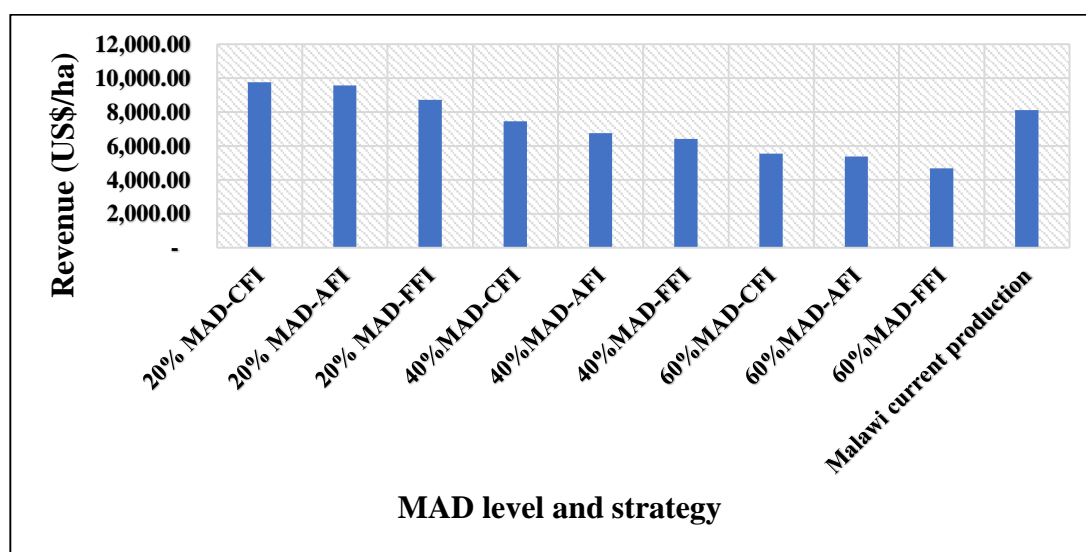


Figure 4.11: Gross margin analysis of irrigated potato under DI

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.

4.5 SUMMARY

In this chapter, the discussion of results in line with the research questions was presented. The discussion included the landowner ship based on matrilineal kinship, strengths and weaknesses of the current irrigation practices in Dedza district. The practices were considered as a combination of the water lifting/delivery methods (based on the gravity-fed canal, bucket/watering can, treadle, solar, motorised pumps) and the irrigation methods which are dominated by furrow irrigation.

In Dedza, almost all the farmers have a fixed size piece of farmland of about 0.22 hectares grown with irrigated potato and the land is either owned through inheritance, rent or both. Gravity fed irrigation schemes have low operating costs for the

conveyance system and ease to use. Short furrows that do not require extensive levelling and grading are commonly used in the study area. Despite being convenient amongst farmers in the area, the furrow irrigation method practiced is labour intensive and time consuming in some irrigation schemes due to their heavily dependence on man power to achieve different in-field tasks. A smaller population of farmers' use bound-basin to reduce surface runoff. However, most of the water within the basins is lost through percolation. Based on the few farmers using available pumping techniques (treadle, motorized, and solar pump), it was observed that using these pumps is efficient and at the same time relatively expensive amongst the smallholder farmers.

The chapter further discussed the influence of deficit and conventional furrow irrigation strategies on irrigation water supply, irrigation scheduling, economic water productivity, and potato plant growth factors. The profitability of potato production under deficit irrigation was established. The results show that with DI, it is possible to expand the area under irrigation, improve water use efficiency and increase productivity in irrigated agriculture. These remain the most important domains of the agro-based economies.

DI has been shown 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.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The chapter presents the major conclusions recommendations based on the study.

5.2 CONCLUSIONS

The major aspects investigated by the study were land ownership in Dedza, effects of AFI, FFI and the different MAD levels on, among other aspects, the potato yield and the profitability of potato production under DI using the gross margins. The major conclusions 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.
- 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, since in Dedza, the farm sizes are fixed and as a result, water saved by an individual farmer would not benefit the farmer by increasing the area under irrigation, has the potential to 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.
- The yields under different irrigation strategies (CFI, AFI, and FFI) within the MAD level were almost the same with CFI giving better yields. The results showed a minimum of 6% and maximum of 49% yield reduction in AFI under the 20% MAD level and FFI under 60% MAD level respectively.

- AFI and FFI under the 20% MAD level show gross profits that are not significantly different from the profits realized under control CFI under the same MAD level. 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.

5.3 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.

5.4 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. Moreover, considering that the experimental plots were on one site of Dedza district and using one cultivar, for the case of Malawi as a whole, 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 would 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.

REFERENCES

- Abdelhafez, A. A., Metwalley, S. M., and Abbas, H. H. (2020). Irrigation: Water resources, types and common problems in Egypt. *Technological and Modern Irrigation Environment in Egypt: Best Management Practices and Evaluation*, 15-34.
- Abdel-Hamid, M., & Abdelhaleem, H. M. (2022). Cost benefits analysis of flexible on-field irrigation systems: a case study. *Innovative Infrastructure Solutions*, 7(1), 7.
- Abdulrahman, F. A., Salih, S. A., and Mahmood, Y. A. (2018). The effect of different irrigation interval on tuber yield and quality of potato (*Solanum tuberosum* L.). *Kurdistan Journal of Applied Research*, 3(2), 27-31.
- Abera, G., and Gebeyaw, M. (2020). Evaluation of Furrow Irrigation Methods for Maize Production in Kobo Girrana Valley, Ethiopia. *Water Management Research*, 03–10, May 2020, Bahir Dar, Ethiopia, 104-111.
- Abera, M., Wale, A., Abie, Y., and Esubalew, T. (2020). Verification of the efficiency of alternate furrow irrigation on amount of water productivity and yield of onion at Sekota Woreda. *Irrigation and Drainage Systems Engineering*, 9(4), 1-5.
- Abidalla, W. A., Naser, A. S., and Mohamed, M. J. (2020). The Dimensions Effect of Border Irrigation Basins on Irrigation Efficiency, Distribution and Uniformity Coefficient. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 69(1), 64-73.
- Abraham, T. (2019). Irrigation Types and Systems. In A. K. Rawat, and U. K. Tripathi, *Advances in Agronomy*. AkiNik Publications, New Delhi: 19-41.
- Abyaneh, H. Z., Jovzi, M., and Albaji, M. (2017). Effect of regulated deficit irrigation, partial root drying and N-fertilizer levels on sugar beet crop (*Beta vulgaris* L.). *Agricultural water management*, 194, 13-23.
- Acar, B., and Sevinçer, B. (2020). Water distribution uniformity of sprinkler irrigation systems for different design and environmental conditions. *International Journal of Agriculture and Economic Development*, 8(2), 8-16.
- Acquah, S. J., Yan, H., Zhang, C., Wang, G., Zhao, B., Wu, H., and Zhang, H. (2018). Application and evaluation of Stanghellini model in the determination of crop evapotranspiration in a naturally ventilated greenhouse. *International Journal of Agricultural and Biological Engineering*, 11(6), 95-103.
- Adhikary, R., and Pa, A. (2020). Clay Pot Irrigation- A Review Study. *Asian Plant Research Journal*, 5(1), 37-42.
- Adu, M. O., Yawson, D. O., Armah, F. A., Asare, P. A., and Frimpong, K. A. (2018). Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation. *Agricultural Water Management*, 197, 79-90.
- Ahmad, K. (2001). Global population will increase to nine billion by 2050, says UN report. *The Lancet*, 357(9259), 864. [https://doi.org/10.1016/s0140-6736\(05\)71800-6](https://doi.org/10.1016/s0140-6736(05)71800-6).
- Danhassan, S. S., and Abubakar, M. G. (2019). Climate change and the dryland resources of Nigeria. A. Ahmed (Ed.). Lap Lambert Academic Publishing.

- Ahmed, W., Safdar, U., Ali, A., Haider, K., Tahir, N., Sajid, S., and Sattar, M. T. (2022). Sustainable water use in agriculture: a review of worldwide Research. *International Journal of Agriculture and Biosciences*, 246-250.
- Akpoti, K., Kabo-bah, A. T., and Zwart, S. J. (2019). Agricultural land suitability analysis: State-of-the-art and outlooks for integration of climate change analysis. *Agricultural systems*, 173, 172-208.
- Alcon, F., Navarro, N., de-Miguel, M. D., and Balbo, A. L. (2019). Drip irrigation technology: Analysis of adoption and diffusion processes. *Sustainable Solutions for Food Security: Combating Climate Change by Adaptation*, 269-285.
- Al-Ghobari, H. M., & Dewidar, A. Z. (2018). Integrating deficit irrigation into surface and subsurface drip irrigation as a strategy to save water in arid regions. *Agricultural Water Management*, 209, 55-61.
- Ali, A. A., Bouchaou, L., Er-Raki, S., Hssaissoune, M., Brouziyne, Y., Ezzahar, J., and Chehbouni, A. (2023). Assessment of crop evapotranspiration and deep percolation in a commercial irrigated citrus orchard under semi-arid climate: Combined Eddy-Covariance measurement and soil water balance-based approach. *Agricultural Water Management*, 275, 1-14.
- Ali, M. H., Hoque, M. R., Hassan, A. A., and Khair, A. (2007). Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. *Agricultural water management*, 92(3), 151-161.
- Ali, S., Xu, Y., Ma, X., Ahmad, I., Jia, Q., Akmal, M., and Jia, Z. (2019). Deficit irrigation strategies to improve winter wheat productivity and regulating root growth under different planting patterns. *Agricultural Water Management*, 219, 1-11.
- Alibabaei, K., Gaspar, P. D., & Lima, T. M. (2021). Crop yield estimation using deep learning based on climate big data and irrigation scheduling. *Energies*, 14(11), 3004.
- Allen, L. N., and MacAdam, J. W. (2020). Irrigation and water management. *Forages: The science of grassland agriculture*, 2, 497-513.
<https://doi.org/10.1002/9781119436669.ch27>.
- Almeida, I. A., de Sousa Pereira, D. J., de Oliveira Costa, J., Quiloango-Chimarro, C. A., and Coelho, R. D. (2022). Dripper clogging: emphasis on the problem and how to minimize impact. *Revista Brasileira de Engenharia de Biosistemas*, 16.
- Alvino, A., and Ferreira, M. I. (2021). Refining Irrigation Strategies in Horticultural Production. *Horticulturae*, 1-6.
- Amanturdiyev, I. (2022). Determining the water-saving irrigation regime and fertilization standards for tomorrow's potatoes. *Journal of Hunan University Natural Sciences*, 49(1), 145-149.
- Ame, M. A., and Shouhua, C. (2022). Economic pipe diameter of laterals in small tube irrigation system. *Alexandria Engineering Journal*, 61(7), 5361-5370.
- Anapalli, S. S., Green, T. R., Reddy, K. N., Gowda, P. H., Sui, R., Fisher, D. K., & Marek, G. W. (2018). Application of an energy balance method for estimating

- evapotranspiration in cropping systems. *Agricultural Water Management*, 204, 107-117.
- Appels, W. M., and Karimi, R. (2021). Analysis of soil wetting patterns in subsurface drip irrigation systems—indoor alfalfa experiments. *Agricultural Water Management*, 250, <https://doi.org/10.1016/j.agwat.2021.106832>.
- Ariza, W., Rodríguez, L. E., Moreno-Echeverry, D., Guerrero, C. A., and Moreno, L. P. (2020). Effect of water deficit on some physiological and biochemical responses of the yellow diploid potato (*Solanum tuberosum* L. Group Phureja). *Agronomía Colombiana*, 38(1), 36-44.
- Aschemann-Witzel, J., and Peschel, A. O. (2019). Consumer perception of plant-based proteins: The value of source transparency for alternative protein ingredients. *Food Hydrocolloids*, 96, 20-28.
- Asriani. (2018). Effect of Communication and Conflict on Teachers' Working Commitment in State Junior High School area of Muna Regency Southeast Sulawesi. *Indonesian Journal of Educational Review*, 5(1), 78-93.
- Atkins, P., and Bowler, I. (2001). Transformation of the farm sector. *Food Society: Economy, Culture, Geography*, London, 56-73.
- Azami, A., Sagin, J., Sadat, S. H., and Hejran, H. (2020). Sustainable Irrigation: Karez System in Afghanistan. *Central Asian Journal of Water Research*, 6(2), 65-86.
- Babaeian, E., Paheding, S., Siddique, N., Devabhaktuni, V. K., and Tuller, M. (2021). Estimation of root zone soil moisture from ground and remotely sensed soil information with multisensor data fusion and automated machine learning. *Remote Sensing of Environment*, 260, 1-13.
- Babakos, K., Papamichail, D., Tziachris, P., Pisinaras, V., Demertzi, K., and Aschonitis, V. (2020). Assessing the robustness of pan evaporation models for estimating reference crop evapotranspiration during recalibration at local conditions. *Hydrology*, 7(3), 62.
- Babiker, A. E., Maria, H. E., Abd Elbasit, M. A. M., Abuali, A. I., Abu-Zerig, M., & Liu, G. (2021). Potential of low-cost subsurface irrigation system in maize (*Zea mays* L.) production in high water scarcity regions. *CIGR Journal*, 42-51.
- Bakr, N., and Bahnassy, M. H. (2018). The Soils of Egypt. In H. El-Ramady, T. Alshaal, N. Bakr, T. Elbana, E. Mohamed, and A. Belar, *Egyptian Natural Resources*. Springer, Switzerland, 33-49.
- Baldwin, G. L., and Stwalley III, R. M. (2022). Opportunities for the scale-up of irrigation systems in Ghana, West Africa. *Sustainability*, 14(14), 1-18.
- Barakat, M. A., Abd El-Mageed, T. A., Elsayed, I. N., and Semida, W. M. (2020). Effect of soil mulching on growth, productivity, and water use efficiency of potato (*Solanum tuberosum* L.) under deficit irrigation. *Archives of Agriculture and Environmental Science*, 5(3), 328-336.
- Baram, S., Dabach, S., Jerszurki, D., Stockert, C. M., and Smart, D. R. (2018). Upscaling point measurements of N₂O emissions into the orchard scale under drip and micro sprinkler irrigation. *Agriculture, ecosystems and environment*, 265, 103-111.

- Barman, U., and Choudhury, R. D. (2020). Soil texture classification using multi class support vector machine. *Information processing in agriculture*, 7(2), 318-332.
- Begum, M., Saikia, M., Sarmah, A., Ojah, N. J., Deka, P., Dutta, P. K., and Ojah, I. (2018). Water management for higher potato production: a review. *International Journal of Current Microbiology and Applied Sciences*, 7(5), 24-33.
- Bellvert, J., Nieto, H., Pelechá, A., Jofre-Čekalović, C., Zazurca, L., and Miarnau, X. (2021). Remote sensing energy balance model for the assessment of crop evapotranspiration and water status in an almond rootstock collection. *Frontiers in Plant Science*, 12, 1-18.
- Berbel, J., Gutiérrez-Martín, C., and Expósito, A. (2018). Impacts of irrigation efficiency improvement on water use, water consumption and response to water price at field level. *Agricultural Water Management*, 203, 423-429.
- Berhanu, M., and Wolde, A. O. (2019). Review on climate change impacts and its adaptation strategies on food security in sub-Saharan Africa. *Agricultural Socio-Economics Journal*, 19(3), 145-154.
- Kimball, B. A., & Bernacchi, C. J. (2006). Evapotranspiration, canopy temperature, and plant water relations. *Managed Ecosystems and CO 2: Case Studies, Processes, and Perspectives*, 311-324.
- Besharat, S., Barão, L., and Cruz, C. (2020). New strategies to overcome water limitation in cultivated maize: Results from sub-surface irrigation and silicon fertilization. *Journal of Environmental Management*, 263, 110398.
- Beyer, M., Kühnhammer, K., and Dubbert, M. (2020). In situ measurements of soil and plant water isotopes: a review of approaches, practical considerations and a vision for the future. *Hydrology and Earth System Sciences*, 24(9), 4413-4440.
- Birpal, S., Mishra, A. K., and Sharma, R. K. (2019). Water front advance under variable border width and initial soil moisture contents under wheat (*Triticum aestivum* L.) crop—I: hydraulics and irrigation efficiencies. *Journal of Water Security*, 5, 1-7.
- Blanco, V., Blaya-Ros, P. J., Torres-Sánchez, R., and Domingo, R. (2020). Influence of regulated deficit irrigation and environmental conditions on reproductive response of sweet cherry trees. *Plants*, 9(1), 94.
<https://doi.org/10.3390/plants9010094>
- de Almeida, C. D. G. C., Gordin, L. C., dos Santos Almeida, A. C., Júnior, J. A. S., de Almeida, B. G., and Provenzano, G. (2023). Assessing different methodologies for irrigation scheduling in protected environment: a case study of green bell pepper. *Irrigation Science*, 41(1), 107-120. <https://doi.org/10.1007/s00271-022-00785-z>.
- Cai, Y., Wu, P., Zhu, D., Zhang, L., Zhao, X., Gao, X., and Dai, Z. (2021). Subsurface irrigation with ceramic emitters: An effective method to improve apple yield and irrigation water use efficiency in the semiarid Loess Plateau. *Agriculture, Ecosystems and Environment*, 313, <https://doi.org/10.1016/j.agee.2021.107404>.

- Cai YaoHui, C. Y., Zhao Xiao, Z. X., Wu PuTe, W. P., Zhang Lin, Z. L., Zhu DeLan, Z. D., and Chen JunYing, C. J. (2019). Effect of soil texture on water movement of porous ceramic emitters: a simulation study. *Water*, 1-13.
- Canales-Ide, F., Zubelzu, S., and Rodríguez-Sinobas, L. (2019). Irrigation systems in smart cities coping with water scarcity: The case of Valdebebas, Madrid (Spain). *Journal of environmental management*, 247, 187-195.
- Cascone, S., Coma, J., Gagliano, A., and Pérez, G. (2019). The evapotranspiration process in green roofs: A review. *Building and environment*, 147, 337-355.
- Cernusak, L. A., Ubierna, N., Jenkins, M. W., Garrity, S. R., Rahn, T., Powers, H. H., and Farquhar, G. D. (2018). Unsaturation of vapour pressure inside leaves of two conifer species. *Scientific reports*, 8(1), 7667.
- Çetin, Ö., and Akalp, E. (2019). Efficient use of water and fertilizers in irrigated agriculture: drip irrigation and fertigation. *Acta Horticulturae et Regioteecturae*, 22(2), 97-102.
- Chafuwa, C. (2017). Priorities for irrigation investment in Malawi (Vol. 28). International food policy research institute
- Chen, Y. G., Cai, Y. Q., Pan, K., Ye, W. M., and Wang, Q. (2021). Influence of dry density and water salinity on the swelling pressure and hydraulic conductivity of compacted GMZ01 bentonite–sand mixtures. *Acta Geotechnica*, 1-18.
- Chikabvumbwa, S. R. (2019). Spatial and Temporal Drought Characterization in View of the Best Irrigation Practices in Central Malawi (Master's thesis). <http://repository.pauwes-cop.net/handle/1/306>.
- Chinula, T. (2019). Improving water and nutrient use efficiency of *Phaseolus vulgaris* after flooded rice in Bwanje Valley irrigation scheme, Malawi (Doctoral dissertation, University of Pretoria). <http://hdl.handle.net/2263/68450>.
- Chiwasa, H., and Kambewa, D. (2018). Demand-based extension models for smallholder farmers in Malawi. In 13th European International Farming Systems Association (IFSA) Symposium, Farming systems: facing uncertainties and enhancing opportunities, 1-5 July 2018, Chania, Crete, Greece (pp. 1-12). International Farming Systems Association (IFSA) Europe.
- Choi, K. S., and Labhsetwar, V. K. (2021). Sustainable agricultural growth for rural development in Asia: a review. *Irrigation and Drainage*, 70(3), 470-478.
- Comas, L. H., Trout, T. J., DeJonge, K. C., Zhang, H., and Gleason, S. M. (2019). Water productivity under strategic growth stage-based deficit irrigation in maize. *Agricultural water management*, 212, 433-440.
- Costabile, P., Costanzo, C., Gangi, F., De Gaetani, C. I., Rossi, L., Gandolfi, C., and Masseroni, D. (2023). High-resolution 2D modelling for simulating and improving the management of border irrigation. *Agricultural Water Management*, 275, 1-14.
- Dahal, K., Li, X. Q., Tai, H., Creelman, A., and Bizimungu, B. (2019). Improving potato stress tolerance and tuber yield under a climate change scenario—a current overview. *Frontiers in plant science*, 10, 563.

- Darko, R. O., Yuan, S., Liu, J., Yan, H., and Ibrahim, A. (2019). Evaluation of Uniformity and Water Conveyance Efficiency of Spray Tube Irrigation System. *Scientific Journal of Agricultural Engineering*, 27-38.
- Dhehibi, B., Salah, M. B., Frijja, A., Aw-Hassan, A., Ouhibi, H. E., and Raisi, Y. M. (2018). Economic and Environmental Evaluation of Different Irrigation Systems for Date Palm Production in the GCC Countries: Case of Oman. *International Conference on Water, Environment, Energy and Society. ICARDA*, 1-17, Djerba Island.
- Dinar, A., Tieu, A., and Huynh, H. (2019). Water scarcity impacts on global food production. *Global Food Security*, 23, 212-226.
- Dingre, S. K., & Gorantiwar, S. D. (2020). Determination of the water requirement and crop coefficient values of sugarcane by field water balance method in semiarid region. *Agricultural Water Management*, 232, <https://doi.org/10.1016/j.agwat.2020.106042>.
- Djaman, K., Irmak, S., Koudahe, K., and Allen, S. (2021). Irrigation management in potato (*Solanum tuberosum* L.) production: A review. *Sustainability*, 13(3), 1504.
- Domínguez-Niño, J. M., Oliver-Manera, J., Girona, J., and Casadesús, J. (2020). Differential irrigation scheduling by an automated algorithm of water balance tuned by capacitance-type soil moisture sensors. *Agricultural Water Management*, 228, 1-11.
- Efimov, A. E., Sitdikova, Y. R., Dobrokhotoy, A. V., and Kozyreva, L. V. (2018). Monitoring evapotranspiration in an agricultural field and determination of irrigation rates and dates by automated mobile field agrometeorological complex. *Water resources*, 45, 133-137.
- Eisenhauer, D. E., Martin, D. L., Heeren, D. M., & Hoffman, G. J. (2021). Microirrigation. In *Irrigation Systems Management* (pp. 297-319). American Society of Agricultural and Biological Engineers.
- El Bergui, O., Abouabdillah, A., Bouabid, R., El Jaouhari, N., Brouziyne, Y., & Bouriou, M. (2020). Agro-physiological response of potato to “sustainable” deficit irrigation in the plain of Saïs, Morocco. In *E3S Web of Conferences* (Vol. 183, p. 03001). EDP Sciences.
- Zin El-Abedin, T. K., Mattar, M. A., Al-Ghobari, H. M., and Alazba, A. A. (2019). Water-saving irrigation strategies in potato fields: Effects on physiological characteristics and water use in arid region. *Agronomy*, 9(4), 172.
- Elhani, S., Haddadi, M., Csákvári, E., Zantar, S., Hamim, A., Villányi, V., and Bánfalvi, Z. (2019). Effects of partial root-zone drying and deficit irrigation on yield, irrigation water-use efficiency and some potato (*Solanum tuberosum* L.) quality traits under glasshouse conditions. *Agricultural Water Management*, 224, <https://doi.org/10.1016/j.agwat.2019.105745>.
- Abd El-Mageed, T. A., Semida, W. M., Taha, R. S., and Rady, M. M. (2018). Effect of summer-fall deficit irrigation on morpho-physiological, anatomical responses,

- fruit yield and water use efficiency of cucumber under salt affected soil. *Scientia horticulturae*, 237, 148-155.
- Elmetwalli, A. H., and Elnemr, M. K. (2020). Influence of deficit irrigation and nitrogen fertilization on potato yield, water productivity and net profit. *Agricultural Engineering International: CIGR Journal*, 22(3), 61-68.
- Ewaid, S. H., Abed, S. A., and Al-Ansari, N. (2019). Crop water requirements and irrigation schedules for some major crops in Southern Iraq. *Water*, 11(4), 756. <https://doi.org/10.3390/w11040756>.
- Eze, S., Dougill, A. J., Banwart, S. A., Hermans, T. D., Ligowe, I. S., and Thierfelder, C. (2020). Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. *Soil and tillage Research*, 201, <https://doi.org/10.1016/j.still.2020.104639>.
- Fandika, I. R., Chipula, G., and Mwepa, G. (2020). Water Use Efficiency Differences in Maize Varieties under Every Furrow and Alternate Furrow Irrigation. *Sustainable Agriculture Research*, 9(2), 17-29.
- Fandika, I. R., Chipula, G., and Mwepa, G. (2021). Water Use Efficiency Differences in Maize Varieties under Every Furrow and Alternate Furrow Irrigation. *Sustainable Agriculture Research*, 9(2), 1-17.
- Fang, Q., Zhang, X., Shao, L., Chen, S., and Sun, H. (2018). Assessing the performance of different irrigation systems on winter wheat under limited water supply. *Agricultural Water Management*, 133-143.
- Fantaw, S., Ayalew, A., Tadesse, D., G/Medhin, Z., and Agegnehu, E. (2019). Evaluation of potato (*Solanum tuberosum* L.) varieties for yield and yield components. *Journal of Horticulture and Forestry*, 48-53.
- Food and Agriculture Organization. (2015). Food and agriculture organization statistics, M-63, Rome.
- Food and Agriculture Organization. (2019). Food and agriculture organization statistics. M-21, Rome.
- Food and Agriculture Organization. (1996). Irrigation Water Management. Training Manual No.10. Irrigation Scheme Operation and Maintenance. ILRI. M-56, Rome.
- Fard, S. E., Yiarnia, M., Farahvash, F., Behrouzfar, E. K., and Rashidi, V. (2021). Arbuscular mycorrhizas and phosphorus fertilizer affect photosynthetic capacity and antioxidant enzyme activity in peppermint under different water conditions. *Acta Agrobotanica*, 73(4).
- Fayed, M. (2020). Drip Irrigation Technology: Principles, Design, and Evaluation. *Technological and Modern Irrigation Environment in Egypt: Best Management Practices and Evaluation*, 275-303.
- Fischer, G., Darkwah, A., Kamoto, J., Kampanje-Phiri, J., Grabowski, P., and Djenontin, I. (2021). Sustainable agricultural intensification and gender-biased land tenure systems: An exploration and conceptualization of interactions. *International Journal of Agricultural Sustainability*, 19(5-6), 403-422.

- Frake, A. N. (2019). Scaling irrigation and malaria risk in Malawi. Michigan State University.
- Frake, A. N., Namaona, W., Walker, E. D., and Messina, J. P. (2020). Estimating spatio-temporal distributions of mosquito breeding pools in irrigated agricultural schemes: a case study at the Bwanje Valley Irrigation Scheme. *Malaria Journal*, 19(1), 1-21.
- Galindo, A., Collado-González, J., Griñán, I., Corell, M., Centeno, A., Martín-Palomo, M. J., and Pérez-López, D. (2018). Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems. *Agricultural water management*, 202, 311-324.
- Gallardo, M., Elia, A., and Thompson, R. B. (2020). Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. *Agricultural Water Management*, 240, <https://doi.org/10.1016/j.agwat.2020.106209>.
- Gan, L., Rad, S., Chen, X., Fang, R., Yan, L., and Su, S. (2018). Clock hand lateral, a new layout for semi-permanent sprinkler irrigation system. *Water*, 10(6), 767.
- Genemo, G., and Seyoum, T. (2021). Effect of decision variables on yield and water productivity of onion under conventional furrow irrigation system in bako woreda, Ethiopia. *International Journal of Agricultural Research, Innovation and Technology (IJARIT)*, 11(2355-2021-1230), 92-100.
- Getnet, A., and Molla, G. Evaluation of Furrow Irrigation Methods for Maize Production in Kobo GirranaValley, Ethiopia. *Water Management Research*, 03–10, May 2020, Bahir Dar, Ethiopia, 104.
- Getts, M. (2018). Lack of Access to Water in Rural Malawi. *Ballard Brief*, 2018(3), 1-7.
- Ghazouani, H., Rallo, G., Mguidiche, A., Latrech, B., Douh, B., Boujelben, A., and Provenzano, G. (2019). Effects of saline and deficit irrigation on soil-plant water status and potato crop yield under the semiarid climate of Tunisia. *Sustainability*, 11(9), 2706.
- Gonçalves, A., Silva, E., Brito, C., Martins, S., Pinto, L., Dinis, L. T., and Correiaa, C. M. (2019). Olive tree physiology and chemical composition of fruits are modulated by different deficit irrigation strategies. *Science of Food and Agriculture*, 684-694.
- Gonzalez-Dugo, V., Lopez-Lopez, M., Espadafor, M., Orgaz, F., Testi, L., Zarco-Tejada, P., and Fereres, E. (2019). Transpiration from canopy temperature: Implications for the assessment of crop yield in almond orchards. *European Journal of Agronomy*, 105, 78-85.
- Gouthami, B., and Kumar, B. A. (2022). Water Management in Maize. *Just Agriculture*, 1-6.
- Government of Malawi. (2018). National Agricultural Investment Plan. Ministry of Agriculture, Irrigation and Water Development, Lilongwe.
- Gräf, M., Immitzer, M., Hietz, P., and Stangl, R. (2021). Water-stressed plants do not cool: Leaf surface temperature of living wall plants under drought stress. *Sustainability*, 13(7), 3910.

- Gu, D., Andreev, K., and Dupre, M. E. (2021). Major trends in population growth around the world. *China CDC weekly*, 3(28), 604.
- Gu, Z., Qi, Z., Burghate, R., Yuan, S., Jiao, X., and Xu, J. (2020). Irrigation scheduling approaches and applications: A review. *Journal of Irrigation and Drainage Engineering*, 146(6), 1-15.
- Guangyong, D. w., Mo, D., Xu, X., Wilkerson, C. J., and Hoogenboom, G. (2021). Evaluation of subsurface, mulched and non-mulched surface drip irrigation for maize production and economic benefits in northeast China. *Irrigation science*, 39, 159-171.
- Guarino, A. S. (2017). The economic implications of global water scarcity. *Research in Economics and Management*, 2(1), 51. <http://dx.doi.org/10.22158/rem.v2n1p51>.
- Gültekin, R., and Ertek, A. (2018). Effects of deficit irrigation on the potato tuber development and quality. *International Journal of Agriculture Environment and Food Sciences*, 2(3), 93-98.
- Gundumogula, M., and Gundumogula, M. (2020). Importance of focus groups in qualitative research. *International Journal of Humanities and Social Science (IJHSS)*, 8(11), 299-302.
- Gupta, A., Rico-Medina, A., and Caño-Delgado, A. I. (2020). The physiology of plant responses to drought. *Science*, 368(6488), 266-269.
- Gupta, P. P. (2021). Economic Water Scarcity: The Beginning of the End of Growth Story. *ADRI*, 23-29.
- Gusen, n. j., Goshit, j. d., Dauda, r., Williams, a. j., and Danye, r. (2017). Nurses' Knowledge Attitude and Practice of Standardized Nursing Language in PSSH, JOS. *West African Journal of Nursing* , 28(1), 21-31.
- Hájíčková, M., Plichta, R., Volařík, D., and Gebauer, R. (2017). Effects of drought and rewatering on growth and transpiration in European beech seedlings late in the growing season. *New Forests*, 48, 773-784.
- Hameed, A. M., Elkhtab, E., Mostafa, M. S., Refaey, M. M., Hassan, M. A. A., El-Naga, M. A., and Aly, A. A. (2021). Amino acids, solubility, bulk density and water holding capacity of novel freeze-dried cow's skimmed milk fermented with potential probiotic *Lactobacillus plantarum* Bu-Eg5 and *Lactobacillus rhamnosus* Bu-Eg6. *Arabian Journal of Chemistry*, 14(8), 1-8.
- Hamoud, Y. A., Shaghaleh, H., Sheteiwy, M., Guo, X., Elshaikh, N. A., Khan, N. U., and Rahim, S. F. (2019). Impact of alternative wetting and soil drying and soil clay content on the morphological and physiological traits of rice roots and their relationships to yield and nutrient use-efficiency. *Agricultural Water Management*, 223, 1-12.
- Hashem, M. S., El-Abedin, T. Z., and Al-Ghobari, H. M. (2018). Assessing effects of deficit irrigation techniques on water productivity of tomato for subsurface drip irrigation system. *International Journal of Agricultural and Biological Engineering*, 11(4), 156-167.
- Hilemicael, K., and Tibebe, M. (2018). Optimal irrigation scheduling for potato (*Solanum tuberosum*) at Holetta. In W. Atlabachew, M. Mohammed, and F.

- Abegaz, Irrigation and Watershed Management. Addis Ababa: Ethiopian Institute of Agricultural Research, 63-66.
- Hill, D., Nelson, D., Hammond, J., and Bell, L. (2021). Morphophysiology of potato (*Solanum tuberosum*) in response to drought stress: paving the way forward. *Frontiers in plant science*, 11, 597554.
- Hiltunen, L. H., Tarvainen, O., Kelloniemi, J., Tanskanen, J., Karhu, J., and Valkonen, J. P. (2021). Soil bacterial community in potato tuberosphere following repeated applications of a common scab suppressive antagonist. *Applied Soil Ecology*, 167, 104096.
- Hooshmand, M., Albaji, M., and zadeh Ansari, N. A. (2019). The effect of deficit irrigation on yield and yield components of greenhouse tomato (*Solanum lycopersicum*) in hydroponic culture in Ahvaz region, Iran. *Scientia horticulturae*, 254, 84-90.
- Huntenburg, K., Dodd, I. C., and Stalham, M. (2021). Agronomic and physiological responses of potato subjected to soil compaction and/or drying. *Annals of applied biology*, 178(2), 328-340.
- Hussain, S., Ahmad, A., Wajid, A., Khaliq, T., Hussain, N., Mubeen, M., and Nasim, W. (2020). Irrigation scheduling for cotton cultivation. *Cotton Production and Uses: Agronomy, Crop Protection, and Postharvest Technologies*, 59-80.
- Iqbal, R., Raza, M. A. S., Toleikiene, M., Ayaz, M., Hashemi, F., Habib-ur-Rahman, M., and Haider, I. (2020). Partial root-zone drying (PRD), its effects and agricultural significance: a review. *Bulletin of the National Research Centre*, 44(1), 1-15.
- Ding, Z., Kheir, A. M., Ali, M. G., Ali, O. A., Abdelaal, A. I., Lin, X. E., and He, Z. (2020). The integrated effect of salinity, organic amendments, phosphorus fertilizers, and deficit irrigation on soil properties, phosphorus fractionation and wheat productivity. *Scientific Reports*, 10(1), 2736. <https://doi.org/10.1038/s41598-020-59650-8>.
- Islam, S. F. U., Sander, B. O., Quilty, J. R., De Neergaard, A., Van Groenigen, J. W., and Jensen, L. S. (2020). Mitigation of greenhouse gas emissions and reduced irrigation water use in rice production through water-saving irrigation scheduling, reduced tillage and fertiliser application strategies. *Science of the Total Environment*, 739, 140215.
- Issaka, Z., Li, H., Yue, J., Tang, P., and Darko, R. O. (2018). Water-smart sprinkler irrigation, prerequisite to climate change adaptation: A review. *Journal of Water and Climate Change*, 9(2), 383-398.
- Jabro, J. D., Stevens, W. B., Iversen, W. M., Allen, B. L., and Sainju, U. M. (2020). Irrigation scheduling based on wireless sensors output and soil-water characteristic curve in two soils. *Sensors*, 20(5), 1336.
- Jasim, A. A., Jabr, A. K., Rawdhan, S. A., and Abdullatif, Z. A. (2020). Effect of subsurface irrigation and drip irrigation on growth and yield of roselle under different irrigation periods. *Indian J. Ecology*, 47(12), 98-100.
- Jefferies, R. A. (1993). Cultivar responses to water stress in potato: effects of shoot and roots. *New Phytologist*, 123(3), 491-498.

- Jensen, C. R., Battilani, A., Plauborg, F., Psarras, G., Chartzoulakis, K., Janowiak, F., and Andersen, M. N. (2010). Deficit irrigation based on drought tolerance and root signalling in potatoes and tomatoes. *Agricultural Water Management*, 98(3), 403-413.
- Jha, S. K., Ramatshaba, T. S., Wang, G., Liang, Y., Liu, H., Gao, Y., and Duan, A. (2019). Response of growth, yield and water use efficiency of winter wheat to different irrigation methods and scheduling in North China Plain. *Agricultural Water Management*, 217, 292-302.
- Jobbágy, J., Bartík, O., Krištof, K., Bárek, V., Virágh, R., and Slány, V. (2022). Design of Hardware and Software Equipment for Monitoring Selected Operating Parameters of the Irrigator. *Sensors*, 22(9), 3549.
- Mwesigwa, J. (2022). Design, construction and testing of an automated drip irrigation water control system (Doctoral dissertation, Makerere University).
- Li, L., Song, X., Xia, L., Fu, N., Feng, D., Li, H., & Li, Y. (2020). Modelling the effects of climate change on transpiration and evaporation in natural and constructed grasslands in the semi-arid Loess Plateau, China. *Agriculture, Ecosystems and Environment*, 302, 107077.
- Kalanda Joshua, M. D., Ngongondo, C., Chipungu, F., Malidadi, C., Liwenga, E., Majule, A., and Lamboll, R. (2020). Strengthening horticultural innovation systems for adaptation to effects of urbanisation and climate variability in peri-urban areas. *Climate Variability and Change in Africa: Perspectives, Experiences and Sustainability*, 137-156.
- Jovanovic, N., Pereira, L. S., Paredes, P., Pôças, I., Cantore, V., and Todorovic, M. (2020). A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO56 methods. *Agricultural water management*, 239, <https://doi.org/10.1016/j.agwat.2020.106267>.
- Kadyampakeni, D. M. (2013). Comparative response of cabbage to irrigation in Southern Malawi. *Journal of Agricultural Science*, 5(8), 1-7.
- Kamwamba-Mtethiwa, J., Wiyo, K., Knox, J., and Weatherhead, K. (2021). Diffusion of small-scale pumped irrigation technologies and their association with farmer-led irrigation development in Malawi. *Water international*, 46(3), 397-416.
- Kandpal, V. (2018). Evaluation of a Solar Powered Variable Flow Tail-water Recovery System for Furrow Irrigation. University of Arkansas.
- Kassaye, K. T., Yilma, W. A., Fisha, M. H., and Haile, D. H. (2020). Yield and water use efficiency of potato under alternate furrows and deficit irrigation. *International Journal of Agronomy*, 2020, 1-11.
- Kateta, S. Y., Kabambe, V., Lowole, M. W., and Nalivata, P. C. (2015). Production practices of potato (*Solanum tuberosum* L.) by farmers in Mzimba District, Northern Malawi. *African Journal of Agricultural Research*, 10(8), 797-802.
- Khalili, F., Aghayari, F., and Ardakani, M. R. (2020). Effect of alternate furrow irrigation on maize productivity in interaction with different irrigation regimes

- and biochar amendment. *Communications in Soil Science and Plant Analysis*, 51(6), 757-768.
- Khuluq, A. D., Widaryanto, E., and Niyhayati, E. (2022). Adaptive strategy of *Stevia rebaudiana* to environmental change in tropical climate based on anatomy and physiology characteristics. *Biodiversitas Journal of Biological Diversity*, 23(11).
- Kibuye, F. A., Gall, H. E., Elkin, K. R., Ayers, B., Veith, T. L., Miller, M., and Elliott, H. A. (2019). Fate of pharmaceuticals in a spray-irrigation system: From wastewater to groundwater. *Science of the Total Environment*, 654, 197-208.
- Klein, T., and Anderegg, W. R. (2021). A vast increase in heat exposure in the 21st century is driven by global warming and urban population growth. *Sustainable Cities and Society*, 73, 103098.
- Koech, R., and Langat, P. (2018). Improving irrigation water use efficiency: A review of advances, challenges and opportunities in the Australian context. *Water*, 10(12), 1771.
- Körner, O., Fanourakis, D., Hwang, M. C. R., Hyldgaard, B., Tsaniklidis, G., Nikoloudakis, N., and Rosenqvist, E. (2021). Incorporating cultivar-specific stomatal traits into stomatal conductance models improves the estimation of evapotranspiration enhancing greenhouse climate management. *biosystems engineering*, 208, 131-151.
- Kucserka, T., Simon, B., and Anda, A. (2018). Decomposition of *Salix* and *Populus* leaves in standard class “A” evaporation pans in Hungary. *Georgikon for Agriculture*, 1-92
- Kumar, N., Poddar, A., Shankar, V., Ojha, C. S. P., and Adeloje, A. J. (2020). Crop water stress index for scheduling irrigation of Indian mustard (*Brassica juncea*) based on water use efficiency considerations. *Journal of Agronomy and Crop Science*, 206(1), 148-159.
- Kumari, A., Upadhyaya, A., Jeet, P., Al-Ansari, N., Rajput, J., Sundaram, P. K., and Kuriqi, A. (2022). Estimation of actual evapotranspiration and crop coefficient of transplanted puddled rice using a modified non-weighing paddy lysimeter. *Agronomy*, 12(11), 2850.
- Lafosse, C., and Fernandez-concha, N. (2013). Protocol for Designing and Conducting Potato Field Experiments for Modeling Purposes. International Potato Center (CIP). Lima 12:
- Lal, R. (2020). Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. *Food security*, 12(4), 871-876. <https://doi.org/10.1007/s12571-020-01058-3>.
- Langewitz, T., Wiedner, K., Polifka, S., and Eckmeier, E. (2021). Pedological properties related to formation and functions of ancient ridge and furrow cultivation in Central and Northern Germany. *Catena*, 198, <https://doi.org/10.1016/j.catena.2020.105049>.
- Lankford, B., Closas, A., Dalton, J., Gunn, E. L., Hess, T., Knox, J. W., and Zwarteveen, M. (2020). A scale-based framework to understand the promises, pitfalls and

- paradoxes of irrigation efficiency to meet major water challenges. *Global Environmental Change*, 65, 102182.
- Laxa, M., Liebthal, M., Telman, W., Chibani, K., and Dietz, K. J. (2019). The role of the plant antioxidant system in drought tolerance. *Antioxidants*, 8(4), 94. <https://doi.org/10.3390/antiox8040094>.
- Lena, B. P., Bondesan, L., Pinheiro, E. A. R., Ortiz, B. V., Morata, G. T., and Kumar, H. (2022). Determination of irrigation scheduling thresholds based on HYDRUS-1D simulations of field capacity for multilayered agronomic soils in Alabama, USA. *Agricultural Water Management*, 259, 107234. <https://doi.org/10.1016/j.agwat.2021.107234>.
- Ierna, A. (2023). Water management in potato. In *Potato Production Worldwide* (pp. 87-100). Academic Press.
- Li, A., Mu, X., Zhao, X., Xu, J., Khayatnezhad, M., and Lalehzari, R. (2021). Developing the non-dimensional framework for water distribution formulation to evaluate sprinkler irrigation. *Irrigation and Drainage*, 70(4), 659-667.
- Li, D., Li, M., Shen, X., Zhou, X., Sun, H., Zhao, Y., and Chen, W. (2020). Response of spatial structure of cotton root to soil-wetting patterns under mulched drip irrigation. *International Journal of Agricultural and Biological Engineering*, 13(5), 153-162.
- Lipan, L., Carbonell-Pedro, A. A., Cárceles Rodríguez, B., Durán-Zuazo, V. H., Franco Tarifa, D., García-Tejero, I. F., ... and Hernández, F. (2021). Can sustained deficit irrigation save water and meet the quality characteristics of mango?. *Agriculture*, 11(5), 448. <https://doi.org/10.3390/agriculture11050448>.
- Liu, C., Ravnskov, S., Liu, F., Rubæk, G. H., and Andersen, M. N. (2018). Arbuscular mycorrhizal fungi alleviate abiotic stresses in potato plants caused by low phosphorus and deficit irrigation/partial root-zone drying. *The Journal of Agricultural Science*, 156(1), 46-58.
- Liu, J., Chen, Z., Kanungo, D. P., Song, Z., Bai, Y., Wang, Y., and Qian, W. (2019). Topsoil reinforcement of sandy slope for preventing erosion using water-based polyurethane soil stabilizer. *Engineering Geology*, 252, 125-135.
- Liu, Y., Han, M., Zhou, X., Li, W., Du, C., Zhang, Y., and Wang, Z. (2022). Optimizing nitrogen fertilizer application under reduced irrigation strategies for winter wheat of the north China plain. *Irrigation Science*, 1-11.
- Loiskandl, W., and Nolz, R. (2021). Requirements for sustainable irrigated agriculture. *Agronomy*, 11(2), 306.
- Loveniers, P. J. (2019). Opportunities and problems concerning potato production and quality in Lam Dong, Vietnam. Ghent University.
- Lu, J., Shao, G., Cui, J., Wang, X., and Keabetswe, L. (2019). Yield, fruit quality and water use efficiency of tomato for processing under regulated deficit irrigation: A meta-analysis. *Agricultural Water Management*, 222, 301-312.
- Ma, X., Sanguinet, K. A., and Jacoby, P. W. (2020). Direct root-zone irrigation outperforms surface drip irrigation for grape yield and crop water use efficiency

- while restricting root growth. *Agricultural Water Management*, 231, <https://doi.org/10.1016/j.agwat.2019.105993>.
- Ma, Y., and Liu, H. (2019). An advanced multiple-layer canopy model in the WRF model with large-eddy simulations to simulate canopy flows and scalar transport under different stability conditions. *Journal of Advances in Modeling Earth Systems*, 11(7), 2330-2351.
- Mabhaudhi, T., Mpandeli, S., Nhamo, L., Senzanje, A., Chimonyo, V. G. P., and Modi, A. T. (2019, September). Options for improving agricultural water productivity under increasing water scarcity in South Africa. In *3rd World Irrigation Forum (WIF3) on Development for Water, Food and Nutrition Security in a Competitive Environment*, Bali, Indonesia (pp. 1-7).
- Mabhaudhi, T., Nhamo, L., & Mpandeli, S. (2021). Enhancing crop water productivity under increasing water scarcity in South Africa. In *Climate Change Science* (pp. 1-18). Elsevier.
- Mafuta, C. (2018). The Value of Green Water Management in Sub-Saharan Africa: A Review. *Journal of Contemporary Water Research & Education*, 165(1), 67-75.
- Malawi, Government. (2018). *Dedza District Socio Economic Profile*. Department of Economic planning and development. Lilongwe, Malawi
- Malawi, Government. (2018). *Dedza District State of Environment and Outlook*. Department of economic planning and development. Lilongwe.
- Mamatov, F., Mirzaev, B., Tursunov, O., Ochilov, S., and Chorjeva, D. (2020, December). Relief, physico-mechanical and technological properties of soil in the cotton growing area. In *IOP Conference Series: Earth and Environmental Science* (Vol. 614, No. 1, p. 012169). IOP Publishing.
- Mansuri, M., Babazadeh, H., Emdad, M. R., and Taleghani, D. (2018). Effect of deficit irrigation management on qualitative and quantitative yield of sugar beet (*Beta vulgaris L.*) in Karaj, Iran. *Applied Ecology & Environmental Research*, 16(1), 455-466.
- Martínez-Romero, A., López-Urrea, R., Montoya, F., Pardo, J. J., and Domínguez, A. (2021). Optimization of irrigation scheduling for barley crop, combining AquaCrop and MOPECO models to simulate various water-deficit regimes. *Agricultural Water Management*, 258, 107219. <https://doi.org/10.1016/j.agwat.2021.107219>.
- Martorano, L. G., Berhe, A. A., da Silva Lima, A. R., Costa, D. C., da Silva Barbosa, A. M., and Marques, M. C. (2018). Water Replenishment in Agricultural Soils: Dissemination of the IrrigaPot Technology. In *Soil Moisture*. IntechOpen, 77-88.
- Masta, N., and Riyanto, S. (2020). The Effect of Transformational Leadership, Perceived Organizational Support and Workload on Turnover Intention Sharia Banking Company in Jakarta. *Saudi Journal of Business and Management Studies*, 5(8), 473-481.
- Matto, G. (2018). Agricultural Information Access and the Use of ICTs among Smallholder Farmers: A Case of Bembeke EPA in Dedza District. *ACADEMIA*, 59-72.

- Mbava, N., Mutema, M., Zengeni, R., Shimelis, H., and Chaplot, V. (2020). Factors affecting crop water use efficiency: A worldwide meta-analysis. *Agricultural Water Management*, 228, 105878.
- McNulty, E., Nielsen, T., and Zeller, M. (2016). Smallholder farmers' willingness to invest in irrigation schemes in Dedza, Malawi. *American Journal of Rural Development*, 4(9), 43-48.
- Mehari, H., Bedadi, B., and Abegaz, F. (2020). Maximizing water productivity of maize using alternate furrow irrigation at clay-loam soil, Raya valley, Ethiopia. *International Journal of Plant Breeding and Crop Science*, 7(2), 771-778.
- Mehmood, F., Wang, G., Gao, Y., Liang, Y., Chen, J., Si, Z., and Duan, A. (2019). Nitrous oxide emission from winter wheat field as responded to irrigation scheduling and irrigation methods in the North China Plain. *Agricultural Water Management*, 222, 367-374.
- Mehrabi, F., and Sepaskhah, A. R. (2019). Partial root zone drying irrigation, planting methods and nitrogen fertilization influence on physiologic and agronomic parameters of winter wheat. *Agricultural Water Management*, 223, <https://doi.org/10.1016/j.agwat.2019.105688>
- Mekoya, A., Bernhofer, C., & Moderow, U. (2019). Estimation of evaporation using daily and ten-minute class-a pan data from automatic measuring pressure sensor instrument at Tharandt, Germany. *International Journal of Environmental Sciences and Natural Resources*, 19(1), 10-18.
- Michela Giuliani, M., Nardella, E., Gagliardi, A., and Gatta, G. (2017). Deficit irrigation and partial root-zone drying techniques in processing tomato cultivated under Mediterranean climate conditions. *Sustainability*, 9(12), 2197.
- Minhas, P. S., Ramos, T. B., Ben-Gal, A., and Pereira, L. S. (2020). Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. *Agricultural Water Management*, 227, <https://doi.org/10.1016/j.agwat.2019.105832>.
- Modi, P. N. (2019). *Irrigation water resources and water power engineering (Vol. 10)*. Rajsons Publications Pvt. Ltd.
- Mohammed, M., Riad, K., and Alqahtani, N. (2021). Efficient iot-based control for a smart subsurface irrigation system to enhance irrigation management of date palm. *Sensors*, 21(12), 3942.
- Moseki, O., Murray-Hudson, M., and Kashe, K. (2019). Crop water and irrigation requirements of *Jatropha curcas* L. in semi-arid conditions of Botswana: applying the CROPWAT model. *Agricultural Water Management*, 225, 105754.
- Mthembu, S. G., Magwaza, L. S., Mashilo, J., Mditshwa, A., and Odindo, A. (2022). Drought tolerance assessment of potato (*Solanum tuberosum* L.) genotypes at different growth stages, based on morphological and physiological traits. *Agricultural Water Management*, 261, 107361.
- Munthali, M. G., Botai, J. O., Davis, N., and Adeola, A. M. (2019). Multi-temporal analysis of land use and land cover change detection for dedza district of Malawi

- using geospatial techniques. *International Journal of Applied Engineering Research*, 1151-1162.
- Munthali, M. G., Davis, N., Adeola, A. M., Botai, J. O., Kamwi, J. M., Chisale, H. L., and Orimoogunje, O. O. (2019). Local perception of drivers of land-use and land-cover change dynamics across Dedza District, Central Malawi Region. *Sustainability*, 11(3), 832.
- Munthali, M. G., Mustak, S., Adeola, A., Botai, J., Singh, S. K., and Davis, N. (2020). Modelling land use and land cover dynamics of Dedza district of Malawi using hybrid Cellular Automata and Markov model. *Remote Sensing Applications: Society and Environment*, 17, 100276.
- Muradov, U., Kattaye, S., Saylixanova, K., and Ibodov, N. (2020). Sprinkler irrigation equipment and types of them. *International Journal of innovations in Engineering research and technology*, 7(05), 45-47.
- Muroyiwa, G. S., Mashonjowa, E., Mhizha, T., Muchuweti, M., and Raeth, P. G. (2022). Estimating crop water requirements for irrigation scheduling of tomato using Aquacrop 5.0 and Cropwat 8.0 models under scarcity and unreliability of rainfall in Harare. *African Journal of Agricultural Research*, 18(12), 1089-1101.
- Mwamakamba, S. N., Sibanda, L. M., Pittock, J., Stirzaker, R., Bjornlund, H., van Rooyen, A., and Kashaigili, J. J. (2017). Irrigating Africa: Policy barriers and opportunities for enhanced productivity of smallholder farmers. *International Journal of Water Resources Development*, 33(5), 824-838.
- Mwiya, R. M., Zhang, Z., Zheng, C., and Wang, C. (2020). Comparison of approaches for irrigation scheduling using AquaCrop and NSGA-III models under climate uncertainty. *Sustainability*, 12(18), 7694.
- Nakawuka, P., Langan, S., Schmitter, P., and Barron, J. (2018). A review of trends, constraints and opportunities of smallholder irrigation in East Africa. *Global food security*, 17, 196-212.
- Namara, R., Awulachew, S. B., and Merrey, D. J. (2006). Review of agricultural water management technologies and practices. In *MoWR/MoARD/USAID/IWMI Workshop* (pp. 37-50).
- Namugga, P., Sibiya, J., Melis, R., and Barekye, A. (2018). Yield Response of Potato (*Solanum tuberosum* L.) Genotypes to late blight caused by *Phytophthora infestans* in Uganda. *American Journal of Potato Research*, 95, 423-434.
- Nanda, M. K., Giri, U., and Bera, N. (2018). Canopy temperature-based water stress indices: Potential and limitations. *Advances in Crop Environment Interaction*, 365-385.
- Narayanamoorthy, A., Devika, N., Suresh, R., and Sujitha, K. S. (2020). Efficiency and viability of drip method of irrigation in groundnut cultivation: an empirical analysis from South India. *Water Policy*, 22(6), 1109-1125.
- Nascimento, A. K., Schwartz, R. C., Lima, F. A., López-Mata, E., Domínguez, A., Izquier, A., and Martínez-Romero, A. (2019). Effects of irrigation uniformity on yield response and production economics of maize in a semiarid zone. *Agricultural Water Management*, 211, 178-189.

- Sharma, N., Hakkim, A. V., and Singh, A. K. (2021). Development and field evaluation of a low-cost automated drip irrigation system. *Journal of Soil and Water Conservation*, 20(2), 188-194.
- Nazari, B., Liaghat, A., Akbari, M. R., and Keshavarz, M. (2018). Irrigation water management in Iran: Implications for water use efficiency improvement. *Agricultural water management*, 208, 7-18.
- Netafim. (2015). Drip irrigation system overview. In *Netafim, Drip Irrigation Handbook: Understanding the Basics*. Copyright 2013, NETAFIM, 7-46.
- Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C. R., Muchara, B., Karuaihe, S. T., and Mpandeli, S. (2020). Climate change impacts on water and agriculture sectors in Southern Africa: Threats and opportunities for sustainable development. *Water*, 12(10), 2673. <https://doi.org/10.3390/w12102673>.
- Nie, W. B., Li, Y. B., Zhang, F., and Ma, X. Y. (2019). Optimal discharge for closed-end border irrigation under soil infiltration variability. *Agricultural Water Management*, 221, 58-65.
- Nikolaou, G., Neocleous, D., Christou, A., Kitta, E., and Katsoulas, N. (2020). Implementing sustainable irrigation in water-scarce regions under the impact of climate change. *Agronomy*, 10(8), <https://doi.org/10.3390/agronomy10081120>.
- Nikolaou, G., Neocleous, D., Katsoulas, N., and Kittas, C. (2019). Irrigation of greenhouse crops. *Horticulturae*, 5(1), <https://doi.org/10.3390/horticulturae5010007>
- Niragire, T., Süheri, S., and Pande, S. K. (2021). Performance Evaluation of Hand-Move Sprinkler Irrigation System: A Case Study in Rwanda. *International Journal of Innovative Approaches Agricultural Research*, 5, 37-51.
- Niswonger, R. G. (2020). An agricultural water use package for MODFLOW and GSFLOW. *Environmental Modelling and Software*, 125, 104617.
- Nogueira, V. H. B., Diotto, A. V., Thebaldi, M. S., Colombo, A., Silva, Y. F., de Castro Lima, E. M., and Resende, G. F. L. (2021). Variation in the flow rate of drip emitters in a subsurface irrigation system for different soil types. *Agricultural Water Management*, 243, <https://doi.org/10.1016/j.agwat.2020.106485>.
- Nur, J., and Ofgea, L. (2019). Effects of Alternate Furrow Irrigation and Its Interval on Yield and Water Use Efficiency of Tomato Production at Erer Woldiya District of Harari Regional State. *Adaptation and Generation of Agricultural Technology*, 26, 327-338.
- Nxumalo, K. A., Hlanze, F., Masarirambi, M. T., and Wahome, P. K. (2020). Effect of intra-row spacing on growth and yield of Irish potato (*Solanum tuberosum* L. cv. Mondial) grown in a sub-tropical environment of Eswatini. *Journal of Agriculture and Sustainability*, 13.
- Nyawade, S. O., Karanja, N. N., Gachene, C. K., Schulte-Geldermann, E., and Parker, M. (2018). Effect of potato hilling on soil temperature, soil moisture distribution and sediment yield on a sloping terrain. *Soil and Tillage Research*, 184, 24-36.
- Obiechefu, G. C., and Emerson, K. (2020). Supplemental Irrigation of Waterleaf crop (*Talinum triangulare*) in a Sub-Saharan tropical region. In *2020 ASABE Annual*

- International Virtual Meeting (p. 1). American Society of Agricultural and Biological Engineers..
- Oke, A., Traore, K., Nati-Bama, A. D., Igbadun, H., Ahmed, B., Ahmed, F., and Zwart, S. (2022). Small-scale irrigation and water management technologies for African agricultural transformation. International Water Management Institute (IWMI).
- Omran, E. S. E., and Negm, A. M. (Eds.). (2020). Technological and Modern Irrigation Environment in Egypt: Best Management Practices and Evaluation (pp. 77-105). Cham, Switzerland: Springer International Publishing.
- Omran, E. S. E., and Negm, A. M. (2020). Introduction to “Technological and Modern Irrigation Environment in Egypt: Best Management Practices and Evaluation”. Technological and Modern Irrigation Environment in Egypt: Best Management Practices and Evaluation, 3-12.
- Onishi, J., Ikeura, H., Paluashova, G. K., Shirokova, Y. I., Kitamura, Y., and Fujimaki, H. (2019). Suitable inflow rate and furrow length for simplified surge flow irrigation. *Paddy and water Environment*, 17, 185-193.
- Özocak, M. (2020). Availability by evaluating rainwater of irrigation and fogging systems in herbal production in greenhouse conditions. *Eurasian Journal of Biological and Chemical Sciences*, 3(2), 160-164.
- Pachore, R. A., and Deore, S. B. (2022). Effect of Moisture Stress on Wheat Crop by IW/CPE Approach on Water Requirement and Water Use Efficiency. *International Journal of Agriculture, Environment and Biotechnology*, 619-625.
- Pandey, B. K., Verma, N. K., Devi, S., Jalikatti, V. N., Kumar, A., and Kumar, P. (2021). Effect of Varieties and Irrigation Methods on Growth and Yield of Wheat (*Triticum aestivum* L.). *International Journal of Agriculture Innovations and Research*, 9(4), 304-307.
- Martínez de Azagra Paredes, A., Del Río San José, J., Reque Kilchenmann, J., Diez Hernández, J. M., and Sanz Ronda, F. J. (2022). Methods for Watering Seedlings in Arid Zones. *Forests*, 13(2), 351.
- Passarelli, S., Mekonnen, D., Bryan, E., and Ringler, C. (2018). Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania. *Food Security*, 10(4), 981-997.
- Patel, N. H., and Prajapati, C. R. (2020). Agricultural sprinkler for irrigation system. *International Journal of Engineering and Technical Research*, 9(5), 162-166.
- Patel, P. K., and Parmar, B. J. (2020). Sprinkler irrigation system and its adoption by potato growers: A case of Banaskantha district. *Indian Journal of Adult Education*, 81(4), 161-168.
- Patnaik, G. P., Srinivasan, G., Bose, K. S. C., Sapthagiri, S., Varshini, S. V., and Jeeva, M. (2022). Improving Water Productivity in Conservation Agriculture. *Agronomy*, 3.
- Pawar, D. D., and Dingre, S. K. (2020). Yield and quality attributes of potato (*Solanum tuberosum* L.) under different irrigation methods and regimes. *Journal of Natural Resource Conservation and Management*, 1(2), 151-156.

- Pazouki, E. (2021). A practical surface irrigation system design based on volume balance model and multi-objective evolutionary optimization algorithms. *Agricultural water management*, 248, 106755.
- Peng, X., Dai, Q., Ding, G., Shi, D., and Li, C. (2019). The role of soil water retention functions of near-surface fissures with different vegetation types in a rocky desertification area. *Plant and Soil*, 441, 587-599.
- Pereira, L. S., and Gonçalves, J. M. (2018). Surface irrigation. In *Oxford Research Encyclopedia of Environmental Science*.
<https://doi.org/10.1093/acrefore/9780199389414.013.248>.
- Peters, T., Mohamed, A. Z., and McMoran, D. W. (2021). Center Pivot Control Panels Should Vary Cycle Time Instead of Run Time to Set a Percent Setting. In 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California (p. 1). American Society of Agricultural and Biological Engineers.
- Pirmoradian, N., and Davatgar, N. (2019). Simulating the effects of climatic fluctuations on rice irrigation water requirement using AquaCrop. *Agricultural water management*, 213, 97-106.
- Placide, R., Theophile, N., Senkeshu, N., Claude, N. J., and Sindi, K. (2019). Performance of CIP and Dutch potato varieties under Rwanda climate conditions. *African Journal of Agricultural Research*, 14(32), 1454-1462.
- Playán, E., Salvador, R., Bonet, L., Camacho, E., Intrigliolo, D. S., Moreno, M. A., and Zapata, N. (2018). Assessing telemetry and remote control systems for water users associations in Spain. *Agricultural Water Management*, 202, 89-98.
- Prestwich, C., and Walker, J. (2016). Sprinkler irrigation. In R. Sampson, *National Engineering Handbook*. United States Department of Agriculture, 1-20. Washington, DC.
- Qin, J., Ramírez, D. A., Xie, K., Li, W., Yactayo, W., Jin, L., and Quiroz, R. (2018). Is partial root-zone drying more appropriate than drip irrigation to save water in China? A preliminary comparative analysis for potato cultivation. *Potato Research*, 61, 391-406.
- Abdelraouf, R. E., El-Shawadfy, M. A., Ghoname, A. A., & Ragab, R. (2020). Improving crop production and water productivity using a new field drip irrigation design. *Plant Archives*, 20(1), 3553-3564.
- Rashad, M. A., Zedan, A. M. I., and Khedr, A. F. (2021). Creating Software to Design a Low-Head Bubbler Irrigation System as an Alternative to Traditional Furrow Irrigation. *Journal of Soil Sciences and Agricultural Engineering*, 12(11), 797-803.
- Ravikumar, V. (2022). Drip Irrigation Components. In *Sprinkler and Drip Irrigation: Theory and Practice* (pp. 151-213). Singapore: Springer Nature Singapore.
- Ravikumar, V. (2022). Hydraulics of Microirrigation Pipes. In *Sprinkler and Drip Irrigation: Theory and Practice* (pp. 247-267). Singapore: Springer Nature Singapore.
- Reyes, J. (2018). Exploring Spatial and Temporal Variability of Soil and Crop Processes for Irrigation Management. *Uknowledge*, 1-13

- Ricci, G. F., Jeong, J., De Girolamo, A. M., and Gentile, F. (2020). Effectiveness and feasibility of different management practices to reduce soil erosion in an agricultural watershed. *Land Use Policy*, 90, 104306.
- Rakhimov, O. K., Khamidov, O. H., and García, T. S. C. (2020). Improvement and Modernization of Agricultural Irrigation. Uzbekistan Case Study. *European Journal of Agriculture and Food Sciences*, 2(4).
- Rout, S., Gulathi, J., and Parasar, B. (2020). Smart Agriculture System: Review. *International Journal of Modern Agriculture*, 674-680.
- Rowe, R. (2018). SOIL MOISTURE Lab one. *Biosystems Engineering*, 1-6.
- Ruth, M.-D., Suseela, D. R., Elias, M., Mulema, A. A., and Myers, E. (2019). Women's empowerment in agriculture: Lessons from qualitative research. Rome: IFPRI.
- Sable, R., Kolekar, S., Gawde, A., Takle, S., and Pednekar, A. (2019). A review on different irrigation methods. *Applied. Agricultural. Research*, 14, 49-60.
- Saha, C., Bhattacharya, P., Sengupta, S., Dasgupta, S., Patra, S. K., Bhattacharyya, K., and Dey, P. (2022). Response of cabbage to soil test-based fertilization coupled with different levels of drip irrigation in an inceptisol. *Irrigation science*, 239-253.
- Sahoo, S. R., Agyeman, B. T., Debnath, S., and Liu, J. (2022). Knowledge-based optimal irrigation scheduling of three-dimensional agro-hydrological systems. *IFAC-PapersOnLine*, 55(7), 441-446.
- Salimi, K., Hosseini, M. B., and Siosemardeh, A. (2017). The Efficacy of Regulated Deficit and Partial Root Zone Drying Irrigation Strategies on Yield and Water Use Efficiency of Potato. *Agricultural Communications*, 5(3), 1-6.
- Sánchez-Blanco, M. J., Ortuño, M. F., Bañon, S., and Álvarez, S. (2019). Deficit irrigation as a strategy to control growth in ornamental plants and enhance their ability to adapt to drought conditions. *The Journal of Horticultural Science and Biotechnology*, 94(2), 137-150.
- Santos, B., and Torres-Quezada, E. A. (2018). Irrigation and Fertilization. In E. Heuvelink, *Tomatoes*. Glasgow: Bell and Bain Ltd, 180-206.
- Santosh, M. P., Hasan, S. A., Nirgude, A. S., and Somnath, Z. P. (2019). IoT Based Farm Automation. *Journal of Advanced Research in Embedded System*, 6(3 & 4), 21-24.
- Sarkar, S., Ramsey, A. F., Cazenave, A. B., and Balota, M. (2021). Peanut leaf wilting estimation from RGB color indices and logistic models. *Frontiers in plant science*, 12, 658621.
- Sarker, K. K., Hossain, A., Murad, K. F. I., Biswas, S. K., Akter, F., Rannu, R. P., and Timsina, J. (2019). Development and evaluation of an emitter with a low-pressure drip-irrigation system for sustainable eggplant production. *AgriEngineering*, 1(3), 376-390.
- Sarker, K. K., Hossain, A., Timsina, J., Biswas, S. K., Kundu, B. C., Barman, A., ... and Akter, F. (2019). Yield and quality of potato tuber and its water productivity are influenced by alternate furrow irrigation in a raised bed system. *Agricultural Water Management*, 224, <https://doi.org/10.1016/j.agwat.2019.105750>.

- Sarker, K. K., Hossain, A., Timsina, J., Biswas, S. K., Malone, S. L., Alam, M. K., ... Bazzaz, M. (2020). Alternate furrow irrigation can maintain grain yield and nutrient content, and increase crop water productivity in dry season maize in sub-tropical climate of South Asia. *Agricultural Water Management*, 238, 106229.
- Sousa-Gallagher, M. J., Mahajan, P. V., and Mezdad, T. (2013). Engineering packaging design accounting for transpiration rate: Model development and validation with strawberries. *Journal of Food Engineering*, 119(2), 370-376.
- Schwartz, R. C., Bell, J. M., Colaizzi, P. D., Baumhardt, R. L., and Hiltbrunner, B. A. (2022). Response of maize hybrids under limited irrigation capacities: Crop water use. *Agronomy Journal*, 114(2), 1324-1337.
- Scoones, I., Murimbarimba, F., and Mahenehene, J. (2019). Irrigating Zimbabwe after land reform: The potential of farmer-led systems. *Water Alternatives*, 12(1), 88-106.
- Seifi, A., Ehteram, M., Soroush, F., & Haghghi, A. T. (2022). Multi-model ensemble prediction of pan evaporation based on the Copula Bayesian Model Averaging approach. *Engineering Applications of Artificial Intelligence*, 114, <https://doi.org/10.1016/j.engappai.2022.105124>.
- Semida, W. M., Abdelkhalik, A., Rady, M. O., Marey, R. A., and Abd El-Mageed, T. A. (2020). Exogenously applied proline enhances growth and productivity of drought stressed onion by improving photosynthetic efficiency, water use efficiency and up-regulating osmoprotectants. *Scientia Horticulturae*, 272, 109580.
- Shaibu, Y. A., Banda, H. M., Makwiza, C. N., and Malunga, J. C. (2015). Grain yield performance of upland and lowland rice varieties under water saving irrigation through alternate wetting and drying in sandy clay loams of Southern Malawi. *Experimental agriculture*, 51(2), 313-326.
- Shammout, M. A. W., Qtaishat, T., Rawabdeh, H., and Shatanawi, M. (2018). Improving water use efficiency under deficit irrigation in the Jordan Valley. *Sustainability*, 10(11), 4317.
- Sharma, B. R., Gulati, A., Mohan, G., Manchanda, S., Ray, I., and Amarasinghe, U. (2018). Water productivity mapping of major Indian crops.
- Sibale, D., Mwenelupembe, G., Chikabumbwa, S., and Chisale, S. (2021). Evaluation of Water Delivery Performance of Nkhafi Irrigation Scheme in Dowa District, Malawi, Africa. *Computational Water, Energy, and Environmental Engineering*, 10(3), 95-107.
- Sidar, R. S. (2019). System, principles and Method of irrigation. *Journal of Pharmacognosy and Phytochemistry*, 8(6), 2574-2579.
- Sabri, J. L. S. (2018). Effectiveness of deficit irrigation scheduling on crop water use efficiency-a case of french beans in Njoro Nakuru County Kenya (Doctoral dissertation, Egerton University).
- Singh, A. K., Bhardwaj, A. K., Verma, C. L., Mishra, V. K., Singh, A. K., Arora, S., and Ojha, R. P. (2019). Soil moisture sensing techniques for scheduling irrigation. *Journal of. Soil Saline and. Water Quality*, 11, 68-76.

- Singh, D., Patel, N., Patra, S., and Singh, N. (2020). Growth and yield of cauliflower under surface and subsurface drip irrigation with primarily treated municipal wastewater in a semi-arid peri-urban area. *Current Science*, 119(8), 1357.
- Sinha, B. L. (2022). A study on performance evaluation of sprinkler irrigation system at farmers field in Chhattisgarh plain. *Pharma Innovation journal*, 11, 485-489.
- Soroush, F., Fathian, F., Khabisi, F. S. H., and Kahya, E. (2020). Trends in pan evaporation and climate variables in Iran. *Theoretical and Applied Climatology*, 142, 407-432.
- Sowmya, N., Babu, P. V., Reddy, U., and Kavitha, P. (2022). Effect of different land configurations and spacings on growth and yield of groundnut (*Arachis hypogaea*) in scarce rainfall zone of Andhra Pradesh. *Farming and Management*, 7(1), 9-13.
- Stark, J. C., Love, S. L., King, B. A., Marshall, J. M., Bohl, W. H., and Salaiz, T. (2013). Potato cultivar response to seasonal drought patterns. *American Journal of Potato Research*, 90, 207-216.
- Stoll, A., Salvatierra-Martínez, R., González, M., Cisternas, J., Rodríguez, Á., Vega-Gálvez, A., and Bravo, J. (2021). Importance of crop phenological stages for the efficient use of PGPR inoculants. *Scientific Reports*, 11(1), 19548.
- Sun, J., Li, Y., Suo, C., and Liu, Y. R. (2019). Impacts of irrigation efficiency on agricultural water-land nexus system management under multiple uncertainties. A case study in Amu Darya River basin, Central Asia. *Agricultural Water Management*, 216, 76-88.
- Suryavanshi, P., and Buttar, G. S. (2020). Influence of different irrigation methods and schedules on water productivity of wheat. *Journal of Soil and Water Conservation*, 19(4), 398-403.
- Taghvaeian, S., Andales, A. A., Allen, L. N., Kisekka, I., O'Shaughnessy, S. A., Porter, D. O., and Aguilar, J. (2020). Irrigation scheduling for agriculture in the United States: The progress made and the path forward. *Transactions of the ASABE*, 63(5), 1603-1618.
- Tarakanov, I. G., Tovstyko, D. A., Lomakin, M. P., Shmakov, A. S., Sleptsov, N. N., Shmarev, A. N., and Ivlev, A. A. (2022). Effects of light spectral quality on photosynthetic activity, biomass production, and carbon isotope fractionation in lettuce, *Lactuca sativa* L., plants. *Plants*, 11(3), 441.
- Tasumi, M. (2019). Estimating evapotranspiration using METRIC model and Landsat data for better understandings of regional hydrology in the western Urmia Lake Basin. *Agricultural Water Management*, 226, <https://doi.org/10.1016/j.agwat.2019.105805>.
- Tayel, M. Y., Pibars, S. K., & Mansour, H. A. (2019). The impact of different closed drip irrigation networks and dripper type on pressure distribution along lateral lines and uniformity. *Plant Archives*, 19(2), 548-553.
- Tejero, I. G., Zuazo, V. H. D., Bocanegra, J. A. J., and Fernández, J. L. M. (2011). Improved water-use efficiency by deficit-irrigation programmes: Implications for saving water in citrus orchards. *Scientia Horticulturae*, 128(3), 274-282.

- Tione, G. (2016). Farmer preference for improved seed potato varieties in Malawi: Case study of Ntcheu and Dedza districts. In Fifth African Higher Education Week and RUFORUM Biennial Conference 2016, "Linking agricultural universities with civil society, the private sector, governments and other stakeholders in support of agricultural development in Africa", Cape Town, South Africa, 17-21 October 2016 (pp. 141-145). RUFORUM.
- Tolossa, T. T. (2020). Effect of mulching techniques and irrigation levels on onion (*Allium cepa* L.) growth parameters under drip irrigation system during dry season of Western Ethiopia. *Turkish Journal of Agriculture-Food Science and Technology*, 8(10), 2081-2088.
- Torres, N., Yu, R., Martínez-Lüscher, J., Kostaki, E., and Kurtural, S. K. (2021). Application of fractions of crop evapotranspiration affects carbon partitioning of grapevine differentially in a hot climate. *Frontiers in Plant Science*, 12, 633600.
- Trust: Newsletter 2022. Basin irrigation scheme Practice in Malawi. 2022.
- United Nations: World Population Prospects 2019: Highlights. 2019.
- Uribe, N., Srinivasan, R., Corzo, G., Arango, D., and Solomatine, D. (2020). Spatio-temporal critical source area patterns of runoff pollution from agricultural practices in the Colombian Andes. *Ecological engineering*, 149, <https://doi.org/10.1016/j.ecoleng.2020.105810>
- López-Urrea, R., Sánchez, J. M., De la Cruz, F., González-Piqueras, J., & Chávez, J. L. (2020). Evapotranspiration and crop coefficients from lysimeter measurements for sprinkler-irrigated canola. *Agricultural Water Management*, 239, 106260.
- Vanham, D., Hoekstra, A. Y., Wada, Y., Bouraoui, F., De Roo, A., Mekonnen, M. M., and Bidoglio, G. (2018). Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4. 2 "Level of water stress". *Science of the total environment*, 613, 218-232.
- Verdooren, L. R. (2020). History of the statistical design of agricultural experiments. *Journal of Agricultural, Biological and Environmental Statistics*, 25(4), 457-486.
- Verhage, F., Cramer, L., Thornton, P., and Campbell, B. (2018). Climate risk assessment and agricultural value chain prioritisation for Malawi and Zambia. Wageningen: CGIAR.
- Vivaldi, G. A., Camposeo, S., Romero-Trigueros, C., Pedrero, F., Caponio, G., Lopriore, G., and Álvarez, S. (2021). Physiological responses of almond trees under regulated deficit irrigation using saline and desalinated reclaimed water. *Agricultural Water Management*, 258, 107172.
- Wagg, C., Hann, S., Kupriyanovich, Y., and Li, S. (2021). Timing of short period water stress determines potato plant growth, yield and tuber quality. *Agricultural Water Management*, 247, <https://doi.org/10.1016/j.agwat.2020.106731>.
- Wallach, R. (2019). Physical characteristics of soilless media. In *Soilless Culture* (pp. 33-112). Elsevier.
- Wang, J., Pan, Z., Pan, F., He, D., Pan, Y., Han, G., and Wang, Z. (2020). The regional water-conserving and yield-increasing characteristics and suitability of soil

- tillage practices in Northern China. *Agricultural Water Management*, 228, 105883.
- Wang, X., Guan, H., Huo, Z., Guo, P., Du, J., and Wang, W. (2020). Maize transpiration and water productivity of two irrigated fields with varying groundwater depths in an arid area. *Agricultural and Forest Meteorology*, 281, <https://doi.org/10.1016/j.agrformet.2019.107849>.
- Wang, Z., Zhou, Z. X., Wang, X. M., and Chen, Z. J. (2018). Relationships between transpiration, water loss, and air conditions during physiological drying. *Drying Technology*, 36(2), 245-254.
- Waqas, M. S., Cheema, M. J. M., Hussain, S., Ullah, M. K., and Iqbal, M. M. (2021). Delayed irrigation: An approach to enhance crop water productivity and to investigate its effects on potato yield and growth parameters. *Agricultural Water Management*, 245, 106576.
- Watras, C. J., Michler, J. R., Lenters, J. D., and Rubsam, J. L. (2019). A low-cost hydrologic observatory for monitoring the water balance of small lakes. *Environmental monitoring and assessment*, 191(9), 548.
- Watson, A. (2020). "The Single Most Important Factor": Fossil Fuel Energy, Groundwater, and Irrigation on the High Plains, 1955–1985. *Agricultural History*, 94(4), 629-663.
- Webber, H. A., Madramootoo, C. A., Bourgault, M., Horst, M. G., Stulina, G., and Smith, D. L. (2008). Plant and soil water dynamics of alternate furrow and regulated deficit irrigation for two legume crops. *Transactions of the ASABE*, 51(4), 1341-1350.
- Wojewodzic, T., Janus, J., Dacko, M., Pijanowski, J., and Tazsakowski, J. (2021). Measuring the effectiveness of land consolidation: An economic approach based on selected case studies from Poland. *Land Use Policy*, 100, <https://doi.org/10.1016/j.landusepol.2020.104888>.
- Woldeselassie, A., Dechassa, N., Alemayehu, Y., Tana, T., & Bedadi, B. (2021). Soil and water management practices as a strategy to cope with climate change effects in smallholder potato production in the Eastern Highlands of Ethiopia. *Sustainability*, 13(11), 6420.
- Yan, F., Zhang, F., Fan, X., Fan, J., Wang, Y., Zou, H., and Li, G. (2021). Determining irrigation amount and fertilization rate to simultaneously optimize grain yield, grain nitrogen accumulation and economic benefit of drip-fertigated spring maize in northwest China. *Agricultural Water Management*, 243, <https://doi.org/10.1016/j.agwat.2020.106440>.
- Yan, H., Hui, X., Li, M., and Xu, Y. (2020). Development in sprinkler irrigation technology in China. *Irrigation and Drainage*, 69, 75-87.
- Yang, B., He, S., Liu, Y., Liu, B., Ju, Y., Kang, D., and Fang, Y. (2020). Transcriptomics integrated with metabolomics reveals the effect of regulated deficit irrigation on anthocyanin biosynthesis in Cabernet Sauvignon grape berries. *Food chemistry*, 314, 126170.

- Yang, M. D., Leghari, S. J., Guan, X. K., Ma, S. C., Ding, C. M., Mei, F. J., and Wang, T. C. (2020). Deficit subsurface drip irrigation improves water use efficiency and stabilizes yield by enhancing subsoil water extraction in winter wheat. *Frontiers in Plant Science*, 11, 508.
- Yannopoulos, S. I., Grismer, M. E., Bali, K. M., and Angelakis, A. N. (2020). Evolution of the materials and methods used for subsurface drainage of agricultural lands from antiquity to the present. *Water*, 12(6), 1767.
- Yao, C., Zhang, L., Wu, P., Liu, Y., Cai, Y., and Zhou, W. (2021). Clogging formation and an anti-clogging method in subsurface irrigation system with porous ceramic emitter. *Agricultural Water Management*, 250, <https://doi.org/10.1016/j.agwat.2021.106770>.
- Yao, N., Li, Y., Xu, F., Liu, J., Chen, S., Ma, H., and He, J. (2020). Permanent wilting point plays an important role in simulating winter wheat growth under water deficit conditions. *Agricultural Water Management*, 229, 105954.
- Yazdanpanah, M., Klein, K., Zobeidi, T., Sieber, S., and Löhr, K. (2022). Why have economic incentives failed to convince farmers to adopt drip irrigation in southwestern Iran?. *Sustainability*, 14(4), 2055.
- Yoon, P. R., and Choi, J. Y. (2020). Effects of shift in growing season due to climate change on rice yield and crop water requirements. *Paddy and Water Environment*, 18, 291-307..
- Yorozu, A., Ishigami, G., and Takahashi, M. (2021, June). Human-Following Control in Furrow For Agricultural Support Robot. In *International Conference on Intelligent Autonomous Systems* (pp. 155-164). Cham: Springer International Publishing.
- Yu, Y., Jiao, Y., Yang, W., Song, C., Zhang, J., and Liu, Y. (2022). Mechanisms underlying nitrous oxide emissions and nitrogen leaching from potato fields under drip irrigation and furrow irrigation. *Agricultural Water Management*, 260, <https://doi.org/10.1016/j.agwat.2021.107270>.
- Zahoor, S. A., Ahmad, S., Ahmad, A., Wajid, A., Khaliq, T., Mubeen, M., and Nasim, W. (2019). Improving water use efficiency in agronomic crop production. *Agronomic Crops: Volume 2: Management Practices*, 13-29.
- Abou Zaki, N., Torabi Haghghi, A., Rossi, P. M., Xenarios, S., and Kløve, B. (2018). An index-based approach to assess the water availability for irrigated agriculture in sub-Saharan Africa. *Water*, 10(7), <https://doi.org/10.3390/w10070896>
- Zaman, M., Shahid, S. A., Heng, L., Zaman, M., Shahid, S. A., and Heng, L. (2018). Irrigation systems and zones of salinity development. *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques*, 91-111.
- Zhuo, L., and Hoekstra, A. Y. (2017). The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint. *Frontiers of Agricultural Science and Engineering*, 4(2), 185-194.
- Zinkernagel, J., Maestre-Valero, J. F., Seresti, S. Y., and Intrigliolo, D. S. (2020). New technologies and practical approaches to improve irrigation management of open

field vegetable crops. *Agricultural Water Management*, 242,
<https://doi.org/10.1016/j.agwat.2020.106404>.

APPENDICES

APPENDIX A1: Data collection for soil characterization

(a) Bulk density

The core method of bulk density determination was used. Aluminum soil sampling rings, woodblock, rubber mallet, fording trowel, sealable bags, marker pen, 1g precision scale, ceramic coffee cups, spade, and microwave oven were the equipment used during the undisturbed soil samples collection.

To extract the undisturbed sample, a sampling ring was driven into the soil using a small mallet and a block of wood (Figure A1.1 A and B). The ring was removed from the soil by cutting around the outside edge with a spade and a small fording trowel was placed underneath the base of the ring to prevent the loss of soil as the ring was being lifted out. The sample was sealed with plastic lids labelled as shown in Figure A1.1C. The sample was later weighed and its weight was recorded in a notebook. The weight of two identical clean empty plastic cups was recorded likewise. The results were subtracted from the weight of the cups to find the actual weight of the soil samples. Then the samples were oven dried for 48 hours in a laboratory environment at a temperature of 105°C. After 48hrs, the samples were cooled and weighed together with the sampling rings. Soil samples were then removed from the sampling rings to weigh the rings only.

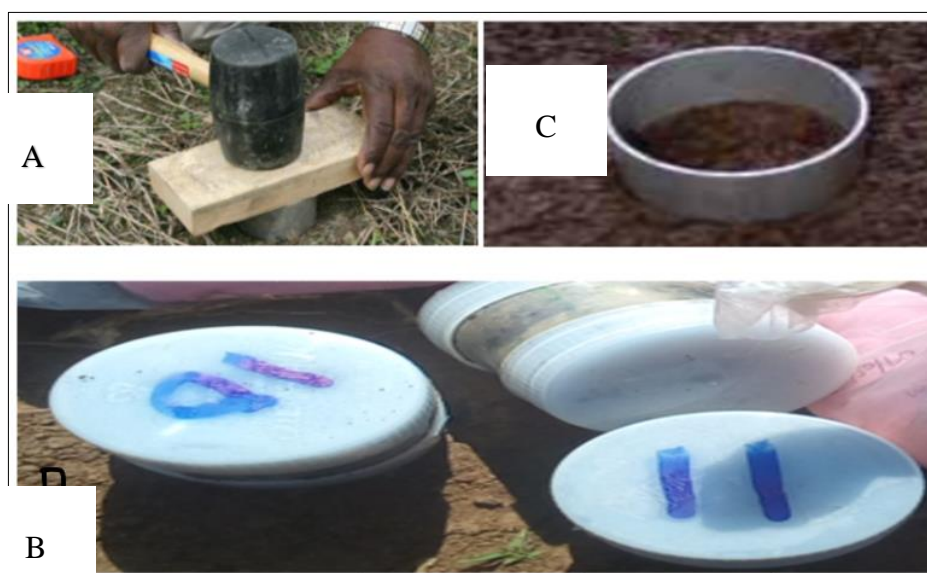


Figure A1.1: Steps of extracting cores of the undisturbed soil sample from the experimental site

The bulk density (ρ_b) was calculated by dividing the weight of dry soil by its volume (Equation A3.1) which is the volume of the sampling cylinder. It was calculated as:

$$\rho_b = \frac{M_s}{V_s} \quad (A3.1)$$

Where:

ρ_b = Bulk density in grams per cubic-centimetre (g/cm^3)

M_s = Mass of oven-dry soil in grams (g)

V_s = Total volume of the same soil in cubic-centimetre (cm^3)

(b) Soil moisture content

The soil moisture content was determined at both the field capacity and permanent wilting point.

(i) Soil moisture content at field capacity and wilting point

The disturbed soil samples were collected for moisture content (MC) determination at FC and permanent wilting point (PWP) (Mehmood *et al.*, 2019). A hand auger (Figure A1.2) was used to collect disturbed samples in the middle of each plot. The samples were collected at an effective depth of 60 cm which is the root depth for potatoes. From the undisturbed soil sample, 25 g of air-dried soil was placed in a crucible and weighed on a digital scale (Figure A1.3).

The air-dried soil sample was then moved into retaining rings on porous plates of the pressure chamber. Water was added to the plates and the sample was allowed to get saturated. The plates were placed in the pressure chambers while thin rubber tubes were connected to the beakers (Figure A1.4).



Figure A1.2: A hand auger is used to get soil samples from different treatment plots



Figure A1.3: Weighing air-dried soil on a digital scale

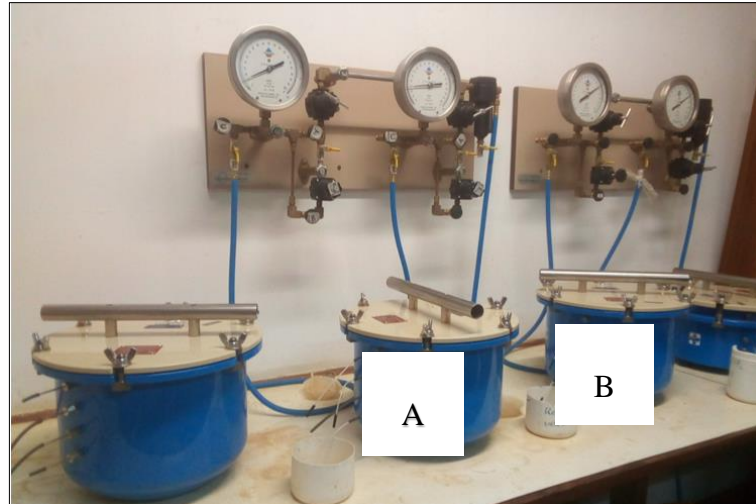


Figure A1.4: Pressure chambers used to determine FC (A) and PWP (B) inside soil science Laboratory of Bunda College

In Figure A1.4A, the suction pressure was set at -3 bars. When water completely stopped coming out through the rubber tubes, the samples were removed and placed in small drying tins for 24 hours. Finally, the field capacity was calculated using Equation A3.2.

$$\theta_m (\%) = \frac{W_{ws} - W_{ds}}{W_{ds}} \times 100 \quad (A3.2)$$

Where:

$\theta_m (\%)$ = Mass-based soil moisture content at FC or PWP (%)

W_{ws} = Weight of wet soil in grams (g)

W_{ds} = Weight of dry soil in grams (g)

(ii) Soil moisture content at wilting point

The laboratory procedure used to determine the PWP was similar to the one used for FC determination except for one step. For PWP, the suction pressure was set at -15 bars. The soil moisture content at PWP was also determined using Equation A3.2.

(c) Soil texture

The soil particle size or texture analysis was performed on air-dried soil. The soil was dispersed into individual particles of sand (2.00 – 0.05mm), silt (0.05 – 0.002mm), and clay (<0.002mm) fractions. The air-dried samples weighing 40g were placed into measuring cylinders where the soil suspensions were formed by the addition of distilled water. 10ml of 10% Calgon solution was also added to each cylinder, as a dispersing agent. The soil suspension was allowed to stand for 10 minutes. There were 27 cylinders each representing a plot. The cylinders with water-soil sample suspension are shown in Figure A1.5,



Figure A1.5: Determination of soil texture in Kasinthula Research Station Lab

The suspension was transferred into the dispersing cup with distilled water and was mixed for two minutes with an electric high-speed stirrer. The suspension was moved into a measuring cylinder and the remaining soil was rinsed into the cylinder with distilled water. The hydrometer was inserted into the suspension, in which the water was added to the mark of 1000 ml and then the hydrometer was removed following the procedure in Korner *et al.* (2018), and Nogueira *et al.* (2021). The cylinder was covered with a tight-fitting cover before inverting the cylinder carefully 10 times to mix the suspension. Three drops of amyl alcohol were added to the soil suspension as a solvent and the hydrometer was gently placed after 20 seconds.

The suspension was left to stand for 40 seconds the time when hydrometer readings were taken again and the temperature of the suspension was measured. The cylinder was covered again with a tight-fitting rubber bung to mix the suspension by inverting the cylinder 10 times and then allowed to stand undisturbed for two hours. Both hydrometer

and temperature were recorded after 2 hours. The hydrometer reading after 40 seconds reflected the grams of silt + clay in 1 litre of the suspension (Barman and Choudhury, 2020). Thus, the sand weight was determined by subtracting the hydrometer value from the original sample weight of 40 grams. Then, the percent of sand was calculated by dividing the sand content in the sample by the total weight of the sample and multiplying by 100 (Equation A3.3).

$$\text{Sand \%} = \frac{\text{Sand content in sample}}{\text{Total weight of sample}} \times 100 \quad (\text{A3.3})$$

After another 2 hours, the silt was assumed to have settled and Equation A3.4 was used.

$$\text{Clay \%} = \frac{\text{Clay content in sample}}{\text{Total weight of sample}} \times 100 \quad (\text{A3.4})$$

The silt content was therefore calculated by subtracting the sum of the clay and sand content from 100 % following Equation A3.5.

$$\text{Silt \%} = 100\% - (\text{clay\%} + \text{sand \%}) \quad (\text{A3.5})$$

Once the sand, silt, and clay distributions were determined, the soil was assigned to a texture class based on the soil textural triangle (Figure 2.10).

APPENDIX A2: ANOVA MEANS


Treatment	Stand count	Plant height	Number of stems	Number of tubers per plant	Tuber length(cm)	Tuber diameter	Number of tubers per m ²	Yield (t/ha)
MAD ₁ T ₀₀	94.66a	38.40a	1.83a	7.77a	8.73a	4.16a	55.16a	22.68a
MAD ₁ T ₀₁	79.66abc	33.96ab	1.56a	7.13a	7.30ab	3.83ab	43.25ab	21.30ab
MAD ₁ T ₀₂	82.33abc	32.30ab	1.43a	6.50a	5.00cd	3.33abc	41.08ab	19.59abc
MAD ₂ T ₀₀	90.33a	31.76ab	1.50a	5.60a	6.36bc	2.96bcd	38.43ab	17.03abcd
MAD ₂ T ₀₁	90.66a	29.96b	1.73a	5.06a	5.20bcd	2.66cd	35.21ab	15.69bcd
MAD ₂ T ₀₂	88.66ab	31.40ab	1.66a	5.23a	4.73cd	2.23cd	35.16ab	15.01cd
MAD ₃ T ₀₀	75.30abc	27.66b	1.46a	5.56a	4.16d	2.30cd	31.96b	13.28d
MAD ₃ T ₀₁	68.66bc	28.96b	1.33a	5.46a	4.63cd	2.13d	28.96b	12.91d
MAD ₃ T ₀₂	62.00c	31.90ab	1.46a	5.23a	3.36d	2.03d	24.71b	11.51d
Analysis test codes (P-value)								
MAD	***	***	ns	**	***	***	**	***
Irrigation	**	ns	ns	ns	***	*	ns	ns
MAD*Irrigation	ns	*	ns	ns	*	Ns	ns	ns

NB: Mean values within the same columns by 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. Here, analysis of variance (ANOVA) the significant test P values were shown (* indicates $P \leq 0.05$, ** indicates $P \leq 0.01$; *** indicates $P \leq 0.001$, highly significant and ns indicate no significance).

APPENDIX A3: ANOVA MEAN VALUES

Treatment	Yield (t/ha)	Number of irrigations	Water use (m ³ /ha)	WUE(Kg/m ³)	Water saved (%)	% Yield reduction
MAD ₁ T ₀₀	22.68a	10	3874.57a	5.85a	0	0
MAD ₁ T ₀₁	21.30ab	10	2534.17b	8.41a	35	6
MAD ₁ T ₀₂	19.59abc	10	2648.37b	7.40a	32	14
MAD ₂ T ₀₀	17.03abcd	6	1866.45c	9.12a	52	25
MAD ₂ T ₀₁	15.69bcd	6	1704.91cd	9.20a	56	31
MAD ₂ T ₀₂	15.01cd	6	1600.28cd	9.38a	59	34
MAD ₃ T ₀₀	13.28d	5	1612.79cd	8.23a	58	41
MAD ₃ T ₀₁	12.91d	5	1178.18d	10.96a	70	43
MAD ₃ T ₀₂	11.51d	5	1381.37cd	8.33a	64	49
Analysis (P-value)						
MAD	***		***	ns		
Irrigation	ns		***	ns		
MAD*Irrigation	ns		**	ns		

APPENDIX B1: APPROVAL OF STUDY


THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka 10101 | Tel: +260-290 258/291 777
Fax: (+260) 211 290 258/253 952 | Email: director.drgs@unza.zm | Website: www.unza.zm /directorates/drgs

APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465

15th March, 2022

REF NO. NASREC-2022-APR-001

Aina Chikankheni,
The University of Zambia
School of Engineering
Department of Agricultural Engineering
P.O. Box 32379
LUSAKA

Dear Ms. Chikankheni,

RE: "INVESTIGATION INTO THE EFFECTS OF DEFICIT IRRIGATION ON POTATO PRODUCTION IN DEDZA DISTRICT - MALAWI"

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	ORDINARY REVIEW	APPROVAL NO. NASREC-2022-APR-001
Approval and Expiry Date	Approval Date: 1 st April, 2022	Expiry Date: 31 st March, 2023
Protocol Version and Date	Version - Nil.	31 st March, 2023
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

Conditions of Approval

Towards Improving Service and Excellence in High Education Beyond Fifty Years

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 3 days.
- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator's or site address.
- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled "late submissions" and will incur a penalty fee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO), both NASREC
- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.
- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.
- A reprint of this letter shall be done at a fee.
- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator's or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair).

Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, typing and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented. Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,



Dr. E. M. Mwanasumo

**CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH
ETHICS COMMITTEE - IRB**

CCI Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies

APPENDIX B2 INDIVIDUAL CONSENT FORM

THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES
NATURAL AND APPLIED SCIENCES RESEARCH ETHICS COMMITTEE

Telephone: +260-211-290258/293937 P.O.Box 32379
Fax: +260-211-290258/293937 Lusaka,
E-mail drgs@unza.zm Zambia.

PARTICIPANT INFORMATION SHEET

This informed consent form is for HAVENA MALISENI in the KUMAKULI of Dedza district who are invited to participate in research titled "Investigation into the Effects of Deficit Irrigation on Potato Production in Dedza District- Malawi".

Name Aina Chikankheni of The University of Zambia, School of Engineering Principle Investigator:
Name of organization: Malawi Government Scholarship Fund Sponsor:

This informed consent form has two parts:

1. Information Sheet (to share information about the study with you)
2. Certificate of consent (For signatures if you choose to participate)

You will be given a copy of the full informed consent form

1 Information Sheet

1.1 Introduction

I am Aina Chikankheni a student at The University of Zambia, School of Engineering. I am doing research on the investigation into the effects of deficit irrigation on potato production in the district. I am going to give you information and invite you to be part of this research. Before you decide, you can talk to anyone you feel comfortable with about the research.

This consent form may contain words that you do not understand. Please ask me to stopas we go through the information and I will take time to explain. If you have questions later, you can ask them of me or another researcher.

1.2 Purpose of the research

Improved water management is one of the strategies to address the problem of inadequate water supply in smallholder irrigation schemes in your community. We want to find ways to stop this from happening. We believe that you can help us by telling us the strength and weaknesses of the current irrigation strategies in the district. We want to learn what strategies are commonly used in this area and why farmers opt to use that particular irrigation strategy. We also want to know more about local irrigation strategies because this knowledge might help us to learn how to better address the problem of inadequate water supply in smallholder irrigation schemes.

1.3 Type of research intervention

This research will involve your participation in answering a questionnaire type of interview that will take about half an hour.

1.4 Participant selection

You are invited to take part in this research because we feel that your experience as a smallholder farmer can contribute much to our understanding and knowledge of current irrigation strategies being practiced in the area.

Do you know why we are asking you to take part in this study?

Do you know what the study is about?

1.5 Voluntary participation

Your participation in this research is entirely voluntary. It is your choice whether to participate or not. If you choose not to participate all the extension services you receive from time to time will continue and nothing will change. Thus, the choice you are about to make will have no bearing on your life as far as extension services are concerned. You are at liberty to change your mind later and stop participating even if you agreed earlier.

If you decide not to take part in this research study, do you know what your options are?

Do you know that you do not have to take part in this research study if you do not wish to?

Do you have any questions?

Procedures

The questions will be read to you and you can say out loud the answer you want me to write down. If you do not wish to answer any of the questions included in the survey, you may skip them and move on to the next question. The information recorded is confidential, your name will not be included in the main report, only a number will identify you, and no one else except myself and possibly my Supervisors from the University of Zambia will have access to this survey.

The research will take place over four months. However, this interview will last for about 15 minutes per person right here in this village. For the remaining time, the experimental plot will be set at Kamgulitse irrigation scheme and you are welcome to visit.

If you decide to take part in the study, do you know how much time will the interview take? Where will it take place?

Do you know how much time will take to answer the questions?

If you agree to take part, do you know if you can stop participating?

Do you know that you may not respond to the questions that you do not wish to respond to? Do you have any more questions?

Use of information

The information we shall get from you will be used to establish the strength and weaknesses of the current irrigation strategies in your area.

There will be no direct benefit to you, but your participation is likely to help us find out more about the strengths and weaknesses of the current irrigation strategies in your area.

You will not be provided any incentive to take part in the research. However, we will give you refreshments for your time. After weighing the harvest, farmers of Kamgulitse irrigation scheme will be allowed to get the rest of the potato from the experimental plots.

Can you tell me if you have understood correctly the benefits that you will have if you take part in the study?

Do you know how the study will pay for using the land within Kamgulitse irrigation scheme?

Confidentiality

The research being done in the community may draw attention and if you participate you may be asked questions by other people in the community. We will not be sharing information about you with anyone outside of the research team. The information that we collect from this research project will be kept private. Upon request, it may be shared with the Malawi Government Scholarship Fund management team.

This protocol has been reviewed and approved by NASREC which is a committee whose task is to make sure that research participants are protected from harm. If you wish to find out more about the IRB, contact:

Chairperson, Natural and Applied Sciences,

Research Ethics Committee,

University of Zambia

P O Box 32379

LUSAKA

OR

Director, Directorate of Research and Graduate Studies

University of Zambia

P O Box 32379

LUSAKA


"Approval to conduct this research has been provided by the University of Zambia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time. In addition, if you are/ or any person is not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the NASREC at the address stated above.

2 Certificate of Informed Consent

I have been invited to participate in a research about investigation into the effect of deficit irrigation on potato production.

The foregoing information has been read to me. I have had the opportunity to ask questions about it and any questions I have been asked have been answered to my satisfaction. I consent voluntarily to be a participant in this study.

Print Name of Participant HAVENA MALISENI

Signature of Participant 

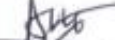
Date 6th JULY 2022 Day/month/year

2.1 If illiterate;

I have witnessed the accurate reading of the consent form to the potential participant, and the individual has had the opportunity to ask questions. I D. mkulama confirm that the individual has given consent freely.

Print name of witness _____

Thumb print of participant

Signature of witness 




Date 6-07-22 Day/month/year

Statement by the researcher/person taking consent

I have accurately read out the information sheet to the potential participant, and to the best of my ability made sure that the participant understands.

I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

A copy of this ICF has been provided to the participant. Print Name of Researcher/person taking the consent AWA CHIKANKHEXI

Signature of Researcher /person taking the consent 

Date 01/07/2022 Day/month/year

CONTACTS FOR QUESTIONS (Names, addresses and phone numbers of the following):

Principal Investigator

Names: Aina T. Chikankheni

Phone: +260977953115 / +265 88 531 33 88

E mail: chikankheniaina@gmail.com

Physical address: e/o Dedza district agriculture office
P.O. Box 49
Dedza
Malawi

APPENDIX C1: FARMER INVOLVEMENT QUESTIONNAIRE

This survey is on farmer involvement in the strength and weaknesses of current irrigation strategies in the area. You are requested to answer ALL the questions in the survey.

- Below are statements that are followed by a range of answers.
- Please read them carefully and see the answer that best explains how much you agree with the statement.
- It will be helpful if you answer sincerely.
- Your accurate information will assist the decision-makers in designing activities and programs that are helpful to the farmers, Agricultural extension workers, district administrators, and other stakeholders in the community.

1. Name of interviewer [-----]
2. Name of respondent [-----]
3. Gender: [-----] 1=Male, 2= Female
4. Marital status [-----] 1=Married, 2= Single, 3= Divorced, 4= Widowed
5. Name of respondent’s village [-----]
6. Highest level of education of respondent [-----] 1= None, 2=Basic, 3= Primary, 4= Secondary, 5= Tertiary
7. Age of the farmer in years [-----] 1= Above 65, 2= 50 to 65, 3= 36 to 49, 4=20 to 35, 5= Below 35
8. What is the most used irrigation strategy in your area for potato production? [-----] 1=use of water can/bucket, 2= use of the gravity-fed canal, 3= use of bound basin, 4= use of treadle pumps, 5=use of motorized pumps, 6= others
9. What are the strengths of the current irrigation strategies STATED in Q8? [-----]

-----]
10. What are the weaknesses of the current irrigation strategies STATED in Q8? [-----]

- -----]
11. What type of crops do you grow under irrigation? [-----] 1=Potato, 2= Beans, 3= Maize, 4= Vegetables
 12. How big is your land grown under POTATO irrigation? [-----] 1= less than 0.1 acre, 2= 0.1 to one acre, 3= 1 to 2.5 acres, 4= more than 2.5 acres
 13. How big is your rented land grown under POTATO irrigation? [-----] 1= less than 0.1 acre, 2= 0.1 to one acre, 3= 1 to 2.5 acres, 4= more than 2.5 acres
 14. What irrigation strategy do YOU use for Q9? [-----] 1=Water can/bucket, 2= Gravity fed canal, 3= Bound basin, 4= Treadle pump, 5=Motorized pump, 6= others
 15. If [1] was among your answers for Q9, proceed to Q14
 16. Do you have problems doing irrigation of potatoes? [-----] 1=Yes, 2= No 3= Sometimes
 17. How often do you irrigate your field within the scheme? -----
 18. What type of problems do you have in the irrigation farming of potatoes? [-----] 1= Technical related, 2= Social-economic related, 3= Financial related, 4= Other
 19. How are Agricultural extension workers in your area involved during the irrigation of potato [-----] 1= Provide technical support, 2= Link farmers to stakeholders for financial support, 3= Coordinating learning farmer visits, 4= Other
 20. How often does your Government help concerning irrigation farming in your area? [----] 1= At least once/financial year, 2= At most once/ financial year, 3= None, 4=Other
 21. Apart from Your Government who helps on issues to do with water management at your irrigation scheme? [-----] 1= World Vision International, 2= United Purpose, 3= CADECOM, 4= Other
 22. As a Potato producer under irrigation, what kind of help would you need from the Government? [-----] 1= Grants in form of fixed assets 2= Grants in form of Variable assets, 3=Soft Loans, 4= other

23. As a Potato producer under irrigation, what kind of help would you need from the Agricultural extension workers? [-----] 1= New knowledge 2= Frequent field backstopping, 3=Linking farmers to markets, 4= other

24. What new knowledge have you gained (if any)? [-----

-----]
-----]

Thank you for your cooperation

APPENDIX C2: FOCUS GROUP DISCUSSION GUIDE

Focus Group Discussion Guide —Farmers groups group members Instructions: This FGD will be conducted with 6 to 12 participants who are members of a farmers group targeted for irrigation.

Introduction: Thank you for the opportunity to speak with you. I am a student doing a study on deficit irrigation, interested in learning more about irrigation agriculture in this area. I assure you that all the information that will be provided by you will be used exclusively for the study and analysis. The session will be recorded but all responses will appear anonymously. This is not a test, and there are no right or wrong answers. The most important thing is that you should feel comfortable and contribute as much as you can. You can express opinions and discuss issues freely.

Background information on participants

For each participant of the FGD, please take down the following information in your notebook

1. Name
2. Age
3. How long have you been a WUA member
4. Ever grown potato? [Y or N]

5. Grew potato in the last cropping season OR currently considering to start growing potato? [Y or N]
6. If growing potato, for how long? 7. Are you a household head? [Y or N]

Strengths and weaknesses of the current irrigation strategies

1. What are the strengths of gravity-fed canal irrigation strategy?
2. What are the weaknesses of gravity-fed canal irrigation strategy?
3. What are the strengths of water can/bucket irrigation strategy?
4. What are the weaknesses of the water can/bucket irrigation strategy?
5. What are the strength of the bound basin irrigation strategy?
6. What are the weaknesses of the bound basin irrigation strategy?
7. What are the strengths of the treadle pump irrigation strategy?
8. What are the weaknesses of the treadle pump irrigation strategy?
9. What are the strengths of the motorized pump irrigation strategy?
10. What are the weaknesses of the treadle pump irrigation strategy?
11. What are the strengths of the solar pump irrigation strategy?
12. What are the weaknesses of the solar pump irrigation strategy?

APPENDIX D: INVOICE FOR SOIL ANALYSIS

Crop and Soil Sciences Department
P. O. Box 219, Lilongwe,
Phone Number: +265 1 277 420 | Fax Number: +265 1 277 364
Account Name: Crop Science Department. **Bank:** Standard
Account Number: 9100002714563. **Branch:** Lilongwe



Invoice # 25

Date: 25/08/2022

Bill To

Ms Aina Chikankheni | Agriculture Officer, MoAFS.
Phone: +265 885 31 33 88

For

Soil Analytical
Service

Item Description	Amount
27 soil samples analysed for %MC @ K510.00 per sample	MWK 8,100.00
27 soil samples analysed for pH @ K850.00 per sample	MWK 13,500.00
27 soil samples analysed for EC @ K850.00 per sample	MWK 13,500.00
27 soil samples analysed for BD @ K1360.00 per sample	MWK 21,600.00
27 soil samples analysed for PD @ K1360.00 per sample	MWK 21,600.00
27 soil samples analysed for FC & WP @ K2000.00 per sample	MWK 40,500.00
27 soil samples analysed for N @ K2040.00 per sample	MWK 32,400.00
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Subtotal	MWK 183,600.00
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APPENDIX E: PUBLISHED PAPER

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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 rain fall 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 its 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

➤ *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).

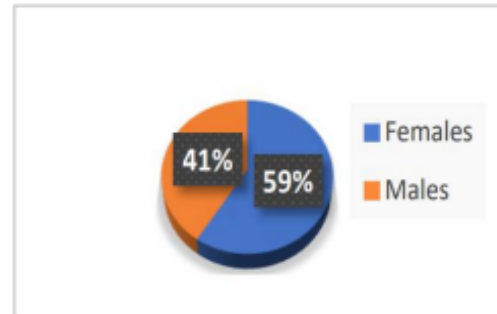


Fig 1 Gender of Participants

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).

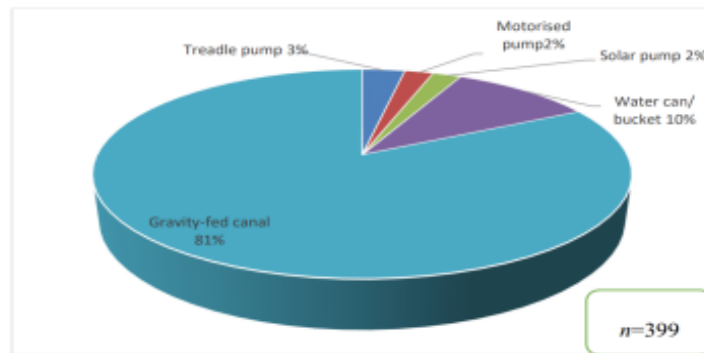


Fig 2 The Current Irrigation Water Lifting and Delivery Method in Dedza District

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 easy 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 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).

➤ *Environmental Factors Affecting Irrigation*

- *Soil Characteristics*

The soil BD of the experimental area ranges from 1.25g/cm³ to 1.66g/cm³ with a mean value of 1.40g/cm³. 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/cm³ 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 (ET₀) 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 ET₀ 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 ET₀ 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).

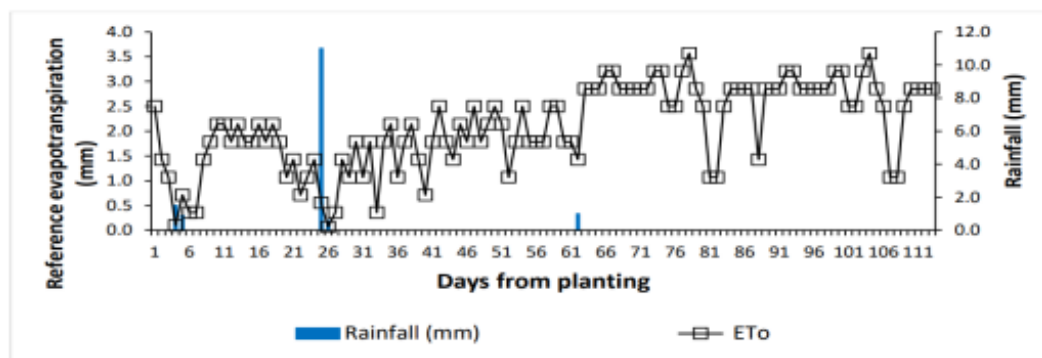


Fig 3 Precipitation Against Reference Evapotranspiration

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

DFP	Month	Tmin ⁰ c	Tmax ⁰ c	RH%	Pe mm	ET ₀ 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

➤ *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.

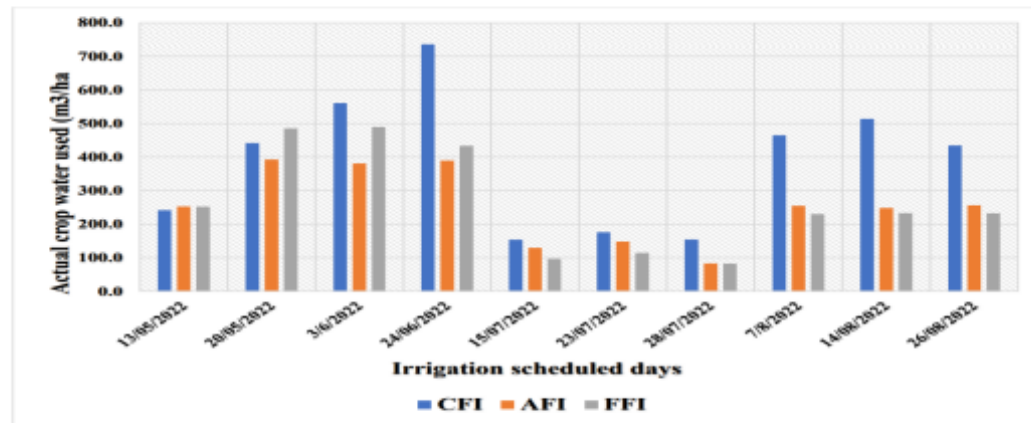


Fig 4 Irrigation Water Distribution within the Irrigation Regime with a 20% Depletion Level

✓ *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.



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

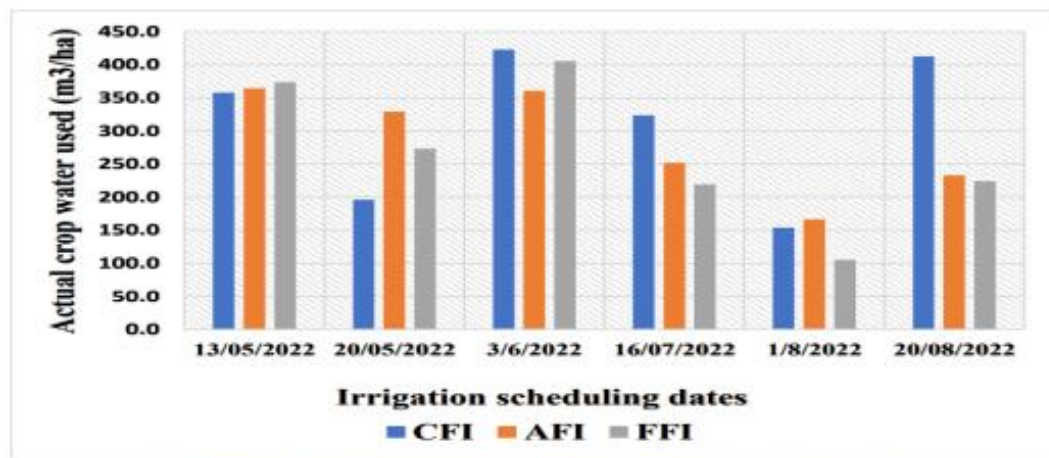


Fig 6 Irrigation Water Distribution within the Irrigation Regime with a 40% Depletion Level

✓ *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 7). 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.



Fig 7 Crop Stand According to the Date of an Irrigation Event

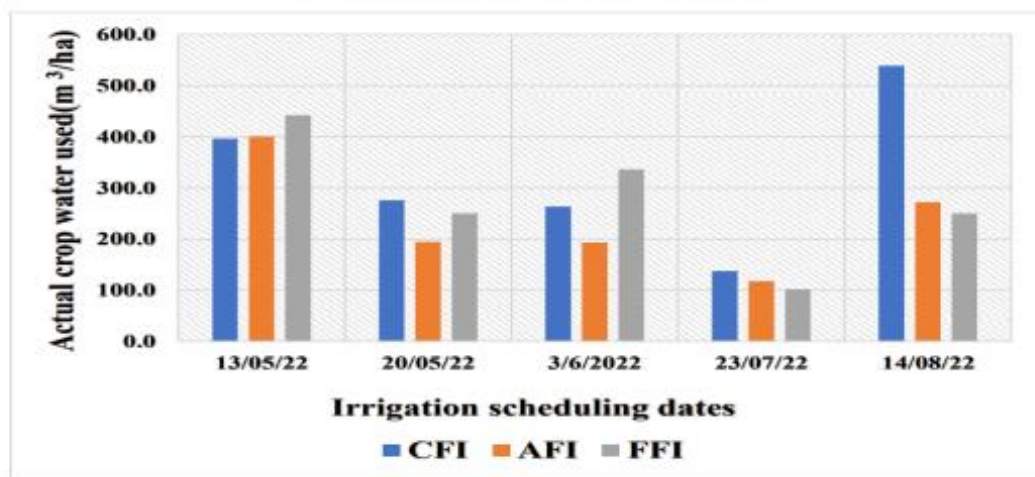


Fig 8 Irrigation Water Distribution within the Irrigation Regime with a 60% Depletion Level

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 9. 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 saved 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.

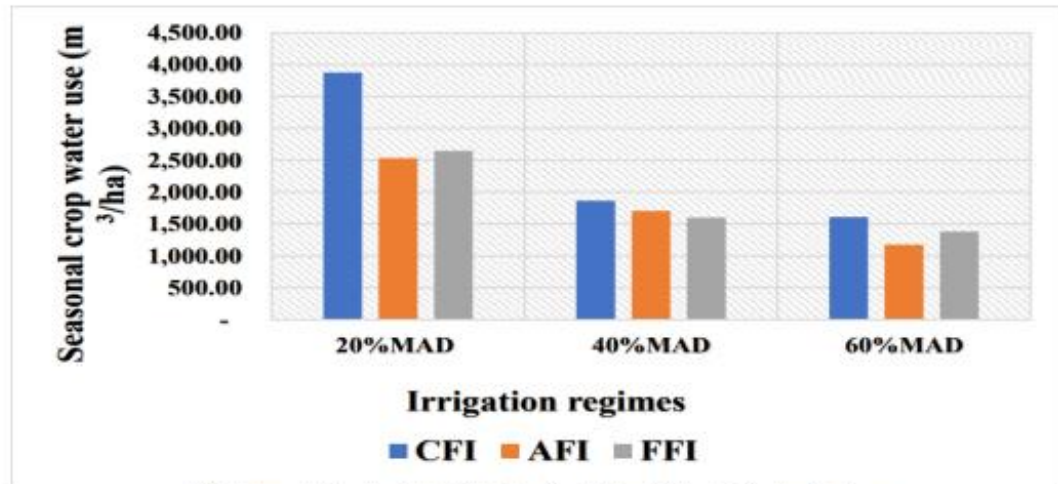


Fig 9 Seasonal Irrigation Water Distribution in all Three Different Irrigation Regimes

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:

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

Where: Y is the amount of irrigation water saved expressed as a percentage, 3875.57m³/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 1,341-2697m³/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 750-1500m³/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). However, in the case of Dodza, 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

Saved water (%)	Actual saved water(m³/ha)	Equivalent area (ha)
0	-	-
35	1,341	0.3
32	1,227	0.3
52	2,009	0.5
56	2,170	0.6
59	2,275	0.6
58	2,264	0.6
70	2,697	0.7
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 different 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 (*Sabia 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% ($P \leq 0.01$) 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 10). 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 ($P \leq 0.01$) 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 Huntentburg *et al.* (2021) who reported that tuber development seemed to respond to systematic moisture stress signals rather than local soil conditions.

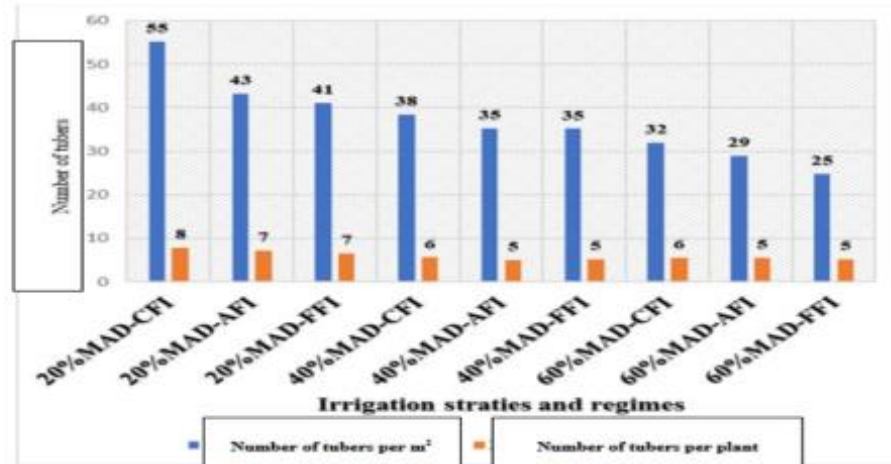


Fig 10 Effects of CFI, AFI, and FFI on the Number of Potato Tubers

✓ *Tuber Length*

The statistical results show that tuber length is significantly different ($P \leq 0.001$) 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% ($P \leq 0.05$) 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

Irrigation strategy	Maximum allowable depletion level		
	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 ($P \leq 0.001$) across the irrigation regimes. Furthermore, the results show that tuber diameter is significantly different at the level of 5% ($P \leq 0.05$) 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 ($P \leq 0.001$) 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	(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

➤ *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\$/m³ (Figure 10). 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\$/m³ (Figure 11). From the results, it is possible to deduce that a highest water profit can be gained per m³ 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\$/m³ (50% increase) or 3.70 US\$/m³ (32% increase) obtained from the AFI and FFI plots respectively under the 20% MAD regime.

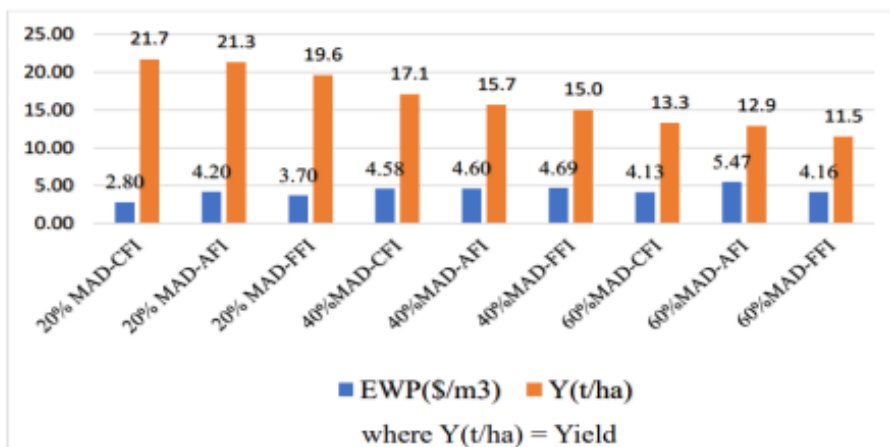


Fig 11 Economic Water Productivity of Potato Production Under Deficit Irrigation

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 rainfed 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 12) 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 12). The current findings agree with Hikemical 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 12 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 m³/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 5.47 US\$/m³ 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 m³ of water under the 3 treatments within the three irrigation regimes of irrigation will let one earn a gain of 5.47 US\$. It is possible to deduce that the highest water profit had been gained per m³ 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\$/m³ (50% increase) or 3.70 US\$/m³ (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.

REFERENCES

- [1]. Abdulrahman, F. A., Salih, S. A., and Mahmood, Y. A. (2018). The Effect of Different Irrigation Interval on Tuber Yield and Quality of Potato (*Solanum tuberosum* L.). *Kurdistan Journal of Applied Research*, 27-31.
- [2]. Abraham, T. (2019). Irrigation Types and Systems. In Rawat, A.K and Tripathi, U.K. *Advances in Agronomy* (pp. 19-41). New Delhi: AkiNik Publications.
- [3]. Ali, M., Hoque, M., Hassan, A., and Khair, A. (2007). Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. *Agricultural Water Management*, 151-161.
- [4]. Ali, S., Xu, Y., Ma, X., Ahmad, I., Jia, Q., Akmal, M. and Jia, Z. (2019). Deficit irrigation strategies to improve winter wheat productivity and regulating root growth under different planting patterns. *Agricultural Water Management*, 1-11.
- [5]. Amanturdiyev, I. (2022). Determining the Water-Saving Irrigation Regime and Fertilization Standards for Tomorrow's Potatoes. *Journal of Human University (Natural Sciences)*, 145-149.
- [6]. Ariza, W., Rodriguez, L. E., Moreno-Echeverry, D., Guerrero, C. A., and Moreno, L. P. (2020). Effect of water deficit on some physiological and biochemical responses of the yellow diploid potato (*Solanum tuberosum* L. Group Phureja). *Agronomia Colombiana*, 36-44.
- [7]. Azami, A., Sagin, J., Sadat, S. H., and Hejran, H. (2020). Sustainable Irrigation: Karez System in Afghanistan. *Central Asian Journal of Water Research*, 1-18.
- [8]. Baldwin, G. L., & Swalley III, R. M. (2022). Opportunities for the Scale-Up of Irrigation Systems in Ghana, West Africa. *Sustainability*, 1-18.
- [9]. Barakat, M., Abd El-Mageed, T. A., Elsayed, I. N., and Semida, W. (2020). Effect of soil mulching on growth, productivity, and water use efficiency of potato (*Solanum tuberosum* L.) under deficit irrigation. *Archives of Agriculture and Environmental Science*, 328-336.
- [10]. Bellver, J., Nieto, H., Pelechá, A., Jofre-Cekalovic, C., Zazurca, L., and Miarnau, X. (2021).
- [11]. Remote Sensing Energy Balance Model for the Assessment of crop Evapotranspiration and water status in an Almond Rootstock Collection. *frontiers in plant science*, 1-18.
- [12]. Berbel, J., Gutierrez-Martin, C., and Exposito, A. (2018). Impacts of irrigation efficiency improvement on water use, water consumption and response to water price at field level. *Agricultural water Management*, 423-429.
- [13]. Bernacchi, C., and Kimball, B. (2006). Evapotranspiration, Canopy Temperature, and Plant Water Relations. *Managed Ecosystems and CO₂*, 311-324.
- [14]. Chiwasa, H., and Kambewa, D. (2018). Demand-based extension models for smallholder farmers in Malawi. *13th European IFSA Symposium* (pp. 1-12). Greece: Researchgate.
- [15]. Cosmas, L. H., Trout, T. J., Dejonge, K. C., Zhang, H., and Gleason, S. M. (2019). Water productivity under strategic growth stage-based deficit irrigation in maize. *Agricultural Water Management*, 433-440.
- [16]. El-Mageed, T. A., Semida, W. M., Taha, R. S., and Rady, M. M. (2018). Effect of summer-fall deficit irrigation on morpho-physiological, anatomical responses, fruit yield and water use efficiency of cucumber under salt affected soil. *Scientia Horticulturae*, 145-155.
- [17]. Fandika, R. L., Chipula, G., and Mwepa, G. (2020). Water Use Efficiency Differences in Maize Varieties under Every. *Sustainable Agriculture Research*, 17-29.

- [18]. Fischer, G., Darkwah, A., Kamoto, J., Kampanje-Phiri, J., Grabowski, P., and Djenontin, I. (2021). Sustainable agricultural intensification and gender-biased land tenure systems: an exploration and conceptualization of interactions. *International Journal of Agricultural Sustainability*, 403-422.
- [19]. Frake, A. N. (2019). *Scaling Irrigation and Malaria Risk in Malawi*. 789 East Eisenhower Parkway: ProQuest LLC.
- [20]. Frake, A. N., Namaona, W., Walker, E. D., and Messina, J. P. (2020). Estimating spatio-temporal distributions of mosquito breeding pools in irrigated agricultural schemes: a case study at the Bwanje Valley Irrigation Scheme. *Malaria Journal*, 1-21.
- [21]. Getts, M. (2018). Lack of Access to Water in Rural Malawi. *Ballard Brief*, 1-17.
- [22]. Gultekin, R., and Ertek, A. (2018). Effects of deficit irrigation on the potato tuber development and quality. *International Journal of Agriculture, Environment and Food Sciences*, 93-98.
- [23]. Hill, D., Nelson, D., Hammond, J., and Bell, L. (2021). Morphophysiology of Potato (*Solanum tuberosum*) in Response to Drought Stress: Paving the Way Forward. *Frontiers in Plant Science*, 1-19.
- [24]. Hooshmand, M., Albaji, M., Nasab, B. S., and Ansari, A. (2019). The effect of deficit irrigation on yield and yield components of greenhouse tomato. *Scientia Horticulturae*, 84-90.
- [25]. Kassaye, K. T., Yilma, W. A., Fisha, M. H., and Haile, D. H. (2020). Yield and Water Use Efficiency of Potato under Alternate Furrows and Deficit Irrigation. *International Journal of Agronomy*, 1-11.
- [26]. Lipan, L., Carbonella-pedro, A., Rodriguez, B., Duran-Zuazo, V., Tarifa, D., Garcia-Tejero, I., .
- [27]. Hernandez, F. (2021, May 15). *Agriculture*. Retrieved from MDPI: <https://doi.org/10.3390/agriculture11050448>.
- [28]. Liu, Y., Han, M., Zhou, X., Wei, L., Du, C., Zhang, Y., . . . Wang, Z. (2022). Optimizing nitrogen fertilizer application under reduced irrigation strategies for winter wheat of the north China plain. *Irrigation Science*, 255-265.
- [29]. Mabhaudhi, T., Mpandeli, S., Nhamo, L., Senzanje, A., Petrova Chimonyo, V. G., and Modi, A.
- [30]. T. (2019). Options for Improving Agricultural Water Productivity Under Increasing Water Scarcity in South Africa. *3rd World Irrigation Forum* (Pp. 1-17). Bali: 3rd World Irrigation Forum.
- [31]. Mabhaudhi, T., Nhamo, L., and Mpandeli, S. (2021). 1 - Enhancing crop water productivity under increasing water scarcity in South Africa. *Climate Change Science*, 1-18.
- [32]. Mthembu, S. G., Magwaza, L. S., Mashilo, J., Mditshwa, A., and Odindo, A. (2022). Drought tolerance assessment of potato (*Solanum tuberosum* L.) genotypes at different growth stages, based on morphological and physiological traits. *Agriculture Water Management*, not specified.
- [33]. Nyawade, S. O., Karanja, N. N., Gachene, C. K., Schulte-Geldermann, E., and Parker, M. (2018). Effect of potato hilling on soil temperature, soil moisture distribution and sediment yield on a sloping terrain. *Soil and Tillage Research*, 24-36.
- [34]. Onishi, J., Ikeura, H., Paluashova, G. K., Shirokova, Y. I., Kitamura, Y., and Fujimaki, H. (2019). Suitable inflow rate and furrow length for simplified surge flow irrigation. *Paddy and water Management*, 185-193.
- [35]. Passarelli, S., Mekonnen, D., Elizabeth, B., and Ringler, C. (2018). Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania. *Food Security*, 981-997.
- [36]. Patnaik, G. P., Srinivasan, G., Subash, K., Bose, C., Saphagiri, S., Varshini, S., and Jeeva, M. (2022). Improving Water Productivity in Conservation Agriculture. In A. K. Rawat, *Advances in Agronomy* (pp. 1-21). Rohini: AkiNik Publications.
- [37]. Qin, J., Ramirez, D. A., Xie, K., Li, W., Yactayo, W., Jin, L., and Quiroz, R. (2018). Is Partial Root-Zone Drying More Appropriate than Drip Irrigation to Save Water in China? A Preliminary Comparative Analysis for Potato Cultivation. *Potato Research*, 391-406.
- [38]. R.E. A., El-Shawadfy, Ghoname, A., and Ragab, R. (2020). Improving Crop Production And Water Productivity Using New Field Drip Irrigation Design. *Plant Archives*, 3553-3564.
- [39]. Sable, R., Kolekar, S., Gawde, A., Takle, S., and Adesh, P. (2019). A Review on Different Irrigation Methods. *International Journal of Applied Agricultural Research*, 49-60.
- [40]. Sarker, K. K., Hossain, A., Timsina, J., Biswas, S. K., Malone, S. L., Alam, M. K. and Bazzaz,
- [41]. M. (2020). Alternate furrow irrigation can maintain grain yield and nutrient content, and increase crop water productivity in dry season maize in subtropical climate of South Asia. *Agricultural Water Management*, 106229.
- [42]. Scoones, I., Murimbarimba, F., and Mahenehene, J. (2019). Irrigating Zimbabwe after Land Reform: The Potential of FarmerLed Systems. *Water alternatives*, 88-106.
- [43]. Semida, W. M., Abdelkhalik, A., Rady, M. O., Marey, R. A., and El-Mageed, T. A. (2020).
- [44]. Exogenously applied proline enhances growth and productivity of drought stressed onion by improving photosynthetic efficiency, water use efficiency and up-regulating osmoprotectants. *Scientia Horticulturae*, 95-80.
- [45]. Shammout, M. W., Qtaishat, T., Rawabdeh, H., and Shatanawi, M. (2018). Improving Water Use Efficiency under Deficit Irrigation in the Jordan Valley. *Sustainability*, 1-12.
- [46]. Sharma, B. R., Gulati, A., Mohan, G., Manchanda, S., Ray, I., & Amarasinghe, U. (2018). *Water Productivity Mapping of Major Indian Crops*. New Delhi: NABARD and ICRIER.

- [47]. Stark, J., Love, S., King, B., Marshall, J., Bohl, W., and Salaiz, T. (2013). Potato Cultivar Response to Seasonal Drought Patterns. *American Journal of Potato Research*, 207-216.
- [48]. Tejero, I. G., Hugo, V., Zuazo, D., Antonio, J., Bocanegra, J., Luis, J., & Fernandez, M. (2011). Improved water-use efficiency by deficit-irrigation programmes: Implications for saving water in citrus orchards. *Scientia Horticulture*, 274-282.
- [49]. Woldeslassie, A., Dechassa, N., Alemayehu, Y., Tana, T., and Bedadi, B. (2021). Soil and Water Management Practices as a Strategy to Cope with Climate Change Effects in Smallholder Potato Production in the Eastern Highlands of Ethiopia. *Sustainability*, 1-19.
- [50]. Yazdanpanah, M., Klein, K., Zobeidi, T., Sieber, S., and Lehr, K. (2022). Why Have Economic Incentives Failed to Convince Farmers to Adopt Drip Irrigation in Southwestern Iran? *Sustainability*, 1-15.
- [51]. *Sustainability*, 1-15.